Comparative thermodynamic and environmental performance of a unique cogeneration power plant using operational data

Whitney Domigan

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COMPARATIVE THERMODYNAMIC AND ENVIRONMENTAL PERFORMANCE OF A UNIQUE COGENERATION POWER PLANT USING OPERATIONAL DATA

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A Thesis Submitted in Partial Fulfillment of the Requirement for Masters of Science in Mechanical Engineering

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Finally, I would like to thank John Rich, Jim Dudish, and especially Jim Weaver from the power station. The data, time, and assistance are all greatly appreciated and made this research possible.
Abstract

The John B. Rich Memorial Power Station, located in the United States, is an 88.4 MW cogeneration power plant that has a unique relationship with its surrounding environment. The power station makes use of a plentiful and local byproduct of coal mining, called culm, as a feedstock. Culm is a low energy combination of anthracite coal, ash, and rock left over from the inefficient removal of rock from usable coal in the peak days of coal mining. For decades, culm deposits have leached pollution into groundwater and inhibited normal plant growth. By using culm, the power station removes a significant pollutant and eyesore from the area. Further, the power station is involved in a land reclamation program that covers land cleared of culm with topsoil and plant life. In order to process the culm, the power station utilizes two circulating fluidized bed (CFB) boilers. The current research uses actual plant data to explore the thermodynamic performance of the plant and discuss the environmental implications of the unique fuel choice. The current plant thermodynamic performance is compared to proposed plant improvement scenarios including the introduction of turbine reheat, an increased production of process steam, and an initial examination of optimal plant load scenarios.

The plant thermodynamic model is created in Matlab™ using about eight months worth of hourly data samples from the plant. Overall, 79 of the thousands of sensors through the plant are used to provide temperature, pressure, and flow rate data. The first and second laws of thermodynamics are used to analyze the plant components, including the boilers, turbine, feedwater heaters, and condenser. The thermodynamic analyses are performed in part to determine properties through the plant, mainly mass flow rates that are not recorded during plant operation, and in part to characterize plant performance. Before the exergy analysis of the boilers can be performed, the streams into and out of each boiler must be characterized in terms of composition, mass, and exergy. Although the energy content of the culm is regularly measured by the power station, the exergy content must be determined based on the culm composition, which is provided by the plant. The exergy content of the flue gas is also determined based on the culm composition.

Finally, the environmental impact of the plant is discussed. A number of upstream processes, such as culm transport and water demineralization, are examined and compared to the same values for a traditional coal fired plant and a wind farm. The use of land for the cogeneration plant is discussed and compared to the land use with the other two power conversion processes.
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<td>BI, BII</td>
<td>boiler model I, II</td>
</tr>
<tr>
<td>$\varepsilon^{CH}$</td>
<td>specific chemical exergy (kJ/kg)</td>
</tr>
<tr>
<td>$\varepsilon^{CH}$</td>
<td>standard molar chemical exergy (kJ/kmol)</td>
</tr>
<tr>
<td>$\bar{g}$</td>
<td>molar Gibbs function (kJ/kmol)</td>
</tr>
<tr>
<td>$h, \tilde{h}$</td>
<td>enthalpy in kJ/kg, kJ/kmol</td>
</tr>
<tr>
<td>HHV</td>
<td>higher heating value</td>
</tr>
<tr>
<td>DAF</td>
<td>dry and ash free</td>
</tr>
<tr>
<td>$l$</td>
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</tr>
<tr>
<td>$M_i$</td>
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<tr>
<td>$P$</td>
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<tr>
<td>$R$</td>
<td>reactant</td>
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<tr>
<td>$s, \bar{s}$</td>
<td>absolute entropy (kJ/kg-K), (kJ/kmol-K)</td>
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<td>$r$</td>
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**Subscripts**

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</tr>
<tr>
<td>cv</td>
<td>control volume</td>
</tr>
<tr>
<td>DAF</td>
<td>dry and ash free basis ultimate and proximate data</td>
</tr>
<tr>
<td>dry</td>
<td>dry basis ultimate and proximate data</td>
</tr>
<tr>
<td>o</td>
<td>standard reference</td>
</tr>
<tr>
<td>p</td>
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</tr>
<tr>
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<tr>
<td>u</td>
<td>useful</td>
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1. Introduction

1.1. Motivation
Over the course of the last few decades, the negative impact human activity can have on the environment has become increasingly apparent. With this realization has come a responsibility to strive for more sustainable, less environmentally harmful technologies. One such technology is a cogeneration power plant; where traditional power plants expel a great deal of waste heat through the energy conversion process, cogeneration power plants redirect “waste heat” to nearby buildings for heat and/or other processes.

Currently, the power sector produces about 70% of the SO₂, and 20% of the NOₓ emissions in the United States [1]. Obviously, the power sector is a huge contributor to many of today’s largest environmental problems, including acid rain, climate change, and general air, water, and land contamination. Alternatives to traditional power plants, such as cogeneration, can decrease the environmental impact of a plant, because fewer resources are needed to generate the same amount of benefit.

The importance and emphasis of improving power plant performance has increased as the government has taken an interest and policy stance on environmental issues, especially with emissions. Since the environmental and human health impacts of the power sector have become known, the government has stepped in to make sure companies behave responsibly in the management of their emissions. President Obama is planning on lowering the countrywide emissions to 80% below 1990 levels by 2050 [2], which is a huge goal. Today, power stations must not only move towards more environmentally responsible technologies for ethical reasons, but because they are, or may soon be, required to do so by law.

The “cap-and-trade” policy [3] has been implemented, requiring that a cap, or the total allowable emissions in a given program, be maintained. The total amount of emissions is parceled into “allowances”, which are units of emissions that can be traded between parties within the program. This policy allows for rewards for parties that have low emissions, as they may sell or not buy allowances, while still allowing for parties that have unavoidable emissions, as they can buy more allowances. If a cap on carbon dioxide is implemented, power plants which use coal based feedstock will be at a distinct disadvantage since any coal based plant produces a great deal of CO₂.

It is with consideration of the above issues- environmental awareness, the harm caused by emissions, and both current and upcoming government policy- that this work is undertaken. The power plant examined in the following pages offers a unique take on the environmental, economic, and policy aspects surrounding the power generation process. It is desirable to quantify where and how this plant is better or worse than comparably sized facilities that are generally considered better or worse sources of electric energy in terms of environmental impact. The current plant will also be compared to a number of improvement scenarios to examine how changes to the plant affect its performance.
1.2. **Statement of Work**

The motivation for this work is to quantify the performance of the cogeneration power plant and compare it to improvement scenarios and other power conversion technologies. The plant performance and the performance of the improvement scenarios will be quantified using thermodynamic and environmental indicators. A thermodynamic model will be generated and implemented using energy and exergy methods. This analysis builds off of a previous analysis of the plant by Bailey et al. [4]. Matlab™ and SimaPro software will be used for the thermodynamic model and the environmental analyses, respectively.

Exergy, also known as available energy, is a second law of thermodynamics based quantity that represents the energy of a system with regards to a reference environment. An exergy analysis will gauge not only the quantity of various energy streams, but the *quality* of the energy. Externalities and lifecycle assessments will also be used through this work. A lifecycle assessment may be used to quantify the environmental impacts of a system over the course of its entire life (construction, use, and decommissioning), however, a full LCA will not be performed on the cogeneration power plant. An externality analysis focuses on impacts a system has, positive or negative, which are not accounted for by market forces (i.e. the owners of the system do not exchange money for damages or benefits their system causes).

1.2.1. Define System Boundaries and Reference States

The definition of system boundaries can have a large effect on the analysis outcome since where boundaries are set determine which streams enter or exit the system. It is therefore necessary to thoughtfully and deliberately establish the boundaries that will best define where energy and exergy enter or exit the system. Any material that passes through the boundary should ideally be considered in subsequent analyses.

Since the exergy of a system is relative to a reference state, the reference state data is important for the exergy analysis. The previous model chose reference state values based on standard data. This work will select reference state variables to be as close to the environment around the plant as possible.

1.2.2. Extension of Thermodynamic Model Using Operational Data

A thermodynamic model of the plant is developed using Matlab™. The analysis of the plant by Bailey et al. [4] relied on one set of analytical data to determine the temperatures, pressures, and flow rates. Although the previous analysis is a useful validation tool, it does not rely on actual plant data or account for changes in plant load across an extended period of time. The new thermodynamic model, which includes first and second law analyses, relies on operational data from the plant whenever possible. The model is verified to be both self consistent and consistent with what is known about the plant. The model will further serve as a baseline from which other electricity generating technologies and plant improvements may be compared.

Matlab™ is primarily used to create the thermodynamic model. A number of Matlab™ subprograms were found through the Matlab™ website to determine certain thermodynamic properties and create diagrams. The program
Engineering Equation Solver (EES) is used to generate T-s and p-h diagrams of the feedwater passing through various points of interest through the plant.

1.2.3. Performance Parameters

Three areas must be considered in an externality study: human health, environmental health, and resource depletion. A number of indicators from literature [5,6] will be used to establish a baseline for the power plant. These indicators include: first law efficiency, exergetic efficiency, cost of exergy destruction, environmental impact factor, and production cost. A number of exergy and energy flow diagrams will also be helpful [7,8].

1.2.4. Improvement Scenarios

Potential areas of improvement will be identified throughout the plant based on found inefficiencies and areas of waste. Possible solutions will be proposed while keeping in mind that the interactions between components may be such that addressing large efficiencies for specific components may not decrease the total impact of the plant [5]. It is likely that different power plant designs will yield higher and lower results for different indicators. It will be necessary to prioritize the importance of each indicator in order to identify the best overall design. The improvements will be brought to the attention of the power plant management with the hopes of implementing at least one suggestion.

1.2.5. SimaPro and Environmental Considerations

SimaPro software [9] uses extensive databases from all over the world to create lifecycle assessments for many processes. After a model of a certain process is created, SimaPro will calculate various inputs and outputs, such as emissions, land use, and raw materials used, generated by the system over the course of its life. By quantifying the in streams and out streams from a system or process, SimaPro helps quantify the environmental impacts of the plant. The SimaPro software will also be used to model two additional energy conversion technologies— a coal fired plant and a wind farm. The emissions of each scenario will be compared to help determine the relative environmental impact of each technology.

The environmental performance of the plant will be gauged in part by approximated emissions levels, which will be based on the fuel composition and use, as well as simple combustion reactions, and in part by SimaPro modeling of certain processes associated with the plant. The land use and fuel use will also be considered when examining the plant.

1.2.6. Comparisons

The objective of this work is not only to examine the plant, but to examine what makes the plant different from others, how it is different, and quantify, to some extent, the differences. It is also important to examine what could make the plant perform better, in terms of thermodynamic and environmental performance, than it does now. The thermodynamic model of the plant as it is now will serve as a baseline. The baseline will be compared in two categories: other current technologies, and to the same plant with possible improvements. Each comparison will be
made using indicators, such as first law efficiencies, exergetic efficiencies, and resource use, quantified through the thermodynamic model or found through literature. As far as possible, the economic, environmental, and thermodynamic performance of each comparison will be quantified.

After the plant improvements have been identified, the improvements will be modeled by modifying the baseline thermodynamic model in Matlab™. The improvements will be proposed only for certain components, further expediting the analysis process. The indicator values for the current design will be compared to the values for the improvement scenarios and for the coal power plant and wind power farm.

1.2.7. Changes to Original Statement of Work

Only a few small changes and changes in emphasis have occurred between the original statement of work and the content of this thesis. Due to complications obtaining operational and other required data, the externalities of the cogeneration power plant are not as thoroughly investigated as originally planned.
2. Background and Literature Review

The plant relevant to this research is complex and unique. This chapter will briefly go over the plant layout, available data pertaining to the plant, and the boiler technology. A brief discussion of the relevance and unique aspects of this work are given. Also included are relevant discussions on current and past research in the fields of thermodynamics, externalities and lifecycle assessments, environmental studies, thermoeconomics, and analytical tools and methodologies.

2.1. Brief Overview of the Plant

The John B. Rich Memorial Power Station, located in Frackville, PA, is an 88 MW cogeneration power station that uses culm as a feedstock. The plant uses two circulating fluidized bed (CFB) boilers to heat steam, which then runs through an eighteen stage turbine to produce electricity. The turbine has five extraction points from which small amounts of steam are drawn for process loads or for use within the plant’s five feedwater heaters. Of the feedwater heaters, four are closed and one is open. The open feedwater heater is called a deaerator (DA). The plant cooling system is comprised of a condenser and four cooling towers. Each plant subsystem will be described in further detail in Chapter 3. An illustration of the plant is shown in Figure 2.1 [10].

Figure 2.1: Illustration of the John B. Rich Memorial Power Station processes.

Cogeneration power systems typically produce both electrical and thermal energy [11]. In a non-cogeneration power plant, a large amount of heat is lost through the overall electricity production process. For example, when
steam is produced and passes through a turbine, it often still contains a great deal of energy, however the steam is usually fed into a condenser and the energy is wasted. Cogeneration power systems capture some of that energy in the form of heat and put it to use, often in space or process heating applications. Because the same amount of fuel may be used to produce two energy products, the negative impacts of cogeneration power plants are generally lower than their non-cogeneration counterparts. The exergetic efficiencies of cogeneration plants also tend to be higher because the plant waste heat is reduced and two useful products are produced.

The most unique aspect of this particular plant is the fuel used. Since culm deposits are environmentally harmful and aesthetically displeasing, the use of culm has positive impacts on the surrounding area. The plant also has a land reclamation program in which the land that has been cleared of culm (about 4 acres a year) is covered with layers of ash, topsoil, and plant life. This creates an interesting interaction with the environment: the plant releases emissions, including particulate matter, CO₂, SOₓ, and NOₓ, into the air, but it also cleans up culm, reclaims land, and avoids the production and transportation of another fuel source.

The plant produces three products: electricity, process steam, and ash. The electricity is sold to PPL, a utilities company (formerly known as Pennsylvania Power & Light [12]). The steam is sent to an adjacent prison facility as process heat. After a screening process for sizing, bottom ash may be sold to the Pennsylvania Department of Transportation for slippery roadway reduction in the winter. The bottom ash has also been approved for use in residential septic systems that use sand mounds. The plant ash was used in concrete until 1997 when a change caused an increase level of carbon in the ash streams.

The plant began operations in 1987 and has a reported on-line status of 92%. A major scheduled shut down occurs each October and a minor shutdown in the spring for regular maintenance, although unscheduled shutdowns occasionally occur.

2.2. Methodology for Current Study

In order to perform an effective analysis on the culm-fired plant, a number of steps were taken. First, the layout of the plant, including an understanding of important and negligible subsystems of the plant is required. The descriptions of the plant-subsystems can be found from Sections 3.2-3.5 and an overview of the total plant system in Section 3.6. The system boundaries can then be drawn and appropriate reference condition selected.

The thermodynamic model of the plant depends largely on the data available from the plant. Although the plant records temperatures, pressures, and flow rates through many areas of the plant, not every desirable piece of data is available. The model is therefore built from not only an understanding of the plant components, but from the available data. The available data also helps inform assumptions for each of the plant components, since unavailable data means the properties must be found alternative ways.

Ideally, each component of the plant would be addressed separately and examined for possible improvements and then examined all together at the end. When the whole plant is examined, it is necessary to employ an iterative
process, as suggested by Giannantoni et al. [5], as an improvement in one sub-system of the plant will affect the performance of other sections. In this work, certain sub-systems are examined for improvements independent of the rest of the plant.

Thermodynamic performance parameters, such as energy and exergy efficiencies, will be generated for each sub-system of the plant as well as the plant as a whole. Matlab™ will be used to model the plant. Matlab™ will also be used for some environmental analysis, mainly the emissions produced by the plant.

After the models have been created, results are validated. Some of the validation is using common sense, some is checking for self-consistency, and some is comparing to literature to see if the results are reasonable.

Giannantoni et al. [5] suggest that a system, particularly a power producing system, can be improved in six major categories: energy, exergy, thermoeconomic, environmental evaluation, and economic. In order to improve an existing system, energy, exergy, and thermoeconomic analyses should first be conducted to determine sources of irreversibility and major inefficiencies. Because of limited costing data, an accurate thermoeconomic analysis is not possible for the cogeneration power plant. For this reason, improvements are based on energy and exergy analyses. When improvements are suggested, each proposal is examined from an environmental standpoint. If appropriate data were available, improvement scenarios would also be examined from an economic standpoint.

McMasters [13] describes a methodology using least squares to determine the unit cost of delivering electricity and steam from a cogeneration power plant. The unit costs are found using the known boiler steam required per unit time, the amount delivered steam per unit time, and the amount of electricity generated. Least squares are used to determine the ratio between pound mass boiler steam generated and pound mass delivered steam, the ratio between pound mass boiler steam generated and kWh delivered electricity, and the internal steam usage. The ratio values can be multiplied to the unit cost of boiler steam to determine the unit cost of delivered steam and delivered electricity.

After the thermodynamic analysis of the plant and the improvement scenarios are performed, a partial lifecycle assessment (LCA) of the plant is performed using SimaPro and qualitative assessments. A SimaPro model of a wind farm and a coal fired plant are also generated in for the sake of comparison and gauging the relative benefits of each system.

### 2.2.1. Graphical Tools

Dincer et al. [14] provide straightforward and useful tools for calculating simple energy and exergy efficiencies for various power plants. Combined energy and exergy diagrams are also highlighted as an effective and compact way to display energy and exergy efficiencies. Wall [8] presents a number of useful exergetic analysis tools including exergetic efficiencies, two types of exergy flow diagrams, exergy utility diagrams (EUDs), lifecycle exergy analysis (LCEA), and exergy economy optimization (EEO). Examples of energy and exergy flow diagrams may be seen in Figure 2.4 (see Section 2.9).
Soeno et al. [15] address the issue of a system’s environmental impact through the quantification of waste material exergy. The researchers determine the exergy flow by summing the exergy of the products, material waste, exhaust heat and losses, and entropy production. The exergetic analysis can be displayed through diagrams that display both exergy and mass flow of a process. Each stage of a process is represented by an equilateral triangle; one side represents input resources, one side represents the products, and the last side represents the material waste. Arrow length is used to represent the magnitude of the exergy and the width is used to signify the mass. Three types of exergy are considered: thermal, chemical, and exergy due to concentration differences.

Not every diagram described above will be useful in this analysis. Energy and exergy diagrams will be generated using Matlab™ to highlight the usefulness of exergy when compared to energy.

2.2.2. Uncertainty

A common concern is found throughout literature concerned with externalities and lifecycle assessments; there is no one set of assumptions, especially in terms of costs, or one scale (for comparing different impacts) by which LCA and externality studies are performed [16, 17]. The non-standard assumptions and scales, along with the impact of boundary and scope definitions, in LCA and externality studies create a wide spectrum of possible outcomes, even when given the same system or process. It is therefore important to acknowledge and minimize uncertainties when performing either of these analyses.

Söderholm and Sundqvist [16] examine the difficulties of placing monetary value on externality parameters. Depending on methods used, the monetary values can vary. A graphical display of a survey of externality costs generated by various power generation methods is given. The graph shows a wide range of costs given due to differing assumptions, conditions, and assigned values.

Spadaro and Rabl [18] present a practical, simple, and transparent method of calculating the uncertainty associated with the damage costs of pollution. The presented method, as opposed to the more common use of Monte Carlo calculations, may be evaluated in a spreadsheet using sums and products.

2.2.3. Software

Matlab™ is used throughout this work to process the plant data and calculate the desired indicators and efficiencies. Two freeware Matlab™ packages are used to access thermodynamic properties for water and air: X-Steam [19] is used to determine the properties of water at various pressures and temperatures, while the IdealAir [20] package is used to determine the properties of air. As implied by the second package name, all air calculations assume an ideal gas model. Another Matlab™ package, called drawSankey [21], is used to create the energy and exergy diagrams. Engineering Equation Solver [22], or EES, is used for the creation of T-s and P-h diagrams. One of the main benefits of this program is its extensive thermodynamic property reference library.
For the lifecycle assessment side of the analysis, as well as the modeling of the coal fired plant and the wind farm, the SimaPro [9] software from PRé Consultants will be used. This particular software is structured in accordance with the ISO 14040 LCA standards.

### 2.3. Relevance of Current Research

There is research throughout literature about how to improve and quantify power plant performances. Analyses cover coal plants, cogeneration plants, gas plants, and a variety of other common and uncommon technologies. The data used for these analyses, however, are average or estimated temperatures, pressure, and flow rates. The raw data available for this research is immense. The results produced from this analysis use actual data whenever it is available. The data is taken from about eight months of plant operations. The data covers the plant at full load, half load, transitional loads, and at full power down. The availability of data also offers many opportunities to validate the generated thermodynamic models.

Other research and analyses about power systems in literature often concentrate their efforts on either a single plant component or the overall plant performance. This research offers a detailed examination of a complex power system at both component and total system levels.

Not only is a great deal of data available for this work, but the accessibility and assistance of plant personnel from the start to finish of the work were invaluable. Two visits were made to the power plant for tours, data collection, and interviews with the Plant Manager (Jim Dudish) and Plant Engineer (Jim Weaver). When operational data is not available, it was often on the advice and experience of the Mr. Weaver that acceptable assumptions were made. There is an opportunity with this research to directly consult with the plant personnel about suggested plant improvements.

This research builds off of the efforts of Bailey et al. [4], but expands the breadth of the research and increases detail and accuracy. The thermodynamic boiler analysis of the previous analysis was stalled by insufficient information about the exergy content of the fuel and flue gas. This work includes calculations for the exergy of both streams. The previous analysis did not have access to the plant operational data, and so the analyses relied on second party plant analyses and estimated data provided by the plant.

This work will not only examine the current plant performance, but compare the plant to improvement scenarios and to other electricity generating systems. The improvement scenarios include both hardware and controls changes for specific components of the plant. Once the analysis is complete the results will be given to the plant for examination.

The power plant examined in this work has unique interactions with the surrounding environment because of the fuel use and boiler technology. Whereas traditional coal or coal based power plants require newly mined fuel, the cogeneration power plant uses a waste material that is found in abundance within 20 miles of the plant. The fuel is also a pollutant, so while the plant does put out emissions, it also cleans up another source of environmental harm.
The unique aspects of this plant make the comparison to more traditional electricity production more interesting. The fuel use also brings up interesting questions about governmental policy and how to account for both the environmental good and bad aspects of such a unique plant. Although the previous analysis examined the environmental side of the plant, this research goes into greater detail and makes comparisons with other electricity producing systems.

2.4. **Plant Data**

The analyses of this work are based on actual operational data whenever possible. Data used includes culm composition samples, emissions levels, and operational data (temperature, pressure, and flow rates).

Culm samples are taken between the processing facility and the plant on a monthly basis for ultimate and proximate analyses, which check the fuel’s quality and composition. If a certain fuel sample is found to be below standard, weekly samples are taken until it is assured that the fuel quality has returned to the expected level. The actual culm composition and a description of the ultimate and proximate analyses are described in Section 2.5.

The plant is required by state and federal law to collect various emissions data including NOx, SOx, particulate emissions, and, recently, CO2. Emission samples are drawn and analyses at the stack and so are the combined effects of combustion from both boilers. The plant stack releases the flue gas into the air after the fly ash has been filtered out. The data is collected using a Continuous Emissions Monitoring System (CEMS), which, as the name implies, takes continuous data samples of regulated emissions to ensure the plant complies with all environmental policies.

An almost continuous record of temperatures, pressures, flow rates, fluid levels, and valve positions is kept for locations of interest throughout the plant. Depending on the importance of a given property at a given location in the plant, samples may be taken many times a second to every few seconds. The data is stored on a history server. Because of a change is the recording software, only data after June 2009 is available for this analysis.

2.5. **Culm**

The cogeneration power plant of this work uses culm as a feedstock. Culm is a byproduct of anthracite coal mining. During the late 1800s and early 1900s at the peak of anthracite coal mining in Pennsylvania, young boys, called “breaker boys” were employed at coal mines to separate out usable coal from the mined material. An example of how the boys worked is shown in Figure 2.2.

Because this sorting method was very crude, a certain amount of coal was sorted out with the rock. The rejected material is what is now called culm. Since culm has low energy content relative to high quality anthracite coal, and because, at the time, there was no economical use for the waste material, culm was left out in huge piles and abandoned. When left in these deposits, culm leaks pollutants, such as aluminum, iron, and sulfates [23] into the soil, making it impossible for normal plant life to grow. More recently, circulating fluidized bed boiler technology has made the use of culm as an energy source economically feasible.
The difference between culm and anthracite coal may be observed in Table 2.1. The ultimate and proximate analyses are two standard methods for determining the composition of coal based fuels. Ultimate analyses determine the individual elemental composition of the fuel, whereas proximate analyses focus on the major components of moisture, ash, carbon and volatile matter. The anthracite coal data is sampled from the Mammoth and Big Lykens seams in Pennsylvania [25]. The culm data is averaged from monthly culm samples taken from the feedstock entering the power station.

Since coal is created from plant matter that has been changed over time with pressure and heat, there is no fixed structure or composition. The variability of coal is seen in Table 2.1, but even with the differences, it is possible to see that, in general, culm has a much higher percentage of ash, a much lower percentage of carbon, and much lower energy content than anthracite.

Table 2.1: Comparison of Anthracite coal composition to anthracite culm composition.

<table>
<thead>
<tr>
<th></th>
<th>As received weight percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Anthracite</td>
</tr>
<tr>
<td><strong>Proximate Analysis (%)</strong></td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>2.1-2.3</td>
</tr>
<tr>
<td>Volatile Matter</td>
<td>3.1-7.5</td>
</tr>
<tr>
<td>Fixed Carbon</td>
<td>80.3-87.7</td>
</tr>
<tr>
<td>Ash</td>
<td>6.9-10.1</td>
</tr>
<tr>
<td><strong>Ultimate Analysis (%)</strong></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>80.9-86.7</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>2.2-3.3</td>
</tr>
<tr>
<td>Oxygen</td>
<td>2.9-4.2</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.5</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.8-1.0</td>
</tr>
<tr>
<td><strong>Heating Value</strong></td>
<td>31,300-31,400 (13,480-13,540)</td>
</tr>
</tbody>
</table>
2.5.1. ASTM Standard Testing

Ultimate and proximate analyses are tests used in industries which use coal based products. These tests are commonly used to insure the quality of fuel by examining the high energy components of the fuel (carbon) next to the components which generally lower the quality of the fuel (moisture and ash). Two standard practices are followed for culm testing: the Standard Practice for Ultimate Analysis of Coal and Coke (ASTM standard D 3176) and Standard Practice for Proximate Analysis of Coal and Coke (ASTM standard D 3172).

The ultimate analysis is used to find the specific composition of the fuel in terms of moisture, carbon, hydrogen, sulfur, nitrogen, ash, and oxygen content. Although the sulfur and nitrogen content do not greatly affect the higher heating value of the fuel, they have an impact on the emissions that will be expected when the fuel is burned. The ultimate analysis produces four sets of data: as-determined, dry, as-received with H and Oₓ, and as-received without H and Oₓ. Within the as-determined data carbon, hydrogen, sulfur, nitrogen, and ash are measured directly from the sample from either the combustion of the material or chemically (as with nitrogen) as required by the standard ASTM procedures. When a test is said to be “with H and Oₓ,” it is implied that the H and Oₓ in the moisture are counted towards the H and O composition categories in the analysis. If H and Oₓ are not included, the H and Oₓ present in the moisture are excluded.

The proximate analysis is more concerned with the fuel components that have a large impact on the energy content of the fuel. The proximate analysis determines the moisture, ash, volatile matter, and fixed carbon of the fuel. The fixed carbon is the main source of energy in fuel, and so the percent fixed carbon is indicative of quality. Ash is mainly inert during combustion, but serves to “dilute” the carbon, thus lowering the energy per unit mass of the fuel. Volatile matter refers to the components of coal, such as sulfur, that are released from the coal at high temperatures. Moisture readily decreases the heat content of the fuel since energy is absorbed during evaporation.

The culm samples are collected as the culm moves from the culm processing facility to the power plant. Daily culm samples are taken and compiled for a monthly composite analysis performed by an outside lab according to the below ASTM standards. For the purposes of the boiler analysis of this work, the as-received without H and Oₓ will be used in order to best represent the composition of the fuel as it enters the boiler.

2.6. Ash

Ash is left over after the combustion of a fuel. In this research, two types of ash arise after culm combustion: fly ash and bottom ash. Fly ash is a fine, powder like residue. Since the fly ash particles are so small, they are not captured when the fluidized particles in the boiler leave the boiler bed and so they exit the boiler with the flue gases. The fly ash is later separated from the gas in the plant baghouse, which uses filters and air pressure to separate out the ash particles.

Bottom ash is composed of larger particles, about the size of gravel, that are removed from the boiler at the bottom of the cyclone chamber. Bottom ash will occasionally fuse together in the high temperatures of the boiler and form
“clinkers”. Clinkers may range from the size of a baseball to larger than a person. Clinkers can cause problems in the boilers because when they are large enough they rest on the boiler bed and can reduce airflow into the boiler.

The quantity of fly ash and bottom ash is important for the thermodynamic model of the boiler since each type of ash leaves the boiler at a different location and temperature. The ash content of culm is measured monthly, however, the power station does not track the total amount of each type of ash after they leave the boiler. Some past analyses were performed to estimate the split between the two types of ash. Results of these studies varied between 40% bottom ash, 60% fly ash to the opposite, so the best guess estimate is a 50/50 split between the two [26].

The power plant has previously performed analyses of the trace elements found in culm ash. Table 2.2 summarizes the findings from the trace analysis given in parts per million (PPM). Since ash is the residue of the fuel once all combustible materials have been depleted, ash may be viewed as the inert material in a given fuel. From this perspective, it may be seen that the exergy of ash is zero, since it is already at equilibrium with its surroundings.

<table>
<thead>
<tr>
<th>Trace Element</th>
<th>Concentration in Culm (PPM)</th>
<th>Concentration in Fly ash (PPM)</th>
<th>Concentration in Bottom Ash (PPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>4316.7</td>
<td>23333.3</td>
<td>16483.3</td>
</tr>
<tr>
<td>Antimony</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Arsenic</td>
<td>11.5</td>
<td>32.9</td>
<td>21.8</td>
</tr>
<tr>
<td>Barium</td>
<td>56.9</td>
<td>188.2</td>
<td>137.2</td>
</tr>
<tr>
<td>Boron</td>
<td>0.7</td>
<td>6.8</td>
<td>6.1</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.3</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Chromium</td>
<td>7.0</td>
<td>34.6</td>
<td>22.9</td>
</tr>
<tr>
<td>Cobalt</td>
<td>5.5</td>
<td>6.2</td>
<td>2.9</td>
</tr>
<tr>
<td>Copper</td>
<td>39.9</td>
<td>34.8</td>
<td>17.2</td>
</tr>
<tr>
<td>Lead</td>
<td>29.7</td>
<td>28.5</td>
<td>16.5</td>
</tr>
<tr>
<td>Manganese</td>
<td>87.6</td>
<td>102.9</td>
<td>70.7</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>2.2</td>
<td>10.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Nickel</td>
<td>11.0</td>
<td>13.9</td>
<td>7.9</td>
</tr>
<tr>
<td>Selenium</td>
<td>11.1</td>
<td>13.8</td>
<td>6.0</td>
</tr>
<tr>
<td>Silver</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Zinc</td>
<td>33.8</td>
<td>32.3</td>
<td>15.9</td>
</tr>
<tr>
<td>Ph</td>
<td>3.4</td>
<td>11.8</td>
<td>11.6</td>
</tr>
</tbody>
</table>

### 2.7. **Circulating Fluidized Bed Boilers**

Circulating fluidized bed (CFB) boilers are a type of boiler technology often used to burn low energy content solid fuels, such as municipal waste and culm. The culm only requires only a small amount of processing before entering the boiler. In a fluidized bed boiler, the fuel particles are suspended in an upward moving gas stream in such a way
as to behave as a fluid [27]. A range of fluidization may occur depending on the type of boiler and the point in the start up process for the boiler.

Figure 2.3 [28] shows the three major stages of a fluidized bed boiler: the combustion chamber, cyclone, and economizers. The chamber on the far left is the combustion chamber where the majority of combustion occurs. The fuel, sorbent, and air are fed into the combustion chamber. The cyclone chamber, middle, separates the fine fly ash from the heavy bottom ash and un-combusted fuel. The heavier materials fall to the bottom of the cyclone chamber and are fed back into the bottom on the combustion chamber. The final chamber on the right contains the superheaters and economizers.

Figure 2.3: Example of a large scale CFB boiler.

A CFB boiler is a type of fluidized bed boiler in which the particles are fluidized in the bed, are captured and separated from the gas when they leave the bed, and then are returned to the bed, thus circulating in a loop. Since the fuel particles pass through the combustion chamber more than once, they have a longer residence time, which allows the bed temperature to be lower while maintaining a low level of unburned fuel. The lower bed temperature results in environmental benefits in terms of lower emissions. As will be explained further in Section 2.8, the
The majority of NO\textsubscript{x} emissions are generally created at temperatures well above that of a CFB boiler. The low temperatures also allow for sorbents to be added to the combustion chamber. Sorbents dissociate in the combustion heat and then associate with SO\textsubscript{x} to capture them in a benign form.

### 2.8. Emissions

Emissions from power plants are environmentally harmful, especially since they are emitted on such a large scale. There are three major emission types of concern in this research: NO\textsubscript{x}, SO\textsubscript{x}, and CO\textsubscript{2}. Other emissions such as particulate matter are also regulated.

The Clean Air Act was first passed in 1970 in order to reduce air pollution and the harmful impacts thereof. Human and environmental health are both considerations for this legislation. Since 1970 the bill has changed forms until the most recent version, which was released in 1990 [29]. The Clean Air Act targets six common pollutants, classified as “criteria pollutants”: particle pollution, ground level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead [30]. The electricity generator sector is a huge contributor to these pollutants, and so each regulation has large ramifications to power plants.

#### 2.8.1. NO\textsubscript{x}

Nitric oxide emissions, NO\textsubscript{x}, may take many forms, including NO or NO\textsubscript{2}. Nitrogen dioxide causes a number of adverse health effects including respiratory irritation as well as contributing to acid rain [31,32]. The Clean Air Act covers the entire NO\textsubscript{x} family, but NO\textsubscript{2} is of the greatest concern because of its known impact on human health and its prevalence.

Nitric oxide emissions are formed a number of ways, but two of the most relevant to power production will be discussed here. At high temperatures, nitrogen from the air combines with oxygen to form NO\textsubscript{2}; this is referred to as thermal NO\textsubscript{2}. Fuel NO\textsubscript{x} is generated from the nitrogen embedded in a given fuel source that combines with oxygen during combustion. Nitric oxide (NO) is thermodynamically favored over NO\textsubscript{2} at temperatures below 1480°C [33] meaning that it is produced in greater quantities than NO\textsubscript{2} at low temperatures, such as those seen in CFB boilers. The opposite is true in traditional coal fired plants where boiler temperatures are well above the reaction temperature for NO\textsubscript{2} production [34]. Thermal NO is formed through three reactions:

\begin{align*}
N_2 + O &\rightarrow NO + N \quad (2.1) \\
N + O_2 &\rightarrow NO + O \quad (2.2) \\
N + OH &\rightarrow NO + H \quad (2.3)
\end{align*}

Fuel NO is formed through the following reaction (2.4) [34] where HCN and NH\textsubscript{3} are common compounds found in coal that include nitrogen.
HCN/NH₃ + O₂ → NO + ... \hspace{2cm} (2.4)

### 2.8.2. SOₓ

Sulfur dioxide is linked to respiratory problems, as well as contributing to acid rain [32]. Around 66% of SO₂ emissions are generated by the combustion of fossil fuels for power generation [35]. Sulfur dioxide is formed when the sulfur component of a fuel reacts with oxygen as shown in reaction (2.5).

\[ S + O₂ → SO₂ \] \hspace{2cm} (2.5)

When possible, power plants such as this cogeneration power plant may add sorbents, such as limestone, to the combustion chamber. Sorbents act to capture the SO₂ generated through combustion. When limestone is used, SO₂ is captured through reactions (2.6) and (2.7).

\[ CaCO₃ → CaO + CO₂ \] \hspace{2cm} (2.6)

\[ CaO + SO₂ + 0.5O₂ → CaSO₄ \] \hspace{2cm} (2.7)

### 2.8.3. CO₂

Carbon dioxide is the most prevalent greenhouse gas, largely because it is produced in large quantities when carbon based fuels are burned. In 2008, the United States produced 5,833 million metric tons of CO₂ from the consumption of fossil fuel [36]. Of those millions of metric tons, 2,125 million (36.4%) were from coal consumption [37].

Carbon dioxide is created during two reactions that occur within the boiler. The first reaction is from the direct conversion of carbon in the coal and oxygen in the air to carbon dioxide, as seen in reaction (2.8).

\[ C + O₂ → CO₂ \] \hspace{2cm} (2.8)

The second way in which CO₂ is generated is from the dissociation of limestone (CaCO₃) in the high temperatures of the boiler. Carbon dioxide is only formed this way when limestone is added as a sorbent to capture SO₂ as seen in Equation (2.6).

The two CO₂ producing reactions contribute to the total emissions of CO₂ in the power plant in question. Carbon dioxide emissions may be reduced in two ways: improve the efficiency of the plant so less fuel is burned for the same power output, causing less CO₂ to be generated for the same amount of power exported, or by capturing the CO₂ after it has already been produced.
Methods for improving plant efficiency include increased responsiveness of controls, improved insulation throughout a power plant, and redirection of waste streams to be used elsewhere. One method of reducing CO\textsubscript{2} production is called oxy-fuel combustion, which improves the efficiency of carbon based fuel combustion by combusting the fuel in a mixture of oxygen and re-circulated flue gas under high pressures [38].

The most practical methods of CO\textsubscript{2} reduction today is to capture the CO\textsubscript{2} after it has been produced. This method allows auxiliary systems to be added after the fact to current systems, which produce high levels of CO\textsubscript{2}. After the combustion process, CO\textsubscript{2} can be captured using monoethanolamine, which acts as a chemical absorbent, and then compressed, and stored in a reservoir [39]. Another method of carbon capture is to form solid CO\textsubscript{2} hydrates; gas hydrates are crystalline compounds that are composed of a small gas molecule surrounded by a lattice of hydrogen bonded water molecules [38].

2.9. Exergy

Exergy and its various applications are at the same time both new and old. Josiah Willard Gibbs first introduced the idea of exergy, although he did not use that term, in 1873, and today’s technical community is still exploring new applications of the concept [8]. Exergy can be explained simply as the amount of energy, relative to the environment, or dead state, which is available to do useful work. The reference environment must be carefully chosen to create a meaningful exergy analysis or model. The reference environment is defined by surroundings with uniform temperature, pressure, and chemical composition [40,41]. Changing any of these environmental parameters can lead to different analysis outcomes.

Energy analyses are based on the first law of thermodynamics, but exergy is based on the second law. Traditional system analysis methods are somewhat limited in the information they can provide; energy analysis does not make a distinction between energy that is usable in a practical sense and energy that is no longer usable. The concept of exergy reflects this difference [42]. Flow diagrams, as seen in Figure 2.4, visually show the disparity between energy and exergy. Upon observation it is easy to see that the sum of the outflows in the energy flow diagram is equal to that of the inflow energy. The sum of the outflow exergy values however, is less than that of the inflow. This is because exergy is destroyed during the process, while energy is not.

As per its definition, exergy can be destroyed as a result of irreversibilities in a system; this characteristic makes it a valuable tool for determining useful system and component level efficiencies. Exergy can also be used in externalities studies, coupled with economics in thermo-economic analyses, and incorporated in lifecycle assessments (LCA). The system’s exergetic efficiency will also be used to qualify the plant’s level of sustainability. The sustainability of the system is closely related to its level of reversibility. The closer the plant exergetic efficiency is to 100%, the less exergy is destroyed within the plant and the closer the plant is to being reversible. The more reversible a system, the more sustainable the system is since there is no permanent damage to the environment.
Exergy has already been successfully applied to the analysis of various power generation plants. Rosen and Dincer [43] discuss the application of exergy to the improvement of a coal-fired electricity generation plant, resulting in suggestions for improving efficiencies for major plant subsystems such as the boiler, condenser, and heat exchangers. In a different article, Rosen et al. [44] use energy and exergy analyses on three configurations of a cogeneration-based district energy system, finding that exergy efficiencies for all three examined configurations are lower than the corresponding energy configurations. The lower exergy efficiencies are expected because they take into account waste heat. The analyses are used to determine system and component level thermodynamic efficiencies, which could then be used to suggest system improvements. Kaushik and Chandra [45] perform an exergetic analysis on a non-ideal cogeneration power plant in an effort to optimize the plant.

![Flow diagrams of condensing power plant](image)

Figure 2.4: Flow diagrams of condensing power plant [8].

### 2.10. Externalities and Lifecycle Assessments

Externality studies focus on costs associated with a given process that have not been internalized by market forces or government regulations [46]. In simple terms, externalities are unpaid for impacts caused by one party that affect another party. An example of an externality may be acid rain damage to a historical monument. The areas examined within externality studies, human health, resource depletion, and environmental health, may also be examined with lifecycle assessments (LCA). Lifecycle assessments are a type of analysis that measures the total
impact of a process or product over the span of its lifetime. An LCA could possibly trace resource consumption and use all the way back to the extraction of raw materials, but this is often impractical.

Dewulf et al. [41] use the concept of exergy to generate a comprehensive resource-based lifecycle impact assessment (LCIA) method. Although LCIA is a common analysis used to quantify the impact of a product or process, in terms of resource “take away” from the environment, a single scale to compare all the various energies involved with the lifecycle is not readily available. All resources can be quantified on the same scale without the use of weighting factors by using exergy. The new method emphasizes the system boundaries in order to define what natural resources, energy flows, and land are entering the industrial system. The method provides thorough analysis because it takes into account the total exergy deprived from the natural system, not just exergy removed from it. For use in a similar assessment, De Meester et al. [47] determine the chemical exergy content of 85 elements and 73 minerals for use in exergetic LCA (ELCA).

### 2.11. Environmental Studies and Exergy

As the over-arching goal of this work is to identify low efficiency areas within the Frackville power plant and suggest improvements, it is vital to keep the plant’s environmental impacts in mind. The current emphasis on the environment that U.S. President Obama is bringing to the government makes the importance of environmental impact, especially emissions, even more important. The aforementioned topics of exergy and externalities have been used to analyze the impacts of power plants on the environment in the past, although exergy to a lesser degree. One must be careful when using the word “sustainability” as there is not a consensus about what the word means or implies.

Rosen [48] presents reasons for using thermodynamics, especially exergy analysis, to address environmental impacts. It is concluded that exergy is an excellent tool in determining inefficiencies within a system, more so than energy analysis alone; by lowering inefficiencies the environmental impact of a system is then reduced. Meyer et al. [49] outline how to perform an exergoenvironmental analysis on an energy conversion system to determine the contribution of each component to the total environmental impact. The analysis for each component includes an exergetic analysis, an LCA, assignment of environmental impacts to the exergy streams, the calculation of exergoenvironmental variables, and the exergoenvironmental evaluation.

Rosen et al. [50] also examine the role of exergy in measuring sustainability. A brief look into the area of externalities is taken. The relationship between exergy and the environment is examined through the destruction of order and the depletion or use of resources. Dewulf and Van Langenhove [17] provide a more quantitative examination of the relationship between exergy and sustainability. A methodology for examining impacts on the ecosphere, the technosphere, and society, including organic material, is examined.

### 2.12. Thermoeconomics

In thermoeconomics, costs are applied to thermodynamics analyses, thus determining the unit cost of energy in a given process. The practice of applying costs to units of energy is especially useful when examining power plants,
for obvious reason; the goal of a power plant is to make money by producing energy. It is therefore valuable to know how much money is spent on each unit of energy produced. The same procedure can also be used with exergy instead of energy. As with thermodynamic analyses, using exergy in a thermoeconomic analysis allows for areas of monetary loss due to waste or loss energy in the process to be targeted.

Kwak et al. [51] performed an exergoeconomics analysis is applied to the combined cycle plant in order to encapsulate the whole cost of production, initial investments, and monetary losses due to irreversibilities in the system. Unit cost values were applied to exergy balance equations to produce cost-balance equations.
3. Experimental Research and Relevant Model Background

This section describes the specifics of the plant and available data before the actual analysis is described. This section details each major plant component as well as the assumptions and operational data associated with the component.

3.1. Operational Data

Data from 79 sensors throughout the plant are used in this work. Currently the plant uses two classes of sensors; higher accuracy sensors (+/- 2%), made by Rosemont, are used for critical locations through the plant, such as high temperature and pressure locations, for measurements of materials, lower accuracy sensors (+/- 4%), made by Bailey, are used for non-critical parameters, such as feedwater temperatures.

In order to access plant operational data, the user must specify the specific start and end time and date desired, the desired sample rate (seconds, minutes, hours, or days), and the data tag number, which indicates the relevant sub-system, data type, and location number. Once each of these parameters is defined, the requested data is exported to an Excel sheet. Table 3.1 summarizes the periods of data available through this analysis.

<table>
<thead>
<tr>
<th>Season</th>
<th>Date and Time</th>
<th>Interval (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly</td>
<td>6/28/09 8:49 AM</td>
<td>1/25/10 7:49 AM</td>
</tr>
<tr>
<td>Summer</td>
<td>8/10/09 1:29 PM</td>
<td>8/11/09 1:29 PM</td>
</tr>
<tr>
<td>Winter</td>
<td>12/10/09 1:37 PM</td>
<td>12/11/09 1:37 PM</td>
</tr>
<tr>
<td>Fall (2)</td>
<td>9/1/09 3:07 PM</td>
<td>9/2/09 3:07 PM</td>
</tr>
<tr>
<td>Fall</td>
<td>9/10/09 1:43 PM</td>
<td>9/11/09 1:43 PM</td>
</tr>
</tbody>
</table>

3.1.1. Removed Data

For the sake of the analysis, sections of the operational data have been removed when the plant was not at usual operations or if the data may be considered faulty. The exported electricity rate (MW) over time is shown in Figure 3.1. The shaded area represents the plant shutdown in October for scheduled repairs. The shutdown time period is not considered during the analysis.
In addition to the shutdown period, a number of other times are removed due to inconsistent or apparently faulty data (such as a negative flow rate or zero electricity production). The following times were removed from the data for the purposes of analysis:

- 7/7/2009 9:49 AM through 7/7/2009 2:49 PM
- 7/18/2009 6:49 AM
- 7/22/2009 4:49 AM
- 8/6/2009 4:49
- 8/31/2009 8:49 AM through 8/31/2009 3:49 PM
- 9/4/09 11:49 PM through 10/19/09 9:49 PM
- 12/1/09 3:49 AM

### 3.2. **Turbine and Generator Subsystem**

The power station feeds the combined steam produced from the plant’s two CFB boilers into a General Electric, 3,600 RPM, custom built, 18-stage impulse turbine divided into a high pressure section and a low pressure section. The turbine uses a hydrogen cooling system.

The high pressure section of the turbine is housed in a small enclosure and is covered with extra insulation to prevent undue heat losses. The low pressure portion of the turbine has its own casing. The turbine set up may be seen in Figure 3.2.

The turbine, shown schematically in Figure 3.3, can handle a steam input flow rate of up to 408,000 kg/h (900,000 lb/h) of steam. On average, just under 5,000 kg/h (10,890 lb/h) of the steam that passes through the turbine is
extracted at extraction point 5 and sold for space and process heating in a nearby prison, however, up to 13,600 kg/h (30,000 lb/h) of the steam may be used for this purpose. In colder months, the steam is also used at the plant and associated office space for heating. Four other extraction points are used to deliver the steam to the plant’s feedwater heaters. The amount of steam drawn from each extraction point depends on a number of factors including the current steam production and process load demands. The amount drawn off at each extraction point is discussed in Section 3.2.1. The turbine extraction points, stage location, and extraction steam use is summarized in Table 3.2. Besides the main extraction points, a small amount of steam, called the steam seal regulator steam, is drawn off of the main steam flow before entrance into the turbine. The steam seal regulator is used to seal the non-contacting vacuum seal around the turbine shaft. The extra pressure provided by the steam seal regulator is not required during normal plant operations when the turbine flow is high enough.

The generator is also manufactured by General Electric and has a nominal efficiency of 95% [4]. Some of the power produced by the generator is used for internal power plant operations while the majority is sold to PPL.

Figure 3.2: (a) Picture of (from left to right) generator, low pressure turbine, high pressure turbine housing. (b) Inside HP turbine housing.

Figure 3.3: Schematic of turbine and generator with control volume
Table 3.2: Turbine extraction points, stage locations, and steam destinations.

<table>
<thead>
<tr>
<th>Extraction Point</th>
<th>Stage Location</th>
<th>Steam Destination</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>8</td>
<td>Process, FWH 5</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>FWH 4, Boiler feed pump turbine drive</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>Deaerator</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>FWH 2</td>
</tr>
<tr>
<td>1</td>
<td>16</td>
<td>FWH 1</td>
</tr>
<tr>
<td>Exhaust</td>
<td>18</td>
<td>Condenser</td>
</tr>
</tbody>
</table>

3.2.1. Assumptions

The turbine analysis requires a number of assumptions to be made. Table 3.3 summarizes the assumptions, which are described in full within this section.

Table 3.3: Turbine model assumptions.

<table>
<thead>
<tr>
<th>No.</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Generator efficiency of 95%</td>
</tr>
<tr>
<td>2</td>
<td>Assumed vapor qualities at Ext. 1 and exhaust</td>
</tr>
<tr>
<td>3</td>
<td>Neglect steam seal extraction</td>
</tr>
<tr>
<td>4</td>
<td>Flow rate through extraction points</td>
</tr>
<tr>
<td>5</td>
<td>Extraction 1 and Extraction 3 temperatures</td>
</tr>
<tr>
<td>6</td>
<td>Heat loss of 1.39% of turbine work</td>
</tr>
<tr>
<td>7</td>
<td>Process condensate return conditions</td>
</tr>
</tbody>
</table>

Discussion of Assumptions:

1. **Generator Efficiency** - The generator has a nominal efficiency, $\eta_{\text{gen}}$, reported by the manufacturer of 95%. This value will be used to back out the turbine work from the net turbine/generator power generation.

2. **Vapor Qualities** - Initially, the vapor qualities at extraction 1 and the exhaust were based off of the heat balance analysis performed on the plant. The heat balance analysis was performed by a contractor hired by the power plant in 1992. The analysis did not depend on actual operational data, and so it was found that using the reported turbine qualities caused a number of errors when applied to the model of this work. The discrepancy implies that although the initial qualities applied to the heat balance analysis, they do not apply well to model the actual plant data.

The qualities recorded in Table 3.4 were determined after the initial thermodynamic model was generated. The values were found using Excel Solver in an iterative process, described in Section 6.4.1.
Table 3.4: Qualities of last two turbine exit points.

<table>
<thead>
<tr>
<th>Location</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction 1</td>
<td>96.9%</td>
</tr>
<tr>
<td>Exhaust</td>
<td>88.3%</td>
</tr>
</tbody>
</table>

Since extraction 1 and the exhaust are saturated mixtures of vapor and liquid, the turbine exhaust pressure and the temperature at extraction 1, for which no operational data is collected, may be determined by taking the saturation pressure or temperature at the corresponding temperature or pressure.

3. **Neglecting Steam Seal Extraction** - As stated in the sub-system description, there is sometimes a small amount of steam drawn off of the main turbine steam inflow used to seal the turbine shaft vacuum. Since the steam seal regulator only draws off a very small portion of the steam, nominally around 0.04% of the main steam flow, and is not used at all during normal operations, this particular stream will be neglected.

4. **Flow Rates Extracted** - Since the plant does not record the amount of steam exiting at each turbine extraction point, the flow rate at each turbine location must be calculated. The flow rate values will be determined based on energy balances and mass balances around different plant subsystems including the condenser, feedwater heaters, and the turbine. These analyses are described in Section 601H.

5. **Missing Extraction Temperatures** - No operational temperature data is collected at extraction 1. Since the extraction steam at extraction 1 is a saturated mixture, the temperature corresponds to the saturated temperature at the recorded pressure.

Although operational data is collected at extraction 3, the temperature probe is assumed to be in error because the recorded temperature is consistently within a few percent, higher and lower, to the extraction 4 temperature. When the original data is used, the T-s diagram seen in Figure 3.4 is found using calculated average data.

As seen from the figure, the average entropy at extraction 3 is clearly out of place in the smooth decrease in entropy and temperature along the extraction points. The extraction 3 properties are also clearly off when examined alongside the heat balance analysis provided by the plant.

Since the operational data in this case is found to be in error, the extraction 3 temperature is calculated based on a 76% decrease from extraction 4. This percentage is taken from the decrease in the corresponding temperatures from the heat balance analysis performed on the plant in 1992.
6. **Heat Loss**- The heat loss, although minor, will be estimated through this work as 1.39% of the total work produced by the turbine. This value is an estimate based on average data and an estimated loss curve for the turbine, seen in Figure 3.5. The average work out of the turbine over the entirety of the collected operational data (78 MW exported from the generator corresponds to 82.1 MW generated in the turbine) is taken and divided by the maximum turbine work over the same period (92 MW exported from the generator corresponds to 96.8 MW generated in the turbine) to find the average load percentage (84.78%). The average load percentage is rounded up to 85% to correspond with the 0.85PF (PF indicates percent full load) curve. The average output is found on the horizontal axis of Figure 3.5 and followed up the bold line to the intersection with the 0.85PF curve. The corresponding loss is then found to be about 1.15 MW. Finally, the average percent heat loss is found by dividing the heat loss (1.15 MW) by the average output (82.1 MW) to find the average percent heat loss from the turbine (1.39%).

7. **Process Condensate Return**- When the process steam is returned to the plant it is mixed with the condensate makeup water before entering the condenser. It is therefore assumed that the process condensate returns to the plant at the same temperature and pressure as the makeup water.
3.2.2. Operational Data

The following table summarizes the available plant operational data associated with the turbine and generator subsystems. Double dashed lines indicate the data is not necessary, while N/A indicates the data is desired, but not available.
Table 3.5: Summary of available plant operational data with DCS Tags.

<table>
<thead>
<tr>
<th>Location</th>
<th>Flow Rate</th>
<th>Temperature</th>
<th>Pressure</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main steam ABFI101+ ABFI201</td>
<td>ABTI306</td>
<td>ABPC301</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Extraction 5 N/A</td>
<td>ABTI343</td>
<td>ABPI309</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Extraction 4 N/A</td>
<td>ABTI337</td>
<td>ABPI312</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Extraction 3 N/A</td>
<td>ABTI331</td>
<td>ABPI315</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Extraction 2 N/A</td>
<td>ABTI325</td>
<td>ABPT318</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Exhaust N/A</td>
<td>N/A</td>
<td>AFPT352</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Process FBFI301</td>
<td>ABTI343</td>
<td>ABPI309</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Generator Output --</td>
<td>--</td>
<td>--</td>
<td>MAJI302</td>
<td></td>
</tr>
</tbody>
</table>

-- indicates data not necessary for analysis
N/A indicates operational data desirable but not available

Since the turbine flow rates are necessary, but not available, they must be determined using analyses of other plant components, as discussed in assumption 4 of Section 3.2.1. The average original operational data for the turbine is given in Appendix B. Although the analysis is performed in SI units, the original operational data is recorded in English.

3.3. **Condenser and Cooling Tower**

The overall plant cooling systems includes a condenser, a cooling tower, four closed feedwater heaters (FWH), and an open feedwater heater called the deaerator (DA). Although the cooling tower is described in this section, it is not included in the overall plant analysis due to insufficient data.

The plant condenser, shown in Figure 3.6, includes four major inflows and one outflow. The turbine exhaust, boiler feed pump turbine (BFPT) exhaust, FWH 1 drain, and condensate makeup all flow into the condenser. The condensate makeup water is stored in the condensate makeup tank into which cleaned well water and the process condensate are stored. A portion of the steam seal regulator steam also feeds into the condenser, but as stated in Section 3.2.1, this particular stream is neglected.

The condenser is separated into two compartments; in the event that a cooling water tube should leak, half the condenser may be closed off to maintain the purity of the feedwater and in order to repair the damage. In such a case the plant is only required to reduce operations to half load instead of fully powering down. Each stream entering the condenser is separated, half and half, into the two condenser compartments. Similarly, the drains from each half of the condenser come together before the condensate pump.
3.3.1. Assumptions

A few assumptions are made around the condenser as listed in Table 3.6. Each assumption is explained in greater detail in this section.

Table 3.6: Condenser model assumptions.

<table>
<thead>
<tr>
<th>No.</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No heat loss to ambient</td>
</tr>
<tr>
<td>2</td>
<td>Saturated liquid streams</td>
</tr>
<tr>
<td>3</td>
<td>Unknown pressures</td>
</tr>
<tr>
<td>4</td>
<td>Unknown temperatures</td>
</tr>
</tbody>
</table>

Discussion of Assumptions:

1. **Heat Loss**- It is assumed that the condenser is perfectly insulated. This means the total heat loss from the condensate and steam entering the condenser is transferred to the cooling water as shown in Figure 3.7 as the quantity $\dot{Q}_c$.

2. **Saturated Liquid Streams**- A number of saturated liquids are associated with the condenser; with reference to Figure 3.7, the condenser drain (C7), condensate makeup water (C4), the drain from FWH 1 (C5), and the cooling water both into (C1) and out of (C2) the condenser are all saturated liquids. Since these locations are saturated in these cases, only the temperature is needed to fix the states.

3. **Unknown Pressures**- Few pressures are initially known around the condenser. Since the temperatures are known for each of the saturated liquids, the corresponding pressures are not necessary. The turbine exhaust and the BFPT exhaust pressures are taken to be equal since all flows into the condenser should be approximately the
same for the sake of efficiency. The turbine pressure is the saturation pressure at the exhaust temperature, as described in Section 3.2.1.

4. Unknown Temperatures- Many of the streams entering the condenser have temperatures that are either unknown or must be taken from other component analyses. The water from FWH 1 and the turbine exhaust are two or the later. The remaining unknown temperatures are for the condensate makeup water (C4) and the boiler feed pump turbine exhaust (C6). The condensate makeup water is stored at temperatures between 10-21°C (50-70°F). The makeup water temperature will be taken as 10°C (50°F) in the winter, 21°C (70°F) in the summer, and 16°C (60°F) in the shoulder months. The boiler feed pump turbine exhaust is a saturated mixture, and so the temperature is taken as the saturated temperature of water at the corresponding pressure.

3.3.2. Operational Data

The data available for the condenser is shown in the table below. There is a significant amount of data required for the condenser analysis that is not directly available. As mentioned in the assumptions, the condensate makeup temperature is assumed based on the season and is assumed to be a saturated liquid.

<table>
<thead>
<tr>
<th>Location</th>
<th>Flow Rate</th>
<th>Temperature</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling water into condenser</td>
<td>--</td>
<td>DATI325</td>
<td>--</td>
</tr>
<tr>
<td>Cooling water out of condenser</td>
<td>--</td>
<td>DATI328</td>
<td>--</td>
</tr>
<tr>
<td>Turbine exhaust</td>
<td>N/A</td>
<td>ACTI410</td>
<td>N/A</td>
</tr>
<tr>
<td>Condensate makeup</td>
<td>ADFI338</td>
<td>N/A</td>
<td>--</td>
</tr>
<tr>
<td>FWH 1 drain to condenser</td>
<td>N/A</td>
<td>AFTI362</td>
<td>--</td>
</tr>
<tr>
<td>Boiler feed pump turbine exhaust</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Condenser drain to condensate pump</td>
<td>ADFI302</td>
<td>ADTI41</td>
<td>--</td>
</tr>
</tbody>
</table>

-- indicates data not necessary for analysis
N/A indicates operational data desirable but not available
3.4. **Feedwater Heaters, Deaerator, and Feed Pump Systems**

The plant’s five feedwater heaters are used primarily to pre-heat feedwater before it enters the boiler. With reference to Figure 3.8, the condensate enters FWH 1 from the condensate pump (F1), which is fed from the condensate drain (C7 in Figure 3.7). The feedwater passes from FWH 1 to FWH 2 (F2) to the deaerator (F3) as shown in Figure 3.8. Once the feedwater leaves the DA (F4) it enters one of the two boiler feed pumps, which are centrifugal pumps, after which it is split into two streams. Only one BFP is used at once - the second is available in case one requires maintenance or repairs. The smaller of the two feedwater streams does not pass through the remaining two feedwater heaters, but is used as spray water in the boilers. The majority of the water (F5) passes through the remaining feedwater heaters before passing through the boiler.

The hot fluid for each of the FWHs is taken from one of the extraction points. Steam from extraction 5, after the process steam is removed, passes through FWH 5 (F15), steam from extraction 4, after the feed for the boiler feed pump turbine is taken, passes through FWH 4 (F13), and on down the line as seen in Figure 3.8. The drain of each FWH is mixed with the hot fluids in an adjacent FWH (F16, F14, F11, F9), also shown in Figure 3.8. The water at the drain of each FWH may be approximated as a saturated liquid. As mentioned, the boiler feed pumps (BFP) are used to pump the spray water and the feedwater to the boiler. The BFP is powered by the boiler feed pump turbine (BFPT) - both components are seen in Figure 3.9. Before steam from extraction 4 enters FWH 4, a portion is redirected to run through the BFPT, and then the exhaust released into the condenser (C6). The BFPT has an assumed efficiency of 95% and powers solely the BFP.

![Figure 3.8: Schematic of feedwater heaters and boiler feed pump.](image-url)
3.4.1. Assumptions

The assumptions associated with the feedwater heater system and the boiler feed pump systems are given in Table 3.8. The assumptions are expanded after the table summary.

Table 3.8: Summary of feedwater heater model assumptions.

<table>
<thead>
<tr>
<th>No.</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Heat loss</td>
</tr>
<tr>
<td>2</td>
<td>Unknown temperatures</td>
</tr>
<tr>
<td>3</td>
<td>Unknown pressures</td>
</tr>
<tr>
<td>4</td>
<td>Saturated liquids</td>
</tr>
<tr>
<td>5</td>
<td>Compressed liquids</td>
</tr>
<tr>
<td>6</td>
<td>Boiler feed pump turbine efficiency</td>
</tr>
</tbody>
</table>

Discussion of Assumptions:

1. **Heat Loss**: It is assumed that the feedwater heaters are perfectly insulated and therefore incur no heat losses. Since there is no data available about the BFPT, it is assumed to have the same heat loss percentage (1.39%) observed in the turbine system.

