Testing and Modeling of the Indirect Solar Drying of Thin Film Mangos

Oliver Montmayeur
oxm8465@rit.edu

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Testing and Modeling of the Indirect Solar Drying of Thin Film Mangos

By:
Olivier Montmayeur

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

Department of Mechanical Engineering
Kate Gleason College of Engineering

Rochester Institute of Technology
Rochester, NY
Submitted December 11th, 2019
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Department of Mechanical Engineering
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Approved by:

Dr. Robert Stevens, Associate Professor
Thesis Advisor, Department of Mechanical Engineering

Dr. Margaret Bailey, Professor
Committee Member, Department of Mechanical Engineering

Professor Sarah Brownell, Lecturer
Committee Member, Department of Design, Development and Manufacturing

Dr. Steven Weinstein, Department Head
Committee Member, Department of Chemical Engineering

Dr. Jason Kolodziej, Associate Professor
Department Representative, Department of Mechanical Engineering
ABSTRACT

In Haiti, 80% of rural people live in dire poverty living on less than a dollar a day. Cultivated and wild grown foods such as mangos and breadfruit could be used to reduce the economic and nutritional disparity for rural communities. Unfortunately in these areas there is a high amount of spoilage due to short harvesting seasons with high yields and lack of preservation options. 80% of breadfruit and 60% of mangoes are lost annually according to a local farmer’s co-op in Borgne, Haiti [1]. Based on a 2018 three-week collaborative design session with Rochester Institute of Technology (RIT) and the local women’s group SEE FANM (women for health, education, and economy), we identified mangos as a potential option for ”transfomayson fwi” - food transformation. Our team proposed drying mangos and then selling them as a juice powder in the off-season.

Food preservation by solar drying has become a widespread practice in developing countries. Dryers use solar energy and other supplementary energy sources to heat air entering a drying chamber. Drying is a complex heat and mass transfer process that can take hours or days depending on the properties of the food such as ripeness and temperature and humidity of the drying air. Many studies have attempted to model the transport of moisture within fruits to predict drying performance while others have experimented with different styles of solar dryer designs. These systems are mostly tested outside in variable ambient conditions where the local temperature, relative humidity, and solar flux constantly fluctuate introducing a significant amount of noise. This ”noise” is a product of these varying external conditions which affects the quality of the drying air and the performance of solar-thermal systems. Testing thermal systems in cold climates such as Rochester makes it impossible to predict performance in tropical regions like Haiti. This work focuses on eliminating many of these external factors in order to remove noise to provide faster and more repeatable testing.

A testing system was designed and built to simulate the output of a solar collector in a tropical environment to explore the impact of the collector size and dryer volumetric flowrate on drying performance in a highly consistent and controlled manner. Testing demonstrated the importance of external conditions during the falling drying rate regime, where internal diffusion typically dominates drying performance. The results of these tests are used to empirically fit a bulk drying model for a shrinking fruit film that exemplifies the impact of external conditions. This model allows for the prediction of drying performance for the first 85% of moisture removed from a
fruit film. A system model is also proposed that seeks to capture the deep layer effect associated with
drying multiple stacks of fruit. By fitting the thin layer and system model to experimental data, a
predictive model is proposed and used to explore design choices for the unglazed transpired solar
collector and horizontal drying chamber used in this study. Personal experience with prototyping
in Haiti led to the coupling of a simple preliminary economic model with the thin layer model to
provide the predicted output per capital spent for this solar dryer design.
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My engineering career has been influenced by many different people and I am grateful to all of them. I hope that this short testimony to their importance in my life does them justice. Foremost I want to thank Dr. Robert Stevens for his pivotal role in my education and life experiences. I came into RIT as a Mechanical Engineer but I had no idea how I was going to tie my education into my passion for helping people. One fateful semester I have Dr. Stevens as a professor for a class every day of the week, one such class being heat transfer. My interest in heat transfer drove me to express interest in an independent study with him on crop drying. Next thing I know I’m traveling to Haiti, working with amazing people, and feeling passionate about my thesis. He has been a great mentor and friend that I know I will reconnect with over the years to come. I can’t think of Haiti and not think about Professor Sarah Brownell and Jemssy Augustama. Sarah has been such an amazing and influential person in my life. The experience of using engineering to help real people in meaningful ways and to make connections with wonderful people in the community of Borgne has been a cherished memory of mine. Her passion instills a great motivation in me to do my best and Jemssy has helped tremendously to make this happen. Both times I visited Haiti Jemssy has been aspirational and resourceful beyond measure. His love for his community and his desire to improve life for everyone has been awe-inspiring. No matter where I will go, I know the “the mountains are calling”.

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The college experience is not complete without meeting other students in the process. I want to thank my senior design team, P19483, for sharing my aspiration for designing a cheap but effective dryer. The work our team, “It takes six to mango”, did on that project ran tangent to my own research, helping motivate and inspire creativity in my work. Everyone’s attitude made the project enjoyable and productive. Going through the thesis process is a unique experience, especially when you have fellow lab members to share it with. Brandon Mark, Kevin Skariah, and Tejan Adhikari have been amazing companions in the whole research process. The ability to talk about research as well as the ability to talk about anything but research with like-minded individuals is a treasured experience. They have been amazing friends and have brought a homely feeling to our Sustainable Energy Lab.

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TERMINOLOGY

Abbreviations

ANFIS = Adaptive-network-based fuzzy inference system
ANN = Artificial neural network
BET = Brunauer, Emmett and Telle model for sorption isotherms
CFD = Computational Fluid Dynamics
GAB = Guggenheim, Anderson and deBoer model for sorption isotherms
HOPE = Haiti Outreach Pwoje Espwa (Project Hope)
MC = Moisture Content
MR = Moisture Ratio
MSD = Multidisplinary Senior Design (RIT program)
NREL = National Renewable Energy Lab
NSRDB = National Solar Radiation Data Base
PID = Proportional Integral Derivative (controller)
PV = Photovoltaic
PVT = Photovoltaic-Thermal (collector)
PWM = Pulse-Width Modulation
RGPB = Rasanbleman Gwoupman Peyizan Bay
RH = Relative Humidity
RIT = Rochester Institute of Technology
RMSE = Root Mean Square Error
SAH = Solar air heater

SEE FANM = Santé/Health, Edikasyon/Education, Ekonomi/Economy for Fanm/Women

SSR = Solid State Relay

TGA = Thermo-Gravimetric Analysis

TMY = Typical Meteorological Year

TSC = Transpired Solar Collector

Nomenclature

\[ A_c = \text{Collector area (m}^2\text{)} \]

\[ c = \text{Molar concentration (mol/m}^3\text{)} \]

\[ C_b = \text{Constant for GAB Equation, relates to sorption enthalpy (-)} \]

\[ C_p = \text{Specific heat (J/kgK)} \]

\[ \bar{C}_p = \text{Combined specific heat of dry fruit and water (J/kgK)} \]

\[ D_0 = \text{Effective diffusivity at high temperatures (m}^2\text{)} \]

\[ D_{\text{eff}} = \text{Effective diffusivity (m}^2\text{)} \]

\[ E_a = \text{Arrhenius constant (J/mol)} \]

\[ h = \text{Convection coefficient (W/m}^2\text{K)} \]

\[ h_{\text{air}} = \text{Enthalpy of air (J/kg)} \]

\[ h_m = \text{Mass transfer coefficient (m/s)} \]

\[ h_r = \text{Radiative heat loss coefficient (W/m}^2\text{K)} \]

\[ I_c = \text{Incident solar intensity (W/m}^2\text{)} \]

\[ j = \text{Current simulation time step (-)} \]
\( k \) = Mass transfer coefficient \((\frac{m}{s})\)

\( K_{GAB} \) = Constant for GAB Equation, relates to sorption enthalpy (-)

\( L \) = Characteristic drying length (m)

\( m_d \) = Dry mass \((kg_{dry})\)

\( m_{dry} \) = Dry mass \((kg_{dry})\)

\( m_{initial} \) = Initial total fruit mass \((kg_{tot})\)

\( m_{total} \) = Total fruit mass \((kg_{tot})\)

\( m_w \) = Wet mass \((kg_{wet})\)

\( \dot{m}_{air} \) = Mass flow rate of air \((\frac{kg_{air}}{s})\)

\( \dot{m}_w \) = Mass flow rate of water \((\frac{kg_{wet}}{s})\)

\( M_e \) = Equilibrium moisture content \((\frac{kg_{wet}}{kg_{dry}})\)

\( M_o \) = Initial moisture content \((\frac{kg_{wet}}{kg_{dry}})\)

\( M_{db} \) = Dry basis moisture content \((\frac{kg_{wet}}{kg_{dry}})\)

\( M_{wb} \) = Wet basis moisture content \((\frac{kg_{wet}}{kg_{tot}})\)

\( M_{mon} \) = Monolayer moisture content in GAB equation \((\frac{kg_{wet}}{kg_{dry}})\)

\( MR \) = Moisture ratio, non-dimensionalized parameter (-)

\( \dot{N} \) = Molar removal rate \((\frac{mol}{s})\)

\( p_w \) = Vapor pressure of water in fruit (Pa)

\( p_{wo} \) = Vapor pressure of pure water at same temperature of \( p_w \) (Pa)

\( Q_u \) = Useful collector heat (W)

\( R \) = Universal gas constant \((\frac{J}{molK})\)

\( Re \) = Reynold’s number based on hydraulic diameter (-)

\( t \) = Time since start of drying (s)
\( T \) = Temperature \((K)\)

\( u_\infty \) = Free airstream velocity \((\text{m/s})\)

\( U \) = Overall heat loss coefficient \((\frac{W}{m^2K})\)

\( V_s \) = Rate air enters collector \((\frac{m}{s})\)

\( x \) = Distance of flow from edge of plate \((m)\)

\( W \) = Wet basis moisture content, weight fraction of water \((\frac{k_{g_{wet}}}{k_{g_{tot}}})\)

\( X \) = Dry basis moisture content \((\frac{k_{g_{wet}}}{k_{g_{dry}}})\)

\( X_{air} \) = Air humidity ratio \((\frac{k_{g_{water}}}{k_{g_{air}}})\)

**Subscripts**

\( drybulb \) = Air drybulb temperature

\( f \) = Final moisture state

\( in \) = Inlet to the tray zone

\( o \) = Initial moisture state

\( out \) = Outlet to the tray zone

\( P \) = Plate

\( 2 \) = Model state related to air above plate

\( 2w \) = Model state related air adjacent to fruit surface

\( 3 \) = Model state related to air below plate

\( \infty \) = Ambient
Greek Symbols

\( \alpha = \) Plate solar absorptivity (-)
\( \alpha_w = \) Water activity level (-)
\( \delta = \) Hydrodynamic boundary thickness (m)
\( \epsilon = \) Collector effectiveness (-)
\( \epsilon_* = \) Error of parameter * in measurement uncertainty (*C, W, etc. )
\( \eta = \) Collector efficiency (-)
\( \nu = \) Kinematic viscosity of air \( (\frac{m^2}{s}) \)
\( \phi = \) Relative Humidity (-)
\( \rho = \) Density of material \( (\frac{kg}{m^3}) \)
1 INTRODUCTION

1.1 Background

In developing countries where individuals live on limited income each day, any improvement in the availability of food or income is valuable. Limited education and availability of employment restricts the economic power for many to overcome their current situation. Families living in remote areas away from city centers often practice farming and harvesting techniques in order to provide food for themselves. For people living in towns such as Borgne, Haiti this is no exception. Despite fruitful yields from crops such as breadfruit and mangos, much of the fruit spoils due to lack of preservation methods and the amount of excess fruit during the harvest season. During the off season there is not enough food and hunger becomes a crippling factor for both adults and children. An interview conducted with the Rasanbleman Gwoupman Peyizan Bay (RGPB) group by Stevens on 3/17/18 revealed that local Haitian farmers claim to waste 80% of breadfruit and 60% of mangos available on both their farms and that which grows naturally [1]. In the Summer of 2018 myself, Stevens, and a group of other RIT students spent three weeks in Haiti working with a local women's group in Borgne, SEE FANM (Sante, Edikayson, Ekonomi FANM - Women for health, education, and economy). The women identified food waste as one of the most important issues for them, financial and health wise. This collaboration yielded a project designed to dry mangos for making drink powder and relies on a previously installed solar dryer. The goal of this project is to provide both a source of income to local women as well as increase access to local and nutritious foods for the community. The average Haitian citizen lives on less than a dollar a day and 80% of those who live in rural areas suffer from dire poverty [12]. Breadfruit is frequently quoted as a powerful tool for overcoming this hunger and economic barrier [13]. I personally returned to Borgne in the Fall of 2019 to experiment with various solar dryer designs to accomplish this. Limited access and high cost of local materials drives the need to make cheap but high quality dryer designs. The amount of fruit spoilage was evident to me as I was walking between communities; I had to stay on the side of the road because there were such a large amount of decaying mangos blocking the path. Each mango represents lost economic and nutritional capital to the community and my friends in Borgne that could be recovered through solar drying. Solar dryers are devices that provide a means of reducing the water content of foodstuffs. Academia and populaces around the world have sought to use solar dryers as a tool to sustainably preserve fruits/agricultural products.
Solar dryers often require no fossil fuels and limited maintenance costs once constructed, allowing a potential sustainable approach to food preservation. Designs frequently lack the ability to dry large amounts of food quickly and consistently. A dryer designed and tested in one location rarely performs identically in a different location. Designs utilizing only natural air circulation with no other heat sources or airflow controls are subject to the inconsistency of solar insolation. Dryers with airflow control but poor solar collector design experience low drying air temperatures and thus low drying rates. Dryers with multiple racks of fruit can perform poorly enough that they dry less fruit than less racks would due to poor airflow. All these issues stem from a decreased quality of the drying air that enters the solar dryer. Dryers are often built without any prior modeling, thus modeling on data collected from those systems is frequently only applicable to that specific dryer construction.

Theoretical modeling to predict drying response often assumes constant external conditions as well as how moisture moves in the foodstuff. Experimental studies reviewed in this work are mostly conducted in outside environments where ambient conditions are allowed to fluctuate; therefore, conditions between tests are inconsistent. This makes it difficult to predict performance of each dryer under different environmental conditions with different food types and sizes. Changes can be made to the dryer design such as increasing collector length to increase overall collector area or changing the collector style to change system performance. Recorded changes in drying performance cannot be solely attributed to the modification of the parameter since there is often environmental noise that might be greater than the effect from the design parameter changed. Variations in wind speed, wind direction, daily solar insolation, cloud cover, ambient temperatures and ambient relative humidity are all factors that affect drying performance. Testing of one system during a high insolation day cannot be equally compared to the performance of a different system on a cloudy day.

The goal of this work is to design a more effective solar dryer for the drying of mangos and other tropical fruits in tropical climates such as Haiti. Testing is conducted throughout this research to provide validation to design choices through the construction of a controlled testing environment. Changes to the flowrate of the air in the system, the thickness of the fruit, and the size of the solar collector were made to develop an understanding of their impact on solar drying. Based on the test results, a predictive drying model is derived and fit experimentally. This model is then used to further explore design choices. This thesis will then conclude with suggestions for
future work options and provide an assessment of a case study.

1.2 Literature Review

In order to design a more effective dryer for tropical climates, many aspects of the current drying technology need to be reviewed. First the parameters used to define the drying process are identified. Next the study explores how the drying process occurs and how it has been modeled. Finally a range of dryer designs is explored to understand the variety of dryer styles and design choices previous studies have made.

1.2.1 Drying Principles

Moisture content is an established way to measure the dryness of a material across industrial and engineering practices. Commonplace in agriculture is to describe the moisture content on a wet basis as

\[
M_{wb} = \frac{m_w}{m_w + m_d}
\]  

(1)

where \(m_w\) is the mass of water in the material and \(m_d\) is the mass of the dry material. This percentage ranges from 0% to 100% and changes during the drying period significantly as the denominator changes with time since it represents the total mass of the product. In some literature, the wet basis moisture content is also denoted by \(W\).

Dry basis moisture content has reportedly been used more frequently in engineering approaches to drying due the denominator being constant as the dry mass is fixed for a foodstuff. \cite{2}.

\[
M_{db} = \frac{m_w}{m_d}
\]  

(2)

The dry basis moisture content will vary from above 1 to 0 for most materials that start with high initial water content. It is also represented in some literature by \(X\) or simply \(M\).

If left in a constant environment, the moisture content of the fruit eventually approaches
the equilibrium moisture content, where there is no pressure gradient between water vapor in the fruit and the vapor in the surrounding drying air [2]. This equilibrium is defined by sorption isotherms which relate moisture content of the fruit’s surface for a given water activity level at a constant temperature [14]. Water activity level is defined as follows:

\[
a_w = \frac{P_w}{P_\text{wo}}
\]  

(3)

Water activity level, \(a_w\), is the relative humidity of the foodstuff where \(P_w\) and \(P_\text{wo}\) are the vapor pressure of the water in the fruit and the vapor pressure of pure water at the same temperature respectively. When a fruit achieves an equilibrium moisture content with the surrounding air, its water activity will be equal to the air’s relative humidity. An example relationship between the moisture content of a fruit and its water activity can be seen in Figure 1. The dotted line represents the equilibrium moisture content of the fruit’s surface during drying.

![Figure 1: Plot of absorption/desorption isotherms [2]](image)

The BET (Brunauer et al.) and GAB (Guggenheim, Anderson, de Boer) equations are widely used to model the relationship between monolayer moisture content and equilibrium moisture content [15] [16]. These models are based on theoretical approximations and assumptions surrounding the adsorption of gas molecules from a given surface. These models provide a relationship that uses multiple parameters determined experimentally. The BET and GAB equations define the relationship between the layer of food on the fruit surface and the layer of air immediately adjacent to it. The GAB equation is similar to the BET equation but instead of two fitting parameters
it uses three. Also the BET equation is only valid for water activity up to 0.50 \[17\]. The GAB equation is popular in the field of food technology and covers water activity ranging from 0-0.99 \[14\]. Common presentation of the GAB equation is as follows:

\[
\frac{M_{eq}}{M_{mon}} = \frac{C_b K_{GAB} \alpha_w}{(1 - K_{GAB} \alpha_w) \ast (1 - K_{GAB} \alpha_w + C_b K_{GAB} \alpha_w)}
\]  

(4)

where \(M_{mon}\) represents the monolayer moisture content. \(C_b\) and \(K_{GAB}\) represent constants related to sorption enthalpies. \(M_{mon}, C_b, K_{GAB}\) can be determined by curve fitting the GAB equation to experimental data. Kiranoudis has done this for several fruits such as bananas \[18\].

1.2.2 Stages of Drying

The phenomena of drying typically consists of several stages: a region of constant drying rate and two regions of decreasing drying rate. Initially there is a short period of thermal transience as the fruit warms up, during which the drying rate increases. After this brief period phase 1 begins where constant drying occurs from the surface of the product where moisture removed from the surface is replaced by diffusion internally such that the available surface for evaporation is the limiting factor \[3\]. During this phase the air adjacent to the fruit is fully saturated. Once phase 1 ends, a falling regime begins where diffusion is slow and moisture diffusion within the fruit limits the drying rate \[2\]. The falling regime can be further subdivided into a 2nd and 3rd phase. The second phase experiences drying limited by the evaporation of moisture as the surface goes from saturated to un-saturated. The third phase is limited by internal diffusion of moisture to the surface caused by the disappearance of the liquid film from the surface as the drying rate asymptotically approaches zero \[19\]. Figure 2 provides a visual representation of these regimes.
Karim suggests that the drying of most agricultural products exists mostly in the falling drying rate period \[20\]. Multiple studies suggest that many products begin at phase II due to their initial moisture content being close to point C on Figure 2 \[2\]. Point C is the critical point where constant drying ends and the falling drying rate regime begins. Most models are derived assuming that drying immediately begins in the falling rate regime.

1.2.3 Thin and Deep Layer Analysis

During the drying process, moisture is removed from the surface of the foodstuff and absorbed into the drying air. Based on the setup of the drying process and the size of the dried product, the drying process can either be considered as thin layer or deep bed drying. In most models the thin layer approach is used where it is assumed that the volume of drying air is much greater than the crop volume \[3\]. Thus any moisture removed from the slice does not impact the characteristics of the drying air in term of its ability to carry water. Deep bed drying on the other hand assumes that as drying air passes over the trays or arrangement of fruit, the air’s ability to carry water changes. Demonstration of deep layer effects is shown in Figure \[3\].
The scenario seen above in Figure 3 is that as the drying air moves up in the dryer, it becomes more saturated and decreases in temperature. Normally each layer of this dryer would dry at the same rate if every portion started at the same initial moisture content in a thin layer analysis. However in deep bed drying the first portion of the drying chamber near the inlet of the air dries the fastest and from there the drying rate decreases. Thus layers at the outlet of the chamber will experience poor drying conditions for an extended period of time when a deep bed layer approach is used. The drying rates in the last trays will go up as the inlet trays dry and no longer add water into the airstream. The peak rate for those trays in a deep bed analysis will be lower than if the trays had been exposed to the inlet conditions the whole time (such as the inlet tray). Presentation of this phenomena is provided by tray discretization performed by Srivastava where the drying chamber is broken up into unique nodal points.

1.2.4 Theoretical Models

Approaches to theoretical models for drying involve solving Fick’s law of mass transport by using several simplifying assumptions. This is done to obtain a closed form for the dry basis moisture content as a function of time. Bulk mass transport is assumed to take place from a homogeneous initial state and continue under constant external conditions. The food product is modeled as an infinite long and wide slab with key assumptions that the product has a uniform initial moisture content and the exposed surface moisture content is in equilibrium with the drying
air at all times. Delgado presents a delineated derivation of the excess moisture ratio (MR) using the infinite series solution from Fick’s 2nd law of diffusion [22].

\[ MR = \frac{M - M_e}{M_o - M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp \left[ -\frac{(2n-1)^2 \pi^2 D_{eff} t}{4L^2} \right] \]  

(5)

where \( M_e \) is the equilibrium moisture content of the fruit for the given temperature and relative humidity of the drying air, which can be modeled by the GAB equation or similar function. \( M_o \) represents the initial moisture content of the foodstuff prior to drying. Typically the infinite sum is replaced by the first term in the series as higher orders approach zero. The first term approximation is shown in Eq. (6).

\[ MR = -\frac{8}{\pi^2} \exp\left(-\frac{\pi^2}{4L^2} D_{eff} t\right) \]  

(6)

Above, the dried product is roughly generalized such that only the \( D_{eff} \) is a parameter specific to the foodstuff and is assumed constant throughout the drying period. \( D_{eff} \) represents the effective diffusivity for the Arrhenius relationship presented below:

\[ D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \]  

(7)

The effective diffusivity is a function of some reference diffusivity at a higher temperature, \( D_0 \), the activation energy, \( E_a \), the universal gas constant, \( R \), and the absolute temperature of the material, \( T \). In the first term approximation the effective diffusion coefficient is assumed to be constant. Therefore the relative humidity and temperature of the surrounding air is also treated as a constant. Eq. (6) is only a function of time and assumes that the fruit is uniformly changing in moisture content with time. It is also assumed that as moisture is removed, internal properties such as diffusivity remain constant and no shrinkage occurs.

1.2.5 Semi-Empirical Models

It is commonplace in many pieces of literature to replace this infinite series and the material specific parameters with generalized functions involving time and empirically derived parameters. The MR proportion remains the same but researchers pick between various semi-theoretical models that have found common place in modeling, both Singh and Apkinar recognize the following
Table 1: Enumeration of various semi-empirical and empirical drying models [9]

<table>
<thead>
<tr>
<th>Model no.</th>
<th>Model name</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Newton</td>
<td>$MR = \exp(-kt)$</td>
</tr>
<tr>
<td>2</td>
<td>Page</td>
<td>$MR = \exp(-kt')$</td>
</tr>
<tr>
<td>3</td>
<td>Modified page</td>
<td>$MR = \exp(-(kt)^p)$</td>
</tr>
<tr>
<td>4</td>
<td>Henderson and Pabis</td>
<td>$MR = a\exp(-kt)$</td>
</tr>
<tr>
<td>5</td>
<td>Logarithmic</td>
<td>$MR = a\exp(-kt) + c$</td>
</tr>
<tr>
<td>6</td>
<td>Two-term</td>
<td>$MR = a\exp(-kgt) + b\exp(-kt)$</td>
</tr>
<tr>
<td>7</td>
<td>Two-term exponential</td>
<td>$MR = a\exp(-kt) + (1-a)\exp(-kgt)$</td>
</tr>
<tr>
<td>8</td>
<td>Wang and Singh</td>
<td>$MR = 1 + at + bt^2$</td>
</tr>
<tr>
<td>9</td>
<td>Diffusion approach</td>
<td>$MR = a\exp(-kt) + (1-a)\exp(-kbt)$</td>
</tr>
<tr>
<td>10</td>
<td>Modified Henderson and Pabis</td>
<td>$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$</td>
</tr>
<tr>
<td>11</td>
<td>Verma et al.</td>
<td>$MR = a\exp(-kt) + (1-a)\exp(-gt)$</td>
</tr>
<tr>
<td>12</td>
<td>Midilli and Kucuk</td>
<td>$MR = a\exp(-kt) + bt$</td>
</tr>
<tr>
<td>13</td>
<td>Thompson</td>
<td>$t = a\ln(MR) + b(\ln(MR))^2$</td>
</tr>
</tbody>
</table>

Statistical analysis is done to derive best fit parameters for accompanying data sets with methods such as chi-squared, mean bias error, and root mean square error. Work done on chili peppers by Akintunde demonstrates this by using the Henderson and Pabis, Newton, Logarithmic, and Page models to fit the drying of uniquely prepared chili peppers [23]. Akintunde pretreated the peppers through water, steam blanching, and an osmotic coating. His conclusions on the pretreatment are based on the experimental data response only (pretreated drying faster), not the semi-empirical model. The four models his study used were applied after data was collected and while the Page model was declared the best fit for the collected data, it only had an RMS that is on the order of .001 higher than the next option. This type of modeling is only useful after a system has been built and data has been collected. This method of mathematical modeling is quite frequently seen in research studies and is limited in its ability to predict responses prior to testing. Other mathematical models have been pursued to provide such estimates prior to testing. Prakash et al. present the analysis of computational fluid dynamics (CFD), adaptive-network-based fuzzy inference system (ANFIS), artificial neural network (ANN), fuzzy modeling, thermal modeling, and lastly mathematical modeling using the MR approach described above [24].

For CFD modeling the following is assumed when analyzing the Navier-Stokes equation: fixed inlet and outlet mass flow rates where the shear stress of the fluid in the air is assumed. Bartzanas et al. used the CFD modeling to predict the ventilation and airflow inside greenhouse
dryers. His study states that the numerical approach found good agreement with experimental results; though he concludes at the end that with a different greenhouse type or wind direction - the results could be different [25]. ANFIS modeling is part of an adaptive neural network that is functionally equivalent to a fuzzy inference systems. ANFIS and ANN are quite similar, where ANFIS utilizes the method designed by Neuro-Taguchi’s method to improve accuracy over ANN [26]. These non-linear controllers take multiple variable inputs and act like a nervous system, adapting and then predicting. Predominately this modeling is done for optimizing energy efficiencies of dryer arrangements to maximize economic value. Bagheri et al. setup a physical dryer for the drying of leafy vegetables. Energy efficiency for the testing is partially based on mass of fruit dried but no comments are made as to the behavior of the drying. Only conclusion provided is that the ANFIS model was able to predict the energy efficiency of the system. Additionally the nature of how the ANFIS model was configured is unclear. Thermal modeling focuses on predicting the collector performance as a way to maximize dryer effectiveness. The vapor pressures in the system from this approach is used to solve for moisture removal in each zone. Arulanandam used this with CFD analysis to predict the response of an unglazed transpired solar collector through simulation but did not include any physical testing [27].

Since the drying time line of most agricultural products falls in the falling rate regime where diffusion within the product determines moisture removal, effort is placed into modeling the transfer phenomena inside of the foodstuff. Yet in Prakash’s review of these six methods, only the CFD and thermal modeling detail specific attempts to model transport phenomena. Rabha et al. preformed modeling for the comparison of ghost chili peppers via open sun and by convection drying, fitting 10 of the MR models shown to the collected data [10]. Rabha et al. also cited studies done by other researchers on various other peppers with different drying methods. By doing so Rabha illustrates how different types of peppers and different types of dryers can result in different "best-fit" models being selected to fit experimental drying curves. This emphasizes the ambiguity of these models as some fits will work better than others for certain setups. Thus there is no one semi-empirical model that is used to predict the response of any setup or pepper type. Table 2 shows the various best fit conclusions for pepper drying as discussed by Rabha et al. [10].
Table 2: Best fit semi-empirical models for various peppers [10]

<table>
<thead>
<tr>
<th>Type of pepper</th>
<th>Dryer</th>
<th>Drying conditions</th>
<th>Drying models/function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green sweet pepper</td>
<td>Forced convection solar dryer and open sun drying</td>
<td>$T = 43.9 - 64.8 , ^\circ C$&lt;br&gt;$V = \text{not available}$</td>
<td>Logarithmic (solar drying) and Midilli and Kucuk (sun drying)</td>
</tr>
<tr>
<td>Red chilli pepper</td>
<td>Direct cabinet type solar dryer and open sun drying</td>
<td>Mean $T = 45 , ^\circ C$&lt;br&gt;$V = \text{not available}$</td>
<td>Page</td>
</tr>
<tr>
<td>Red pepper</td>
<td>Cabinet dryer</td>
<td>$T = 50 - 60 , ^\circ C$&lt;br&gt;$V = \text{not available}$</td>
<td>Page</td>
</tr>
<tr>
<td>Green chilli Balujuri</td>
<td>Overflow-underflow/through flow drying chamber</td>
<td>$T = 40 - 60 , ^\circ C$&lt;br&gt;$V = 0.1 - 1 , m/s$</td>
<td>Page</td>
</tr>
<tr>
<td>Sweet pepper</td>
<td>Cabinet dryer</td>
<td>$T = 40 - 70 , ^\circ C$&lt;br&gt;$V = 1.5 , m/s$</td>
<td>Logarithmic</td>
</tr>
<tr>
<td>Red bell pepper</td>
<td>Convective dryer</td>
<td>$T = 50 - 80 , ^\circ C$&lt;br&gt;$V = 2.5 , m/s$</td>
<td>Modified page</td>
</tr>
<tr>
<td>Green bell pepper</td>
<td>Ventilated oven</td>
<td>$T = 30 - 70 , ^\circ C$&lt;br&gt;$V = 0.85 - 1.09 , m/s$</td>
<td>Page and Newton</td>
</tr>
<tr>
<td>Bird’s eye chilli</td>
<td>Fluidized bed dryer</td>
<td>$T = 50 - 70 , ^\circ C$&lt;br&gt;$V = \text{not available}$</td>
<td>Second degree polynomial function</td>
</tr>
<tr>
<td>Green pepper</td>
<td>Microwave oven</td>
<td>$T$ and $V$ not available</td>
<td>Midilli and Kucuk model</td>
</tr>
</tbody>
</table>

1.2.6 Empirical Models

It is apparent from Table 2 that different approaches to drying and different foodstuffs demand different models. There are a few fully empirical models that Delgado suggested in his review of modeling approaches that directly relate moisture content with time without any physical connection to the drying process, whereas the MR models shown in Table 1 are adaptations of Fick’s law albeit simplified.

Akpinar et al. considered these empirical based models in their investigation into the optimal thin layer drying models for potatoes, apples and pumpkins. [11]. While Akpinar determined the Midilli and Kucuk to be the best fit for all three fruits, the empirical fits demonstrated as much error as many of the other semi-empirical fits presented. The empirical and semi-empirical models presented above contain generalized fitting parameters that can be tweaked to obtain excellent results such as the results shown below in Table 3. These parameters generally lack physical significance to the drying phenomena and are all only used for individual studies. The Modified Page model is mathematically identical to the Page model but does offer the ability to give the parameter $k$ a physical meaning. However, no studies presented in this review have used the optimized fits from one study to model data collected from a different test. Also little to no commentary is made on the differences between the constants determined by different studies for the same fruit for the papers reviewed in this section. The extent of comparisons made is the confirmation of the drying regimes seen during testing being in “good agreement” with other studies [23][9]. Table 3 presents...
statistical analysis performed by Akpınar for the drying of pumpkin.

Table 3: Presentation of goodness of fit from a study performed by Akpınar [11]

<table>
<thead>
<tr>
<th>Model name</th>
<th>$R$</th>
<th>$I^2$</th>
<th>$R$</th>
<th>$I^2$</th>
<th>$R$</th>
<th>$I^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T = 80 , ^\circ C, V = 1.5 , m/s; 1$st tray</td>
<td></td>
<td></td>
<td>Potato $(12.5 \times 12.5 \times 25)$</td>
<td>Apple $(12.5 \times 12.5 \times 25)$</td>
<td>Pumpkin</td>
<td></td>
</tr>
<tr>
<td>Newton</td>
<td>0.99871</td>
<td>$1.88 \times 10^{-4}$</td>
<td>0.99875</td>
<td>$2.35 \times 10^{-4}$</td>
<td>0.98973</td>
<td>$2.14 \times 10^{-3}$</td>
</tr>
<tr>
<td>Page</td>
<td>0.99942</td>
<td>$8.92 \times 10^{-5}$</td>
<td>0.99930</td>
<td>$1.43 \times 10^{-4}$</td>
<td>0.99930</td>
<td>$1.55 \times 10^{-4}$</td>
</tr>
<tr>
<td>Modified Page</td>
<td>0.99942</td>
<td>$8.92 \times 10^{-5}$</td>
<td>0.99930</td>
<td>$1.43 \times 10^{-4}$</td>
<td>0.99930</td>
<td>$1.55 \times 10^{-4}$</td>
</tr>
<tr>
<td>Modified Page</td>
<td>0.99871</td>
<td>$1.97 \times 10^{-4}$</td>
<td>0.99876</td>
<td>$2.53 \times 10^{-4}$</td>
<td>0.98973</td>
<td>$2.26 \times 10^{-3}$</td>
</tr>
<tr>
<td>Henderson and Pabis</td>
<td>0.99915</td>
<td>$1.30 \times 10^{-4}$</td>
<td>0.99885</td>
<td>$2.34 \times 10^{-4}$</td>
<td>0.99235</td>
<td>$1.69 \times 10^{-3}$</td>
</tr>
<tr>
<td>Logarithmic</td>
<td>0.99917</td>
<td>$1.34 \times 10^{-4}$</td>
<td>0.99993</td>
<td>$1.6 \times 10^{-3}$</td>
<td>0.99757</td>
<td>$5.72 \times 10^{-4}$</td>
</tr>
<tr>
<td>Two term</td>
<td>0.99970</td>
<td>$5 \times 10^{-5}$</td>
<td>0.99885</td>
<td>$2.76 \times 10^{-4}$</td>
<td>0.99235</td>
<td>$1.91 \times 10^{-3}$</td>
</tr>
<tr>
<td>Two-term exponential</td>
<td>0.99970</td>
<td>$5.56 \times 10^{-5}$</td>
<td>0.99869</td>
<td>$2.68 \times 10^{-4}$</td>
<td>0.98952</td>
<td>$2.31 \times 10^{-3}$</td>
</tr>
<tr>
<td>Wang and Singh</td>
<td>0.95661</td>
<td>$6.63 \times 10^{-3}$</td>
<td>0.98977</td>
<td>$2.07 \times 10^{-3}$</td>
<td>0.99902</td>
<td>$2.17 \times 10^{-4}$</td>
</tr>
<tr>
<td>Diffusion approach</td>
<td>0.99970</td>
<td>$4.77 \times 10^{-5}$</td>
<td>0.99941</td>
<td>$1.31 \times 10^{-4}$</td>
<td>0.99912</td>
<td>$2.08 \times 10^{-4}$</td>
</tr>
<tr>
<td>Modified Henderson and Pabis</td>
<td>0.99970</td>
<td>$5.56 \times 10^{-5}$</td>
<td>0.99885</td>
<td>$3.38 \times 10^{-4}$</td>
<td>0.99234</td>
<td>$2.21 \times 10^{-3}$</td>
</tr>
<tr>
<td>Verma et al.</td>
<td>0.99969</td>
<td>$4.78 \times 10^{-5}$</td>
<td>0.99940</td>
<td>$1.31 \times 10^{-4}$</td>
<td>0.99911</td>
<td>$2.09 \times 10^{-4}$</td>
</tr>
<tr>
<td>Midilli and Kucuk</td>
<td><strong>0.99989</strong></td>
<td><strong>$1.79 \times 10^{-5}$</strong></td>
<td><strong>0.99996</strong></td>
<td><strong>$1.00 \times 10^{-5}$</strong></td>
<td><strong>0.99967</strong></td>
<td><strong>$8.38 \times 10^{-5}$</strong></td>
</tr>
</tbody>
</table>

From Table 3 it can be seen that all of these fits are extremely close in the correlation category and in the chi-squared analysis. Without any system parameters these models can be fit roughly to any data once testing has finished and experimental data can be compared against. Dissa et al. fit the Page model to the drying of Amelie mango as a better model than the Henderson & Pabis Model. An example fit of their model to the drying performance of differently sized mango slices is presented in Figure 4.
The statistical fits for Dissa’s study are quite close and both are shown to fit the data well. Dissa fails to explain where this data was collected as their schematic shows multiple trays stacked vertically but doesn’t clarify which tray data was collected from. Regardless, the study by Dissa has a common issue shared by other studies that collect experimental data and then fit with the above models: fitting is done after a setup has been constructed and all data has been collected. These models can easily fit a given set of data due to the general exponential decay dictated by Fick’s law. However, this is not useful in predicting what the drying trend for a foodstuff is expected to be before a dryer is physically built and tested.