2. **Unknown Temperatures**: The temperature at the inlet of FWH 2 (F2), which is also the exiting condensate from FWH 1, is found using the plant heat balance analysis and the temperatures at the inlet to FWH 1 (F1) and the flow from FWH 2 into the DA (F3). Using the relationship between the temperatures found at those three locations on the heat balance analysis, an equation is found to determine the missing temperature.

\[
T_{F2} = \frac{0.6629T_{F1} + 1.1839T_{F3}}{2} \tag{3.1}
\]

Equation (3.1) was determined using Excel Solver (see Appendix C) and the heat balance analysis data. The temperature subscripts correspond to reference locations numbers in Figure 3.8.
The temperature of the steam entering FWH 1 (F8) is taken to be equivalent to the extraction temperature at extraction 1. As described in the turbine assumption section (Section 3.2.1), the temperature at turbine extraction 1 is found by taking the saturation temperature at the corresponding pressure.

3. **Unknown Pressures** - The first unknown pressure that will be addressed is the pressure of the condensate entering FWH 1 (F1). This fluid comes from the condensate pump. Since the pressure on the upstream side of the pump (C7) is known, it is assumed that the pressure increase is the same as the relative increase seen in the heat balance analysis. In the case of the condensate pump, the pressure at the condenser drain is multiplied by 108.334: on the heat balance analysis, the pressure at C7 is 1.2 psi and the pressure at F1 is 130 psi. Dividing the pressure at F1 by the pressure at C7 gives 130/1.2 = 108.334. Since it’s assumed that there is no pressure loss through the piping, the condensate pressure remains constant until it enters the DA.

The pressure of the feedwater into the boiler, which is the same as the condensate leaving FWH 5, is known. Using the same constant pressure scenario, the pressures upstream of the FWH 5 exit, until the BFP, are equal.

4. **Saturated Liquids** - The drain of each of the feedwater heaters is assumed to be a saturated liquid. With this information, a temperature reading alone is enough to fix the drain water’s state.

5. **Compressed Liquids** - The liquid leaving the condensate pump is at a high enough pressure that it is compressed. The condensate through FWH 1 and 2 are therefore compressed liquids as well since there is assumed to be no pressure drops through the piping.

6. **Boiler Feed Pump Efficiency** - The boiler feed pump turbine is assumed to have an efficiency of 95%.

### 3.4.2. Operational Data

There are many unknowns in terms of raw data around the feedwater heaters and the boiler feed pump systems. Table 3.9 outlines the known, unknown, and unnecessary data for the systems.

### 3.5. **Boiler Subsystem**

The cogeneration power station uses two CFB boilers; Figure 3.10(a) shows the streams into and out of the boiler in a simple schematic and Figure 3.10(b) gives a more detailed illustration from the power plant enlarged from Figure 2.1. The simple schematic will be used for the modeling of the boilers. The boilers each have a foot-print of 15’ x 30’ x 100’ (4.6 x 9.1 x 30.5 meters). Before culm is added during the boiler start up, the boiler temperatures are raised to around 870°C (1600°F) using #2 fuel oil.

Each boiler has two primary air streams that enter from the boiler bed to fluidize the fuel particles and provide oxygen for combustion. The two secondary air streams and the three duct burner air streams enter the boilers further
up the combustion chamber. The secondary blowers send air above the flame in the chamber to help reduce NOx and SOx emissions. Approximately 20% excess air is used in the boilers.

Each boiler also has two culm and two limestone feeds which are adjusted depending on the power load and emissions levels. It should be noted that the emission levels are monitored at the stack, which emits combined gases of both boilers. The plant adjusts the limestone addition depending on the SO2 levels at the stack, so although one boiler may be responsible for an increase in a SO2, both boilers will have an increase in limestone addition.

The feedwater passes through the boiler in a series of small tubes for increased exposure to the combustion heat. Spray water is used if the feedwater temperature goes above 505°C (940°F) in order to prevent damage to the feedwater tubes. The superheated steam from the boilers is combined, forming the main steam flow, which is channeled to the turbine.

The boiler is the most complicated component of the power plant. The complications are largely introduced by the combustion reactions within the boiler. The exergy content of the fuel must be calculated since culm is discussed so little within literature. The exergy of the flue gas, which depends largely on the culm composition, must also be determined before proceeding with the thermodynamic analyses of the plant.

**Table 3.9: Summary of data tags used for the feedwater system.**

<table>
<thead>
<tr>
<th>Location</th>
<th>Flow Rate</th>
<th>Temperature</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWH 1 condensate in</td>
<td>ADFI302</td>
<td>ADTI315</td>
<td>N/A</td>
</tr>
<tr>
<td>FWH 2 condensate in</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>DA condensate in</td>
<td>N/A</td>
<td>ADTI306</td>
<td>N/A</td>
</tr>
<tr>
<td>DA drain</td>
<td>N/A</td>
<td>AETI309</td>
<td>N/A</td>
</tr>
<tr>
<td>FWH 4 condensate in</td>
<td>N/A</td>
<td>AETI333</td>
<td>N/A</td>
</tr>
<tr>
<td>FWH 5 condensate in</td>
<td>N/A</td>
<td>AETI328</td>
<td>N/A</td>
</tr>
<tr>
<td>FWH 5 condensate out</td>
<td>AEFI101 + AEFI201</td>
<td>AETI101</td>
<td>AEPI101</td>
</tr>
<tr>
<td>FWH 1 steam in</td>
<td>N/A</td>
<td>N/A</td>
<td>AFPT352</td>
</tr>
<tr>
<td>FWH 1 drain</td>
<td>N/A</td>
<td>AFTI362</td>
<td>--</td>
</tr>
<tr>
<td>FWH 2 steam in</td>
<td>N/A</td>
<td>ABTI325</td>
<td>ABPT318</td>
</tr>
<tr>
<td>FWH 2 drain</td>
<td>N/A</td>
<td>AFTI350</td>
<td>--</td>
</tr>
<tr>
<td>DA steam in</td>
<td>N/A</td>
<td>ABTI331</td>
<td>ABPI315</td>
</tr>
<tr>
<td>FWH 4 steam in</td>
<td>N/A</td>
<td>ABTI337</td>
<td>ABPI312</td>
</tr>
<tr>
<td>FWH 4 drain</td>
<td>N/A</td>
<td>AFTI325</td>
<td>--</td>
</tr>
<tr>
<td>FWH 5 steam in</td>
<td>N/A</td>
<td>ABTI343</td>
<td>ABPI309</td>
</tr>
<tr>
<td>FWH 5 drain</td>
<td>N/A</td>
<td>AFTI313</td>
<td>--</td>
</tr>
</tbody>
</table>

-- indicates data not necessary for analysis
N/A indicates operational data desirable but not available
Figure 3.10: (a) Schematic of boiler showing all entering and exiting streams. (b) Illustration of inner boiler workings.

3.5.1. Assumptions

In order to examine the boiler in a meaningful and manageable way, two models are constructed with progressively more realistic assumptions made. Table 3.10 summarizes the assumptions associated with each of the models.
Table 3.10: Summary of boiler model assumptions.

<table>
<thead>
<tr>
<th>No.</th>
<th>Assumption</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BI</td>
</tr>
<tr>
<td>1</td>
<td>Higher Heating Value</td>
<td>√</td>
</tr>
<tr>
<td>2</td>
<td>Neglect boiler blowdown</td>
<td>√</td>
</tr>
<tr>
<td>3</td>
<td>120% theoretical air</td>
<td>√</td>
</tr>
<tr>
<td>4</td>
<td>Moisture and ash included in culm</td>
<td>√</td>
</tr>
<tr>
<td>5</td>
<td>Increased flue gas temperature</td>
<td>√</td>
</tr>
<tr>
<td>6</td>
<td>Plant based reactant conditions</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Residue culm reactants</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>NO\textsubscript{x} emissions included</td>
<td></td>
</tr>
</tbody>
</table>

Discussion of Assumptions:

1. **Higher Heating Value** - The higher heating value (HHV) of the fuel will be used through the analysis. The HHV is tested frequently by the power plant and so is readily available. The higher heat value of the fuel assumes that the hydrogen in the fuel after combustion is converted to liquid water. The HHV is higher than the LHV because the LHV takes the water to be vaporized, which requires more energy. Although in reality the hydrogen is converted to vapor, the water created through the conversion of hydrogen to water is small compared to the moisture content already present in the fuel. The difference, therefore, between the HHV and LHV is negligible for the purposes of this work. The exergy analysis will also use the HHV as it reflects the maximum amount of energy that could be recovered from the culm.

2. **Neglect Blowdown** - In order to maintain a high level of purity in the feedwater, a small amount of blowdown is removed from the boiler feedwater. The boiler maintains a continuous blowdown of about 1% of the feedwater flow, making it negligible.

3. **120% Theoretical Air** - The plant reports that approximately 120% theoretical air (TA) is blown into the boiler for combustion. Although the air into the boiler is measured, the TA will change depending on the fuel composition. The estimated 20% excess air will be used as a working estimate.

   Note that the percent TA does not impact any of the exergy values used in this analysis. The exergy values used are related to the reference environment, which includes air, but the exergetic analysis does not rely on the amount of air present in a given reaction.

4. **Moisture and Ash Included in Culm** - Although dry and ash free (DAF) data is often used to model coal based fuels, the assumption that culm has neither ash or moisture is unrealistic. Culm has a high percentage of ash, compared to normal anthracite coal, and high moisture content. Neglecting these two terms will significantly increase the energy and exergy content per kg of culm. Both moisture and ash will therefore be considered in each model.
Since ash is the non-combustible portion of the fuel, it is considered to be inert. This means the exergy of the ash streams out of the boiler are zero since they are at equilibrium with the reference state.

5. **Increased Flue Gas Temperature**: The temperature of the flue gas leaving the boiler is not directly collected at the plant, however, the temperature of the flue gas entering the baghouse is measured. Since the baghouse is just downstream of the boiler, the baghouse entrance temperature is used, but increased by 80°C. The average entrance temperature into the baghouse using the operational data is around 170°C; literature suggests that flue gas temperatures expected to be anywhere between 150-250°C [52], so the increased temperature is within a reasonable range.

6. **Reactant Conditions**: The enthalpy of a given compound depends in part on its temperature. Part of the first law of thermodynamics finds the difference between the enthalpy of each reactant at the reference temperature and the inlet temperature. It is therefore a simplification of the model to assume that the reactants enter the boiler at the reference conditions because that component of the enthalpy analysis will cancel out. Model BI assumes that the reactants enter at the reference temperature. Model BII will assume that the limestone enters the boiler at the temperature half way between the reference temperature and the boiler room temperature to account for warming that occurs during storage in the limestone silo. The culm enthalpy is folded into the higher heating value of the fuel and so is not dependent on the entering temperature.

On the recommendation of the plant engineer, the duct air is taken to be at the same temperature as the secondary air.

7. **Residue Culm Components**: Limiting reactants are defined as reactants that, once depleted, cause a given reaction to cease. For the purposes of model BI the culm components (carbon, hydrogen, etc.) will be taken as the limiting reactants and, as such, will be completely depleted during the combustion reactions. For example, since carbon will be a limiting reactant with zero residue after the reaction is completed, each carbon atom from the culm will be combined with two oxygen to create carbon dioxide. Because the carbon is completely converted to carbon dioxide, it will be assumed for model BI that there is no carbon residue in the bottom or fly ash.

Model BII will take the unburned carbon into account. The residue carbon is of special interest because the amount of carbon residue in the ash is indicative of the completeness of the fuel combustion. Although changes to the plant have been made since, an analysis of the unburned carbon in the plant ash was performed in 2006. According to this analysis, ash contains about 9% carbon. It will be assumed in Model BII that 9% of the ash is carbon. The percent of the carbon that is not burned may be found by multiplying the percent ash by the percent of ash that is carbon.

8. **NOx Emissions**: As discussed in Section 2.8.1, NOx may be formed either from the nitrogen in the air, N2, or from nitrogen in the fuel, which may come in a number of molecules. Since the temperatures of the boiler are lower than necessary for thermal NOx reactions, only fuel NOx will be considered.
The plant NOx emission are so far below the permissible values, as regulated on both a federal and state level, that they are of little concern to the plant. Because the levels are so low, it will be assumed in model BI that the NOx emissions are negligible. The NOx emissions will be taken into account in model BII. Because the CEMS data from the plant does not differentiate between NO and NO2, and because the operational temperature is far below the temperature to create NO2, all the NOx emission data from the plant will be assumed to be fuel NO.

### 3.5.2. Boiler Chemical Reactions

Based on their respective assumptions, each boiler model will consider a different set of chemical reactions to describe the combustion process. The main components of culm are carbon, hydrogen, sulfur, nitrogen, oxygen, moisture, and ash. The reactions will include these major components of the culm combusting with 20% excess air (generally referred to as $\lambda$), composed of 21% oxygen and 79% nitrogen. Although there are other elements within culm, those listed exist in the most significant amounts.

#### 3.5.2.1. Model BI

The basic reactions for carbon, hydrogen, and sulfur (Reactions (3.2)–(3.4)) during combustion are described by Coskun et al. [53]. Recall that for Model BI NOx reactions are not considered.

\[
C + (1 + \lambda)(O_2 + 3.76N_2) \rightarrow CO_2 + \lambda O_2 + 3.76(1 + \lambda)N_2 \tag{3.2}
\]

\[
H + (1 + \lambda)(O_2 + 3.76N_2) \rightarrow \frac{1}{2} H_2O + (0.75 + \lambda)O_2 + 3.76(1 + \lambda)N_2 \tag{3.3}
\]

\[
S + (1 + \lambda)(O_2 + 3.76N_2) \rightarrow SO_2 + \lambda O_2 + 3.76(1 + \lambda)N_2 \tag{3.4}
\]

\[
CaCO_3 \rightarrow CaO + CO_2 \tag{3.5}
\]

\[
CaO + SO_2 + (1 + \lambda)(O_2 + 3.76N_2) \rightarrow CaSO_4 + (0.5 + \lambda)O_2 + 3.76(1 + \lambda)N_2 \tag{3.6}
\]

\[
2N \rightarrow N_2 \tag{3.7}
\]

\[
2O \rightarrow O_2 \tag{3.8}
\]

Reactions (3.5) and (3.6), which show limestone related reactions, are used by Martin et al. [54] in an exergy analysis of a co-combustion, meaning two different fuel sources are used, fluidized bed boiler using low grade coal.
and biomass. The nitrogen and oxygen present in the culm is only converted to N$_2$ and O$_2$ through the reactions given by (3.7) and (3.8).

### 3.5.2.2. Model BII

Model BII includes residue carbon and NO$_x$ emissions. In order to approximate the NO$_x$ emissions an additional nitrogen reaction is used. It was found by examining the CEMS emission data combined with the culm composition that approximately 1.3% of the nitrogen in the fuel is converted to NO. Thus the amount of NO leaving the boilers is found by multiplying the amount of fuel nitrogen by 0.013. The remaining amount of fuel nitrogen is converted to N$_2$ by Reaction (3.7). The percent residue carbon is given as $r$. The final set of reactions includes Reactions (3.3)-(3.6) and (3.8), and the following.

\[
C + (1 + \lambda)(O_2 + 3.76N_2) \rightarrow (1 - r)CO_2 + (\lambda + r)O_2 + 3.76(1 + \lambda)N_2 + rC
\]  
\[N + (1 + \lambda)(O_2 + 3.76N_2) \rightarrow NO + (0.5 + \lambda)O_2 + 3.76(1 + \lambda)N_2 \]  

### 3.5.2.3. Calculating Chemical Coefficients

The coefficients of the products in the above boiler model reactions have already been solved for by balancing the number of atoms of each type on each side of the reaction. The mass balance procedure for the first five reactions of model BI is shown as an example. The mass balance for model BII follows the same logic, but with slightly different chemical reactions.

The reactions used in model BI, excluding the limestone reactions, are duplicated in Equations (3.11) to (3.15), however, the reactant coefficients are left in variable form.

\[
C + (1 + \lambda)(O_2 + 3.76N_2) \rightarrow CO_2 + v_1O_2 + v_2N_2 \]  
\[
H + (1 + \lambda)(O_2 + 3.76N_2) \rightarrow \frac{1}{2}H_2O + v_3O_2 + v_4N_2 \]  
\[
S + (1 + \lambda)(O_2 + 3.76N_2) \rightarrow SO_2 + v_5O_2 + v_6N_2 \]  
\[
2N \rightarrow N_2 \]  
\[
2O \rightarrow O_2 \]
Note that from these reactions, the flue gas will be composed of CO₂, H₂O, SO₂, and air (O₂ and N₂). The product coefficients, \( v_i \), are found by balancing the elements on each side of the reaction. For example, in the first reaction, \( v_1 \) is found by balancing the number of oxygen atoms on each side as shown in Equation (3.16).

\[
2(1 + \lambda) = 2 + 2v_1 \tag{3.16}
\]

Simplifying Equation (3.16) for \( v_1 \) yields Equation (3.17).

\[
v_1 = \lambda \tag{3.17}
\]

When the logic of Equations (3.16) and (3.17) is followed, Reactions (3.11) through (3.15) become Equations (3.18)-(3.22) which are the reactions listed in Section 3.5.2.1.

\[
C + (1 + \lambda)(O_2 + 3.76N_2) \rightarrow CO_2 + \lambda O_2 + 3.76(1 + \lambda)N_2 \tag{3.18}
\]

\[
H + (1 + \lambda)(O_2 + 3.76N_2) \rightarrow \frac{1}{2} H_2O + (0.75 + \lambda) O_2 + 3.76(1 + \lambda)N_2 \tag{3.19}
\]

\[
S + (1 + \lambda)(O_2 + 3.76N_2) \rightarrow SO_2 + \lambda O_2 + 3.76(1 + \lambda)N_2 \tag{3.20}
\]

\[
2N \rightarrow N_2 \tag{3.21}
\]

\[
2O \rightarrow O_2 \tag{3.22}
\]

### 3.5.3. Operational Data

Because the correct operation of the boiler is vital for both the productivity and safety of the power station, there is a wealth of data associated with this plant component. Table 3.11 summarizes the available data. Note that “N/A” indicates the data is not available and double dashes indicate the data is not needed for the analyses of this work.

### 3.6. Total Plant System

At this point, each of the major plant components has been described and their specific assumptions discussed. The sum of the subsystems is what makes up the plant as a whole, and it is important to understand how each system is interconnected. Figure 3.11 shows a layout of the entire plant as it will be examined in the thermodynamic analyses described in Chapter 4.

#### 3.6.1. System Boundaries

The system boundaries for the thermodynamic analysis of the plant will encompass the land directly around the power station building. The inflows to the system include air, well water, mine water, return process condensate,
Table 3.11: Summary of boiler data tags.

<table>
<thead>
<tr>
<th>Location</th>
<th>Flow Rate</th>
<th>Temperature</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedwater Out</td>
<td>ABFI101</td>
<td>ABTI103</td>
<td>ABPI102</td>
</tr>
<tr>
<td>Feedwater In</td>
<td>AEFI101</td>
<td>AETI101</td>
<td>AEPI101</td>
</tr>
<tr>
<td>Culm</td>
<td>JCFI185+JCFI186</td>
<td>N/A</td>
<td>--</td>
</tr>
<tr>
<td>Limestone</td>
<td>NJCFI188+JCFI189</td>
<td>N/A</td>
<td>--</td>
</tr>
<tr>
<td>Primary Air</td>
<td>BAFI150A + BAFI150B</td>
<td>BATI101</td>
<td>--</td>
</tr>
<tr>
<td>Secondary Air</td>
<td>BAFI152 + BAFI153</td>
<td>BATI155</td>
<td>--</td>
</tr>
<tr>
<td>Duct Air</td>
<td>BAFI155 + BAFI156  + BAFI157</td>
<td>BATI155</td>
<td>--</td>
</tr>
<tr>
<td>Flue Gas</td>
<td>N/A</td>
<td>JPTI131</td>
<td>--</td>
</tr>
<tr>
<td>Fly Ash</td>
<td>N/A</td>
<td>JPTI131</td>
<td>--</td>
</tr>
<tr>
<td>Bottom Ash</td>
<td>N/A</td>
<td>JCTI104</td>
<td>--</td>
</tr>
</tbody>
</table>

-- indicates data not necessary for analysis
N/A indicates operational data desirable but not available

Figure 3.11: Schematic overview of entire plant.

Table 3.12: Summary of general and plant wide assumptions

<table>
<thead>
<tr>
<th>No.</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Steady state</td>
</tr>
<tr>
<td>2</td>
<td>Ideal gases</td>
</tr>
<tr>
<td>3</td>
<td>Composition of materials</td>
</tr>
<tr>
<td>4</td>
<td>Negligible losses</td>
</tr>
<tr>
<td>5</td>
<td>Negligible potential and kinetic energy changes</td>
</tr>
<tr>
<td>6</td>
<td>Plant based reference conditions</td>
</tr>
</tbody>
</table>
culm, and limestone. The main outflows from the system include ash, exhaust (emissions, particulate matter, air, and moisture), waste heat, process steam, and electricity.

Upstream processes of the plant, such as water purification and culm processing, will not be directly considered by the thermodynamic analysis, although some of the power used internally in the plant may be directed towards these processes. The land reclamation side of the plant will also be put aside for this portion of the thermodynamic analysis.

3.6.2. Assumptions

There are six assumptions, summarized in Table 3.12 on the previous page, which hold for each subsystem model or become important when the plant as a whole is examined. Each of the assumptions is described in depth in this section.

Discussion of Assumptions:

1. Steady State- Each model is assumed to operate at steady state. The John B. Rich Memorial Power Station has a 92% on-line status, meaning the plant is producing power approximately 92% of the year. The largest transient the boiler can experience is during start up and shut down times, which occurs infrequently. Whenever possible the plant runs at a steady load. In recent years, a steady load could be either at full or half production. It is therefore a fair assumption to perform these analyses at steady state.

   Although the steady state analysis will provide valuable and useful information, in recent years a transient analysis approach has become increasingly significant. Due to economic factors, mainly the decrease in wholesale electricity prices and constant operation costs, the plant has found it necessary to lower power production by up to 50% during low electricity demand hours. Because of the increased frequency of non-steady state operations, this work could be expanded to examine the impacts of cycling between full and half operation capacity on a daily period.

2. Ideal Gases- The air flow into the boiler, the flue gas exiting the boiler, and the exhaust exiting the stack are all assumed to be ideal gasses.

3. Composition of Materials- In order to simplify each model, the material compositions will be taken as their purest and simplest forms. This assumption will affect the air, culm, limestone, and water compositions. The air entering the boiler will be modeled as 21% oxygen and 79% nitrogen. Although air is composed of other compounds as well, oxygen and nitrogen are the most prevalent.

   The culm composition will be based purely on the ultimate and proximate analysis data provided by the plant. With this assumption, culm is composed of carbon, hydrogen, sulfur, nitrogen, oxygen, moisture, and ash.
The limestone sorbent used will be composed purely of calcium carbonate (CaCO₃). Finally, all feed and cooling water will be assumed to be free of impurities.

4. **Negligible Losses:** Through the course of this work it will often be necessary to assume there are no energy losses through the plant piping. This allows data available at one end of a pipe (such as at the turbine exhaust) to be used at the other end of the pipe (such as the inlet to the condenser).

5. **Neglect Change in Kinetic and Potential Energy:** Since the heat transfer and work outputs of the plant are so large, the changes in kinetic and potential energies will be small in comparison. The affects of changes in kinetic and potential energies will therefore be neglected throughout this work.

6. **Plant Based Reference Environment:** The reference environment for an exergy analysis is very important because exergy, unlike energy, is a comparative term between a system and a reference environment. By choosing a different reference environment (defined by temperature, pressure, and chemical composition), the exergy analysis will produce different outcomes.

The plant analysis will compare results between two sets of reference conditions: standard SI reference conditions and realistic reference conditions over the months of available data. The standard reference conditions will be used in order to compare this analysis to similar analyses in literature. Frackville, PA is located at an elevation of 1,470 ft (448 m) above sea level, which corresponds to 0.961 bar (96.07 kPa). Each of the realistic reference temperatures are based on average seasonal temperatures for Frackville. A summary of all reference conditions is shown in Table 3.13.

Table 3.13: Summary of Reference Conditions

<table>
<thead>
<tr>
<th>Reference set</th>
<th>Pressure bar</th>
<th>Temperature K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>1.013</td>
<td>298</td>
</tr>
<tr>
<td>June, 2009</td>
<td>0.961</td>
<td>293</td>
</tr>
<tr>
<td>July, 2009</td>
<td>0.961</td>
<td>294</td>
</tr>
<tr>
<td>August, 2009</td>
<td>0.961</td>
<td>295</td>
</tr>
<tr>
<td>September, 2009</td>
<td>0.961</td>
<td>290</td>
</tr>
<tr>
<td>October, 2009</td>
<td>0.961</td>
<td>284</td>
</tr>
<tr>
<td>November, 2009</td>
<td>0.961</td>
<td>282</td>
</tr>
<tr>
<td>December, 2009</td>
<td>0.961</td>
<td>273</td>
</tr>
<tr>
<td>January, 2010</td>
<td>0.961</td>
<td>272</td>
</tr>
</tbody>
</table>

3.6.3. **Operational Data**

The data used for the total plant analysis includes the entirety of the data described in the previous sections. The total analysis also includes the power exported from the plant, DCS tag MPJI301.
4. Thermodynamic Models

The thermodynamic model of the power plant is created with a number of purposes in mind:

1. To determine basic thermodynamic properties at all points of interest through the plant.
2. To describe the current performance of the plant in terms of common thermodynamic measures, such as energy based efficiencies, as well as less common, but more useful, parameters, such as exergy based efficiencies.
3. To create a basis on which plant improvement suggestions may be made.
4. To model improvement suggestions.
5. To create a basis of comparison by which this cogeneration power plant may be compared to other types of power generation.

Because of insufficient data, it is impossible to analyze each plant subsystem independent of the others. A combination of isolated and interconnected analyses are required in order to determine all necessary properties and flow rates at each point of interest through the model.

4.1. Previous Work

Bailey et al. [4] perform the initial analysis of the power plant. Bailey’s work provides a starting point for this current work. The following section outlines the original power plant analysis. The assumptions on which the original analysis is based are slightly different than those employed in the current analysis. The schematic used in the previous analysis is seen in Figure 4.1. Each of the numbered locations has an associated set of properties taken from a past heat balance analysis of the plant undertaken by an external consultant in the 1990’s.

Figure 4.1: Schematic of the Frackville cogeneration power plant used in the original plant analysis [4].
4.1.1. Thermodynamic Model
The original model was built using a combination of EES and Excel. Instead of using operational data over a period of time, the model uses a single fixed state at each location of interest throughout the plant.

Since the calculation of culm exergy is new to this study, the previous analysis could not take into account the exergy performance of the boiler or of the total plant system. The lack of exergy data was one of the major limitations of the original model.

4.1.2. Externalities Study
The externality study previously performed on the Frackville power plant is brief, although it does point out where the study could be expanded. Figure 4.2 was given in the previous work as an example of information required for a full externality study.

Figure 4.2: Example of information required for an externality study. Created by Bailey et al. [4].
The study examines the costs of two pollutants, SO2 and NO2. General emission data for coal-fired power plants are used to generate the externality costs of these two pollutants for a conventional coal power plant, a total of $7,352,500/year. The emissions of the culm-based power plant are taken as 10% of a conventional power plant, thus resulting in $735,350/year for the cogeneration power plant. The unit costs per pound of pollutant are largely due to “years of life loss” and health care costs due to adverse health effects from the pollutants.

4.2. **Basic Thermodynamic Model**

Each subsystem model includes specific assumptions as well as the set of general assumptions stated in Section 3.6.2. Using the general assumptions, the basic thermodynamic equations (energy and exergy balances) may be simplified to a state all the models may use. Each location of interest through the plant is given a location reference number. The number consists of a letter- B for boiler, T for turbine, F for feedwater heater, or C for condenser- and a number indicating the location. The overall plant schematic with the reference numbers is given in Figure 4.3.

**Figure 4.3:** Plant schematic with location reference numbers.

4.2.1. **General Energy Balance**

The basic energy balance for a control volume \((cv)\) is given in Equation (4.1).
\[
\frac{dE_{cv}}{dt} = \sum \dot{Q}_{cv} - \sum W_{cv} + \sum_{i=1}^{\# \text{inlets}} \dot{m}_i \left( h + \frac{v_i^2}{2} + gz \right)_i \\
- \sum_{j=1}^{\# \text{exits}} \dot{m}_j \left( h + \frac{v_j^2}{2} + gz \right)_j
\]  

(4.1)

Throughout this research, \( E \) represents energy, \( Q \) heat transfer, \( W \) work, \( m \) mass, \( h \) enthalpy, \( V \) velocity, \( g \) the gravitational constant, and \( z \) height from a reference point. Each of the subcomponents assumes steady state conditions as well as negligible kinetic and potential energy effects. The energy balance thus simplifies to Equation (4.2).

\[
0 = \sum \dot{Q}_{cv} - \sum W_{cv} + \sum_{i=1}^{\# \text{inlets}} \dot{m}_i h_i - \sum_{j=1}^{\# \text{exits}} \dot{m}_j h_j
\]  

(4.2)

Equation (4.2) may be further simplified as required by the assumptions and schematic of each subsystem.

### 4.2.1.1. Enthalpy Calculations

The enthalpy of a compound at a state other than standard is defined in Equation (4.3).

\[
h(T, p) = h_f^o + [h(T, p) - h(T_o, p_o)] = h_f^o + \Delta h
\]  

(4.3)

Temperature is given as \( T \), pressure as \( p \), and \( h_f^o \) represents enthalpy of formation. There are a number of streams through the plant that require special enthalpy considerations. Since all gases are taken as ideal gas, and their properties therefore solely dependent on temperature, the change in enthalpy for any gas in the models may be found with Equation (4.4). It is also the case that the enthalpy of solids depend vary little on pressure, since they are incompressible, and so solid materials may also have enthalpy values based solely on temperature.

\[
\Delta h = \int_{T_1}^{T_2} c_p(T) dT
\]  

(4.4)

### 4.2.2. General Exergy Balance

The basic exergy balance for a control volume given in Equation (4.5) where exergy is given as \( \mathcal{E} \) and specific exergy as \( \dot{e} \). A temperature around a given control volume is given as \( T_o \).
Exergy is defined in Equation (4.5) as the combined effects of physical and chemical exergy, \( \Phi^{CH} \). Equation (4.6) defines the total exergy of a material at a given state.

\[
\Phi = \Phi^{CH} + \left[ h - h_o - T_o(s - s_o) + \frac{V^2}{2} + gz \right]
\]  

(4.6)

Considering the general assumption of steady state, Equation (4.5) simplifies to Equation (4.7).

\[
0 = \sum_{k} \left( 1 - \frac{T_o}{T_{b,k}} \right) \dot{Q}_{b,k} - W_{cv} + \sum_{i=1}^{\text{# inlets}} \dot{m}_i \Phi_i - \sum_{j=1}^{\text{# exits}} \dot{m}_j \Phi_j - \dot{E}_d
\]  

(4.7)

When kinetic and potential energies are neglected, the bracketed term in Equation (4.6) becomes Equation (4.8), where \( \Phi_f \) is the flow exergy.

\[
\Phi_f = (h - h_o) - T_o(s - s_o)
\]  

(4.8)

In both steady state and transient cases, the exergy destruction may be found either from the exergy balance (solve for \( \dot{E}_d \)) or from Equation (4.9).

\[
\dot{E}_d = T_o \sigma
\]  

(4.9)

Where \( \sigma \) for a control volume is the entropy production, defined by Equation (4.10).

\[
\sigma = \frac{dS_{cv}}{dt} + \sum_{j=1}^{\text{# exits}} \dot{m}_j S_j - \sum_{i=1}^{\text{# inlets}} \dot{m}_i S_i - \sum_k \frac{\dot{Q}_k}{T_{b,k}}
\]  

(4.10)

Entropy production at steady state is defined with Equation (4.11).

\[
\sigma = \sum_{j=1}^{\text{# exits}} \dot{m}_j S_j - \sum_{i=1}^{\text{# inlets}} \dot{m}_i S_i - \sum_k \frac{\dot{Q}_k}{T_{b,k}}
\]  

(4.11)
4.3. **Explanation of Matlab™ Matrices Structure**

The arrays used through the Matlab™ code have a standard structure that should be understood before examining the code. Before any calculations are made, eight Excel spreadsheets, listed in Table 4.1, are imported into Matlab™. Five of the spreadsheets contain the operational data; there is one file for each of the major plant subsystems—boiler 1, boiler 2, turbine, condenser, and FWH system. Each of the imported files, originally in English units, is given a variable name: “b1” for boiler 1, “b2” for boiler 2, “tu” for the turbine, “c” for the condenser, and “f” for the FWH system. Two of the remaining imported files contain data from the ultimate analysis for the coal; one on a dry basis, and one on an as-received basis. The final file contains the chemical properties of the compounds that pass through the boiler. The chemical properties included are the molar mass, standard chemical exergy, enthalpies of formation, and specific heats. The full Matlab™ code is given in Appendix C. A screenshot of the code used for importing the operational data is given in Figure 4.4.

Table 4.1: Summary of data files used in analysis.

<table>
<thead>
<tr>
<th>File Contents</th>
<th>Matlab™ variable name</th>
<th>File Name with full data</th>
<th>File Name with Steady State data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational data for boiler 1</td>
<td>b1</td>
<td>B1.xls</td>
<td>B1_SS.xls</td>
</tr>
<tr>
<td>Operational data for boiler 2</td>
<td>b2</td>
<td>B2.xls</td>
<td>B2_SS.xls</td>
</tr>
<tr>
<td>Operational data for turbine</td>
<td>tu</td>
<td>Tu.xls</td>
<td>Tu_SS.xls</td>
</tr>
<tr>
<td>Operational data for condenser</td>
<td>c</td>
<td>Cond.xls</td>
<td>Cond_SS.xls</td>
</tr>
<tr>
<td>Operational data for feedwater heaters</td>
<td>f</td>
<td>FWH.xls</td>
<td>FWH_SS.xls</td>
</tr>
<tr>
<td>Average ultimate analysis of culm on dry basis</td>
<td>UA_d</td>
<td>UA_d_avg.xls</td>
<td>--</td>
</tr>
<tr>
<td>Average ultimate analysis of culm on as received basis</td>
<td>UA_r</td>
<td>UA_r_avg.xls</td>
<td>--</td>
</tr>
<tr>
<td>Chemical and thermodynamic properties of compounds used in analysis</td>
<td>prop</td>
<td>properties.xls</td>
<td>--</td>
</tr>
</tbody>
</table>

Figure 4.4: Matlab™ code for importing and unpacking operational and plant data.
Each of the sub-system files contains a column for the flow rates, temperatures, and pressures for each of the component’s locations of interest. The operational data for each spreadsheet is organized in the same way: if there are X locations of interest, the first X columns are for flow rates, the second X columns are for temperature, and the third X columns are for pressures. Any other relevant information for a given component is added to the end of the pressure data. As an example- the turbine has seven locations of interest, the inlet, five extraction points, and the exhaust, so X=7 in this case. Columns 1-7 are reserved for flow rates, columns 8-14 are for temperatures, and columns 15-21 are for pressures. The process steam flow rate, steam flows from both boilers, and generator export take up columns 22-25. Each row of data represents data from one point in time, and so all the files have the same number of rows. The specific numbering system for each of the components will be given in the appropriate section of this chapter.

4.4. Feedwater Heater, Turbine, and Condenser Subsystems

In order for complete energy and exergy analyses of the feedwater heaters, turbines, or the condenser to occur, the state of the steam or condensate at each notable location must be known. It is preferable to fix the state of a location using temperature and pressure operational data. If both pieces of information are not known the state is fixed by assuming or calculating a value for the missing data or assuming the state is a saturated liquid or vapor.

4.4.1. Determining Flow Rates

Figure 4.5, a copy of Figure 3.8, should be used for reference through the model of the feedwater heaters. Table 4.2 gives descriptions for each of the locations through the figure, as well as the associated Matlab™ column reference numbers for the feedwater heater system operational data.

Figure 4.5: Schematic of FWH system with reference tags for analysis.

There are relatively few locations through the plant at which flow rates are measured. The strategy for finding missing flow rates through the feedwater heaters is thus: energy and mass balances are performed around FWH 5 to determine the entering steam flow from extraction 5. Using the information from the analysis around FWH 5, a similar set of analyses are performed around FWH 4 to find the steam entering FWH 4. A large control volume is then taken around the turbine, condenser, DA, FWH 2, and FWH 1 to find the flow of steam into the DA. Again, energy and mass balances are taken around FWH 2 and then FWH 1 in order to determine the unknown steam in
flow rates. Once the flow rates of the steam entering each FWH are found, the flow rates out of each extraction point on the turbine except extraction 4 may be found.

Table 4.2: Description of reference numbers for FWH system.

<table>
<thead>
<tr>
<th>Location number</th>
<th>Description</th>
<th>Matlab™ Column references</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>FWH 1 condensate in from condensate pump</td>
<td>Flow Rate</td>
</tr>
<tr>
<td>F2</td>
<td>FWH 2 condensate in from FWH 1</td>
<td>1</td>
</tr>
<tr>
<td>F3</td>
<td>DA condensate in from FWH 2</td>
<td>2</td>
</tr>
<tr>
<td>F4</td>
<td>DA drain to BFP</td>
<td>3</td>
</tr>
<tr>
<td>F5</td>
<td>FWH 4 condensate in from BFP</td>
<td>4</td>
</tr>
<tr>
<td>F6</td>
<td>FWH 5 condensate in from FWH 4</td>
<td>5</td>
</tr>
<tr>
<td>F7</td>
<td>FWH 5 condensate out to boilers</td>
<td>6</td>
</tr>
<tr>
<td>F8</td>
<td>FWH 1 steam in from extraction 1</td>
<td>7</td>
</tr>
<tr>
<td>F9</td>
<td>FWH 1 drain to condenser</td>
<td>8</td>
</tr>
<tr>
<td>F10</td>
<td>FWH 2 steam in from extraction 2</td>
<td>9</td>
</tr>
<tr>
<td>F11</td>
<td>FWH 2 drain to FWH 1</td>
<td>10</td>
</tr>
<tr>
<td>F12</td>
<td>DA steam in from extraction 3</td>
<td>11</td>
</tr>
<tr>
<td>F13</td>
<td>FWH 4 steam in from extraction 4</td>
<td>12</td>
</tr>
<tr>
<td>F14</td>
<td>FWH 4 drain to DA</td>
<td>13</td>
</tr>
<tr>
<td>F15</td>
<td>FWH 5 steam in from extraction 5</td>
<td>14</td>
</tr>
<tr>
<td>F16</td>
<td>FWH 5 drain to FWH 4</td>
<td>15</td>
</tr>
<tr>
<td>--</td>
<td>Feedwater into Boiler 1</td>
<td>16</td>
</tr>
<tr>
<td>--</td>
<td>Feedwater into Boiler 2</td>
<td>49</td>
</tr>
</tbody>
</table>

Figure 4.6: Schematic of connections between plant components.
The connections between the feedwater heaters, turbine, boiler feed pump and turbine, and condenser is shown in Figure 3.11, repeated in Figure 4.6 for reference. In order to determine the flow rate through extraction 4 the flow rate through the boiler feed pump turbine (BFPT) must be found. An energy balance surrounding the boiler feed pumps (BFP), along with the assumed boiler feed pump turbine (BFPT) efficiency, gives the work out of the BFPT. An energy balance around the BFPT is performed and the mass flow rate through the turbine calculated. Mass balances are then taken around the turbine to determine all extraction flow rates and the exhaust flow rate. At this point in the analysis, all flow rates into the condenser are known.

### 4.4.1.1. Feedwater Heater 5

The schematic, labeling, and control volume used for the FWH 5 analyses are shown in Figure 4.7. The assumptions and available data for the analysis of FWH 5 are given in Section 3.4.

![Figure 4.7: Schematic of feedwater heater 5.](image)

The flow rate, temperature, and pressure of the feedwater to the boilers (F7) are known. The enthalpy and entropy values at each location are readily found based on temperature and the saturated liquid assumption for F6, and F16, and based on the known temperature and pressure for F15. The data used at location F15 are equal to those at extraction 5. Mass balances around FWH 5 give Equations (4.12) and (4.13).

\[
\dot{m}_{F7} = \dot{m}_{F6} \tag{4.12}
\]

\[
\dot{m}_{F16} = \dot{m}_{F15} \tag{4.13}
\]

Simplifying the general energy balance equation (Equation (4.2)) gives Equation (4.14).

\[
0 = \dot{m}_{F16} h_{F16} + \dot{m}_{F7} h_{F7} - (\dot{m}_{F15} h_{F15} + \dot{m}_{F6} h_{F6}) \tag{4.14}
\]

Combining the conservation of mass equations of Equations (4.13) and (4.12) to the energy balance, Equation (4.14), gives Equation (4.15).

\[
0 = \dot{m}_{F15}(h_{F16} - h_{F15}) + \dot{m}_{F7}(h_{F7} - h_{F6}) \tag{4.15}
\]
Equation (4.15) may be rearranged to solve for \( \dot{m}_{F15} \) as shown in Equation (4.16).

\[
\dot{m}_{F15} = \frac{\dot{m}_{F7}(h_{F7} - h_{F6})}{(h_{F15} - h_{F16})}
\]  

(4.16)

By Equation (4.13) and Equation (4.12), all mass flows through FWH 5 are now known.

The coding for FWH 5 is shown in Figure 4.8. Also shown in the figure are two lines of code, beginning \( F(:,2) \) and \( F(:,3) \), which will be part of the analysis of FWH 2 and FWH 1 in Sections 4.4.1.4 and 4.4.1.5.

\[
\begin{align*}
\% \text{ FWH 5} \\
F(:,6) &= F(:,7) ; \quad \% \text{ COM condensate} \\
F(:,15) &= (F(:,7) . * (hF(:,7) - hF(:,6))) . / \ldots \\
       & \quad (hF(:,15) - hF(:,16)) ; \quad \% \text{ Energy balance} \\
F(:,16) &= F(:,15) ; \quad \% \text{ COM steam/drain}
\end{align*}
\]

Figure 4.8: Coding for FWH5 analysis.

4.4.1.2. Feedwater Heater 4

The schematic, labeling, and control volume used for the FWH 4 analyses are shown in Figure 4.9. The assumptions and available data for the analysis of the feedwater heaters are given in Section 3.4.

From the analysis around FWH 5, \( \dot{m}_{F16} \) and \( \dot{m}_{F6} \) are known. Mass balances around FWH 4 give Equations (4.17) and (4.18).

\[
\dot{m}_{F6} = \dot{m}_{F5}
\]  

(4.17)

\[
\dot{m}_{F14} = \dot{m}_{F16} + \dot{m}_{F13}
\]  

(4.18)

Simplifying the general energy balance equation around FWH 4 yields Equation (4.19).
Applying Equations (4.17) and (4.18) to Equation (4.19) yields Equation (4.20).

\[ 0 = \dot{m}_5 h_5 + \dot{m}_{14} h_{14} - (\dot{m}_8 h_8 + \dot{m}_{13} h_{13} + \dot{m}_6 h_6) \]  

(4.19)

The energy balance may be rearranged further to give Equation (4.21).

\[ 0 = \dot{m}_6 (h_6 - h_5) + \dot{m}_{13} (h_{14} - h_{13}) + \dot{m}_{16} (h_{14} - h_{16}) \]  

(4.20)

(4.21)

Finally, Equation (4.21) may be solved for \( \dot{m}_{13} \) as shown in Equation (4.22).

\[ \dot{m}_{13} = \frac{\dot{m}_6 (h_5 - h_6) + \dot{m}_{16} (h_{16} - h_{14})}{(h_{14} - h_{13})} \]  

(4.22)

By Equation (4.17) and Equation (4.18), all mass flows through FWH 4 are now known. The code for the FWH 4 analysis is shown in Figure 4.10.

Figure 4.10: Code for FWH 4 analysis.

### 4.4.1.3. Deaerator

A similar methodology to the previous two sections was initially taken around the DA. It was found, however, that due to the accumulated error inherent in any set of assumptions, conservation of mass was not met through this approach. In order to make the model consistent and prevent violations of natural laws, a different approach is taken. As seen in Figure 4.11, a large control volume is drawn around the turbine, the DA, FWH 2, FWH 1, and the condenser. The assumptions and available data for the analysis of the feedwater heaters are given in Section 3.4.

From the analysis around FWH 4, \( \dot{m}_{F13} \) and \( \dot{m}_{F14} \) are known. The \( \dot{m}_{T2} \) value is found through a simple mass balance, shown in Equation (4.23).

\[ \dot{m}_{T2} = \dot{m}_{T25} + \dot{m}_{F15} \]  

(4.23)
\( m_{T25} \) is mass flow rate of the process steam, seen in Figure 4.11, which is collected as operational data. Since the condensate flow (C7) and the condensate make up water (C4) are also known values, and \( m_{F3} \) is equal to the condensate flow, a mass balance around the whole control volume may be given as Equation (4.24).

\[
    m_{T1} + m_{C4} = m_{T2} + m_{F13} + m_{F12} + m_{F3}
\]  

(4.24)

Equation (4.25) shows Equation (4.24) rearranged to solving for \( m_{F12} \).

\[
    m_{F12} = m_{T1} + m_{C4} - m_{T2} - m_{F13} - m_{F3}
\]  

(4.25)

Finally, the flow rate from the condensate drain is found by performing a separate mass balance around the DA as seen in Equation (4.26).

\[
    m_{F4} = m_{F14} + m_{F12} + m_{F3}
\]  

(4.26)

The coding for the DA analysis is given in Figure 4.12.
4.4.1.4. Feedwater Heater 2

The schematic, labeling, and control volume used for the FWH 2 analyses are shown in Figure 4.13. The assumptions and available data for the analysis of the feedwater heaters are given in Section 3.4.

Since no other streams enter or leave the condensate flow between the recorded condenser drain flow (C7), shown in Figure 4.11, and FWH 2 condensate out (F3), shown in Figure 4.5, a mass balances around FWH 2 will yield Equations (4.27) and (4.28).

\[ m_{F3} = m_{F2} = m_{F1} = m_{C7} \]  \hspace{1cm} (4.27)

\[ m_{F10} = m_{F11} \]  \hspace{1cm} (4.28)

Simplifying the general energy balance equation gives Equation (4.29).

\[ 0 = m_{F11}h_{F11} + m_{F3}h_{F3} - (m_{F10}h_{F10} + m_{F2}h_{F2}) \]  \hspace{1cm} (4.29)

Applying Equations (4.28) and (4.27) to the energy balance produces Equation (4.30).

\[ 0 = m_{F11}(h_{F11} - h_{F10}) + m_{F2}(h_{F3} - h_{F2}) \]  \hspace{1cm} (4.30)

Solving for \( m_{F10} \) in Equation (4.30) gives Equation (4.31).
By Equation (4.28) and Equation (4.27), all mass flows through FWH 2 are now known. Figure 4.14 shows the coding used to calculate the flow rates through FWH 2.

\[
m_{F_{11}} = \frac{m_{F_2}(h_{F_2} - h_{F_3})}{(h_{F_{11}} - h_{F_{10}})} \quad (4.31)
\]

Figure 4.14: Code for FWH 2 analysis. \(Q_{FWH2}\) represents the FWH4 heat loss, but is set to zero for this analysis.

### 4.4.1.5. Feedwater Heater 1

The schematic, labeling, and control volume used for the FWH 1 analyses are shown in Figure 4.15. The assumptions and available data for the analysis of the feedwater heaters are given in Section 3.4.

![Figure 4.15: Schematic of feedwater heater 1.](image)

From the analysis around FWH 2, \(m_{F_{11}}\) is known. Mass balances around FWH 1 give Equations (4.32) and (4.33).

\[
m_{F_1} = m_{F_2} \quad (4.32)
\]

\[
m_{F_9} = m_{C_5} = m_{F_8} + m_{F_{11}} \quad (4.33)
\]

The flow rate at \(C_5\) is the flow from FWH 1 into the condenser and is referenced in Figure 4.15. A mass balance, given in Equation (4.34), is found by simplifying Equation (4.2).
0 = \dot{m}_{F2} h_{F2} + \dot{m}_{F9} h_{F9} - (\dot{m}_{F1} h_{F1} + \dot{m}_{F8} h_{F8} + \dot{m}_{F11} h_{F11}) \tag{4.34}

Applying Equations (4.32) and (4.33) to the energy balance gives Equation (4.35).

0 = \dot{m}_{F2} (h_{F2} - h_{F1}) + (\dot{m}_{F8} + \dot{m}_{F11}) h_{F9} - (\dot{m}_{F8} h_{F8} + \dot{m}_{F11} h_{F11}) \tag{4.35}

Equation (4.35) is further simplified to find Equation (4.36).

0 = \dot{m}_{F2} (h_{F2} - h_{F1}) + \dot{m}_{F8} (h_{F9} - h_{F8}) + \dot{m}_{F11} (h_{F9} - h_{F11}) \tag{4.36}

Finally, the flow rate through F8 is found by solving Equation (4.36) for \(\dot{m}_{F8}\) as shown in Equation (4.37).

\[
\dot{m}_{F8} = \frac{\dot{m}_{F2} (h_{F1} - h_{F2}) + \dot{m}_{F11} (h_{F11} - h_{F9})}{(h_{F9} - h_{F8})} \tag{4.37}
\]

By Equation (4.32) and Equation (4.33), all mass flows through FWH 1 are now known. Figure 4.16 shows the code used for the FWH 1 analysis.

**4.4.1.6. Boiler Feed Pump and Boiler Feed Pump Turbine**

In order to find the flow rate through the boiler feed pump, which is needed to determine the remaining turbine extraction and exhaust flow rates, both the boiler feed pump and the boiler feed pump turbine must be examined together. The BFPT directly powers whichever two of the three BFP are in operation at a given time.

First, an energy balance around the BFP, shown in Figure 4.17(a), is performed to determine the work input. Figure 4.17 gives the BFP and BFPT schematics.

Assuming no heat loss, an energy balance around the BFP yields the work into the BFP, shown in Equation (4.38).

\[
-W_{BFP} = \dot{m}_{F4} (h_{F4} - h_{F8}) \tag{4.38}
\]

Since the work produced through the BFPT is used directly for the BFP, the work generated by the BFPT can be found by applying an efficiency term, \(\eta_{BFPT}\), to the turbine as shown in Equation (4.39).
The BFPT is taken to have a heat loss of 1.39% of the work generated (see Section 3.4.1), so the heat loss from the BFPT is given in Equation (4.40).

\[
\dot{Q}_{\text{BFPT}} = -0.0139 \dot{W}_{\text{BFPT}}
\]  

An energy balance around the BFPT may be given as in Equation (4.41).

\[
\dot{Q}_{\text{BFPT}} - \dot{W}_{\text{BFPT}} = \dot{m}_{C6}(h_{C6} - h_x)
\]  

The properties at \( x \) are taken to be the same as at turbine extraction 4 (T3 on Figure 4.3) so that \( h_x = h_{T3} \). Solving for \( \dot{m}_{C6} \) yields Equation (4.42).

\[
\dot{m}_{C6} = \frac{\dot{Q}_{\text{BFPT}} - \dot{W}_{\text{BFPT}}}{(h_{C6} - h_{T3})}
\]  

The coding for the BFP and BFPT analyses are given in Figure 4.18.

Figure 4.17: (a) Boiler feed pump schematic, and (b) Boiler feed pump turbine.
Figure 4.18: Coding for BFP and BFPT analyses to determine the flow rate of steam through the BFPT. The variable H is assigned as the heat loss percentage (H = 0.0139) throughout the code.

4.4.1.7. Turbine

The final unknown flow rates are associated with the turbine. The location reference numbers for the turbine are shown on Figure 4.19. The reference data for the operational data relevant to the turbine analysis are listed in Table 4.3. The assumptions and available data for the turbine analysis are given in Section 3.2.

Figure 4.19: Turbine Schematic with location numbers used in analyses.

| Table 4.3: Description of reference numbers for turbine system. |
| --- | --- | --- | --- | --- |
| Location number | Description | Flow Rate | Temperature | Pressure |
| T1 | Inlet | 1 | 8 | 15 |
| T2 | Extraction 1 | 2 | 9 | 16 |
| T3 | Extraction 2 | 3 | 10 | 17 |
| T4 | Extraction 3 | 4 | 11 | 18 |
| T5 | Extraction 4 | 5 | 12 | 19 |
| T6 | Extraction 5 | 6 | 13 | 20 |
| T7 | Exhaust | 7 | 14 | 21 |
| -- | Generator power export | 22 | -- | -- |
| -- | Boiler 1 steam flow | 23 | -- | -- |
| -- | Boiler 2 steam flow | 24 | -- | -- |
| -- | Process steam flow | 25 | -- | -- |
| -- | Plant power export | 26 | -- | -- |
The remaining unknown flow rates through the turbine extraction points are found through simple conservation of mass principles and listed in Equations (4.43) through (4.48). Refer to Figure 4.3 and Figure 4.19 for reference location numbers.

Extraction 5 (found prior in Equation (4.23)):
\[ \dot{m}_{T2} = \dot{m}_{F15} + \dot{m}_{T2S} \] (4.43)

Extraction 4:
\[ \dot{m}_{T3} = \dot{m}_{F13} + \dot{m}_{C6} \] (4.44)

Extraction 3:
\[ \dot{m}_{T4} = \dot{m}_{F12} \] (4.45)

Extraction 2:
\[ \dot{m}_{T5} = \dot{m}_{F10} \] (4.46)

Extraction 1:
\[ \dot{m}_{T6} = \dot{m}_{F8} \] (4.47)

Turbine Exhaust:
\[ \dot{m}_{T7} = \dot{m}_{C3} = \dot{m}_{T1} - \dot{m}_{T2} - \dot{m}_{T3} - \dot{m}_{T4} - \dot{m}_{T5} - \dot{m}_{T6} \] (4.48)

The coding for these mass flow calculations are given in Figure 4.20. Also shown in the figure are calculations to fill in the condenser data matrix with relevant information from the FWH and turbine data matrices.

\begin{verbatim}
% Turbine Flows
Tu(:,3) = C(:,6) + F(:,11);  % Extraction 4
Tu(:,4) = F(:,12);           % Extraction 3
Tu(:,5) = F(:,10);           % Extraction 2
Tu(:,6) = F(:,8);            % Extraction 1
Tu(:,7) = Tu(:,1) - Tu(:,2) - Tu(:,3) - Tu(:,4) ... - Tu(:,5) - Tu(:,6);  % Exhaust

% Remaining condenser flows
C(:,5) = F(:,9);            % FWH l drain to condenser
C(:,7) = F(:,1);            % Flow out to condensate pump
C(:,3) = Tu(:,7);           % Turbine exhaust into condenser
\end{verbatim}

Figure 4.20: Coding for remaining turbine and condenser flow rate values.
4.4.1.8. Condenser

The reference numbers for the condenser are shown in Figure 4.21. The corresponding reference descriptions and Matlab™ column references are given in Table 4.4. The assumptions and available data for the condenser analysis are given in Section 3.3. The assumptions explain that the cooling water, which cycles between the cooling towers and condenser in a closed loop, is considered to be outside of the condenser control volume.

![Condenser schematic and location numbers used in analysis. Note the cooling water is outside the control volume.](image)

Table 4.4: Description of reference numbers for condenser system.

<table>
<thead>
<tr>
<th>Location number</th>
<th>Description</th>
<th>Matlab™ Column references</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Cooling water from towers</td>
<td>Flow Rate: 1, Temperature: 8, Pressure: 15</td>
</tr>
<tr>
<td>C2</td>
<td>Cooling water to towers</td>
<td>Flow Rate: 2, Temperature: 9, Pressure: 16</td>
</tr>
<tr>
<td>C3</td>
<td>Turbine exhaust</td>
<td>Flow Rate: 3, Temperature: 10, Pressure: 17</td>
</tr>
<tr>
<td>C4</td>
<td>Condensate makeup</td>
<td>Flow Rate: 4, Temperature: 11, Pressure: 18</td>
</tr>
<tr>
<td>C5</td>
<td>FWH 1 drain to condenser</td>
<td>Flow Rate: 5, Temperature: 12, Pressure: 19</td>
</tr>
<tr>
<td>C6</td>
<td>BFPT exhaust</td>
<td>Flow Rate: 6, Temperature: 13, Pressure: 20</td>
</tr>
<tr>
<td>C7</td>
<td>Drain to condensate pump</td>
<td>Flow Rate: 7, Temperature: 14, Pressure: 21</td>
</tr>
</tbody>
</table>

The flow rates into and out of the condenser have already been determined through the analyses of the feedwater heaters, boiler feed pump turbine, and turbine in Sections 4.4.1.5-4.4.1.7.

4.4.2. Energy Analysis

The main benefits of an energy analysis are to determine all relevant flow rates through the system and to set up a baseline for comparison between this power station and other power generation systems. Quantifying the heat losses throughout the plant, the work produced or used, and energetic efficiencies will be discussed in this section.
4.4.2.1. Feedwater Heaters

The heat loss through each of the feedwater heaters and the deaerator are assumed to be negligible, as discussed in Section 3.4. The efficiency of the FWH in this case is a measure of how well the energy of the steam transfers to the condensate. This research assumes negligible losses, and therefore the entirety of the heat lost through the condensation of steam through a given FWH is transferred to the condensate. Because of this assumption, each FWH will have 100% thermal efficiency.

4.4.2.2. Condenser

The purpose of the condenser within the plant is to condense the “used” steam boilers by dissipating a great deal of heat to the cooling tower so that it may be passed through pumps to the boilers. An energy balance around the condenser yields the heat loss into the cooling water, $Q_C$, as seen in Equation (4.49). See Figure 4.21 for reference.

$$Q_C = \dot{m}_{c7} h_{c7} - (\dot{m}_{c3} h_{c3} + \dot{m}_{c8} h_{c8} + \dot{m}_{c9} h_{c9} + \dot{m}_{c4} h_{c4})$$

(4.49)

Since there is assumed to be no heat loss from the condenser to the outside air, the magnitude of the heat transfer from the condenser is equal to the magnitude of the heat transfer into the cooling water, $Q_C$. An energy balance around the cooling water may then be solved to find the mass flow rate of the cooling water. The mass flow rate of the cooling water is given in Equation (4.50).

$$\dot{m}_{C1} = \frac{-\dot{Q}_C}{(h_{c2} - h_{c1})}$$

(4.50)

The code for the energy analysis for the condenser is given in Figure 4.22.

```plaintext
% Condenser Analysis
Q_C = i.C(:,7).*i.hC(:,7) - i.C(:,3).*i.hC(:,3)...
     - i.C(:,4).*i.hC(:,4) - i.C(:,5).*i.hC(:,5)...
     - i.C(:,6).*i.hC(:,6);  % Heat transfer to cooling water

m_CW = -Q_C./(i.hf(:,2) - i.hf(:,1));  % Flow rate of cooling water
C(:,1) = m_CW;  % Insert cooling water flow into C
C(:,2) = m_CW;  % Insert cooling water flow into C
```

Figure 4.22: Code for condenser energy analysis.

4.4.2.3. Turbine

There are two available options for determining the turbine power output. One method is based on the generator electrical output and assumed generator efficiency, while the other is based on an energy balance using the turbine inlet and outlet data and an assumed heat loss. In the following derivations and equations, the use of the first method will
be indicated by the subscript “TI” and the use of the second method by the subscript “TII”. If the equation applies to either method, the subscript “T” is used.

The heat loss from the turbine has already been described in the turbine assumptions (Section 3.2.1) to be 1.39% of the turbine work production. In the Matlab™ code, seen in Figure 4.23, the heat loss percentage is given as the variable H. The equation used to determine the turbine heat loss, \( \dot{Q}_{LT} \), is given in Equation (4.51) and applies to both turbine work methods.

\[
\dot{Q}_{LT} = -0.0139 \dot{W}_T
\]  

(4.51)

Note that two heat loss values may arise depending on which turbine work value is used. The turbine work used will be indicated in the subscript of the heat loss variable. In the first method of finding the turbine work, \( \dot{W}_T \) is found using operational data for the generator electricity generation, \( \dot{W}_{gen} \), and the generator efficiency, \( \eta_{gen} \). Equation (4.52) gives the turbine work found using the first method.

\[
\dot{W}_{TI} = \frac{\dot{W}_{gen}}{\eta_{gen}}
\]  

(4.52)

The second method is based on an energy balance around the turbine. The initial steady state energy balance around the turbine is given in Equation (4.53).

\[
\dot{Q}_{LTI} - \dot{W}_{TII} = (\dot{m}_{T2}h_{T2} + \dot{m}_{T3}h_{T3} + \dot{m}_{T4}h_{T4} + \dot{m}_{T5}h_{T5} + \dot{m}_{T6}h_{T6} + \dot{m}_{T7}h_{T7}) - \dot{m}_{T1}h_{T1}
\]  

(4.53)

The heat loss term in Equation (4.53) can be replaced by Equation (4.51). The next two steps of simplification for the turbine energy balance are given in Equations (4.54) and (4.55).

\[
-0.0139 \dot{W}_{TII} = (\dot{m}_{T2}h_{T2} + \dot{m}_{T3}h_{T3} + \dot{m}_{T4}h_{T4} + \dot{m}_{T5}h_{T5} + \dot{m}_{T6}h_{T6} + \dot{m}_{T7}h_{T7}) - \dot{m}_{T1}h_{T1}
\]  

(4.54)

\[
-1.0139 \dot{W}_{TII} = (\dot{m}_{T2}h_{T2} + \dot{m}_{T3}h_{T3} + \dot{m}_{T4}h_{T4} + \dot{m}_{T5}h_{T5} + \dot{m}_{T6}h_{T6} + \dot{m}_{T7}h_{T7}) - \dot{m}_{T1}h_{T1}
\]  

(4.55)

Equation (4.55) may be rearranged to solve for the turbine work as shown in Equation (4.56).

\[
\dot{W}_{TII} = -[(\dot{m}_{T2}h_{T2} + \dot{m}_{T3}h_{T3} + \dot{m}_{T4}h_{T4} + \dot{m}_{T5}h_{T5} + \dot{m}_{T6}h_{T6} + \dot{m}_{T7}h_{T7}) - \dot{m}_{T1}h_{T1}] / 1.0139
\]  

(4.56)
A value for the generator work can be estimated based on $W_{TII}$. The generator work based on method two is given in Equation (4.57).

$$W_{gen,TII} = W_{TII} \eta_{gen}$$ \hspace{1cm} (4.57)

In order to quantify how much process heat energy is available for use, a simple energy balance around the process steam is performed. In accordance with the assumptions stated in Section 3.2.1, the process steam is assumed to return to the plant at the same temperature and pressure as the condensate makeup water. With this assumption the process heat is calculated using Equation (4.58) with reference to Figure 4.6. The process steam properties are identical to those of extraction 5, so $h_{T25} = h_{F}$.

$$\dot{Q}_{process} = \dot{m}_{T25}(h_c - h_T)$$ \hspace{1cm} (4.58)

The turbine isentropic efficiency, given in Equation (4.59), compares the actual turbine work to the ideal isentropic case. The ideal case is called the isentropic work, $W_{T,s}$, given in Equation (4.60).

$$\eta_{s,T} = \frac{W_{TII}}{W_{T,s}}$$ \hspace{1cm} (4.59)

$$W_{s,T} = \dot{m}_{T1}h_{T1} - (\dot{m}_{T2}h_{T2,s} + \dot{m}_{T3}h_{T3,s} + \dot{m}_{T4}h_{T4,s} + \dot{m}_{T5}h_{T5,s} + \dot{m}_{T6}h_{T6,s} + \dot{m}_{T7}h_{T7,s})$$ \hspace{1cm} (4.60)

Note that the isentropic efficiency, calculated in Equation (4.60), is based on an energy balance and so $W_{TII}$ is used in the isentropic efficiency. The code for the turbine energy analysis, using both calculation methods, is given in Figure 4.23.