1.2.7 Study Observations

The goal of selecting a semi-empirical model is to avoid the challenges of fully theoretical models. Often fully theoretical models require fundamental parameters that can be exceedingly difficult to obtain and often vary too greatly between foodstuffs. By using semi-empirical MR models, a sufficient model can possibly be obtained to predict the drying behavior of an individual
type of fruit. By using these good moisture content fits, engineers can predict drying response of identical system designs for thin layer analysis with constant drying conditions. Studies are often unclear as to how the drying trays are arranged inside the drying chamber: stacked vertically, stacked horizontally, spacing between trays, etc. Studies that do mention having multiple trays often are ambiguous on what tray the displayed results are from or they use data from the tray directly adjacent to the inlet. When trays are placed in series, where air from the collector passes across each sequentially while absorbing moisture, the conditions for all trays after the first tray are changing with time for a given set of dryer inlet conditions.

Rabha et al. tested 9kg of ghost chili pepper in a long horizontal bed with air blower and double pass dryer. However, only a 200g sample taken from the tray adjacent to the drying chamber inlet was used to fit the semi-theoretical model. No other data was provided from this study as to the drying performance of the rest of the foodstuff in this dryer setup [10]. Hedge et al. also tested a dryer design for drying bananas utilizing a single pass collector, axial air flow controller, and a vertically stacked drying chamber. This study also failed to specify which tray was being measured for the results reported. However they did test flow rates of $0.5 \frac{m}{s}$, $1.0 \frac{m}{s}$, and $2.0 \frac{m}{s}$ where $1.0 \frac{m}{s}$ was the most effective flow rate for their setup [8].

The semi-empirical MR models are based on the assumption that there is roughly a bulk moisture content and that the equilibrium moisture content is constant with time [22]. Models such as the Page equation have fitting parameters that are highly dependent on exterior conditions. Prakash reviews a study by Misra and Brooker (1980) that showed a high dependence on temperature, velocity, and relative humidity of the drying air [19]. For a dryer exposed to constant ambient drying air and solar insolation, the properties of the drying air entering the drying chamber would remain constant (i.e. $M_e$). However, in cases where the equilibrium moisture content fluctuates the following model for the moisture ratio is often used:

$$MR = \frac{M}{M_0}$$

The ratio presented in Eq. (8) suggests that the drying of a food product under dynamic conditions will eventually approach zero moisture content. This derivation is used in multiple studies to account for variable inlet conditions to the system and is sometimes preferred over Eq. [5]. López et al preferred this model over the $M_e$ version presented by Delgado when drying pear in
a forced convection tunnel [28]. They assumed the drying process was isothermal, minimal shrinking occurred, and that mass transport was mainly by diffusion; however they declined to comment why they used Eq. (8). Faal et al. argues that $M_e$ can be very small compared to $M_0$ for very long drying times and thus can be neglected [29]. Akpinar et al. also suggest that this would be used in cases where the relative humidity of the drying air constantly fluctuates [30]. Theoretical models focus on modeling moisture transport as a function of internal resistances whilst the other two model types only consider external mechanisms. Thus empirical and semi-empirical only directly correlate moisture content with time and have no physical connection to drying phenomena. These two models are valid in the range of air velocity, temperature, and humidity that they were developed in and not necessarily valid under different sets of conditions [19].

1.2.8 Solar Dryer Classification

To facilitate drying, solar dryers are constructed to take advantage of ambient insolation to expedite the drying process. The design of solar dryers is intended to provide a drying process faster than that of open/natural solar drying. Depending on the application, the construction of the solar dryer will differ. Most dryers are composed of three major components: a drying chamber, a solar collector or solar air heater (SAH), and a component that facilitates air flow. Dryer styles can be broadly defined by the six categories depicted in Figure 5.
Active type dryers rely on an external energy source to drive air flow through the collector and drying chamber, often by use of an electrical fan. Passive systems rely on natural circulation of air and thus require a chimney system to generate flow. Integral type dryers rely solely on solar radiation incident on the housing while indirect dryers use solar collectors to preheat drying air before entering the dryer chamber. Direct type dryers expose food products directly to solar rays and are therefore only used when damage due to solar exposure is not a concern. While indirect systems require more complicated designs and higher construction costs; they also typically experience higher efficiencies and more drying control than the integral design [5]. Mixed mode dryers use a solar collector in combination with direct solar gains on the drying fruit.

Passive systems are useful in remote applications where materials are limited and there is no access to electrical power. However active drying systems maintain more consistent and controllable air flow rates through the system. Ayensu et al. used a mixed mode passive system with chimney to achieve drying of various foods twice as fast as open sun drying [31]. Dissa et al. constructed a passive indirect system with chimney and reports a significant decrease in drying rate.
during night time with no solar radiation. This shows the reliance of indirect passive systems on daily insolation and lack of good airflow at night due to natural circulation [32]. Tomar comments that active systems can help achieve higher dryer efficiency and better product quality [33]. To investigate the thermal advantages of adding an active system, Singh et al. designed a setup where natural and forced convection were explored for the same system. They showed that drying chamber temperatures were significantly higher for the indirect system with forced flow versus the passive alternative. Also they demonstrated that natural convection was generally better for mixed mode dryers than forced convection was [34]. López et al. demonstrate this with a tunnel dryer that utilizes forced convection to achieve improved and more consistent drying of prickly pear cactus. The enclosed system effectively held ambient conditions constant and allowed improved drying through a variable-speed fan [28]. McDoom et al. sought to recycle hot air flow back into the system for the drying of cocoa and coconut as illustrated in Figure 6.

![Figure 6: Drying chamber with recirculation of drying air](image)

McDoom’s setup used power from an electrical grid to power the heater in the hot air box and used photovoltaic cells to run the blower. By recirculating air into the chamber, McDoom was able to save roughly 30% of energy usage for both the drying of coconut and cocoa [6]. Hybrid dryers are common in more developed areas where electrical power is readily available. Frequently hybrid systems are based around keeping dryer operating conditions steady through the use of backup heating sources. Often materials with sensible or latent heat storage capabilities are used to accomplish this. Material options in this case range from natural materials such as water or
stones to manufactured products such as waxes. Otherwise heat generating sources such as process exhausts, fuels, or electrical devices are used. Boughali et al. installed a resistor heater to keep inlet air temperatures above a fixed minimum value and connected the system air blower to the power supply as well. An example of their setup is shown in Figure 7.

This indirect hybrid solar dryer is more practical for developed areas because the design requires an electrical power source. Boughali’s design uses the solar component to provide the main source of energy for heating the drying air, but the drying chamber design having an outlet at the bottom relies heavily on the powered blower to facilitate air flow. When analyzing the system data for the drying of tomatoes, Boughali also implements the semi-empirical models discussed in Section 1.2.6 of this paper. Using the Middili model the paper commented that the unique structure of their dryer meant that lower flow rates were better suited for removing moisture. Interest was also demonstrated in running further experimentation in multiple seasons of the year. However the conclusions on the effects of a dryer parameter in one setup will be different from those of another. Hedge et al. drying of bananas built the following indirect active solar dryer in Figure 8.
Hegde et al. used the axial fan in their setup to drive flow velocities of 0.5, 1.0 and 2.0 m/s air through the system. Their analysis, which did not use any semi-empirical models, led to them to see that the 1.0 m/s flow produced the best results. In fact, they found that low flows for their dryer design actually rendered the bananas undesirable for consumption due to the fruit becoming incredibly dried. Different dryer designs require specific investigations to determine optimum operating conditions, thus the difficulty of using semi-empirical models to assist design choices. Generic models fail to encompass the specificity of dryer components and conclusions from studies are frequently unique to the dryer and operating conditions associated with the investigation. However dryers still can be classified in common categories as depicted by Ekechukwu in Figure 5.

1.2.9 Solar Collectors

The goal of solar crop dryers is to provide a more effective way to dry foodstuffs than the conventional method of open drying. Losses due to crop deterioration from climate/weather changes and pests often limit the utility of open sun drying. When constructing a solar dryer, solar collectors are used to preheat incoming air to the dryer. For a constant enthalpy, increasing
incoming air temperature decreases moisture content and relative humidity of the drying air, thus allowing for lower moisture equilibriums. Collectors typically combine different orientations of coverings, air flow passes, and glazings to enhance heat transfer to the drying air. Ekechukwu et al. broadly classify collectors into bare plate and covered plate variants [35].

Flat plate collectors are generally comprised of the following components: glazing, tubes, absorber plates, manifolds, insulation, and a container. Glazing is usually applied in the form of glass plating such that solar irradiation is easily transmitted but infrared heat heat loss is blocked from leaving the collector. Absorber plates are used to retain heat from the transmitted solar radiation and transfer it to the working fluid traveling through the system. Tubes, manifolds, and containers are used to direct flow through the system. Solar collectors are focused on absorbing as much solar energy at the lowest cost, since they are stationary they are typically pointed to the equator and operate in the temperature range of 30 – 80°C [36]. It is common in very low cost applications to use uncovered/unglazed solar collectors for domestic purposes such as pool heating.

Flat plate collectors are modified to achieve different utility based purposes. Including multiple passes in a collector is one way to alter its heat transfer effectiveness. Ho et al. designed a double pass collector with recycling that used a portion of the air leaving the collector to preheat the incoming air. By doing this Ho discovered that while thermal losses were increased by preheating the air, the improved heat transfer coefficient for the collector outweighed those losses [37]. Double pass collectors generally have higher thermal efficiency as effective heat transfer area is increased without much additional construction cost [38]. Tian et al. review the different installations of photovoltaic/thermal (PVT) collectors for the dual output of low temperature air and electrical power. As transmitted light through a glass cover impacts the photovoltaic cell, the device collects excess heat. By passing air over the device, convective cooling occurs and air exits the collector at low temperatures for purposes such as domestic water heating [39]. While this dual energy provision is useful, PVTs are generally less thermally efficient than conventional collector arrangements. This is due to the low absorptivity factor, high radiation losses, and reflection losses [40]. Large installations of parabolic dish collectors can be used in industrial applications to heat up working fluid in vapor power cycles for electricity production. Unlike typical flat plate collectors, parabolic devices have the ability to move with the sun’s trajectory to optimize solar absorption. Parabolic trough collectors operate similarly to the dish type, but are far superior in that they only need to track solar insolation in two dimensions - whereas dishes require 3 dimensional tracking. This
allows them to achieve higher temperatures and can scale to provide energy for large scale processes [39].

Developments over time have improvised on this classification, creating broader categories for solar air collectors for industrial and agricultural processes. Recently added to the list of bare/covered, glazed/unglazed, and single/multi pass collectors are transpired solar collectors (TSCs) [41]. Work done in this thesis will be based on a TSC system for the preheating of drying air. A typical layout of a TSC is shown in Figure 9.

![Figure 9: Schematic of transpired solar collector system](image)

TSCs consist of a perforated absorber plate and a plenum under negative pressure to pull outside air across the solar heated absorber plate. If done properly, convective losses can be nearly completely mitigated, resulting in a highly efficient collector for low temperature applications. Typical flat plate collectors utilize glazings to reduce radiant/convective heat loss at the absorber surface. However this can be ignored with TSCs due to the removal of convective boundary layers and the effective heat transfer at the dryer surface enabling low temperature operation of the collector—thus reducing radiant losses [42]. Kutscher has performed multiple studies into the performance of TSCs such as the modeling of thermal heat loss from the surface of a corrugated collector due to wind effects [43]. Similarly, modeling was done by Kutscher to prevent poor flow
conditions that many building integrated TSCs were experiencing, treating this fluid movement like flow through pipes with additional pressure drops [44]. Their low temperature application make them ideal for providing drying air for crop drying. The transpired sheets can be made out of flexible materials and rolled up after use, an option not available for other collector systems. Switching from highly conductive materials such as aluminum to lower conductivity styrene or polyethylene not only has minimal thermal penalties, it also provides cost savings and corrosion resistance [45].

Regardless of the solar collector style, the overall dryer design commonly falls under two broad categories of active and passive dryers

Sizing the transpired collector is likewise a crucial design consideration when minimizing system cost and maximizing drying effectiveness. Below a simplified model for determining the exit temperature of the collector is shown [46][41].

\[ Q_u = \dot{m} C_p \Delta T = \eta I_c A_c \]  

Equation (9) is commonly used for the change in temperature of the incoming air, it is the \( Q_u \) that models treat differently. The right side is the effective change in temperature in the thermal mass \( \dot{m} C_p \) and \( Q_u \) is the useful energy retrieved by the collector. Dryer design parameters such as collector area, material selection, and other pertinent design modifications will affect \( Q_u \). \( I_c \) and \( A_c \) represent the incident solar intensity and collector area respectively, which is universal across collectors. Vandecker presents the following derivation of the dryer efficiency, \( \eta \), based on Kutscher’s assumption that the transpired collector acts like an isothermal plate [47]:

\[ \eta = \frac{\alpha_s}{1 + \frac{h_r}{\epsilon \rho C_p V_s}} \]  

where \( \alpha_s \) represents the plate solar absorptivity, \( \epsilon \) is the collector effectiveness, and \( h_r \) the radiative heat loss coefficient - both of which are specific to the collector arrangement. \( \rho \) and \( C_p \) are the density and specific heat of the incoming air, respectively, with \( V_s \) being the velocity at which air is sucked through the surface. Using Eq. (9) and Eq. (10), the temperature rise across the collector relative to ambient is calculated by:

\[ \Delta T = \frac{\alpha I_c}{\frac{U}{\epsilon} + \rho C_p V_s} \]  

TSCs can be modified by changing parameters such as hole diameters, plate thicknesses, plate material, and hole pitch. Mark investigates the characterization of transpired collectors through the parameterization of \( \frac{h_r}{\epsilon} \) as a unique property of the collector. This ratio, also restated as the
effective heat loss coefficient divided by the effectiveness, \( \frac{U}{\varepsilon} \), is proposed by Mark to be a function of the suction velocity, \( V_s \), into the surface of the transpired collector \[48\]. A transpired collector is a cheap and effective option as the drying system’s solar collector, especially as a wide range of design choices can be pursued.

1.2.10 Past Work at RIT

Previous work with a transpired solar collector drying system and chimney here at RIT by Huselstein led to the development of a theoretically derived model. Huselstein worked on fitting a fundamental derivation to data collected from the drying of bananas, also utilizing the GAB model but using first principles to model mass transport phenomena \[49\]. The system was operated in outside ambient conditions and trays were weighed every 30 minutes. Huselstein comments that the parameters that were measured would likely change from test to test and that the developed model needed improvement in predicting the middle 70% of the drying time line of their passive dryer \[49\]. The model tended to over predict drying on the first day and under predict on the second. The effects of poor system design is noticed by a multidisciplinary senior design (MSD) team at RIT whose serpentine dryer design led to ineffective drying conditions. The control tray which was dried under open sun saw more moisture removed than any of the trays inside the dryer \[18\]. Noticeably the team comments that a large factor in this scenario was the lack of good airflow in the dryer and poor design of the collector \[50\]. Dryer setup of Huselstein and the RIT MSD team are as follows in Figure 10.
Figure 10: System schematics of Huselstein’s (a) and the RIT MSD team’s (b) design

From Figure 10a/10b there are two major components in common to note. Both designs utilize a passive chimney system and stack multiple trays of fruit in the drying chamber. Inconsistent natural convection and deep bed drying effects in the dryer have negative impacts on the drying performance of these systems. Air flow is of particular concern for effective dryer designs. Shuckla identifies dryer flow rate as one of the significant barriers to the growth of the technology [41]. When testing a chimney based solar dryer, Afriyie commented on velocity deviations due to internal resistance of the dryer framework that impeded natural convection [51]. Natural convection is inconsistent and air circulation can be further impeded by poor drying chamber design. Both of these can slow and even stagnate airflow through the system; this can be severe enough to cause fruit to reabsorb moisture. If the flowrate is to be kept consistent, as seen in Hegde et al. drying of bananas, then a system such as an axial flow fan is utilized [8].

The fruit drying model from Huselstein’s work, which was developed by Stevens and Weinstein in RIT’s Sustainable Energy Lab, was used to simulate drying and explore the impacts on drying performance by adjusting system parameters: solar collector area, thermal storage amount, flow rate, flow rate control and collector loss factors. Eight trays of bananas, starting with 1kg each and 6mm thick, are simulated from an initial content of 72.2% on a wet basis. The fruit is assumed to have: a constant effective diffusivity, a constant mass transfer coefficient, and uniform drying on both sides of the fruit. Equilibrium moisture content is calculated using the GAB model and the fruit slice is separated into 51 nodes.
Simulations were done by Dr. Robert Stevens in April 2018 using the first two days of typical meteorological year (TMY) weather data for Borgne, Haiti obtained from the National Solar Radiation Database to provide ambient conditions for the model. Weather assumptions include a collector slope of 30 degrees with 0 degrees azimuth, 0.2 ground reflectance, and a relative humidity model from M.G. Lawrence [52]. The model was simulated over that time frame with 10 minute time steps between calculations. Outputs from the model included: tray moisture content, temperature at the outlet of each tray, moisture flow rate, and relative humidity at the outlet of each tray. Fruits are considered dried when below 12% wet moisture content.