### 4.4.3. Exergy Analysis

#### 4.4.3.1. Feedwater Heaters

The most relevant exergy information about the feedwater heaters is the exergy destruction. As an example of how the exergy destruction is found, an exergy balance around FWH 1 is performed. The initial exergy balance around FWH 1, shown in Figure 4.15, assuming steady state, is given in Equation (4.61).

$$0 = \dot{m}_{F9}e_{F9} + \dot{m}_{F11}e_{F11} + \dot{m}_{F1}e_{F1} - \dot{m}_{F2}e_{F2} - \dot{m}_{F9}e_{F9} - \dot{E}_{d,FWH1}$$ \hspace{1cm} (4.61)

By simply solving for the exergy destruction and applying Equation (4.32), the exergy destruction for FWH 1, given in Equation (4.62), is found.
By performing an exergy balance around the rest of the feedwater heaters, the exergy destruction equations, given in Equations (4.63) through (4.66), are found.

\[
\dot{\varepsilon}_{d,FWH} = \dot{m}_{F8} e_{F8} + \dot{m}_{F11} e_{F11} + \dot{m}_{F1} (e_{F1} - e_{F2}) - \dot{m}_{F9} e_{F9}
\]  

(4.62)

The total exergy destroyed through the FWH is given in Equation (4.67).

\[
\dot{\varepsilon}_{d,FWH} = \dot{\varepsilon}_{d,FWH1} + \dot{\varepsilon}_{d,FWH2} + \dot{\varepsilon}_{d,DA} + \dot{\varepsilon}_{d,FWH4} + \dot{\varepsilon}_{d,FWH5}
\]  

(4.67)

The code for the exergy loss and exergy destruction at the condenser is given in Figure 4.25.

4.4.3.2. Condenser

The condenser exergy loss is based off of the condenser heat transfer to the cooling water. The condenser exergy loss is approximately the same as the exergy loss through the cooling tower since the heat transferred to the cooling water is released to ambient. The exergy loss from the condenser is given in Equation (4.68). The boundary temperature around the condenser is given as the turbine room temperature, \(T_{b,T}\), because both components are located in the same area in the plant. The reference temperature is given as \(T_o\).

\[
\dot{\varepsilon}_{d,C} = \left(1 - \frac{T_o}{T_{b,T}}\right) \dot{Q}_C
\]  

(4.68)

A steady state exergy balance around the condenser is given in Equation (4.69).

\[
0 = \left(1 - \frac{T_o}{T_{b,T}}\right) \dot{Q}_C + \dot{m}_{C3} e_{C3} + \dot{m}_{C4} e_{C4} + \dot{m}_{C5} e_{C5} + \dot{m}_{C6} e_{C6} - \dot{m}_{C7} e_{C7} - \dot{\varepsilon}_{d,C}
\]  

(4.69)

Rearranging Equation (4.69) to solve for exergy destroyed in the condenser, \(\dot{\varepsilon}_{d,C}\), yields Equation (4.70).

\[
\dot{\varepsilon}_{d,C} = \left(1 - \frac{T_o}{T_{b,T}}\right) \dot{Q}_C + \dot{m}_{C3} e_{C3} + \dot{m}_{C4} e_{C4} + \dot{m}_{C5} e_{C5} + \dot{m}_{C6} e_{C6} - \dot{m}_{C7} e_{C7}
\]  

(4.70)

The code for the exergy loss and exergy destruction at the condenser is given in Figure 4.25.
% Energy analysis
Q_process = 1. * T_{in}(: , 25) .* [1. * h_{i}(: , 4) - 1. * h_{i}(: , 3)];  % Process heat

% Using method I- operational data for generator export to find turbine work
U_gen = 1. * T_{in} (: , 25);  % Work produced by generator
U_TI = (1 / i. ngen) * U_gen;  % Turbine work using generator export
Q_l_TI = -1. * H_{T} * U_TI;  % Turbine heat loss using method I

% Using method II- using energy balance around turbine
U_TII = (1. * T_{in} (: , 1) .* h_{i} (: , 1) - 1. * T_{in} (: , 2) .* h_{i} (: , 2) ... - 1. * T_{in} (: , 11) .* h_{i} (: , 11) / (1 + i. ngen))  % Turbine work
U_s_TII = (1. * T_{in} (: , 1) .* h_{i} (: , 1) - 1. * T_{in} (: , 2) .* h_{i} (: , 2) ... - 1. * T_{in} (: , 11) .* h_{i} (: , 11)) / (1 + i. ngen);  % Turbine isentropic work
U_gen_TII = U_TII * i. ngen;  % Generator export using U_TII
Q_l_TII = -1. * H_{T} * U_TII;  % Turbine heat loss using method II
et = U_TII / U_s_TII;  % Isentropic Turbine efficiency

Figure 4.23: Energy analysis for the turbine using methods one and two for calculating the turbine work.

F_Energy analysis
Ed_1_F = 1. * F(:, 8) .* i. ef(:, 8) + 1. * F(:, 11) .* i. ef(:, 11) ... + 3. * F(:, 1) .* (1. * ef(:, 1) - 1. * ef(:, 2)) ... - 3. * F(:, 9) .* i. ef(:, 9);  % Ed FORM 1
Ed_2_F = 1. * F(:, 2) .* (1. * ef(:, 2) - 1. * ef(:, 3)) ... + 2. * F(:, 10) .* (1. * ef(:, 10) - 1. * ef(:, 11));  % Ed FORM 2
Ed_DAP = 1. * F(:, 12) .* i. ef(:, 12) + 1. * F(:, 3) .* i. ef(:, 3) ... + 3. * F(:, 14) .* i. ef(:, 14) - 1. * F(:, 4) .* i. ef(:, 4);  % Ed DAP
Ed_5_F = 1. * F(:, 15) .* (1. * ef(:, 15) - 1. * ef(:, 16)) ... + 2. * F(:, 7) .* (1. * ef(:, 7) - 1. * ef(:, 8));  % Ed FORM 5
Ed_total_F = Ed_1_F + Ed_2_F + Ed_DAP + Ed_4_F + Ed_5_F;  % Total Ed through Pumps

Figure 4.24: Exergy analysis code for the feedwater heaters.

F_1_C = Q_{C} * (1 - T_{in} / T_{in});  % Exergy loss

Ed_C = (1 - T_{in} / T_{in}) * Q_{C} + 1. * C(:, 3) .* i. ec(:, 3) ... + 1. * C(:, 4) .* i. ec(:, 4) + 1. * C(:, 5) .* i. ec(:, 5) ... + 1. * C(:, 6) .* i. ec(:, 6) ... - 1. * C(:, 7) .* i. ec(:, 7);  % Exergy destroyed at condenser

Figure 4.25: Code for exergy destruction at the condenser.
The exergy loss from the turbine, given in Equation (4.71), is based off of the turbine heat loss (Equation (4.51)).

\[
\dot{E}_{LT} = \left(1 - \frac{T_o}{T_{b,T}}\right) \dot{Q}_{LT}
\]  
(4.71)

As with any of the systems, two methods of determining the turbine exergy destruction are available; the exergy destruction may be determined by rearranging an exergy balance or by multiplying the entropy production by the reference temperature, as seen in Equation (4.9).

First, the exergy balance method will be used. Equation (4.72) gives the initial steady state exergy balance around the turbine.

\[
0 = \left(1 - \frac{T_o}{T_{b,T}}\right) \dot{Q}_{LT} - \dot{W}_T + \dot{m}_T e_{T1} - (\dot{m}_{T2} e_{T2} + \dot{m}_{T3} e_{T3} + \dot{m}_{T4} e_{T4} + \dot{m}_{T5} e_{T5} + \dot{m}_{T6} e_{T6}
+ \dot{m}_{T7} e_{T7}) - \dot{E}_{d,T}
\]  
(4.72)

Either of the turbine work values and their corresponding heat loss values may be used and indicated in the subscripts. The exergy destruction, shown in Equation (4.73), is found by rearranging Equation (4.72).

\[
\dot{E}_{d,T,e} = \left(1 - \frac{T_o}{T_{b,T}}\right) \dot{Q}_{LT} - \dot{W}_T + \dot{m}_T e_{T1} - (\dot{m}_{T2} e_{T2} + \dot{m}_{T3} e_{T3} + \dot{m}_{T4} e_{T4} + \dot{m}_{T5} e_{T5} + \dot{m}_{T6} e_{T6}
+ \dot{m}_{T7} e_{T7})
\]  
(4.73)

The “e” in the exergy destruction subscript indicates the exergy balance method was used.

An entropy balance, which may be used with the either turbine energy analysis method, is given in Equation (4.74).

\[
\dot{s}_T = \dot{m}_{T2} s_{T2} + \dot{m}_{T3} s_{T3} + \dot{m}_{T4} s_{T4} + \dot{m}_{T5} s_{T5} + \dot{m}_{T6} s_{T6} + \dot{m}_{T7} s_{T7} - \dot{m}_{T1} s_{T1} - \left(\frac{T_o}{T_{b,T}}\right) \dot{Q}_{LT}
\]  
(4.74)

The second exergy destruction value for the turbine is given in Equation (4.75).

\[
\dot{E}_{d,T} = T_o \dot{s}_T
\]  
(4.75)
Differences in the exergy destruction methods will arise when the first method of turbine work calculation is used. These differences will be discussed in Chapter 6.

The exergetic efficiency of the turbine, given in Equation (4.76), compares the change in flow exergy from the inlet to the outlet of the turbine to the work produced. The exergetic efficiency may be calculated using either turbine work method.

\[ \varepsilon_T = \frac{W_T}{m_{T1}e_{T1} - m_{T7}e_{T7}} \]  

(4.76)

Another important aspect of the turbine system is the process steam. The exergy of the process steam is found by performing a simple exergy balance around the process steam. The exergy of the process steam is given in Equation (4.77). Since the process steam exits with the same properties as extraction 5, \( e_{T25} = e_{T2} \).

\[ \dot{e}_{\text{process}} = m_{T25}(e_{f,4} - e_{f,2}) \]  

(4.77)

The coding for the process steam exergy is shown in Figure 4.26 (a). The exergy analysis using the first turbine work method is shown in Figure 4.26 (b). The exergy analysis using the second method of turbine work is shown in Figure 4.26 (c).

4.5. **Boiler Subsystem**

The boiler analysis is the most complicated of the sub-systems. The chemical reactions occurring within the boiler make the system much more variable and unpredictable than other systems. In order to best model the boiler, three separate thermodynamic models are employed, each with an increasing level of complexity. The assumptions, a discussion of the boiler models, and available data for the boiler analysis are discussed in Section 3.5.

A boiler schematic with reference number tags is shown in Figure 4.27. The figure shows assumed directions for the useful heat transfer, \( \dot{Q}_u \), and the heat loss, \( \dot{Q}_{LB} \). The Matlab™ references are listed in Table 4.5.

Although the boiler system has 17 entry or exit points, many of the locations are separate feeds for the same material at the same temperature and pressure. Because there are so many repeats in the thermodynamic properties, a separate system, summarized in Table 4.6, is used to organize the thermodynamic properties for the boiler system. Table 4.6 gives the stream type, the location reference numbers which use that particular stream, and the corresponding Matlab™ column in which the data is stored. Finally, a separate array, shown in Table 4.5, system is made to contain the enthalpy of formation, chemical exergy, molar mass, and specific heat for the culm and flue gas species.
Figure 4.26: Coding for the exergy analysis of the turbine. (a) The process exergy and (b) the exergy analyses using the energy calculations based on the generator data (method I) and (c) the energy calculations based on a turbine energy balance (method II).
Figure 4.27: Schematic of boiler with reference numbers and assumed heat transfer directions.

Table 4.5: Description of reference numbers for boiler system.

<table>
<thead>
<tr>
<th>Location number</th>
<th>Description</th>
<th>Matlab™ Column references</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>Feedwater in</td>
<td>Flow Rate</td>
</tr>
<tr>
<td>B2</td>
<td>Superheated steam out</td>
<td>2</td>
</tr>
<tr>
<td>B3</td>
<td>Spray water</td>
<td>3</td>
</tr>
<tr>
<td>B4</td>
<td>Culm feed 1</td>
<td>4</td>
</tr>
<tr>
<td>B5</td>
<td>Culm feed 2</td>
<td>5</td>
</tr>
<tr>
<td>B6</td>
<td>Limestone feed 1</td>
<td>6</td>
</tr>
<tr>
<td>B7</td>
<td>Limestone feed 2</td>
<td>7</td>
</tr>
<tr>
<td>B8</td>
<td>Bottom ash</td>
<td>8</td>
</tr>
<tr>
<td>B9</td>
<td>Fly ash</td>
<td>9</td>
</tr>
<tr>
<td>B10</td>
<td>Flue gas</td>
<td>10</td>
</tr>
<tr>
<td>B11</td>
<td>Primary air 1</td>
<td>11</td>
</tr>
<tr>
<td>B12</td>
<td>Primary air 2</td>
<td>12</td>
</tr>
<tr>
<td>B13</td>
<td>Duct burner air 1</td>
<td>13</td>
</tr>
<tr>
<td>B14</td>
<td>Duct burner air 2</td>
<td>14</td>
</tr>
<tr>
<td>B15</td>
<td>Duct burner air 3</td>
<td>15</td>
</tr>
<tr>
<td>B16</td>
<td>Secondary air 1</td>
<td>16</td>
</tr>
<tr>
<td>B17</td>
<td>Secondary air 2</td>
<td>17</td>
</tr>
</tbody>
</table>
Table 4.6: Description of reference numbers for boiler system enthalpy, entropy, and exergy arrays.

<table>
<thead>
<tr>
<th>Location</th>
<th>Location numbers included</th>
<th>Matlab™ Column references</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedwater in</td>
<td>B1</td>
<td>1</td>
</tr>
<tr>
<td>Superheated steam out</td>
<td>B2</td>
<td>2</td>
</tr>
<tr>
<td>Bottom ash</td>
<td>B8</td>
<td>3</td>
</tr>
<tr>
<td>Fly ash</td>
<td>B9</td>
<td>4</td>
</tr>
<tr>
<td>Flue gas</td>
<td>B10</td>
<td>5</td>
</tr>
<tr>
<td>Primary air</td>
<td>B11+B12</td>
<td>6</td>
</tr>
<tr>
<td>Secondary and duct burner air</td>
<td>B13+ B14+ B15+ B16+ B17</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 4.7: Description of reference numbers for boiler system chemical species.

<table>
<thead>
<tr>
<th>Where species is found</th>
<th>Species</th>
<th>Chemical symbol</th>
<th>Matlab™ Column reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Culm</td>
<td>Moisture</td>
<td>H₂O</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Ash</td>
<td>N/A</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Carbon</td>
<td>C</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Hydrogen</td>
<td>H</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Nitrogen</td>
<td>N</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Sulfur</td>
<td>S</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Oxygen</td>
<td>O</td>
<td>7</td>
</tr>
<tr>
<td>Limestone</td>
<td>Calcium carbonate</td>
<td>CaCO₃</td>
<td>8</td>
</tr>
<tr>
<td>Boiler</td>
<td>Calcium oxide</td>
<td>CaO</td>
<td>9</td>
</tr>
<tr>
<td>Air into boiler and flue gas</td>
<td>Oxygen</td>
<td>O₂</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Nitrogen</td>
<td>N₂</td>
<td>11</td>
</tr>
<tr>
<td>Flue gas</td>
<td>Carbon dioxide</td>
<td>CO₂</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Water (g)</td>
<td>H₂O</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Sulfur dioxide</td>
<td>SO₂</td>
<td>14</td>
</tr>
<tr>
<td>Mixed with ash</td>
<td>Calcium sulfate</td>
<td>CaSO₄</td>
<td>15</td>
</tr>
<tr>
<td>Flue gas</td>
<td>Nitrogen oxide</td>
<td>NO</td>
<td>16</td>
</tr>
</tbody>
</table>

4.5.1.1. Calculating Culm Exergy

Because culm is not a widely used fuel source, there is insufficient data available in literature regarding either its energy or chemical exergy content. Because of this, it is necessary to calculate the exergy of culm based on the ultimate analysis (UA) data provided by the power station, seen in Table 2.1. Because the same chemical reference environment will be used throughout each of the boiler models, the same chemical exergy values for culm can be used for each model.

Bilgen and Kaygusuz [55] determine the exergy content of coal based fuels based on the higher heating value (HHV) of the fuel. The higher heating value is, in turn, determined based on the ultimate and proximate analyses of the fuel. As discussed in Section 3.5.1, the HHV is used instead of the LHV despite the fact that any water after combustion is a vapor because the exergy represents the maximum possible energy potential of the fuel. The chemical exergy is based on three values: the chemical exergy of dry and ash freed (DAF) culm, which is found using the HHV, the chemical exergy of the moisture in the culm, and the chemical exergy of the ash within the culm. Each of these components must be determined before the total chemical exergy can be known.
The basic equation for the chemical exergy of a fuel, $\bar{E}_{\text{fuel}}^{CH}$, is given by Bilgen by subtracting the difference between the chemical potential, that is to say, the chemical exergy, of the products and the reactants using the molar Gibbs function of the fuel. A line over a given variable indicates the value is on a molar basis. Equation (4.78) shows the general form of this procedure.

$$\bar{E}_{\text{fuel}}^{CH} = \bar{g}_{\text{fuel}}(T_o, p_o) - \left( \sum_p v_p \bar{g}_p - \sum_R v_R \bar{g}_R \right)$$  \hspace{1cm} (4.78)

In Equation (4.78), the Gibbs function on a molar basis is given as $\bar{g}$, the variable $v$ represents the coefficient of a given substance within a chemical reaction, the subscript $P$ indicates a produce, the subscript $R$ indicates a reactant. The Gibbs function may also be expressed as the difference between the molar enthalpy and the temperature multiplied by the molar entropy. Since the enthalpy of a fuel is the energy stored in the fuel, and the HHV of the fuel is the energy released during combustion, $\bar{H}_{\text{fuel}} = \bar{h}_{\text{fuel}}$. Equation (4.78) may be expanded to Equation (4.79).

$$\bar{E}_{\text{fuel}}^{CH} = \bar{H}_{\text{fuel}}(T_o, p_o) - T_o \left[ s_{\text{fuel}} + \sum_p v_p s_p - \sum_R v_R s_R \right] - \left( \sum_p v_p \bar{E}_{p}^{CH} - \sum_R v_R \bar{E}_{R}^{CH} \right)$$  \hspace{1cm} (4.79)

The general culm combustion reaction includes the culm composition, based on the ultimate analyses, reactants, and the resulting products of combustion. A general form of the combustion reaction is given in Equation (4.80).

\[
\sum_{i=1}^{\text{# components}} v_{\text{culm}}(UA)_{i,\text{DAF}} + \sum_{j=1}^{\text{# reactants}} v_{R_j} \rightarrow \sum_{k=1}^{\text{# products}} v_P P_k
\]  \hspace{1cm} (4.80)

In Equation (4.80), $(UA)$ represents the percentage of each component of culm from the ultimate analysis. The reaction given in Equation (4.80) is on a dry and ash free basis (DAF), so the culm composition components should exclude moisture and ash. The culm components that will be included are carbon (subscript $C$), hydrogen (subscript $H$), oxygen (subscript $O$), nitrogen (subscript $N$), and sulfur (subscript $S$). Since all of the ultimate analysis results include ash, the DAF fractions need to be calculated. Equation (4.81) [56] shows how to calculate the DAF culm composition fraction for a general culm component (subscript $i$).

\[
(UA)_{i,\text{DAF}} = \frac{(UA)_{i,\text{dry}}}{(100 - (UA)_{\text{ash, dry}})/100}
\]  \hspace{1cm} (4.81)
In order to determine the coefficient of each culm component, the DAF fraction of the component is divided by its molar mass to convert the coefficients from a mass basis to a molar basis. \( v_i \) is represented on a fractional, not a percentage, basis, so it is also divided by 100 as seen in Equation (4.82). \( v \) has units of \( \text{kmol/kg} \).

\[
v_{i,\text{culm}} = \frac{(UA)_{i,\text{DAF}}}{100M_i}
\]  

(4.82)

The Matlab\textsuperscript{TM} code for the DAF fraction of the culm components and for the culm coefficients are found using for loops as shown in Figure 4.28.

```
% Convert Dry basis to DAF basis (DAF = Dry/((100-Da)/100)
for i=1:8
    UA_DAF(:,i) = (UA_d(:,i) .^ ((100-UA_d(:,2))./100).*(-1));
end

% Find the culm components in kmol/kg
for i=1:6
    v_culm(:,i) = UA_DAF(:,i)./(100*M(:,i));
end
```

Figure 4.28: Coding for ultimate analysis on dry and ash free (DAF) basis and the culm coefficients.

When Equation (4.80) through Equation (4.82) are combined, Reaction (4.83) is found. The nitrogen that would otherwise be included with the oxygen in air is excluded since it does not take part in the combustion reactions themselves.

\[
\left( v_{C,\text{culm}}C + v_{H,\text{culm}}H + v_{O,\text{culm}}O + v_{N,\text{culm}}N + v_{S,\text{culm}}S \right)_{\text{DAF}} + v_{O_2}O_2
\]

\[
\rightarrow v_{CO_2}CO_2 + v_{H_2O}H_2O + v_{SO_2}SO_2 + v_{N_2}N_2
\]

(4.83)

The culm component coefficients given in Equation (4.83) are found using Equation (4.82). Since atoms are not destroyed in the boiler, the same number of each type coming into the boiler must equal the number coming out. The atoms may be rearranged, but they are not fundamentally changed. Using the logic outlined in Section 3.5.2.3, the remaining stoichiometric coefficients in Reaction (4.83) are found. The values of the coefficients are listed in Equation (4.84) through Equation (4.88).

\[
v_{O_2} = v_{C,\text{culm}} + \frac{1}{4}v_{H,\text{culm}} + v_{S,\text{culm}} - \frac{1}{2}v_{O,\text{culm}}
\]

(4.84)

\[
v_{N_2} = \frac{1}{2}v_{N,\text{culm}}
\]

(4.85)

\[
v_{CO_2} = v_{C,\text{culm}}
\]

(4.86)
\[v_{SO_2} = v_{S,culm}\]  
\[v_{H_2O(g)} = \frac{1}{2}v_{H,culm}\]  

The Matlab\textsuperscript{\textregistered} code for Equations (4.84)-(4.88) are given in Figure 4.29.

```matlab
% Determine stoichiometric coefficients
v(:,17) = v_culm(:,3) + 0.25*v_culm(:,9)
+ v_culm(:,6) - 0.5*v_culm(:,7); % air in = v_O2 in
v(:,10) = v(:,17); % O2
v(:,11) = 0.5*v_culm(:,5); % H2
v(:,12) = v_culm(:,3); % CO2
v(:,14) = v_culm(:,6); % H2O (g)
v(:,13) = 0.5*v_culm(:,4); % H2O (g)
```

Figure 4.29: Code for calculation of stoichiometric coefficients for the combustion reaction given in Reaction (4.83).

In accordance with the analysis by Bilgen, after the reaction coefficients are found, the HHV of culm on a DAF basis is calculated using Equation (4.89). Equation (4.89) is an expression originally developed by Janka and Malhotra \[57\] that relates fuel composition to the heating value. The resulting HHV is in kJ/kg.

\[
HHV_{DAF} = \left[ \frac{152190(UA)_{H,DAF} + 98767}{100} \left( \frac{(UA)_{C,DAF}}{300} + \frac{(UA)_{H,DAF}}{100} \right) \right] - \frac{(UA)_{O,DAF} - (UA)_{S,DAF}}{800} \]  

(4.89)

The \((UA)_{H,DAF}\), \((UA)_{C,DAF}\), \((UA)_{O,DAF}\), and \((UA)_{S,DAF}\) values are found using Equation (4.81) and do not have units. It is also possible to calculate the absolute entropy for culm on a DAF basis using Equation (4.90), which was also developed by Janka and Malhotra \[57\].

\[
s_{DAF} = v_{c,culm}\left[ 37.1653 - 31.4767e^{-0.564682(v_H/v_{c+N,culm})} \right. \\
+ 20.1145 \left( \frac{v_O}{v_c + v_N} \right)_{c,culm} + 54.3111 \left( \frac{v_N}{v_c + v_N} \right)_{c,culm} \\
+ 44.6712 \left( \frac{v_S}{v_c + v_N} \right)_{c,culm} \]  

(4.90)

The chemical exergy on a DAF basis may be determined by substituting Equations (4.89) and (4.90) into Equation (4.79) as shown in Equation (4.91).
Finally, the total chemical exergy of the culm, shown in Equation (4.92), is calculated. There are three components of the total chemical exergy of culm: the chemical exergy on a DAF basis, given in Equation (4.91), the chemical exergy of the moisture in the culm, and the chemical exergy of the ash in the culm. The chemical exergy of liquid water, which is the state of the moisture in culm as it enters the boiler, can be found in look up tables [40]. Since ash is assumed to be inert through the combustion process, the chemical exergy of ash is zero. The total culm exergy is given in Equation (4.92) where the as-received (AR) ultimate analysis data is used.

\[
\varepsilon_{CH}^{culm} = \frac{100 - (UA)_{H_2O(l),AR} - (UA)_{AR,AR}}{100} \cdot \varepsilon_{DAF} + \frac{(UA)_{H_2O(l),AR}}{100M_{H_2O}} \cdot \varepsilon_{H_2O(l)}^{CH} + \frac{(X_{A})_{AR} \cdot \varepsilon_{CH}^{Ash}}{0} \tag{4.92}
\]

Simplified, Equation (4.92) becomes Equation (4.93).

\[
\varepsilon_{CH}^{culm} = \frac{100 - (UA)_{H_2O(l),AR} - (UA)_{AR,AR}}{100} \cdot \varepsilon_{DAF} + \frac{(UA)_{H_2O(l),AR}}{100M_{H_2O}} \cdot \varepsilon_{H_2O(l)}^{CH} \tag{4.93}
\]

The chemical exergy described by Equation (4.93) can be used during the exergy analysis for both boiler models. The code for the calculations of the culm HHV, entropy, DAF chemical exergy, and final chemical exergy are shown in Figure 4.30.

### 4.5.1.2. Ash Thermodynamic Properties

The enthalpy of ash may be calculated using in Btu/lb based on the ash temperature in degree Fahrenheit [58] as seen in Equation (4.94). The relationship between the enthalpy and temperature, the effects of pressure being negligible, for ash are described in the authoritative book on steam systems “Steam” [27].

\[
h_A = \begin{cases} 
7.735829 \cdot 10^{-5} \cdot T^2 + 0.1702036 \cdot T - 13.36106, & T < 500 \\
2.408712 \cdot 10^{-5} \cdot T^2 + 0.2358873 \cdot T - 32.88512, & T \geq 500 
\end{cases} \tag{4.94}
\]

The enthalpy may easily be converted to kJ/kg by dividing the calculated enthalpy by 0.42992.

The chemical exergy of ash is taken as zero since it’s assumed to be inert. The exergy of the ash is then taken to be the flow exergy. The chemical exergy of other products of combustion that exit the boiler through the ash are added to the ash exergy separately.
The code for the ash thermodynamic properties is given in Figure 4.31. The properties are calculated separately for the fly ash and the bottom ash because each ash stream leaves the boiler at a different location and temperature. An “if loop” is used in order to make the calculation for each time set of data (each row). The original operational data (matrix b1) is used since the temperatures it contains are already in degrees Fahrenheit, which are required for Equation (4.94). Note that 176 is added to the temperature in the fly ash calculations. This is in accordance with the increased flue gas temperature assumption given in Section 3.5.1.

4.5.1.3. Mass Balance using Extent of Reaction

A mass balance of the components entering and exiting the boiler is performed in order to help quantify the emissions and to determine the composition of the flue gas. The composition is then used to determine the chemical exergy of the flue gas, which is essential for the boiler thermodynamic models. Since the mass exiting the boiler (flue gas and ash) is equal to the mass entering the boiler (fuel and air), as known by the conservation of mass principle, the flue gas mass flow rate is given as in Equation (4.95).

\[
\dot{m}_{FG} = \dot{m}_{fuel} + \dot{m}_{air} - \dot{m}_{ash}
\] (4.95)

Note that the mass of the flue gas does not include the fly ash, even though they leave the boiler through the same exit. In order to determine the mass of each product of the combustion reactions, the extent of reaction method is used. The amount and type of each molecule entering the boiler do not equate to those leaving the boiler because of the chemical reactions that occur. The extent of reaction approach accounts for the amount of each molecule entering and exiting the boiler, as well as the generation or destruction of each type of molecule due to the chemical reactions. The extent of reaction, \( \xi \), is used to connect the generation or destruction of a given compound to each relevant reaction. The extent of reaction method is particularly helpful when a series of reactions occur, as they do with boiler models BI and BII.

The general form of a molar balance using extent of reactions is given in Equation (4.96).

\[
\frac{dn_i}{dt} = \hat{n}_{i,in} - \hat{n}_{i,out} + \sum_{j=1}^{\#rxns} v_{i,j} \xi_j
\] (4.96)

In Equation (4.96), the subscript \( i \) represents a given compound (reactant or product), \( j \) represents a given reaction, \( \hat{n} \) is the molar flow rate and \( v_{i,j} \) is the coefficient for a given compound in a given equation. When the coefficients are put into Equation (4.96) they are given a positive sign if they are a product of the reaction and a negative sign if they are a reactant. One molar balance is generated for each unique compound in a set of reactions and one extent of reaction variable exists for each reaction.
Figure 4.30: Code for calculations of the DAF HHV, entropy, and exergy for culm as well as the final culm exergy value.

```matlab
% Calculate Higher Heating Values
\nonline
\text{HHV}_{\text{DAF}} = (132190 + UA_{\text{DAF}}(:,4)/100) \times (UA_{\text{DAF}}(:,3)/300) \ldots 
+ UA_{\text{DAF}}(:,4)/100 - (UA_{\text{DAF}}(:,7) - UA_{\text{DAF}}(:,6))/800; 
\text{HHV}_{\text{D}} = UA_{\text{D}}(:,8)^*2.326; 
\text{HHV}_{\text{r}} = UA_{\text{r}}(:,8)^*2.326; 
```

Figure 4.31: Code for calculation of bottom and fly ash thermodynamic properties.

```matlab
% Calculate entropy and exergy (DAF, AH, and complete) for culm
\text{s}_{\text{DAF}} = [v_{\text{culm}}(:,1), v_{\text{culm}}(:,1)] - (v_{\text{culm}}(:,1) * v_{\text{culm}}(:,1)) \ldots 
+ 20(u_{\text{culm}}(:,1) * v_{\text{culm}}(:,1)) \ldots 
+ 54(u_{\text{culm}}(:,1) * v_{\text{culm}}(:,1)) \ldots 
+ 44.67127(u_{\text{culm}}(:,1) * v_{\text{culm}}(:,1)) \ldots 
```

Figure 4.31: Code for calculation of bottom and fly ash thermodynamic properties.

```matlab
\text{Bottom ash properties- enthalpy equations require deg F and result in enthalpy in Btu/lb. Conversion added to result in kJ/kg.}
\text{for } i=1:lb
\text{if } b1(i,15) < 600 
\text{hbl}(i,3) = (7.735819*10^-5 * b1(i,15))^2 \ldots 
+ 0.1702038 * b1(i,15) - 33.85065 / (0.42992); 
\text{else} 
\text{hbl}(i,3) = (2.408712*10^-5 * b1(i,15))^2 \ldots 
+ 0.2358673 * b1(i,15) - 12.18512 / (0.42992); 
\text{end}
\text{end}
\text{hbl}(i,3) = (hbl(i,3) - \text{ho}_{\text{A}}) - T_o * (hbl(i,3)); \text{ Exergy of Bl}
```

```matlab
\text{Fly ash properties- enthalpy equations require deg F and result in enthalpy in Btu/lb. Conversion added to result in kJ/kg.}
\text{for } i=1:lb
\text{if } b1(i,16)+176 < 600 
\text{hbl}(i,4) = (7.735819*10^-5 * b1(i,16)+176)^2 \ldots 
+ 0.1702038 * b1(i,16)+176 - 33.85065 / (0.42992); 
\text{else} 
\text{hbl}(i,4) = (2.408712*10^-5 * b1(i,16)+176)^2 \ldots 
+ 0.2358673 * b1(i,16)+176 - 12.18512 / (0.42992); 
\text{end}
\text{end}
\text{hbl}(i,4) = (hbl(i,4) - \text{ho}_{\text{A}}) - T_o * (hbl(i,4)); \text{ Exergy of Fl}
```

```matlab
\text{Chemical exergy of ash}
\text{e}_{\text{ash_other_B1}} = \text{m}_{\text{O}}(:,3)^*\text{e}_{\text{ch}}(i,3) + \text{m}_{\text{O}}(:,15)^*\text{e}_{\text{ch}}(i,15); 
```

```matlab
78
To demonstrate the extent of reaction method the analysis is performed on boiler model BI. The reactions given in Equations (3.2) to (3.6) from Section 3.5.2.1 are repeated here for reference. The only change from the original reactions is that the excess air value, $\lambda$, has been set to 20%.

\[ C + 1.2(O_2 + 3.76N_2) \rightarrow CO_2 + 0.2O_2 + 4.512N_2 \]  
\[ (4.97) \]

\[ H + 1.2(O_2 + 3.76N_2) \rightarrow \frac{1}{2}H_2O + 0.95O_2 + 4.512N_2 \]  
\[ (4.98) \]

\[ S + 1.2(O_2 + 3.76N_2) \rightarrow SO_2 + 0.2O_2 + 4.512N_2 \]  
\[ (4.99) \]

\[ CaCO_3 \rightarrow CaO + CO_2 \]  
\[ (4.100) \]

\[ CaO + SO_2 + 1.2(O_2 + 3.76N_2) \rightarrow CaSO_4 + 0.7O_2 + 4.512N_2 \]  
\[ (4.101) \]

\[ 2N \rightarrow N_2 \]  
\[ (4.102) \]

\[ 2O \rightarrow O_2 \]  
\[ (4.103) \]

In model BI there are seven reactions, which mean that seven extent of reaction values will arise. There are thirteen unique compounds within the seven reactions. Of the compounds, the flow rates of the culm components are known from the culm flow rate and the ultimate analysis data. The flow rate of the air entering the boiler and the limestone (CaCO$_3$) are known from the operational data. The total flows of air flow, culm flow, and limestone flow may be found for each boiler using Equations (4.104)-(4.106).

\[ \dot{m}_{\text{air}} = \dot{m}_{PA} + \dot{m}_{SA} + \dot{m}_{\text{Duct air}} \]  
\[ (4.104) \]

\[ \dot{m}_{\text{culm}} = \dot{m}_{\text{culm 1}} + \dot{m}_{\text{culm 2}} \]  
\[ (4.105) \]

\[ \dot{m}_{\text{lime}} = \dot{m}_{\text{lime 1}} + \dot{m}_{\text{lime 2}} \]  
\[ (4.106) \]

From the known mass flow rates, the molar flow rates of O$_2$, N$_2$, and the culm components may also be found. The molar flow rates for the air components, seen in Equations (4.107) and (4.108), are found based on the total inflow of air.

\[ \dot{n}_{O_2,\text{in}} = \frac{0.21\dot{m}_{\text{air}}}{M_{O_2}} \]  
\[ (4.107) \]
The molar flow rates for the culm components are given in Equations (4.110) to (4.116). The molar flow rates are found by dividing the mass flow rate of a component by the molar mass of the component. The mass flow rate is found by multiplying the culm mass flow rate by $K$ where $K$ is given in Equation (4.109). Note that there is not molar flow rate for the ash because ash composition is unknown.

\[
K_i = \frac{(U\Lambda)_{AR,i}}{100}
\]  
(4.109)

\[
\dot{n}_{H_2O,in} = \frac{K_{H_2O}\dot{m}_{culm}}{M_{H_2O}}
\]  
(4.110)

\[
\dot{m}_{Ash,in} = K_{Ash}\dot{m}_{culm}
\]  
(4.111)

\[
\dot{n}_{C,in} = \frac{K_{C}\dot{m}_{culm}}{M_C}
\]  
(4.112)

\[
\dot{n}_{H,in} = \frac{K_{H}\dot{m}_{culm}}{M_H}
\]  
(4.113)

\[
\dot{n}_{N,in} = \frac{K_{N}\dot{m}_{culm}}{M_N}
\]  
(4.114)

\[
\dot{n}_{S,in} = \frac{K_{S}\dot{m}_{culm}}{M_S}
\]  
(4.115)

\[
\dot{n}_{O,in} = \frac{K_{O}\dot{m}_{culm}}{M_O}
\]  
(4.116)

The molar flow rate of limestone into the boiler, Equation (4.117), is based on the mass flow rate of limestone.

\[
\dot{n}_{CaCO_3,in} = \frac{\dot{m}_{lime}}{M_{CaCO_3,in}}
\]  
(4.117)

Equation (4.118) gives the estimated exiting molar flow rate of the emission NO based on the molar flow rate of nitrogen into the boiler and the CEMS data.

\[
\dot{n}_{NO,ext} = 0.013\dot{n}_{N,in}
\]  
(4.118)
Since only model BII takes NO into account, Equation (4.118) is calculated only when model BII is chosen.

The coding for Equations (4.109)-(4.117) is given in Figure 4.32. The values of $K$ and the molar flow rates of the culm components are determined using “if loops”, as shown in the code. The coding for the NO molar flow rate is seen in Figure 4.33.

![Code for determining inflows of materials into boilers](image)

![Code for calculating molar flow rate of NO leaving the boiler. Note that this value is only calculated when model BII is selected.](image)

In order to determine the remaining flow rates out of the boiler, Equation (4.96) at steady state is applied to each compound for which a flow rate is known. The resulting molar balances are shown in Equations (4.119)-(4.125). The underlined terms in the equations are set to zero since each of the compounds are used completely or, in the case of NO, there is no flow of the compound into the boiler. Each of the culm components and the limestone inflow are converted completely for model BI, so each of the molar flow rates out are set to zero. The compounds that are generated within the boiler have molar flow rates entering the boiler set to zero. CaO is generated in the boiler, but also converted completely, and so both the molar flows in and out are set to zero.
Carbon:
\[ 0 = \dot{n}_{C,in} - \dot{n}_{C,out} - \dot{x}_1 \]  
(4.119)

Hydrogen:
\[ 0 = \dot{n}_{H,in} - \dot{n}_{H,out} - \dot{x}_2 \]  
(4.120)

Sulfur:
\[ 0 = \dot{n}_{S,in} - \dot{n}_{S,out} - \dot{x}_3 \]  
(4.121)

Limestone:
\[ 0 = \dot{n}_{CaCO_3,in} - \dot{n}_{CaCO_3,out} - \dot{x}_4 \]  
(4.122)

Calcium oxide:
\[ 0 = \dot{n}_{CaCO_3,in} - \dot{n}_{CaCO_3, out} - \dot{x}_5 + \dot{x}_4 \]  
(4.123)

Nitrogen:
\[ 0 = \dot{n}_{N,in} - \dot{n}_{N,out} - \dot{x}_6 \]  
(4.124)

Oxygen:
\[ 0 = \dot{n}_{O,in} - \dot{n}_{O,out} - \dot{x}_7 \]  
(4.125)

It is observed that each of the molar balance equations has one known and one unknown variables. Each of the equations may be solved for the unknown extent of reaction values. A list of the extent of reaction values for models BI and BII are given in Table 4.8.

<table>
<thead>
<tr>
<th>Extent of Reaction</th>
<th>BI</th>
<th>BII</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \dot{x}_1 )</td>
<td>( \dot{n}_{C,in} )</td>
<td>( \dot{n}_{C,in} )</td>
</tr>
<tr>
<td>( \dot{x}_2 )</td>
<td>( \dot{n}_{H,in} )</td>
<td>( \dot{n}_{H,in} )</td>
</tr>
<tr>
<td>( \dot{x}_3 )</td>
<td>( \dot{n}_{S,in} )</td>
<td>( \dot{n}_{S,in} )</td>
</tr>
<tr>
<td>( \dot{x}_4 )</td>
<td>( \dot{n}_{CaCO_3,in} )</td>
<td>( \dot{n}_{CaCO_3,in} )</td>
</tr>
<tr>
<td>( \dot{x}_5 )</td>
<td>( \dot{x}_4 )</td>
<td>( \dot{x}_4 )</td>
</tr>
<tr>
<td>( \dot{x}_6 )</td>
<td>( 0.5\dot{n}_{N,in} )</td>
<td>( \dot{n}_{N,O,out} )</td>
</tr>
<tr>
<td>( \dot{x}_7 )</td>
<td>( 0.5\dot{n}_{O,in} )</td>
<td>( \frac{\dot{n}_{N,in} - \dot{x}_6}{2} )</td>
</tr>
<tr>
<td>( \dot{x}_8 )</td>
<td>--</td>
<td>( \frac{\dot{n}_{O,in}}{2} )</td>
</tr>
</tbody>
</table>

Figure 4.34 shows the code for determining the extent of reaction values for models BI (Figure 4.34(a)) and BII (Figure 4.34(b)).
Once the extents of reactions are known, the unknown molar flows may be determined by substituting known values into Equation (4.96). As an example, the unknown molar flow of CO₂ for model BI is found. A steady state molar balance for CO₂ is generated in Equation (4.126).

\[ 0 = \dot{n}_{CO_2, in} - \dot{n}_{CO_2, out} + \dot{X}_1 + \dot{X}_4 \quad (4.126) \]

Once again, the underlined equation is set to zero since there is no flow of CO₂ into the boiler. Solving for the molar flow of CO₂ out of the boiler gives Equation (4.127).

\[ \dot{n}_{CO_2, out} = \dot{X}_1 + \dot{X}_4 \quad (4.127) \]

A similar procedure is followed for each compound in each model. In the case of model BII, the level of NO out of the boiler is estimated based on the CEMS data. Table 4.9 lists the equations for each of the exiting molar flow rates for models BI and BII. The Matlab™ code for the equations listed in Table 4.9 is shown in Figure 4.35.

The mass flow of each combustion product is found by substituting the appropriate extent of reaction values from Table 4.8 into the molar flows listed in Table 4.9 and converting them to a mass basis. When the known molar flow rates are applied, all unknown mass flow rates may be found. As an example: if the molar flow rate of the O₂ produced through the reaction model BII is desired, the appropriate molar flow listing from Table 4.9 is taken, as shown in Equation (4.128).
Table 4.9: Summary of molar mass flows out of the boiler for each boiler model.

<table>
<thead>
<tr>
<th>Molar flow out</th>
<th>BI</th>
<th>BII</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \hat{n}_{O_2} )</td>
<td>( \hat{n}<em>{O_2,in} + \hat{x}</em>{r} \hat{x} - \hat{x}_1 - 0.25 \hat{x}_2 - \hat{x}_3 - 0.5 \hat{x}_5 )</td>
<td>( \hat{n}_{O_2,in} - (1-r) \hat{x}_1 - 0.25 \hat{x}_2 - \hat{x}_3 - 0.5(\hat{x}_5 + \hat{x}_6) + \hat{x}_6 )</td>
</tr>
<tr>
<td>( \hat{n}_{N_2} )</td>
<td>( \hat{n}_{N_2,in} + \hat{x}_7 )</td>
<td>( \hat{n}_{N_2,in} + \hat{x}_7 )</td>
</tr>
<tr>
<td>( \hat{n}_{CO_2} )</td>
<td>( \hat{x}_1 + \hat{x}_4 )</td>
<td>( (1-r) \hat{x}_1 + \hat{x}_4 )</td>
</tr>
<tr>
<td>( \hat{n}_{H_2O} )</td>
<td>( \hat{n}_{H_2O,in} + 0.5 \hat{x}_2 )</td>
<td>( \hat{n}_{H_2O,in} + 0.5 \hat{x}_2 )</td>
</tr>
<tr>
<td>( \hat{n}_{CaSO_4} )</td>
<td>( \hat{x}_3 - \hat{x}_5 )</td>
<td>( \hat{x}_3 - \hat{x}_5 )</td>
</tr>
<tr>
<td>( \hat{n}_C )</td>
<td>( \hat{x}_5 )</td>
<td>( \hat{x}_5 )</td>
</tr>
<tr>
<td>( \hat{n}_C )</td>
<td>( 0 )</td>
<td>( r\hat{n}_{C,in} )</td>
</tr>
</tbody>
</table>

(a) % Calc remaining molar flows
\[
\begin{align*}
N_{10}(i:10) &= N_{11}(i:10) + X_{1}(i:7) - X_{1}(i:1) - X_{1}(i:3) \\
&\quad - 0.25*X_{1}(i:2) - 0.5*X_{1}(i:5); \quad \% N\ out\ CO2 \\
N_{10}(i:11) &= N_{11}(i:11) + X_{1}(i:6); \quad \% N\ out\ N2 \\
N_{10}(i:12) &= X_{1}(i:4) + X_{1}(i:4); \quad \% N\ out\ CO2 \\
N_{10}(i:13) &= 0.5*X_{1}(i:2) + N_{11}(i:1); \quad \% N\ out\ H20\ (g) \\
N_{10}(i:14) &= X_{1}(i:3) - X_{1}(i:5); \quad \% N\ out\ SO2 \\
N_{10}(i:15) &= X_{1}(i:5); \quad \% N\ out\ CaSO4
\end{align*}
\]

(b) % Calc remaining molar flow rates leaving boiler
\[
\begin{align*}
N_{10}(i:10) &= N_{11}(i:10) - (1-cancel)*X_{1}(i:1) - 0.25*X_{1}(i:2) \\
&\quad - X_{1}(i:3) - 0.5*(X_{1}(i:5)+X_{1}(i:6)) + X_{1}(i:5); \quad \% N\ out\ CO2 \\
N_{10}(i:11) &= N_{11}(i:11) + X_{1}(i:7); \quad \% N\ out\ N2 \\
N_{10}(i:12) &= (1-cancel)*X_{1}(i:1) + X_{1}(i:4); \quad \% N\ out\ CO2 \\
N_{10}(i:13) &= 0.5*X_{1}(i:2) + N_{11}(i:1); \quad \% N\ out\ H20 \\
N_{10}(i:14) &= X_{1}(i:3) - X_{1}(i:5); \quad \% N\ out\ SO2 \\
N_{10}(i:15) &= X_{1}(i:5); \quad \% N\ out\ CaSO4 \\
N_{10}(i:3) &= cancel*N_{11}(i:3); \quad \% N\ out\ C
\end{align*}
\]

Figure 4.35: Code for calculating the remaining molar flow rates for models (a) BI and (b) BII.

\[
\hat{n}_{O_2,out} = \hat{n}_{O_2,in} - (1-r)\hat{x}_1 - 0.25\hat{x}_2 - \hat{x}_3 - 0.5\hat{x}_5 - \hat{x}_6 \tag{4.128}
\]

The appropriate extent of reaction values from Table 4.8 are inserted into Equation (4.128) to yield Equation (4.129).

\[
\hat{n}_{O_2,out} = \hat{n}_{O_2,in} - (1-r)\hat{n}_{C,in} - n_{H,in} - n_{S,in} - 0.5\hat{x}_4 - \frac{\hat{n}_{O,in} - \hat{x}_6}{2} \tag{4.129}
\]

In this case two more extent of reaction values are required from Table 4.8 to give Equation (4.130).
\[ \dot{n}_{O_2, out} = \dot{n}_{O_2, in} - (1 - r)\dot{n}_{C, in} - 0.25\dot{n}_{H, in} - \dot{n}_{S, in} - 0.5\dot{n}_{CaCO_3, in} - \frac{\dot{n}_{O, in} - \dot{n}_{N_2, out}}{2} \]  

(4.130)

Each of the molar flows on the left hand side of the equation are known, and so the molar flow rate of O₂ out of the boiler may be found.

As the final step in the mass balance analysis, the molar flow rates are converted into mass flow rates using the relationship given in Equation (4.131).

\[ \dot{m}_i = \dot{n}_i M_i \]  

(4.131)

The total mass flow of each stream of ash is one half of the total inflow of ash. Finally, the flue gas is found by summing the mass flow rates of all the exiting gases. The Matlab™ code for the final molar to mass conversions is given in Figure 4.36.

```
\% Convert to mass flows (kmol/s) to (kg/s) for each species
\% General conversion
\textit{for} i=1:16
  \textit{mli}(i,1) = \textit{Nli}(i,1).*\textit{Mli}(1,1);
  \textit{mlo}(i,1) = \textit{Nlo}(i,1).*\textit{Mli}(1,1);
\textit{end}

\% Correct ash conversion
\textit{mli}(i,2) = R(1,2).*\textit{m_culn_b1};
\textit{mlo}(i,2) = \textit{mli}(i,2);
\textit{m_lo}(1,2) = \textit{mli}(1,2);

\% Limestone mass flow rates
m_lo = \textit{mlo}(1,2)/2;
\textit{m_fa} = \textit{mlo}(2,2);

\% Flue gas flow rate out
\textit{for} i=1:hr
  m_fg(i,1) = sum(\textit{mlo}(i,10:16)) - \textit{mlo}(i,15); \textit{\% FG = (sum of exiting gases)}
\textit{end}
```

Figure 4.36: Code for converting molar flow rates to mass flow rates.

**4.5.1.4. Flue Gas Thermodynamic Properties**

As described by Coskun et al. [53], the specific heat for flue gas may be determined based on the specific heat of its components. Both boiler models assume an ideal gas model, so the specific heat of each component is dependent on temperature alone.
The amount of air required to complete the combustion process without limestone is given by Coskun et al. as Equation (4.132). This amount of air is referred to as the stoichiometric air, \( m_{\text{air, st}} \). \( K_i \) represents the fraction of the corresponding element in the culm composition as given in Equation (4.109).

\[
m_{\text{air, st}} = 11.445(2.9978K_H - 0.3747K_O + 0.3747K_S + K_C)
\]  

(4.132)

Assuming 1 kg of fuel is used, Equation (4.132) may be applied to Equation (4.95), which is a mass balance around the boiler, to produce the mass of the flue gas, \( m_{FG} \), seen in Equation (4.133).

\[
m_{FG} = 11.445(1 + \lambda)(2.9978K_H - 0.3747K_O + 0.3747K_S + K_C) + (1 - K_A)
\]  

(4.133)

The total stoichiometric mass, \( m_{\text{total, st}} \), for 1 kg of fuel is found using Equation (4.134).

\[
m_{\text{total, st}} = m_{\text{air, st}} + (1 - K_{\text{ash}})
\]  

(4.134)

The specific heat of flue gas is given by Coskun et al. as the sum the specific heat of the flue gas components with the stoichiometric amount of air and the specific heat of the excess air. The specific heat of flue gas is given in Equation (4.135).

\[
c_{p,FG} = \left[ \frac{c_{p,CO_2}}{a_C + b_N + c_H + d_S} \right] \left( \frac{m_{\text{total, st}}}{m_{FG}} \right) + f_A
\]  

(4.135)

The components of Equation (4.135) are given in Equations (4.136)-(4.141). The temperatures are required to be in Kelvin; other variables are given in fraction or percentage form.

\[
a_C = \frac{a_m}{a_{cp}} = \frac{966K_C}{m_{\text{total, st}}}
\]  

(4.136)

\[
b_N = \frac{b_m}{b_{cp}} = \frac{(0.767m_{\text{air, st}} + K_N)/m_{\text{total, st}}}{0.9094 + 1.69 \cdot 10^{-4}T - 11135T^{-2}}
\]  

(4.137)

\[
c_H = \frac{c_m}{c_{cp}} = \frac{(8.938K_H + K_{H_2O})/m_{\text{total, st}}}{0.5657 - 6.68 \cdot 10^{-6}T - 10465T^{-2}}
\]  

(4.138)

\[
d_S = \frac{d_m}{d_{cp}} = \frac{2K_S/m_{\text{total, st}}}{\exp[2.679 - 151.16T^{-1} - 0.289 \ln T]}
\]  

(4.139)

\[
f_A = f_m \cdot c_{p,A} = \left( \frac{\lambda m_{\text{air, st}}}{m_{FG}} \right)(0.7124 \cdot 1.00011^T \cdot T^{0.051})
\]  

(4.140)
The code for in Equations (4.136)-(4.141) is given in Figure 4.37.

\[ c_{p,CO_2} = 0.1874 \cdot 1.000061^T \cdot T^{0.2665} \]  

(4.141)

Since the specific heat capacity of the flue gas is now known, the enthalpy and entropy values of the flue gas may be calculated assuming constant specific heats and an ideal gas model. With these assumptions, the enthalpy for the flue gas is given in Equation (4.142).

\[ h_{FG} = c_{p,FG} T_{FG} \]  

(4.142)

In order to calculate the flue gas exergy, the change in entropy is required. The change in enthalpy between the flue gas and environmental temperatures is given in Equation (4.143).

\[ s_{FG} - s_0 = c_{p,FG} \ln \left( \frac{T_{FG}}{T_0} \right) - R_{avg} \ln \left( \frac{p_{FG}}{p_0} \right) \]  

(4.143)
\( R_{\text{avg.}} \) is the average flue gas universal gas constant. The universal gas constant value may be calculated, however, a series of simplifications to Equation (4.143) cause the calculation to be unnecessary. If the pressure difference is taken to be negligible, the Equation (4.143) simplifies to Equation (4.144).

\[
 s_{\text{FG}} - s_o = c_{p,\text{FG}} \ln \left( \frac{T_{\text{FG}}}{T_o} \right) 
\]  

(4.144)

The necessary components to determine the exergy of the flue gas are now all known. The composition of the flue gas may be coupled with tabulated chemical exergy values to determine the total chemical exergy of the flue gas, given in Equation (4.145).

\[
 e_{\text{CH}}^{\text{FG}} = \sum_{i=1}^{n} \dot{m}_i e_{i}^{\text{CH}} 
\]  

(4.145)

\( \dot{m}_i \) is the mass flow rate of a given flue gas component, calculated from the boiler mass balance, and \( e_{i}^{\text{CH}} \) is the corresponding chemical exergy value.

The flow exergy is found using Equation (4.142) and Equation (4.144) into the flow exergy equation given in Equation (4.8). The flow exergy of the flue gas is given in Equation (4.146).

\[
 e_{f,\text{FG}} = c_{p,\text{FG}} (T_{\text{FG}} - T_o) - T_o \left[ c_{p,\text{FG}} \ln \left( \frac{T_{\text{FG}}}{T_o} \right) \right] 
\]  

(4.146)

Equation (4.146) may also be given as Equation (4.147).

\[
 e_{f,\text{FG}} = c_{p,\text{FG}} \left[ (T_{\text{FG}} - T_o) - T_o \ln \left( \frac{T_{\text{FG}}}{T_o} \right) \right] 
\]  

(4.147)

The total exergy is calculated by substituting Equation (4.147) and Equation (4.145) into Equation (4.6) to get Equation (4.148).

\[
 \hat{e}_{\text{FG}} = \sum_{i=1}^{n} \dot{m}_i e_{i}^{\text{CH}} + \dot{m}_{\text{FG}} c_{p,\text{FG}} \left[ (T_{\text{FG}} - T_o) - T_o \ln \left( \frac{T_{\text{FG}}}{T_o} \right) \right] 
\]  

(4.148)

The code for calculating the specific heat, enthalpy, and flow exergy of the flue gas is given in Figure 4.38.
4.5.2. Energy Analysis

Once the unknown exergy values have been found, the first law of thermodynamic analysis of the boiler is fairly straightforward. Martin et al. [945] perform a similar thermodynamic analysis on a fluidized bed boiler that uses low-grade coal and biomass as feedstock. The procedure for creating the thermodynamic model for the boiler is modified from the process outlined by Martin et al., especially in the case of the limestone heat transfer discussed in this section.

There are four heat transfer terms that are included in the boiler analysis: useful heat transfer, fuel energy content, endothermic limestone reaction heat transfer, and the heat loss through the boiler walls. The two heat transfer values that leave the boiler control volume, heat loss and useful heat, are shown in Figure 4.39, which has been copied from Figure 4.27 in the introduction to this section.

The useful heat transfer $\dot{Q}_u$ is the transfer between the heat generated during combustion and the feedwater. This source is the largest and most significant. $\dot{Q}_u$ is determined based on the change between the inlet and outlet...
feedwater conditions. The boiler models consider the superheated steam outlet (B2) and the feedwater inlet (B1). Spray water is added to the initial inflow of feedwater, so the flow through B2 is greater than the flow through B1. Since the spray water enters the boiler at the same temperature and pressure as the feedwater, the thermodynamic properties of the feedwater and spray water are the same (i.e. \( h_{B_1} = h_{B_3} \)). Equation (4.149) is found by conservation of mass.

\[
\dot{m}_{B_2} = \dot{m}_{B_2} - \dot{m}_{B_1} \quad (4.149)
\]

The useful heat transfer \( \dot{Q}_u \), may then be defined as in Equation (4.150).

\[
\dot{Q}_u = (\dot{m}h)_{B_1} + (\dot{m}h)_{B_3} - (\dot{m}h)_{B_2} \quad (4.150)
\]

Combining Equations (4.149) and (4.150) yields Equation (4.51).

\[
\dot{Q}_u = \dot{m}_{B_2}(h_{B_1} - h_{B_2}) \quad (4.151)
\]

The total fuel energy content for each boiler is the mass flow rate of the fuel entering the boiler times the HHV of the fuel as shown in Equation (4.152).

\[
Q_{culm} = \dot{m}_{culm}(HHV)_{culm} \quad (4.152)
\]

The boiler energy efficiency is given as the ratio between the energy entering the boiler and the useful energy leaving the boiler. The efficiency is then given in Equation (4.153).

\[
\eta_B = \frac{-\dot{Q}_u}{Q_{culm}} \quad (4.153)
\]

The negative sign is added so both the useful heat (leaving the boiler) and the culm energy (entering the boiler) have the same sign.

The final heat transfer is lost between the boiler walls and the boiler room. The heat loss through the boiler wall may be calculated one of two ways. The first method for the boiler heat loss, \( \dot{Q}_{LB} \), is to use an energy balance around a boiler and solve for the heat loss. The second method, \( \dot{Q}_{Lest} \), is to apply an estimated 3% heat loss [59] of the energy entering the boiler (the total culm energy). The 3% heat loss value is found in literature to be the approximate heat loss of two CFB boilers rated at 300 MWe. The second method of calculation will be the same for each boiler model since the heat energy entering the boiler is always the same.

\[
\dot{Q}_{Lest} = 0.03\dot{Q}_{culm} \quad (4.154)
\]
The code for Equations (4.150) through (4.154) is given in Figure 4.40. The values for the useful heat transfer, fuel energy, boiler energy efficiency, and estimated boiler heat loss are the same for both boiler models.

![Equation Table]

Figure 4.40: Code for calculation of useful boiler heat transfer, heat energy entering the boiler, estimated heat loss, and boiler energy efficiency.

Since the limestone reactions have a total endothermic effect, meaning they require an addition of heat to occur, the limestone reaction component of the boiler energy balance may be treated as a separate heat transfer term, $Q_{\text{lime}}$. The heat absorbed during the limestone reactions - Reactions (3.5) and (3.6) may be found using an energy balance on a molar basis as shown in Equation (4.155).

$$
Q_{\text{lime}} = \sum_{k=1}^{\# \text{products}} \dot{n}_k (\tilde{h}_p + \Delta \tilde{h})_p - \sum_{j=1}^{\# \text{reactants}} \dot{n}_j (\tilde{h}_p + \Delta \tilde{h})_R
$$  \hspace{1cm} (4.155)

For ease of reference, Reaction (3.5) will be referred to as the first limestone reaction (lime Reaction 1) and Reaction (3.6) will be referred to as the second limestone reaction (lime Reaction 2).

### 4.5.2.1. Model BI

Since model BI assumes the reactants enter the boiler at standard reference conditions (i.e. $h_R(T, p) = h_R(T_o, p_o) = 0$), Equation (4.155) simplifies, for model BI only, to Equation (4.156).

$$
Q_{\text{lime, BI}} = \sum_{k=1}^{\# \text{products}} (\dot{n}_k \tilde{h}_p^o)_{\text{p}} - \sum_{j=1}^{\# \text{reactants}} (\dot{n}_j \tilde{h}_p^o)_R + \sum_{k=1}^{\# \text{products}} \dot{n}_p \Delta \tilde{h}_p
$$  \hspace{1cm} (4.156)

The BI subscript indicates the heat transfer to be relevant to the first boiler model. The reactants for both boiler models include air, culm, and limestone. The products include calcium sulfate (a solid that exits with the ash), bottom ash, fly ash, and flue gas. The flue gas is composed of oxygen, nitrogen, CO2, SO2, and water. Equation (4.156) is applied to include both Reactions (3.5) and (3.6) to yield Equation (4.157).
\[ Q_{lime,BI} = \sum_{\text{lime Reaction 1}} \left[ \dot{n}_p (\bar{h}_f + \Delta \bar{h})_p - (\tilde{n} \bar{h}_f)_{R1} \right] + \sum_{\text{lime Reaction 2}} \left[ \dot{n}_p (\bar{h}_f + \Delta \bar{h})_p - (\tilde{n} \bar{h}_f)_{R2} \right] \quad (4.157) \]

Since the relevant products and reactants are known, \( \dot{Q}_{lime,BI} \) becomes Equation (4.158).

\[ \dot{Q}_{lime,BI} = \left[ \dot{n}_{CaO} (\bar{h}_f + \Delta \bar{h})_{CaO} - \dot{n}_{CaCO_3} (\bar{h}_f + \Delta \bar{h})_{CaCO_3} \right]_{\text{lime Reaction 1}} + \left[ \dot{n}_{CaSO_4} (\bar{h}_f + \Delta \bar{h})_{CaSO_4} + \dot{n}_{O_2,\text{out}} (\bar{h}_f + \Delta \bar{h})_{O_2,\text{out}} - \dot{n}_{O_2,\text{in}} (\bar{h}_f + \Delta \bar{h})_{O_2,\text{in}} - \dot{n}_{N_2,\text{in}} (\bar{h}_f + \Delta \bar{h})_{N_2,\text{in}} \right]_{\text{lime Reaction 2}} \quad (4.158) \]

Note that the CO2 counted here is only the CO2 produced in the limestone reactions, not combustion, since combustion is a separate set of equations. The air is assumed to enter the boiler at the reference temperature and the enthalpy of formations for O2 and N2 are zero, while the exiting air is already included in the flue gas calculations and must be omitted here. The limestone enters the boiler at the reference temperature as well, so the limestone change in enthalpy term drops out. The calcium oxide produced in Reaction (3.5) is equal to the amount used in Reaction (3.6), so the two calcium oxide terms cancel. Equation (4.159) results.

\[ \dot{Q}_{lime,BI} = \dot{n}_{CO_2,\text{lime Reaction 1}} (\bar{h}_f + \Delta \bar{h})_{CO_2} - \dot{n}_{CaCO_3} (\bar{h}_f)_{CaCO_3} + \dot{n}_{CaSO_4} (\bar{h}_f + \Delta \bar{h})_{CaSO_4} - \dot{n}_{SO_2} (\bar{h}_f + \Delta \bar{h})_{SO_2} \quad (4.159) \]

Since the calcium sulfate is divided evenly between the bottom ash and the fly ash, as discussed in Section 3.5.1, it exits the boiler at two temperatures, which must be reflected in the limestone heat transfer as shown in Equation (4.160).

\[ \dot{Q}_{lime,BI} = \dot{n}_{CO_2,\text{lime Reaction 1}} (\bar{h}_f + \Delta \bar{h})_{CO_2} - \dot{n}_{CaCO_3} (\bar{h}_f)_{CaCO_3} + \dot{n}_{CaSO_4} (\bar{h}_f + 0.5(\Delta \bar{h}_{FA} + \Delta \bar{h}_{BA}))_{CaSO_4} - \dot{n}_{SO_2} (\bar{h}_f + \Delta \bar{h})_{SO_2} \quad (4.160) \]

Finally, the limestone heat transfer is converted into a mass basis by dividing the molar flow rates by the corresponding molar masses. Applying these two last steps allows the limestone heat transfer to be incorporated in an energy balance. The final conversion is shown in Equation (4.161).
\[ \dot{Q}_{\text{lime,BI}} = m_{\text{CO}_2, \text{lime Reaction 1}} (\tilde{h}_f^{\phi} + \Delta \tilde{h})_{CO_2} - m_{\text{CaCO}_3} (\tilde{h}_f^{\phi})_{CaCO_3} \]
\[ + m_{\text{CaSO}_4} (\tilde{h}_f^{\phi} + 0.5 (\Delta \tilde{h}_{F_{\text{Fe}}} + \Delta \tilde{h}_{B_{\text{Al}}})_{CaSO_4} \]
\[ - m_{\text{SO}_2} (\tilde{h}_f^{\phi} + \Delta \tilde{h})_{SO_2} \] (4.161)

Since the mass flow rate of CO\(_2\) used in Equation (4.161) should only account for the CO\(_2\) produced in Reaction (3.5), and since one CO\(_2\) molecule is produced for each CaCO\(_3\) molecule entering the boiler, it may be concluded that the molar flow rate of CO\(_2\) and CaCO\(_3\) in Reaction (3.5) are equal. Therefore, applying Equation (4.131) to the molar flow rates of CO\(_2\) and CaCO\(_3\) gives Equation (4.162).

\[ \dot{n}_{\text{CO}_2, \text{lime Reaction 1}} = \dot{n}_{\text{CaCO}_3} = \frac{m_{\text{CO}_2, \text{lime Reaction 1}}}{M_{\text{CO}_2}} = \frac{\dot{m}_{\text{lime}}}{M_{\text{CaCO}_3}} \] (4.162)

Equation (4.162) may be solved to find the mass flow rate of the CO\(_2\) produced during the limestone reactions. Combining the new CO\(_2\) flow rate, Equation (4.161), and the change in enthalpy value for an ideal gas or solid (Equation (4.4)), gives the final limestone heat transfer, shown in Equation (4.163). Note that the temperatures must be in Kelvin. The thermodynamic properties used in Equation (4.163) must be converted to a mass basis, as shown, when mass flow rates are used.

\[ \dot{Q}_{\text{lime,BI}} = \dot{m}_{\text{lime}} \left( \frac{M_{\text{CO}_2}}{M_{\text{CaCO}_3}} \right) (h_f^{\phi} + \rho c_p T_{FG})_{CO_2} - \dot{m}_{\text{lime}} (h_f^{\phi})_{CaCO_3} \]
\[ + m_{\text{CaSO}_4} (\tilde{h}_f^{\phi} + 0.5 c_p (T_{FG} + T_{BA}))_{CaSO_4} \]
\[ - m_{\text{SO}_2} (h_f^{\phi} + c_p T_{FG})_{SO_2} \] (4.163)

The total heat transfer in model BII is given in Equation (4.164).

\[ \sum \dot{Q}_{\text{BI}} = \dot{Q}_{\text{L,BI}} + \dot{Q}_u + \dot{Q}_{\text{culm}} + \dot{Q}_{\text{lime,BI}} \] (4.164)

An energy balance around the boiler may be rearranged to determine the heat loss from the boiler as shown in Equation (4.165).

\[ \dot{Q}_{\text{L,BI}} = -\dot{Q}_u - \dot{Q}_{\text{culm}} - \dot{Q}_{\text{lime,BI}} + \dot{m}_{B_{\text{Fe}}} h_{FG} + \dot{m}_{B_{\text{Fe}}} h_{FA} + \dot{m}_{B_{\text{Fe}}} h_{BA} \] (4.165)

The coding for the energy analysis of a boiler using model BI is given in Figure 4.41.
4.5.2.2. **Model BII**

The energy balance for the Model BII is the more complicated of the boiler models. Not only does this model include NO emissions, but the reactants are not assumed to enter the boiler at the reference conditions.

As with the analysis of model BI, the limestone heat transfer component is calculated separately using Equation (4.162). The only difference is that the change in enthalpy term is used for the limestone addition since it doesn’t enter at reference conditions in model BII. The air portion of the reaction is incorporated into the energy balance using the air flow and enthalpy. The limestone heat transfer is then given in Equation (4.166).

\[
\dot{Q}_{\text{lime,BII}} = m_{\text{lime}} \left( \frac{M_{\text{CO}_2}}{M_{\text{CaCO}_3}} \right) (h_f^p + c_p T_{\text{FG}})_{\text{CO}_2} - m_{\text{lime}} (h_f^p + c_p T_{\text{lime,in}})_{\text{CaCO}_3} + m_{\text{CaSO}_4} (h_f^p + 0.5c_p (T_{\text{FG}} + T_{\text{BA}}))_{\text{CaSO}_4} - m_{\text{SO}_2} (h_f^p + c_p T_{\text{FG}})_{\text{SO}_2}
\]  

(4.166)

The boiler heat loss for model BII is basically Equation (4.165) with the addition of the inflow primary and secondary (which includes the duct burner air) air as seen in Equation (4.167).

\[
\dot{Q}_{\text{LBII}} = -\dot{Q_u} - \dot{Q}_{\text{culm}} - \dot{Q}_{\text{lime,BII}} + \dot{m}_{\text{B10}} h_{\text{FG}} + \dot{m}_{\text{B9}} h_{\text{FA}} + \dot{m}_{\text{B8}} h_{\text{BA}} - \dot{m}_{\text{PA}} h_{\text{FA}} - \dot{m}_{\text{SA}} h_{\text{SA}}
\]  

(4.167)

The code for the energy analysis of the boiler using model BII is given in Figure 4.42.
4.5.2.3. Combined Boiler Effects

The code shown in the energy analyses for models BI and BII show only the calculations for one of the two boilers as noted by "b1" in the variable names throughout the code. The same calculations are performed for the second boiler. In anticipation of the analysis of the total power plant, it is desirable to determine the combined effects of both boilers. The results from model BII are used since they more accurately represent the boilers. The total heat loss, total useful heat transfer, total heat into the boilers, and average boiler efficiency are given in Equations (4.168)-(4.171).

\[
\begin{align*}
Q_{\text{Total,B}} &= Q_{b1,BII} + Q_{b2,BII} \\
Q_{u,\text{Total,B}} &= Q_{b1,u} + Q_{b2,u} \\
Q_{\text{culm,Total}} &= Q_{b1,culm} + Q_{b2,culm} \\
\eta_{B,\text{avg}} &= \frac{\eta_{b1} + \eta_{b2}}{2}
\end{align*}
\]

(4.168) (4.169) (4.170) (4.171)

The Matlab™ code for the combined boiler effects are given in Figure 4.43. The code checks which boiler model has been used and creates the combined boiler effects using the appropriate boiler model data.
4.5.3. Exergy Analysis

The previously unknown exergy values for the culm and flue gas are found from Sections 4.5.1.1 and 4.5.1.4. Once the chemical exergy values are known, the exergetic analysis may proceed.

The useful exergy value is based off of the useful heat transfer value as shown in Equation (4.172). In the case of the useful heat transfer, the boundary temperature is taken as the temperature within the boiler, $T_{chamber}$, since the heat transfer to the feedwater occurs across tubes carrying the feedwater through the boiler.

$$E_u = \dot{Q}_u \left(1 - \frac{T_o}{T_{chamber}}\right)$$ (4.172)

The culm exergy is found by multiplying the mass flow rate of culm into the boiler by the chemical exergy of the fuel. Since the chemical exergy of the fuel is much greater than the flow exergy, the flow exergy for the fuel will be neglected. The exergy value of the fuel is given in Equation (4.173).

$$E_{culm} = \dot{m}_{culm} \dot{e}^{CH}_{culm}$$ (4.173)

The boiler exergetic efficiency, given in Equation (4.174), is the ratio between the useful exergy and the exergy input.

$$\eta_{ex} = \frac{E_u}{E_{in}}$$ (4.174)
When the boiler heat loss value, $Q_l$, is used, the exergy loss associated with the heat loss is defined with Equation (4.175). The temperature of the boiler room, $T_{b,B}$, gives the approximate temperature in the room housing the boiler; this temperature is used since the heat loss is across the boiler walls and into the boiler room.

\[
\dot{E}_l = Q_l \left(1 - \frac{T_o}{T_{b,B}}\right)
\]  

(4.175)

There are a number of exergy terms that differ between models BI and BII, but for which the same equation can be used. Since the properties of the streams in and out of the boiler are determined before the thermodynamic model is implemented in the Matlab\textsuperscript{TM} code, the following equations are “self correcting”; if a term is not applicable to a given model, the flow rate or thermodynamic property of the term will already be set to zero. Since the term will be set to zero before the thermodynamic model is implemented, the term will drop out and the final solution will follow the correct model assumptions. The terms for which this applies are the airflow exergy into the boiler, the flue gas exergy, the ash exergy, and the limestone exergy. The exergy of the air streams into the boiler are given in Equation (4.176). The exergy given is the complete exergy of the air, which includes the chemical and flow exergies.

\[
\dot{E}_{air} = \dot{m}_{PA}e_{PA} + \dot{m}_{SA}e_{SA}
\]  

(4.176)

Note that for model BI the temperature entering the boiler and reference temperature are the same. This causes the flow exergy of the air to cancel to zero since the change in enthalpy and the change in entropy are zero.

The flue gas exergy value is given in Equation (4.148), and so the flue gas exergy may be calculated using Equation (4.177).

\[
\dot{E}_{FG} = \dot{m}_{FG}e_{FG} + \sum_{i=1}^{n} \dot{m}_i e_{i}^{CH}
\]  

(4.177)

Note that the sum of the chemical exergy values depends on the flow rate of a given flue gas component; when a component, such as NO, is not present, the mass flow rate will be zero, and the term will drop out.

The ash exergy includes the flow exergy of the ash for both models, the chemical exergy of calcium sulfate, and finally the chemical exergy of the residue carbon for model BII. The ash exergy is given in Equation (4.178).

\[
\dot{E}_{ash} = \dot{m}_{ash}e_{f,ash} + \dot{m}_{CaSO_4}e_{CaSO_4}^{CH} + \dot{m}_c e_c^{CH}
\]  

(4.178)
Finally, the limestone exergy is given with Equation (4.179).

\[ \dot{E}_{lime} = m_{lime} e^{CH}_{CaCO_3} \]  

(4.179)

The exergy for limestone does not include the exergy flow because the inflow of limestone into the boiler is small compared to the chemical exergy. The Matlab™ Code for the general boiler exergy analysis is given in Figure 4.44.

---

**Figure 4.44: Code for general boiler exergy analysis.**

### 4.5.3.1. Model BI

The ash exergy for model BI is simplified from Equation (4.178) to Equation (4.180). It should be noted that the ash exergy for model BI is not calculated separately within the code.

\[ \dot{E}_{ash,BI} = \dot{m}_{ash} e_{ash} + \dot{m}_{CaSO_4} e^{CH}_{CaSO_4} \]  

(4.180)

The flue gas exergy for model BI is given in Equation (4.180). Within the code, as with the ash exergy, the flue gas exergy will naturally simplify due to zero flow rate values and so is not calculated separately for each model.

\[ \dot{E}_{FG,BI} = \dot{m}_{FG} e_{FG} + (\dot{m} e^{CH})_{O_2, out} + (\dot{m} e^{CH})_{CO_2} + (\dot{m} e^{CH})_{H_2O(g)} + (\dot{m} e^{CH})_{SO_2} \]  

(4.181)

The exergy lost through the boiler walls when the boiler heat loss is found using an energy balance is used is given in Equation (4.182).
An exergy balance around the boiler using model BI is given in Equation (4.183).

\[ 0 = \dot{E}_u + \dot{E}_{\text{cuim}} + \dot{E}_{L,BI} + \dot{E}_{\text{lime}} + \dot{E}_{\text{air}} - \dot{E}_{\text{ash,BI}} - \dot{E}_{FG,BI} - \dot{E}_{d,BI} \]  

Equation (4.183) may be rearranged to solve for the exergy destruction value, shown in Equation (4.184).

\[ \dot{E}_{d,BI} = \dot{E}_u + \dot{E}_{\text{cuim}} + \dot{E}_{L,BI} + \dot{E}_{\text{lime}} + \dot{E}_{\text{air}} - \dot{E}_{\text{ash,BI}} - \dot{E}_{FG,BI} \]  

The code for the exergy analysis of the boilers using model BI is given in Figure 4.45.

```makefile
% Model BI for boiler 1
E_1_BI_b1 = Q_1_BI_b1.*((1-T_o/T_b,B)); % BI Exergy loss

Ed_BI_b1 = E_u_b1 + E_cuim_b1 + \ E_{L_BI_b1} + \ E_{lime_b1} + \ E_{air_b1} + \ E_{\text{ash_total_b1}} + \ E_{FG_total_b1}; % BI Ed from exergy balance
```

**Figure 4.45:** Code for model BI exergy analysis.

### 4.5.3.2. Model BII

The final boiler model includes the full list of boiler assumptions, including residue carbon and NO production. The final ash exergy equation is given in Equation (4.185).

\[ \dot{E}_{\text{ash,BII}} = \dot{m}_{\text{ash}}e_{\text{ash}} + \dot{m}_{\text{CaSO}_4}e_{\text{CaSO}_4} + \dot{m}_{c}e_{c}^{CH} \]  

The flue gas exergy for model BII includes NO generation. The flue gas exergy for model BII is given in Equation (4.186).

\[ \dot{E}_{FG,BII} = \dot{m}_{FG}e_{FG} + (\dot{m} e_{CH})_{O_2,\text{out}} + (\dot{m} e_{CH})_{C,\text{out}} + (\dot{m} e_{CH})_{CO_2} + (\dot{m} e_{CH})_{H_2O(g)} + (\dot{m} e_{CH})_{\text{SO}_2} + (\dot{m} e_{CH})_{NO} \]  

The exergy lost through the boiler walls is given in Equation (4.187).

\[ \dot{E}_{L,BII} = \dot{Q}_{L,BII}\left(1 - \frac{T_o}{T_{b,B}}\right) \]  

The exergy destruction is found using an exergy balance and rearranging to solve for the exergy destruction value, given in Equation (4.188).
\[ \dot{E}_{d,\text{BII}} = \dot{E}_u + \dot{E}_{\text{culm}} + \dot{E}_{i,\text{BII}} + \dot{E}_{\text{lime}} + \dot{E}_{\text{air}} - \dot{E}_{\text{ash,BII}} - \dot{E}_{FG,\text{BII}} \]  

(4.188)

The code for the exergy analysis using model BII is given in Figure 4.46.

```
% Model BII for boiler 1
E_1_b1_BII = Q_1_b1_BII.*(1-Td_b1);  % BII Exergy loss

Ed_BII_b1 = E_u_b1 + E_1_b1_BII...
+ E_air_b1 + E_culm_b1 + E_lime_b1...
- |E_ash_total_b1 + E_FG_total_b1);  % BII Ed from exergy balance
```

Figure 4.46: Matlab™ code for exergy analysis of the boiler using model BII.

### 4.5.3.3. Combined Boiler Effects

As with the boiler energy analysis, it is desirable to know the combined effects of a number of boiler exergy parameters. The combined effects of interest include the total exergy loss, total exergy destruction, total exergy input from culm, total air exergy, total lime exergy, and the average boiler exergetic efficiency. The mentioned combined parameters are listed in Equations (4.189)-(4.196).

\[ \dot{E}_{i,\text{total,B}} = \dot{E}_{b1,i,\text{BII}} + \dot{E}_{b2,i,\text{BII}} \]  

(4.189)

\[ \dot{E}_{d,\text{total,B}} = \dot{E}_{d,b1,\text{BII}} + \dot{E}_{d,b2,\text{BII}} \]  

(4.190)

\[ \dot{E}_{in,B} = \dot{E}_{b1,\text{culm}} + \dot{E}_{b2,\text{culm}} \]  

(4.191)

\[ \dot{E}_{\text{air,\text{total,B}}} = \dot{E}_{b1,\text{air}} + \dot{E}_{b2,\text{air}} \]  

(4.192)

\[ \dot{E}_{\text{lime,\text{total,B}}} = \dot{E}_{b1,\text{lime}} + \dot{E}_{b2,\text{lime}} \]  

(4.193)

\[ \dot{E}_{\text{ash,\text{total,B}}} = \dot{E}_{b1,\text{ash}} + \dot{E}_{b2,\text{ash}} \]  

(4.194)

\[ \dot{E}_{FG,\text{total,B}} = \dot{E}_{b1,FG} + \dot{E}_{b2,FG} \]  

(4.195)

\[ \varepsilon_{B,\text{avg}} = \frac{\varepsilon_{B1} + \varepsilon_{B2}}{2} \]  

(4.196)

The code for the combined exergy effects are given in Figure 4.47.
4.6. **Total Plant System**

The overall system analysis will be used to gauge the suggested improvements, as well as provide a baseline for comparison to other energy producing systems. The total plant system will take into account the inflows and outflows of the plant, neglecting the cooling towers. Figure 4.48 summarizes the “inlet/outlet” overview of the plant.

The total plant analysis calls on the analyses performed in Sections 4.4 and 4.5 to build up the overall performance of the plant. In order to create the baseline for comparison, the overall plant energy and exergy efficiencies, and total exergy destruction will all be determined. For the purposes of the total plant analysis, boiler model BII will be used since it provides a more complete view of the boiler systems.

The plant analyses may be performed with either the first of second turbine models. Unless otherwise specified, the total plant equations are general and either turbine model may be used. When one specific model is used, the
subscripts will indicate which model is used with either TI or TII. The code for both scenarios will be given throughout the energy and exergy analyses.

4.6.1. Energy Analysis

From the previous analyses, the heat losses from the turbine (Equation (4.51)), condenser (Equation (4.49)), and boilers (Equation (4.168)) are known. Although the condenser heat loss is transferred to the cooling water, the heat in the cooling water must be dissipated to the atmosphere, and so is lost from the plant. The total heat loss from the plant is the sum of the losses from the components, given in Equation (4.197).

\[
\hat{Q}_{P,I} = \hat{Q}_{I,total} + \hat{Q}_{I,T} + \hat{Q}_{C}
\]  

(4.197)

The heat added to the plant is taken from the boiler analyses as the sum of the heat content of the culm, shown in Equation (4.198).

\[
\hat{Q}_{P,in} = \hat{Q}_{culm,total}
\]  

(4.198)

The power used internally in the plant supports processes such as pumps, fans (including the cooling tower fans), lighting, and other office power needs. Since the power used throughout the plant is produced at the plant, the work used for supporting systems is found as the difference between the generated and exported work as shown in Equation (4.199).

\[
\hat{W}_{P, internal} = \hat{W}_{gen} - \hat{W}_{P, export}
\]  

(4.199)

The internal work is based only on the operational data. In order to estimate the exported work based on the second method of turbine work, the internal work is considered to be the same, and the exported work calculated using Equation (4.200).

\[
\hat{W}_{P, export, TII} = \hat{W}_{gen, TII} - \hat{W}_{P, internal}
\]  

(4.200)

The desirable products of the plant are the power export and the process steam while the input energy is the heat content of the culm. The overall “energy efficiency” of the plant compares the energy input, given in Equation (4.198) above, to the desired outputs, consisting of the exported work and the process steam energy (Equation (4.58)). This performance criterion is also known as the energy utilization factor (EUF) [60] and is given in Equation (4.201).

\[
EUF_p = \frac{\hat{Q}_{process} + \hat{W}_{P, export}}{\hat{Q}_{P,in}}
\]  

(4.201)
It is necessary to note that the energy efficiency adds a work value and a heat transfer value together. While this method is often used, it is not ideal because the two types of energy are not strictly of the same type or the same practical value [60].

The plant thermal efficiency neglects the process heat because it is small compared to the exported power and the heat input to the plant. The thermal efficiency of the plant is given in Equation (4.202).

$$\eta_{th} = \frac{W_{P, export}}{Q_{P, in}}$$  \hspace{1cm} (4.202)

The code for the total plant energy analysis is given in Figure 4.49.

```matlab
% Energy values
Q_u_total_P = Q_u_total_B;  % Total useful heat transfer
Q_in_P = Q_in_B;  % Total heat input from fuel

% Internal power use
W_export_P = 1.0e6*1.000;  % Exported kW
W_internal_P = W_gen - W_export_P;  % Internal power use

% Plant energy analysis using TI
Q_i_total_P_TI = Q_i_total_B + Q_C...
+ Q_L_TI;  % Total plant heat loss

EUF_P_TI = Q_process...
+ W_export_P./(Q_in_P);  % Plant XOF
n_th_P_TI = W_export_P./(Q_in_P);  % Plant thermal efficiency

% Plant energy analysis using TII
Q_i_total_P_TII = Q_i_total_B + Q_C...
+ Q_L_TII;  % Total plant heat loss

W_export_P_TII = W_gen_TII...
- W_internal_P;  % Exported kW

EUF_P_TII = Q_process...
+ W_export_P_TII./(Q_in_P);  % Plant XOF
n_th_P_TII = (W_export_P_TII)./(Q_in_P);  % Plant energy efficiency
```

Figure 4.49: Code for calculation of (a) internal plant power use and (b) total plant energy analysis using turbine models.

### 4.6.2. Exergy Analysis

The total exergy loss from the plant, given in Equation (4.203), is the sum of the exergy loss through the boilers (Equation (4.189)), turbine (Equation (4.71)), and condensers (Equation (4.68)).

$$\dot{E}_{LP} = \dot{E}_{i, total B} + \dot{E}_{L T} + \dot{E}_{C}$$  \hspace{1cm} (4.203)
The total exergy destroyed through the plant is another telling criterion for the plant. The exergy destroyed through the plant is found by summing the exergy destroyed through the boilers (Equation (4.190)), turbine (Equation (4.73)), condenser (Equation (4.70)), and feedwater heaters (Equation (4.67)). The total plant exergy destruction is given in Equation (4.204).

\[ E_{d,p} = E_{d,\text{total,B}} + E_{d,T} + E_{d,C} + E_{d,F} \]  

(4.204)

The total useful exergy out of the plant is given as the sum of the exported exergy and the process exergy (Equation (4.77)). The exergy exported from the plant is approximately equal to the exported power since electricity is such high quality energy as shown in Equation (4.205).

\[ E_{\text{export}} = W_{P,\text{export}} \]  

(4.205)

The total useful exergy out of the plant is given in Equation (4.206).

\[ E_{\text{out,useful}} = E_{\text{export}} + |E_{\text{process}}| \]  

(4.206)

The problem with using traditional energy efficiency for a cogeneration power plant of adding two different types of energy together, mentioned in Section 4.6.1 after defining Equation (4.201), is remedied through the application of exergy. Using exergy levels the playing field, so to speak, between the work energy and the heat energy. The exergy efficiency of the plant, given in Equation (4.207), is found by comparing the useful input exergy to the useful output exergy.

\[ \varepsilon_P = \frac{|E_{\text{process}}| + E_{\text{B,export}}}{E_{\text{B,in}}} \]  

(4.207)

The total exergy into the plant, see Figure 4.48, is the sum of the exergy streams of the fuel, limestone, air, and makeup water into the plant. The makeup water and limestone streams are small compared to the fuel and so may be neglected. When the air enters the power plant it is at ambient conditions (before preheating for use in the boiler) and so the entering air has a flow exergy of zero. The exergy of the air entering the plant contains only the chemical exergies of the nitrogen and oxygen it contains. The total exergy into the plant is then given in Equation (4.208).

\[ E_{\text{in,total,P}} = E_{\text{in,B}} + m_{\text{air,total,B}} \left( 0.21 e^{\text{CH}_4}_D + 0.79 e^{\text{CH}_4}_N \right) \]  

(4.208)

The coefficients in front of the chemical exergy values account for the percentage of air composed of oxygen and nitrogen.

The total exergy out of the plant, see Figure 4.48, includes the exergy of the ash (Equation (4.194)), flue gas (Equation (4.181) or (4.186) depending on the boiler model used), useful exergy (Equation (4.206)), and exergy loss (Equation (4.203)). The total exergy out of the plant is given in Equation (4.209).

\[ E_{\text{out,in}} = E_{\text{out,B}} + m_{\text{air,total,B}} \left( 0.21 e^{\text{CH}_4}_D + 0.79 e^{\text{CH}_4}_N \right) - E_{\text{process}} \]  

(4.209)
The code for the total plant exergy calculations is given in Figure 4.50.

\[
\hat{E}_{\text{out,total},P} = \hat{E}_{\text{ash,total},B} + \hat{E}_{\text{FG,total},B} + \hat{E}_{\text{out,u,P}} + |\hat{E}_{\text{LP}}|
\]  

(4.209)

4.6.3. Improvements

There are many locations throughout the plant that could be improved, however, economic reasoning limits which of these improvements may feasibly be implemented. The possibilities discussed and explored through this work are compared based on the changes in overall plant performance in terms of the thermodynamic performance and the environmental performance.

Each of the following suggestions will be compared to a baseline data set in order to ascertain what change makes the greatest change in the plant performance. The baseline data set will include boiler model BII, a carbon residue of 9%, all relevant operational data, and the current plant configuration. The turbine in each of the improvement scenarios will be analyzed using the second method of turbine work, which uses an energy balance approach (see Section 4.4.2.3).
4.6.3.1. Cogeneration Steam Use

Currently, the plant uses only a small percentage of the available cogeneration steam available because electricity may be sold for a higher profit than steam. Since the steam is drawn off in the high pressure portion of the turbine, which is very high quality steam, the electricity production decreases when the steam draw increases. The table below summarizes the current cogeneration steam use. It is desirable to quantify the possible benefits, in terms of plant efficiency, of using more of the generated steam.

Table 4.10: Summary of process steam use.

<table>
<thead>
<tr>
<th>Location</th>
<th>Flow (kg/s)</th>
<th>% of inlet steam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average turbine inlet</td>
<td>84.86</td>
<td>100</td>
</tr>
<tr>
<td>Average process steam use</td>
<td>1.00</td>
<td>1.18</td>
</tr>
<tr>
<td>Maximum process steam use</td>
<td>2.50</td>
<td>2.95</td>
</tr>
<tr>
<td>Minimum process steam use</td>
<td>0.10</td>
<td>0.12</td>
</tr>
</tbody>
</table>

The plant reports it is possible for the turbine to accept around 900,000 lb/h of steam and deliver up to 30,000 lb/h of process steam; this equates to 3.33% of the inlet steam delivered as steam. For the purposes of the increased process steam analysis, the process steam flow rate will be calculated as

\[ m_{\text{proc}} = 0.0333 m_{T1} \]  

(4.210)

The increased process steam use will change the flow of steam from extraction 5, shown in Figure 4.19. The increase in process steam is the difference between the current use and the suggested use shown in the above equation. The steam through extraction 5 will be increased by the current and suggested steam use:

\[ m_{T2,\text{proc}} = m_{T2} + (m_{\text{proc}} - m_{T25}) \]  

(4.211)

It is assumed that the flow rates through the remaining extraction points remain the same. The resulting change in the turbine exhaust is given as:

\[ m_{T7,\text{proc}} = m_{T1} - m_{T2,\text{proc}} - m_{T3} - m_{T4} - m_{T5} - m_{T6} \]  

(4.212)

The code for the mass flow rates through the turbine using increased process steam is shown in Figure 4.51.

The turbine performance, including turbine work, generator work, heat loss, exergy destruction, and isentropic and exergetic efficiencies, may be calculated using the energy and exergy balance methods given in Sections 4.4.2.3 and 4.4.3.3 with the increased process steam flow rates. The turbine work is expected to decrease since more steam is removed than previously. The derivations are not shown as they are the same as with the turbine energy method in the turbine analyses, however, the Matlab™ code is given in Figure 4.52.
The overall plant performance indicators in the previous two sections (4.6.1 and 4.6.2) may be used with the relevant increased process steam use work values. The basic equations have already been given, so only the code for the total plant analysis using increased process steam is shown in Figure 4.53. The exported power is given in Equation (4.200), the useful exported exergy is given in Equation (4.206), the EUF is defined in Equation (4.201), the thermal efficiency of the plant is defined in Equation (4.202), and the exergetic efficiency of the plant is given in Equation (4.207).
Currently, the steam exiting the turbine at extraction 2, extraction 1, and the turbine exhaust are vapor/liquid mixtures. While the plant, obviously, may still operate under these conditions, the moisture traveling through the turbine will result in a higher rate of turbine wear. It is therefore a proposed improvement to introduce steam reheat through the turbine. The reheat process redirects the steam after extraction 3 back to the boiler for additional heat transfer before returning to the turbine. Since the steam transitions from the superheated region to the saturated mixture region between extraction 3 at the 12th stage of the turbine, and extraction 2 at the 14th stage of the turbine, the steam reheat will occur between stages 13 and 14.

Figure 4.54: Schematic of turbine reheat scenario. A control volume around the reheat section of the boiler is shown.

A simple analysis of the reheat process is performed using averaged data and a number of assumptions. First, it is assumed that after the reheat, the pressures of the later extraction points are equal to the corresponding pressures without reheat. Second, the exhaust temperature is increased by 30°C to put it solidly in the superheated region. Third, it is assumed that the percent temperature drop observed between each extraction point in the operational data
remains the same. This implies that if the temperature of one extraction point is known, the temperatures of the points on either side may be approximated. Figure 4.54 depicts the turbine reheat scenario.

The steam before extraction 3 is taken to have the properties listed in Equations (4.213)-(4.215).

\[ m_x = \dot{m}_{T1} - \dot{m}_{T2} - \dot{m}_{T3} \tag{4.213} \]
\[ T_x = T_{T4} \tag{4.214} \]
\[ p_x = p_{T4} \tag{4.215} \]

The reheat steam is then taken to have the following listed in Equations (4.216)-(4.218).

\[ m_{R1} = \dot{m}_{T1} - \dot{m}_{T2} - \dot{m}_{T3} - \dot{m}_{T4} \tag{4.216} \]
\[ T_{R1} = T_{T4} \tag{4.217} \]
\[ p_{R1} = p_{T4} \tag{4.218} \]

Returning, the reheat steam has the following listed in Equations (4.219)-(4.221).

\[ m_{R2} = \dot{m}_{R1} \tag{4.219} \]
\[ T_{R2} = T_{T5'} \tag{4.220} \]
\[ p_{R2} = p_{T5'} \tag{4.221} \]

From the average original analysis data, the percent temperature drops between the extraction points are found. The relationships are given in Equations (4.222) and (4.223).

\[ \frac{T_{T7}}{T_{T6}} = 0.4 \tag{4.222} \]
\[ \frac{T_{T6}}{T_{T5}} = 0.7 \tag{4.223} \]

The same relationships are used to determine the temperatures at T6’ and T5’ based on the assumed exhaust temperature. The temperatures are T6’ and T5’ are given in Equations (4.224) and (4.225).
\[ T_{T \rho} = \frac{T_{T \rho}}{0.4} \quad (4.224) \]
\[ T_{T \sigma} = \frac{T_{T \rho}}{0.7} \quad (4.225) \]

The new post-reheat values are now known. These values, coupled with the assumed pressure values, will give the enthalpy, entropy, and exergy values at each extraction.

A heat balance around the small control volume shown in Figure 4.54 gives the extra heat required for the reheat. The required extra heat is given in Equation (4.226).

\[ Q_R = \dot{m}_{R2} \Delta h_{R2} - \dot{m}_{R1} \Delta h_{R1} \quad (4.226) \]

Equation (4.226) simplifies based on conservation of mass and the scenario assumptions to Equation (4.227).

\[ \dot{Q}_R = \dot{m}_{R1} (h_{T \sigma} - h_{T \rho}) \quad (4.227) \]

The energy necessary for the reheat corresponds to an increase in culm usage. The reheat heat transfer should be equal to the heat released from the excess culm use. Therefore the reheat heat transfer may be set equal to the HHV of culm, which represents the culm energy content, multiplied by an unknown mass flow rate for the culm required for the reheat, as seen in Equation (4.227).

\[ \dot{Q}_R = \dot{m}_{R,culm} (HHV)_{culm} \quad (4.228) \]

Equation (4.227) may be rearranged to give the required feed of culm, shown in Equation (4.229).

\[ \dot{m}_{R,culm} = \frac{\dot{Q}_R}{(HHV)_{culm}} \quad (4.229) \]

The total amount of heat energy into the boilers is the sum of the original culm use and the

As done previously in Equation (4.51), the heat transfer for the turbine with reheat is taken as 1.39% of the work produced. With the assumed heat loss, the energy balance simplified to Equation (4.230).

\[ W_{R,T} = \frac{(m \Delta h)_{inlet} - (m \Delta h)_{outlet}}{1.0139} \quad (4.230) \]

Equation (4.230) uses the definitions given in Equations (4.231) and (4.232).
\begin{align*}
(mh)_{inlet} &= \dot{m}_1 h_{T1} + \dot{m}_2 h_{R2} \\
(mh)_{outlet} &= \dot{m}_2 h_{T2} + \dot{m}_3 h_{T3} + \dot{m}_s h_x + \dot{m}_{T5'} h_{T5'} + \dot{m}_{T6'} h_{T6'} + \dot{m}_{T7'} h_{T7'}
\end{align*}
(4.231)
(4.232)

The isentropic work is given in Equation (4.233).

\[ W_{R,Ts} = (mh)_{inlet} - (mh)_{outlet} \]
(4.233)

The term \((mh)_{outlet}\) is defined in Equation (4.234).

\begin{align*}
(mh)_{outlet} &= \dot{m}_2 h_{T2,s} + \dot{m}_3 h_{T3,s} + \dot{m}_s h_{x,s} + \dot{m}_{T5'} h_{T5',s} + \dot{m}_{T6'} h_{T6',s} \\
&\quad + \dot{m}_{T7'} h_{T7',s}
\end{align*}
(4.234)

Note that enthalpy values at T2, T3, and x are determined by the corresponding pressure and the entropy value as T1, whereas the enthalpy values at T5’, T6’, and T7’ are found from the corresponding pressures and the entropy at R2.

The energy and exergy based turbine performance parameters may be calculated using the equations found in Sections 4.4.2.3 and 4.4.3.3 with the appropriate turbine reheat data.

The calculations of the reheat scenario values at T7’, T6’, T5’, and R1 are shown in Figure 4.55(a), the calculations of the reheat location R2 and the isentropic enthalpy values are shown in Figure 4.55(b). The code for the reheat mass flow rates is given in Figure 4.55(c). The code for the calculation of the required additional culm flow is given in Figure 4.56. Figure 4.57(a) gives the energy analysis code and Figure 4.57(b) gives the exergy analysis code. The overall plant parameters found in Sections 4.6.1 and 4.6.2 may also be applied with the corresponding reheat data. The code for the plant performance with turbine reheat is given in Figure 4.58.
Figure 4.55: Code used for calculating (a&b) temperatures, pressures, and thermodynamic properties of turbine reheat locations as well as (c) unknown mass flow rates.

(a) Define properties downstream from reheat

\[ s_{in} = \text{mean}(i.Tu(:,1)); \] % Average entropy at turbine inlet

\% Turbine Exhaust

\[ T_{T7} = \text{mean}(i.Tu(:,14)) + 30; \] % Increased exhaust temperature
\[ p_{T7} = \text{mean}(i.Tu(:,13)); \] % Average pressure at exhaust
\[ h_{T7} = \text{XSteam('h_pT',p_{T7},T_{T7})); \] % Exhaust enthalpy
\[ s_{T7} = \text{XSteam('s_pT',p_{T7},T_{T7})); \] % Exhaust entropy
\[ e_{T7} = |h_{T7} - i.ho| - T_{0}*s_{T7} - i.so); \] % Exhaust exergy flow

\% Extraction 1

\[ T_{T6} = T_{T7}/0.4; \] % New Ext. 1 temperature
\[ p_{T6} = \text{mean}(i.Tu(:,20)); \] % Average pressure at Ext. 1
\[ h_{T6} = \text{XSteam('h_pT',p_{T6},T_{T6})); \] % Ext. 1 enthalpy
\[ s_{T6} = \text{XSteam('s_pT',p_{T6},T_{T6})); \] % Ext. 1 entropy
\[ e_{T6} = |h_{T6} - i.ho| - T_{0}*s_{T6} - i.so); \] % Ext. 1 exergy flow

\% Extraction 2

\[ T_{T5} = T_{T6}/0.7; \] % New Ext. 2 temperature
\[ p_{T5} = \text{mean}(i.Tu(:,19)); \] % Average pressure at Ext. 2
\[ h_{T5} = \text{XSteam('h_pT',p_{T5},T_{T5})); \] % Ext. 2 enthalpy
\[ s_{T5} = \text{XSteam('s_pT',p_{T5},T_{T5})); \] % Ext. 2 entropy
\[ e_{T5} = |h_{T5} - i.ho| - T_{0}*s_{T5} - i.so); \] % Ext. 2 exergy flow

\% Reheat flow from turbine to boiler

\[ T_{R1} = \text{mean}(i.Tu(:,11)); \] % Temperature - average Ext. 3
\[ p_{R1} = \text{mean}(i.Tu(:,18)); \] % Pressure - average Ext. 3
\[ h_{R1} = \text{XSteam('h_pT',p_{R1},T_{R1})); \] % Enthalpy
\[ s_{R1} = \text{XSteam('s_pT',p_{R1},T_{R1})); \] % Entropy
\[ e_{R1} = |h_{R1} - i.ho| - T_{0}*s_{R1} - i.so); \] % Flow exergy

\% Reheat return to turbine

\[ T_{R2} = T_{T5}/1.5; \] % Temperature increase by \%150
\[ p_{R2} = p_{R1}; \] % Constant pressure through reheat
\[ h_{R2} = \text{XSteam('h_pT',p_{R2},T_{R2})); \] % Enthalpy
\[ s_{R2} = \text{XSteam('s_pT',p_{R2},T_{R2})); \] % Entropy
\[ e_{R2} = |h_{R2} - i.ho| - T_{0}*s_{R2} - i.so); \] % Exergy flow

\% Isentropic enthalpies downstream of reheat

\[ h_{T7} = \text{XSteam('h_pT',p_{T7},s_{R2})); \] % Isentropic enthalpy
\[ h_{T6} = \text{XSteam('h_pT',p_{T6},s_{R2})); \] % Isentropic enthalpy
\[ h_{T5} = \text{XSteam('h_pT',p_{T5},s_{R2})); \] % Isentropic enthalpy
\[ h_{R1} = \text{XSteam('h_pT',p_{R1},s_{T1})); \] % Isentropic enthalpy

(b) Mass flow rates for reheat

\[ m_R = \text{mean}(i.Tu(:,1) - i.Tu(:,2)); \] % Reheat steam flow
\[ - i.Tu(:,3) - i.Tu(:,4)); \] % Flow of Ext. 3 and reheat

\[ m_X = \text{mean}(i.Tu(:,1) - i.Tu(:,2)); \] % Reheat steam flow
\[ - i.Tu(:,3)); \] % Flow of Ext. 3 and reheat

Figure 4.55: Code used for calculating (a&b) temperatures, pressures, and thermodynamic properties of turbine reheat locations as well as (c) unknown mass flow rates.
Figure 4.56: Code for determining additional culm flow required for reheat.

\[
\begin{align*}
\text{Q}_R &= m \cdot R^* (h_{R2} - h_{R1}); \quad \% \text{Heat transfer into reheat steam} \\
m \cdot R_{culm} &= Q_R / \text{i.HHV}_R; \quad \% \text{Culm required for reheat}
\end{align*}
\]

\[
\begin{align*}
&W_{T,R} = \text{mean}((m \cdot R^* h_{R2} + i.Tu(:,1) \cdot i.h(t(:,1)) ... \\
&- i.Tu(:,2) \cdot i.h(t(:,2)) - i.Tu(:,3) \cdot i.h(t(:,3)) ... \\
&- m \cdot x \cdot h_{R1} - i.Tu(:,5) \cdot h_{T5} - i.Tu(:,6) \cdot h_{T6} ... \\
&- i.Tu(:,7) \cdot h_{T7})/|1-i.R|); \quad \% \text{Turbine work} \\
&W_{s,T,R} = \text{mean}((m \cdot R^* h_{R2} + i.Tu(:,1) \cdot i.h(t(:,1)) ... \\
&- i.Tu(:,2) \cdot i.h(t(:,2)) - i.Tu(:,3) \cdot i.h(t(:,3)) ... \\
&- m \cdot x \cdot h_{R1} - i.Tu(:,5) \cdot h_{T5} - i.Tu(:,6) \cdot h_{T6} ... \\
&- i.Tu(:,7) \cdot h_{T7})/|1-i.R|); \quad \% \text{Turbine isentropic work}
\end{align*}
\]

\[
\begin{align*}
&n_{is} = W_{T,R}/W_{s,T,R}; \quad \% \text{Isentropic eff.} \\
&Q_{1,T,R} = -|1.R| \cdot W_{T,R}; \quad \% \text{Turbine heat loss} \\
&W_{\text{gen,R}} = W_{T,R} \cdot \text{i.\text{gen}}; \quad \% \text{Net generator work}
\end{align*}
\]

(a)

Figure 4.57: Code for turbine (a) energy analysis and (b) exergy analysis with reheat.

\[
\begin{align*}
&W_{T,R} = \text{mean}((m \cdot R^* h_{R2} + i.Tu(:,1) \cdot i.h(t(:,1)) ... \\
&- i.Tu(:,2) \cdot i.h(t(:,2)) - i.Tu(:,3) \cdot i.h(t(:,3)) ... \\
&- m \cdot x \cdot h_{R1} - i.Tu(:,5) \cdot h_{T5} - i.Tu(:,6) \cdot h_{T6} ... \\
&- i.Tu(:,7) \cdot h_{T7})/|1-i.R|); \quad \% \text{Turbine exergy efficiency} \\
&E_{T,R} = \text{mean}((m \cdot R^* e_{R2} + i.Tu(:,1) \cdot i.e(t(:,1)) ... \\
&- i.Tu(:,2) \cdot i.e(t(:,2)) - i.Tu(:,3) \cdot i.e(t(:,3)) ... \\
&- m \cdot x \cdot i.e(t(:,4)) - i.Tu(:,5) \cdot e_{T5} ... \\
&- i.Tu(:,6) \cdot e_{T6} - i.Tu(:,7) \cdot e_{T7} ... \\
&+ (1-i.T)/T_{Th} \cdot Q_{1,T,R} - W_{T,R}; \quad \% \text{Exergy destruction} \\
&s_{T,R} = \text{mean}(-(m \cdot R^* s_{R2} - i.Tu(:,1) \cdot s_{t}((:,1)) ... \\
&+ i.Tu(:,2) \cdot s_{t}((:,2)) + i.Tu(:,3) \cdot s_{t}((:,3)) ... \\
&+ m \cdot x \cdot s_{t}((:,4)) + i.Tu(:,5) \cdot s_{T5} ... \\
&+ i.Tu(:,6) \cdot s_{T6} + i.Tu(:,7) \cdot s_{T7} ... \\
&- (1/T_{Th}) \cdot Q_{1,T,R}; \quad \% \text{Entropy production rate} \\
&E_{T,R} = T_{h} \cdot s_{T,R}; \quad \% \text{Ed at turbine}
\end{align*}
\]

(b)
4.6.3.3. **Effect of Plant Operational Load**

Although it is often unavoidable for the plant to reduce its operational load due to economic, safety, or maintenance reasons, it is desirable to quantify the effects of changing the operational load on the plant performance. Figure 4.59 shows the high and low load time periods over a sample time period of six days. The plant begins to decrease the plant load around 9pm each night and returns to full load around 9am the next day. The plant takes about three hours to reduce the load from 90 MW to 63 MW and another three hours to return. Thus the plant spends about twelve hours a day at full load, six hours at reduced load, and six hours in transition between the two.

To quantify the effects of operational load, the available data is divided into three groups based on the generator output: high load (above 85 MW), low load (below 65 MW), and transitional load operations (between 65-85 MW). To separate the data, a single Matlab array called “load” is created with a row for each timestamp of the operational data. A value of 1 in “load” is indicative of a low load at the corresponding operational data, a value of 2 is indicative of a transition, and a value of 3 is indicative of a high operational load. The data is filtered using the piece of code shown in Figure 4.60.

The plant performance parameters will be compared between each load scenario to determine if the operational load of the plant makes a significant difference in the plant performance. Part of the code for sorting through the thermodynamic analysis results is shown in Figure 4.61. The parameters chosen for comparison are efficiencies for the turbine and boiler and basic energy and exergy parameters for the whole plant system. Although not every parameter is compared, those chosen provide an overview of how the plant performance changes with the operational load.

```matlab
% Plant energy analysis with reheat
W_export_P_R = W_gen_R - mean(W_internal_P); % Exported power

Q_in_R = mean(Q_culp_h1 + Q_culp_h2) + Q_R; % Total heat input

m_culp_P_R = mean(i.m_culp_h1 + i.m_culp_h2); ...
+m_R_culp; % Total culm use

Q_u_R = mean(Q_u_total_P - Q_R); % Useful heat transfer

EUF_R = mean(|-Q_process + W_export_P_R|./Q_in_R); % EUF

n_th_R = (W_export_P_R)./(Q_in_R); % Plant thermal efficiency

% Plant exergy analysis with reheat
E_u_R = mean(Q_u_R.*(1-To/T_chamber)); % Useful exergy

E_in_R = E_culp_h1 + E_culp_h2 + i.e_culp.m_R_culp; % Exergy into plant

E_out_u_R = W_export_P_R - E_process; % Exergy out

cps_F_R = E_out_u_R./E_in_R; % Exergy efficiency
```

Figure 4.58: Code for total plant with turbine reheat (a) energy analysis and (b) exergy analysis.
Figure 4.59: Sample of operational data of generator output.

```
load = 2*ones(1, row, 1); % Create an array with default middle load
for j=1:row
    if 1.Tu(3,32)< 65000 % Low load
        load(j,1) = 1;
    elseif 1.Tu(3,32) > 95000 % High load
        load(j,1) = 3;
    end
end
```

Figure 4.60: Code for sorting operational data based on exported electricity.