The dryer model was varied in the following ways. For the collector, area is allowed to vary between $1\text{m}^2$ and $2\text{m}^2$. Flow rate varies linearly with solar insolation up to $1000\frac{W}{m^2}$ for peak flows of $0.02$ and $0.04\frac{m^3}{s}$; flow also is kept at a minimum rate when solar insolation falls below a minimum threshold value. Figure 11 is an example of one of the concluding trends seen from the simulation.

![Graph](image)

Figure 11: Previous model predictions of impact of increasing collector area on drying performance

The trend observed in Figure 11 is the system response for the dryer granted all other parameters are held constant and is true for the ambient conditions provided for this set of simulations. Figure 11 shows that there is a trend of increasing fruit percentage dried with increasing collector area. It can be surmised that eventually adding collector area will not provide additional
drying for the given set of drying parameters. Modification of the collector design has a large effect on exit temperature and leads to improved performance. How slices are prepared, in terms of thickness, also had an impact in this model. When compared to the base case simulation, decreasing slice size from 6mm to 5mm increased the number of trays dried from 50% to 62.5%. The study suggests that the simulation should be run again under a different set of ambient conditions from the weather data where insolation is not as high and consistent as it was for this investigation.

1.2.11 Review Summary

Modeling of the drying process of any foodstuff is critical to better system design and prediction of drying times. Maximizing the amount of dried fruit in a given period is important for preservation especially where spoilage rates are high, such as in the Ivory Coast where agricultural losses can be as high as 30% [53]. However most modeling approaches often over simplify and do not account for realistic conditions. Ekechukwu suggests that most moisture models fail due to the oversimplification of assumptions when fully theoretical approaches are used [3]. However, empirical models are only better when predicting specific products under specific conditions. Differences in fruit shapes, ripeness, and composition are all factors that can be difficult to encompass for theoretical models. Thus in the literature there is a greater emphasis on semi-empirical models that better suit specific foodstuffs [2]. However these models appear to be mainly effective at fitting data that has already been collected rather than predicting system responses for design purposes. Reported dryer arrangements use a form of inducing air flow, a solar collector, a drying chamber filled with racks, and occasionally some form of heat storage or back-up heating system. Semi-empirical and empirical models fail to accommodate any of these design parameters and thus offer little suggestions for system design. Theoretical models, while often unable to precisely predict drying response, give understanding of drying trends. The goal of this study is not to derive a fundamental model that accurately predicts the drying response of fruit. Rather the goal is to use a model that provides possible general trends to guide testing done with an experimental setup. Testing in unpredictable ambient conditions makes it difficult to confidently compare results. However, if a controlled testing environment can be created to mimic inlet conditions to the drying chamber; then conditions between tests can be reliably compared. This would allow a better comparison between the conditions simulated in a theoretical model and those experienced by a physical setup.
2 RESEARCH QUESTION

How can we explore design changes to solar dryers in a consistent and conclusive manner that accurately reflects performance in tropical environments?

This question will be approached by combining physical testing with theoretical modeling. First an experimental setup is designed and constructed that allows for the production of drying air at a desired temperature, relative humidity, and volumetric flowrate. Testing with this setup supports the development of a bulk diffusion based model that predicts 85% of the drying process for individual trays of pressed mango. A system level model is proposed to complement this thin film model by predicting the effects of moisture removal from each tray of food on the drying air quality - also known as a deep layer approach. The coupling of these two models provides a predictive tool for the performance of drying systems in tropical environments such as Haiti. Previous prototyping of solar dryers in Haiti leads to a simple preliminary economic model that when coupled with the drying model estimates the cost/benefit relationship between various design options.
3 EXPERIMENTAL METHODOLOGY

The teststand used for this thesis was designed during the Fall of 2018. Its purpose is to allow the control of the flowrate, temperature, and relative humidity of air entering any drying chamber design. To model the performance of a solar dryer in Borgne, Haiti the following must be achieved: the air entering the system has to be brought up to tropical conditions (30°C and 80% RH), the air is then passed through a collector which raises the temperature of the air while keeping the moisture ratio constant. Thus the goal of the teststand is to produce air of the same properties as the stream exiting a collector in a tropical climate. The climate in Rochester, NY can vary dramatically throughout the year - even within a season. Testing air based systems outside can be extremely difficult because of this. The teststand is thus designed with three major components: a component to add heat, a component to add moisture, and a component to induce airflow through the system. An overview of the system design is shown in Figure 12.

Figure 12: Component level diagram of teststand

Figure 12 illustrates the intended operation of the system with a broad overview of the components. Air enters the ducting system in the top left of the diagram due to the pressure drop induced by the fan. The passing air enters into a series of two heaters that add thermal energy to the stream. This hot air is then humidified in a chamber by misting water on a pad. A flexible duct at the humidifier exit allows the attachment of the system to a variety of different drying
chambers. The exhaust from the drying chamber is partially vented to the room and partially recirculated back to the inlet through a return duct. By recirculating some of the air, the overall sizing and energy requirements of the heater/humidifier pair is much lower and more feasible. The final construction of the setup is shown in Figure 13.

3.1 Major Teststand Components

The design, construction, and assembly of the teststand were all performed in the Sustainable Energy Lab here at RIT. The large hardware components of the teststand are the heater, fan, humidification system, and dryer box. The heater system is made of two 600W Omega air heaters (AHF-06120) that are connected in series. Placed before the heaters is a variable speed pulse width modulated (PWM) axial fan (SAN ACE 92 9CRA). The fan provides up to 1560 Pa of static pressure with a potential max airflow of $0.097 \frac{m^3}{s}$ (205 CFM). Coupled with the rest of the system, the fan is able to provide between $0.009 \frac{m^3}{s}$ to $0.038 \frac{m^3}{s}$ of airflow (20 to 80 CFM).

The humidification system is housed inside of a tact welded aluminum box. Ducting mounted on either side provides the intake and exhaust air paths. A positive displacement pump
mounted underneath the table pulls filtered water from a reservoir and sprays it out of misting
nozzles mounted inside the humidifier box. The pressure in the line is controlled by a bypass relief
valve that allows for the tuning of the misting pattern. The misting nozzles spray into the passing
airstream and onto an Aprilaire humidification matrix. Water not absorbed into the airstream
drains out the bottom of the box through an air sealed tube that deposits back into the water
reservoir.

The drying chamber is a 1/4th scale model of a solar dryer built by a multidisciplinary
senior design team at RIT (Project 19483). The dryer features a horizontal chamber that can be
opened and loaded with fruit from the side. The teststand version is made from 25.4mm extruded
polystyrene foam board and has inlet/outlet flanges that attach to the flexible duct of the teststand.
Insulated flexible duct and straight duct connect the system components together, creating an open
system with re-circulation.

3.2 Teststand Sensors and Data Acquisition

Throughout the course of each test various signals are recorded for reference and control
purposes. A series of K type thermocouples are used throughout the system for recording air
temperatures: before and after the heater as well as before and after the drying chamber. The
relative humidity before and after the drying chamber is measured using Omega HX71 sensors.
These sensors are powered with an external power supply and output 0-5 Vdc (correlating linearly
to 0-100% RH). The placement of these devices is shown in Figure 12. All the above signals are
communicated to the desktop PC via a National Instruments USB-6341 and cDAQ-9181. The
USB-6341 also records voltages from a shunt resistor and Ohio Semitronics voltage transducer to
determine the power entering the heaters. Mounted underneath the drying chamber are three
Vernier force sensors that are attached to platforms located inside the drying chamber. These
sensors communicate with a LabQuest DAQ that sends the force measurements of the fruit trays
to the teststand desktop PC via USB. Any manual weight measurements are taken on a Tree LCT
scale.
3.3 Teststand Control System

All the hardware components on the teststand are managed by a control box mounted on the left side of the table. During each test the control box maintains a desired inlet temperature and relative humidity entering the drying chamber. This is done using solid state relays (SSR) and Watlow EZ-Zone controllers. The power supplies for the heaters and the pump both run through SSRs, which the controllers will open and close when using a PID negative feedback loop control scheme. The power for the axial fan also runs into the box to allow for instant on/off control. The USB-6341 provides a PWM duty cycle to the fan to change the speed while the control box turns the fan on/off. All lines are fused for current protection and temperature limit switches are placed on the heaters for no flow protection. If the fan is disabled at any point while the heaters are on, the limit switches will cut power to the heater to prevent damage to the heaters or the surrounding teststand. The PC periodically updates the controller setpoints and adjusts the fan speed, but its main function is data collection. The control box handles all the hardware power control and operates separately from the PC. The conceptual block diagram for this is shown in Figure 14.

![Diagram](image)

**Figure 14:** System overview of control variables, airflow is represented by the chain of red arrows on the right side of the diagram
This provides a general overview of the system block design. Measured physical signals are used to drive the PID control system response for each variable. A more detailed wiring diagram for the setup can be found in Appendix D.

### 3.4 Simulation Scheme

National Instruments LabView is used to run all tests based on predetermined setpoints for the temperature, relative humidity, and volumetric flowrate of air entering the drying chamber. The setpoints for a given simulation are determined from typical meteorological (TMY) data from the National Renewable Energy Lab (NREL) for the region of Borgne, Haiti ($19.8444^\circ$N, $72.5227^\circ$W) and a model for an unglazed transpired solar collector with 12mm hole spacings. TMY data is typically given at one hour intervals so smaller timesteps are created by linearly interpolating between the reported conditions. Using equations [9] and [10] from the literature review section, the outlet temperature of the collector can be determined based on the parameter $\frac{h_r \epsilon}{c}$. Based on testing done in the Sustainable Energy Lab at RIT, the following model for the unglazed collector with absorptivity, $\alpha$, of 0.94 is used as a conservative approach to modeling the collector performance [48].

\[
\frac{U}{\epsilon} = 26.969 \frac{W}{m^2K} - 179.11 \frac{J}{m^3K} * V_c \left[ \frac{W}{m^2K} \right]
\]

(12)

where $V_c$ is the suction velocity of air approaching the plate. Using Matlab 2017b the solar and ambient air conditions are determined throughout the entire simulation duration. For all constant condition testing the ambient conditions were assumed to be constant at $800 \frac{W}{m^2}$, $30^\circ$C, and 80% humidity. The inlet conditions for those tests are constant as a result, examples of which are shown below in Table 4.

<table>
<thead>
<tr>
<th>$A_c [m^2]$</th>
<th>$\dot{V} [m^3/s]$</th>
<th>Temperature [°C]</th>
<th>Relative Humidity [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.55</td>
<td>0.016</td>
<td>52.5</td>
<td>24</td>
</tr>
<tr>
<td>5.10</td>
<td>0.022</td>
<td>53.8</td>
<td>23</td>
</tr>
<tr>
<td>1.28</td>
<td>0.022</td>
<td>46.6</td>
<td>33</td>
</tr>
<tr>
<td>4.2</td>
<td>0.037</td>
<td>50.7</td>
<td>27</td>
</tr>
<tr>
<td>2.55</td>
<td>0.037</td>
<td>47.7</td>
<td>31</td>
</tr>
</tbody>
</table>
The LabView program steps through the time steps in the data file, setting the controller setpoints and updating the fan duty cycle. All force sensor measurements are taken at 10 minute increments and the system setpoints are typically updated every 10 minutes as well. All system parameters such as temperatures, relative humidities, and the volumetric flowrate are recorded every minute. The volumetric flowrate is measured by doing an energy balance on the heater and assuming losses through insulated walls are negligible, so that the flowrate is:

\[
\dot{V} = \frac{Q}{C_P \Delta T \rho}
\]  

where \( Q \) is the thermal energy provided by the heaters as calculated by measuring the voltage and current via the shunt resistor and voltage transducer. \( C_P \) is the specific heat of air and \( \rho \) is the density of air, both of which are assumed to be constant. Finally, the temperature rise, \( \Delta T \), is physically measured using K-Type thermocouples placed at the inlet and exit of the heaters. Flowrate is controlled by a predetermined system calibration that converts desired flowrates into duty cycle percents that are written to the fan via the USB-6341.

Once the test is started with the appropriate setpoint file from Matlab, it will run until the stop code in the file or upon user termination. During this time the user doesn’t need to interact with the system unless manual measurements are desired. The system automatically shuts down airflow and heating/humidification at "night" when there is no flux and starts/ends the simulation on its own. At the end of each test the user will have two files, one containing all the system parameters for each minute and one with the weight measurements for every 10 minutes. The ability of the system to track a variable condition simulation is shown in Figure 15. Flowrate is reported in CFM in this figure for ease of plotting all parameters on the same axis.
Figure 15: Desired system setpoints versus actual testing conditions for July 1st to 2nd

The system continually updates the controllers to track the changing setpoints as shown by the step changes in Figure 15. At "night", a one hour shutdown period, the heater, humidifier, and fan are shut off - causing the exponential decay and zero flowrate during the 9-10hr and 19-20hr period. The force sensors are tared upon initializing the test and report the respective weight of each of the stacks of trays, which is converted into grams by LabView. The data is later extracted and then processed to determine parameters such as moisture removal rate or the fruit wet basis moisture content over time. Figure 16 shows a visual of the quality of a sample of data acquired from the sensors.
3.5 Test Procedure

All testing in this thesis was performed on Kent mangos bought from a local grocery store. Fruit was bought only from Happy Chameleon Farms to reduce variability across tests caused by product differences from produce suppliers. Mangos are stored in the lab area until they become soft to the touch and visually very ripe. The goal of designing a better drying system is to preserve fruit that is near spoilage, thus fruit is stored until it approaches that point. For fruit to be prepared for testing it must be peeled, mashed, spread, and weighed according to the test specifics.

Once fruit has fully ripened and become very soft they are washed in water, peeled, and transferred to a temporary container. Clear defects or signs of spoilage are removed from mangos after being peeled by hand with a vegetable peeler. Once all the mangos for a test are peeled and checked for irregularities, the flesh of the mango is removed by hand. The ends of the mango and pit are disposed in a compost bin, leaving only a container of loose mango flesh left. The mango flesh is then kneaded and broken apart by hand until it is a coarse mush/pulp. The reason for doing this
by hand is to mimic the processing method that would be performed by users in Haiti. During the completion of my senior capstone project, MSD 19483, our Haitian customers/stakeholders agreed that mangos would be mashed up into a pulp prior to being dried. This allowed simple preparation for drying and eased creation of mango powder post drying.

The container of mango pulp is now ready for testing. During the test the mangos sit on plastic grill mats on top of aluminum plates. The height of the chamber was originally 100mm high, which was reduced to 80mm by adding a spacer. This was done to reduce the amount of air that was bypassing the fruit when only two trays were added per stack. Manual measurements are taken by individually weighing each tray in each stack of fruit with the LCT scale. The drying chamber setup for all manual measurements is shown in Figure 17.

![Figure 17: Drying chamber setup for manual measurements](image)

The naming convention shown in Figure 17 is used for all tests in this study. As an example, the letter "A" indicates the bottom tray in a stack and the number "1" indicates the tray is in stack 1. The trays in a stack are placed on top of each other and are supported by bolts attached to each plate. The bolts stick out 25mm from the bottom of the plate to create a constant air channel height between the stacks. For all automatically recorded tests, part of the chamber is taken up by the force sensors. These sensors eliminate the need to stop the test to record tray weights and allow for a more detailed record of the drying process. The orientation of the drying chamber with force sensors is shown in Figure 18.

![Figure 18: Orientation of the drying chamber with force sensors](image)
Airflow below the plate is blocked by pieces of wood such that the top tray has airflow on both sides whereas the bottom has airflow mainly from above it. Some flow does pass underneath, but the holes the force sensors pass through are bagged to prevent air leakage out of the chamber. For all automatic measurements, only three stacks with two trays each are used as shown by Figure 18.

Each tray is made of 1.6mm 5052 aluminum and supports a grill mat on which the mango film is placed. The grill mats are used as they provide an easy way to remove the fruit once dried - the aluminum plates are for structural support. Originally the plates were made of wood but were switched due to the warping of the material. The stacks were unstable due to the bowed nature of the wood, causing poor airflow patterns. Changing the trays from wood to aluminum had a significant impact on drying performance as discussed in Section 4.3.

Mango is spread out onto the mats using an adjustable press. The side rails of the press can be adjusted to various heights to change the thickness of the film. All constant and variable condition tests were performed at a fruit thickness of 2mm, which had a significantly faster drying time than larger thicknesses. The mats themselves are 327 by 264 millimeters - roughly 85% of the mat is covered with mango for each test. The approximate area the mango takes up is kept constant every time but the mango surface itself is not smooth. On average the mango thickness will be 2mm, but the clumping of mango flesh with the liquid film creates a rough surface. Mango is added to the tray to roughly 170 grams total weight, flattened out, weighed again with any excess mass of 170 grams being removed. This is done for each tray in all three stacks, resulting in 340 grams of mango per stack with total of 1020 grams of wet+dry mass per test. The force sensors are
zeroed with the aluminum trays only, then the mats with mango are added to each stack. All mats are labeled and weighed prior to the experiment so the raw data can be tared later. Once testing is complete the mango leather is peeled off the trays and placed in plastic Ziploc bags. Each stack is placed in the same bag and the total bag weight is measured at that time and written on the bag.

### 3.6 Moisture Content Validation

The raw data collected is the total mass of each stack, which includes the dry and wet mass components of the fruit. In order to determine the moisture content, dry or wet, of the fruit the dry mass must be known. This can be done by completely drying out the fruit until no weight changes occur. To do this for every single stack of every test is both energy and time intensive. Therefore an average initial moisture content will be assumed for every test, allowing for the dry mass to be calculated using Eq. (1).