```
% Operational load comparisons
i = 1;
1 = 1;
h = 1;
for j=1:3665
    if load(j) == 1 % Low load
        n_E_avg_low(1) = n_E_avg(1);
        e_B_avg_B(1) = e_B_avg_B(1);
        nTs_low(1) = nTs(1);
        e_B_T(1) = e_B_T(1);
        Q.l_total_P_TI_low(1) = Q.l_total_P_TI(1);
        Y.export_P_low(1) = Y.export_P(1);
        Q.in_P_low(1) = Q.in_P(1);
        HEP_P_TI_low(1) = HEP_P_TI(1);
        n.ch_P_TI_low(1) = n.ch_P_TI(1);
        Ed_total_P_TI_low(1) = Ed_total_P_TI(1);
        E.in_total_low(1) = E.in_total(1);
        E.L.P_TI_low(1) = E.L.P_TI(1);
        Y.out_u_TI_low(1) = Y.out_u_TI(1);
        e_B_T(1) = e_B_T(1);
        r=1+1;
    elseif load(j) == 2 % Transitional load
        n_E_avg_trans(i) = n_E_avg(i);
        e_B_avg_B(i) = e_B_avg_B(i);
        nTs_trans(i) = nTs(i);  
        e_B_T(1) = e_B_T(1);
    end
end
```

Figure 4.61: Part of the code used to sort thermodynamic parameters into low, transient, and high load cases.
5. Environmental Considerations

The cogeneration power plant has a unique combination of environmental interactions. A traditional coal fired plant requires an influx of new fuel that requires both mining and transport. The traditional plant also emits pollutants through normal operations into the air, water, and soil of the surrounding area. While the cogeneration plant does emit pollutants, the extraction of culm does not cause a large negative impact. The externality analysis of the plant will be largely qualitative since the system is so complex and so unique.

Figure 5.1 shows some of the complexities of the plant’s environmental interactions. Shown in the figure is the upstream fuel extraction process: culm banks are cleared and transported to the processing facility. Fuel extraction does generate some pollution through truck emissions, but it also creates cleared land. The processed culm is conveyed to the plant and burned along with limestone to produce steam and emissions. Steam passes through the turbine to produce process steam and electricity. The ash from the boiler is used, along with the cleared land, to reclaim lost natural environments. With a traditional coal plant, the only real positive outputs would be the electricity and perhaps the ash from the plant, but here we see that land is cleared, process steam produced, as well as the electricity and ash production.
Figure 5.1 shows how the cogeneration power plant causes negative impacts (emissions from the boiler and machinery), but also how the plant imparts positive impacts (land use and reclamation, power generation, process steam production). The endeavor of this chapter is to discuss how the positive and negative impacts of the plant interact, and how the positive and negative impacts of other power systems compare, namely a wind system and a coal system. The results to the environmental analysis will be discussed in this section as well as the background information required to obtain and understand the results.

5.1.1. Assumptions

Although the majority of the plant environmental analysis will be qualitative, there are a number of assumptions to keep in mind. The assumptions for the plant environmental interactions are listed in Table 5.1.

Table 5.1: Summary of assumptions for plant environmental analysis.

<table>
<thead>
<tr>
<th>No.</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>System boundaries</td>
</tr>
<tr>
<td>2</td>
<td>Emissions</td>
</tr>
<tr>
<td>3</td>
<td>Resource use and yearly production</td>
</tr>
</tbody>
</table>

Discussion of Assumptions:

1. **System Boundaries**- The system boundaries for the externality analysis are larger than those for the thermodynamic analysis. The externality analysis takes into account many supporting processes of the plant operation including the culm extraction and processing, water attainment, water processing, waste water, land use, and emissions. Although it could be argued that the externality impacts of the plant cover the globe, the boundary will be drawn to include only the apparent and strong impacts the plant has on the surrounding area.

2. **Emissions**- It will be assumed that the CO$_2$, NO$_x$, and SO$_x$ emissions are related solely to the fuel consumption (i.e. a linear increase in fuel use corresponds to a linear increase in emissions). With this assumption the relative environmental benefits of some of the suggested improvement scenarios may be quantified to an extent.

3. **Resource Use and Yearly Production**- It will be assumed, by recommendation of plant personnel, that the culm is transported 13 miles (8.05 km) from a culm bank to the processing facility [61], and then ash will be transported back to the culm bank site for land reclamation. The fuel and the ash will be transported on 40 ton trucks with an efficiency of 50%. The truck information is based on a SimaPro 40 tonne truck model.

The land use portion of this analysis will be performed over the lifetime of the plant, but the resource use will be taken on a yearly basis. Table 5.2 summarizes some of the important input and output data for the current plant. The data shown for the cogeneration plant is taken from average operational data taken over the course of a year with a 92% down time. Many of the environmental impacts of the items listed in Table 5.2 may be quantified using SimaPro, although others will only be qualitatively discussed.
### Table 5.2: Summary of plant inputs and outputs on average and over the course of a year.

<table>
<thead>
<tr>
<th>Item</th>
<th>Average Data</th>
<th>Annual Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quantity</td>
<td>Units</td>
</tr>
<tr>
<td>Culm used</td>
<td>17.66 kg/s</td>
<td>512371 tonne</td>
</tr>
<tr>
<td>Culm transport by 40 ton truck</td>
<td>16 km</td>
<td>1.17 x10¹¹ tkm</td>
</tr>
<tr>
<td>Limestone used</td>
<td>0.1361 kg/s</td>
<td>3948 tonne</td>
</tr>
<tr>
<td>Limestone transport by 28 ton truck</td>
<td>65 km</td>
<td>3.62 x10⁷ ton-km</td>
</tr>
<tr>
<td>Minewater cleaned and used</td>
<td>1.3 x10⁶ gal/day</td>
<td>4.36 x10⁸ gallon</td>
</tr>
<tr>
<td>Well water demineralized</td>
<td>26.77 gal/min</td>
<td>1.29 x10⁷ gallon</td>
</tr>
<tr>
<td>Electricity generated</td>
<td>78.29 MW</td>
<td>630655 MWh</td>
</tr>
<tr>
<td>Process heat delivered</td>
<td>1.00 kg/s</td>
<td>2.90 x10⁷ kg</td>
</tr>
<tr>
<td>Ash</td>
<td>6.43 kg/s</td>
<td>1.87 x10⁵ tonne</td>
</tr>
<tr>
<td>Minewater returned</td>
<td>115 kg/s</td>
<td>8.80 x10⁶ gallon</td>
</tr>
<tr>
<td>Land reclaimed</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

#### 5.1.2. SimaPro

The SimaPro models are compared using their relative land use, water use, and emissions from supporting processes (such as fuel transportation). In order to compare the models on a common basis, each of the SimaPro models is set up using the amount of electricity produced by the cogeneration plant over the course of a year. The common production value between each of the systems ensures that they are compared on a similar basis. The SimPro models also exclude the infrastructure processes since they are compared on a one year basis and the infrastructure processes for the cogeneration plant are unknown. The models will also exclude long term emissions, again because only the impact from a year’s worth of electricity will be compared.

#### 5.1.2.1. Traditional Coal Fired Plant

The coal fired plant modeled in the SimaPro software is located in Italy. The plant has the same output as does the cogeneration power plant. The plant uses a mixture of coal that includes newly mined and stock coal material from all over the world; over the course of a year, the plant uses 244 long tons of coal with a heat content of 18 MJ/kg and 56.3 long tons of brown coal at 8 MJ/kg. The coal is taken from a combination of stock piles and underground mines. The ETH-ESU 96 database from SimaPro is used.

#### 5.1.2.2. Wind Farm

The wind turbine described in SimaPro is a composite of three wind farms that are located in Sool, Grenchenberg, and Simplon, each in Germany. The Sool turbine has been in existence since 1986 and has the capacity to deliver an average of 14868 kw over a year of. The rotor has two blades for a total diameter of 12.5 meters. The Sool wind plant makes up 11% of the composite model.

The Grenchenberg wind power plant has existed since 1994 and has an average power delivery of 99964 kWh/year. The rotor has three blades with a total diameter of 23.8 meters. The Grenchenberg plant makes up 74% of the total wind farm model.
The Simplon wind power plant has been in operation since 1991 and can deliver 20864 kWh on average each year. The rotor has two blades with a total diameter of 12.5 meters. The Simplon wind farm makes up the last 15% of the wind farm model.

The average lifetime of the moving parts is 20 years and non-moving parts is 50 years for each of the wind farms. The ETH-ESU 96 database from SimaPro is used.

### 5.1.2.3. SimaPro Land Use Metric

SimaPro categorizes land into four types, as seen in Table 5.3, depending on the level of human influence over the area. The severity of land use is then gauged on the change in land use, i.e. the change from the land’s initial category to the category after the process has taken place. The land use is thus measured by the severity of change in land type (change in category from initial to final given in the form (initial category)-(final category)), area effected (how much land was used), and the duration of time the land is affected.

**Table 5.3: Land use categories defined by SimaPro.**

<table>
<thead>
<tr>
<th>Category</th>
<th>System Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Natural</td>
<td>No human influence at all</td>
</tr>
<tr>
<td>II</td>
<td>Modified</td>
<td>Naturally regenerated forest and range</td>
</tr>
<tr>
<td>III</td>
<td>Cultivated</td>
<td>Farmland, sown pasture, plantation, aquaculture ponds</td>
</tr>
<tr>
<td>IV</td>
<td>Built</td>
<td>Dominated by buildings, railways, airports, docks, dams, mines</td>
</tr>
</tbody>
</table>

Since humans have some influence over every part of the Earth, category I is not used. The severity of land use IV-IV is only used for systems built on land that is already occupied, such as photovoltaic panels on the roof of a building.

To calculate the land use score, the land area is multiplied by the years spent in the construction, operation, and dismantling phases of the lifecycle, and then divided by a functional unit. In the case of a coal plant, the functional unit may be the energy content of the fuel.

After the useful life of an energy conversion process, it is assumed that a new system takes the place of the old system, and so the land does not return to a restored state. In the case of resource extraction, however, it is assumed that the area is abandoned, and so returns to a lower land category over a period of time. The standard time periods used for the restoration of land are shown in Table 5.4.

**Table 5.4: Time periods for land recultivation.**

<table>
<thead>
<tr>
<th>Level of recultivation</th>
<th>Duration (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cat. IV to III</td>
<td>5</td>
</tr>
<tr>
<td>Cat. III to II</td>
<td>50</td>
</tr>
<tr>
<td>Cat. II to I</td>
<td>100,000</td>
</tr>
</tbody>
</table>
5.2. **Environmental Performance**

The thermodynamic performance of the plant may differ from other types of plants, as will be discussed in Chapter 6, however, it is the fuel use and resulting environmental impact that sets the John B. Rich Memorial Power Station apart from many other power systems. Through this section the SimaPro results for this plant and the other two power system models will be given and discussed.

5.2.1. SimaPro Results

A summary of some of the SimaPro results are given in Table 5.5. The cogeneration listed emissions are from the CEMS data.

Table 5.5: Tabulated results from SimaPro and cogeneration power plant results.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Cogeneration plant</th>
<th>Coal fired plant</th>
<th>Wind Farm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water use (turbine use/unspecified) (m³)</td>
<td>4.88E+04/1.65E+06</td>
<td>4.69E+05/8.32E+06</td>
<td>2.34E+04/428.47</td>
</tr>
<tr>
<td>NOx (kg)</td>
<td>7.54E+04</td>
<td>5.46E+05</td>
<td>345</td>
</tr>
<tr>
<td>SO₂ (kg)</td>
<td>5.88E+05</td>
<td>1.24E+06</td>
<td>157.92</td>
</tr>
</tbody>
</table>

The SimaPro models for both types of electrical power generation assume that some amount of the electricity used for normal operations of the plant are from other power systems. For example, the coal fired plant assumes a certain amount of power from a nuclear plant and the wind farm assumes hydropower. The water use under the wind farm category is largely due to the hydropower use upstream from the wind farm itself.

It may also be noted that if the unspecified water use is assumed to be used for cooling water in the coal fired plant that the cogeneration plant uses less water. This could be in part because the cogeneration power plant uses waste heat for useful purposes instead of dissipating it to the cooling water. The source of cooling water for the coal fired plant is unknown, but it would be safe to assume that in most cases mine water is not used since the coal plant is not located directly by the mines its fuel originates from.

5.2.2. Discussion of Land Use

As explained in Section 5.1.2.3, SimaPro quantifies land use by incorporating the change in environment the land undergoes, the duration the land is used for, and the time it takes for the land to revert to its original or a more natural state. The land use metric used in SimaPro, however, is not applicable to the cogeneration power plant of this work.

The typical land use model, which the SimaPro land use model follows, anticipates the following sequence of events:

1. Before use the land is in a more natural state, meaning there is little human influence on the area.
2. Construction and life of the system convert the land to a less natural state, meaning there is an increase of human activity and influence in the area.
3. The system is decommissioned or abandoned.
4. The land slowly reverts back to a more natural state after the day to day human influence of the system is gone. The greater the change from the original state of the land the longer the reversion takes.

The cogeneration system, on the other hand, follows the following procedure:

1. The land was previously used as a dumping site for a low grade pollutant. Although there is no human activity, the land is not in a natural state because it cannot support normal plant or wild life.
2. Construction and life of cycle convert one plot of land to a less natural state by building the power plant, roadways, and processing facility. Every year four acres of land are cleared of the low grade pollutant and reclaimed with ash, topsoil, and plant life.
3. The system is decommissioned.
4. The land reversion back to a natural state is accelerated due to the reclamation process.

The cogeneration system not only reverts land to a more natural state throughout its lifecycle, but also accelerates the natural reversion that occurs after plant operations end. Even wind power, which does relatively little damage to the land of an area, does not accelerate the reversion process.

The SimaPro results for the coal fired plant and wind farm land use are given in Table 5.6. Both the coal fired plant and the wind farm require a combination of dry land and sea floor land for normal operations. The sea floor use is associated with offshore drilling required for oil use within either system.

Table 5.6: SimaPro land use results for coal fired plant and wind farm.

<table>
<thead>
<tr>
<th>Land use type (m²a)</th>
<th>Coal fired plant</th>
<th>Wind farm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land use II-III</td>
<td>5738.59</td>
<td>232.09</td>
</tr>
<tr>
<td>Land use II-III, sea floor</td>
<td>4159.68</td>
<td>4608.44</td>
</tr>
<tr>
<td>Land use II-IV</td>
<td>353.08</td>
<td>5.70</td>
</tr>
<tr>
<td>Land use II-IV, sea floor</td>
<td>428.77</td>
<td>475.02</td>
</tr>
<tr>
<td>Land use III-IV</td>
<td>22.02</td>
<td>0.4315</td>
</tr>
<tr>
<td>Total</td>
<td>10702.13</td>
<td>5321.69</td>
</tr>
</tbody>
</table>

The total land use of the coal fired plant is almost double that of the composite wind farm. The large land use II-III category for the coal fired plant is largely due to the fact that some of the power used at the coal fired plant originates from a nuclear power plant. The land use for nuclear power plants is always high because nuclear waste requires a long time to break down. The length of time for the waste to break down factors into the land use value, making it significantly higher than it would be if the waste broke down quickly. Since the cogeneration power plant generates all the power required for plant processes, the land use II-III would be much lower.
6. Results and Discussion

The analysis performed on the plant produced many results, ranging from exergy values, to mass flow rates, to efficiencies. In the following section each of the results will be summarized and discussed. The potential errors and known errors will be indicated and discussed.

After the current model has been discussed and validated, the plant will be compared to the improvement scenarios modeled in Section 4.6.3.

6.1. Calculated Exergy Values

The air and water based exergy values throughout the plant are relatively easy to determine because the enthalpy and entropy values for both substances are well documented and understood. Exergy associated with coal based fuels, which have inconsistent compositions and have non-uniform molecular structures, are less well understood. The procedures for determining the exergy of culm and flue gas are given in Sections 4.5.1.1 and 4.5.1.4, respectively.

6.1.1. Culm

The culm exergy calculations are based on the dry ultimate analysis of the fuel, meaning that the moisture is excluded for the analysis. The exergy of culm is largely dependent on the measured higher heating value (HHV) of the fuel as well. Table 6.1 gives the average dry ultimate analysis and the dry and ash free composition of fuel found in Section 4.5.1.1.

Table 6.1: Average ultimate analysis on dry and DAF basis.

<table>
<thead>
<tr>
<th>Component</th>
<th>Ultimate Analysis (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry</td>
</tr>
<tr>
<td>Moisture</td>
<td>0</td>
</tr>
<tr>
<td>Ash</td>
<td>42.99</td>
</tr>
<tr>
<td>Carbon</td>
<td>50.80</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>1.51</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.63</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.48</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>3.58</td>
</tr>
<tr>
<td>HHV (kJ/kg)</td>
<td>18,326</td>
</tr>
</tbody>
</table>

Figure 6.1 shows a comparison of calculated and measured HHV values for culm samples for the monthly ultimate and proximate analyses taken between January 1999 and April 2009. It is apparent from Figure 6.1 that the calculated DAF values for HHV and chemical exergy are much higher than the values for the measured HHV and the total exergy values. Upon reflection, the lower measured and total exergy values make sense; once ash is factored in, the energy content of the culm is essentially diluted. Similarly, moisture lowers the energy and exergy content of culm because of its diminished energy content relative to carbon.
On both a total and a DAF basis, the chemical exergy values for culm are higher than the corresponding HHV. This is not expected because exergy is a measure of the quality of the energy of a material, while the HHV is tied into the enthalpy of formation. The quality of the energy of a material cannot be greater than the energy required to form it. Since the procedure outlined in 4.5.1.1 is intended for coal based fuels, which have significantly less ash content; when the fuel composition is taken on a DAF basis, the fuel contains almost 90% carbon.

Table 6.2 summarizes the average measured and calculated HHV and exergy data for culm based on monthly ultimate and proximate analysis data from the plant. From the table it can be seen that the average measured HHV of culm (which includes ash and moisture) is about 17,000 kJ/kg, whereas the average HHV of anthracite coal is about 31,000 kJ/kg [25]. Note that the anthracite coal HHV value is approximately equivalent to the calculated HHV of culm on a DAF basis. The exergy of anthracite coal has not been calculated.

Table 6.2: Average culm HHV and exergy data and anthracite coal HHV.

<table>
<thead>
<tr>
<th>Culm dry and ash free</th>
<th>Culm including ash and moisture</th>
<th>Anthracite</th>
</tr>
</thead>
<tbody>
<tr>
<td>HHV (kJ/kg)</td>
<td>32,569</td>
<td>15,603</td>
</tr>
<tr>
<td>Exergy (kJ/kg)</td>
<td>34,291</td>
<td>16,746</td>
</tr>
</tbody>
</table>

*Calculated values*

Bilgen [55] gave many examples of exergy and HHV results from coal samples taken from 32 mines throughout Turkey. Table 6.4 summarizes the ultimate and proximate analyses and thermodynamic properties of the culm used.
Table 6.3: Data for culm compared to Turkish coal sample data compiled by Bilgen et al. [55].

<table>
<thead>
<tr>
<th>Fuel Sample</th>
<th>Proximate Analysis (%)</th>
<th>Ultimate Analysis on DAF basis (%)</th>
<th>Thermodynamic Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>Ash</td>
<td>$HHV_{DAF}$ (kJ/kg)</td>
</tr>
<tr>
<td>Culm</td>
<td>14.75</td>
<td>36.43</td>
<td>32,568</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>28.09</td>
<td>13.34</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>23.46</td>
<td>17.64</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>21.61</td>
<td>15.95</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>41.20</td>
<td>22.71</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>28.28</td>
<td>37.38</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>36.44</td>
<td>25.89</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>38.12</td>
<td>28.48</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>36.27</td>
<td>24.92</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>40.81</td>
<td>8.77</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>38.53</td>
<td>15.56</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>38.58</td>
<td>13.51</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>26.36</td>
<td>22.11</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>27.33</td>
<td>19.52</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>22.05</td>
<td>7.63</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>19.85</td>
<td>20.19</td>
</tr>
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<td></td>
<td>16</td>
<td>14.96</td>
<td>26.92</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>25.43</td>
<td>12.18</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>19.44</td>
<td>19.47</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>17.20</td>
<td>5.75</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>17.57</td>
<td>17.79</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>15.91</td>
<td>27.02</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>18.64</td>
<td>22.98</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>20.24</td>
<td>16.71</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>20.31</td>
<td>15.22</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>23.04</td>
<td>32.86</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>29.49</td>
<td>39.35</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>40.94</td>
<td>18.34</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>28.02</td>
<td>16.82</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>39.25</td>
<td>15.11</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>38.08</td>
<td>12.42</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>31.17</td>
<td>22.32</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>35.20</td>
<td>20.22</td>
</tr>
</tbody>
</table>
at the cogeneration power plant and Turkish coal samples. The data for the coal samples with the highest and lowest total exergy values have been shaded for ease of comparison.

Upon examination, it is found that the exergy of culm is in the higher half of the data samples given in Table 6.4. It may also be observed that the culm sample contains the highest exergy value on a DAF basis. Bilgen et al. found a relationship between the hydrogen to carbon and oxygen to carbon ratios; the higher the ratios, the lower the exergy values tend to be because less energy is contained in O-C and H-C bonds than in C-C bonds. Culm has extraordinarily low ratios; culm has an H:C ratio of 0.03 and an O:C ratio of 0.009, whereas Sample 19, which has the highest exergy value, has H:C and O:C ratios of 0.07 and 0.32, respectively. Although the energy and exergy in culm is greatly diluted by the high ash content, the usable fuel contains many high energy bonds, thus giving culm a large exergy content.

### 6.1.2. Flue Gas

The flue gas analysis is also based on the fuel composition as well as the approximate chemical reactions that occur within the boiler as outlined in Section 4.5.1.4. The flue gas analysis calculates the specific heat, enthalpy, entropy, and exergetic flow of the gas leaving the boilers. Since the flue gas is taken to be an ideal gas, its properties are solely dependent on the flue gas temperature. Table 6.3 summarizes the average flue gas properties over the entire operational data set for boilers 1 and 2. It may be seen in Table 6.3 that the flow exergy of the flue gas is about half of the chemical exergy of the flue gas. Both the specific heat and the flow exergy of the flue gas are very close to linearly related to the flue gas temperature. The relationships between the specific heat and flow exergy of the flue gas and the flue gas temperature are shown in Figure 6.2(a) and Figure 6.2(a), respectively.

#### Table 6.4: Summary of flue gas properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Boiler 1</th>
<th>Boiler 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>247.95</td>
<td>242.07</td>
</tr>
<tr>
<td>Specific Heat (kJ/kg-K)</td>
<td>0.970</td>
<td>0.965</td>
</tr>
<tr>
<td>$e_{FG}$ (kJ/kg)</td>
<td>62.88</td>
<td>60.02</td>
</tr>
<tr>
<td>$m_{FG}$ (kg/s)</td>
<td>58.48</td>
<td>59.30</td>
</tr>
<tr>
<td>$e_{f,FG}m_{FG}$ (MW)</td>
<td>3.71</td>
<td>3.59</td>
</tr>
<tr>
<td>Total exergy flow of FG components (MW)</td>
<td>8.61</td>
<td>8.78</td>
</tr>
</tbody>
</table>
Figure 6.2: Relationships between flue gas temperature and (a) specific heat and (b) flow exergy.

6.2. Operational Data and Calculations

The tables given in this section represent the average important data (flow rate, temperature, and pressure) through all of the plant subsystems from the analyses. Much of the data in this section is calculated or modified as described in Chapters 3 and 4. The original operational data, average from the complete set of data used for the analysis, are
given in Appendix B. The full plant schematic with location reference numbers shown in Figure 6.3 may be used for reference. Figure 6.4 repeats the boiler schematic with location reference numbers from Figure 4.27.

Figure 6.3: Full plant schematic with location reference numbers.

Figure 6.4: Schematic of the boiler system with location reference numbers.

The final flow rates, temperatures, and pressures for boiler 1 are given Table 6.5, while the thermodynamic properties are given in Table 6.6. The same data for boiler 2 are given Table 6.7 and Table 6.8, respectively.
final operational data for the feedwater heaters are given in Table 6.9 and the corresponding thermodynamic properties are given in Table 6.10. The final flow rates, temperatures, pressures for the turbine are given in Table 6.11 and the turbine thermodynamic properties in Table 6.12. The condenser flow rate, temperature, and pressure data are given in Table 6.13 and its thermodynamic properties in table 6.14. It may be noted that the sum of the feedwater into the boiler (B1+B3) is less than that of the steam flow out (B2). This is likely due to the assumed neglect of the boiler blowdown.

Table 6.5: Final average data used in boiler 1 analysis.

<table>
<thead>
<tr>
<th>Location Reference Number</th>
<th>SI Units</th>
<th>English Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flow Rate (kg/s)</td>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>B1</td>
<td>43.32</td>
<td>202.14</td>
</tr>
<tr>
<td>B2</td>
<td>43.40</td>
<td>495.63</td>
</tr>
<tr>
<td>B3</td>
<td>0.30</td>
<td>--</td>
</tr>
<tr>
<td>B4</td>
<td>4.12</td>
<td>--</td>
</tr>
<tr>
<td>B5</td>
<td>4.66</td>
<td>--</td>
</tr>
<tr>
<td>B6</td>
<td>0.04</td>
<td>12.58</td>
</tr>
<tr>
<td>B7</td>
<td>0.03</td>
<td>12.58</td>
</tr>
<tr>
<td>B8</td>
<td>1.60</td>
<td>433.73</td>
</tr>
<tr>
<td>B9</td>
<td>1.60</td>
<td>247.95</td>
</tr>
<tr>
<td>B10</td>
<td>58.47</td>
<td>--</td>
</tr>
<tr>
<td>B11</td>
<td>19.43</td>
<td>40.44</td>
</tr>
<tr>
<td>B12</td>
<td>17.74</td>
<td>--</td>
</tr>
<tr>
<td>B13</td>
<td>1.68</td>
<td>--</td>
</tr>
<tr>
<td>B14</td>
<td>1.70</td>
<td>--</td>
</tr>
<tr>
<td>B15</td>
<td>1.76</td>
<td>--</td>
</tr>
<tr>
<td>B16</td>
<td>3.39</td>
<td>42.76</td>
</tr>
<tr>
<td>B17</td>
<td>7.35</td>
<td>--</td>
</tr>
</tbody>
</table>

-- indicates data not necessary for analysis

* 1000 lb/h

Table 6.6: Final average thermodynamic data for boiler 1.

<table>
<thead>
<tr>
<th>Description of Location</th>
<th>SI Units</th>
<th>English Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Enthalpy (kJ/kg)</td>
<td>Entropy (kJ/kg-K)</td>
</tr>
<tr>
<td>B1</td>
<td>867.15</td>
<td>2.33</td>
</tr>
<tr>
<td>B2</td>
<td>3363.02</td>
<td>6.58</td>
</tr>
<tr>
<td>B8</td>
<td>370.19</td>
<td>--</td>
</tr>
<tr>
<td>B9</td>
<td>217.84</td>
<td>--</td>
</tr>
<tr>
<td>B10</td>
<td>505.09</td>
<td>--</td>
</tr>
<tr>
<td>B6+B7</td>
<td>313.70</td>
<td>1.75</td>
</tr>
<tr>
<td>B13 to B17</td>
<td>316.03</td>
<td>1.75</td>
</tr>
</tbody>
</table>

-- indicates data not necessary for analysis
Table 6.7: Final average data used in boiler 2 analysis.

<table>
<thead>
<tr>
<th>Location Reference Number</th>
<th>SI Units</th>
<th>English Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flow Rate (kg/s)</td>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>B1</td>
<td>41.64</td>
<td>202.15</td>
</tr>
<tr>
<td>B2</td>
<td>41.47</td>
<td>504.85</td>
</tr>
<tr>
<td>B3</td>
<td>0.30</td>
<td>--</td>
</tr>
<tr>
<td>B4</td>
<td>4.21</td>
<td>--</td>
</tr>
<tr>
<td>B5</td>
<td>4.66</td>
<td>--</td>
</tr>
<tr>
<td>B6</td>
<td>0.03</td>
<td>12.58</td>
</tr>
<tr>
<td>B7</td>
<td>0.03</td>
<td>12.58</td>
</tr>
<tr>
<td>B8</td>
<td>1.62</td>
<td>437.75</td>
</tr>
<tr>
<td>B9</td>
<td>1.62</td>
<td>242.07</td>
</tr>
<tr>
<td>B10</td>
<td>59.30</td>
<td>--</td>
</tr>
<tr>
<td>B11</td>
<td>19.24</td>
<td>42.15</td>
</tr>
<tr>
<td>B12</td>
<td>18.10</td>
<td>--</td>
</tr>
<tr>
<td>B13</td>
<td>1.70</td>
<td>--</td>
</tr>
<tr>
<td>B14</td>
<td>1.82</td>
<td>--</td>
</tr>
<tr>
<td>B15</td>
<td>1.71</td>
<td>--</td>
</tr>
<tr>
<td>B16</td>
<td>3.77</td>
<td>42.93</td>
</tr>
<tr>
<td>B17</td>
<td>7.50</td>
<td>--</td>
</tr>
</tbody>
</table>

-- indicates data not necessary for analysis

* 1000 lb/h

Table 6.8: Final average thermodynamic data for boiler 2.

<table>
<thead>
<tr>
<th>Description of Location</th>
<th>SI Units</th>
<th>English Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Enthalpy (kJ/kg)</td>
<td>Entropy (kJ/kg-K)</td>
</tr>
<tr>
<td>B1</td>
<td>867.17</td>
<td>2.33</td>
</tr>
<tr>
<td>B2</td>
<td>3386.11</td>
<td>6.61</td>
</tr>
<tr>
<td>B8</td>
<td>411.59</td>
<td>--</td>
</tr>
<tr>
<td>B9</td>
<td>211.72</td>
<td>--</td>
</tr>
<tr>
<td>B10</td>
<td>497.25</td>
<td>--</td>
</tr>
<tr>
<td>B6+B7</td>
<td>315.42</td>
<td>1.75</td>
</tr>
<tr>
<td>B13 to B17</td>
<td>316.20</td>
<td>1.75</td>
</tr>
</tbody>
</table>

-- indicates data not necessary for analysis
Table 6.9: Final average data used in the feedwater heater analysis.

<table>
<thead>
<tr>
<th>Location Reference Number</th>
<th>SI Units</th>
<th>English Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flow Rate (kg/s)</td>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>F1</td>
<td>56.21</td>
<td>40.13</td>
</tr>
<tr>
<td>F2</td>
<td>56.21</td>
<td>81.50</td>
</tr>
<tr>
<td>F3</td>
<td>56.21</td>
<td>117.52</td>
</tr>
<tr>
<td>F4</td>
<td>85.55</td>
<td>153.14</td>
</tr>
<tr>
<td>F5</td>
<td>84.96</td>
<td>155.77</td>
</tr>
<tr>
<td>F6</td>
<td>84.96</td>
<td>176.04</td>
</tr>
<tr>
<td>F7</td>
<td>84.96</td>
<td>202.14</td>
</tr>
<tr>
<td>F8</td>
<td>3.83</td>
<td>88.27</td>
</tr>
<tr>
<td>F9</td>
<td>7.51</td>
<td>47.39</td>
</tr>
<tr>
<td>F10</td>
<td>3.68</td>
<td>121.80</td>
</tr>
<tr>
<td>F11</td>
<td>3.68</td>
<td>89.37</td>
</tr>
<tr>
<td>F12</td>
<td>21.67</td>
<td>175.27</td>
</tr>
<tr>
<td>F13</td>
<td>3.22</td>
<td>236.23</td>
</tr>
<tr>
<td>F14</td>
<td>7.67</td>
<td>165.77</td>
</tr>
<tr>
<td>F15</td>
<td>4.45</td>
<td>289.18</td>
</tr>
<tr>
<td>F16</td>
<td>4.45</td>
<td>185.06</td>
</tr>
</tbody>
</table>

* 1000 lb/h

Table 6.10: Final average thermodynamic data for feedwater heater analysis.

<table>
<thead>
<tr>
<th>Location Reference Number</th>
<th>SI Units</th>
<th>English Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Enthalpy (kJ/kg)</td>
<td>Entropy (kJ/kg-K)</td>
</tr>
<tr>
<td>F1</td>
<td>168.77</td>
<td>0.57</td>
</tr>
<tr>
<td>F2</td>
<td>341.85</td>
<td>1.09</td>
</tr>
<tr>
<td>F3</td>
<td>493.69</td>
<td>1.50</td>
</tr>
<tr>
<td>F4</td>
<td>645.90</td>
<td>1.87</td>
</tr>
<tr>
<td>F5</td>
<td>665.13</td>
<td>1.89</td>
</tr>
<tr>
<td>F6</td>
<td>752.55</td>
<td>2.08</td>
</tr>
<tr>
<td>F7</td>
<td>867.15</td>
<td>2.33</td>
</tr>
<tr>
<td>F8</td>
<td>2600.01</td>
<td>7.34</td>
</tr>
<tr>
<td>F9</td>
<td>198.43</td>
<td>0.67</td>
</tr>
<tr>
<td>F10</td>
<td>2715.34</td>
<td>7.30</td>
</tr>
<tr>
<td>F11</td>
<td>374.35</td>
<td>1.18</td>
</tr>
<tr>
<td>F12</td>
<td>2803.80</td>
<td>6.98</td>
</tr>
<tr>
<td>F13</td>
<td>2912.92</td>
<td>6.88</td>
</tr>
<tr>
<td>F14</td>
<td>700.83</td>
<td>2.00</td>
</tr>
<tr>
<td>F15</td>
<td>3006.29</td>
<td>6.80</td>
</tr>
<tr>
<td>F16</td>
<td>785.73</td>
<td>2.19</td>
</tr>
</tbody>
</table>
Table 6.11: Final average data used in the turbine analysis.

<table>
<thead>
<tr>
<th>Location Reference Number</th>
<th>SI Units</th>
<th>English Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flow Rate (kg/s)</td>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>T1</td>
<td>84.86</td>
<td>501.19</td>
</tr>
<tr>
<td>T2</td>
<td>5.45</td>
<td>289.18</td>
</tr>
<tr>
<td>T3</td>
<td>5.89</td>
<td>236.23</td>
</tr>
<tr>
<td>T4</td>
<td>21.67</td>
<td>175.27</td>
</tr>
<tr>
<td>T5</td>
<td>3.68</td>
<td>121.80</td>
</tr>
<tr>
<td>T6</td>
<td>3.83</td>
<td>88.27</td>
</tr>
<tr>
<td>T7</td>
<td>44.34</td>
<td>43.55</td>
</tr>
</tbody>
</table>

* 1000 lb/h

Table 6.12: Final average thermodynamic data for turbine analysis.

<table>
<thead>
<tr>
<th>Location Reference Number</th>
<th>SI Units</th>
<th>English Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Enthalpy (kJ/kg)</td>
<td>Entropy (kJ/kg-K)</td>
</tr>
<tr>
<td>T1</td>
<td>3382.26</td>
<td>6.62</td>
</tr>
<tr>
<td>T2</td>
<td>3006.29</td>
<td>6.80</td>
</tr>
<tr>
<td>T3</td>
<td>2912.92</td>
<td>6.88</td>
</tr>
<tr>
<td>T4</td>
<td>2803.80</td>
<td>6.98</td>
</tr>
<tr>
<td>T5</td>
<td>2715.34</td>
<td>7.30</td>
</tr>
<tr>
<td>T6</td>
<td>2600.01</td>
<td>7.34</td>
</tr>
<tr>
<td>T7</td>
<td>2322.39</td>
<td>7.38</td>
</tr>
</tbody>
</table>

Table 6.13: Final average data used in the condenser analysis.

<table>
<thead>
<tr>
<th>Location Reference Number</th>
<th>SI Units</th>
<th>English Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flow Rate (kg/s)</td>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>C1</td>
<td>580.41</td>
<td>25.10</td>
</tr>
<tr>
<td>C2</td>
<td>580.41</td>
<td>34.94</td>
</tr>
<tr>
<td>C3</td>
<td>44.34</td>
<td>43.55</td>
</tr>
<tr>
<td>C4</td>
<td>1.69</td>
<td>10.00</td>
</tr>
<tr>
<td>C5</td>
<td>7.51</td>
<td>47.39</td>
</tr>
<tr>
<td>C6</td>
<td>2.67</td>
<td>43.55</td>
</tr>
<tr>
<td>C7</td>
<td>56.21</td>
<td>39.67</td>
</tr>
</tbody>
</table>

* 1000 lb/h
Table 6.14: Final average thermodynamic data for condenser analysis.

<table>
<thead>
<tr>
<th>Location Reference Number</th>
<th>SI Units</th>
<th>English Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SI Units</td>
<td>English Units</td>
</tr>
<tr>
<td></td>
<td>Enthalpy (kJ/kg)</td>
<td>Entropy (kJ/kg-K)</td>
</tr>
<tr>
<td>C1</td>
<td>105.24</td>
<td>0.37</td>
</tr>
<tr>
<td>C2</td>
<td>146.38</td>
<td>0.50</td>
</tr>
<tr>
<td>C3</td>
<td>2322.39</td>
<td>7.38</td>
</tr>
<tr>
<td>C4</td>
<td>42.02</td>
<td>0.15</td>
</tr>
<tr>
<td>C5</td>
<td>198.43</td>
<td>0.67</td>
</tr>
<tr>
<td>C6</td>
<td>2268.19</td>
<td>7.21</td>
</tr>
<tr>
<td>C7</td>
<td>166.18</td>
<td>0.57</td>
</tr>
</tbody>
</table>

6.3. Baseline Thermodynamic Results

This section outlines the baseline thermodynamic results. The baseline results take advantage of the full range of data available. Boiler model BII, described in Section 3.5, is used since it more accurately represents the combustion process.

6.3.1. Energy Analysis

The energy analysis results for the condenser, turbine, and total plant are given in this section. Each of the tables given in this section list the parameter, the baseline value, and the equation used.

The only energy parameter found for the condenser is the heat transfer to the cooling water, \( \dot{Q}_C \). The baseline heat transfer value for the condenser is found to be -101.12 MW. The negative sign signifies that the heat is leaving the condenser, which is expected.

Baseline results found using turbine method I are shown in Table 6.15 and results found using method II are given in Table 6.16. The process load heat value, \( \dot{Q}_{\text{process}} \), found using Equation (4.58), has a value of -2.97 MW. Now that the baseline results are given, the difference between the two methods of turbine work are apparent; method I yields a turbine work that is approximately 17% higher than the value found using method II- both turbine work results are highlighted in the respective tables. The reasons behind this error will be discussed in Section 6.4.1.2, but has to do with the accumulated errors inherent in method II. Because of those errors, the turbine work found using method I is assumed to be more accurate.

Table 6.15: Baseline energy results for turbine using method I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (MW)</th>
<th>Equation used</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \dot{Q}_{\text{L,T}} )</td>
<td>-1.15</td>
<td>(4.51)</td>
</tr>
<tr>
<td>( W_{\text{T1}} )</td>
<td>82.39</td>
<td>(4.52)</td>
</tr>
<tr>
<td>( W_{\text{gen}} )</td>
<td>78.27</td>
<td>Operational data</td>
</tr>
</tbody>
</table>
The turbine isentropic efficiency is found to be approximately 79.2% using method II. Method I cannot be used to find the isentropic efficiency because the isentropic efficiency depends on an energy balance method to determine the isentropic work. If the isentropic work were compared to the method I turbine work the result would be skewed and unusable.

Table 6.16: Baseline energy results for turbine using method II.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Equation used</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{LTII}$</td>
<td>-0.96</td>
<td>MW</td>
<td>(4.51)</td>
</tr>
<tr>
<td>$W_{TII}$</td>
<td>68.75</td>
<td>MW</td>
<td>(4.56)</td>
</tr>
<tr>
<td>$W_{gen.TII}$</td>
<td>65.311</td>
<td>MW</td>
<td>(4.57)</td>
</tr>
<tr>
<td>$W_{s,T}$</td>
<td>86.508</td>
<td>MW</td>
<td>(4.60)</td>
</tr>
<tr>
<td>$\eta_{s,T}$</td>
<td>0.792</td>
<td>%</td>
<td>(4.59)</td>
</tr>
</tbody>
</table>

The energy baseline data for both boilers are found in Table 6.17, with important results highlighted. It may be observed that the parameters vary slightly between the two boilers. Although the boilers are nominally the same, they have slightly different operating conditions and so produce different results. Table 6.17 gives the boiler heat loss for boiler 1 to be 15.03 MW and the total heat content of the culm entering the boiler to be 137.06 MW, which means about 11% of the heat input to the boiler room air through heat loss. The heat loss from boiler 2 is given as 20.44 MW and the culm energy stream is 138.38 MW, which means the second boiler looses about 15% of the incoming energy through heat loss. Very little energy is lost due to the limestone reactions-less than 1% of the culm energy is used in the limestone reactions in both boilers.

Table 6.17: Baseline boiler energy analysis for both boilers. Boiler model BII used.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value for Boiler 1</th>
<th>Value for Boiler 2</th>
<th>Units</th>
<th>Equation used</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{culm}$</td>
<td>137.06</td>
<td>138.38</td>
<td>MW</td>
<td>(4.152)</td>
</tr>
<tr>
<td>$Q_u$</td>
<td>-107.91</td>
<td>-104.13</td>
<td>MW</td>
<td>(4.150)</td>
</tr>
<tr>
<td>$Q_{LTII}$</td>
<td>-15.03</td>
<td>-20.44</td>
<td>MW</td>
<td>(4.165)</td>
</tr>
<tr>
<td>$Q_{lime.BII}$</td>
<td>-0.27</td>
<td>-0.25</td>
<td>MW</td>
<td>(4.166)</td>
</tr>
<tr>
<td>$\eta_B$</td>
<td>0.796</td>
<td>0.765</td>
<td>%</td>
<td>(4.153)</td>
</tr>
</tbody>
</table>

The combined boiler effects using boiler model BI and BII are listed in Table 6.18. Overall, both boilers combined have an average efficiency of 78%. The total heat loss is about 35.47 MW, which represents almost 13% of the total fuel energy (275.44 MW) entering the boilers. The main difference between the two boiler models is in the boiler heat loss. The boiler heat loss using model BI is much smaller than that for boiler model BII because of the difference in the flue gas compositions.

The total plant analysis energy analysis results are given in Table 6.19. The plant has a total heat loss of 70.69 MW when using the turbine method I. About half of the heat entering the plant (275.44 MW) is lost through heat losses (137.74 MW using turbine method I) in various components.
Table 6.18: Energy results from both boilers for models BI and BII.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model BI</th>
<th>Model BII</th>
<th>Units</th>
<th>Equation used</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{Q}_{\text{cuml, total}}$</td>
<td>275.44</td>
<td></td>
<td>MW</td>
<td>(4.170)</td>
</tr>
<tr>
<td>$\dot{Q}_{\text{u, total, B}}$</td>
<td>-212.04</td>
<td></td>
<td>MW</td>
<td>(4.169)</td>
</tr>
<tr>
<td>$\dot{Q}_{\text{l, total}}$</td>
<td>-1.71</td>
<td>-35.47</td>
<td>MW</td>
<td>(4.168)</td>
</tr>
<tr>
<td>$\dot{Q}_{\text{lime, total, B}}$</td>
<td>-0.52</td>
<td></td>
<td>MW</td>
<td>(4.166)</td>
</tr>
<tr>
<td>$\eta_{B, \text{avg}}$</td>
<td>0.781</td>
<td></td>
<td>%</td>
<td>(4.171)</td>
</tr>
</tbody>
</table>

Table 6.19: Energy analysis for plant system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value using method TI</th>
<th>Value using method TII</th>
<th>Units</th>
<th>Equation used</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{Q}_{P, l}$</td>
<td>-137.74</td>
<td>-137.55</td>
<td>MW</td>
<td>(4.197)</td>
</tr>
<tr>
<td>$\dot{Q}_{P, in}$</td>
<td>275.44</td>
<td></td>
<td>MW</td>
<td>(4.199)</td>
</tr>
<tr>
<td>$W_{P, export}$</td>
<td>70.69</td>
<td>57.73</td>
<td>MW</td>
<td>Operational data/(4.200)</td>
</tr>
<tr>
<td>$W_{P, internal}$</td>
<td>7.58</td>
<td></td>
<td>MW</td>
<td>(4.199)</td>
</tr>
<tr>
<td>$EUF_{P}$</td>
<td>0.268</td>
<td>0.220</td>
<td>%</td>
<td>(4.201)</td>
</tr>
<tr>
<td>$\eta_{th}$</td>
<td>0.257</td>
<td>0.209</td>
<td>%</td>
<td>(4.202)</td>
</tr>
</tbody>
</table>

6.3.2. Exergy Analysis

The feedwater heater exergy destruction values are given in Table 6.20. By far the greatest exergy destruction occurs in the deaerator. Unlike the other feedwater heaters, the DA is open, meaning that the superheated steam from extraction 3 (see Figure 6.3) mixes with the condensate entering from FWH 2 and the FWH 4 drain. There is a very large difference between the entropy of the steam entering the DA (F12) and the DA drain (F4), which lends itself to the large exergy destruction value. The process of the fluid streams mixing also produces entropy, thus increasing the exergy destruction further. The total exergy destruction from all five feedwater heaters is given as 14.01 MW.

Table 6.20: Baseline exergy destruction values for feedwater heaters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (MW)</th>
<th>Equation used</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{d,FWH1}$</td>
<td>0.579</td>
<td>(4.62)</td>
</tr>
<tr>
<td>$E_{d,FWH2}$</td>
<td>0.196</td>
<td>(4.63)</td>
</tr>
<tr>
<td>$E_{d,DA}$</td>
<td>12.83</td>
<td>(4.64)</td>
</tr>
<tr>
<td>$E_{d,FWH4}$</td>
<td>0.156</td>
<td>(4.65)</td>
</tr>
<tr>
<td>$E_{d,FWH5}$</td>
<td>0.156</td>
<td>(4.66)</td>
</tr>
<tr>
<td>$E_{d,FWH}$</td>
<td>14.01</td>
<td>(4.67)</td>
</tr>
</tbody>
</table>

The condenser exergy analysis yields an exergy loss value and an exergy destruction value, both given in Table 6.21. There is a large amount of exergy loss from the condenser, indicated by the negative sign, but the exergy destruction is not large compared to the exergy destruction of other system components.
Two sets of turbine exergy analysis data may be produced because of the two methods of turbine analysis. The results using method I are given in Table 6.22 and the results using method II are given in Table 6.23. Note that the difference between the exergy destruction when the method II is used is non-existent, whereas the difference using method I is large.

The exergy destruction for method I using the exergy balance method is found to be almost zero, and depending on the reference conditions used may be negative. Exergy destruction can never be negative in a real system since entropy production cannot be negative. The reason the negative sign occurs in this instance has to do with the turbine work using method I being much larger than the work found using method II. When the larger work value is used in the exergy balance subtracts the turbine work directly, whereas the entropy balance method does not. Since a balance method produces a smaller work value, when the larger work value is subtracted in the exergy balance an impossible exergy destruction value is found. Since exergy destruction cannot be negative or zero in a real system, the entropy balance method must be used.

The turbine exergetic efficiency using method I is higher than that for method II (70.4% vs. 58.4%). Since method I is a more accurate method for determining the turbine work, the 70.4% efficiency is taken. The process exergy value is found to be -1.20 MW.

The baseline boiler exergy results are given in Table 6.24. The exergy of the culm entering each boiler is higher than the energy content of the fuel given in Table 6.17. As discussed in Section 6.1.1, the calculated culm exergy is higher than the recorded HHV. While this difference is not expected, it may be explained by the high ash and moisture content of culm. The exergy loss based on the heat loss from the boiler shows that the loss is actually less
significant than the energy analysis would imply since the difference between the environmental and boiler room temperatures are not that great. There is, however, a significant amount of exergy destruction occurring in each boiler; about 30% of the exergy entering the boiler in the fuel is destroyed through the combustion process. The exergy efficiency of each boiler is around 54%, which is significantly less than the energy efficiencies, which were around 78%. The smaller efficiency reflects the large exergy destruction value.

Table 6.24: Baseline boiler exergy results for boiler 1 and boiler 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value from boiler 1</th>
<th>Value from boiler 2</th>
<th>Units</th>
<th>Equation used</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{culm}}$</td>
<td>147.11</td>
<td>148.52</td>
<td>MW</td>
<td>(4.173)</td>
</tr>
<tr>
<td>$E_{\text{air}}$</td>
<td>2.54</td>
<td>2.59</td>
<td>MW</td>
<td>(4.176)</td>
</tr>
<tr>
<td>$E_{\text{lime,BII}}$</td>
<td>0.0007</td>
<td>0.0007</td>
<td>MW</td>
<td>(4.187)</td>
</tr>
<tr>
<td>$E_{\text{ash,BII}}$</td>
<td>5.20</td>
<td>5.31</td>
<td>MW</td>
<td>(4.185)</td>
</tr>
<tr>
<td>$E_{\text{FG,BII}}$</td>
<td>12.32</td>
<td>12.36</td>
<td>MW</td>
<td>(4.186)</td>
</tr>
<tr>
<td>$E_{\text{L,BII}}$</td>
<td>-1.05</td>
<td>-1.40</td>
<td>MW</td>
<td>(4.187)</td>
</tr>
<tr>
<td>$E_{\text{d,BII}}$</td>
<td>50.19</td>
<td>53.98</td>
<td>MW</td>
<td>(4.188)</td>
</tr>
<tr>
<td>$\epsilon_{\text{BII}}$</td>
<td>-0.556</td>
<td>-0.534</td>
<td>%</td>
<td>(4.174)</td>
</tr>
</tbody>
</table>

The total exergy values of both boilers combined are given in Table 6.25 for both boiler model BI and BII. Overall, with boiler models, the boilers have a fuel exergy flow of 295.63 MW and 0.14 kW of limestone exergy. The larger differences between the two models are the inflow of exergy of the air, and outflows from the boiler. Since model BI assumes the air enters at the reference temperature, the air flow exergy is zero, whereas it is 5.13 MW for model BII. The ash and flue gas exergy values differ since both models assume different compositions.

Table 6.25: Total baseline exergy results from both boilers for both boiler models.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model BI</th>
<th>Model BII</th>
<th>Units</th>
<th>Equation used</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{culm,total,B}}$</td>
<td>295.63</td>
<td></td>
<td>MW</td>
<td>(4.191)</td>
</tr>
<tr>
<td>$E_{\text{air,total,B}}$</td>
<td>0.00</td>
<td>5.13</td>
<td>MW</td>
<td>(4.192)</td>
</tr>
<tr>
<td>$E_{\text{lime,total,B}}$</td>
<td>0.0014</td>
<td></td>
<td>MW</td>
<td>(4.193)</td>
</tr>
<tr>
<td>$E_{\text{ash,total,B}}$</td>
<td>1.95</td>
<td>10.51</td>
<td>MW</td>
<td>(4.194)</td>
</tr>
<tr>
<td>$E_{\text{FG,total,B}}$</td>
<td>25.02</td>
<td>24.68</td>
<td>MW</td>
<td>(4.195)</td>
</tr>
<tr>
<td>$E_{\text{L,total,B}}$</td>
<td>-0.10</td>
<td>-2.44</td>
<td>MW</td>
<td>(4.189)</td>
</tr>
<tr>
<td>$E_{\text{d,total,B}}$</td>
<td>110.87</td>
<td>100.37</td>
<td>MW</td>
<td>(4.190)</td>
</tr>
<tr>
<td>$\epsilon_{\text{avg,B}}$</td>
<td>-0.545</td>
<td></td>
<td>%</td>
<td>(4.196)</td>
</tr>
</tbody>
</table>

The plant baseline exergy results are given Table 6.26. The plant delivers around 71.79 MW of useful exergy (electricity and process heat) when method TI is used, and only 58.82 MW when method TII is used. The difference is due to method TII producing a lower turbine work value. Overall the plant has an exergetic efficiency of about 24.38% using method TI.
Table 6.26: Plant baseline exergy results.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value using method TI</th>
<th>Value using method TII</th>
<th>Units</th>
<th>Equation used</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{E}_{LP}$</td>
<td>-8.10</td>
<td>-8.09</td>
<td>MW</td>
<td>(4.203)</td>
</tr>
<tr>
<td>$\dot{E}_{dP}$</td>
<td>138.05</td>
<td>137.87</td>
<td>MW</td>
<td>(4.204)</td>
</tr>
<tr>
<td>$\dot{E}_{\text{export}}$</td>
<td>70.69</td>
<td></td>
<td>MW</td>
<td>(4.205)</td>
</tr>
<tr>
<td>$\dot{E}_{\text{out,}P}$</td>
<td>71.79</td>
<td>58.82</td>
<td>MW</td>
<td>(4.206)</td>
</tr>
<tr>
<td>$\dot{E}_{\text{in, total},P}$</td>
<td>300.58</td>
<td></td>
<td>MW</td>
<td>(4.208)</td>
</tr>
<tr>
<td>$\dot{E}_{\text{out, total},P}$</td>
<td>115.09</td>
<td>102.11</td>
<td>MW</td>
<td>(4.209)</td>
</tr>
<tr>
<td>$\varepsilon_p$</td>
<td>0.243</td>
<td>0.198</td>
<td>%</td>
<td>(4.207)</td>
</tr>
</tbody>
</table>

6.3.3. Graphical Representations

Temperature-entropy (T-s) diagrams are useful to ensure a given process has no irreversibilities. A T-s diagram is generated for the feedwater and steam throughout the plant. Figure 6.3 may be used as reference for indicated reference locations. The ideal turbine process would be isentropic, so the change in entropy from locations T1 to T7 would be zero. As this is a real process, however, there is an increase in entropy between each state of the turbine. It may also be observed that the steam in the turbine enters the liquid/vapor mixture region between T5 and T6. The greatest increase in entropy and temperature occurs across the boiler, between F7 and T1. The increase in entropy is consistent with the large exergy destruction value found for each boiler.

A pressure-enthalpy (p-h) diagram is also given in Figure 6.6 to illustrate the changing properties of the feedwater throughout the plant. Two notable locations on the P-h diagram are C4-F1 and F4-F5. Between these sets of locations are pumps; between C4 and F1 is the condensate pump and between F4 and F5 is the boiler feed pump. The feedwater is pushed into the compressed liquid region after each pump. The pressure is constant across FWH1 and FWH2, but drops when the condensate enters the DA.

Energy and exergy flow diagrams, discussed in Section 2.2.1, are used to visualize the flow of energy or exergy through a system or subsystem of the plant. The boiler systems represent the greatest source of exergy destruction through the plant. Energy and exergy flow diagrams for the combined boiler system, given in Figure 6.7, help demonstrate the magnitude of the exergy destruction in the boiler. The energy flow diagram for the boiler is given in Figure 6.7(a) and the exergy flow diagram in Figure 6.7(b). Some of the main differences between the energy and exergy analyses of the boiler are emphasized in Figure 6.7. The inflow of air energy in Figure 6.7(a) makes up almost 11% of the energy into the plant, however, the air exergy flow shown in Figure 6.7(b) makes up only 1.8% of the total exergy into the boiler. The difference is that although the air holds a given amount of energy, only a small portion of that energy is useful.

The turbine analysis also yields energy and exergy flow diagrams, given in Figure 6.8(a) and Figure 6.8(b) respectively. In both the turbine energy and exergy flow diagrams the steam at extraction 3 and the exhaust make up the largest exiting streams since those two streams have the greatest flow rates. Both streams are smaller in the exergy flow diagram.
An exergy flow diagram is produced for the entire plant is given in Figure 6.9. The exergy waste streams from the plant- the ash, flue gas, and heat loss, are small compared to the exergy destroyed. The process heat and internal power use are likewise very small compared to the exergy destruction and the exergy export.

Figure 6.5: T-s diagram for feedwater and steam through plant.

Figure 6.6: P-h diagram for feedwater through the plant.
Figure 6.7: Boiler flow diagrams for (a) energy and (b) exergy. Arrow width represents magnitude.
Figure 6.8: (a) Energy and (b) exergy flow diagrams for turbine.
6.4. **Model Validation and Error**

The availability of data gives many opportunities for validation of the thermodynamic model. The turbine and the boiler are the most important plant components and so they will be the focus of validation.

6.4.1. **Turbine Errors and Iterations**

Through the turbine analysis two main issues arose; the final two exiting streams from the boiler are vapor/liquid mixtures and so their states could not be fixed and the two methods of turbine work calculations result in significantly different work values.

6.4.1.1. **Turbine Quality**

The turbine quality issue will be discussed first. The first attempt at fixing the states at the final extraction point and the exhaust was to use the quality used in the heat balance performed in the plant in the 1990’s. It was found, however, that the qualities pulled from the heat balance resulted in decreasing entropy values at T6 and T7, which points to an flaw in the values.

Excel was used to determine qualities using the steady state portion of the operational data. A screenshot of the spreadsheet set up is given in Figure 6.10. Approximate flow rates, temperatures, pressures, and enthalpy values are placed in the appropriate cells for the turbine, feedwater heaters, and condenser since those systems are all required to determine the turbine work using an energy balance. The turbine work using method II is calculated based on the cell data.
Another block of cells, shown in the bottom right hand corner of Figure 6.10, lists the saturated vapor and liquid values for the enthalpy and entropy values at extraction 1 and the exhaust. The enthalpy and entropy at extraction 1 and the exhaust are calculated based on the saturated vapor and liquid thermodynamic properties and an estimated quality.

![Figure 6.10: Screenshot of spreadsheet used to determine the quality at extraction 1 and the turbine exhaust.](image)

Excel Solver is used to find the minimum error between the two work methods by changing the quality values and ensuring that there is no decrease in entropy between any of the extraction points in the turbine. Initially, the heat loss percentage, turbine efficiency, and boiler feed pump turbine efficiency were included as variables in the Solver. Eventually, the heat loss and efficiencies were removed because although they reduced the error, they did so in a way that was unrealistic (such as zero heat loss or 100% efficiency). Using this method, the qualities of $x_{\text{ext. 1}} = 0.97$ and $x_{\text{exhaust}} = 0.89$ were found. Problems arose, however, when the found qualities were applied to the whole set of operational data. As shown in Figure 6.11, the entropy values at extraction 2 exceed the entropy values of extraction 1 and the exhaust during low load time periods.

In order to fix the turbine quality problem, a second Excel spreadsheet was made to determine the qualities when the plant operates at low load. It was found that at low load the quality at extraction 1 is approximately 0.99 and at the exhaust it is approximately 0.90. Using the appropriate qualities depending on the plant load, Figure 6.12 is found. The improvement is substantial, however, there are still a number of times when the entropy at extraction 2 is higher than the other two locations. It is possible that at lower loads the steam remains in the superheated region through
the entire turbine. Since only the pressure or the temperature is available at the last two turbine locations, this hypothesis cannot be tested.

Figure 6.11: Original qualities with high and low load scenarios.

Figure 6.12: Entropy at extraction 2, extraction 1, and turbine exhaust using variable qualities.
6.4.1.2. **Turbine Work Error**

Comparing turbine work calculated from each method will help gauge the accuracy of the thermodynamic model. The work found using Equation (4.52) is assumed to be accurate because it relies on the fewest assumptions. The error between the two methods is given in Equation (6.1).

\[ \text{error}_{\dot{w}_T} = 100 \times \left( \frac{\dot{W}_{TI} - \dot{W}_{TI}}{\dot{W}_{TI}} \right) \tag{6.1} \]

Using data from Table 6.22 and Table 6.23, the average error is found to be about 17%. Preferably this error would be smaller, however, for a model of this size it is not unreasonable. The turbine work using method I relies on two pieces of information: the measured generator power export and the assumed generator efficiency. The turbine work using method II, on the other hand, relies on the analysis of each of the five feedwater heaters, the boiler feed pump, and the boiler feed pump turbine. Additionally, the turbine work relies on 32 sensors for temperature, pressure, and flow rate data, each of which has a range of accuracy errors. Even if each assumption is reasonable, the errors accumulate and surface in the turbine work.

6.4.2. **Boiler Errors and Iterations**

The boiler system has a large impact on the overall power plant system, and so the system model should be validated in all possible ways. The boiler heat loss and the boiler emissions results will be discussed and compared to other available models in the sections below.

6.4.2.1. **Boiler Heat Loss**