To determine this average initial moisture content a thermogravimetric analysis (TGA) was performed on a random sample of the constant condition tests. These samples were dried by the drying chamber but still contain small amounts of moisture. Small 10-25mg samples were taken from five bags after the bags are weighed again to verify no re-adsorption of water had occurred. Samples are placed in a platinum cup and suspended in a sealed chamber and purged with nitrogen. The chamber is brought up to 120°C at a heating rate of 10°C/min and held for one hour. Temperatures above 120°C experience internal decomposition of the fruit itself. During this time the weight of the sample is being measured, allowing for the calculation of the amount of moisture removed from the sample. Figure [10] is an example plot of the weight change of a sample.
Figure 19: Example data collected from thermogravimetric analysis operation

The stabilized percent on each of these plots represents the amount of the collected sample that was comprised of dry matter. The whole bag is assumed to be in equilibrium before the sample is collected, meaning that if 75% of the sample is dry mass - then 75% of the whole bag is drymass. The drymass can be used to determine the initial moisture content from the manipulation of Eq. (1).

\[
M_{wb,initial} = 1 - \frac{m_{dry}}{m_{total,initial}}
\]  

This calculation is done for each of the five random samples, random in the selection of the test and stack the sample is from. On average the initial moisture content of the fruit is 84%. The deviations of the five tests are shown below in Table 5.
Since all trays start with 170 grams of mango pulp, each tray contains roughly 27.2 grams of dry mass. Knowing this the moisture content of the fruit can be calculated at any point in the test after raw data has been collected using Eq. \( \text{(14)} \). This dry mass and initial moisture content was assumed for every tray of all tests unless something unusual is noticed during fruit preparation or when weighing the final mass after the test has been done. For these exceptions this is documented and a sample from that test is run through the TGA to verify the initial moisture content.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Actual MC</th>
<th>Predicted MC</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>85.0%</td>
<td>84.0%</td>
<td>-1.2%</td>
</tr>
<tr>
<td>14</td>
<td>84.2%</td>
<td>84.0%</td>
<td>-0.2%</td>
</tr>
<tr>
<td>15</td>
<td>85.4%</td>
<td>84.0%</td>
<td>-1.6%</td>
</tr>
<tr>
<td>19</td>
<td>81.9%</td>
<td>84.0%</td>
<td>2.6%</td>
</tr>
<tr>
<td>21</td>
<td>83.5%</td>
<td>84.0%</td>
<td>0.6%</td>
</tr>
</tbody>
</table>
4 RESULTS AND DISCUSSION

4.1 Testing Summary

Testing was completed during the months of April to July 2019. During this time various modifications were made to the teststand. Initially tray weights were recorded manually every hour for as long as possible and only constant condition tests were possible due to technical limitations. These issues were remedied with the installation of the force sensors and a new desktop. Some preliminary testing was performed with the older setup: manual measurements with wooden support trays. All tests used for modeling were performed with the force sensors sitting on aluminum trays with the automatic drying chamber arrangement in Figure 18. Over 35 tests were completed but not all tests are reported due to technical complications or abnormalities in the mangos.

4.1.1 Overview of Testing Performed

Testing consisted of two different styles of conditions. The first is the constant condition test where the inlet temperature, relative humidity, and flowrate are kept constant. The second is the variable condition test where real TMY data is used to simulate an average day in Borgne, Haiti. In variable tests the inlet setpoints for temperature, relative humidity, and flowrate are changing with the ambient temperature and solar flux. Twelve constant condition and two variable condition tests were run at fruit thicknesses of two millimeters. The selection of two millimeters was determined after three tests of thicknesses (2mm, 4mm, and 6mm) under the same constant conditions was performed. The area of the collector and volumetric flowrate through the system is varied across the constant condition tests. Changing the collector area affects the dryer inlet temperature. Varying the flowrate affects the volume of air passing through the drying chamber and the inlet temperature. Faster flowrates for the same collector area yield lower drying temperatures but more available thermal energy and higher airstream velocity inside the chamber. Table 6 provides a visual of the testing performed where tests marked with an * are collected twice and each box reports the temperature and relative humidity associated with that test.
Table 6: Range of flowrates and collector areas explored

<table>
<thead>
<tr>
<th>Collector Area [m²]</th>
<th>Flowrate [m³/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.016</td>
</tr>
<tr>
<td>1.28</td>
<td>[46.6°C 33%]</td>
</tr>
<tr>
<td>1.90</td>
<td>[49.1°C 29%]</td>
</tr>
<tr>
<td>2.55</td>
<td>[52.5°C 24%]</td>
</tr>
<tr>
<td>2.70</td>
<td>[52.0°C 25%]</td>
</tr>
<tr>
<td>3.25</td>
<td></td>
</tr>
<tr>
<td>3.35</td>
<td>[52.0°C 25%]</td>
</tr>
<tr>
<td>4.20</td>
<td></td>
</tr>
<tr>
<td>5.10</td>
<td></td>
</tr>
</tbody>
</table>

Each of the tests performed takes between 5 to 24 hours to complete. Testing is typically terminated by the user after the weight of each stack has stabilized for at least 20 minutes. Constant conditions tests have fixed flowrates, inlet temperatures, and inlet relative humidities for the entire testing period of 24 hours. Variable condition tests are set to follow a certain trend with the ambient solar flux. Using NREL TMY data, the incident solar flux on a horizontal surface is calculated for every timestep. For the tests performed in this thesis the drying process starts when the calculated incident flux reaches 400 $\text{W/m}^2$. The day ends when the solar flux falls below this threshold, entering a one hour night cycle where there is no flow before starting the next day. During the day the flowrate varies linearly with solar flux as shown below:

$$\dot{V} = \begin{cases} 
0 & I < 400 \text{W/m}^2 \\
\dot{V}_{\text{max}} \frac{I}{1000 \text{W/m}^2} & 400 \text{W/m}^2 \leq I 
\end{cases}$$

(15)

Applying this piecewise function to a sample set of NREL TMY data for July 1st yields the following variation in volumetric flowrate with solar flux in Figure 20.
This established relationship of flowrate to solar flux is used for variable conditions only, constant tests maintain a set flowrate for the duration of the test. For both constant and variable conditions tests, the last two unknown parameters are the temperature and relative humidity of the ambient environment.

Ambient temperatures are directly taken from the NREL TMY dataset, however the relative humidities have been modified from their original values in this study. NREL TMY appears to assume the relative humidity is 55% the entire year, which is not realistic. The relative humidity is typically higher. To use more conservative conditions we have modified the relative humidity in two ways. For constant condition testing we assumed ambient air was at 30°C and 80% RH with an incident solar flux of 800 $\text{W/m}^2$. For variable conditions a different approach is taken. The assumption is that the humidity ratio in the air is constant at $0.0216 \frac{\text{kg water}}{\text{kg air}}$ all the time, suggesting no rainfall occurs during any of the tests. The value of $0.0216 \frac{\text{kg water}}{\text{kg air}}$ is the moisture ratio associated with air at 30°C and 80% RH. The ambient temperature and this proposed humidity ratio is used to determine the ambient relative humidity at any point during the day using established ASHRAE relationships found in Section 5.4.1. This coupled with the solar flux at each time step, typically 10 minutes, is used to simulate a 2-3 day drying period.
4.1.2 Measurement Uncertainty

Some of the data collected in the setup is used for validating that simulation conditions are being met during the test. Readings such as relative humidities, dryer inlet and outlet temperatures are recorded to allow for post review in the case of abnormal test results. All other readings are used during the test operation or in the post analysis of data. Any variation in the inlet temperature, relative humidity, or volumetric flowrate from the intended setpoint is considered consistent between all tests. The posted measurement uncertainty for the sensors used in the experiment is shown in Table 7.

Table 7: Instrument uncertainties and affected parameters

<table>
<thead>
<tr>
<th>Instrument Type</th>
<th>Model</th>
<th>Uncertainty</th>
<th>Parameters</th>
<th>Affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermocouple</td>
<td>Type-K</td>
<td>±1°C</td>
<td>All temperatures Q</td>
<td></td>
</tr>
<tr>
<td>Relative Humidity Sensor</td>
<td>OMEGA -HX71-V1</td>
<td>±4%</td>
<td>All RHs</td>
<td></td>
</tr>
<tr>
<td>Shunt Resistor+Voltage Transducer</td>
<td>NI-USB-6341</td>
<td>±50W</td>
<td>Heater Power Q</td>
<td></td>
</tr>
<tr>
<td>Weighing Scale</td>
<td>LCT-50000</td>
<td>±1g</td>
<td>$m_{dry}$, $m_{total,initial}$</td>
<td></td>
</tr>
<tr>
<td>Force Sensor</td>
<td>Vernier Dual Range</td>
<td>±5g</td>
<td>$m_{total}$</td>
<td></td>
</tr>
</tbody>
</table>

The uncertainty from the relative humidity sensor is not used in any modeling calculations and is for reference only. The uncertainty in the flowrate is a function of the measured temperature difference across the heaters, the shunt resistor and voltage transducer measurements, and the assumed specific heat and density of the airflow. Calculations for the influence of the measured parameters on the volumetric flowrate can be found in Appendix A. Overall the volumetric flowrate has a typical relative uncertainty of 15% from the stated value when considering the combined uncertainty of the above parameters. This error is larger at higher temperatures but does not effect the analysis presented in this thesis other than suggesting that the range of flowrates explored is larger than reported.

4.1.3 Moisture Content Calculation

The more important uncertainty in the results is the variation in the reported moisture contents, which are affected by the Scale and Force Sensor uncertainties. Moisture content on a
wet basis is calculated in the following way for this investigation:

\[ M_{wb} = 1 - \beta \frac{m_{tot,t=0} - m_{mat}}{m_{tot} - m_{mat}} \tag{16} \]

The initial percentage of fruit mass that is made up of dry components is represented by \( \beta \). This value is assumed to have an absolute uncertainty, \( \epsilon_\beta \), of 2.0% as determined from the moisture content validation presented in Section 3.6. The term \( m_{tot,t=0} \) is the initial weight of the stack excluding the metal support structure. This value is found by adding the combined weight of the mango mash and mat of each tray on the LCT-50000. This measurement was assumed to have a conservative uncertainty, \( \epsilon_{m_{tot,t=0}} \), of 2 grams since each stack has two trays. The term \( m_{mat} \) represents the summation of each of the grill mat weights and also has an uncertainty, \( \epsilon_{m_{mat}} \), of 2 grams. Finally \( m_{tot} \) is the stack weight at any given time in the experiment as measured by the force sensors. Since the sensors operate in the \( 0 - 50N \pm 0.05N \) range, the uncertainty of any given weight measurement, \( \epsilon_{m_{tot}} \), is 5 grams. Using Eq. (16), an expression for the uncertainty in the calculated wet basis moisture content at any time can be derived:

\[
\Delta M_{wb} = \sqrt{ \left( \frac{\beta \epsilon_{m_{tot,t=0}}}{m_{tot} - m_{mat}} \right)^2 + \left( \frac{\beta \epsilon_{m_{mat}} (m_{tot,t=0} - m_{mat})}{(m_{tot} - m_{mat})^2} \right)^2 + \left( \frac{\beta \epsilon_{m_{tot}} (m_{mat} - m_{tot,t=0})}{(m_{tot} - m_{mat})^2} \right)^2 + \left( \frac{\delta M_{wb}}{\delta \beta} \epsilon_\beta \right)^2 } \tag{17} 
\]

where \( \frac{\delta M_{wb}}{\delta \beta} = \frac{m_{mat} - m_{tot,t=0}}{m_{tot} - m_{mat}} \tag{18} \)

4.2 Methods of Analysis

Throughout the many changes to the teststand there is a necessity to develop methods of comparing results from different tests. This section presents various options for analyzing the drying performance using the weight data recorded throughout each test. These methods will allow for a better characterization of changes in drying performance in order to make informed conclusions about the impact of design choices.
4.2.1 Dry Basis Moisture Content

Already shown before in Figure 16 is the wet basis moisture content, which effectively represents the weight fraction of water in the film at any given moment. Similar information can be presented using the dry basis moisture content as shown in Figure 21.

![Figure 21: Dry basis plot of Figure 16 for variable conditions on July 1st](image)

The dry basis moisture content is the ratio of the mass of water to the mass of dry material in the sample. The time rate change in the dry basis moisture content is directly proportional to the mass removal rate of water. This provides a different perspective on the drying rate as a function of time as the moisture removal rate is more readily observable from the graph whereas the wet basis moisture content plot presents a better sense of whether the fruit is dry enough.

4.2.2 Moisture Removal Rate

The moisture removal rate itself can be plotted directly for specified time steps. For data taken before automatic measurements were available, a forward difference approach was taken in
determining the moisture removal rate.

\[ \dot{m}_{w,j} = \frac{m_{\text{tot},j} - m_{\text{tot},j+1}}{t_{j+1} - t_{j}} \]  

(19)

Here the change in the total mass, \( m_{\text{tot}} \), is found by taking the difference in masses from the current time, \( j \), and the time step after at \( j + 1 \). The parameter \( t \) represents the time that has passed since the drying process started. The denominator is thus the difference in time since the current measurement and the next one. The forward difference is fairly discontinuous for the 1 hour time steps, but generally provides a sense of the peak removal rates of water from the film for comparing tests of various thicknesses or inlet conditions.

The central difference is used for the automatically measured data and provides a smoother approach to understanding the removal rate.

\[ \dot{m}_{w,j} = \frac{m_{\text{tot},j-1} - m_{\text{tot},j+1}}{t_{j+1} - t_{j-1}} \]  

(20)

These measures of the drying rate help show the decreasing nature of the dehydration process. The central and forward difference moisture removal rate vary significantly due to the time steps between discrete measurements made of the tray weights during the test. The extent of this can be seen below in Figure 2247
Figure 22: Comparison of central and forward difference moisture removal rate calculations for a flowrate of 0.022 \( m^3 \), 50.8°C, 26% RH

The moisture removal rate has four different sections in Figure 22. There is a brief initial thermal transience where the moisture removal rate is increasing. This is followed by a two hour segment of fairly constant drying with a slight decrease in removal rate over the period. Lastly a falling regime is observed with a constant falling period lasting until five hours - leading into a sporadic decline where the last amount of moisture is being removed.

With the ten minute timesteps in tray weight measurements, the selection of a forward or central difference approach to calculating the moisture removal rate bears significance. The central difference provides a smoother and less noisy representation of the drying rate. This method will be used in all later comparisons between the removal rates for different tests.

4.2.3 Dryer Efficiency

The moisture removal rate can be further applied to gain a sense of the efficiency of the system. The efficiency of the system is defined as the ratio of energy used for evaporation of water
The numerator in the expression represents the thermal energy required to evaporate water from the fruit surface in the past time step. This is calculated by taking the central difference moisture removal rate defined in Eq. (20) and multiplying it by the latent heat of vaporization of water $\hat{H}_{w,v}$. The denominator shows the useful energy gain across the collector relative to ambient. The mass of air passing through the collector, represented by $\dot{V}_{\text{air}}\rho_{\text{air}}$, has some gain in enthalpy $\Delta h$ between the ambient air and the air exiting the collector. For the constant condition tests the denominator is constant, therefore efficiency decreases over time as the fruit dries out and the rate of water evaporating decreases. For variable condition tests the available energy varies with the solar flux incident on the collector. Adding additional trays or stacks will always result in higher efficiencies, but requires larger drying chambers and more tray materials.

4.2.4 Time to Dry

The longer a fruit with high moisture content is exposed to the environment, the more likely it will spoil. A metric to capture this element of the drying process, called the "Time to Dry", is thus proposed. This value represents the number of hours it takes an individual stack to reach a specific moisture content. Due to instrumentation precision, low moisture contents experience the highest amount of uncertainty as just the error from the force sensors, five grams, can shift the wet basis moisture content as much as 8%. A higher value of 45% wet basis (0.82 on a dry basis), will be used to determine the time to dry. At this moisture content the bulk of the drying process has already occurred since 85% of the initial moisture in the fruit has already been removed as shown in Appendix B.

4.3 Experimental Trends

Testing in this study began with determining what the reference test case should be. This involved determining the thickness of the film, how the tray weights are measured, and how the
trays are stacked. Once these were determined, tests with set temperatures, relative humidities, and flowrates were run for combinations of volumetric flowrates and collector areas. The results of these tests at each step in this process are shown in this section.

4.3.1 Fruit Thickness Impact

For a given film surface area, increasing the amount of mass per tray increases the height of the mango mash. A thicker layer will allow for more mango to be processed at a time, but will affect the time the fruit takes to dry. To determine which thickness of mango should be used for all tests in this thesis, film heights of 2mm, 4mm, and 6mm were tested under constant inlet conditions of 50.8°C, 26.4% RH, and 0.022 m³/s (47 CFM). Testing was performed on 6mm thick wooden trays 330mm x 406mm in size. The mango area is confined to roughly a 305mm x 244mm area on the mat, with approximately 170g of mango for a 2mm film height, 340g for a 4mm height, and 510g for a 6mm height. The dry basis moisture contents for all three tests is shown in Figure 23.

![Figure 23: Drying of mango at different thicknesses on wooden trays for a flowrate of 0.022 m³/s at 50.8°C, and 26% RH](image)
The data in Figure 23 was taken manually at 1 hour increments. Therefore it was difficult to record data for longer than a 12 hour period without testing through the night. The 2mm test was completed in a single day, thus data for the entire process is available. Three different tests were completed to capture the different stages of drying of the 4mm thickness. This is the reason three different 4mm tests are shown, as data from the beginning and the end was captured by three different experiments. The error bars on all plots for manual tests will be smaller due to an uncertainty of 1g instead of 5g by using the LCT scale rather than the force sensors. The initial moisture contents were also measured on a per case basis, thus the starting values are different across all three thicknesses.

From the results shown in Figure 23 the thickness 2mm is chosen for multiple reasons. Preparing the 6mm was extremely difficult due to the sheer volume of liquid/solid - both maintaining a consistent surface area of the film and handling the tray during weight measurements was challenging. The 4mm and 6mm tests took at least two 8 hour days of ideal conditions to dry whereas the 2mm test dried in roughly one day. This smaller thickness simplifies testing in the lab and reduces the amount of material needed for each test. This also reduces the probability of spoilage during the drying process, both in the lab as well as in the field.

4.3.2 Multiple Stack Impact

At this point the height of the drying chamber was 100mm, with only two trays for each stack. We noticed that the majority of air was passing well above the fruit and therefore contributing little to the drying process. The chamber height was reduced to 80mm tall by adding another foam board, and a total of three stacks with three wooden trays each was used. Again the same conditions as the thickness test were used for a thickness of 2mm. Manual measurements were still being taken as visible by the one hour time steps in Figure 24.
Figure 24: Drying of mango at 2mm for stacked wooden trays with a flowrate of $0.022\frac{m^3}{s}$, 50.8°C, and 26% RH

Generally the bottom trays, A1/B1, dry slower than the trays above them since there is no airflow underneath the bottom trays - which sit flat on the chamber floor. The top trays experience better airflow and thus typically dry faster than lower trays in the same stack. A deep layer effect is observed in all tray levels where each successive tray dries slower than the previous tray (B1 is slower than A1). The limitation of the teststand design is that only three trays can be stacked vertically and only four stacks can be placed in the chamber. The chamber design itself, a long horizontal rectangle, causes uneven airflow that may be avoided with other system designs.

4.3.3 Tray Material Impact

At this point in the experimental process we discovered that the wood trays were warping in the chamber. Not only did this create difficulty in stacking the trays, but also it created irregular and undesirable flow patterns in the chamber. We decided to replace the tray material with 1.6mm aluminum trays to see if performance improved. At this time force sensors were added to each stack
of trays to log tray weight continuously during each test. This allowed for the comparison of the full drying cycle for both the wood plates and metal plates at 2mm thickness at 10min intervals as shown in Figure 25.

![Figure 25: Drying of first stack at 2mm thickness for wood and aluminum trays at 0.022 m³/s, 50.8°C and 26% RH](image)

The difference in drying performance is considerable as seen in Figure 25. The aluminum tray stacks reached 25% dry basis moisture content in 6.4 hours while the wooden trays took 8 hours. Adding the metal trays did provide for uniform channels, easier loading and unloading operations, and an overall more robust test setup. The trays also provide additional heat transfer by replacing the bottom fruit interface with a thermally conductive material rather than an insulative one. The inlet conditions were identical between these two tests. The only changed parameter was the tray material. This alone had a significant impact as expected due to the lower thermal resistance of the plate. This demonstrates the importance of external conditions in the falling rate regime. All data presented in the rest of this thesis is collected using aluminum trays with 10min time steps.
4.3.4 Flow Rate Impact

Figure 26 shows the variation of the "time to dry" metric defined in Section 4.2.4 for various flowrates for a fixed collector area.

For a constant collector area, the volumetric flowrate through the system was varied. Therefore not only is the velocity of the air through the chamber changing, but also the temperature and RH leaving the collector. Although lower flowrates do result in higher temperatures and lower relative humidities, the drying times increase with lower flowrates as seen in Figure 26. The unclear component of the trend shown in Figure 26 is whether a local maximum or a plateau point is found for increasing flowrates. There will be a point where air is moving so fast that the air has too low of a temperature rise across the collector and fruit will not reach desired drying conditions. Within the uncertainty of the measurements, it is unclear that for the flowrate range tested if drying performance will remain constant or continue to decrease with increasing flowrates above $0.037 \, m^3/s$.

In the first stack there is a slight decreasing trend with the time to dry with increasing flowrates, but these points are arguably within the error bars. An example error bar is shown on the graph.
to show the relative size of this uncertainty. The second stack has a stronger trend with flowrate whereas the third stack may suggest a critical point. This critical point is between the $0.030 \frac{m^3}{s}$ and $0.037 \frac{m^3}{s}$ for the third stack and suggests that the third stack’s time to dry may start to increase with increasing flowrates. However this conclusion is debatable due to experimental uncertainty.

By analyzing the same set of data in Figure 26 with a different method, the trends observed can potentially be explained. One possibility not explored in this study is to run these same tests but with additional stacks of fruit. This would allow for the assessment of whether time to dry trends similar to the third stack’s trend also occurs with stacks deeper in the chamber. For the results in Figure 26 we reviewed the peak moisture removal rate during the drying process. After calculating the moisture removal rate using Eq. (20), the maximum rate of each stack is plotted in Figure 27.

![Figure 27: Moisture removal rate for all stacks at 2.55m² collector area with varying flowrates](image)

In the range of $0.016 \frac{m^3}{s}$ to $0.030 \frac{m^3}{s}$ there is a general increasing trend in peak moisture removal rates. Interestingly the trend appears to split in two for the highest flowrate $0.037 \frac{m^3}{s}$. This trend is again unclear as it is heavily affected by the force sensor uncertainty. For a fixed collector area, higher flowrates will have lower temperatures. It is possible that while higher transfer
coefficients are beneficial to the first two stacks, the temperature of the air entering the last stack is low enough that drying performance decreases as compared to $0.030\frac{m^3}{s}$. Overall the highest flowrate may be achieving a cumulative system removal rate that is higher than lower flowrates. This would cause more moisture to be absorbed into the airstream before entering the third stack, which would explain why the time to dry for the third stack at $0.037\frac{m^3}{s}$ is higher than the time to dry for $0.030\frac{m^3}{s}$. A larger drying chamber would allow the observation of whether a fourth or fifth stack behaves similarly at higher flowrates. Likewise going to higher flowrates than those explored in this study would provide insight into whether the peak removal rates continue their respective trends. From the data collected, higher flowrates provide better drying performance for a fixed collector area despite lower drying temperatures and higher humidities.

### 4.3.5 Collector Area Impact

A similar comparison can be made with a fixed flowrate but varying the simulated collector areas. With this variation only the temperature and relative humidity changes as shown in Figure 28.

![Figure 28: Time to reach 45% wet basis for various collector areas with a flowrate of $0.037\frac{m^3}{s}$](image)

Figure 28: Time to reach 45% wet basis for various collector areas with a flowrate of $0.037\frac{m^3}{s}$
Increasing collector area increases the inlet temperature and decreases the inlet relative humidity. There is a weak, but positive correlation between the drying performance and increasing collector area in Figure 28. Not only does increasing the air temperature lower the vapor pressure in the drying air, but also it increases the surface vapor pressure of the fruit for most of the drying period. This is evident from the shift in the drying performance from a collector area of 1.28\( m^2 \) to a collector area of 2.55\( m^2 \). However there appears to be a plateau in this trend between the 3.35\( m^2 \) and 4.2\( m^2 \) collector areas, especially for the first stack. An approach to explaining this is shown in Figure 29.

![Figure 29: First stack moisture removal rate for a flowrate of 0.037\( \frac{m^3}{s} \) at various collector areas](image)

Figure 29 provides a clear justification of the trends seen in Figure 28. First the smallest collector area of 1.28\( m^2 \) has a noticeably lower moisture removal rate than all the other collectors. This can be readily supported by the test inlet conditions of 43.0\(^\circ\)C and 39% relative humidity which continues to dry after the other tests have already finished. Increasing the temperature of the air has a significant impact for the higher collector areas. Areas of 3.35\( m^2 \) and 4.2\( m^2 \) have overall higher initial moisture removal rates as compared to an area of 2.55\( m^2 \). However a lack of difference between those two higher collector sizes is visually evident. This supports the time to dry trend in Figure 28 where both take roughly 3.2 hours to reach 82% dry basis moisture content.
The removal rates demonstrate a clear diminishing return with respect to increasing collector area. The benefits of increasing the collector area are more apparent for stacks farther into the chamber, thus adding having a fourth and fifth stack would likely take advantage of the higher collector areas. The ideal drying scenario is where the exit airstream is as saturated as possible since this would maximize the dryer efficiency. There is a limit where the airstream vapor pressure is greater than the vapor pressure in the fruit stacks at the end of the drying chamber and would cause re-adsorption of water.

4.3.6 Drying Regimes in Deep Layer Drying

The discussions in Section 4.3.4 and Section 4.3.5 are focused on exploring the effect of external parameter changes on drying performance. Most food products start the drying process in the falling rate regime, where moisture removal rate is decreasing with time. This is caused by internal diffusion limiting moisture transfer to the surface and is suggested to be the main mechanism limiting moisture transfer [19]. Moisture removal rates for all three stacks under a set of constant conditions are plotted to investigate this in Figure 30.

![Figure 30: Moisture removal rates for all stacks for a flowrate of 0.037 m³/s at 47.7°C and 31% RH](image)

Figure 30: Moisture removal rates for all stacks for a flowrate of 0.037 m³/s at 47.7°C and 31% RH
All three stacks of fruit experience an initial thermal transience as they are warmed from room temperature to a higher temperature. After this initial period the trends between all the stacks create an interesting story. The first stack experiences a potentially brief period of constant drying, but immediately proceeds to fall at a constant rate. The first stack experiences the inlet temperature of 47.7°C and 31% RH for the whole entire drying process. While stack one experiences constant conditions, the next two stacks are experiencing variable conditions as less moisture is being added by the first stack into the airstream as the drying process goes on. Visually it appears that the second and third stack are experiencing constant drying rates for nearly three hours. This is caused by two factors changing simultaneously. First the moisture removal rate for most fruits decreases with decreasing moisture content, as evident from stack one and presented by Prakash [19]. Second, as the moisture removal rate from stack one decreases the drying potential in the air is increasing as the air is at higher temperatures and lower relative humidities when entering stack two. This suggests that the drying process is still in the falling rate regime and that the variable conditions from deep layer effects are driving the trends in Figure 30. This is consistent with many of the studies presented in the literature review applying empirical models to the trays directly adjacent to the inlet of the drying chamber - where conditions are comparatively more constant than trays deeper in the chamber.

The trend in removal rate for stack two and three would be expected if the inlet conditions to these stacks were constant and the fruit had a constant drying regime. This is not the case as the inlet conditions to each stack are changing with time. This should increase the removal rate for each stack but this doesn’t occur because moisture removal rate is also decreasing with decreasing moisture content as internal diffusion plays an increasing role. If external conditions aren’t influential in the falling rate regime, the removal rates for stack two and three should look similar to stack one. The fact that this doesn’t occur encourages the development of a model that focuses on external conditions affecting thin film drying.
5 SEMI-EMPIRICAL MODEL DEVELOPMENT

5.1 Determination of Model Scope

The approach to understanding how the drying process might be modeled in a simpler way starts with understanding what factors impact moisture removal rates. The adjustment of air temperature and flowrate has been performed so the influence of external parameters on the drying of fruits can be captured. This is in no way neglecting the importance of internal diffusion in the fruit, but rather the goal is to probe the effect of drying air properties during the falling rate regime. Therefore it is important to identify what portion of the drying process is most influenced by changes in external conditions. When plotting the moisture removal rates of the first stack for all constant condition tests against the wet basis moisture content regardless of flowrate or collector size, an interesting trend develops as shown in Figure 31.

![Figure 31: Moisture removal rate for the first stack of all constant condition tests](image)

There are four distinct regions visible in Figure 31. First there is some initial thermal transience associated with the start of the test for moisture contents between 84%-80%. The fruit warms up and moisture removal rate increases during this period. Then there is the region between
80% and 45% where the removal rate is slowly falling in a loose pattern for all tests. After roughly the 40%-45% region the moisture removal rate follows a tight pattern until reaching a sporadic region at the end of the drying process. The assumption here is that the first two regions (45% to 84%) are functions of external and internal conditions whereas the last two regions are a strong function of internal conditions. This is shown by plotting the average moisture removal rates in these regions against each other as shown in Figure 32.

![Figure 32: Average moisture removal rates for various collector areas with a flowrate of 0.037 m$^3$/s and wet basis range of 30-40% and 65-75%](image)

For the band of 65% to 75% moisture content, there is a clear positive correlation between the average moisture removal rate and collector size (higher temperature and lower relative humidity). The average moisture removal rate in the lower region of 30% to 40% is clearly not a function of collector area. Tighter trends in Figure 31 are indicative that external conditions do not cause changes to the drying performance. The broader spread of moisture removal rates above 45% wet basis moisture content (0.82 dry basis) shows external conditions influencing the drying process. This has been alluded to in previous studies where using moisture ratio models with varying external conditions has led to different effective water diffusivities being calculated. Corzo et al. dried 3mm mangoes slices at 50, 60, 70 and 80°C for chamber air velocities of 1.80 m/s and 1.91 m/s. They
found that the effective water diffusivity increased with temperature for each constant flowrate and increased with flowrate for each constant temperature \[55\]. Therefore variations in the falling rate regime of 45% to 84% are proposed to be caused by differences in the flowrates and temperatures across the tests. This is visually apparent by the drying performance of a variable condition test in Figure 33.

Figure 33: Moisture removal rate for all stacks during July 1st with a collector area of 2.55m\(^2\) and maximum flow of 0.037 m\(^3\)/s.

For all the constant condition tests, the moisture removal rates reflect the falling rate regime that most fruits start in. Therefore if external conditions had little effect on the drying performance, the peak moisture removal rates should occur at the beginning of the drying process. From Figure 33 it is evident that during the first day the moisture removal rate is increasing with the solar flux initially. As the solar flux increases, the temperature and flowrate of the drying air also increase. During the first few hours the drying potential is increasing as the relative humidity of the airstream is decreasing. However the peak rate is not at the peak flux, indicating that there are other factors influencing the process. The first stack reaches 45% moisture content at roughly four hours, which is where the moisture removal rate starts to drop. This is well before the peak inlet temperature and solar flux that occurs at five hours. This is also the case for the other two
stacks where despite a higher drying potential being available - the drying performance is still lower. Any moisture removal rates after the 8th hour are either part of sensor noise or the last few grams of moisture being removed.

A simple model that focuses on modeling the external interaction with the fruit film should therefore be based in this region. If the mango film starts at 84% wet basis moisture content, then roughly 85% of the initial moisture will have been removed once that mango reaches 45% moisture content (see Appendix B).

5.2 Review of a Simplified Mass Transfer Model

To verify the domain of the model between 45% and 84% wet basis moisture content (0.82 to 5.25 dry basis), the moisture removal for the first stack of all constant condition tests is plotted against the dry basis as well. This is done by applying a very simple mass transfer model against this data. The goal of doing this is to get another perspective on the influence of external parameters on the moisture removal rate, not to propose a predictive model. The fundamental model for mass diffusion by concentration differences is helpful in this case and is as follows:

\[ \dot{N} = kA(c - c_\infty) \]  

(22)

where the molar removal rate, \( \dot{N} \), is a function of the surface area, \( A \), the mass transfer coefficient, \( k \), the moisture concentration at the fruit surface, \( c \) and the moisture concentration in the free airstream, \( c_\infty \). This model can be converted to a mass basis by substitution and assuming that the surface temperature is equal to the free airstream temperature to yield the following:

\[ \dot{X} = h_m \rho A(P - P_\infty) \]  

(23)

Now the time rate change of the dry basis moisture content, \( \dot{X} \), is a function of the vapor pressure differences between the film surface, \( P \), and the airstream, \( P_\infty \). All the terms in front are again assumed constant and could simply be represented by \( h_m \), the mass transfer coefficient. Ekechukwu proposes a simple linear model for moisture diffusion based on Eq. (23) that assumes in the range of interest the dry basis moisture content is linearly proportional to the vapor pressure.
\[ \dot{m} = h_m \rho A (X - X_{eq}) \]  (24)

The equilibrium moisture content in this scenario is set to the average dry basis moisture content attained by the end of all the tests, 13.6%. It is important to acknowledge that this assumption and many of the others made above, such as the fruit surface being the same temperature as the freestream air, are known to be invalid for a realistic predictive model. The point of these assumptions is to allow a simplified model to be applied to experimental measurements. Using the data collected, the moisture removal rate, \( \dot{m} \), and the instantaneous dry basis moisture content, \( X \), is known at any point. Thus the quantity \( h_m \rho A \) can be solved for, which should reflect upon a functional form for the mass transfer coefficient as shown in Figure 34.

![Figure 34: Mass transfer coefficient from simple mass transfer model versus dry basis moisture content](image)

Using Eq. (24) a very clear trend can be observed for the mass transfer coefficient versus the dry basis moisture content. Between dry basis moisture contents of 0.8 and 5.25 (44.4% and
84% wet basis) there is a clear trend amongst all the constant condition tests. After this point the quantity \( h_m \rho A \) varies dramatically, particularly below 30% wet basis moisture content. The crude assumption regarding the equilibrium moisture content and ignorance of any internal diffusive effects likely contributes to the perceived trend that the mass transfer coefficient is increasing with time. However the focus of this analysis is to reinforce the proposed model range of 45% to 84% wet basis moisture content. A more specific model will be derived for the experimental setup in Section 5.3 in this range based on external conditions being the major factor in the drying process.

The analysis above demonstrates a few of the many approaches that can be taken to assess data collected from the drying process. In the interest of predicting drying performance for various system designs, a model based on the data collected will be derived. This model, discussed in the next section, will be based in the regime identified above of 45% to 84% wet basis moisture content. Thus results from constant condition tests will be used to fit the model’s unknown parameters. This model will then be validated against variable condition tests to see both the effects of a variable testing environment versus a constant condition one and the ability of the model to predict drying performance. This model can then be explored to gain insight into further manipulation of design parameters and their impacts on drying performance.

5.3 Thin Layer Model Derivation

In order to understand the effect of changing design parameters such as collector area, number of stacks, or system flowrate - it is useful to have a predictive model that can be probed. Not only could parameter choices in the range the model was calibrated be explored, but also there is a potential for extrapolating outside of the probed space. Tests performed in this investigation have guided the direction of the project focus and many of the assumptions made. By choosing a thin film thickness the intent is to reduce the effects of internal diffusion and have generally shorter drying times. With this perspective, the following diagram in Figure 35 is used to develop a drying model for the thin layer drying of a shrinking film where lumped properties are assumed.
The control volume indicates that there is a thin film of solid mango and water sitting on an impermeable aluminum plate. This suggests that mass transfer is only between the fruit and air at state 2, whereas heat transfer occurs between the solid and both air at states 2 and 3. Since the effects of internal diffusion are assumed to be negligible, both a bulk temperature, $T$, and bulk wet basis moisture content, $W$, are used for the film. The density, $\rho$, and specific heat, $\bar{C}_P$, of the film are composed of wet and dry elements whose properties are referenced. There is assumed to be no variation of any of these properties throughout the thickness of the film $L$.

The state $2_w$ represents the air layer directly adjacent to the fruit surface and is assumed to be in equilibrium with the fruit. States 2 and 3 represent the free airstream passing over and under the fruit respectively. Mass transfer only occurs with respect to the air water fraction, $W_{2,\infty}$, and the mass transfer coefficient of water in that fluid, $k$. However the assumption is that this control volume is stacked on top of itself for any number of trays. This means that the tray below this control volume would be exchanging moisture with $W_{3,\infty}$, affecting it’s moisture ratio and temperature, $W_{2,\infty}$ and $T_{2,\infty}$. Heat transfer occurs based on the experimentally fit model values in Section 5.5.1 for $h_2$ and $h_3$.