The average boiler heat loss from both boilers according to the thermodynamic model is 35.47 MW, as shown in Table 6.18 in Section 6.3. The percent heat loss is the ratio between the heat loss value and the total heat entering the boiler from culm. Since the average total input of heat energy is 275.44 MW, the average heat loss percentage of the boilers is 12.88%. Lu et al. [59] modeled the dissipating heat loss from two CFB boilers. It was found that the boilers had approximate heat loss values of 3% of the input heat. Using Equation (4.154), which applies the 3% heat loss, the boiler heat loss is found to be 8.26 MW. There is a difference of almost 10% between the two methods of boiler heat loss calculation.

There are a number of factors that explain the difference. First, the estimated heat loss found by Lu et al. was determined for much larger boilers (300 MWe) than used at the cogeneration power plant (44 MWe each). Generally speaking, if two boilers of different sizes are both operating at the same percent full load, the larger of the boilers will have a smaller heat loss percentage [62], which implies that the percent heat loss from the cogeneration power station boilers could be greater than the estimated 3% found in literature.

Secondly, the boiler energy analysis is based on a number of simplifications and average data. The ultimate and proximate analyses are not available at the almost continuous rate the plant operational data are recorded at. This means that the energy and exergy values used for the culm and flue gas streams through the boiler analysis do not
exactly coincide with the actual values at a given time set of data. The culm and limestone are fed into the boiler via conveyor belts. The operational data for the culm and limestone feeds are based on the conveyor speed and so do not give an exact flow rate on a mass basis. The difference between the actual and calculated energy and exergy streams into the boiler could help account for the difference in the boiler heat loss values.

### 6.4.2.2. Boiler Emissions

Estimated values for the SO\(_x\), NO\(_x\), and CO\(_2\) levels leaving the power plant are generated based on the fuel and limestone use and the boiler reactions listed in Reactions (3.2)-(3.10). The plant has provided limited CEMS data (see Section 2.4) to which the calculated emissions may be compared. The CEMS data is given in concentration, not in mass flow rates, so the CEMS data is converted to mass flow rate using ideal gas assumptions before the comparison is made. The average CEMS data used for the boiler emissions error check are given in Table 6.27.

#### Table 6.27: Average CEMS data for total stack flow rate, concentration of SO\(_2\) and NO\(_x\), and temperature.

<table>
<thead>
<tr>
<th>Stack flow rate (ft(^3)/h)</th>
<th>Concentration SO(_2) (PPM)</th>
<th>Concentration NO(_x) (PPM)</th>
<th>Temperature (deg F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.49E+07</td>
<td>139.28</td>
<td>17.97</td>
<td>190</td>
</tr>
</tbody>
</table>

The estimated average molar mass of the flue gas is determined using the molar mass and flow rates of the flue gas components calculated through the boiler analysis. The flue gas composition data is given in Table 6.28.

#### Table 6.28: Flue gas data used to calculate an estimated flue gas molar mass.

<table>
<thead>
<tr>
<th>Type</th>
<th>Molar weight (kg/kmol)</th>
<th>Total flue gas flow (kg/s)</th>
<th>Total flue gas flow (kmol/s)</th>
<th>Mole fraction</th>
<th>Fraction Total Molar Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>O(_2)</td>
<td>32</td>
<td>1.41</td>
<td>0.04</td>
<td>0.01</td>
<td>0.36</td>
</tr>
<tr>
<td>N(_2)</td>
<td>28.01</td>
<td>84.53</td>
<td>3.02</td>
<td>0.77</td>
<td>21.47</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>44.01</td>
<td>27.15</td>
<td>0.62</td>
<td>0.16</td>
<td>6.89</td>
</tr>
<tr>
<td>H(_2)O (g)</td>
<td>18.02</td>
<td>4.62</td>
<td>0.26</td>
<td>0.07</td>
<td>1.17</td>
</tr>
<tr>
<td>SO(_2)</td>
<td>64.06</td>
<td>0.06</td>
<td>0.0009</td>
<td>0.0002</td>
<td>0.01</td>
</tr>
<tr>
<td>CaSO(_4)</td>
<td>136.142</td>
<td>0.19</td>
<td>0.0014</td>
<td>0.0004</td>
<td>0.05</td>
</tr>
<tr>
<td>NO</td>
<td>30.0061</td>
<td>0.00</td>
<td>0.0001</td>
<td>0.0000</td>
<td>0.0007</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>117.95</td>
<td>3.94</td>
<td>29.96</td>
<td></td>
</tr>
</tbody>
</table>

Using the molar weight of the flue gas calculated in Table 6.28, the density of the flue gas is found to be 0.773 lb\(_{\text{mf}}\)/ft\(^3\). Using the flue gas density, the mass flow rate of the flue gas, SO\(_2\), and NO\(_x\) may be found. The resulting flow rates are compared to the calculated estimated emissions in Table 6.29.

#### Table 6.29: Flow rates of stack flow, SO\(_2\), and NO\(_x\).

<table>
<thead>
<tr>
<th></th>
<th>Stack flow rate (kg/s)</th>
<th>Flow rate of SO(_2) (kg/s)</th>
<th>Flow rate of NO(_x) (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEMS data</td>
<td>145.06</td>
<td>0.0202</td>
<td>0.0026</td>
</tr>
<tr>
<td>Calculated data</td>
<td>117.95</td>
<td>0.0575</td>
<td>0.0026</td>
</tr>
</tbody>
</table>
As discussed in Section 4.5.1.3, the NO emission calculations are based on the CEMS data, and so the error between the two is zero on average. The SO₂ emissions were not based on the CEMS data since the reactions that produce SO₂ are better understood than those for NO production. It is readily observed, however, that the SO₂ emissions deviate significantly from the CEMS data.

There are a number of reasons for the deviations. First, the CEMS data collected is for a single month- January, 2009. The culm and limestone flow rates corresponding to the CEMS data are unknown, so there is likely a difference between the calculated and CEMS data due to different flow rates. There is also the issue of the reaction model accuracy. In reality, many more reactions occur through the combustion process, and reaction rates depend on many factors, including temperature, particular surface areas, and time [63]. The possibility of further exploring the boiler reactions is discussed in Section 6.6.1.

The calculated emissions levels are not used within this work to quantify the plant environmental performance because of the large difference compared to the CEMS data. The calculated emissions may be used to measure the relative performance of the improvement scenarios, and the CEMS data may be compared to the emissions in other SimaPro models.

6.5. Thermodynamic Comparisons and Discussion

The baseline plant performance has been established. Over an eight month period, the plant had an average thermal efficiency of 25.7% and an exergy efficiency of 24.3%. The improvement scenarios modeled in Section 4.6.3 will be discussed in the following sections. The relative advantages and disadvantages of each scenario will be discussed.

6.5.1. Cogeneration Steam Use

Examining the plant exergy efficiency in Equation (4.207), it is observed that an increase in the process steam use will increase the overall plant efficiency. Using the procedure outlined in Section 4.6.3.1., the process steam use is increased from an average flow rate of 1.00 kg/s to an average flow rate of 2.83 kg/s as given in Table 6.30. Figure 6.3 may be used for reference.

<table>
<thead>
<tr>
<th>Location reference number</th>
<th>Current (kg/s)</th>
<th>Increased process steam use (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T25</td>
<td>1.00</td>
<td>2.83</td>
</tr>
<tr>
<td>T1</td>
<td>84.86</td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>5.45</td>
<td>7.28</td>
</tr>
<tr>
<td>T3</td>
<td>5.89</td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>21.67</td>
<td></td>
</tr>
<tr>
<td>T5</td>
<td>3.68</td>
<td></td>
</tr>
<tr>
<td>T6</td>
<td>3.83</td>
<td></td>
</tr>
<tr>
<td>T7</td>
<td>44.34</td>
<td>42.52</td>
</tr>
</tbody>
</table>

Table 6.30: Turbine flow rates with the current and increased process steam use.
The process steam use is almost tripled when the maximum amount is used. The increased process steam increases the flow out of extraction 5 (T2) in order to provide for the extra steam use. Consequently, the flow rate at the turbine extraction is decreased.

The thermodynamic performance of the turbine and complete power plant also change with the increase in process steam use, as seen in Table 6.31. It is found that the overall exergy performance of the plant is increases and the energy performance decreases with the increased use of process steam. The thermal efficiency, calculated using Equation (4.202), is the ratio between the electricity leaving the plant and the energy entering the plant in the fuel. Since the fuel use is the same with the current and increased process steam use, and since the increased process steam means less electricity is generated, the thermal efficiency decreases. The exergetic efficiency, however, increases by a small amount. The exergetic efficiency counts the process steam as a useful product of the plant, and so the overall plant exergetic efficiency increases.

Table 6.31: Turbine and plant performance with and without increased process steam use.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current</th>
<th>Increased process steam use</th>
<th>Equation used</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{W}_{T3}$</td>
<td>68.75</td>
<td>67.51</td>
<td>(4.56)</td>
</tr>
<tr>
<td>$Q_{T3}$</td>
<td>-0.96</td>
<td>-0.94</td>
<td>(4.51)</td>
</tr>
<tr>
<td>$Q_{\text{process}}$</td>
<td>-2.97</td>
<td>-8.38</td>
<td>(4.58)</td>
</tr>
<tr>
<td>$\eta_{s,T}$</td>
<td>0.7920</td>
<td>0.7916</td>
<td>(4.59)</td>
</tr>
<tr>
<td>$E_{\text{process}}$</td>
<td>-1.20</td>
<td>-3.07</td>
<td>(4.77)</td>
</tr>
<tr>
<td>$E_{d,T3}$</td>
<td>14.53</td>
<td>14.22</td>
<td>(4.75)</td>
</tr>
<tr>
<td>$\xi_{T3}$</td>
<td>0.584</td>
<td>0.574</td>
<td>(4.76)</td>
</tr>
<tr>
<td>$W_{P,\text{export}}$</td>
<td>57.73</td>
<td>56.55</td>
<td>(4.200)</td>
</tr>
<tr>
<td>$EUF_{P}$</td>
<td>0.220</td>
<td>0.235</td>
<td>(4.201)</td>
</tr>
<tr>
<td>$\eta_{th}$</td>
<td>0.209</td>
<td>0.205</td>
<td>(4.202)</td>
</tr>
<tr>
<td>$E_{\text{out,u,P}}$</td>
<td>58.82</td>
<td>59.62</td>
<td>(4.209)</td>
</tr>
<tr>
<td>$\xi_{p}$</td>
<td>0.198</td>
<td>0.201</td>
<td>(4.207)</td>
</tr>
</tbody>
</table>

6.5.2. Turbine Reheat

When the reheat scenario, modeled in Section 4.6.3.2, is performed, the data given in Table 6.32 and Table 6.33 are found. The reheat steam flow is found to be 51.85 kg/s using Equation (4.216). The flow rate of steam leaving the turbine prior to extraction 3 is found to be 73.53 kg/s using Equation (4.213).

A T-s diagram comparing the turbine steam with the current plant configuration and the reheat scenario are given in Figure 6.13. The T-s diagram shows how the temperature and entropy increase between T4 and R2 as the steam passes back through the turbine. In the reheat scenario the turbine exhaust is well into the superheated region, whereas the current system has a vapor/liquid mixture at the last two extractions.
Table 6.32: Operational data used and calculated in turbine reheat analysis.

<table>
<thead>
<tr>
<th>Location</th>
<th>Reference Number</th>
<th>SI Units</th>
<th>English Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Flow Rate (kg/s)</td>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>T1</td>
<td>84.86</td>
<td>501.19</td>
<td>96.57</td>
</tr>
<tr>
<td>T2</td>
<td>5.45</td>
<td>289.18</td>
<td>17.76</td>
</tr>
<tr>
<td>T3</td>
<td>5.89</td>
<td>236.23</td>
<td>9.92</td>
</tr>
<tr>
<td>T4</td>
<td>21.67</td>
<td>175.27</td>
<td>4.73</td>
</tr>
<tr>
<td>R1</td>
<td>51.85</td>
<td>175.27</td>
<td>4.73</td>
</tr>
<tr>
<td>R2</td>
<td>51.85</td>
<td>394.02</td>
<td>4.73</td>
</tr>
<tr>
<td>T5'</td>
<td>3.68</td>
<td>262.68</td>
<td>1.49</td>
</tr>
<tr>
<td>T6'</td>
<td>3.83</td>
<td>183.87</td>
<td>0.66</td>
</tr>
<tr>
<td>T7'</td>
<td>44.34</td>
<td>73.55</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Table 6.33: Thermodynamic properties at all locations with turbine reheat.

<table>
<thead>
<tr>
<th>Location</th>
<th>Reference Number</th>
<th>SI Units</th>
<th>English Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Enthalpy (kJ/kg)</td>
<td>Entropy (kJ/kg-K)</td>
</tr>
<tr>
<td>T1</td>
<td>3382.26</td>
<td>6.62</td>
<td>1502.75</td>
</tr>
<tr>
<td>T2</td>
<td>3006.29</td>
<td>6.80</td>
<td>1077.20</td>
</tr>
<tr>
<td>T3</td>
<td>2912.92</td>
<td>6.88</td>
<td>960.65</td>
</tr>
<tr>
<td>T4</td>
<td>2803.80</td>
<td>6.98</td>
<td>822.19</td>
</tr>
<tr>
<td>R1</td>
<td>2803.80</td>
<td>6.98</td>
<td>0.824</td>
</tr>
<tr>
<td>R2</td>
<td>3260.20</td>
<td>7.80</td>
<td>1.04</td>
</tr>
<tr>
<td>T5'</td>
<td>2998.30</td>
<td>7.89</td>
<td>0.757</td>
</tr>
<tr>
<td>T6'</td>
<td>2845.40</td>
<td>7.96</td>
<td>0.585</td>
</tr>
<tr>
<td>T7'</td>
<td>2637.20</td>
<td>8.36</td>
<td>0.264</td>
</tr>
</tbody>
</table>

Figure 6.13: T-s diagram of steam through turbine with and without reheat.
The energy analysis for the turbine reheat scenario is tabulated in Table 6.34 along with turbine data using method II, repeated from Table 6.16. The reheat is compared to the turbine analysis using method II because both models depend on energy balances. Even though method I is more accurate, method II will be more comparable to the reheat analysis. The introduction of turbine reheat increases the heat loss, but it more significantly increases the production of electricity. The isentropic efficiency drops with reheat because the extra process increases the entropy production. The required extra heat energy requires an extra 1.52 kg/s of culm.

Table 6.34: Comparison of baseline turbine energy performance to performance with reheat.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value for current plant (MW)</th>
<th>Value with reheat (MW)</th>
<th>Equation used</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{L,TII}$</td>
<td>-0.96</td>
<td>-1.06</td>
<td>(4.51)</td>
</tr>
<tr>
<td>$W_{TII}$</td>
<td>68.75</td>
<td>76.32</td>
<td>(4.56)</td>
</tr>
<tr>
<td>$W_{gen,TII}$</td>
<td>65.311</td>
<td>72.50</td>
<td>(4.57)</td>
</tr>
<tr>
<td>$W_{s,T}$</td>
<td>86.508</td>
<td>97.92</td>
<td>(4.60)</td>
</tr>
<tr>
<td>$\eta_{s,T}$</td>
<td>0.792</td>
<td>0.779</td>
<td>(4.59)</td>
</tr>
<tr>
<td>$Q_R$</td>
<td>--</td>
<td>23.67</td>
<td>(4.228)</td>
</tr>
</tbody>
</table>

The reheat exergy analysis is compared to the exergy analysis for the turbine using method II in Table 6.35. Although the isentropic efficiency of the turbine goes down with the introduction of reheat, the exergetic efficiency goes up since more electricity is produced and electricity is a very high quality form of energy. There is also more exergy destruction with the reheat because, as mentioned before, the extra process creates more entropy.

Table 6.35: Exergy analysis for turbine with and without reheat.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value for current plant (MW)</th>
<th>Value with reheat (MW)</th>
<th>Equation used</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{E}_{e,TII}$</td>
<td>-0.05</td>
<td>-0.06</td>
<td>(4.71)</td>
</tr>
<tr>
<td>$\dot{E}_{d,TII}$</td>
<td>14.53</td>
<td>16.50</td>
<td>(4.75)</td>
</tr>
<tr>
<td>$\varepsilon_{TII}$</td>
<td>0.584</td>
<td>0.658</td>
<td>(4.76)</td>
</tr>
</tbody>
</table>

Finally, some of the total plant energy performance parameters may be used for comparison, given in Table 6.36. It may also be found that the total useful heat transfer with reheat is 235.71 MW using Equation (4.150). The plant exergy performance comparisons are made in Table 6.37, which shows the turbine exergy efficiency increases with turbine reheat.

Table 6.36: Plant energy parameters with and without reheat.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value for current plant (MW)</th>
<th>Value with reheat (MW)</th>
<th>Equation used</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{P,in}$</td>
<td>275.44</td>
<td>299.11</td>
<td>(4.198)</td>
</tr>
<tr>
<td>$W_{P,export}$</td>
<td>57.73</td>
<td>64.92</td>
<td>(4.200)</td>
</tr>
<tr>
<td>$EU_F$</td>
<td>0.220</td>
<td>0.227</td>
<td>(4.201)</td>
</tr>
<tr>
<td>$\eta_{th}$</td>
<td>0.209</td>
<td>0.217</td>
<td>(4.202)</td>
</tr>
</tbody>
</table>
Table 6.37: Plant exergy parameters with and without reheat.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value using method TII (MW)</th>
<th>Value with reheat (MW)</th>
<th>Equation used</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{E}_{o}\text{ut,H,P}$</td>
<td>58.82</td>
<td>66.01</td>
<td>(4.205)</td>
</tr>
<tr>
<td>$\epsilon_p$</td>
<td>0.198</td>
<td>0.211</td>
<td>(4.207)</td>
</tr>
</tbody>
</table>

Overall, the reheat scenario will reduce the wear on the turbine blades while producing a greater amount of usable energy. The total plant efficiencies, both in terms of energy and exergy, increase a small amount with reheat. The turbine isentropic efficiency decreases slightly, but the turbine exergy efficiency increases.

The down side of the turbine reheat is the high initial costs to purchase and install the turbine with reheat. If the plant is to consider this option they would likely wait until a new turbine is required to buy the reheat turbine. The reheat scenario also consumes more fuel, which corresponds to an increase in emissions. Depending on changes to regulatory policy and the economy the plant may or may not want to consider the turbine option.

### 6.5.3. Effects of Plant Operational Load

The effects of the operational load can be quantified to a point by generating plots of certain performance parameters vs. the plant load as indicated by the generator output. The load will be plotted against the plant exergetic and thermal efficiency (Figure 6.14) and the total plant exergy destruction (Figure 6.15). From the plots it may be observed that the plant operations used in this data are primarily in the high load region by the density of the data points in the 80-90 MW generator export range. There is also a high density of data points in the 55-60 MW range.

Figure 6.14 shows that the plant efficiencies increase when the plant operates at a higher load, however, Figure 6.15 also shows that the exergy destruction through the plant increases in the upper range of generator export. The operational load plots suggest that it makes sense for the plant to operate at a higher operational load whenever possible since the plant operates more efficiently overall. The outlier data could be from rare combinations of plant operational conditions or from sensor errors that did not surface during normal analysis.

When the actual data for the different operational loads are compared in Table 6.38, it is found that energy and exergy efficiency values for plant components and the overall plant increase as the operational load increases except for the exergy loss and exergy destruction values, which are highest during the transient phase. The increased exergy destruction implies that more irreversibilities occur in the system when the plant is not in steady state. From low load to high load the overall plant exergetic efficiency increases from 23.2% to 25.1%. It should be stressed that the model is not dynamic, and so the transitional load is a steady state analysis using transitional data.
Figure 6.14: Plot of generated export and plant efficiencies.

Figure 6.15: Total plant exergy destruction as a function of the generator export.
Table 6.38: Average performance parameters at low, transitional, and high plant operational loads.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low load</th>
<th>Transitional load</th>
<th>High load</th>
<th>Equation used</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_{B,avg}$</td>
<td>0.775</td>
<td>0.755</td>
<td>0.790</td>
<td>(4.171)</td>
</tr>
<tr>
<td>$\epsilon_{avg,B}$</td>
<td>-0.54</td>
<td>-0.53</td>
<td>-0.55</td>
<td>(4.196)</td>
</tr>
<tr>
<td>$\eta_{s,T}$</td>
<td>0.77</td>
<td>0.80</td>
<td>0.80</td>
<td>(4.59)</td>
</tr>
<tr>
<td>$\dot{Q}_{P,in}$</td>
<td>210.25</td>
<td>288.51</td>
<td>300.89</td>
<td>(4.198)</td>
</tr>
<tr>
<td>$\dot{Q}_{P,J}$</td>
<td>-98.09</td>
<td>-149.80</td>
<td>-152.12</td>
<td>(4.197)</td>
</tr>
<tr>
<td>$W_{P,export}$</td>
<td>50.96</td>
<td>70.57</td>
<td>79.48</td>
<td>Operational data</td>
</tr>
<tr>
<td>$EUF_{P}$</td>
<td>0.257</td>
<td>0.260</td>
<td>0.275</td>
<td>(4.201)</td>
</tr>
<tr>
<td>$\eta_{th}$</td>
<td>0.245</td>
<td>0.248</td>
<td>0.265</td>
<td>(4.202)</td>
</tr>
<tr>
<td>$E_{in,total,P}$</td>
<td>229.63</td>
<td>314.65</td>
<td>328.32</td>
<td>(4.208)</td>
</tr>
<tr>
<td>$E_{out,u,P}$</td>
<td>51.82</td>
<td>71.84</td>
<td>80.63</td>
<td>(4.206)</td>
</tr>
<tr>
<td>$E_{l,P}$</td>
<td>-4.47</td>
<td>-10.01</td>
<td>-9.20</td>
<td>(4.203)</td>
</tr>
<tr>
<td>$E_{d,P}$</td>
<td>111.44</td>
<td>148.70</td>
<td>147.02</td>
<td>(4.204)</td>
</tr>
<tr>
<td>$\epsilon_{p}$</td>
<td>0.232</td>
<td>0.235</td>
<td>0.251</td>
<td>(4.207)</td>
</tr>
</tbody>
</table>

6.5.4. Effects of Reference Condition Selection

The results given so far have used realistic reference conditions, however, in order to compare results with many similar analyses in literature, standard conditions are also used. Since exergy analyses depend largely on reference conditions, it’s important to examine how the reference condition affects the results. Table 6.39 gives some of the plant performance parameters. Note that the energy parameters are equal in both cases, but the exergy parameters are different. The largest differences are seen between the total plant exergy loss, the exergy destruction, and the total exergy out. The baseline exergy loss is -8.09 MW, while the same parameter with standard conditions is -1.54 MW. The exergy destruction value is 137.87 MW for the baseline and 143.13 MW for the standard conditions. The total exergy out of the plant for the baseline model is 202.11 MW and with standard conditions is 94.49 MW.

Table 6.39: Comparison of baseline with analysis using standard conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
<th>Baseline with Standard Conditions</th>
<th>Equation used</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{Q}_{P,J}$</td>
<td>-137.74</td>
<td>-137.74</td>
<td>(4.197)</td>
</tr>
<tr>
<td>$\dot{Q}_{P,in}$</td>
<td>275.44</td>
<td>275.44</td>
<td>(4.198)</td>
</tr>
<tr>
<td>$W_{P,export}$</td>
<td>70.69</td>
<td>70.69</td>
<td>(4.200)</td>
</tr>
<tr>
<td>$W_{P,internal}$</td>
<td>7.58</td>
<td>7.58</td>
<td>(4.199)</td>
</tr>
<tr>
<td>$EUF_{P}$</td>
<td>0.268</td>
<td>0.268</td>
<td>(4.201)</td>
</tr>
<tr>
<td>$\eta_{th}$</td>
<td>0.257</td>
<td>0.257</td>
<td>(4.202)</td>
</tr>
<tr>
<td>$E_{l,P}$</td>
<td>-8.09</td>
<td>-1.54</td>
<td>(4.203)</td>
</tr>
<tr>
<td>$E_{d,P}$</td>
<td>137.87</td>
<td>143.13</td>
<td>(4.204)</td>
</tr>
<tr>
<td>$E_{out,u,P}$</td>
<td>70.69</td>
<td>70.69</td>
<td>(4.205)</td>
</tr>
<tr>
<td>$E_{out,total,P}$</td>
<td>58.82</td>
<td>58.72</td>
<td>(4.206)</td>
</tr>
<tr>
<td>$E_{in,total,P}$</td>
<td>300.58</td>
<td>300.87</td>
<td>(4.208)</td>
</tr>
<tr>
<td>$E_{out,total,P}$</td>
<td>102.11</td>
<td>94.49</td>
<td>(4.209)</td>
</tr>
<tr>
<td>$\epsilon_{p}$</td>
<td>0.198</td>
<td>0.198</td>
<td>(4.207)</td>
</tr>
</tbody>
</table>
6.5.5. Literature

The boilers of this plant are also compared to a number of other boiler technologies. The boiler comparison is important since the most unique aspect of this plant is the boiler and fuel combination. Due to the importance of the boiler performance in the overall plant performance, the boiler comparison should be indicative of the comparative performance of the power plant overall.

Energy and exergy analyses are performed on a number of non-CFB steam boilers [52] using standard reference conditions. It is found that the boiler energy efficiencies range from 72.46% for a boiler using nanofluids [52], to 84% for a boiler using sugarcane bagasse [64], to 93.76% for a boiler using heavy fuel oil [65]. Results found through this work, 78.1%, are well within this range. Boiler exergy efficiencies have been given as 24.89% [52], 27.6% [64], and 43.8% [65]. The exergy efficiency for the boilers in this analysis, 53.6%, is higher than these analyses. These results suggest that CFB boilers using culm create less exergy destruction than a variety of other common steam boilers.

6.6. Recommendations for Future Work

A system as complex as a large scale power plant has hundreds of possible areas for further research and modeling. A number of those possibilities are selected and discussed here as promising areas of discussion.

6.6.1. Boiler Chemical Reaction Analysis

The least understood aspect of this work is the boiler combustion process. In reality, boiler reactions and reaction rates depend on the temperature, particle size, residence time, distribution, and location within the boiler. A huge number of variables are open to examination with the boiler reaction analysis.

A clear model of the boiler reactions would give stronger predictions of how certain improvements impact the emissions of the plant. The current model predicts emissions based on the amount of fuel use, but in reality there are many more factors at play. A detailed chemical analysis of the boiler could help the plant engineers choose optimal temperatures and flow rates for minimizing emissions and/or improving thermodynamic performance. Also, if the plant had a reliable way to measure the SO2 emissions leaving each plant they could reduce limestone use by only increasing limestone in the boiler that has high SO2 levels. Currently limestone addition is increased in both boilers if high SO2 levels are detected at the stack.

Another area to explore with the chemical reactions is the effects of reduced carbon residue in the ash. Currently the residue carbon in around 9% of the ash; a decrease in the residue carbon would increase the heat released during combustion, but it would also increase the about of CO2 released. An optimal residue carbon percentage could be determined in terms of boiler efficiency, emissions reduction, or economic benefit. It may also be found that the percent carbon residue is insignificant.
6.6.2. Culm Preheat or Drying Using Process Steam

The generated steam is currently used for process heating of the plant offices and machine shop and the nearby prison facility. There may, however, be other uses for the steam. During the cold winter months, the plant often has a problem with the moist culm freezing and clumping, causing problems with the culm feed system. At times, the clumping is bad enough that the entrance into the culm silo is effectively blocked and plant personnel must manually unclog the silo opening. A number of issues arise from this: first, plant personnel have to spend time monitoring and attending to the culm feed. Second, if the silo opening is not unclogged before the silo empties, the power station must use fuel oil as an alternative, which is more expensive than culm. In order to reduce this problem, it is possible that some of the cogeneration steam could be redirected to help pre-heat or dry the culm before it enters the plant.

The process steam could flow around the culm conveyor belt in order to prevent freezing or the fuel could be dried. The heating process could be applied at a low level as or before the culm enters the plant, or at a more intensive level right before the culm is deposited in the silo. It has already been shown from this analysis that increasing the process steam use improves the overall plant efficiencies. More heat would be required to dry the fuel, but the energy and exergy of the fuel would also increase more than with a low level of heating.

The change in the energy and exergy values of the fuel could greatly affect the analysis of the boiler and the plant as a whole because of the decrease in moisture in the fuel. The plant currently does not use the maximum available process steam because electricity is more valuable, however, the decrease in problems and man-hours which the culm pre-heating may cause could be worth the decrease in electricity production.

6.6.3. Thermoeconomic Analysis

Currently there is no thermoeconomic analysis of the plant, largely due to the lack of economic data for the streams into and out of the plant. A thermoeconomic analysis could be coupled with the various analyses for the current plant configuration and the improvement scenarios to help understand the economic feasibility of the improvement suggestions. The thermoeconomics of the cogeneration power plant could also be compared to thermoeconomic analyses to understand if and how the costs of electricity production differ between the different technologies.

6.6.4. Cooling Tower Analysis

Another possible area for future work is the cooling tower analysis. As discussed in the description of the plant, the cooling tower utilizes four fans: three fixed speed and one variable speed. The variable speed fan is a much more efficient method of moving air through the towers, however, the initial cost of the equipment is higher.

The analysis of the benefits of replacing one to all of the fixed speed fans with variable speed fans could be performed along with a time-to-payback analysis.
6.7. **General Summary and Discussion**

A thermodynamic model of a cogeneration power plant is generated. The model incorporates energy and exergy analyses of the power plant’s boilers, turbine, feedwater heater system, and condenser. An analysis of the plant on a whole is also produced. The plant is found to have a thermal efficiency of 25% and an exergetic efficiency of 24%. Actual operational data is used for model validation.

Three improvement scenarios are explored: increased use of process steam, turbine reheat, and optimal operational load. As far as possible, the three improvement scenarios are quantified using the same parameters as used on the current plant. It is found that the turbine reheat and the increased process steam use both increase the turbine efficiency and the overall plant efficiencies.

The environmental aspects of the plant, mainly the use of culm and the plant’s land reclamation project, are examined and compared to the environmental aspects of a traditional coal fired plant and a wind farm. It is found that the environmental impact of the cogeneration power plant can be considered less than that of a coal fired plant and more than that of a wind farm. The question of how to quantify the land reclamation and “reverse land use” (meaning the land starts in a less natural state and the move towards more natural is expedited by the power plant processes) is brought up since the land use is one of the more unique aspects of the plant.

Although the cogeneration system discussed is not environmentally benign, it has many improvements over a coal fired plant, namely that it cleans up a pollutant instead of mining for fresh coal. A potentially interesting way to examine and think of this particular plant is that it is a cleanup facility (of the culm scared areas) with the extra benefits of electricity and steam production. When considering the environmental and social benefits of the cogeneration power plant it is important to keep in mind that if the electricity generated at the plant were not produced at the cogeneration plant, it would be produced elsewhere. Comparatively, the cogeneration power station has many benefits to other power sources, especially coal fired plants.
Appendix A: Tabulated Thermodynamic and Chemical Properties

Appendix A contains the thermodynamic data used through this work that is not calculated through the Matlab™ code. The code calculates the properties for water, steam, and air. Table A.1 lists the data required for the analysis on a molar basis. Table A.2 lists data on a mass basis.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Molar Mass (kg/kmol)</th>
<th>$\overline{H}^\circ_f$ (kJ/kmol)</th>
<th>$\overline{s}^\circ$ (kJ/kmol-K)</th>
<th>$\overline{e}_p$ (kJ/kmol-K)</th>
<th>$\overline{c}_H$ (kJ/kmol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>18.02</td>
<td>--</td>
<td>69.948</td>
<td>--</td>
<td>2.771615</td>
</tr>
<tr>
<td>C</td>
<td>12.01</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>2844.285</td>
</tr>
<tr>
<td>H</td>
<td>1.008</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>N</td>
<td>14.01</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>S</td>
<td>32.0655</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>O</td>
<td>16</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>100.0875</td>
<td>-120.4897</td>
<td>--</td>
<td>0.007926</td>
<td>0.099826</td>
</tr>
<tr>
<td>CaO</td>
<td>56.077</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>O₂</td>
<td>32</td>
<td>--</td>
<td>205.146</td>
<td>--</td>
<td>3.876953</td>
</tr>
<tr>
<td>N₂</td>
<td>28.01</td>
<td>--</td>
<td>191.61</td>
<td>--</td>
<td>0.917712</td>
</tr>
<tr>
<td>CO₂</td>
<td>44.01</td>
<td>-203.1721</td>
<td>213.794</td>
<td>0.018023</td>
<td>10.25877</td>
</tr>
<tr>
<td>H₂O</td>
<td>18.02</td>
<td>--</td>
<td>188.824</td>
<td>--</td>
<td>29.25594</td>
</tr>
<tr>
<td>S O₂</td>
<td>64.06</td>
<td>-72.1547</td>
<td>284.094</td>
<td>0.009718</td>
<td>76.37041</td>
</tr>
<tr>
<td>CaSO₄</td>
<td>136.1416</td>
<td>-77.2987</td>
<td>--</td>
<td>0.005376</td>
<td>--</td>
</tr>
<tr>
<td>NO</td>
<td>30.0061</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>98.73762</td>
</tr>
</tbody>
</table>

-- indicates data not necessary for analysis
Table A.2: Tabulated thermodynamic and chemical properties on a mass basis.

<table>
<thead>
<tr>
<th>Substance</th>
<th>$h_f^0$ (kJ/kg)</th>
<th>$\tilde{s}^0$ (kJ/kg-K)</th>
<th>$\tilde{c}_p$ (kJ/kg-K)</th>
<th>$\tilde{e}^{CH}$ (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>--</td>
<td>1260.463</td>
<td>--</td>
<td>49.94451</td>
</tr>
<tr>
<td>C</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>34159.87</td>
</tr>
<tr>
<td>H</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>N</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>S</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>O</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>-12059.5</td>
<td>--</td>
<td>0.79331</td>
<td>9.991308</td>
</tr>
<tr>
<td>CaO</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>O₂</td>
<td>--</td>
<td>6564.672</td>
<td>--</td>
<td>124.0625</td>
</tr>
<tr>
<td>N₂</td>
<td>--</td>
<td>5366.996</td>
<td>--</td>
<td>25.70511</td>
</tr>
<tr>
<td>C O₂</td>
<td>-8941.6</td>
<td>9409.074</td>
<td>0.7932</td>
<td>451.4883</td>
</tr>
<tr>
<td>H₂O</td>
<td>--</td>
<td>3402.608</td>
<td>--</td>
<td>527.192</td>
</tr>
<tr>
<td>S O₂</td>
<td>-4622.23</td>
<td>18199.06</td>
<td>0.62251</td>
<td>4892.288</td>
</tr>
<tr>
<td>CaSO₄</td>
<td>-10523.6</td>
<td>--</td>
<td>0.731936</td>
<td>--</td>
</tr>
<tr>
<td>NO</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>2962.731</td>
</tr>
</tbody>
</table>

-- indicates data not necessary for analysis
Appendix B:  Original Operational Data

Operational data for boiler 1 are given in Table B.1. The operational data for boiler 2 are given in Table B.2. Units that deviate from the listed units in the table header are noted. Refer to Figure 4.39 for location reference numbers. The original operational data for the turbine is given in Table B.3. Refer to Figure 4.19 for location reference numbers. The original operational data for the feedwater heater system is given in Table B.4. Refer to Figure 4.5 for location reference numbers. The original operational data for the condenser system is given in Table B.5. Refer to Figure 4.21 for location reference numbers.

Table B.1: Original operational data for boiler 1.

<table>
<thead>
<tr>
<th>Location Reference Number</th>
<th>SI Units</th>
<th>English Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flow Rate (kg/s)</td>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>B1</td>
<td>43.32</td>
<td>202.14</td>
</tr>
<tr>
<td>B2</td>
<td>43.50</td>
<td>495.63</td>
</tr>
<tr>
<td>B3</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>B4</td>
<td>4.12</td>
<td>--</td>
</tr>
<tr>
<td>B5</td>
<td>4.66</td>
<td>--</td>
</tr>
<tr>
<td>B6</td>
<td>0.04</td>
<td>--</td>
</tr>
<tr>
<td>B7</td>
<td>0.03</td>
<td>--</td>
</tr>
<tr>
<td>B8</td>
<td>--</td>
<td>433.73</td>
</tr>
<tr>
<td>B9</td>
<td>--</td>
<td>167.95</td>
</tr>
<tr>
<td>B10</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>B11</td>
<td>19.43</td>
<td>40.44</td>
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<tr>
<td>B12</td>
<td>17.74</td>
<td>--</td>
</tr>
<tr>
<td>B13</td>
<td>1.68</td>
<td>--</td>
</tr>
<tr>
<td>B14</td>
<td>1.70</td>
<td>--</td>
</tr>
<tr>
<td>B15</td>
<td>1.76</td>
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</tr>
<tr>
<td>B16</td>
<td>3.39</td>
<td>42.76</td>
</tr>
<tr>
<td>B17</td>
<td>7.35</td>
<td>--</td>
</tr>
</tbody>
</table>

-- indicates operational data not available

*pounds per hour
Table B.2: Original operational data for boiler 2.

<table>
<thead>
<tr>
<th>Location Reference Number</th>
<th>SI Units</th>
<th>English Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flow Rate (kg/s)</td>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>B1</td>
<td>41.64</td>
<td>202.15</td>
</tr>
<tr>
<td>B2</td>
<td>41.47</td>
<td>504.85</td>
</tr>
<tr>
<td>B3</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>B4</td>
<td>4.21</td>
<td>--</td>
</tr>
<tr>
<td>B5</td>
<td>4.66</td>
<td>--</td>
</tr>
<tr>
<td>B6</td>
<td>0.03</td>
<td>--</td>
</tr>
<tr>
<td>B7</td>
<td>0.03</td>
<td>--</td>
</tr>
<tr>
<td>B8</td>
<td>--</td>
<td>437.75</td>
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<td>B9</td>
<td>--</td>
<td>162.07</td>
</tr>
<tr>
<td>B10</td>
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<td>--</td>
</tr>
<tr>
<td>B11</td>
<td>19.24</td>
<td>42.15</td>
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<tr>
<td>B12</td>
<td>18.10</td>
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<td>1.70</td>
<td>--</td>
</tr>
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</tr>
<tr>
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</tr>
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<td>3.77</td>
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</tr>
<tr>
<td>B17</td>
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</tr>
</tbody>
</table>

-- indicates operational data not available

*pounds per hour

Table B.3: Original operational data for turbine.

<table>
<thead>
<tr>
<th>Location Reference Number</th>
<th>SI Units</th>
<th>English Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flow Rate (kg/s)</td>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>T1</td>
<td>--</td>
<td>501.19</td>
</tr>
<tr>
<td>T2</td>
<td>--</td>
<td>289.18</td>
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<tr>
<td>T3</td>
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<td>236.23</td>
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<td>121.80</td>
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<tr>
<td>T6</td>
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<td>--</td>
</tr>
<tr>
<td>T7</td>
<td>--</td>
<td>43.55</td>
</tr>
<tr>
<td>T25</td>
<td>1.00</td>
<td>--</td>
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</table>

Power Exports
Generator 78.27
Plant 70.69

-- indicates operational data not available
Table B.4: Original operational data for feedwater heaters.

<table>
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<tr>
<th>Location Reference Number</th>
<th>SI Units</th>
<th>English Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flow Rate (kg/s)</td>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>F1</td>
<td>--</td>
<td>40.13</td>
</tr>
<tr>
<td>F2</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>F3</td>
<td>--</td>
<td>117.52</td>
</tr>
<tr>
<td>F4</td>
<td>--</td>
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<td>--</td>
<td>176.04</td>
</tr>
<tr>
<td>F8</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>F9</td>
<td>--</td>
<td>47.39</td>
</tr>
<tr>
<td>F10</td>
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<td>--</td>
</tr>
<tr>
<td>F11</td>
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<td>89.37</td>
</tr>
<tr>
<td>F12</td>
<td>--</td>
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<td>--</td>
<td>165.77</td>
</tr>
<tr>
<td>F15</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>F16</td>
<td>--</td>
<td>185.06</td>
</tr>
</tbody>
</table>

-- indicates operational data not available

*gallons per minute

Table B.5: Original operational data for condenser.

<table>
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<th>SI Units</th>
<th>English Units</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>Flow Rate (kg/s)</td>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>C1</td>
<td>--</td>
<td>25.20</td>
</tr>
<tr>
<td>C2</td>
<td>--</td>
<td>34.94</td>
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<td>--</td>
<td>--</td>
</tr>
<tr>
<td>C6</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>C7</td>
<td>--</td>
<td>39.67</td>
</tr>
</tbody>
</table>

-- indicates operational data not available

*gallons per minute
Appendix C: Matlab™ code

There are multiple parts to the Matlab™ code used in this analysis. The program names and relationship to one another is shown in Figure C.1 where the arrows point from a sub-program to the program that calls on it. Each of the nine programs will be given in this appendix.

![Figure C.1: Map of programs used in thermodynamic analysis.]

The program “Total_plant” defines the reference environment and model choice, imports the operational data, calls on the programs “FWH_Turbine_Condenser_properties”, “Culm_exergy_calculations”, “Boiler1_properties”, and “Boiler2_properties”, each of which determine all the required flow rate, temperature, pressure, and thermodynamic properties of the plant subsystems. The code “fg” is called on by both sets of boiler code to determine the thermodynamic properties of the flue gas as outlined in Section 4.5.1.4. The “mass1” and “mass2” codes determine the composition of the flue gas and the flow rates of each component of the gas using the extent of reaction method described in Section 4.5.1.3. The code for the “Boiler1_properties” and “Boiler2_properties” are identical besides the changes in variables to represent the boiler number. The same for “mass1” and “mass2”. The final program, “Compare_models” is used to calculate the thermodynamic parameters discussed in Chapter 4.

The code will be given in the following order: Total_plant, FWH_Turbine_Condenser_properties, Culm_exergy_calculations, Boiler1_properties, mass1, fg, Boiler2_properties, mass2, and Compare_models.
% Code to calculate all necessary temperature, pressure, flow rate, 
% enthalpy, entropy, and exergy values for plant system
% Notes on imported data structures:
The data is split between four excel files:
- FWH.xls holds data for the feedwater heaters
- Tu.xls holds data for the turbine
- C.xls holds data for the condenser
- B1.xls holds data for boiler 1
- B2.xls holds data for boiler 2
  * Each row represents a time at which a measurement was taken.
  * In the original excel files the time stamps are given.
  * Each system has a certain number of locations, X, of interest
    where data is taken (ex: the turbine has an inlet, 5 extraction
    points, and an exhaust, so X = 7)
  * Each excel file has a column for the flow rate at each location
    and then a column for the temperature at each location,
    and then a column for the pressure at each location. This means
    the first 3X columns of each excel file hold the location property
    data. Columns after that present to hold other relevant data.
**************************************************************************
% Clear previous work
clear all
%**************************************************************************
% Declare global variables
global Tb_B Tb_T Mn_B ref_env Season test tu c
%**************************************************************************
% Declare environment and model selection
Tb_B = 305;      % Boiler room temp in K
Tb_T = 300.15;   % Turbine room temp in K
Season = 4;      % Season (spring =1, summer = 2, fall = 3, winter = 4)
ref_env = 1;     % Model selection for reference environment
Mn_B = 2;        % Model selection for boiler
**************************************************************************
% Import Operational Data
f = xlsread('C:\Documents and Settings\wed8908\My Documents\MATLAB\FWH.xls');  % FWH data
tu = xlsread('C:\Documents and Settings\wed8908\My Documents\MATLAB\Tu.xls');  % Turbine data
c = xlsread('C:\Documents and Settings\wed8908\My Documents\MATLAB\Cond.xls'); % Condenser data
b1 = xlsread('C:\Documents and Settings\wed8908\My Documents\MATLAB\B1.xls');  % Boiler 1 data
b2 = xlsread('C:\Documents and Settings\wed8908\My Documents\MATLAB\B2.xls');  % Boiler 2 data
[row,col] = size(f); % Get row and column size for data
To = xlsread('C:\Documents and Settings\wed8908\My Documents\MATLAB\To.xls');  % Environmental temperatures
% Import Culm Ultimate and Proximate Analyses
UA_d = xlsread('C:\Documents and Settings\wed8908\My Documents\MATLAB\UA_d_avg.xls'); % Dry basis
UA_r = xlsread('C:\Documents and Settings\wed8908\My Documents\MATLAB\UA_r_avg.xls'); % As-received basis
res = 0.09*mean(UA_r(:,2))/100; % Carbon residue

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% Import Chemical Properties
    prop = xlsread('C:\Documents and Settings\wed8908\My Documents\MATLAB\properties.xls');

% Unpack Chemical Properties from imported data
    M = prop(1,:);     % Molar mass (kg/kmol)
    e_ch = prop(2,:);  % Standard Chemical Exergy (from Model II) (kJ/kg)
    hf_ch = prop(3,:); % Standard enthalpy of formation (kJ/kg)
    cp = prop(4,:);    % Specific heat capacity (kJ/kg-K)

%**************************************************************************
% Reference environment conditions
    if ref_env == 2
        Po = 0.961; % (bar) chosen by frackville altitude
        To(1:row,1) = 273;
    else
        Po = 1.013; % (bar) standard pressure
        To(1:row,1) = 298; % (K) standard temperature
    end

%**************************************************************************
% Air properties at reference conditions
    ha = zeros(row,1);
    sa = ha;
    ho = ha;
    so = ha;
    ho_A = ha;

    for i = 1:row
        IdealAir(To(i),'T','h','si'); % Enthalpy of reference air
        ha(i) = test;
        IdealAir(To(i),'T','so','si'); % Entropy of reference air
        sa(i) = test;
    end

% Water properties at reference conditions
    if To(i)<273
        ho(i) = 0; % if reference water is frozen, h(To) = 0
        so(i) = 0; % if reference water is frozen, h(To) = 0
    elseif To(i) == 273
        ho(i) = 0; % if reference water is frozen, h(To) = 0
        so(i) = 0; % if reference water is frozen, h(To) = 0
    else
        ho(i) = XSteam('h_pT',Po,(To(i)-273)); % Enthalpy of reference water
        so(i) = XSteam('s_pT',Po,(To(i)-273)); % Entropy of reference water
    end

% Ash enthalpy at reference conditions (kJ/kg)
    ho_A(i) = ( (7.735829*10^-5)*(To(i)*9/5-459.67)^2 + ... 
             0.17020036*(To(i)*9/5-459.67) - 13.36106)/0.42992;

    if ho_A(i) < 0
        ho_A(i) = 0;
    end
    clc

%**************************************************************************
% Run programs to find temperatures, pressures, flow rates, enthalpy, and
% entropy values at all locations

FWH_Turbine_Condenser_properties_change_To

CuIm_exergy_calculations_change_To

Boiler1_properties_change_To

Boiler2_properties_change_To

%**************************************************************************
% Convert data and properties to english units
% Temperature (deg C to deg F)
F_eng(:,17:32) = (9/5)*F(:,17:32)+32;       % FWH
Tu_eng(:,8:14) = (9/5)*Tu(:,8:14)+32;       % Turbine
C_eng(:,8:14) = (9/5)*C(:,8:14)+32;         % Condenser
B1_eng(:,18:34) = (9/5)*B1(:,18:34)+32;     % Boiler 1
B2_eng(:,18:34) = (9/5)*B2(:,18:34)+32;     % Boiler 2

% Convert pressure (bar to psi)
F_eng(:,33:48) = F(:,33:48)*(1/.068948);    % FWH
Tu_eng(:,15:21) = Tu(:,15:21)*(1/.068948);  % Turbine
C_eng(:,15:21) = C(:,15:21)*(1/.068948);    % Condenser
B1_eng(:,35:51) = B1(:,35:51)*(1/.068948);  % Boiler 1
B2_eng(:,35:51) = B2(:,35:51)*(1/.068948);  % Boiler 2

% Convert flow rates (kg/s to KPPH)
F_eng(:,1:16) = F(:,1:16)/0.12599777778;    % FWH
Tu_eng(:,1:7) = Tu(:,1:7)/0.12599777778;    % Turbine
C_eng(:,1:7) = C(:,1:7)/0.12599777778;      % Condenser
B1_eng(:,1:17) = B1(:,1:17)/0.12599777778;  % Boiler 1
B2_eng(:,1:17) = B2(:,1:17)/0.12599777778;  % Boiler 2
B1_eng(:,6:7) = B1(:,6:7)/0.00012599777778; % Boiler 1 PPH to kg/s
B2_eng(:,6:7) = B2(:,6:7)/0.00012599777778; % Boiler 2 PPH to kg/s

% Convert kJ/kg to Btu/lb
hf_eng = hf*0.42992; ht_eng = ht*0.42992; hc_eng = hc*0.42992;
hb1_eng = hb1*0.42992; hb2_eng = hb2*0.42992;

ef_eng = ef*0.42992; et_eng = et*0.42992; ec_eng = ec*0.42992;
eb1_eng = eb1*0.42992; eb2_eng = eb2*0.42992;

% Convert kJ/kg-K to Btu/lb-R
sf_eng = sf*0.238846; st_eng = st*0.238846; sc_eng = sc*0.238846;
sb1_eng = sb1*0.238846; sb2_eng = sb2*0.238846;

%**************************************************************************
% Save results
save('C:\Documents and Settings\wed8908\My Documents\Results\all\defense_std')
% FWH, Turbine, Condenser, and Boiler analyses
% NOTE: Assumptions explained in Assumption sections in Chapter 3 of thesis
%       Unless otherwise noted, SI units used:
%       - enthalpy (kJ/kg)
%       - entropy (kJ/kg-K)
%       - exergy (kJ/kg)
%       - temperature (deg C)
%       - pressure (bar)
%       - flow rate (kg/s)
%**************************************************************************
% Declare global variables
global To ho so H
%**************************************************************************
% Declare known and decided variables
ngen = 0.95;                 % Generator efficiency
n_BFPT = 0.95;               % BFPT efficiency
H = 0.0139;                  % Heat loss factor for turbine
x_ex1_h = 0.97;              % Quality at extraction 1 at high loads
x_exh_h = 0.89;              % Quality at turbine exhaust at high loads
x_ex1_l = 0.99;              % Quality at extraction 1 at low loads
x_exh_l = 0.90;              % Quality at turbine exhaust at low loads
x_BFPT = 0.87;               % Quality at BFPT exhaust
% Factors that may be used to adjust properties from extraction points
% to FWH steam inlets
fact_ext1 = 1; % Extraction 1
fact_ext2 = 1; % Extraction 2
fact_ext3 = 1; % Extraction 3
fact_ext4 = 1; % Extraction 4
%**************************************************************************
% Establish size and number of locations for each data set
[row,col] = size(f); % Get row and column size for data
loc_f = 16; % Number of inlet/extraction/outlet points
loc_t = 7; % Number of inlet/extraction/outlet points
loc_c = 7; % Number of inlet/extraction/outlet points
%**************************************************************************
% Set up matrices for location properties
% FWH
F = zeros(row,50);     % Array for operational data with SI units
hf = zeros(row,loc_f); % Enthalpy array for FWH
sf = hf;               % Specific entropy array for FWH
ef = hf;               % Exergy array for FWH
% Condenser
C = zeros(row,21);     % Array for operational data with SI units
hc = zeros(row,loc_c); % Enthalpy array for condenser
sc = hc;               % Specific entropy array for condenser
ec = hc;               % Exergy array for condenser
% Turbine
Tu = zeros(row,25);    % Array for operational data with SI units
ht = zeros(row,loc_t); % Enthalpy array for turbine
st = ht;               % Specific entropy array for turbine
et = ht;               % Exergy array for turbine
hts = ht;              % Isentropic enthalpy array for turbine
%**************************************************************************
% Estimated temperatures in deg F. Calculations made before conversion to SI units since relationships taken from heat balance analysis using English units:

\[
f(:,18) = \frac{0.6629 \times f(:,17) + 1.1839 \times f(:,19)}{2}; \quad \% \text{Condensate into FWH 2}
\]

\[
tu(:,11) = tu(:,10) \times 0.76; \quad \% \text{Ext 3 temp based on } 76\% \text{ decrease from Ext 4}
\]

% Estimate condensate well temperature depending on season

\[
\text{if } \text{Season} == 2 \\
\quad c(:,11) = 70; \quad \% \text{Approximate temp of well water during summer}
\text{elseif } \text{Season} == 4 \\
\quad c(:,11) = 50; \quad \% \text{Approximate temp of well water during winter}
\text{else} \\
\quad c(:,11) = 60; \quad \% \text{Approximate temp of well water during spring/fall}
\text{end}
\]

% Convert data to SI units
% Convert temperatures (deg F to deg C)
\[
F(:,17:2\times loc_f) = \left(\frac{5}{9}\right)\left(f(:,(17):2\times loc_f)-32\right); \quad \% \text{FWH}
\]
\[
Tu(:,(loc_t+1):(2\times loc_t)) = \left(\frac{5}{9}\right)\left(tu(:,(loc_t+1):(2\times loc_t))-32\right); \quad \% \text{Turbine}
\]
\[
C(:,8:9) = \left(\frac{5}{9}\right)\left(c(:,8:9)-32\right); \quad \% \text{Condenser}
\]
\[
C(:,11) = \left(\frac{5}{9}\right)\left(c(:,11)-32\right); \quad \% \text{Condenser}
\]
\[
C(:,14) = \left(\frac{5}{9}\right)\left(c(:,14)-32\right); \quad \% \text{Condenser}
\]

% Convert pressure (psi to bar)
\[
F(:,39) = f(:,39) \times 0.068948; \quad \% \text{FWH}
\]
\[
Tu(:,15:21) = tu(:,15:21) \times 0.068948; \quad \% \text{Turbine}
\]

% Convert KPPH to kg/s
\[
F(:,49:50) = f(:,49:50) \times 0.12599777778; \quad \% \text{FWH}
\]
\[
Tu(:,23:25) = tu(:,23:25) \times 0.12599777778; \quad \% \text{Turbine}
\]

% Convert GPM to kg/s using density based on temp
\[
\text{for } i = 1:row \\
\quad F(i,1) = f(i,1) \times \left(3.7854 \times 10^{-3}\right)/60 \times \left(3.7854 \times 10^{-3}\right)/60; \quad \% \text{Condensate flow from condenser}
\quad C(i,4) = c(i,4) \times \left(3.7854 \times 10^{-3}\right)/60 \times \left(3.7854 \times 10^{-3}\right)/60; \quad \% \text{Condensate make up}
\text{end}
\]

% Power MW to kW
\[
Tu(:,22) = tu(:,22) \times 1000; \quad \% \text{Generator export}
\]

% Unknown saturated or mixture temperatures and pressures
\[
\text{for } i = 1:row \\
\quad Tu(i,21) = \text{XSteam('psat_T',Tu(i,14))}; \quad \% \text{Pressure at turbine exhaust}
\quad Tu(i,13) = \text{XSteam('Tsat_p',Tu(i,20))}; \quad \% \text{Temp at Ext. 1}
\quad C(i,21) = \text{XSteam('psat_T',C(i,14))}; \quad \% \text{Condenser drain pressure}
\text{end}
\]

% Copy values that exist in more than one operational data array
% Insert temperatures for steam into FWH matrix
\[
F(:,24) = Tu(:,13); \quad \% \text{Ext. 1 temp = FWH 1 inlet steam temp}
\]
\[
F(:,26) = Tu(:,12); \quad \% \text{Ext. 2 temp = FWH 2 inlet steam temp}
\]
\[
F(:,28) = Tu(:,11); \quad \% \text{Ext. 3 temp = DA inlet steam temp}
\]
\[
F(:,29) = Tu(:,10); \quad \% \text{Ext. 4 temp = FWH 4 inlet steam temp}
\]
\[
F(:,31) = Tu(:,9); \quad \% \text{Ext. 5 temp = FWH 5 inlet steam temp}
\]
% Insert pressure for steam into FWH matrix
F(:,40) = Tu(:,20); % Ext. 1 pressure = FWH 1 inlet steam pressure
F(:,42) = Tu(:,19); % Ext. 2 pressure = FWH 2 inlet steam pressure
F(:,44) = Tu(:,18); % Ext. 3 pressure = DA inlet steam pressure
F(:,45) = Tu(:,17); % Ext. 4 pressure = FWH 4 inlet steam pressure
F(:,47) = Tu(:,16); % Ext. 5 pressure = FWH 5 inlet steam pressure

% For condensate flow
F(:,33) = C(:,21)*108.334; % Pressure through FWH 1 and 2
F(:,34) = F(:,33); % Pressure through FWH 1 and 2
F(:,35) = F(:,34); % Pressure through FWH 1 and 2
F(:,38) = F(:,39); % Pressure through FWH 4 and 5
F(:,37) = F(:,38); % Pressure through FWH 4 and 5

% Insert pressure for condenser Matrix
C(:,17) = Tu(:,21); % Turbine exhaust
C(:,20) = Tu(:,21); % BFPT exhaust

% Insert temperatures for Cond Matrix
for i=1:row
    C(i,13) = XSteam('Tsat_p',C(i,20)); % BFPT exhaust
end
C(:,10) = Tu(:,14); % Turbine exhaust temperature
C(:,12) = F(:,25); % FWH 1 drain temp

%**************************************************************************
% Determine thermodynamic properties for turbine
%**************************************************************************
% Extraction enthalpy, entropy, and isentropic enthalpy values
for i=1:row
    % When both temperature and pressure are known:
    % Enthalpy values based on pressure and temp
    % Entropy values based on pressure and temp
    % Isentropic enthalpy values based on pressure and inlet entropy
    for j=1:5
        ht(i,j) = XSteam('h_pT',Tu(i,(14+j)),Tu(i,7+j));
        st(i,j) = XSteam('s_pT',Tu(i,(14+j)),Tu(i,7+j));
        hts(i,j) = XSteam('h_ps',Tu(i,(14+j)),st(i,1));
    end

% Vapor/liquid mixture for Ex 1 and exhaust
% Enthalpy values based on temp and vapor fraction
% Entropy values based on temp and vapor fraction
% Isentropic enthalpy values based on pressure and inlet entropy
for j=6:7
    if j == 6 % Ex 1
        if Tu(i,22)< 65000
            x = x_ex1_l; % Define quality of mixture for low load
        else
            x = x_ex1_h; % Define quality of mixture for high load
        end
        ht(i,j) = XSteam('h_px',Tu(i,14+j),x);
        st(i,j) = XSteam('sL_p',Tu(i,14+j))...
            + x*(XSteam('sV_p',Tu(i,14+j))- XSteam('sL_p',Tu(i,14+j)));
        hts(i,j) = XSteam('h_ps',Tu(i,14+j),st(i,1));
    end % Exhaust
    if Tu(i,22)< 65000
        x = x_exh_l; % Define quality of mixture for low load
    else
x = x_exh_h;  % Define quality of mixture for high load
end
ht(i,j) = XSteam('h_Tx',Tu(i,7+j),x);
st(i,j) = XSteam('sL_T',Tu(i,7+j)) + x*(XSteam('sV_T',Tu(i,7+j)) - XSteam('sL_T',Tu(i,7+j)));  
hts(i,j) = XSteam('h_ps',Tu(i,14+j),st(i,1));
end
end
end

for j = 1:loc_t
    et(:,j) = (ht(:,j) - ho(:,1)) - To(1,:)*(st(:,j) - so(:,1));  % Exergy flow
end

%**************************************************************************
% Determine thermodynamic properties for FWH
% Enthalpy and entropy values dependent on turbine properties
hf(:,8) = ht(:,6)*fact_ext1;  % FWH 1 steam in
hf(:,10) = ht(:,5)*fact_ext2;  % FWH 2 steam in
hf(:,12) = ht(:,4)*fact_ext3;  % DA steam in
hf(:,13) = ht(:,3)*fact_ext4;  % FWH 4 steam in
hf(:,15) = ht(:,2);  % FWH 5 steam in
sf(:,8) = st(:,6)*fact_ext1;  % FWH 1 steam in
sf(:,10) = st(:,5)*fact_ext2;  % FWH 2 steam in
sf(:,12) = st(:,4)*fact_ext3;  % DA steam in
sf(:,13) = st(:,3)*fact_ext4;  % FWH 4 steam in
sf(:,15) = st(:,2);  % FWH 5 steam in

% Calculate new enthalpy and entropy values
for i=1:row
    for j=1:loc_f
        % Saturated liquids- based on temperature
        if j==4 || j==9 || j==11 || j==14 || j==16
            sf(i,j) = XSteam('sL_T',F(i,loc_f+j));
            hf(i,j) = XSteam('hL_T',F(i,loc_f+j));
            F(i,j+32) = XSteam('p_hs',hf(i,j),sf(i,j));
        end
        % Compressed liquids- based on pressure and temperature
        if j==1 || j==2 || j==3 || j==5 || j==6 || j==7
            hf(i,j) = XSteam('h_pT',F(i,32+j),F(i,16+j));
            sf(i,j) = XSteam('s_pT',F(i,32+j),F(i,16+j));
        end
    end
end

for j = 1:loc_f
    ef(:,j) = (hf(:,j) - ho(:,1)) - To(1,:)*(sf(:,j) - so(:,1));  % Exergy flow
end

%**************************************************************************
% Determine thermodynamic properties for condenser
% Enthalpy and entropy values dependent on turbine and FWH properties
hc(:,3) = ht(:,7);  % Turbine exhaust
hc(:,5) = hf(:,9);  % FWH 1 drain
sc(:,3) = st(:,7);  % Turbine exhaust

%**************************************************************************
\[ \text{sc}(:,5) = \text{sf}(:,9); \] % FWH 1 drain

\[ \text{ec}(:,3) = (\text{hc}(:,3) - \text{ho}(:,1)) - \text{To}.*(\text{sc}(:,3) - \text{so}(:,1)); \] % Turbine exhaust

\[ \text{ec}(:,5) = (\text{hc}(:,5) - \text{ho}(:,1)) - \text{To}.*(\text{sc}(:,5) - \text{so}(:,1)); \] % FWH 1 drain

% Calculate new enthalpy and entropy values
for i=1:row
  for j = 1:loc_c
    % Saturated liquids- based on temperature
    if j==1 || j==2 || j==4 || j==7
      \[ \text{hc}(i,j) = \text{XSteam('hL_T',C(i,loc_c+j));} \]
      \[ \text{sc}(i,j) = \text{XSteam('sL_T',C(i,loc_c+j));} \]
    end
  end

  % Saturated mixture- based on temperature and vapor fraction
  \[ \text{hc}(i,6) = \text{XSteam('h_Tx',C(i,13),x_{BFPT});} \]
  \[ \text{sc}(i,6) = \text{XSteam('sL_T',C(i,13))+ x_{BFPT}* ...} \]
  \[ \text{XSteam('sV_T',C(i,13))-XSteam('sL_T',C(i,13))});} \]
end

for j = 1:loc_c
  \[ \text{ec}(:,j) = (\text{hc}(:,j) - \text{ho}(:,1)) - \text{To}.*(\text{sc}(:,j) - \text{so}(:,1)); \] % Exergy flow
end

%**************************************************************************
% Determine missing pressure data for condenser.
\[ \text{C}(:,18) = \text{C}(:,20); \] % Condensate makeup water
\[ \text{C}(:,19) = \text{C}(:,20); \] % FWH 1 drain
%**************************************************************************