The development of this model has been in collaboration with Dr. Steven Weinstein from Chemical Engineering in the Kate Gleason College of Engineering at RIT. The proposed control volume, system level equations, and all simplifications of the model have been corroborated with Dr.
Weinstein [56]. The following represents the system level equation for the mass transfer component of the model.

\[
\frac{d}{dt} \int_{V(t)} C_1 \, dV + \int_{\partial V(t)} C_1 (u_1 - u) \, \hat{n} \, ds = 0 \tag{25}
\]

This states that the time rate change of the concentration within the film, \( C_1 \), as contained in the control volume, \( V \), is equal to the concentration leaving the moving control surface. The concentration movement relative to the shrinking surface velocity is represented by \( u_1 - u \) and only occurs at the top surface. This movement is assumed to be constant between all differential area elements, \( ds \), across the fruit surface. Throughout the drying process the fruit area is assumed to be constant such that only the height of the film is changing with time. Also it is reasonably assumed that only liquid components, water, are transferred across the fruit-air interface while the solid flesh remains in the control volume at all time. Through multiple simplifications and the assumption that molar fractions are analogous to weight fractions, the following final model is derived.

\[
\frac{dW}{dt} = -\frac{k}{\rho_0 (1 - W_0) L_0} \frac{W_{2w} - W_{2,\infty}}{1 - W_{2w}} (1 - W)^2 \tag{26}
\]

This summarizes the mass transfer relation that occurs throughout the drying process of a thin shrinking film. The term \( \rho_0 (1 - W_0) L_0 \) represents the initial dry mass per unit area where \( \rho_0 \) is the combined dry+wet mass density, \( W_0 \) is the initial wet basis moisture content, and \( L_0 \) is the initial film height. The surface air weight fraction of water, \( W_{2w} \), is determined by using the GAB model to cross the interface with known values of the surface temperature, \( T \), and the film water fraction (or wet basis moisture content) \( W \). The airstream water fraction, \( W_{2,\infty} \), is known as an inlet condition or is calculated based on the later proposed system model. The process is driven by the mass transfer coefficient, \( k \), which is determined experimentally in Section 5.5 Eq. 26 allows the determination of the fruit moisture content at any point in time when coupled with the heat transfer model proposed below.

\[
C_1 L\tilde{C}_P \frac{dT}{dt} = h_2 (T_{2,\infty} - T) + h_3 (T_{3,\infty} - T) - \frac{k (y_{2w} - y_{2,\infty})}{1 - y_{2w}} \Delta \hat{H}_{v,w} \tag{27}
\]

The time rate change of the temperature of the film is proportional to the heat transfer
provided from the two airstreams relative to the energy utilized to vaporize water. There are
other terms related to the movement of the film surface, but these are negligible as compared to
the convection at the surface and the heat utilized in evaporating moisture. The prefix \(C_1LCP\)
represents a lumped thermal mass based on the current composition of the film. The latent heat
of vaporization of water, \(\Delta \hat{H}_{v,w}\), is multiplied by a term that is equivalent to the mass flux of
water leaving the film. This term is equal to \(\dot{m}_w\), which can be determined using the mass transfer
expression from Eq. (26). By transferring this molar based expression to a mass based expression,
the following final form is presented.

\[
\frac{dT}{dt} = \frac{1}{\rho LCP} (h_2(T_{2\infty} - T) + h_3(T_{3\infty} - T) - \frac{k(W_{2w} - W_{2,\infty})}{1 - W_{2w}} \Delta \hat{H}_{v,w})
\]

(28)

Now the coupled mass and heat transfer equations can be used to fully describe the pro-
posed drying response of a thin shrinking film. The mass transfer coefficient, \(k\), and the heat trans-
fer coefficient, \(h\), are determined using experimental data in Section 5.5.1. All other fundamental
parameters will be identified in the next section through established references and relationships.

### 5.4 Thin Layer Model Implementation

#### 5.4.1 Determination of Fundamental Parameters

In order to use the model proposed, values for fundamental parameters must be selected.
Once values are selected, a system model is then applied to allow the modeling of multiple stacks
of fruit. Shown below are the fundamental reference parameters used in this investigation.
Table 8: Referenced fundamental parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Mango Specific Heat</td>
<td>$C_{P, \text{ref}}$</td>
<td>3740</td>
<td>J kgK</td>
<td>[57]</td>
</tr>
<tr>
<td>Density of Water</td>
<td>$\rho_{\text{wet}}$</td>
<td>1000</td>
<td>kg m$^{-3}$</td>
<td>[58]</td>
</tr>
<tr>
<td>Water Specific Heat</td>
<td>$C_{P, \text{wet}}$</td>
<td>4187</td>
<td>J kgK</td>
<td>[58]</td>
</tr>
<tr>
<td>Density of Air</td>
<td>$\rho_{\text{air}}$</td>
<td>1.225</td>
<td>kg m$^{-3}$</td>
<td>[58]</td>
</tr>
<tr>
<td>Kinematic Viscosity of Air (27°C)</td>
<td>$\nu_{\text{air, low}}$</td>
<td>15.89 * 10$^{-6}$</td>
<td>m$^2$ s$^{-1}$</td>
<td>[58]</td>
</tr>
<tr>
<td>Kinematic Viscosity of Air (77°C)</td>
<td>$\nu_{\text{air, high}}$</td>
<td>20.92 * 10$^{-6}$</td>
<td>m$^2$ s$^{-1}$</td>
<td>[58]</td>
</tr>
</tbody>
</table>

With these values, other necessary parameters can be calculated in order to run the model. As the fruit film dries, its internal properties change as the solid component of the fruit becomes a larger portion of the total composition. The density of the solid portion of the fruit is unknown and has been calculated from measurements taken in the lab. After five samples of the same starting and ending moisture content were dried, the thickness of the film is measured. On average this thickness, $L_f$, is 0.33mm with 3.8 grams of moisture and 27.2 grams of solid mass. Continuing with the assumption that 85% of the 327mm x 264mm mat, $A_{\text{mat}}$, is occupied by mango, the solid density $\rho_{\text{dry}}$ is calculated:

$$\rho_{\text{dry}} = \frac{m_{\text{dry}}}{(0.85)A_{\text{mat}}L_f - \frac{m_{\text{wet}}}{\rho_{\text{wet}}}}$$  \hspace{1cm} (29)$$

To determine the specific heat of the solid component of the mango film, the ASHRAE Handbook on Refrigeration is referenced [57]. Given a reference moisture content, $W_{\text{ref}}$, of 0.8171 and the specific heats in Table 8, the following equation is used.

$$C_{P, \text{dry}} = \frac{C_{P, \text{ref}} - W_{\text{ref}}C_{P, \text{wet}}}{1 - W_{\text{ref}}}$$  \hspace{1cm} (30)$$

The values for these two calculations are shown below and are used in the simulation to determine the fruit properties at any given moisture content:
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Mango Specific Heat</td>
<td>$C_{p,\text{dry}}$</td>
<td>1743</td>
<td>$J/kgK$</td>
</tr>
<tr>
<td>Dry Mango Density</td>
<td>$\rho_{\text{dry}}$</td>
<td>1356</td>
<td>$kg/m^3$</td>
</tr>
</tbody>
</table>

In equations (26) and (28), the terms $W_{2w}$ and $W_{2\infty}$ are part of the simulated model. Since this study has assumed nominal conditions of 30°C and 80% RH, the moisture ratio of the air, $X_{2\infty}$, can be determined. All psychometric relationships are taken from the 2013 ASHRAE Handbook of Fundamentals [59]. The weight fraction of water in the air at any point can be found simply by the following:

$$W_{2\infty} = \frac{X_{2\infty}}{1 + X_{2\infty}}$$  \hspace{1cm} (31)

The weight fraction of water in the air at the fruit surface is determined using the GAB expression from Eq. (4). Assuming that the air temperature adjacent to the fruit is the same temperature as the film, the moisture content of the film can be used to determine the relative humidity of the air layer. For both $X_{2w}$ and $X_{2\infty}$ the following psychometric relationship is used:

$$X_{\text{air}} = 0.622 \frac{\phi P_{ws}}{P_{tot} - \phi P_{ws}}$$  \hspace{1cm} (32)

The typical value for the atmospheric pressure, $P_{tot}$, is 101.325 kPa. The saturation pressure of water at the air temperature, $P_{ws}$, is multiplied by the relative humidity, $\phi$. Collectively this yields the moisture ratio (dry basis moisture content) of the air. When solving the GAB equation to get the relative humidity at the fruit surface, there are three unknown fitting parameters that need to be determined. In this study the nominal values at three reference temperatures of these unknown constants is cited from Talla et al. at 40, 50, and 60°C [60]. The values reported in this paper are used to fit Arrhenius relationships of the following form:

$$C = A_1 \exp(A_2/T)$$  \hspace{1cm} (33)
The Arrhenius relationship for each of the three reference parameters requires two fitting terms that scale with the absolute temperature of the interface. The values used for these fits are detailed below.

Table 10: GAB Constants

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$A_1$</th>
<th>$A_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.00040168</td>
<td>5100.63</td>
</tr>
<tr>
<td>M</td>
<td>0.00014537</td>
<td>2032.26</td>
</tr>
<tr>
<td>K</td>
<td>2.5333</td>
<td>274.48</td>
</tr>
</tbody>
</table>

5.4.2 System Model for Multiple Stacks

Using the above expressions and parameters, the drying of a single stack of fruit can be simulated for a given set of inlet conditions. Across a single tray the properties of the drying air and the film are assumed to be constant. In each time step the moisture content and temperature of the fruit film is updated using the surrounding air conditions of the previous timestep. This is done until the termination of the simulation. In order to extend the model to additional stacks downstream, some assumptions are made about the mass/heat transfer occurring. Foremost it is assumed the chamber is well insulated thus there is no change in enthalpy across the chamber or tray:

$$h_{air, out} = h_{air, in}$$  \hspace{1cm} (34)

In order to determine the exit condition of the air leaving a stack, which is the inlet condition to the next stack, two properties of the air are needed. Knowing the enthalpy is constant, the moisture removal rate of the previous stack is used to determine the new moisture ratio of the drying air in that channel. This is calculated as follows:

$$X_{air, out} = X_{air, in} + \frac{\dot{m}_{wet}}{\dot{m}_{air}}$$  \hspace{1cm} (35)
All moisture removed from a fruit film is assumed to be absorbed by the drying air in the channel above it. Using the mass transfer model the moisture removal rate, \( \dot{m}_w \), is determined. For a given volumetric flowrate set in the system and an assumed air density from Table 8, the mass flow rate of air, \( \dot{m}_{air} \), can be determined. Once the moisture ratio of the air is determined, the following expression from ASHRAE 2013 is used:

\[
\dot{h}_{air} = 1006\left(\frac{J}{kgC^2}\right)T_{drybulb} + X_{air,2}(2501000 + 1860\left(\frac{J}{kgC^2}\right)T_{drybulb}) \quad \left(\frac{J}{kg}\right) \tag{36}
\]

This allows the determination of the dry bulb temperature of the airstream, \( T_{drybulb} \), which completes the values needed as inputs into the next stack. Equation (31) can be solved to determine the relative humidity of the air for reference. Between stacks it is assumed that there is no change in flowrate, chamber cross section, or air properties. This indicates that a constant volume is moving across each film collecting moisture and decreasing in temperature. With the heat and mass transfer models coupled with the stack relationships identified above, the model is able to simulate a deep layer / multi-stack system. To finish the model the mass and heat transfer coefficients are determined experimentally.

### 5.5 Fit and Simulation of Thin Layer Model

Now that a model has been derived, the unknown coefficients for heat and mass transfer need to be determined. Using experimental data collected from the constant condition tests, these parameters are fit based on general hydrodynamic relationships. The goodness of fit of these models for the range of data collected is then commented on and explored in this section.

#### 5.5.1 Fit of Model for Constant Conditions

All simulations are executed using Matlab 2017b, allowing for the simple optimization of some of the model inputs to match the collected experimental data. The model itself is implemented using a first order Runge-Kutta method with one minute time steps. In the model proposed in Section 5.3, the only unknown parameters are the convection coefficients, \( h_2 \) and \( h_3 \), and the mass transfer coefficient \( k \). Thus a general functional relation is proposed to capture variations in these
variables. Heat transfer is assumed to occur on both sides of all trays except the bottom as the air passage was mostly blocked off. The heat transfer coefficient of both channels is assumed to be identical with the heat transfer on the bottom tray represented by a proposed factor of 1.5 times the convection coefficient instead of 2 like the top trays. The convection coefficient functional form is assumed in Eq. (37).

\[ h = A_1 Re^m \]  

(37)

The terms \( A_1 \) and \( m \) represent unknown fitting parameters to be found through optimization. The convection coefficient is thus proposed to be only a function of the Reynolds number, \( Re \), and is constant for tests of the same volumetric flowrate. The Reynolds number is calculated using a hydraulic diameter of 46mm. The mass transfer coefficient is assumed to be linearly related to the convection coefficient as follows:

\[ k = A_2 h \]  

(38)

where \( A_2 \) is the proportionality constant. This leaves three unknown fitting variables that must be determined through an optimization scheme. For this thesis Matlab’s fminsearch is used to find the best set of coefficients for the data collected. Twelve constant condition tests are used in the optimization scheme and then these fitted models are then applied to the variable condition scenarios. The goodness of fit in this scheme is the root mean square error (RMSE) between the predicted wet basis moisture content and the experimentally determined value:

\[ RMSE = \sqrt{\frac{\sum_{n=1}^{N} (M_{wet,exp} - M_{wet,pre})^2}{N - 1}} \]  

(39)

Matlab’s fminsearch minimizes this error by varying the fitting parameters to find the best fit. Initially this was done for only the constant condition tests for data corresponding to wet basis moisture contents above 45%. From Figures 31 and 34 there is a clear spread in moisture removal rates for moisture contents above 45%. After that threshold diffusion becomes the limiting factor and the moisture removal rate appears to be independent of the process air conditions.
Fitting the model in this region results in the following functional forms:

\[ h = 0.3047Re^{0.5053} \frac{W}{m^2K}, \quad k = \frac{h}{4000} \frac{m}{s} \]  

There is no temperature dependence in the above expressions because the influence of the process air temperature should show up in the GAB equation in Eq. (18) and the heat transfer model, Eq. (20). The constant condition tests are then run through the chamber model again to observe the ability of the general fit to predict the drying performance. The best fit of the model is shown in Figure 36.

Figure 36: Comparison of model prediction of wet basis moisture content versus experimental data for \(0.0162m^3/s\), \(A=2.55m^2\)

These three plots represent different ways of viewing the fit of the model against the experimental data. The first graphic illustrates the visual overlay of experimental data with associated error bars and the predicted response of the model for the calculated moisture content (MC). At the lowest flowrate the model appears to track the wet basis moisture content well. The difference between the data and the model versus moisture content is shown by the middle graph. The model typically over predicts the first half of the drying process and underpredicts the second
half. All experimental data has a characteristic s-spline shape to it and the model is only able to capture the left side of this curve. This is understandable since internal diffusion effects are ignored by the derived model, which are the dominating force in the second part of the falling rate regime. Over the range of 50% to 84% the agreement is very good, which is reinforced by the last graph. This figure provides a comparison between a perfect fit, the solid line, and where the model falls in relation to that line. For the first part of this line the model is above the perfect fit and is below the fit for the other half. This is the best fit of the constant condition tests, the worst case fit is shown in Figure 37.

Figure 37: Comparison of model prediction of wet basis moisture content versus experimental data for $0.022 \frac{m^3}{s}$, $A=5.1m^2$

The fit for the worst case struggles to capture the drying behavior between 60% and 40% wet basis moisture content. The fit is close to the measured point until about 65% wet basis, at which point it quickly drops out of the lower error bar range. This is reinforced by the third plot where the predicted data is on the perfect fit line until 60%. In perspective, if the worst case fit accurately predicts drying performance until 60% wet basis (1.5 dry basis) - it is able to predict 70% of the initial moisture being removed. A numerical sense of the goodness of fit of the model
for all the constant condition tests can be viewed in Table 11.

Table 11: RMSE values for all constant condition tests reported

<table>
<thead>
<tr>
<th>Flowrate $[\text{m}^3 \text{s}^{-1}]$</th>
<th>Collector Area $[\text{m}^2]$</th>
<th>Temperature $[\text{C}]$</th>
<th>Relative Humidity $[%]$</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.016</td>
<td>2.55</td>
<td>52.5</td>
<td>24</td>
<td>0.0151</td>
</tr>
<tr>
<td>0.022</td>
<td>1.28</td>
<td>46.6</td>
<td>33</td>
<td>0.0222</td>
</tr>
<tr>
<td>0.022</td>
<td>1.90</td>
<td>49.1</td>
<td>29</td>
<td>0.0273</td>
</tr>
<tr>
<td>0.022</td>
<td>2.55</td>
<td>50.8</td>
<td>26</td>
<td>0.0339</td>
</tr>
<tr>
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<td>52.0</td>
<td>25</td>
<td>0.0473</td>
</tr>
<tr>
<td>0.022</td>
<td>5.10</td>
<td>53.8</td>
<td>23</td>
<td>0.0614</td>
</tr>
<tr>
<td>0.030</td>
<td>2.55</td>
<td>49.1</td>
<td>29</td>
<td>0.0480</td>
</tr>
<tr>
<td>0.030</td>
<td>2.55</td>
<td>49.1</td>
<td>29</td>
<td>0.0241</td>
</tr>
<tr>
<td>0.037</td>
<td>1.28</td>
<td>43.0</td>
<td>39</td>
<td>0.0233</td>
</tr>
<tr>
<td>0.037</td>
<td>2.55</td>
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<td>0.0422</td>
</tr>
<tr>
<td>0.037</td>
<td>3.35</td>
<td>49.4</td>
<td>28</td>
<td>0.0246</td>
</tr>
<tr>
<td>0.037</td>
<td>4.20</td>
<td>50.7</td>
<td>27</td>
<td>0.0861</td>
</tr>
</tbody>
</table>

In all of the constant condition tests reported the model fit is similar to Figure 36, where the moisture content is higher than experimentally reported in the first half of the process and lower in the second half of the regime. The optimization method used attempts to balance this aspect of the model, yielding the error trends above. Increasing the convection coefficient or the mass transfer coefficient will reduce error at the beginning of the process but increase error on the other end as the fitted curve become steeper. In the model proposed by Eq. (26) the driving potential between the drying air and the fruit surface is fairly constant for the first portion of the drying process. Since the inlet moisture ratio and temperature is constant, the driving potential in the airstream does not vary for the first tray throughout the test. The GAB model for dry basis moisture contents above 1 yields relative humidities at the surface that are all in the range of > 90%. Therefore the difference between the vapor pressures of these components stays relatively constant. This is shown in Figure 38 by plotting the experimentally calculated moisture removal rate versus the model’s prediction.
This provides insight into the model discrepancy from the collected data and how the model functions. At the beginning and end of the range of moisture contents observed in this fit the model is overpredicting the moisture removal rates. This is evident in the predicted moisture content being lower than what is actually reported. Similarly there is a large period of time where the model underpredicts the moisture removal rate, causing the opposite effect - both of which are visible in Figure 38. The effect of the constant driving potential is shown by the plateau in the predicted moisture removal for 4 hours of the drying process. This removal rate quickly decreases as the surface relative humidity drops with decreasing fruit moisture content.