% Determine FWH flow rate based on COM and energy balances
% Turbine inlet flow rate = sum of B1 and B2 steam flows
\[ \text{Tu}(:,1) = \text{Tu}(:,23) + \text{Tu}(:,24); \]

% Known FWH flows
\[ \text{F}(:,7) = \text{F}(:,49) + \text{F}(:,50); \] % COM total FW into boilers equals...
% flow rate of condensate leaving FWH 5
\[ \text{F}(:,2) = \text{F}(:,1); \] % COM
\[ \text{F}(:,3) = \text{F}(:,2); \] % COM

% FWH 5
\[ \text{F}(:,6) = \text{F}(:,7); \] % COM condensate
\[ \text{F}(:,15) = (\text{F}(:,7).* (\text{hf}(:,7)-\text{hf}(:,6)))/... \]
\[ \text{hf}(:,15)-\text{hf}(:,16)); \] % Energy balance
\[ \text{F}(:,16) = \text{F}(:,15); \] % COM steam/drain

% FWH 4
\[ \text{F}(:,5) = \text{F}(:,6); \] % COM condensate
\[ \text{F}(:,13) = (\text{F}(:,5).* (\text{hf}(:,6)-\text{hf}(:,5)))+... \]
\[ \text{F}(:,16).* (\text{hf}(:,14)-\text{hf}(:,16)))/... \]
\[ \text{hf}(:,13)-\text{hf}(:,14)); \] % Energy balance
\[ \text{F}(:,14) = \text{F}(:,13) + \text{F}(:,16); \] % COM steam/drains

% Now can determine that:
\[ \text{Tu}(:,2) = \text{F}(:,15) + \text{Tu}(:,25); \] % Ext. 5 = FWH 5 steam in + process
% DA
F(:,12) = Tu(:,1) + C(:,4) - Tu(:,2) - F(:,13) - F(:,3); % COM around turbine, FWH 1&2, condenser
F(:,4) = F(:,12) + F(:,3) + F(:,14); % COM drain

% FWH 2
F(:,11) = (F(:,2).*(hf(:,2)-hf(:,3)))./(hf(:,11)-hf(:,10)); % Energy balance
F(:,10) = F(:,11); % COM steam/drain

% FWH 1
F(:,8) = (F(:,1).*hf(:,2)-hf(:,1))+...% Energy balance
     (hf(:,8)-hf(:,9));
F(:,9) = F(:,8) + F(:,11); % COM steam/drain

%***********************************************************************
% Boiler feed pump turbine analysis
% W_BFP = F(:,4).*(hf(:,4)-hf(:,5)); % Energy balance- work into BFP
% W_BFPT = -W_BFP./n_BFPT; % Work produced by BFPT
% Q_BFPT = -H*W_BFPT; % BFPT heat loss
%***********************************************************************

% Determine remaining flow rates
% Flow rate through BFPT
C(:,6) = (Q_BFPT-W_BFPT)./(hc(:,6)-ht(:,3)); % Energy balance

% Turbine flows
Tu(:,3) = C(:,6) + F(:,13); % Extraction 4
Tu(:,4) = F(:,12); % Extraction 3
Tu(:,5) = F(:,10); % Extraction 2
Tu(:,6) = F(:,8); % Extraction 1
Tu(:,7) = Tu(:,1) - Tu(:,2) - Tu(:,3) - Tu(:,4)...% Exhaust
    - Tu(:,5) - Tu(:,6);

% Remaining condenser flows
C(:,5) = F(:,9); % FWH 1 drain to condenser
C(:,7) = F(:,1); % Flow out to condensate pump
C(:,3) = Tu(:,7); % Turbine exhaust into condenser
% Culm Exergy
% Based on paper by Bilgen, 2008
% **************************************************************************
% Assuming: Using DAF data (although exergy found includes moisture and ash)
% Theoretical air (O2 + 3.76N2)
% **************************************************************************
% Known Values: Values for C, H, O, N, S, M, and ash, HHV (from plant)
% **************************************************************************
% Import data:
[row_culm, col_culm] = size(UA_d);
% **************************************************************************
% Set up Arrays
s = zeros(1,17); % Absolute entropy
e = e_ch.*M; % Standard chemical exergy
UA_DAF = zeros(row_culm, col_culm); % DAF conversion of UA data
v_culm = zeros(row_culm, col_culm); % Coefficient for culm component
v = zeros(row_culm, 17); % Stoichiometric coefficients
e_DAF = zeros(row_culm, 1); % DAF exergy of culm
% Absolute entropy of components (kJ/kmol-K)
s(1,10) = 205.146; % O2
s(1,11) = 191.61; % N2
s(1,12) = 213.794; % CO2
s(1,13) = 188.824; % H2O (g)
s(1,14) = 284.094; % SO2
s(1,1) = 69.948; % H2O (l)
% Convert Dry basis to DAF basis (DAF = Dry/((100-DA)/100)
for i=1:8
UA_DAF(:,i) = UA_d(:,i)./((100-UA_d(:,2))./100);
end
% Find the culm components in kmol/kg
for i=1:8
v_culm(:,i) = UA_DAF(:,i)./(100*M(1,i));
end
% Determine stoichiometric Coefficients
v(:,17) = v_culm(:,3) + 0.25*v_culm(:,4)...
+ v_culm(:,6)- 0.5*v_culm(:,7); % Air in = v_O2 in
v(:,10) = v(:,17); % O2
v(:,11) = 0.5*v_culm(:,5); % N2
v(:,12) = v_culm(:,3); % CO2
v(:,14) = v_culm(:,6); % SO2
v(:,13) = 0.5*v_culm(:,4); % H2O (g)
% Calculate Higher Heating Values
% Using Eq. 10 from Bilgen in (kJ/kg)
HHV_DAF = (152190*UA_DAF(:,4)/100+98767).*((UA_DAF(:,3)/300)...
+ UA_DAF(:,4)/100 -(UA_DAF(:,7)-UA_DAF(:,6))./800);
% Conversion of measured HHV (dry) from Btu/lb to kJ/kg
HHV_d = UA_d(:,8)*2.326;
HHV_r = UA_r(:,8)*2.326;
% Calculate entropy and exergy (DAF, AF, and complete) for culm
s_DAF = v_culm(:,3).*(-37.1653 - 31.4767*... 
exp(-0.564682*(v_culm(:,4)/(v_culm(:,3)+v_culm(:,5)))))...
+ 20.1145*(v_culm(:,7)/(v_culm(:,3)+v_culm(:,5)))))...
+ 54.3111*(v_culm(:,5)/(v_culm(:,3)+v_culm(:,5))))...
+ 44.6712*(v_culm(:,6)./(v_culm(:,3)+v_culm(:,5))); %**************************************************************************
% Calculate chemical exery of culm on DAF basis in (kJ/kg) for i = 1:row
  e_DAF(:,1) = - To(i,1).*(s_DAF(:,1) + s(1,10)*v(:,10) - s(1,11)*v(:,11)...
               - v(:,12)*s(:,12) - v(:,13)*s(:,13) - v(:,14)*s(:,14))...
                 + (v(:,12)*e(:,12) + v(:,13)*e(:,13) + v(:,14)*e(:,14)...
                   + e(1,11)*v(:,11) - e(1,10)*v(:,10)) + HHV_DAF(:,1); end
%**************************************************************************
% e_final includes moisture and ash. As recieve data used in order to
% to account for moisture and ash effects e_culm = 0.01*(100-UA_r(:,1)-UA_r(:,2)).*e_DAF(:,1)...
  + UA_r(:,1)/(100*N(1,1))*e(1,1);
% Boiler 1 property calculations
% NOTE: Assumptions explained in Assumption sections in Chapter 3 of thesis
% Unless otherwise noted, SI units used:
%  - enthalpy (kJ/kg)
%  - entropy (kJ/kg-K)
%  - exergy (kJ/kg)
%  - temperature (deg C)
%  - pressure (bar)
%  - flow rate (kg/s)
%**************************************************************************
% Declare global Variables

global To ho so ha sa test br B1 m_PA_b1 m_SA_b1 m_culm_b1

global m_lime_b1 m1i m1o Mn_B Tb_B
%**************************************************************************

% Establish size and number of locations for each data set
[br,bc] = size(b1); % Get row and column size for data
loc_b = 17; % Number of inlet/extraction/outlet points
%**************************************************************************

% Set up matrices for location properties
B1 = b1; % Array for operational data with SI units
hb1 = zeros(br,7); % Enthalpy array
sb1 = hb1; % Specific entropy array
eb1 = hb1; % Exergy array
%**************************************************************************

% Convert to SI
% Convert flow rates
B1(:,1:loc_b) = b1(:,1:loc_b)*0.12599777778; % KPPH to kg/s
B1(:,6:7) = b1(:,6:7)*0.00012599777778; % PPH to kg/s

% Convert temp in deg F to deg C
B1(:,(loc_b+1):(2*loc_b)) = (5/9)*(b1(:,(loc_b+1):(2*loc_b))-32);

% Increase FG temp 80 deg C
increase_FG_temp = B1(:,26) + 80;
B1(:,26) = increase_FG_temp;

% Convert pressure from psi to bar
B1(:,(2*loc_b+1):(3*loc_b)) = (b1(:,(2*loc_b+1):(3*loc_b)))*(.068948);
%**************************************************************************

% Set limestone entrance temperature
B1(:,23) = 0.5*(To(:,1)+Tb_B) - 273;
B1(:,24) = 0.5*(To(:,1)+Tb_B) - 273;

% Mass balances
% Spray
B1(:,3) = (F(:,4)-F(:,5))/2;

% Sum of inflows by type
m_culm_b1 = B1(:,4)+B1(:,5); % Total culm in
m_lime_b1 = B1(:,6)+B1(:,7); % Total limestone in
m_PA_b1 = B1(:,11)+B1(:,12); % Total primary air in
m_SA_b1 = B1(:,13)+B1(:,14)+B1(:,15)...+
+ B1(:,16)+B1(:,17); % Total secondary and duct air

% Determine mass flows of ashes and flue gas- outputs m_ba, m_fa, m_fg
[B1(:,8),B1(:,9),B1(:,10),X_react1] = massb1(Mn_B);
%**************************************************************************

% Determine thermodynamic properties
% Primary and secondary air properties
for i=1:br
    % Primary air
    IdealAir(B1(i,28)+273,'T','h','si');    % Enthalpy of PA
    hbl(i,6) = test;
    IdealAir(B1(i,28)+273,'T','so','si');   % specific entropy of PA
    sbl(i,6) = test;

    % Secondary and duct air
    IdealAir(B1(i,33)+273,'T','h','si');    % Enthalpy of SA
    hbl(i,7) = test;
    IdealAir(B1(i,33)+273,'T','so','si');   % specific entropy of SA
    sbl(i,7) = test;
    clc
end

% Total exergy for input air (flow+chemical), kJ/kg
eb1(:,6) = (hb1(:,6)-ha(:,1)) - To(:,1).*(sb1(:,6)-sa(:,1))... 
            + 0.21*e_ch(10) + 0.79*e_ch(11);

eb1(:,7) = (hb1(:,7)-ha(:,1)) - To(:,1).*(sb1(:,7)-sa(:,1))... 
            + 0.21*e_ch(10) + 0.79*e_ch(11);

% Feedwater properties
for i=1:br
    % Saturated liquids- properties based on temperature
    hbl(i,1) = XSteam('h_pT',B1(i,35),B1(i,18)); % Enthalpy
    sbl(i,1) = XSteam('s_pT',B1(i,35),B1(i,18)); % Entropy

    % Superheated steam- properties based on temperature and pressure
    hbl(i,2) = XSteam('h_pT',B1(i,36),B1(i,19)); % Enthalpy
    sbl(i,2) = XSteam('s_pT',B1(i,36),B1(i,19)); % Entropy
end

% Feedwater total exergy (flow + chemical) (kJ/kg)
    eb1(:,1) = (hb1(:,1)- ho(:,1)) - To.*(sb1(:,1)- so(:,1))... 
               + e_ch(1);          % FW in and spray water (l)
    eb1(:,2) = (hb1(:,2)- ho(:,1)) - To.*(sb1(:,2)- so(:,1))... 
               + e_ch(13);         % FW out (g)

% Bottom ash properties- enthalpy equations require deg F and result in
% enthalpy in Btu/lb. Conversion added to result in kJ/kg.
for i=1:br
    if b1(i,25) < 600
        hbl(i,3)=(((7.735829*10^-5)*b1(i,25).^2 ... 
            + 0.1702036*b1(i,25) - 13.36106)/0.42992);
    else
        hbl(i,3)=(((2.408712*10^-5)*(b1(i,26)+176).^2 ... 
            + 0.2358873*(b1(i,26)+176) - 32.88512)/0.42992);
    end

    eb1(:,3) = (hbl(:,3) - ho_A(:,1)) - To.*(sbl(:,3));  % Exergy of BA
end

% Fly ash properties- enthalpy equations require deg F and result in
% enthalpy in Btu/lb. Conversion added to result in kJ/kg.
for i=1:br
    if (b1(i,26)+176) < 600
        hbl(i,4)=(((7.735829*10^-5)*b1(i,26)+176).^2 ... 
            + 0.1702036*(b1(i,26)+176) - 13.36106)/0.42992);
    else
        hbl(i,4)=(((2.408712*10^-5)*(b1(i,26)+176).^2 ... 

+ 0.2358873*(b1(i,26)+176) - 32.88512)/0.42992);  
    end  
  end  
eb1(:,4) = (hb1(:,4) - ho_A(:,1)) - To.*{sb1(:,4)}; % Exergy of FA  
% Chemical exery of ash  
e_ash_other_b1 = m1o(:,3)*e_ch(1,3) + m1o(:,15)*e_ch(1,15);  

% Flue gas properties (assuming limestone effects are negligable)  
% Determine composition, Cp, and flow exergy of flue gas.  
for i = 1:br  
    [hb1(i,5),eb1(i,5),Cp_b1(i)] =  
    fg_change_To(m_culm_b1(i,1),B1(i,26),To(i));  
end  
% Flue gas exergy also contains exergy of gases  
e_FG_other_b1 = m1o(:,10).*e_ch(:,10) + m1o(:,11).*e_ch(:,11)  
+ m1o(:,12).*e_ch(:,12) + m1o(:,13).*e_ch(:,13)  
+ m1o(:,14).*e_ch(:,14) + m1o(:,16).*e_ch(:,16);
% Function to calculate mass flow rates out of boiler for bottom ash, fly ash, and flue gas with or without limestone (depending on boiler model)

function [m_ba,m_fa,m_fg,X1] = massb1(mod)

% Declare global variables
global UA_r br res M m_PA_b1 m_SA_b1 m_culm_b1 m_lime_b1 m1o m1i
%*********************************************************************
% Set up matrices to be used in calculations
N1i = zeros(br,16); % Array for molar flow in
N1o = zeros(br,16); % Array for molar flow out
K = zeros(1,7); % Array for fractions of culm components
m1i = zeros(br,16); % Array for mass flow in
m1o = zeros(br,16); % Array for mass flow out
m_ba = zeros(br,1); % Array for bottom ash flow
m_fg = m_ba; % Array for flue gas flow
%**********************************************************************
% Define known values
% Known mass flows (kg/s)
mi_air = m_SA_b1 + m_PA_b1; % Air in (SA includes duct burner air)
% Fractions of culm compositions
for i = 1:7
    K(1,i) = UA_r(:,i)./100;
end
%**********************************************************************
% Initial calculations for flows
% Ni (kmol/s) for culm components
for i = 1:7
    N1i(:,i) = m_culm_b1(:,1).*(K(1,i)/M(1,i));
end
% Inflow of limestone
N1i(:,8) = m_lime_b1./M(1,8);
% Inflow of O2 and N2 based on air inflow
N1i(:,10) = 0.21*mi_air./M(1,10); % Ni O2
N1i(:,11) = 0.79*mi_air./M(1,11); % Ni N2
%**********************************************************************
% Calculate extent of reactions and molar flows
if mod == 2 % Model BII: NOx taken into account
    % Estimated NO release based on CEMS data and UA results
    N1o(:,16) = 0.013*N1i(:,5);
    % Extent of reactions
    X1(:,1) = N1i(:,3); % X1 = Ni_C
    X1(:,2) = N1i(:,4); % X2 = Ni_H
    X1(:,3) = N1i(:,6); % X3 = Ni_S
    X1(:,4) = N1i(:,8); % X4 = Ni_CaCO3
    X1(:,5) = X1(:,4); % X5 = X4
    X1(:,6) = N1o(:,16); % X6 = NO_NO
    X1(:,7) = 0.5*(N1i(:,5)-X1(:,6)); % X7 = (Ni_N -X6)/2
    X1(:,8) = 0.5*(N1i(:,7)); % X8 = (Ni_O)/2
    % Calc remaining molar flow rates leaving boiler
    N1o(:,10) = N1i(:,10) - (1-res)*X1(:,1) - 0.25*X1(:,2)...
        - X1(:,3) - 0.5*(X1(:,5)+X1(:,6)) + X1(:,8); % N out O2
    N1o(:,11) = N1i(:,11) + X1(:,7); % N out N2
    N1o(:,12) = (1-res)*X1(:,1) + X1(:,4); % N out CO2
    N1o(:,13) = 0.5*X1(:,2) + N1i(:,1); % N out H20
end
N1o(:,14) = X1(:,3) - X1(:,5);          % N out SO2
N1o(:,15) = X1(:,5);                    % N out CaSO4
N1o(:,3) = res*N1i(:,3);                % N out C
else % Model BI: NOx neglected
  % Extent of reactions
  X1(:,1) = N1i(:,3);                 % X1 = Ni_C
  X1(:,2) = N1i(:,4);                 % X2 = Ni_H
  X1(:,3) = N1i(:,6);                 % X3 = Ni_S
  X1(:,4) = N1i(:,8);                 % X4 = Ni_CaCO3
  X1(:,5) = X1(:,4);                  % X5 = X4
  X1(:,6) = 0.5*N1i(:,5);             % X6 = 0.5*Ni_N
  X1(:,7) = 0.5*N1i(:,7);             % X7 = 0.5*Ni_O

  % Calc remaining molar flows
  N1o(:,10) = N1i(:,10) + X1(:,7) - X1(:,1)- X1(:,3) - 0.25*X1(:,2) - 0.5*X1(:,5);   % N out O2
  N1o(:,11) = N1i(:,11)+ X1(:,6);     % N out N2
  N1o(:,12) = X1(:,1) + X1(:,4);      % N out CO2
  N1o(:,13) = 0.5*X1(:,2) + N1i(:,1); % N out H2O (g)
  N1o(:,14) = X1(:,3) - X1(:,5);      % N out SO2
  N1o(:,15) = X1(:,5);                % N out CaSO4
end

%**********************************************************************
% Convert to mass flows (kmol/s) to (kg/s) for each species
% General conversion
for i=1:16
    m1i(:,i) = N1i(:,i).*M(1,i);
    m1o(:,i) = N1o(:,i).*M(1,i);
end

% Correct ash conversion
m1i(:,2) = K(1,2)*m_culm_b1;
  m1o(:,2) = m1i(:,2);

% Limestone mass flow rates
m_ba = m1o(:,2)/2;
m_fa = m_ba;

% Flue gas flow rate out
for i=1:br
    m_fg(i,1) = sum(m1o(i,10:16)) - m1o(i,15); % FG = (sum of exiting gases)
end
end
% Function for finding flue gas properties
% Paper by Coskun, 2009
% "Steam" Ch 9
% Assuming no limestone added
% FG temp between 100 K and 1200 K
% Ref combustion- C of all gases defined depending on CO2
% 20% excess air
% p and po are approximately the same

function [h_fg, e_fg, Cp_fg] = fg_change_To(m_culm, fg_T, To)

% Declare global variables
global UA_r

%**********************************************************************
% Initial known values
lam = 0.2; % Percent excess air
n = lam + 1;
T_fg = fg_T+273;
K = UA_r/100;
%**********************************************************************
% Conservation of mass
m_air_st = (11.445)*(2.9978*K(1,4)- 0.3747*K(1,7) + 0.3747*K(1,6)+ K(1,3)); % Stoichiometric amount of air
m_fg = (11.445*n)*(2.9978*K(1,4)- 0.3747*K(1,7) + 0.3747*K(1,6)+ K(1,3)) + (1 - K(1,2)); % Flue gas flow rate
m_tot_st = m_air_st + (1 - K(1,2)); % Total stoichiometric mass
%**********************************************************************
% Non Temperature dependent coefficients
aC = (3.667*K(1,3))/m_tot_st; % a_c = a_m
bm = (0.767*m_air_st+ K(1,5))./m_tot_st; % b_m
cm = (8.938*K(1,4)+K(1,1))./m_tot_st; % c_m
dm = (2*K(1,6))/m_tot_st; % d_m
fm = (lam*m_air_st)/m_fg; % f_m
%**********************************************************************
% Determining specific heat

% Sub-components for coefficient b
b_cp = 0.9094 + (1.69*10^-4)*T_fg - (11135*T_fg^-2); % b_cp
bN = bm/b_cp; % b_c

% Sub-components for coefficient c
ch = cm/c_cp; % c_c

% Sub-components for coefficient d
dS = exp(2.679 - 151.16*T_fg^-1 - 0.289*log(T_fg)); % d_cp

% fa
f_cp = 0.7124*(1.00011^T_fg)*(T fg^0.051); % Cp,A
fA = fm*f_cp; % f_A

% Specific heat capacity of flue gas (kJ/kg-K)
Cp_fg = \frac{C_p_c}{(aC + bN + cH + dS)} \left(\frac{m_{tot\_st}}{m_{fg}}\right) + fA;

\% Flow Exergy of flue gas (kJ/kg)
e_fg = Cp_fg*\{(T_{fg}-To) - To*\log(T_{fg}/To)\};

\% Change in enthalpy (kJ/kg)
h_fg = Cp_fg*(T_{fg});

end
% Boiler 2 property calculations
% NOTE: Assumptions explained in Assumption sections in Chapter 3 of thesis
% Unless otherwise noted, SI units used:
% - enthalpy (kJ/kg)
% - entropy (kJ/kg-K)
% - exergy (kJ/kg)
% - temperature (deg C)
% - pressure (bar)
% flow rate (kg/s)
**************************************************************************
% Declare global Variables
global To ho so ha sa test br B2 m_PA_b2 m_SA_b2 m_culm_b2
global m_lime_b2 m2i m2o Mn_B Tb_B
**************************************************************************
% Establish size and number of locations for each data set
[br,bc] = size(b2); % Get row and column size for data
loc_b = 17; % Number of inlet/extraction/outlet points
**************************************************************************
% Set up matrices for location properties
  B2 = b2; % Array for operational data with SI units
  hb2 = zeros(br,7); % Enthalpy array
  sb2 = hb2; % Specific entropy array
  eb2 = hb2; % Exergy array
**************************************************************************
% Convert to SI
% Convert flow rates
B2(:,1:loc_b) = b2(:,1:loc_b)*0.12599777778; % KPPH to kg/s
B2(:,6:7) = b2(:,6:7)*0.00012599777778; % PPH to kg/s
% Convert temp in deg F to deg C
B2(:,(loc_b+1):(2*loc_b)) = (5/9)*(b2(:,(loc_b+1):(2*loc_b))-32);
% Increase FG temp 80 deg C
  increase_FG_temp = B2(:,26) + 80;
  B2(:,26) = increase_FG_temp;
% Convert pressure from psi to bar
B2(:,(2*loc_b+1):(3*loc_b)) = (b2(:,(2*loc_b+1):(3*loc_b)))*(.068948);
**************************************************************************
% Set limestone entrance temperature
  B2(:,23) = 0.5*(To(:,1)+Tb_B) - 273;
  B2(:,24) = 0.5*(To(:,1)+Tb_B) - 273;
% Mass balances
% Spray
  B2(:,3) = (F(:,4)-F(:,5))/2;
% Sum of inflows by type
  m_culm_b2 = B2(:,4)+B2(:,5); % Total culm in
  m_lime_b2 = B2(:,6)+B2(:,7); % Total limestone in
  m_PA_b2 = B2(:,11)+B2(:,12); % Total primary air in
% Determine mass flows of ashes and flue gas- outputs m_ba, m_fa, m_fg
[B2(:,8),B2(:,9),B2(:,10),X_react2] = massb2(Mn_B); % outputs m_ba, m_fa, m_fg
**************************************************************************
% Determine thermodynamic properties
% Primary and secondary air properties
for i=1:br
    % Primary air
    IdealAir(B2(i,28)+273,'T', 'h', 'si'); % Enthalpy of primary air (kJ/kg)
    hb2(i,6) = test;
    IdealAir(B2(i,28)+273,'T', 'so', 'si'); % specific entropy of primary air (kJ/kg-K)
    sb2(i,6) = test;
    % Secondary and duct air
    IdealAir(B2(i,33)+273,'T', 'h', 'si'); % Enthalpy of secondary air (kJ/kg)
    hb2(i,7) = test;
    IdealAir(B2(i,33)+273,'T', 'so', 'si'); % specific entropy of secondary air (kJ/kg-K)
    sb2(i,7) = test;
    clc
end
% Total exergy for input air (flow+chemical), kJ/kg
eb2(:,6) = (hb2(:,6)-ha(:,1)) - To(:,1).*(sb2(:,6)-sa(:,1)) + 0.21*e_ch(10) + 0.79*e_ch(11);
eb2(:,7) = (hb2(:,7)-ha(:,1)) - To(:,1).*(sb2(:,7)-sa(:,1)) + 0.21*e_ch(10) + 0.79*e_ch(11);

% Feedwater properties
for i=1:br
    % Saturated liquids- properties based on temperature
    hb2(i,1) = XSteam('h_pT', B2(i,35), B2(i,18)); % Enthalpy
    sb2(i,1) = XSteam('s_pT', B2(i,35), B2(i,18)); % Entropy
    % Superheated steam- properties based on temperature and pressure
    hb2(i,2) = XSteam('h_pT', B2(i,36), B2(i,19)); % h FW out
    sb2(i,2) = XSteam('s_pT', B2(i,36), B2(i,19)); % s FW out
end
% Feedwater total exergy (flow + chemical) (kJ/kg)
eb2(:,1) = (hb2(:,1)- ho(:,1)) - To.*((sb2(:,1)- sa(:,1)) + e_ch(1)); % FW in and spray water (l)
eb2(:,2) = (hb2(:,2)- ho(:,1)) - To.*((sb2(:,2)- sa(:,1)) + e_ch(13)); % FW out (g)

% Bottom ash properties- enthalpy equations require deg F and result in % enthalpy in Btu/lb. Conversion added to result in kJ/kg.
for i=1:br
    if b2(i,25) < 600
        hb2(i,3) = ((7.735829*10^-5*b2(i,25).^2 ... + 0.1702036*b2(i,25) - 13.36106)/0.42992);
    else
        hb2(i,3) = ((2.408712*10^-5*b2(i,25).^2 ... + 0.2358873*b2(i,25) - 32.88512)/0.42992);
    end
end
eb2(:,3) = (hb2(:,3) - ho_A(:,1)) - To.*((sb2(:,3))); % total exergy of BA

% Fly ash properties- enthalpy equations require deg F and result in % enthalpy in Btu/lb. Conversion added to result in kJ/kg.
for i=1:br
    if (b2(i,26)+176) < 600
        hb2(i,4) = (((7.735829*10^-5)*(b2(i,26)+176).^2 ... 
            + 0.1702036*(b2(i,26)+176) - 13.36106)/0.42992);
    else
        hb2(i,4) = (((2.408712*10^-5)*(b2(i,26)+176).^2 ... 
            + 0.2358873*(b2(i,26)+176) - 32.88512)/0.42992);
    end
end

eb2(:,4) = (hb2(:,4) - ho_A(:,1)) - To.*(sb2(:,4)); % Exergy of FA
% Chemical exerxy of ash
e_ash_other_b2 = m2o(:,3)*e_ch(1,3)+ m2o(:,15)*e_ch(1,15);

% Flue gas properties (assuming limestone effects are negligible)
% Determine composition, Cp, and flow exergy of flue gas.
for i = 1:br
    [hb2(i,5),eb2(i,5),Cp_b2(i)] = 
        fg_change_To(m_culm_b2(i,1),B2(i,26),To(i));
end
% Flue gas exergy also contains exergy of gases
e_FG_other_b2 = eb2(:,5) + m2o(:,10).*e_ch(:,10) + 
    m2o(:,11).*e_ch(:,11)... 
    + m2o(:,12).*e_ch(:,12) + m2o(:,13).*e_ch(:,13)... 
    + m2o(:,14).*e_ch(:,14) + m2o(:,16).*e_ch(:,16);
% Function to calculate mass flow rates out of boiler for bottom ash, fly ash, and flue gas with or without limestone (depending on boiler model)

function [m_ba,m_fa,m_fg,X2] = massb2(mod)

% Declare global variables
global UA_r br res M m_PA_b2 m_SA_b2 m_culm_b2 m_lime_b2 m2o m2i
%************************************************
% Set up matrices to be used in calculations
N2i = zeros(br,16); % Array for molar flow in
N2o = zeros(br,16); % Array for molar flow out
K = zeros(1,7);     % Array for fractions of culm components
m2i = zeros(br,16); % Array for mass flow in
m2o = zeros(br,16); % Array for mass flow out
m_ba = zeros(br,1); % Array for bottom ash flow
m_fg = m_ba;        % Array for flue gas flow
%************************************************
% Define known values
% Known mass flows (kg/s)
mi_air = m_SA_b2 + m_PA_b2;  % Air in (SA includes duct burner air)
% Fractions of culm compositions
for i = 1:7
    K(1,i) = UA_r(:,i)./100;
end
% Inflow of limestone
N2i(:,8) = m_lime_b2./M(1,8);
N2i(:,10) = 0.21*mi_air./M(1,10);  % Ni O2
N2i(:,11) = 0.79*mi_air./M(1,11);  % Ni N2
%************************************************
% Initial calculations for flows
% Ni (kmol/s) for culm components
for i = 1:7
    N2i(:,i) = m_culm_b2(:,1).*(K(1,i)/M(1,i));
end
% Inflow of lime
N2i(:,8) = m_lime_b2./M(1,8);
N2i(:,10) = 0.21*mi_air./M(1,10);  % Ni O2
N2i(:,11) = 0.79*mi_air./M(1,11);  % Ni N2
%************************************************
% Calculate extent of reactions and molar flows
if mod == 2 % Model BII: NOx taken into account
    % Estimated NO release
    N2o(:,16) = 0.013*N2i(:,5);

    % Extent of reactions
    X2(:,1) = N2i(:,5);     % X1 = Ni_C
    X2(:,2) = N2i(:,4);     % X2 = Ni_H
    X2(:,3) = N2i(:,6);     % X3 = Ni_S
    X2(:,4) = N2i(:,8);     % X4 = Ni_CaCO3
    X2(:,5) = X2(:,4);      % X5 = X4
    X2(:,6) = N2o(:,16);    % X6 = NO
    X2(:,7) = 0.5*(N2i(:,5)-X2(:,6));  % X7 = (Ni_N -X6)/2
    X2(:,8) = 0.5*(N2i(:,7)); % X8 = (Ni_O)/2

    % Calc remaining molar flows
    N2o(:,10) = N2i(:,10) - (1-res)*X2(:,1) - 0.25*X2(:,2)
    - X2(:,3) - 0.5*(X2(:,5)+X2(:,6)) + X2(:,8);  % N out O2
    N2o(:,11) = N2i(:,11) + X2(:,7);               % N out N2
    N2o(:,12) = (1-res)*X2(:,1) + X2(:,4);        % N out CO2
    N2o(:,13) = 0.5*X2(:,2) + N2i(:,1);           % N out H2O
end
\[ N_{2o}(t, 14) = X_2(t, 3) - X_2(t, 5); \quad \% \text{N out SO}_2 \]
\[ N_{2o}(t, 15) = X_2(t, 5); \quad \% \text{N out CaSO}_4 \]
\[ N_{2o}(t, 3) = \text{res} \times N_{2i}(t, 3); \quad \% \text{N out C} \]

\textbf{else} \quad \% \text{Model BI : NOx neglected}

\% Extent of reactions
\[ X_2(t, 1) = N_{2i}(t, 3); \quad \% X_1 = \text{Ni}_C \]
\[ X_2(t, 2) = N_{2i}(t, 4); \quad \% X_2 = \text{Ni}_H \]
\[ X_2(t, 3) = N_{2i}(t, 6); \quad \% X_3 = \text{Ni}_S \]
\[ X_2(t, 4) = N_{2i}(t, 8); \quad \% X_4 = \text{Ni}_CaCO_3 \]
\[ X_2(t, 5) = X_2(t, 4); \quad \% X_5 = X_4 \]
\[ X_2(t, 6) = 0.5 \times N_{2i}(t, 5); \quad \% X_6 = 0.5 \times \text{Ni}_N \]
\[ X_2(t, 7) = 0.5 \times N_{2i}(t, 7); \quad \% X_7 = 0.5 \times \text{Ni}_O \]

\% Calc remaining molar flows
\[ N_{2o}(t, 10) = N_{2i}(t, 10) + X_2(t, 7) - X_2(t, 1) - X_2(t, 3) \]
\[ - 0.25 \times X_2(t, 2) - 0.5 \times X_2(t, 5); \quad \% \text{N out O}_2 \]
\[ N_{2o}(t, 11) = N_{2i}(t, 11) + X_2(t, 6); \quad \% \text{N out N}_2 \]
\[ N_{2o}(t, 12) = X_2(t, 1) + X_2(t, 4); \quad \% \text{N out CO}_2 \]
\[ N_{2o}(t, 13) = 0.5 \times X_2(t, 2) + N_{2i}(t, 1); \quad \% \text{N out H}_2O (g) \]
\[ N_{2o}(t, 14) = X_2(t, 3) - X_2(t, 5); \quad \% \text{N out SO}_2 \]
\[ N_{2o}(t, 15) = X_2(t, 5); \quad \% \text{N out CaSO}_4 \]

\textbf{end}

\% Convert to mass flows (kmol/s) to (kg/s) for each species

\% General conversion
\textbf{for} i=1:16
\[ m_{2i}(t, i) = N_{2i}(t, i) \times M(1, i); \]
\[ m_{2o}(t, i) = N_{2o}(t, i) \times M(1, i); \]
\textbf{end}

\% Correct ash conversion
\[ m_{2i}(t, 2) = K(1, 2) \times m_{\text{culm}_b2}; \]
\[ m_{2o}(t, 2) = m_{2i}(t, 2); \]

\% Limestone mass flow rates
\[ m_{\text{ba}} = m_{2o}(t, 2)/2; \]
\[ m_{\text{fa}} = m_{\text{ba}}; \]

\% Flue gas flow rate out
\textbf{for} i=1:br
\[ m_{\text{fg}}(i, 1) = \text{sum}(m_{2o}(i, 10:16)) - m_{2o}(i, 15); \quad \% \text{FG} = (\text{sum of exiting gases}) \]
\textbf{end}

\textbf{end}
% Code to calculate useful thermo parameters using previously calculated % properties
%**************************************************************************
% Clear previous work
  clear all
  clc
%**************************************************************************
% Declare global variables
  global Tb_B Tb_T Mn_B
%**************************************************************************
% Declare environment and model selection
  Tb_B = 305;   % Boiler room temp in K
  Tb_T = 300.15;  % Turbine room temp in K
  T_chamber = 860+273;  % Temperature in boiler chamber
  ref_env = 2;
  Mn_B = 2;
%**************************************************************************
% i = open('C:\Documents and Settings\wed8908\My Documents\Results\all\defense_std.mat');
%**************************************************************************
% Reference environment conditions
  if ref_env == 2
    Po = 0.961; % (bar) chosen by frackville altitude
    To = xlsread('C:\Documents and Settings\wed8908\My Documents\MATLAB\To.xls');   % Environmental temperatures
  else
    Po = 1.013; % (bar) standard pressure
    To = 298;  % (K) standard temperature
  end
%**************************************************************************
% Sort through rows to find high and low load scenarios based on the % exported electricity being less than 65 MW (low load) or above 85 MW % (high load). The "load" array gives a value of 1 to low loads, 2 to % middle loads, and 3 to high loads.
  load = 2*ones(i.row,1);  % Create an array with default middle load
  for j=1:i.row
    if i.Tu(j,22)< 65000        % Low load
      load(j,1) = 1;
    elseif i.Tu(j,22) > 85000   % High load
      load(j,1) = 3;
    end
  end
%**************************************************************************
% Boiler energy analyses
% B1 energy values common to each boiler model
  Q_u_b1 = i.B1(:,2).*...(i.hb1(:,1)-i.hb1(:,2));  % B1 useful heat transfer
  Q_culm_b1 = i.m_culm_b1.*i.HHV_r;   % B1 heat content of fuel
  Q_l_est_b1 = 0.03*Q_culm_b1;  % Estimated heat loss
  n_b1 = -Q_u_b1./Q_culm_b1;    % B1 energy efficiency
%**************************************************************************
% B2 energy values common to each boiler model
  Q_u_b2 = i.B2(:,2).*...(i.hb2(:,1)-i.hb2(:,2));  % B2 useful heat transfer
  Q_culm_b2 = i.m_culm_b2.*i.HHV_r;   % B2 heat content of fuel
  Q_l_est_b2 = 0.03*Q_culm_b2;  % Estimated heat loss
  n_b2 = -Q_u_b2./Q_culm_b2;    % B2 energy efficiency
%**************************************************************************
% Boiler model-specific energy calculations
  if Mn_B == 1
    % Boiler model-specific energy calculations
  end

% Model BI for boiler 1
Q_lime_b1_BI = (i.M(1,12)/i.M(1,8))*i.m_lime_b1.*(i.hf_ch(1,12)...
  + i.cp(1,12)*(i.B1(:,26) + 273))...
  - i.m_lime_b1.*((i.hf_ch(1,8)))...
  + i.mlo(:,15).*((i.hf_ch(1,15)...
  + 0.5*i.cp(1,15)*((i.B1(:,25) + 273)...
  + (i.B1(:,26)+273))))...
  - i.mlo(:,14).*((i.hf_ch(1,14))+ i.cp(1,14)...
  *(i.B1(:,26) + 273)); % Limestone heat transfer

Q_l_b1_BI = -Q_u_b1 - Q_culm_b1 - Q_lime_b1_BI...
  + i.B1(:,10).*i.hb1(:,5) + i.B1(:,9).*i.hb1(:,4)...
  + i.B1(:,8).*i.hb1(:,3); % Heat loss using energy balance

Q_T_b1_BI = Q_u_b1 + Q_culm_b1...
  + Q_l_b1_BI + Q_lime_b1_BI; % Total heat transfer

% Model BI for boiler 2
Q_lime_b2_BI = (i.M(1,12)/i.M(1,8))*i.m_lime_b2.*(i.hf_ch(1,12)...
  + i.cp(1,12)*(i.B2(:,26) + 273))...
  - i.m_lime_b2.*((i.hf_ch(1,8))...
  + i.cp(1,8)*(i.B2(:,23) + 273))...
  + i.m2o(:,15).*((i.hf_ch(1,15)...
  + 0.5*i.cp(1,15)*((i.B2(:,25) + 273)...
  + (i.B2(:,26)+273))))...
  - i.m2o(:,14).*((i.hf_ch(1,14))+ i.cp(1,14)...
  *(i.B2(:,26) + 273)); % Limestone heat transfer

Q_l_b2_BI = -Q_u_b2 - Q_culm_b2 - Q_lime_b2_BI...
  + i.B2(:,10).*i.hb2(:,5) + i.B2(:,9).*i.hb2(:,4)...
  + i.B2(:,8).*i.hb2(:,3); % Heat loss using energy balance

Q_T_b2_BI = Q_u_b2 + Q_culm_b2...
  + Q_l_b2_BI + Q_lime_b2_BI; % Total heat transfer

elseif Mn_B == 2
% Model BII for boiler 1
Q_lime_b1_BII = (i.M(12)/i.M(8))*i.m_lime_b1.*(i.hf_ch(1,12)...
  + i.cp(1,12)*(i.B1(:,26) + 273))...
  - i.m_lime_b1.*((i.hf_ch(1,8)))...
  + i.cp(1,8)*(i.B1(:,23) + 273))...
  + i.mlo(:,15).*((i.hf_ch(1,15)...
  + 0.5*i.cp(1,15)*((i.B1(:,25) + 273)...
  + (i.B1(:,26)+273))))...
  - i.mlo(:,14).*((i.hf_ch(1,14))+ i.cp(1,14)...
  *(i.B1(:,26) + 273)); % Limestone heat transfer

Q_l_b1_BII = -Q_u_b1 - Q_culm_b1 - Q_lime_b1_BII...
  + i.B1(:,10).*i.hb1(:,5) + i.B1(:,9).*i.hb1(:,4)...
  + i.B1(:,8).*i.hb1(:,3) - i.m_PA_b1.*i.hb1(:,6)...
  - i.m_SA_b1.*i.hb1(:,7); % Heat loss using energy balance

Q_T_b1_BII = Q_u_b1 + Q_l_b1_BII; % Total heat transfer

% Model BII for boiler 2
Q_lime_b2_BII = (i.M(12)/i.M(8))*i.m_lime_b2.*(i.hf_ch(1,12)...
  + i.cp(1,12)*(i.B2(:,26) + 273))...
  - i.m_lime_b2.*((i.hf_ch(1,8)))...
  + i.m2o(:,15).*((i.hf_ch(1,15)...
  + 0.5*i.cp(1,15)*((i.B2(:,25) + 273)...
  + (i.B2(:,26)+273))))...
  - i.m2o(:,14).*((i.hf_ch(1,14))+ i.cp(1,14)...
  *(i.B2(:,26) + 273)); % Limestone heat transfer

Q_l_b2_BII = -Q_u_b2 - Q_culm_b2 - Q_lime_b2_BII...
  + i.B2(:,10).*i.hb2(:,5) + i.B2(:,9).*i.hb2(:,4)...
  + i.B2(:,8).*i.hb2(:,3); % Heat loss using energy balance

Q_T_b2_BII = Q_u_b2 + Q_culm_b2...
  + Q_l_b2_BII + Q_lime_b2_BII; % Total heat transfer

else

% Model BII for boiler 1
Q_lime_b1_BII = (i.M(12)/i.M(8))*i.m_lime_b1.*(i.hf_ch(1,12)...
  + i.cp(1,12)*(i.B1(:,26) + 273))...
  - i.m_lime_b1.*((i.hf_ch(1,8)))...
  + i.mlo(:,15).*((i.hf_ch(1,15)...
  + 0.5*i.cp(1,15)*((i.B1(:,25) + 273)...
  + (i.B1(:,26)+273))))...
  - i.mlo(:,14).*((i.hf_ch(1,14))+ i.cp(1,14)...
  *(i.B1(:,26) + 273)); % Limestone heat transfer

Q_l_b1_BII = -Q_u_b1 - Q_culm_b1 - Q_lime_b1_BII...
  + i.B1(:,10).*i.hb1(:,5) + i.B1(:,9).*i.hb1(:,4)...
  + i.B1(:,8).*i.hb1(:,3) - i.m_PA_b1.*i.hb1(:,6)...
  - i.m_SA_b1.*i.hb1(:,7); % Heat loss using energy balance

Q_T_b1_BII = Q_u_b1 + Q_l_b1_BII; % Total heat transfer

% Model BII for boiler 2
Q_lime_b2_BII = (i.M(12)/i.M(8))*i.m_lime_b2.*(i.hf_ch(1,12)...
  + i.cp(1,12)*(i.B2(:,26) + 273))...
  - i.m_lime_b2.*((i.hf_ch(1,8)))...
  + i.m2o(:,15).*((i.hf_ch(1,15)...
  + 0.5*i.cp(1,15)*((i.B2(:,25) + 273)...
  + (i.B2(:,26)+273))))...
  - i.m2o(:,14).*((i.hf_ch(1,14))+ i.cp(1,14)...
  *(i.B2(:,26) + 273)); % Limestone heat transfer

Q_l_b2_BII = -Q_u_b2 - Q_culm_b2 - Q_lime_b2_BII...
  + i.B2(:,10).*i.hb2(:,5) + i.B2(:,9).*i.hb2(:,4)...
  + i.B2(:,8).*i.hb2(:,3); % Heat loss using energy balance

Q_T_b2_BII = Q_u_b2 + Q_culm_b2...
  + Q_l_b2_BII + Q_lime_b2_BII; % Total heat transfer
end
\[ Q_{l\ b2\ BII} = -Q_u_b2 - Q_{culm\ b2} - Q_{lime\ b2\ BII} + i.B2(:,10).*i.hb2(:,5) + i.B2(:,9).*i.hb2(:,4) - i.m\_SA\_b2.*i.hb2(:,7); \]

\[ Q_{T\ b2\ BII} = Q_u_b2 + Q_{l\ b2\ BII}; \]

\[ \%\ Boiler\ Exergy\ analysis \]

\% B1 exergy values common to each boiler model

\[ E_{u\ b1} = Q_u_b1.*(1-To./T\_chamber); \]

\[ E_{culm\ b1} = i.m\_culm\ b1.*(i.e\_culm); \]

\[ E_{air\ b1} = i.m\_PA\_b1.*i.eb1(:,6) + i.m\_SA\_b1.*i.eb1(:,7); \]

\[ E_{lime\ b1} = i.m\_lime\ b1.*i.e\_ch(1,8); \]

\[ E_{FG\ total\ b1} = i.B1(:,10).*i.eb1(:,5) + i.e\_FG\_other\_b1; \]

\[ E_{ash\ total\ b1} = i.B1(:,8).*i.eb1(:,3) + i.B1(:,9).*i.eb1(:,4) + i.e\_ash\_other\_b1; \]

\[ \text{eps\_b1} = E_{u\ b1}/E_{culm\ b1}; \]

\% B2 exergy values common to each boiler model

\[ E_{u\ b2} = Q_u_b2.*(1-To./T\_chamber); \]

\[ E_{culm\ b2} = i.m\_culm\ b2.*(i.e\_culm); \]

\[ E_{air\ b2} = i.m\_PA\_b2.*i.eb2(:,6) + i.m\_SA\_b2.*i.eb2(:,7); \]

\[ E_{lime\ b2} = i.m\_lime\ b2.*i.e\_ch(1,8); \]

\[ E_{FG\ total\ b2} = i.B2(:,10).*i.eb2(:,5) + i.e\_FG\_other\_b2; \]

\[ E_{ash\ total\ b2} = i.B2(:,8).*i.eb2(:,3) + i.B2(:,9).*i.eb2(:,4) + i.e\_ash\_other\_b2; \]

\[ \text{eps\_b2} = E_{u\ b2}/E_{culm\ b2}; \]
E_l_b2 = Q_l_b2_BII.*(1-To./Tb_B); % Lost exergy

% Boiler model-specific energy calculations
if Mn_B == 1
% Model BI for boiler 1
E_l_BI_b1 = Q_l_BI_b1.*(1-To./Tb_B); % BI Exergy loss
Ed_BI_b1 = E_u_b1 + E_l_BI_b1...
+ E_air_b1 + E_culm_b1 + E_lime_b1...
- (E_ash_total_b1 + E_FG_total_b1); % BI Ed from exergy balance

% Model BI for boiler 2
E_l_BI_b2 = Q_l_BI_b2.*(1-To./Tb_B); % BI Exergy loss
Ed_BI_b2 = E_u_b2 + E_l_BI_b2...
+ E_air_b2 + E_culm_b2 + E_lime_b2...
- (E_ash_total_b2 + E_FG_total_b2); % BI Ed from exergy balance
elseif Mn_B == 2
% Model BII for boiler 1
E_l_b1_BII = Q_l_b1_BII.*(1-To./Tb_B); % BII Exergy loss
Ed_BII_b1 = E_u_b1 + E_l_b1_BII...
+ E_air_b1 + E_culm_b1 + E_lime_b1...
- (E_ash_total_b1 + E_FG_total_b1); % BII Ed from exergy balance

% Model BII for boiler 1
E_l_b2_BII = Q_l_b2_BII.*(1-To./Tb_B); % BII Exergy loss
Ed_BII_b2 = E_u_b2 + E_l_b2_BII...
+ E_air_b2 + E_culm_b2 + E_lime_b2...
- (E_ash_total_b2 + E_FG_total_b2); % BII Ed from exergy balance
end

%**************************************************************************
% Combined boiler effects
if Mn_B == 1 % Boiler model BI
Q_l_total_B = Q_l_b1_BI + Q_l_b2_BI; % Total boiler heat loss
Q_u_total_B = Q_u_b1 + Q_u_b2; % Total useful heat transfer
Q_culm_total = Q_culm_b1 + Q_culm_b2; % Total heat input from culm
n_B_avg = (n_b1+n_b2)./2; % Average boiler efficiency

E_l_total_B = E_l_b1_BI + E_l_b2_BI; % Total exergy loss
Ed_total_B = Ed_BI_b1 + Ed_BI_b1; % Total exergy destruction
E_in_B = E_culm_b1 + E_culm_b2; % Total culm exergy
E_air_total_B = E_air_b1 + E_air_b2; % Total exergy of air
E_lime_total_B = E_lime_b1 + E_lime_b1; % Total exergy of limestone
E_ash_total_B = E_ash_total_b1...
+E_ash_total_b1; % Total exergy of ash
E_FG_total_B = E_FG_total_b1...
+ E_FG_total_b2; % Total exergy of FG
eps_avg_B = (eps_b1 + eps_b2)./2; % Average boiler exergy eff.
else % Boiler model BII
Q_l_total_B = Q_l_b1_BII + Q_l_b2_BII; % Total boiler heat loss
Q_u_total_B = Q_u_b1 + Q_u_b2; % Total useful heat transfer
Q_culm_total = Q_culm_b1 + Q_culm_b2; % Total heat input from culm
n_B_avg = (n_b1+n_b2)./2; % Average boiler efficiency
end
E_l_total_B = E_l_b1_BII + E_l_b2_BII; \% Total exergy loss
Ed_total_B = Ed_BII_b1 + Ed_BII_b2; \% Total exergy destruction
E_in_B = E_culm_b1 + E_culm_b2; \% Total culm exergy
E_air_total_B = E_air_b1 + E_air_b2; \% Total exergy of air
E_lime_total_B = E_lime_b1 + E_lime_b2; \% Total exergy of limestone
E_ash_total_B = E_ash_total_b1... + E_ash_total_b2; \% Total exergy of ash
E_FG_total_B = E_FG_total_b1... + E_FG_total_b2; \% Total exergy of FG
eps_avg_B = (eps_b1 + eps_b2)./2; \% Average boiler exergy eff.
end

%**************************************************************************
% Condenser Analysis
Q_C = i.C(:,7).*i.hc(:,7) - i.C(:,3).*i.hc(:,3)... - i.C(:,4).*i.hc(:,4) - i.C(:,5).*i.hc(:,5)... - i.C(:,6).*i.hc(:,6); \% Heat transfer to cooling water
m_CW = -Q_C./(i.hf(:,2) - i.hf(:,1)); \% Flow rate of cooling water
i.C(:,1) = m_CW; \% Insert cooling water flow into C
i.C(:,2) = m_CW; \% Insert cooling water flow into C
E_l_C = Q_C.*(1-To(:,1)./Tb_T); \% Exergy loss
Ed_C = E_l_C + i.C(:,3).*i.ec(:,3)... + i.C(:,4).*i.ec(:,4) + i.C(:,5).*i.ec(:,5)... + i.C(:,6).*i.ec(:,6)... - i.C(:,7).*i.ec(:,7); \% Exergy destroyed at condenser
%**************************************************************************
% FWH exergy analysis
Ed_1_F = i.F(:,8).*i.ef(:,8) + i.F(:,11).*i.ef(:,11)... + i.F(:,1).*i.ef(:,1)-i.ef(:,2)... - i.F(:,9).*i.ef(:,9); \% Ed FWH 1
Ed_2_F = i.F(:,2).*i.ef(:,2) - i.ef(:,3)... + i.F(:,10).*i.ef(:,10) - i.ef(:,11)); \% Ed FWH 2
Ed_DA_F = i.F(:,12).*i.ef(:,12) + i.F(:,3).*i.ef(:,3)... + i.F(:,14).*i.ef(:,14) - i.F(:,4).*i.ef(:,4); \% Ed DA
Ed_4_F = i.F(:,13).*i.ef(:,13) + i.F(:,16).*i.ef(:,16)... + i.F(:,5).*i.ef(:,5)-i.ef(:,6)... - i.F(:,14).*i.ef(:,14); \% Ed FWH 4
Ed_5_F = i.F(:,15).*i.ef(:,15) - i.ef(:,16)... + i.F(:,7).*i.ef(:,6) - i.ef(:,7)); \% Ed FWH 5
Ed_total_F = Ed_1_F + Ed_2_F + Ed_DA_F... + Ed_4_F + Ed_5_F; \% Total Ed through FWHs
%**************************************************************************
% Turbine and generator analysis
% Energy analysis
Q_process = i.Tu(:,25).*i.hc(:,4)-i.ht(:,2)); \% Process heat
W_gen = i.Tu(:,22); \% Work produced by generator
\[ W_{TI} = \left( \frac{1}{\text{ngen}} \right) W_{gen} \] % Turbine work using generator export
\[ Q_{l_{TI}} = -i_H \times W_{TI} \] % Turbine heat loss using method I

% Using method II - using energy balance around turbine
\[ W_{TII} = \frac{(i.Tu(:,1) \times i.ht(:,1) - i.Tu(:,2) \times i.ht(:,2)\ldots - i.Tu(:,3) \times i.ht(:,3) - i.Tu(:,4) \times i.ht(:,4)\ldots - i.Tu(:,5) \times i.ht(:,5) - i.Tu(:,6) \times i.ht(:,6)\ldots - i.Tu(:,7) \times i.ht(:,7))}{(1+i.H)} \] % Turbine work
\[ W_{s_{TII}} = (i.Tu(:,1) \times i.ht(:,1) - i.Tu(:,2) \times i.hts(:,2)\ldots - i.Tu(:,3) \times i.hts(:,3) - i.Tu(:,4) \times i.hts(:,4)\ldots - i.Tu(:,5) \times i.hts(:,5) - i.Tu(:,6) \times i.hts(:,6)\ldots - i.Tu(:,7) \times i.hts(:,7)) \] % Turbine isentropic work
\[ W_{gen_{TII}} = W_{TII} \times \text{ngen} \] % Generator export using \( W_{TII} \)
\[ Q_{l_{TII}} = -i_H \times W_{TII} \] % Turbine heat loss using method II
\[ nTs = \frac{W_{TII}}{W_{s_{TII}}} \] % Isentropic turbine efficiency

% Exergy analysis
\[ E_{process} = i.Tu(:,25) \times (i.ec(:,4) - i.et(:,2)) \] % Process steam exergy
\[ E_{l_{TI}} = Q_{l_{TI}} \times (1 - To(:,1) / Tb_T) \] % Exergy loss\[ \text{sig}_{TI} = i.Tu(:,2) \times i.st(:,2) + i.Tu(:,3) \times i.st(:,3)\ldots + i.Tu(:,4) \times i.st(:,4) + i.Tu(:,5) \times i.st(:,5)\ldots + i.Tu(:,6) \times i.st(:,6) + i.Tu(:,7) \times i.st(:,7)\ldots - i.Tu(:,1) \times i.st(:,1)\ldots - (1/Tb_T) \times Q_{l_{TI}} \] % Entropy production using \( W_{TI} \)
\[ E_{d_{TI}} = -i.Tu(:,2) \times i.et(:,2) - i.Tu(:,3) \times i.et(:,3)\ldots - i.Tu(:,4) \times i.et(:,4) - i.Tu(:,5) \times i.et(:,5)\ldots - i.Tu(:,6) \times i.et(:,6) - i.Tu(:,7) \times i.et(:,7)\ldots + i.Tu(:,1) \times i.et(:,1)\ldots + E_{l_{TI}} - W_{TI} \] % Ed using exergy bal.
\[ E_{d_{TI}} = To(:,1) \times \text{sig}_{TI} \] % Ed at turbine
\[ \varepsilon_{TI} = \frac{W_{TI}}{i.Tu(:,1) \times i.et(:,1)\ldots - i.Tu(:,7) \times i.et(:,7)} \] % Exergy efficiency of turbine using \( W_{TI} \)

% Using method II
\[ E_{l_{TII}} = Q_{l_{TII}} \times (1 - To(:,1) / Tb_T) \] % Exergy loss
\[ \text{sig}_{TII} = i.Tu(:,2) \times i.st(:,2) + i.Tu(:,3) \times i.st(:,3)\ldots + i.Tu(:,4) \times i.st(:,4) + i.Tu(:,5) \times i.st(:,5)\ldots + i.Tu(:,6) \times i.st(:,6) + i.Tu(:,7) \times i.st(:,7)\ldots - i.Tu(:,1) \times i.st(:,1)\ldots - (1/Tb_T) \times Q_{l_{TII}} \] % Entropy production
\[ E_{d_{TII}} = -i.Tu(:,2) \times i.et(:,2) - i.Tu(:,3) \times i.et(:,3)\ldots - i.Tu(:,4) \times i.et(:,4) - i.Tu(:,5) \times i.et(:,5)\ldots - i.Tu(:,6) \times i.et(:,6) - i.Tu(:,7) \times i.et(:,7)\ldots + i.Tu(:,1) \times i.et(:,1)\ldots + E_{l_{TII}} - W_{TII} \] % Ed using exergy bal.
\begin{verbatim}
Ed_TII = To(:,1).*sig_TII; % Exergy destroyed at turbine using W_TII

eps_TII = (W_TII)/(i.Tu(:,1).*i.et(:,1)... -i.Tu(:,7).*i.et(:,7)); % Exergy efficiency of turbine using W_TII

% Plant analysis
% Energy values
Q_u_total_P = Q_u_total_B; % Total useful heat transfer
Q_in_P = Q_culm_total; % Total heat input from culm

% Internal power use
W_export_P = i.tu(:,26)*1000; % Exported kW
W_internal_P = W_gen - W_export_P; % Internal power use

% Plant energy analysis using TI
Q_l_total_P_TI = Q_l_total_B + Q_C... + Q_l_TII; % Total plant heat loss
EUF_P_TI = (-Q_process... + W_export_P)/(Q_in_P); % Plant EUF
n_th_P_TI = (W_export_P)/(Q_in_P); % Plant thermal efficiency

% Plant energy analysis using TII
Q_l_total_P_TII = Q_l_total_B + Q_C... + Q_l_TII; % Total plant heat loss
W_export_P_TII = W_gen_TII... - W_internal_P; % Exported kW
EUF_P_TII = (-Q_process... + W_export_P_TII)/(Q_in_P); % Plant EUF
n_th_P_TII = (W_export_P_TII)/(Q_in_P); % Plant energy efficiency

% Exergy values
E_in_total = E_in_B + (i.m_PA_b1 + i.m_SA_b1... + i.m_PA_b2 + i.m_SA_b2).*{(0.21*i.e_ch(10)... + 0.79*i.e_ch(11)}; % Total exergy into plant

% Exergy analysis using TI
Ed_total_P_TI = Ed_TI + Ed_BII_b1 + Ed_BII_b2 + Ed_C... + Ed_total_F; % Total exergy destroyed through the plant
E_l_P_TI = E_l_total_B + E_l_C + E_l_TII; % Exergy loss
E_out_u_TI = W_export_P - E_process; % Valued exergy output
E_out_total_TI = E_ash_total_B + E_FG_total_B... + E_out_u_TI - E_l_P_TI; % Total exergy out of plant
eps_P_TI = E_out_u_TI/E_in_B; % Exergy efficiency of plant

% Exergy analysis using TII
Ed_total_P_TII = Ed_TII_e + Ed_BII_b1 + Ed_BII_b2... + Ed_C + Ed_total_F; % Total Ed through the plant
\end{verbatim}
E_l_P_TII = E_l_total_B + E_l_C + E_l_TII;  % Exergy loss
E_out_u_TII = W_export_P_TII - E_process;  % Valued exergy output
E_out_total_TII = E_ash_total_B + E_FG_total_B...
    + E_out_u_TII - E_l_P_TII;             % Total exergy out of plant
eps_P_TII = E_out_u_TII./E_in_B;           % Exergy efficiency of plant

% Operational load comparisons
l = 1;
t = 1;
h = 1;
for j=1:i.row
    if load(j) == 1         % Low load
        n_B_avg_low(l) = n_B_avg(j);
        eps_avg_B_low(l) = eps_avg_B(j) ;
        nTs_low(l) = nTs(j) ;
        eps_T(l) = eps_TI(j);
        Q_l_total_P_TI_low(l) = Q_l_total_P_TI(j) ;
        W_export_P_low(l) = W_export_P(j);
        Q_in_P_low(l) = Q_in_P(j);
        EUF_P_TI_low(l) = EUF_P_TI(j);
        n_th_P_TI_low(l) = n_th_P_TI (j);
        Ed_total_P_TI_low(l) = Ed_total_P_TI(j);
        E_in_total_low(l) = E_in_total(j) ;
        E_l_P_TI_low(l) = E_l_P_TI(j) ;
        E_out_u_TI_low(l) = E_out_u_TI(j);
        eps_P_TI_low(l) = eps_P_TI(j) ;
        l=l+1;
    elseif load(j) == 2     % Transitional load
        n_B_avg_tran(t) = n_B_avg(j);
        eps_avg_B_tran(t) = eps_avg_B(j) ;
        nTs_tran(t) = nTs(j) ;
        Q_l_total_P_TI_tran(t) = Q_l_total_P_TI(j) ;
        W_export_P_tran(t) = W_export_P(j);
        Q_in_P_tran(t) = Q_in_P(j);
        EUF_P_TI_tran(t) = EUF_P_TI(j);
        n_th_P_TI_tran(t) = n_th_P_TI (j);
        Ed_total_P_TI_tran(t) = Ed_total_P_TI(j);
        E_in_total_tran(t) = E_in_total(j) ;
        E_l_P_TI_tran(t) = E_l_P_TI(j) ;
        E_out_u_TI_tran(t) = E_out_u_TI(j);
        eps_P_TI_tran(t) = eps_P_TI(j);
        t = t+1;
    elseif load(j) == 3     % High load
        n_B_avg_high(h) = n_B_avg(j);
        eps_avg_B_high(h) = eps_avg_B(j) ;
        nTs_high(h) = nTs(j) ;
Q_l_total_P_TI_high(h) = Q_l_total_P_TI(j);  
W_export_P_high(h) = W_export_P(j);  
Q_in_P_high(h) = Q_in_P(j);  
EUF_P_TI_high(h) = EUF_P_TI(j);  
n_th_P_TI_high(h) = n_th_P_TI (j);  
Ed_total_P_TI_high(h) = Ed_total_P_TI(j);  
E_in_total_high(h) = E_in_total(j);  
E_l_P_TI_high(h) = E_l_P_TI(j);  
E_out_u_TI_high(h) = E_out_u_TI(j);  
eps_P_TI_high(h) = eps_P_TI(j);  
h = h+1;
end
end

% Results of low/trans/high analysis 
R_Op_load(1,1)=mean(n_B_avg_low);  
R_Op_load(2,1)=mean(eps_avg_B_low);  
R_Op_load(3,1)=mean(nTs_low);  
R_Op_load(4,1)=mean(Q_in_P_low)/1000;  
R_Op_load(5,1)=mean(Q_l_total_P_TI_low)/1000;  
R_Op_load(6,1)=mean(W_export_P_low)/1000;  
R_Op_load(7,1)=mean(EUF_P_TI_low);  
R_Op_load(8,1)=mean(n_th_P_TI_low);  
R_Op_load(9,1)=mean(E_in_total_low)/1000;  
R_Op_load(10,1)=mean(E_out_u_TI_low)/1000;  
R_Op_load(11,1)=mean(E_l_P_TI_low)/1000;  
R_Op_load(12,1)=mean(Ed_total_P_TI_low)/1000;  
R_Op_load(13,1)=mean(eps_P_TI_low);  
R_Op_load(1,2)=mean(n_B_avg_tran);  
R_Op_load(2,2)=mean(eps_avg_B_tran);  
R_Op_load(3,2)=mean(nTs_tran);  
R_Op_load(4,2)=mean(Q_in_P_tran)/1000;  
R_Op_load(5,2)=mean(Q_l_total_P_TI_tran)/1000;  
R_Op_load(6,2)=mean(W_export_P_tran)/1000;  
R_Op_load(7,2)=mean(EUF_P_TI_tran);  
R_Op_load(8,2)=mean(n_th_P_TI_tran);  
R_Op_load(9,2)=mean(E_in_total_tran)/1000;  
R_Op_load(10,2)=mean(E_out_u_TI_tran)/1000;  
R_Op_load(11,2)=mean(E_l_P_TI_tran)/1000;  
R_Op_load(12,2)=mean(Ed_total_P_TI_tran)/1000;  
R_Op_load(13,2)=mean(eps_P_TI_tran);  
R_Op_load(1,3)=mean(n_B_avg_high);  
R_Op_load(2,3)=mean(eps_avg_B_high);  
R_Op_load(3,3)=mean(nTs_high);  
R_Op_load(4,3)=mean(Q_in_P_high)/1000;  
R_Op_load(5,3)=mean(Q_l_total_P_TI_high)/1000;  
R_Op_load(6,3)=mean(W_export_P_high)/1000;  
R_Op_load(7,3)=mean(EUF_P_TI_high);  
R_Op_load(8,3)=mean(n_th_P_TI_high);  
R_Op_load(9,3)=mean(E_in_total_high)/1000;  
R_Op_load(10,3)=mean(E_out_u_TI_high)/1000;  
R_Op_load(11,3)=mean(E_l_P_TI_high)/1000;  
R_Op_load(12,3)=mean(Ed_total_P_TI_high)/1000;  
R_Op_load(13,3)=mean(eps_P_TI_high);
% Increased process steam analysis
% Mass flow rate calculations
m_proc = 0.0333*i.Tu(:,1);  % Maximum process steam
m_T2_proc = i.Tu(:,2) + (m_proc-i.Tu(:,25));  % Flow through Ext. 5
m_T7Proc = i.Tu(:,1) - m_T2_proc - i.Tu(:,3) - i.Tu(:,4)
    - i.Tu(:,5) - i.Tu(:,6);  % Flow through exhaust

% Turbine energy analysis
W_T_proc = (i.Tu(:,1).*i.ht(:,1) - m_T2_proc.*i.ht(:,2)
    - i.Tu(:,3).*i.ht(:,3) - i.Tu(:,4).*i.ht(:,4)
    - i.Tu(:,5).*i.ht(:,5) - i.Tu(:,6).*i.ht(:,6)
    - m_T7Proc.*i.ht(:,7))/(1+i.H);  % W_T w/ max process steam
Ws_T_proc = (i.Tu(:,1).*i.hnts(:,1) - m_T2_proc.*i.hnts(:,2)
    - i.Tu(:,3).*i.hnts(:,3) - i.Tu(:,4).*i.hnts(:,4)
    - i.Tu(:,5).*i.hnts(:,5) - i.Tu(:,6).*i.hnts(:,6)
    - m_T7Proc.*i.hnts(:,7));  % Ws_T with max process steam

W_gen_proc = i.ngen*W_T_proc;  % Generator export
Q_l_T_proc = -i.H*W_T_proc;  % Turbine heat loss
Q_process_proc = m_proc.*(i.hc(:,4)-i.ht(:,2));  % Max process heat
nTs_proc = W_T_proc./Ws_T_proc;  % Isentropic efficiency

% Turbine exergy analysis
sig_T_proc = m_T2_proc.*i.st(:,2)
    + i.Tu(:,3).*i.st(:,3) + i.Tu(:,4).*i.st(:,4)
    + i.Tu(:,5).*i.st(:,5) + i.Tu(:,6).*i.st(:,6)
    + m_T7Proc.*i.st(:,7) - i.Tu(:,1).*i.st(:,1)
    - (1/Tb_T)*Q_l_T_proc;  % Entropy production rate
Ed_T_proc = To(:,1).*sig_T_proc;  % Exergy destroyed at turbine

E_process_proc = m_proc.*(i.ec(:,4)-i.et(:,2));  % Max process exergy
eps_T_proc = (W_T_proc)./mean(i.Tu(:,1).*i.et(:,1)
    - m_T7Proc.*i.et(:,7));  % Exergy efficiency

% Plant analysis with max process steam
W_export_P_proc = W_gen_proc - W_internal_P;  % Plant export
E_out_u_P_proc = W_export_P_proc - E_process_proc;  % Exergy leaving plant

EUF_proc = (-Q_process_proc + W_export_P_proc)./(Q_in_P);  % EUF
n_th_proc = (W_export_P_proc)./(Q_in_P);  % Plant energy efficiency
eps_P_proc = E_out_u_P_proc./E_in_B;  % Plant exergy eff

%**************************************************************************
% Turbine reheat analysis- uses average operational data
% Define properties downstream from reheat
\[ s_{T1} = \text{mean}(i.st(:,1)); \] % Average entropy at turbine inlet

% Turbine Exhaust
\[ T_{T7} = \text{mean}(i.Tu(:,14)) + 30; \] % Increased exhaust temperature
\[ p_{T7} = \text{mean}(i.Tu(:,21)); \] % Average pressure at exhaust
\[ h_{T7} = \text{XSteam}('h_pT', p_{T7}, T_{T7}); \] % Exhaust enthalpy
\[ s_{T7} = \text{XSteam}('s_pT', p_{T7}, T_{T7}); \] % Exhaust entropy
\[ e_{T7} = (h_{T7} - i.ho) - \text{mean}(To) * (s_{T7} - i.so); \] % Exhaust exergy flow

% Extraction 1
\[ T_{T6} = \frac{T_{T7}}{0.4}; \] % New Ext. 1 temperature
\[ p_{T6} = \text{mean}(i.Tu(:,20)); \] % Average pressure at Ext. 1
\[ h_{T6} = \text{XSteam}('h_pT', p_{T6}, T_{T6}); \] % Ext. 1 enthalpy
\[ s_{T6} = \text{XSteam}('s_pT', p_{T6}, T_{T6}); \] % Ext. 1 entropy
\[ e_{T6} = (h_{T6} - i.ho) - \text{mean}(To) * (s_{T6} - i.so); \] % Ext. 1 exergy flow

% Extraction 2
\[ T_{T5} = \frac{T_{T6}}{0.7}; \] % New Ext. 2 temperature
\[ p_{T5} = \text{mean}(i.Tu(:,19)); \] % Average pressure at Ext. 2
\[ h_{T5} = \text{XSteam}('h_pT', p_{T5}, T_{T5}); \] % Ext. 2 enthalpy
\[ s_{T5} = \text{XSteam}('s_pT', p_{T5}, T_{T5}); \] % Ext. 2 entropy
\[ e_{T5} = (h_{T5} - i.ho) - \text{mean}(To) * (s_{T5} - i.so); \] % Ext. 2 exergy flow

% Reheat flow from turbine to boiler
\[ T_{R1} = \text{mean}(i.Tu(:,11)); \] % Temperature - average Ext. 3
\[ p_{R1} = \text{mean}(i.Tu(:,18)); \] % Pressure - average Ext. 3
\[ h_{R1} = \text{XSteam}('h_pT', p_{R1}, T_{R1}); \] % Enthalpy
\[ s_{R1} = \text{XSteam}('s_pT', p_{R1}, T_{R1}); \] % Entropy
\[ e_{R1} = (h_{R1} - i.ho) - \text{mean}(To) * (s_{R1} - i.so); \] % Flow exergy

% Reheat return to turbine
\[ T_{R2} = \frac{T_{T5}}{1.5}; \] % Temperature increase by %150
\[ p_{R2} = p_{R1}; \] % Constant pressure through reheat
\[ h_{R2} = \text{XSteam}('h_pT', p_{R2}, T_{R2}); \] % Enthalpy
\[ s_{R2} = \text{XSteam}('s_pT', p_{R2}, T_{R2}); \] % Entropy
\[ e_{R2} = (h_{R2} - i.ho) - \text{mean}(To) * (s_{R2} - i.so); \] % Exergy flow

% Isentropic enthalpies downstream of reheat
\[ h_{sT7} = \text{XSteam}('h_ps', p_{T7}, s_{R2}); \] % Isentropic enthalpy
\[ h_{sT6} = \text{XSteam}('h_ps', p_{T6}, s_{R2}); \] % Isentropic enthalpy
\[ h_{sT5} = \text{XSteam}('h_ps', p_{T5}, s_{R2}); \] % Isentropic enthalpy
\[ h_{sR1} = \text{XSteam}('h_ps', p_{R1}, s_{T1}); \] % Isentropic enthalpy

% Mass flow rates for reheat
\[ m_{R} = \text{mean}(i.Tu(:,1) - i.Tu(:,2) - i.Tu(:,3) - i.Tu(:,4)); \] % Reheat steam flow
\[ m_{x} = \text{mean}(i.Tu(:,1) - i.Tu(:,2) - i.Tu(:,3)); \] % Flow of Ext. 3 and reheat

% Turbine energy analysis with reheat
\[ Q_{R} = m_{R} * (h_{R2} - h_{R1}); \] % Heat transfer into reheat steam
\[ m_{R\_culm} = Q_{R} / \text{i.HHV}_r; \] % Culm required for reheat
\[ W_{T\_R} = \text{mean}(m_{R} * h_{R2} + i.Tu(:,1) * i.ht(:,1) - i.Tu(:,2) * i.ht(:,2) - i.Tu(:,3) * i.ht(:,3) - m_{x} * i.ht(:,4) - i.Tu(:,5) * h_{T5} - i.Tu(:,6) * h_{T6} - i.Tu(:,7) * h_{T7})/(1+i.H); \] % Turbine work

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\[ W_{s\_T\_R} = \text{mean}\{(m_R \cdot h_{R2} + i.Tu(:,1) \cdot i.ht(:,1) - i.Tu(:,2) \cdot i.hts(:,2) - i.Tu(:,3) \cdot i.hts(:,3) - m_x \cdot h_{s\_R1} - i.Tu(:,5) \cdot h_{s\_T5} - i.Tu(:,6) \cdot h_{s\_T6} - i.Tu(:,7) \cdot h_{s\_T7})\}; \quad \% \text{Turbine isentropic work} \]

\[ nTs_{\_R} = \frac{W_{T\_R}}{W_{s\_T\_R}}; \quad \% \text{Isentropic eff.} \]

\[ Q_{l\_T\_R} = -(i.H) \cdot W_{T\_R}; \quad \% \text{Turbine heat loss} \]

\[ W_{\text{gen}\_R} = W_{T\_R} \cdot i\text{.ngen}; \quad \% \text{New generator work} \]

\% Turbine exergy analysis
\[ E_{l\_T\_R} = Q_{l\_T\_R} \cdot (1 - \text{mean}(To)/Tb_{\_T}); \quad \% \text{Exergy loss} \]

\[ e_{ps\_T\_R} = (W_{T\_R})/(\text{mean}(i.Tu(:,1) \cdot i.et(:,1) - i.Tu(:,7) \cdot e_{T7}); \quad \% \text{Turbine exergy efficiency} \]

\[ E_{d\_T\_R\_e} = \text{mean}(m_R \cdot e_{R2} + i.Tu(:,1) \cdot i.et(:,1) - i.Tu(:,2) \cdot i.et(:,2) - i.Tu(:,3) \cdot i.et(:,3) - m_x \cdot i.et(:,4) - i.Tu(:,5) \cdot e_{T5} - i.Tu(:,6) \cdot e_{T6} - i.Tu(:,7) \cdot e_{T7}) + E_{l\_T\_R} - W_{T\_R}; \quad \% \text{Exergy destruction} \]

\[ \text{sig}_{\_T\_R} = \text{mean}(-m_R \cdot s_{R2} - i.Tu(:,1) \cdot i.st(:,1) + i.Tu(:,2) \cdot i.st(:,2) + i.Tu(:,3) \cdot i.st(:,3) + m_x \cdot i.st(:,4) + i.Tu(:,5) \cdot s_{T5} + i.Tu(:,6) \cdot s_{T6} + i.Tu(:,7) \cdot s_{T7}) - (1/Tb_{\_T}) \cdot Q_{l\_T\_R}; \quad \% \text{Entropy production rate} \]

\[ E_{d\_T\_R} = \text{mean}(To) \cdot \text{sig}_{\_T\_R}; \quad \% \text{Ed at turbine} \]

\% Plant energy analysis with reheat
\[ W_{\text{export}\_P\_R} = W_{\text{gen}\_R} - \text{mean}(W_{\text{internal}\_P}); \quad \% \text{Exported power} \]

\[ Q_{\text{in}\_R} = \text{mean}(Q_{\text{culm}\_b1} + Q_{\text{culm}\_b2}) + Q_{\_R}; \quad \% \text{Total heat input} \]

\[ m_{\text{culm}\_P\_R} = \text{mean}(i.m_{\text{culm}\_b1} + i.m_{\text{culm}\_b2}) + m_R_{\text{culm}}; \quad \% \text{Total culm use} \]

\[ Q_{\text{u}\_R} = \text{mean}(Q_{\text{u\_total}\_P} - Q_{\_R}); \quad \% \text{Useful heat transfer} \]

\[ \text{EUF}_{\_R} = \text{mean}((-Q_{\text{process}} + W_{\text{export}\_P\_R})/Q_{\text{in}\_R}); \quad \% \text{EUF} \]

\[ n_{\text{th}\_R} = (W_{\text{export}\_P\_R})/(Q_{\text{in}\_R}); \quad \% \text{Plant thermal efficiency} \]

\% Plant exergy analysis with reheat
\[ E_{\text{u}\_R} = \text{mean}(Q_{\text{u}\_R} \cdot (1 - \text{mean}(To)/T_{\text{chamber}}); \quad \% \text{Useful exergy} \]

\[ E_{\text{in}\_R} = E_{\text{culm}\_b1} + E_{\text{culm}\_b2} + i.e_{\text{culm}} \cdot m_R_{\text{culm}}; \quad \% \text{Exergy into plant} \]

\[ E_{\text{out\_u}\_R} = W_{\text{export}\_P\_R} - E_{\text{process}}; \quad \% \text{Exergy out} \]

\[ e_{ps\_P\_R} = E_{\text{out\_u}\_R}/E_{\text{in}\_R}; \quad \% \text{Exergy efficiency} \]
EXPLORING THE USE OF EXERGY AND EXTERNALITY PARAMETERS TO EXAMINE A COGENERATION POWER PLANT

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Abstract. Within the last few decades, the importance of reducing negative human impacts on the environment has been recognized and established as a desirable goal. A number of methods have been employed to target and reduce negative impacts. Thermodynamics have been heavily used to identify system inefficiencies and identify ways in which inefficiencies can be reduced. More recently, exergy, a concept based on the second law of thermodynamics, has been used as an improvement on energy analysis alone. This paper discusses plans to re-examine an analysis of an 88.4 MW culm-based cogeneration power plant in the United States. An extended literature review and an overview of the planned research will be discussed. The plant in question uses local deposits of culm, a pollutant waste product of anthracite coal mining, as a feedstock. Before use within the plant, the culm is processed in a nearby facility to remove indigenous rock from usable coal. The previous work included limited first and second law analyses applied to actual operating data collected from the power plant; the planned work will expand the original work to generate a more complete and useful evaluation of the plant. Energy and exergy efficiencies will be determined at both component and system levels. The final analysis will also include an extended externality study to examine the impacts of the plant in terms of the environment, economics, and human health. The externality study of this particular plant is somewhat more complex than that of a traditional power plant because while pollutants are released into the environment through the energy conversion process, culm is removed from the surrounding area, which is beneficial. Further, rock and ash from the combustion process are used for the reclamation of land previously covered with culm. A lifecycle assessment will be performed during the externalities study to examine the environmental impacts of the plant. Exergy will be used through these analyses in order to quantify the many inputs and outputs of the system on a single scale. Once the extention of the previous analysis is complete, further research plans include component optimization and implementation of practical system improvements.

Keywords: Cogeneration, culm, exergy, externalities

1. INTRODUCTION

Newer and stricter emission policies appear as the impacts of pollution on the environment, natural resources, and human health are more fully understood. For ethical, legal, and economic reasons, power generation companies must work towards improving their overall plant efficiencies, lower their emissions, and all in all strive for more benign power production. The John B. Rich Memorial Power Station in Frackville, PA is designed in such a way that it produces fewer negative impacts on the environment than traditional coal-fired plants and therefore produces fewer impacts on human health and natural resources. The power station is a cogeneration power plant, meaning that a number of what would traditionally be waste streams are redirected to do useful work.

The plant feedstock is culm. Culm is a by-product of anthracite coal mining that has accumulated over the decades of Pennsylvania coal mining. During active mining, culm is deposited in huge piles around the mining area. Over time, these deposits leak harmful pollutants into the soil and ground water, making the land unable to support plant life.

The extended analysis of the cogeneration power plant will rely heavily on two methods of analysis: exergetic analysis and externality studies. The former analysis is useful in identifying processes within a system in which thermodynamic losses and waste occur. As discussed by Curtiss et al. (1996), externality studies focus on costs associated with a given process that have not been internalized by market forces or government regulations. In simple terms, externalities are unpaid for impacts caused by one party that affect another party.

In order to quantify the performance of the plant based on exergetic and externality analyses, a number of parameters will be examined. Parameters are areas of interest that will provide some insight into how the plant is
performing or affecting the surrounding area. Exergy parameters will include exergy destroyed and exergetic efficiency, while externality parameters will include the effects of the culm banks and the effects of emissions.

2. DISCUSSION OF EXERGY

Exergy can be explained simply as the amount of energy, relative to the environment, or dead state, which is available to do useful work. The reference environment is defined by a surrounding area with uniform temperature, pressure, and chemical composition, as explained by Moran and Shapiro (2004) and by Dewulf et al. (2007). As discussed by Chengquin et al. (2002), an improperly chosen dead state condition can lead to a poor estimation of the system’s exergetic efficiency. It is important that the reference environment be carefully chosen in order to create a meaningful exergetic analysis or model because exergy is relative; different dead state choices can lead to different analysis outcomes.

Energy analyses are based on the first law of thermodynamics, but exergy analyses are based on the second law. In a recent work, Dewulf et al. (2008) explain that traditional system analysis methods are somewhat limited in the information they can provide; energy analysis does not make a distinction between energy that is usable in a practical sense and energy that is not. As per its definition, exergy can be destroyed as a result of irreversibilities in a system; this characteristic makes it a valuable tool for determining useful system and component level efficiencies. Exergy can also be used in externalities studies, coupled with economics in thermoeconomic analyses, and incorporated in lifecycle assessments (LCA).

Exergy has been successfully applied to the analysis of various power generation plants. Rosen and Dincer (2003) discuss the application of exergy to the improvement of a coal-fired electricity generation plant, resulting in suggestions for improving efficiencies for major plant subsystems such as the boiler, condenser, and heat exchangers. In a different article, Rosen et al. (2005) use energy and exergy analyses on three configurations of a cogeneration-based district energy system, finding that exergetic efficiencies for all three examined configurations are lower than the corresponding energy efficiencies. The lower exergy efficiencies are expected because they take into account waste heat. The analyses are used to determine system and component level thermodynamic efficiencies, which could then be used to suggest system improvements. Kaushik et al. (2005) perform an exergetic analysis on a generalized cogeneration power plant in an effort to optimize the plant. Kaushik et al. specifically examined the effects of irreversibilities in the system on the cogeneration plant performance.

In thermoeconomics, costs are applied to thermodynamics analyses, thus determining the unit cost of energy in a given process. The practice of applying costs to units of energy is especially useful when examining power plants, for obvious reason; the goal of a power plant is to make money by producing electricity, so it is valuable to know how much money is spent on each unit of power produced. The same thermoeconomic procedure can also be used with exergy instead of energy. As with thermodynamic analyses, using exergy in a thermoeconomic analysis allows for areas of waste or loss energy in the process to be targeted, but thermoeconomics examine these in terms of money instead of energy.

Kwak et al. (2003) perform an exergoeconomics analysis on a combined cycle plant in order to encapsulate the whole cost of production, initial investments, and monetary losses due to irreversibilities in the system. Unit cost values are applied to exergy balance equations to produce cost-balance equations.

3. DISCUSSION OF EXTERNALITIES

As previously defined, externalities examine costs not accounted for in market mechanisms. An example of an externality may be acid rain damage to a historical monument; acid rain resulting from SO x emissions creates damage to the monument, however those responsible for the emissions do not pay for any repairs. The main areas examined within externality studies (human health, resource depletion, and environmental health) are also examined within LCA. Lifecycle assessments are a type of analysis that measures the total impact of a process or product over the span of its lifetime. An LCA could trace resource consumption and use all the way back to the extraction of raw materials, but this is often impractical because of the massive scale of such an analysis.

Externality studies and LCA analyses are two sides of the same coin; both analyses examine impacts in the same areas, mentioned above. The main difference between the two analyses is that externality studies strive to account for impacts that are not accounted for in the market, while LCA examines costs associated with and paid for to provide a product. A more complete picture of the plant’s impacts will be seen in the planned work through the examination of both the costs accounted for and costs not accounted for by the market.

Dewulf et al. (2007) use the concept of exergy to generate a comprehensive resource-based lifecycle impact assessment (LCIA) method. Although LCIA is a common analysis used to quantify the impact of a product or process in terms of resource “take away” from the environment, a single scale to compare all the various energies involved with the lifecycle is not readily available. All resources can be quantified on the same scale without the use of weighting factors by using exergy. The new method emphasizes the system boundaries in order to define
what natural resources, energy flows, and land are entering the industrial system. The method provides a thorough analysis because it takes into account the total exergy deprived from the natural system, not just exergy removed from it. For use in a similar assessment, De Meester et al. (2006) determine the chemical exergy content of 85 elements and 73 minerals for use in exergetic LCA (ELCA).

4. CONSIDERING ENVIRONMENTAL IMPACTS

As the over-arching goal of the planned work is to identify low efficiency areas within the Frackville cogeneration power plant and suggest improvements, it is vital to keep the plant’s environmental impacts in mind. The new emphasis on the environment that President Obama brings to the government makes the consideration of environmental impacts, especially emissions, even more important. The aforementioned topics of exergy and externalities have been used to analyze the impacts of power plants on the environment in the past, although exergy to a lesser degree.

Rosen (2002) presents reasons for using thermodynamics, especially exergy, to address environmental impacts. It is concluded that exergy is an excellent tool in determining inefficiencies within a system, more so than energy analysis alone; by lowering exergetic inefficiencies the environmental impact of a system can be reduced. Meyer et al. (2007) outline how to perform an “exergoenvironmental analysis” on an energy conversion system. An exergoenvironmental study determines the contribution of each component, in terms of exergy, to the total environmental impact of the system in a similar manner that a thermoeconomic study examines the contribution of each component to the total cost of a system. The analysis for each component includes an exergetic analysis, an LCA, assignment of environmental impacts to the exergy streams, the calculation of exergoenvironmental variables, and the exergoenvironmental evaluation.

Rosen et al. (2008) also examine the role of exergy in measuring sustainability. Rosen et al. discuss how a system’s exergetic efficiency can be used to qualify its level of sustainability, where complete sustainability is defined as having zero waste emissions or negative impacts on the environment. The sustainability of the system is closely related to its level of reversibility; the closer the plant exergetic efficiency is to 100%, the less exergy is destroyed within the plant and the closer the plant is to being reversible. A brief look into the area of externalities is also taken. The relationship between exergy and the environment is examined through the destruction of order and the depletion or use of resources. Dewulf and Van Langenhove (2002) provide a more quantitative examination of the relationship between exergy and sustainability. Dewulf and Van Langenhove define a non-sustainable process as one in which raw materials are removed from the ecosphere at a rate greater than they can be generated or if the process release harmful products into the environment. A methodology for examining impacts on the ecosphere, the technosphere, and society, including organic material, is examined. It can be noted that both these sets of research define sustainability is slightly different terms, thus highlighting the importance of explicitly defining sustainability within a given work.

5. OVERVIEW OF POWER PLANT

The power plant in question is an 88.4 MW culm based cogeneration power plant, schematic seen in Fig. 1, located in Frackville, Pennsylvania, USA. A small percentage of the steam coming off of the custom built, 18-stage impulse turbine (13,600 kg/h) is used for space and process heating in a nearby prison, as well as heating for the plant and attached office space.
Culm has lower energy content than anthracite coal - 3224 kJ/kg compared to 5160 kJ/kg. Before the culm can be fed into the boilers, it must be transported to a processing facility adjacent to the power plant, processed, and then transported via conveyor belt, seen in Fig. 2, to the power plant. The culm is placed in a dense liquid to separate the relatively heavy rock from the usable coal. The usable material is removed using centripetal motion. Unlike the fine powdered coal used in the more traditional pulverized coal power plant, culm is crushed into a more sand-like consistency. After the preparation process is complete, the culm is fed into two circulating fluidized bed (CFB) boilers. CFB boilers process low grade fuels, like culm, and allow for a greater resident time for the fuel within the boiler compared to traditional boilers, thereby allowing boiler temperatures to be lower than in other boilers. Nitrogen and oxygen react at temperatures above about 1480 °C, which is significantly higher than the CFB boiler temperature (~860°C). Also, the lower boiler temperature allows limestone to be added, which reacts with the sulfur released during culm combustion to form benign calcium sulfide. The lower temperature of the boiler thus causes two major pollutants, SOx and NOx, to be reduced to levels similar to comparably sized natural gas plants.
The power station sells the generated electricity to PPL (formerly known as Pennsylvania Power and Light), a power utility company that distributes the electricity throughout Pennsylvania. According to Dudish and Weaver (2009), prior to 2007, the John B. Rich Memorial Power Station was on a fixed rate contract with PPL. Since the end of said contract the power station has sold electricity to PPL at costs that vary by the hour. The overall wholesale cost of electricity has recently fallen, making the emphasis on efficiency even more important. Although it would seems that improvements to the plant design are more desirable in tough economic times, there will be a limit to what plant improvements can be implemented because it is necessary that such changes pay for themselves within a couple of years. The short payback time will limit plant improvements to either smaller changes or changes that will have a large impact the efficiency of the plant.

6. INITIAL ANALYSES

This work is built on previous work performed by Bailey et al. (2006). The previous work included a thermodynamic first and second law analysis of certain components of the plant and a brief externality study of the plant.

6.1. Initial Thermodynamic Model

The previous thermodynamic analysis is modeled using Engineering Equation Solver (EES) software. The thermodynamic model uses limited actual plant data including temperature, pressure, mass flow rate, etc. First law analyses are included for the turbine, boiler, condenser and total plant processes. Second law analyses are performed for the turbine, boiler, and total plant processes. It is assumed that the environmental temperature, $T_e$, is the temperature immediately surrounding each component, not the environmental temperature outside of the plant. Table 1 and Tab. 2 show the results from these analyses.

<table>
<thead>
<tr>
<th>Energy Flow Path</th>
<th>Power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator output</td>
<td>88.4</td>
</tr>
<tr>
<td>Power back to plant</td>
<td>7.25</td>
</tr>
<tr>
<td>Net power</td>
<td>81.2</td>
</tr>
<tr>
<td>Process heat rate</td>
<td>8.53</td>
</tr>
<tr>
<td>$Q_{\text{fuel}}$</td>
<td>309.5</td>
</tr>
<tr>
<td>$Q_{\text{steam}}$</td>
<td>251</td>
</tr>
</tbody>
</table>

Table 1. Initial energy first law analysis flow rates from Bailey et al. (2006).

<table>
<thead>
<tr>
<th>Component</th>
<th>$S_{\text{gen}}$ (kW/K)</th>
<th>$X_{\text{destroyed}}$ (MW)</th>
<th>$\dot{m}(e_{f1} - e_{f2})$ (MW)</th>
<th>Change in exergy ($dE_{\text{cv}}/dt$)</th>
<th>2nd law efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine</td>
<td>24.3</td>
<td>7.3</td>
<td>100.4</td>
<td>-1.22</td>
<td>92.70%</td>
</tr>
<tr>
<td>Boiler</td>
<td>474.8</td>
<td>146.3</td>
<td>...</td>
<td>-188.2</td>
<td>...</td>
</tr>
<tr>
<td>Cycle</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>34.5% (est.)</td>
</tr>
</tbody>
</table>

Table 2. Second law analysis of cogeneration plant from Bailey et al. (2006).

In the above tables, $Q_{\text{fuel}}$ is the total rate of energy associated with the culm feedstock added during the heat addition process, $Q_{\text{steam}}$ is the rate of heat transferred to the steam through the boiler, $S_{\text{gen}}$ is the entropy production...
rate associated with each component, $X_{\text{destroyed}}$ is the exergy destruction rate through each component included in Tab. 2, and $\dot{m}(e_{f1} - e_{f2})$ is the change in specific flow exergy rate through each component listed.

As can be seen in Tab. 2, there is no second law efficiency for the boiler. This is due to difficulties obtaining an exergy content value for the fuel. Some difficulties arose because the data used for the analysis is limited by the information recorded by the power plant- for instance, the power plant does not have accurate mass flow rates for all streams coming into and out of the boiler.

### 6.2. Initial Externality Analysis

The Frackville based plant is particularly interesting from an externality point of view. Culm deposits may be found where anthracite coal has been mined. When left in these deposits, culm leaches pollutants, such as aluminum, iron, and sulfates into the soil, making it impossible for normal plant life to grow, which then affects the area’s wildlife. Transportation of culm from the deposits to the culm processing facility produces pollution, as does the preparation process, but the culm pollutants no longer leak into the soil. Another positive effect the plant has on the surrounding area is water cleanup; make up water for the cooling towers is drawn from old mine pits, cleaned, and then returned to nearby streams when it is no longer needed. The water drawn from the mines is returned much cleaner than it was found. Further, the bottom ash, fly ash, and rock by-products of the culm preparation and combustion are used to reclaim the land scarred by the culm deposits. The cogeneration power plant has a complex relationship with the environment around it; pollution is produced with the transportation of culm and the production of energy, but land reclamation is also made possible. It is also important to keep in mind that the electrical power generated by the cogeneration power plant would, for better or worse, be produced in another plant if not this one.

The externality study previously performed on the Frackville power plant is brief, although it does point out where the study can be expanded. The previous study examines the costs of two pollutants, SO$_2$ and NO$_2$. General emission data for coal-fired power plants are used to generate the externality costs (including damages due to ozone formation, acid rain, and to human health) of these two pollutants for a conventional coal power plant, a total of 7,352,500 USD/year. Some estimates place culm based plant emissions to be 85-95% lower than those of comparably sized coal plants. The emissions of the culm-based power plant are therefore taken as 10% of a conventional power plan, resulting in an estimated externality cost of 735,350 USD/year.

### 7. RESEARCH PLANS

Of course, there is plenty of room to expand the initial results. The data available to the previous researchers was limited, however, since their analysis, more has become available. The restrictions on plant data mentioned previously will not be as much of an issue as before, however, some desirable data, such as mass flow rates, will still be estimated. The previous externality assessment was also limited to only a few environmental impacts, SO$_2$ and NO$_2$. Although these are prevalent and important pollutants, many other impacts exist that are equally valid. In the planned research, the thermodynamic model will be expanded to account for some deficiencies within the previous and initial work. The externality study will also be expanded to account for a number of other important factors such as CO$_2$. Unit cost values will be applied to aspects of the thermodynamic model and the externality study. By applying the cost values, the economic side of plant operation will be examined alongside the plant efficiencies and impacts. The economic analysis will provide insight into exactly where money is spent in the plant and how much inefficiencies and wastes are costing, or at least not earning, the plant owner.

Recent literature offers many ways in which a system can be analyzed with the end goal of suggesting improvements. Giannantoni et al. (2005) explain that a system, particularly a power producing system, can be improved in five major categories: energy, exergy, thermo-economic, environmental evaluation, and economic. In order to improve an existing system, energy, exergy, and thermo-economic analyses should first be conducted to determine sources of irreversibility and major inefficiencies. Once these problem areas have been identified and a number of feasible solutions proposed, each proposal is examined from an environmental and an economic standpoint. By allowing for flexibility within the work plan, necessary changes to previous steps may be made in an effort to arrive at the most impactful and practical suggestions possible.

### 7.1. Using Exergy and Externality Parameters

Many of the applications of exergy and externalities have been discussed throughout the literature review. The benefit of using exergy and externalities instead of energy and lifecycle assessments alone is that the former analyses provide a more clear and precise picture of where waste occurs in a process and who or what the process effects. The actual waste of the plant processes, indicated by exergy efficiencies, is especially important when making decisions about changes to the plant.
As discussed before, it is important to keep in mind what changes to the plant can actually be implemented and which improvements cannot be. It may be determined that the plant efficiency will be most improved by replacing the whole CFB boiler with a different type of technology, but this advice from a business standpoint is unrealistic, especially as a couple year payback time has moved from desirable to necessary. It may be found, however, that it is cost effective to add more insulation to the boiler in the superheater area. While such an addition may not improve the plant efficiency to as great a degree as replacing the whole boiler, it is a more realistic improvement at a more reasonable cost.

The exergy and externality parameters will be used as factors in optimization schemes to help determine how the plant could or should be improved. The cost function for such optimization schemes could be plant profits or plant efficiencies. Constraints to consider in an optimization scheme could be a certain number of years until payback, maintaining maximum power generation, and emission limits set by the government. Two potential areas for optimization are the cooling towers fans, only one of which is variable speed with the other three with high and low speeds, and maximizing the culm combustion within the boiler.

7.2. Thermodynamic Model

The improved thermodynamic model will more closely examine a number of major plant components and the plant as a whole. The analyses for the boiler, turbines, condenser, pumps, feedwater heaters, and other components of the plant will be reexamined and improved where necessary. An analysis of the overall plant will also be conducted. The EES software will be used to solve the model and observe how parameter changes (for example the environmental temperature due to seasonal change) can affect the plant performance.

Exergy will continue to be an important part of the plant analysis. By identifying both areas of exergy destruction and areas of exergy loss, a better idea will be formed of where plant improvements can be made. It will also be useful to rank the exergy efficiencies of and exergy destroyed at the different major plant components in order to identify where improvements will make the largest difference in the overall plant efficiency.

One problem encountered by the previous researchers was that although the energy content of culm is known, the exergy content is not. As discussed by Bilgen and Kaygusuz (2008), information such as the ash and moisture content, higher heating value, and chemical composition of culm can be used to determine the exergy content of a fuel. As part of the exergy analysis in the forthcoming work, the exergy of culm will be calculated based on data collected from culm samples coming into the plant.

A number of tools will be used as a basis by which the current power plant performance can be compared with proposed improvements. Both a thermodynamic analysis using energy and exergy and an externalities study (including an exergetic LCA) will be performed on the plant before making suggestions for plant improvement. It is necessary that these analyses be performed before possible improvements are generated because the performance of the plant cannot be defined in terms of efficiencies alone.

McMasters (2002) describes a methodology using least squares to determine the unit cost of delivering electricity and steam from a cogeneration power plant. The unit costs are found using the known boiler steam required per unit time, the amount of delivered steam per unit time, and the amount of electricity generated. Least squares are used to determine the ratio between kg boiler steam generated and kg delivered steam, the ratio between kg boiler steam generated and kWh delivered electricity, and the internal steam usage. The ratio values can be multiplied to the unit cost of boiler steam to determine the unit cost of delivered steam and delivered electricity. This type of analysis may become useful during the thermoeconomic study of the cogeneration power plant as unit costs must be applied to each term in the thermodynamic balance equations in order to determine the economic impacts of the plant components.

Dincer et al. (2007) provide straightforward and useful tools for calculating simple energy and exergy efficiencies for various power plants. Combined energy and exergy diagrams are also highlighted as effective and compact ways to display energy and exergy efficiencies. Wall (2003) presents a number of useful exergetic analysis tools including exergetic efficiencies, two types of exergy flow diagrams, exergy utility diagrams (EUDs), lifecycle exergy analysis (LCEA), and exergy economy optimization (EEO). The diagrams presented by Dincer et al. and Wall will be used to help understand the differences between the energy and exergy efficiencies of the plant and display the analysis information in a more meaningful way.

7.3. Externality Analysis

The externality study of the power plant from the previous work has a number of limitations. The complexities of the plant’s impact on the surrounding area make an externality study particularly difficult; some of the complications can be seen in Fig. 3 in which the major streams involved with the plant processes are shown. The culm pathway from culm bank to boiler is shown by a bold line, whereas the dashed lines indicate the pathway of all water through the plant. Harmful or wasteful products are indicated by square boxed text, while beneficial or useful
products are indicated by rounded boxed text. Harmful products include the emissions produced through the power generation process, while an example of waste is steam coming out of the cooling towers. On the other hand, a beneficial result of the entire process is cleared land and a useful product is the ash from combustion. The pollutants and emissions shown in this figure will be examined, starting with a more detailed examination of SO\textsubscript{x} and NO\textsubscript{x} emissions, and then examining CO\textsubscript{2} emissions. Carbon dioxide emissions are particularly important to examine because of the new U.S. administration’s plans for more stringent Cap-and-Trade policies on carbon emissions.

![Mind map for externalities of the cogeneration power plant](image)

Figure 3. Mind map for externalities of the cogeneration power plant

The intricacies of the relationship between the plant and the surrounding environment center on the fact that the total cycle of the plant, including the transportation of the culm to the plant, produces emissions, but at the same time also produces positive effects such as the removal of culm deposits and land reclamation. The study is further complicated when it is considered that the electricity and heat generated by the power plant would come from another, potentially “dirtier”, source if not this plant. It is therefore an oversight to examine the cogeneration power plant without considering possible impacts of attaining the electricity from another source. The alternative power plant to the cogeneration plant would not necessarily use a waste product as its feedstock, requiring a great deal of energy before electricity can even be generated. Because there are few power sources that release emissions at levels as low as the culm based cogeneration power plant, it must also be considered that an alternative energy source would likely increase the emissions released into the environment per unit electricity produced by a significant amount.

A lifecycle assessment will also be performed on the plant. The LCA should examine the impacts of the plant over its entire lifetime, but because the plant infrastructure is so complex, it will likely be easier to use LCA as a comparative tool between the cogeneration power plant and a similarly sized traditional coal fired power plant. By comparing the similar plants, the construction and end of life stages of the plants could be assumed about the same, leaving the plant operation as the difference. An analysis focusing on the operation stage of the plant will be a much simpler analysis to complete. The LCA information attained through the analysis will be helpful during the externality study because both analyses examine the impacts of the plant on human health, resource depletion, and environmental health. Because LCA analyses are more widely used and standardized than externality analyses, the inclusion of the LCA will help validate and support the externality study performed. The software SimaPro will be used to assist in the LCA.

Soeno et al. (2003) address the issue of a system’s environmental impact through the quantification of waste material exergy. The researchers determine the exergy flow by summing the exergy of the products, material waste, exhaust heat and losses, and entropy production. The exergetic analysis can be displayed through diagrams that
display both exergy and mass flow of a process. Each stage of a process is represented by an equilateral triangle; one side represents input resources, one side represents the products, and the last side represents the material waste. Arrow length is used to represent the magnitude of the exergy and the width is used to signify the mass. The environmental impact of the plant, as mentioned before, is an important part of the planned work’s analysis. Because the cogeneration power plant has such unique handling of waste streams, it will be interesting to examine the impacts of the plant through the methodology suggested by Soeno et al.

A common concern about externalities and lifecycle assessments is voiced throughout literature; Dewulf and Van Langenhove (2002) and Söderholm and Sundqvist (2003) explain that there is no single set of assumptions, especially in terms of costs, or one scale (for comparing different impacts) by which LCA and externality studies are performed. The non-standard assumptions and scales, along with the impact of boundary and scope definitions, in LCA and externality studies create a wide spectrum of possible outcomes, even when given the same system or process. It is therefore important to the current work to acknowledge and minimize uncertainties when performing either of these types of analyses.

Sundqvist (2004) examine the difficulties of placing monetary values on externality parameters. Depending on methods used, the assigned monetary values can vary. A graphical display of a survey of externality costs generated by various power generation methods is given in which a wide range of costs are found due to differing assumptions, conditions, and assigned values. Because externality studies are examined in terms of the monetary cost of unaccounted for impacts, it is important to keep consider the range of values that may be generated depending on the assumptions made in the work. One method of accounting for such uncertainties is suggested by Spadaro and Rabl (2008), who present a practical, simple, and transparent method of calculating the uncertainty associated with the damage costs of pollution. The presented method, as opposed to the more common use of Monte Carlo calculations, may be evaluated in a spreadsheet using sums and products.

CONCLUSION

The plan for a thermodynamic and externality analysis of an 88.4 MW cogeneration power plant using operation data is discussed. The plant in question has been examined before, but not to the same extent as the planned work. Previous literature on the subjects of exergy, power plant analysis, and externalities has been examined and summarized. Future work will include expanded first and second law thermodynamic analyses, an externality study including a lifecycle assessment, optimization of various plant components, and suggested changes in the plant for improved operations.

Certain exergy parameters, such as exergy destruction, losses, and efficiencies, and externality parameters, such as the effects of culm deposits on the Pennsylvania landscape and wildlife, and the effects of culm removal and land reclamation, will play a large role in assessing the performance of the power plant. The exergy parameters will be used to locate areas in the plant that are not utilizing energy to its fullest. The externality parameters will show both the damage and the benefits caused by the plant activity. An optimization study is planned that will include the mentioned parameters as factors in an attempt to maximize plant profits and minimize payback times for changes to the plant. Practical improvements for the plant will be suggested based on the results and presented to power plant personnel for consideration.

REFERENCES


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Comparative Thermodynamic Performance of a Cogeneration Power Plant Using Plant Operational Data

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Abstract: The John B. Rich Memorial Power Station, located in the United States, is an 88.4 MW cogeneration power plant with a unique relationship with its surrounding environment. The power station makes use of a plentiful and local byproduct of coal mining, called culm, as a feedstock. Culm is a low energy combination of anthracite coal and rock left over from the inefficient removal of rock from usable coal in the peak days of coal mining. For decades, culm deposits have leached pollution into groundwater and inhibited normal plant growth. By using culm, the power station removes a significant pollutant and eyesore from the area. Further, the power station is involved in a land reclamation program that covers land cleared of culm with topsoil and plant life. In order to process the culm, the power station utilizes two circulating fluidized bed (CFB) boilers. This work uses actual plant data to explore the thermodynamic performance of the plant. The first and second laws of thermodynamics are used to analyze the plant components, including the boilers, turbine, feedwater heaters, and condenser. The thermodynamic analyses are performed in part to determine properties through the plant, mainly mass flow rates that are not recorded during plant operation, and in part to characterize plant performance. Before the exergy analysis of the boilers can be performed, the streams into and out of each boiler must be characterized in terms of composition, mass, and exergy. Although the energy content of the culm is regularly measured by the power station, the exergy content must be determined based on the culm composition, which is provided by the plant. The exergy content of the flue gas is also determined based on the culm composition. The effects of sensor accuracy are briefly examined. The boiler performance is compared to other boiler technologies. A simple model of the plant with steam reheat is compared to the current plant configuration as well.

Keywords: Cogeneration, culm, exergy.

1. Introduction

The John B. Rich Memorial Power Station, in operation since the late 1980’s, has pursued a unique fuel source (culm) and uses a relatively new boiler technology. Culm is a low-grade anthracite coal by-product with an energy content of 3224 kJ/kg, compared to 5160 kJ/kg for anthracite coal [1].

As more and more power sources options become available, it has become increasingly relevant to quantify the performance of a given technology. Since there are so many available technologies and power sources, it is necessary to quantify performance in a way that enables one to make informed decisions in terms of cost, reliability, practicality, and environmental impact. In this work, the performance of the plant will be quantified and the boiler performance will be examined alongside other technologies.

Work was previously performed on the power station [1, 2], but will be expanded and improved upon during this analysis in a number of ways. First, this analysis takes advantage of actual temperature, pressure, and flow rate data collected throughout the plant, whereas the previous analyses used estimated and analytical data only. Second, this work includes a more detailed examination of the boiler and the interactions between each of the major sub-systems of the plant. Finally, this work suggests and models possible plant improvements.

2. Background

2.1. Exergy

The thermodynamic analysis of the plant will include an energy analysis as well as an exergy analysis. Unlike energy, exergy is not conserved, but may be destroyed through irreversibility. Exergy is also a comparative value; all exergy
measurements and analyses are performed with reference to a “dead state” or reference environment. The reference environment includes a uniform and unchanging temperature, pressure, and chemical composition [3].

2.2. Power station description

The power station in question delivers up to 88.4 MW of electricity to a local utility and 13,600 kg/h of steam to an adjacent correctional facility. On average, only about 4,939 kg/h of process steam is delivered from the plant.

The low operational temperature of CFB boilers (~860°C) cause two major emissions, NOₓ and SOₓ, to be much lower than a traditional pulverized coal power plant. NOₓ emissions are reduced because the reactions which produce the most NOₓ occur at temperatures above ~1480°C, which is much higher than CFB operational temperatures. The low CFB temperatures also allow limestone to be added to the combustion chambers, which effectively capture SO₂ formed during combustion, thereby reducing harmful SOₓ emissions.

The cogeneration plant uses an 18-stage turbine. Steam is extracted at 5 locations through the turbine to be used elsewhere in the plant or off site to serve a local district heating load. The turbine isentropic efficiency and the generator efficiency are reported by the manufacturer as 80% and 95%, respectively [2].

The total plant feedwater path may be seen in Fig. 1. The labels shown in the diagram are used through the models in the following sections.

*Fig. 1. Schematic of the feedwater path through the plant.*
2.3. Operational data

Data is collected throughout the power plant to monitor both resource use and for safety considerations. This analysis takes advantage of 79 of the hundreds of temperature, pressure, and flow rate data collection points through the plant. Each sensor has an associated accuracy range that will be used to help gauge model error.

3. Thermodynamic models

A few basic assumptions are made across all the models described in this work. These assumptions include steady-state operations, negligible kinetic and potential energy effects, and ideal gas models for air and flue gas. Since exergy is with reference to a dead state, the environmental conditions are as realistic as possible. This work uses seasonal average temperatures and pressure at the plant elevation (0.961 bar, 267-192.5 K).

3.1. Boiler sub-system

A control volume approach is taken around the boiler combustion chamber. The feedwater tubes are taken to be outside the boiler control volume.

Two sources of heat transfer are considered: \( \dot{Q}_{u,B} \) is the heat transfer from the combustion chamber to the feedwater, and \( \dot{Q}_{l,B} \) is the heat loss through the boiler walls. A simplified boiler schematic may be seen in Fig. 2.

![Figure 2. Schematic of boiler sub-system with control volume.](image)

3.1.1. Combustion reactions

The boiler model assumes 120% theoretical air and 9% residue carbon \((r=0.09)\) in the ash leaving the boiler. The residue carbon value is based on an analysis performed on the ash by the power plant. It should also be noted that the NO\(_x\) emissions are assumed to be all in the form of NO since NO is thermodynamically favoured over NO\(_2\) at temperatures below 1480°C [4]. The opposite is true in traditional coal fired plants where boiler temperatures are well above the reaction temperature for NO\(_2\) production [5].

The chemical reactions [4-6] within the boiler are given as:

\[
C + 1.2(Air) \rightarrow (1-r)CO_2 + (0.2 + r)O_2 + 4.512N_2 + rC \\
H + 1.2(Air) \rightarrow 0.5H_2O + 0.95O_2 + 4.512N_2
\]

(1)
\[ S + 1.2(\text{Air}) \rightarrow \text{SO}_2 + 0.2\text{O}_2 + 4.512\text{N}_2 \] (3)

\[ \text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2 \] (4)

\[ \text{CaO} + \text{SO}_2 + 1.2(\text{Air}) \rightarrow \text{CaSO}_4 + 0.7\text{O}_2 + 4.512\text{N}_2 \] (5)

\[ N + 1.2(\text{Air}) \rightarrow \text{NO} + 0.7\text{O}_2 + 4.512\text{N}_2 \] (6)

\[ O + 1.2(\text{Air}) \rightarrow \text{NO} + 1.2\text{O}_2 + 4.012\text{N}_2 \] (7)

where \((\text{Air}) = (\text{O}_2 + 3.76\text{N}_2)\).

### 3.1.2. Boiler energy considerations

Neglecting the fan and pump work, an energy balance around each boiler is given as

\[
\sum \dot{Q}_B = \dot{m}_{FG}(h_f^o + \Delta h)_{FG} + \dot{m}_{FA}(h_f^o + \Delta h)_{FA} + \dot{m}_{RA}(h_f^o + \Delta h)_{RA} - \dot{m}_{PA}(h_f^o + \Delta h)_{PA} - \dot{m}_{SA}(h_f^o + \Delta h)_{SA} - \dot{m}_{culm}(h_f^o + \Delta h)_{culm} - \dot{m}_{\text{CaCO}_3}(h_f^o + \Delta h)_{\text{CaCO}_3}\]

where \(\dot{m}_{PA}\) is the sum of the primary air streams, \(\dot{m}_{SA}\) is the sum of the secondary and duct burner air streams, \(\dot{m}_{culm}\) is the total culm used, \(\dot{m}_{\text{CaCO}_3}\) is the total limestone into the boiler, and

\[
\sum \dot{Q}_B = \dot{\bar{Q}}_{1,B} + \dot{\bar{Q}}_{u,B}.
\]

The energies associated with the formation of the flue gas and ashes are released or absorbed during the combustion process. Therefore, the enthalpy of formation values for the flue gas and ashes are included in the culm combustion energy release, described by the higher heating value of the fuel.

The change in enthalpy of the flue gas may be found with the ideal gas model, the ultimate and proximate analyses for culm, and the flue gas temperature [6]. The specific heat of flue gas model does not account for limestone addition, however, the effects of NO and SOx reduction are only about 1% worst case [6] and so are neglected. The enthalpies of both ashes are calculated as functions of temperature [4]. The limestone term in (8) is determined based on the limestone reactions using the following format:

\[
\dot{m}_{\text{CaCO}_3}(h_f^o + \Delta h)_{\text{CaCO}_3} = \sum_p \left[ \dot{n}_p (h_f^o + \Delta h)_p \right] - \sum_R \left[ \dot{n}_R (h_f^o + \Delta h)_R \right]
\] (9)

When a mass balance is performed on (4) and (5) it is found that \(\dot{n}_{\text{CaCO}_3} = \dot{n}_{\text{CO}_2} = \dot{n}_{\text{SO}_2} = \dot{n}_{\text{CaSO}_4}\). The limestone temperature as it enters the boiler is approximated as the reference temperature, however, the formation of CaSO4 occurs at the boiler chamber temperature. Therefore, the changes in enthalpy for the reactants in (9) cancel to zero, while the changes in enthalpy for the reactants do not. Equation (9) then becomes
The change in enthalpy values are calculated using the assumption of constant specific heat, while the enthalpy of formation values are found from chemical property tables [8].

The useful heat transfer for each boiler describes the heat delivered into the feedwater. This value may be found by examining the change in enthalpy of the feedwater entering and exiting the boiler heaters.

\[
\dot{Q}_{u,B} = \dot{m}_{FW} (h_{FW} - h_{SHS})
\]  

(11)

The boiler heat loss may then be found by solving (8) for \(\dot{Q}_{i,B} \):

\[
\dot{Q}_{i,B} = \dot{m}_{FA} \Delta h_{FA} + \dot{m}_{A4} \Delta h_{A4} - \dot{m}_{P4} \Delta h_{P4} - \dot{m}_{SA} \Delta h_{SA} - \dot{Q}_{u,B} - \dot{m}_{culm} (HHV) - \dot{m}_{CaCO3} (h^\circ_{f,0} + \Delta h)_{CaCO3}
\]  

(12)

The boiler efficiency is given as the ratio between the energy content of the fuel and the heat transferred to the feedwater.

\[
\eta_B = \frac{\dot{Q}_{u,B}}{\dot{Q}_{culm}} = \frac{\dot{Q}_{u,B}}{\dot{m}_{culm} (HHV)}
\]  

(13)

### 3.1.3. Boiler exergy considerations

The chemical exergy balance for the boiler may be used to find the exergy destroyed in the boiler:

\[
\dot{E}_{d,B} = (1 - T_o / T_B) \dot{Q}_{u,B} - (1 - T_o / T_c) \dot{Q}_{u,B} + \dot{m}_{PA} e_{PA} + \dot{m}_{SA} e_{SA} + \dot{m}_{culm} e_{culm}
\]

\[
+ \dot{m}_{CaCO3} e_{CaCO3} - \dot{m}_{B10} e_{B10}
\]

\[
+ \dot{m}_{B9} e_{B9} + \dot{m}_{B8} e_{B8}
\]

(14)

The flue gas exergy is calculated based on the flue gas temperature and the culm composition [6]. The culm exergy is also calculated based on the chemical composition of the fuel [7]. The exergetic efficiency for the boiler is given as the ratio between the useful exergy and the input exergy.

\[
\varepsilon_B = \frac{(1 - T_o / T_c) \dot{Q}_{u,B}}{\dot{E}_{culm} + \dot{E}_{PA} + \dot{E}_{SA} + \dot{E}_{CaCO3}}
\]  

(15)

### 3.2. Turbine, feedwater heaters, and condenser sub-systems

Although temperature and pressure data may be determined from plant data or using assumptions, the only flow rates recorded are the condensate makeup water (C4 on Fig. 1), steam out of boilers (T1 on Fig. 1), and the feedwater into the boilers (F7 on Fig. 1). By applying conservation of mass and energy balances to the feedwater heaters, the remaining mass flow rates may be found.

#### 3.2.1. Feedwater heater analysis
It is assumed that heat loss is negligible for each feedwater heater. Using conservation of mass through the feedwater heaters in Fig. 1, it is readily seen that

\[ \dot{m}_{F7} = \dot{m}_{F6} = \dot{m}_{F5} \]  \hspace{1cm} (16)

\[ \dot{m}_{F3} = \dot{m}_{F2} = \dot{m}_{F1} \]  \hspace{1cm} (17)

\[ \dot{m}_{F16} = \dot{m}_{F15} \]  \hspace{1cm} (18)

\[ \dot{m}_{F14} = \dot{m}_{F16} + \dot{m}_{F13} \]  \hspace{1cm} (19)

\[ \dot{m}_{F4} = \dot{m}_{F14} + \dot{m}_{F12} \]  \hspace{1cm} (20)

\[ \dot{m}_{F11} = \dot{m}_{F10} \]  \hspace{1cm} (21)

\[ \dot{m}_{F9} = \dot{m}_{F11} + \dot{m}_{F8} \]  \hspace{1cm} (22)

Solving an energy balance around FWH 5 for the flow rate at F15 and substituting in (16) and (18) gives

\[ \dot{m}_{F15} = \frac{\dot{m}_{F7}(h_{F7} - h_{F6})}{(h_{F15} - h_{F16})} \]  \hspace{1cm} (23)

An energy balance around FWH 4 and substituting (16), (19), and (23) may be solved for the flow rate through F13

\[ \dot{m}_{F13} = \dot{m}_{F6}(h_{F5} - h_{F6}) + \dot{m}_{F16}(h_{F16} - h_{F14}) \]  \hspace{1cm} (24)

If a control volume is applied around the turbine, condenser, FWH 2, and FWH 1, it may also be found with conservation of mass that

\[ \dot{m}_{F12} = \dot{m}_{F1} + \dot{m}_{C4} - \dot{m}_{F3} - \dot{m}_{F13} \]  \hspace{1cm} (25)

An energy balance around FWH 2 along with (17), and (21) gives

\[ \dot{m}_{F10} = \frac{\dot{m}_{F3}(h_{F2} - h_{F3})}{(h_{F11} - h_{F10})} \]  \hspace{1cm} (26)

An energy balance around FWH 1 with (17), (21), and (26) gives

\[ \dot{m}_{F8} = \frac{\dot{m}_{F2}(h_{F1} - h_{F2}) + \dot{m}_{F11}(h_{F11} - h_{F9})}{(h_{F9} - h_{F8})} \]  \hspace{1cm} (27)

Using (16) - (27), all flow rates through the FWH system are now known. The turbine extraction flow rates may now be calculated thus:

Extraction 5: \[ \dot{m}_{T2} = \dot{m}_{F15} + \dot{m}_{T25} \]  \hspace{1cm} (28)

Extraction 4: \[ \dot{m}_{T3} = \dot{m}_{F13} + \dot{m}_{C6} \]  \hspace{1cm} (29)
where $\dot{m}_{C6}$ is found by applying an energy balance around the boiler feed pump to find the work input, and then using that work in an energy balance around the boiler feed pump turbine and solving for $\dot{m}_{C6}$.

Extraction 3: $\dot{m}_{T4} = \dot{m}_{F12}$ \hspace{1cm} (30)

Extraction 2: $\dot{m}_{T5} = \dot{m}_{F10}$ \hspace{1cm} (31)

Extraction 1: $\dot{m}_{T6} = \dot{m}_{F8}$ \hspace{1cm} (32)

Turbine exhaust:

\[ m_{T7} = \dot{m}_{T1} - \dot{m}_{T2} - \dot{m}_{T3} - \dot{m}_{T4} - \dot{m}_{T5} - \dot{m}_{T6} \] \hspace{1cm} (33)

Finally, the missing flow rates through the condenser are found using conservation of mass:

\[ \dot{m}_{C3} = \dot{m}_{T7} \] \hspace{1cm} (34)

\[ \dot{m}_{C5} = \dot{m}_{F9} \] \hspace{1cm} (35)

\[ \dot{m}_{C7} = \dot{m}_{C3} + \dot{m}_{C4} + \dot{m}_{C5} + \dot{m}_{C6} \] \hspace{1cm} (36)

### 3.2.2. Turbine energy considerations

Based on plant information, the turbine exhaust and extraction 1 flows are taken to be mixtures with respective qualities of 89% and 97%. The heat loss from the turbine is based on a heat loss curve provided by the plant; it is assumed that the turbine heat loss is 0.7% of the work produced by the turbine, or

\[ \dot{Q}_{l,T} = -0.007\dot{W}_T \] \hspace{1cm} (37)

The work produced by the turbine may be calculated two ways. First, the generator efficiency may be applied to the generator export, which is carefully monitored by the plant. Second, an energy balance may be performed around the turbine using the calculated mass flow rates, assumed heat loss, and available temperature and pressure data. These work values will be referred to as $\dot{W}_{T,1}$ and $\dot{W}_{T,2}$, respectively, in the results section. Ideally these two values should be identical, however, because of assumptions and sensor errors, they are not.

An energy balance around the turbine gives

\[ \dot{Q}_{l,T} - \dot{W}_T = \sum_{out} \dot{m}h - \sum_{in} \dot{m}h \] \hspace{1cm} (38)

When (37) is applied to (38), the turbine work may be solved for as

\[ \dot{W}_T = -\left( \frac{1}{1.007} \right) \left[ \dot{m}_{T1}h_{T1} - \left( \dot{m}_{T2}h_{T2} + \dot{m}_{T3}h_{T3} + \dot{m}_{T4}h_{T4} + \dot{m}_{T5}h_{T5} + \dot{m}_{T6}h_{T6} + \dot{m}_{T7}h_{T7} \right) \right] \] \hspace{1cm} (39)

The isentropic turbine efficiency is useful for comparative and validation purposes, and may be calculated using

\[ \eta_s = \frac{\dot{W}_T}{\dot{W}_{Ts}} \] \hspace{1cm} (40)
where
\[
\dot{W}_{Ts} = \left( \frac{1}{1.007} \right) [\dot{m}_{T1} h_{T1} - (\dot{m}_{T2} h_{T2,s} + \dot{m}_{T3} h_{T3,s} + \dot{m}_{T4} h_{T4,s} + \dot{m}_{T5} h_{T5,s} + \dot{m}_{T6} h_{T6,s} + \dot{m}_{T7} h_{T7,s})] \tag{41}
\]

### 3.2.3. Turbine exergy considerations

The exergy destruction around the turbine is found from an exergy balance, which yields
\[
\dot{E}_{T,d} = \left( 1 - \frac{T_o}{T_{b,T}} \right) \dot{Q}_T - \dot{W}_T + \dot{m}_{T1} e_{f,T1} - \left[ \dot{m}_{T2} e_{f,T2} + \dot{m}_{T3} e_{f,T3} + \dot{m}_{T4} e_{f,T4} + \dot{m}_{T5} e_{f,T5} + \dot{m}_{T6} e_{f,T6} + \dot{m}_{T7} e_{f,T7} \right] \tag{42}
\]

The exergy efficiency compares the exergy of the desired output streams, meaning the turbine work, to the change in flow exergy across the turbine. The turbine exergy efficiency is then given as
\[
e_T = \frac{\dot{W}_T}{\dot{m}_{T1} e_{f,T1} - \dot{m}_{T7} e_{f,T7}} \tag{43}
\]

### 3.2.4. Feedwater heaters and condenser

The heat transfer to the cooling water that passes through the condenser is found using an energy balance:
\[
\dot{Q}_C = \dot{m}_{C7} h_{C7} - (\dot{m}_{C6} h_{C6} + \dot{m}_{C5} h_{C5} + \dot{m}_{C4} h_{C4} + \dot{m}_{C3} h_{C3}) \tag{44}
\]

The exergy destroyed in the condenser and each of the feedwater heaters are found by applying exergy balances to give
\[
\dot{E}_{d,C} = \left( 1 - \frac{T_o}{T_{b,T}} \right) \dot{Q}_C - \dot{m}_{C7} e_{C7} \tag{45}
\]
\[
\dot{E}_{d,FWH-1} = \dot{m}_{F8} e_{F8} + \dot{m}_{F11} e_{F11} \tag{46}
\]
\[
\dot{E}_{d,FWH-2} = \dot{m}_{F2} (e_{F2} - e_{F3}) \tag{47}
\]
\[
\dot{E}_{d,DA} = \dot{m}_{F12} e_{F12} + \dot{m}_{F3} e_{F3} \tag{48}
\]
\[ \dot{E}_{d,FWH-4} = \dot{m}_{F13}e_{F13} + \dot{m}_{F16}e_{F16} + \dot{m}_{F5}(e_{F5} - e_{F6}) - \dot{m}_{F14}e_{F14} \quad (49) \]

\[ \dot{E}_{d,FWH-5} = \dot{m}_{F15}(e_{F15} - e_{F16}) + \dot{m}_{F7}(e_{F7} - e_{F6}) \quad (50) \]

### 3.3. Total plant analysis

The total plant analysis pulls the subsystem analyses together to find the total performance of the plant. The total heat loss from the plant is given as the sum of the heat loss of each component

\[ \dot{Q}_{l,p} = \dot{Q}_{l,B_{\text{total}}} + \dot{Q}_{l,T} + \dot{Q}_{l,C} \quad (51) \]

where \( \dot{Q}_{l,B_{\text{total}}} \) is the sum of the heat losses from each boiler.

The work used internally for supporting the various pumps, fans, and lighting through the plant is found by taking the difference between the net power out of the plant, \( \dot{W}_{P,\text{net}} \), and power output of the turbine, \( \dot{W}_{\text{gen}} \).

\[ \dot{W}_{P,\text{in}} = \dot{W}_{\text{gen}} - \dot{W}_{P,\text{net}} \quad (52) \]

The energy utilization factor (EUF) for the plant takes into account the energy within the process steam, the electrical energy exported from the plant, and the total heat input into the plant. The EUF is given as [9]

\[ \text{EUF} = \frac{\dot{m}_{T25}(h_{C4} - h_{T25}) + \dot{W}_{P,\text{net}}}{\dot{Q}_{\text{culm}_{\text{total}}}} \quad (53) \]

where \( \dot{Q}_{\text{culm}_{\text{total}}} \) is the fuel energy added to the plant.

Since energy of the process steam is only a small fraction of the electrical energy, it may be neglected to find the plant thermal efficiency.

\[ \eta_{\text{th},P} = \frac{\dot{W}_{P,\text{net}}}{\dot{Q}_{\text{culm}_{\text{total}}}} \quad (54) \]

The energy types in the numerator of (53) are of differing qualities, which makes the EUF a sub-ideal performance indicator. The exergetic efficiency, given below, is a better measure of the plant performance since exergy accounts for the different types of energy. The net exergy out of the plant is equal to \( \dot{W}_{P,\text{net}} \).

\[ \varepsilon_p = \frac{\dot{m}_{T25}(e_{f,C4} - e_{f,T25}) + \dot{W}_{P,\text{net}}}{\dot{E}_{P,\text{in}}} \quad (55) \]

where the exergy input is equal to
\[ \dot{E}_{P,\text{in}} = \dot{m}_{culm} e_{culm} \]  

(56)

The total exergy destruction through the plant is given as the sum of the destruction in each subsystem

\[ \dot{E}_{d,P} = \dot{E}_{d,B} + \dot{E}_{d,T} + \dot{E}_{d,C} + \dot{E}_{d,F} \]  

(57)

3.3.1. Turbine improvements

The moisture content at extraction 1 and the turbine exhaust will wear the turbine blades at a faster rate than if the steam was superheated. With this in mind, the addition of steam reheat, shown in Fig. 3, between extraction 3 and 2 is explored.

![Figure 3. Schematic of simple turbine reheat scenario.](image)

<table>
<thead>
<tr>
<th>Energy Parameter (MW)</th>
<th>Previous Analysis</th>
<th>Current Work Using ( \dot{W}_{T,1} )</th>
<th>Current Work Using ( \dot{W}_{T,2} )</th>
<th>With Turbine Reheat</th>
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</tr>
<tr>
<td>( \dot{W}_{T} )</td>
<td>NA</td>
<td>90.17</td>
<td>77.81</td>
<td>85.87</td>
</tr>
<tr>
<td>( \dot{W}_{\text{gen}} )</td>
<td>88.4</td>
<td>85.66</td>
<td>73.92</td>
<td>81.57</td>
</tr>
</tbody>
</table>
Table 2. Summary of significant exergy parameters. NA indicates that data is not available.

<table>
<thead>
<tr>
<th>Exergy Parameter (MW)</th>
<th>Previous Analysis</th>
<th>Current Work Using $\dot{W}_{T,1}$</th>
<th>Current Work Using $\dot{W}_{T,2}$</th>
<th>With Turbine Reheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{E}_{\text{cum}}$</td>
<td>NA</td>
<td>314.26</td>
<td>314.26</td>
<td>342.66</td>
</tr>
<tr>
<td>$\dot{E}<em>{\text{PA} + \dot{E}</em>{\text{Sd}}}$</td>
<td>NA</td>
<td>5.77</td>
<td>5.77</td>
<td>NA</td>
</tr>
<tr>
<td>$\dot{E}_{\text{CO}_2}$</td>
<td>NA</td>
<td>0.002</td>
<td>0.002</td>
<td>NA</td>
</tr>
<tr>
<td>$\dot{E}_{\text{in, total}}$</td>
<td>NA</td>
<td>320.03</td>
<td>320.03</td>
<td>NA</td>
</tr>
<tr>
<td>$\dot{E}_{\text{process}}$</td>
<td>NA</td>
<td>1.66</td>
<td>1.66</td>
<td>NA</td>
</tr>
<tr>
<td>$\dot{E}_{\text{out, total}}$</td>
<td>NA</td>
<td>79.34</td>
<td>67.64</td>
<td>75.3</td>
</tr>
<tr>
<td>$\dot{E}_{\text{d,T}}$</td>
<td>7.3</td>
<td>13.43</td>
<td>13.43</td>
<td>14.78</td>
</tr>
<tr>
<td>$\dot{E}_{\text{d,C}}$</td>
<td>NA</td>
<td>5.53</td>
<td>5.53</td>
<td>NA</td>
</tr>
<tr>
<td>$\dot{E}_{\text{d,B total}}$</td>
<td>146.3</td>
<td>452.22</td>
<td>452.22</td>
<td>NA</td>
</tr>
<tr>
<td>$\dot{E}_{\text{d,FWH total}}$</td>
<td>NA</td>
<td>15.78</td>
<td>15.78</td>
<td>NA</td>
</tr>
<tr>
<td>$\dot{E}_{\text{d,total}}$</td>
<td>NA</td>
<td>486.96</td>
<td>486.96</td>
<td>NA</td>
</tr>
</tbody>
</table>

An analysis of the reheat process is performed using averaged data and a number of assumptions. The temperature at T7’ in Fig. 3 is assumed to be the temperature at T7 increased by 30°C to place it solidly in the superheated region. The temperatures upstream are back calculated from the T7’ temperature based on the relationships between the temperatures in the operational data- for instance, the temperature decrease of 40% is observed in the operational data between T6 and T7, so the temperature at T6’ will be found by applying a 40% increase from T7’. The pressures are assumed to remain unchanged from the no-reheat case.

Although the reheat will impact the feedwater heaters, condenser, and air and limestone addition to the boilers, this analysis will not go into such great detail. The heat required to increase the steam temperature and the necessary fuel use increase are both found. Since the overall efficiencies are based mainly on the fuel use and the power export, they may also be found.

4. Initial results

The analyses are performed using data collected at hourly intervals from Dec. 7- Dec. 30, 2009. These dates are chosen because of the even operation load throughout. Since the data used is from a winter month, the average winter reference conditions (0.961 bar, 267 K) will be used. The heat transfer and work parameters are listed in Tab. 1. Exergy parameters are in Table 2. Finally, the efficiency measures are given in Table 3.
Table 3. Summary of energy and exergy efficiencies. NA indicates that data is not available.

<table>
<thead>
<tr>
<th>Efficiencies (%)</th>
<th>Previous Analysis</th>
<th>Current Work Using $\dot{W}_{T,1}$</th>
<th>Current Work Using $\dot{W}_{T,2}$</th>
<th>With Turbine Reheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_B$</td>
<td>81</td>
<td>79.78</td>
<td>79.78</td>
<td>NA</td>
</tr>
<tr>
<td>$\eta_{T_h}$</td>
<td>~80</td>
<td>NA</td>
<td>82.19</td>
<td>79.82</td>
</tr>
<tr>
<td>$\eta_{th}$</td>
<td>26</td>
<td>25.63</td>
<td>21.74</td>
<td>22.15</td>
</tr>
<tr>
<td>EUF</td>
<td>29</td>
<td>26.98</td>
<td>23.10</td>
<td>23.38</td>
</tr>
<tr>
<td>$\varepsilon_T$</td>
<td>92.7</td>
<td>67.61</td>
<td>58.31</td>
<td>65.82</td>
</tr>
<tr>
<td>$\varepsilon_B$</td>
<td>NA</td>
<td>55.76</td>
<td>55.76</td>
<td>NA</td>
</tr>
<tr>
<td>$\varepsilon_p$</td>
<td>~34.5</td>
<td>25.40</td>
<td>21.63</td>
<td>22.18</td>
</tr>
</tbody>
</table>

The turbine reheat process requires an additional fuel use of 1.77 kg/s based on the additional energy transfer required to reheat the steam and the culm HHV.

5. Discussion

Of the two sets of outcomes from the current work, the first, based on the generator output, is more accurate for reasons outlined in the following section. It should be noted, however, that the reheat analysis should be compared to the second set of current work outcomes, based on the energy balance around the turbine. This is because the reheat analysis also depends on the energy balance method to determine the turbine work. Although the method is less accurate, the relative improvement of the reheat scenario may be seen and understood.

5.1. Accuracy

For the most part the results from this work and the previous work are within range. It may be noted, however, that there is a very large difference in the boiler exergy destruction rate. Because the previous analysis did not have a measurement of the culm exergy content, the methods in which they calculated the exergy destruction were very rough, whereas this work goes into detail about each exergy stream. The differences between the analyses have three major sources: actual data use, which includes effects of sensor accuracy, different reference conditions, and slightly different assumptions through the models. The error between the two turbine work methods is found to be 13.7%. Although this is a high error, the accuracy errors of the sensors must be considered. Since 36 sensors are used in the calculation of $\dot{W}_{T,2}$, and only 1 sensor for $\dot{W}_{T,1}$, it is expected that $\dot{W}_{T,2}$ is less accurate than $\dot{W}_{T,2}$. A range of turbine work can be established using the operational data and the corresponding sensor accuracies. An upper bound of 81.84 MW is found if all operational data is adjusted using the accuracies to yield the maximum turbine work, and a lower bound of 76.84 MW when the data is adjusted to yield the minimum turbine work. The sensor error therefore accounts for some of the turbine work error, but not all. The rest of the error between the two values may be attributed to assumptions used.

5.2. Comparisons

Although the picture given by the reheat to current comparison is incomplete, it does show how the overall plant performances increase when steam reheat is introduced. Since more energy overall will be entering the turbine, more power may be produced.

Energy and exergy analyses are performed on a number of non-CFB steam boilers [10]. It is found that the boiler energy efficiencies range from 72.46% for a boiler using nanofluids [10], to 84% for a boiler...
using sugarcane bagasse [11], to 93.76% for a boiler using heavy fuel oil [12]. Results found through this work, 79.8%, are well within this range.

Boiler exergy efficiencies have been given as 24.89% [10], 27.6% [11], and 43.8% [12]. The exergy efficiency for the boilers in this analysis, 55.8%, is higher than these analyses. These results suggest that CFB boilers using culm create less exergy destruction than a variety of other common steam boilers.

Although the efficiencies of the plant examined in this work may be better or worse than other plants, the environmental aspects of the plant are relatively desirable. There is little energy expended in the transport and preparation of culm as a fuel source. It is also notable that the culm deposits throughout mining country are harmful to the environment. When compared to the impact of a pulverized coal power station, the environmental impacts of the plant examined in this work are small. A traditional coal plant necessitates coal mining, transport, and pulverization, all of which take a great deal of energy, infrastructure, and labor.

5.3. Future work and conclusion

In order to have a better understanding of the environmental impact of the system, a more detailed examination of the combustion process and emissions in the boilers is needed. There are also many other plant improvements that will be quantified, such as the effects of increased process steam use and decreasing the residue carbon in the ash. Finally, the environmental impacts of the plant will be expanded and quantified through an externality analysis.

A thermodynamic analysis is performed on an 88 MW cogeneration power plant using actual operational data. The turbine is found to have an isentropic efficiency of 82.19% and an exergetic efficiency of 67.61%. The boiler is found to have energy and exergy efficiencies of 79.78% and 55.76%, respectively. The overall plant has a thermal efficiency of 25.63% and an exergetic efficiency of 25.40%.

**Nomenclature**

- $h, \bar{h}$ : enthalpy, kJ/kg, kJ/kmol
- $h_f^o, \bar{h}_f^o$ : enthalpy of formation, kJ/kg, kJ/kmol
- $r$ : residue carbon, %
- $s$ : entropy, kJ/(kg K)
- $\dot{m}$ : mass flow rate, kg/s
- $\dot{n}$ : molar flow rate, kmol/s
- $\dot{E}_d$ : exergy destroyed, MW
- $\dot{Q}$ : heat transfer, MW
- $\dot{W}$ : work, MW

**Greek symbols**

- $\eta$ : energy efficiency
- $\varepsilon$ : exergy efficiency

**Subscripts and superscripts**

- $c$ : combustion chamber
- $FG$ : flue gas
- $FA$ : fly ash
- $BA$ : bottom ash
FW  feedwater
SHS  super heated steam
T  turbine
B  boiler
F  feedwater heaters
C  condenser
P  plant
gen  generator
s  isentropic
u  useful
l  loss

References

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