5.5.2 Model Fit for Multiple Trays

The model goodness fit is determined for the first stack only as the inlet conditions to the stack are known. Inlet conditions to the second and third stack are not known and are variable with time. By fixing the inlet conditions in the simulation and incorporating a system level model, the goodness of fit of the model for additional stacks in a constant condition test can be explored.
The system level fit for a constant condition test is shown in Figure 39.

Figure 39: Comparison of model prediction of stack moisture contents versus experimental data for constant conditions of 0.016 m$^3$, A=2.55 m$^2$, 52.5°C, 24% RH

In the system model, moisture removed from each tray is absorbed into the passing airstream. This increases the relative humidity of the airstream and decreases its temperature. In the model this directly effects the surface temperature of the fruit and drying potential in the airstream for each successive stack. This effect is visible in the collected data and in the model, however the extent of this effect is not the same. While the model is able to track the moisture content for the first portion of the drying process of a constant condition scenario, it is unable to do so for a variable condition environment as evident from the deviation of stack 2 and stack 3 from the data. This effect also occurs unsurprisingly in the variable condition test shown in Figure 40.
It is clear that the model is overpredicting the moisture removal rate in variable condition cases. There are many possible causes that could explain this difference. The first and foremost is that internal diffusion plays a larger role in the drying process than the lumped model attempts to capture. This is not contested but rather is assumed to be more influential in the latter half of the drying process - that other factors are affecting the model’s accuracy in the region of interest.

5.5.3 Exploration of Model Deviations

One potential reason for the model deviation is the utilization of the GAB model to determine the fruit surface vapor pressure. As previously stated, the GAB model is valid for effectively all water activity levels. However it seems that solving the GAB equation for a water activity for a given surface moisture content is potentially not a valid approach in this application. This is worth noting since the fit from Talla et al. is for water activities from 5.6% to 85%. This is not the case as shown below for the first stack’s predicted relative humidities in Figure 41.
Figure 41: Plot of first stack surface relative humidity for $2.55\,m^2$ collector with maximum flow $0.037\,\frac{m^3}{s}$ on July 1st

Once the model passes below one (1) on a dry basis moisture content, the surface relative humidity drops quickly with decreasing fruit moisture content. This is seen by a nose dive shape in the surface water activity. The model is based in a dry basis region of 0.82 to 5.25 and the first stack reaches 0.82 around the 200 minute mark. By utilizing the GAB model the surface relative humidity is calculated by back solving the GAB relationship with a known surface moisture content. The dry basis moisture content corresponding to a water activity of 85% is between 0.9 and 1, dependent on temperature. This means that nearly the entire region the model is based on is outside the range that the GAB model was fit for as shown in Figure 42.
In the region of 5.6% to 85% of the GAB model, higher fruit temperatures/drying air temperatures will lead to lower equilibrium moisture contents. Conversely when solving the model for water activity levels, higher temperatures will yield higher surface water activities for given moisture content. A dry basis moisture content of 0.25 corresponds to a water activity of 58% at 40°C and 63% at 50°C. However in the region above 85%, where the GAB model was not fit for, the opposite occurs. A dry basis moisture content of 3.0 corresponds to a water activity of 92% at 40°C and 90% at 50°C. The GAB model in this upper region has little variation in the calculated water activity for different temperatures at a given moisture content. This could potentially explain why the deep layer drying is not captured by either the constant or variable condition fit.

A possible explanation for why the constant and variable condition fits are significantly different from each other may be caused by the parameter space explored by the constant condition tests. The temperature and flowrate setpoints for all constant condition tests as well as the variable test on July 1st is shown in Figure 43.

Figure 42: GAB fit for $X_{eq}$ of mangos for water activities between 5.6% and 85% and temperatures of 40, 50 and 60°C
The mindset when choosing the parameters for constant condition tests was to explore the effect of the volumetric flowrate and collector size on the drying performance. Each of these tests ran under a constant flux of $800 \frac{W}{m^2}$, thus the potential range of temperatures was relatively limited as evident in Figure 43. The variable condition demonstrates the combined effect of increasing flux from the first half of the day (represented by the top line), increasing flowrate, and increasing ambient temperature. The third stack on July 1st reached 45% moisture content around the peak of the day at five hours (the top right of the figure). This means that only one or two points of the constant condition tests fall close to the actual setpoints for variable conditions. Two hours of the day are spent below $0.028 \frac{m^3}{s}$ and the remaining three hours are spent above. Combining this with the constant condition fit in Figure 40 suggests that our model over-predicts moisture removal rates associated with lower flows and temperatures with the current transfer coefficient models.

If the models for the heat and mass transfer coefficients are corrected, there is still an underlying issue with the system model. This is evident from Figure 39 where the first stack may fit but all other stacks are drastically over-predicted in performance. A possible explanation to this may be that air passing over the fruit is not fully mixed as assumed by the model. The air
passing between each tray in the model is assumed to be fully mixed before entering the next tray, which infers that all moisture absorbed from the previous fruit tray has been distributed evenly in the volume of air. Air abruptly exits from a bent flexible duct into a 150mm precamber before it enters the 25mm channels above each tray in the drying chamber. It then travels approximately 1m along the trays until it exits the third stack.

In this whole span of the chamber, it is possible that flow is still developing along the length of the plates. As the flow progresses down the plates, the mass transfer and hydrodynamic boundary layers are likely still developing. The flow scenario in this setup is two parallel plates where the bottom plate is rough due to the fruit surface. For the low flows tested in this study, the flow along the plate surface could be treated as external flow. The flow itself is laminar with external flow Reynolds numbers between 70,000 and 150,000 and the boundary layers would develop from both plates until meeting at a height of 12-13mm. Ignoring the rough surface of the mango film, the Blasius approach to calculating boundary layer thickness is used [61].

\[
\delta(x) = \frac{4.9x}{(u_\infty x/\nu)^{\frac{1}{2}}} 
\]  

(41)

The boundary layer thickness at any length of external flow on flat plate, \(\delta(x)\), can be found using the distance from the edge of the plate, \(x\), the freestream velocity, \(u_\infty\), and the kinematic viscosity, \(\nu\). Plotting this for the range of volumetric flowrates tested, the predicted growth of the boundary layer in each channel is shown in Figure 44.
Figure 44: Thickness of hydrodynamic boundary layer across length of testing chamber for various flowrates

Higher flowrates will disrupt the boundary layer more and thus take longer to develop as seen in Figure 44. As most of the variable conditions take place under higher flowrates, it would be reasonable to assume that the boundary layer is still developing. Over the span of the flowrates tested, the average boundary layer thickness across all flowrates for the length of the chamber is approximately 10mm. For a chamber height of 25mm, ignoring a boundary layer developing on the top plate, the boundary layer in contact with the fruit is only 40% of that height on average. By extension it is proposed that the mass transfer layer is also developing in this span of the chamber. The other 60% of the chamber would contain air not mixing with the boundary layer, supporting the suggestion that the air flow is not fully mixed between stacks of trays.

5.5.4 Proposed Model Corrections

Based on the discussion in Section 5.5.3, the following changes are proposed for the heat/mass transfer models and the system model used in this study. The goal of these changes is to produce a better fitting model for the variable condition tests so that it can be used to better
predict drying performance than the current model is able to.

After determining that the span of the constant condition tests largely resides outside typical variable conditions, we propose refitting the heat and mass transfer model constants. The fit will be done in a similar fashion as in Section 5.5 except using the first stack of variable testing for July 1st and July 17th. The variable conditions between these two days are similar and feature a collector area of $2.55m^2$ with a maximum flow of $0.037\frac{m^3}{s}$. After running a best fit of the heat and mass transfer models, Eq. (37) and Eq. (38), the following change of parameters is determined in Table 12:

Table 12: Proposed heat and mass transfer model coefficient adjustments

<table>
<thead>
<tr>
<th>Fit</th>
<th>$h$</th>
<th>$k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>$0.3047Re^{0.5053}$</td>
<td>$\frac{h}{1000}$</td>
</tr>
<tr>
<td>Variable</td>
<td>$0.2054Re^{0.5419}$</td>
<td>$\frac{h}{5042}$</td>
</tr>
</tbody>
</table>

Overall the model coefficient changes yield lower transfer coefficients with a slightly stronger variance with the Reynolds number. This is consistent with comparison of the variable condition setpoints versus the space explored with the constant condition tests in Figure 43. Using these new model coefficients, Figure 45 shows the updated prediction of drying performance on July 1st.
Figure 45: Corrected model predictions for performance of a 2.55m$^2$ collector with maximum flowrate of 0.037 m$^3$/s on July 1st.

The fit in Figure 45 shows good agreement for the first stack in the range of dry basis moisture contents between 5.25 and 1. The next two stacks still fail to accurately represent the deep layer drying effect caused by having multiple stacks in the drying chamber. This motivates the following correction to the system model for the drying chamber.

In Section 5.5.3, it is proven that over the length of the drying chamber the boundary layer is continuing to develop. Therefore not all of the drying air is actively mixing with the moisture absorbed from the fruit surface. A certain percentage of the air is moving along the fruit surface, absorbing moisture, while the other portion is flowing along the top of the drying chamber. To account for this the following adaptation of Eq. (35) is proposed.

$$X_{2,\text{out}} = X_{2,\text{in}} + \frac{\dot{m}_\text{wet}}{\dot{m}_\text{air}}$$  \hspace{1cm} (42)

Moisture removed from each tray is absorbed into the drying air above the tray, however not all of the air is mixing together. While the boundary layer develops only a certain percentage,
C, of the air will be exposed to the added moisture. For the same moisture removal rate, \( \dot{m}_{wet} \), less airflow will result in higher moisture ratios. Therefore the conditions of the drying air entering the next tray will be more saturated than if all of the drying air, C=1, was mixing together. Using similar optimization schemes as in Section 5.5, a value of C=0.40 was determined. This value suggests that 40% of the air flowing over the chamber is mixing with the absorbed moisture of that tray. This is consistent with the ratio of the average boundary layer thickness of 10mm to the channel height of 25mm discussed in Section 5.5.3. This updated system model and the updated heat/mass transfer models in this section are used to again predict the drying performance under variable conditions on July 1st as shown in Figure 46.

![Figure 46: Model predictions for performance of a 2.55m² collector with maximum flowrate of 0.037 m³/s on July 1st](image)

The agreement of all stacks is within measurement uncertainty in Figure 46. All fits line up until a dry basis moisture content of 0.9 (47% wet basis) and present an accurate prediction of the drying performance in the region the model is focused on. These updated coefficients for the heat/mass transfer models and the new system model will be used in the next section to predict drying performance.
5.6 Extrapolation of Model for Performance Prediction

With the established mass and heat transfer models, the simple system model allows for the exploration of multiple tray drying. Based on the mass and heat transfer coefficient forms determined earlier, various inputs can be varied to understand how they impact drying productivity. All exploration in this section will be focused on 2mm mango pulp starting on July 1st in Borgne, Haiti.

5.6.1 Model Prediction of Multiple Stack Drying

The drying day starts at 8h when the flux first exceeds $400 \frac{W}{m^2}$ and ends at 16h when the flux drops below $400 \frac{W}{m^2}$. During the day the temperature and relative humidity of air entering the collector and the drying chamber inlet is changing. Air exiting the collector is based on the single unglazed transpired collector model in Eq. (9). The volumetric flowrate is also changing between 40% and 100% of the maximum flow based on Eq. (15). The air conditions exiting the collector (temperature, relative humidity, volumetric flowrate) are the inlet conditions to the first stack in the chamber.

Our drying model is then applied to determine the change in fruit moisture content and temperature, Eq. (26) and Eq. (28). The system model, Eq. (34) and Eq. (42), is then used to set the conditions of the air entering the next stack. Each tray has the same assumed starting conditions of 170g at 84% wet basis moisture content with two trays per stack. Each stack is 25mm apart and each tray is stacked 25mm above the previous one. A stack is considered dry if the weighted dry basis moisture content, the total mass of water in the stack divided by the total mass of dry fruit in the stack, falls below 0.82 dry basis. Once a tray reaches 0.25 on a dry basis, it is removed from the stack so it won’t reabsorb moisture. The performance of the dryer with a total of ten stacks on July 1st is shown in Figure 47.
Figure 47: Dry basis moisture content predicted by model for ten stacks on July 1st with a collector area of 2.55m$^2$ and maximum flowrate of 0.037 m$^3$/s.

Figure 47 illustrates the deep layer drying effect from each successive stack, with stack 1 being the farthest to the left and each stack to the right deeper in the dryer chamber. In this scenario a 2.55m$^2$ collector with a maximum flowrate of 0.037 m$^3$/s for one day is shown. There is a sudden shift in each moisture content curve at the lower 30% of the plot since the top tray is drying faster than the bottom tray. Since each tray is removed at 25% on a dry basis, its effective moisture removal rate goes to zero once it’s taken out. This is confirmed by Figure 47 as the derivative of the dry basis plot is proportional to the moisture removal rate, so the sudden decrease in slope indicates the top tray has stopped drying. This is not relevant in the following analysis since the fitting of the model was selected in the range of 45% to 84% wet basis moisture contents. All commentary is focused on this region.

The mindset guiding the modeling presented in this investigation emphasizes thin layer drying, which was motivated by thickness testing done initially in the lab. If a thicker film was chosen, then testing over two days would become a more relevant parameter. However testing has been focused on single day drying where the film is able to reach a desirable moisture level.
within 8-10 hours. Similarly no work has been done to focus on equilibrium modeling when no flow conditions occur. In the current model no flow would simply result in no change in moisture content or temperature, which is not realistic. Stacks within the chamber, if the chamber was sealed, would come to equilibrium with each other during the night. Limiting simulations to one day reduces the number of assumptions made and matches the testing done in the lab.

5.6.2 Model Prediction of Dryer Performance

With the established scope of what the model will explore, the model is run for collector areas between $1 m^2$ and $5 m^2$ and flowrates of $0.016 m^3/s$ to $0.047 m^3/s$. The parameter time to dry is used with a critical dry basis moisture content of 82%, which represents 85% of water removed and is the end of the range the model is calibrated for. Figure 48 shows the time to dry for two of the collector areas.

![Figure 48](image)

Figure 48: Time for stacks to reach 82% dry basis moisture content for various flowrates and collector areas

The model is run for various flowrates ($0.016 m^3/s, 0.022 m^3/s, 0.030 m^3/s, 0.037 m^3/s, 0.047 m^3/s$) and
the time it takes each stack to reach 82% dry basis moisture content is recorded. Along each line the time to dry increases as expected due to deep layer drying effects. Increasing the flowrate decreases the time to dry for every stack, however the extent to which this occurs varies. For the first two stacks there seems to be little variability in the drying performance. Vertically the lines are spaced closely, indicating minimal reductions in the time to dry with flowrate for that stack. This is evident since stacks at position four and deeper experience greater reduction in drying times with increasing flowrate than the inlet stacks. Each successive flowrate is able to dry more stacks in the time period presented. Increasing the collector area allows more stacks to be dried in the same period as a larger potential is available. This increase is comparatively small, one additional tray dried for most of the flowrates when the collector area is effectively doubled. This conclusion is tied to the collector model being used for this investigation, which is an unglazed single layer transpired collector. This begins to suggest that flowrate has a much more influential role in drying multiple stacks as compared to the collector area. A different perspective on the utility of increasing flowrates is shown by the total dryer efficiencies in Figure 49.

![Figure 49: Total dryer efficiency for each additional stack for collector area of 5m² and peak flowrates averaged over the first three hours of simulation](image)

Each point represents the cumulative efficiency of all the stacks before it, a point on stack...
three represents moisture removed from stacks one to three divided by the total available thermal energy from the collector. The total available thermal energy increases with flowrate, which explains the decrease in efficiency on a per stack basis. Past the first stack, the gap in efficiency between the flowrates decreases each additional stack. Regardless of the collector area it seems that there is a maximum dryer efficiency in the 30% to 35% span for the reasonable range of collector areas explored. Much larger collector and flowrates or a different stack configuration would likely be needed to break past this limit, which is unrealistic for small standalone systems using fabric/thin plastic for transpired collectors. The plastic style systems could be scaled to larger sizes, but this would require more capital and design materials. The overall effects of increasing collector area and flowrate on the total number of stacks dried is shown in Figure 50.

Figure 50: Number of stacks dried in a single day for various peak flowrates and collector areas

In general the drying performance improves with increasing flowrates and collector area. Larger collector areas experience a greater improvement in drying performance with increasing flowrate. At low drying temperatures, as in 1$m^2$ of collector, the driving potential in the air is very low. Increasing the flowrate leads to higher transfer coefficients but has little effect for low collector area cases. At low flowrates, the performance is nearly identical for all three collector areas due
to low transfer coefficients. When selecting a larger collector, the benefits to drying performance are gained at higher flowrates. In the flow rate range physically tested (0.016 m³/s - 0.037 m³/s), the collector areas of 2.55 m² and 5 m² have only a single stack difference. Even at 0.047 m³/s, which is an extrapolation of the model, there is only a two stack increase when doubling the collector area.

5.6.3 Simple Economic Case Study Extension of Model Predictions

While this is a 30% increase in total drying performance, roughly the same amount of collector material could be used to build another collector of 2.55 m². However, this decision would potentially also require another set of fans and photovoltaic cells as well as other structure materials. In the applications explored by the RIT Sustainable Energy Lab in Borgne, Haiti, a collector of 5 m² was built with a total flowrate capacity of 0.142 m³/s. Ten 0.016 m³/s fans run on two solar cells. In this instance the sunken cost of the fans and photovoltaics was already made. Two collectors using half the area and half the fans could be made without much additional cost as the fans/photovoltaics are the largest cost in a transpired collector dryer systems.

This leads to the question of whether a roughly 100% increase in building materials is worth a 30% increase in drying performance when going from 2.55 m² to 5 m² of collector. Outside of the technical setting of this analysis, the motivation for having two smaller collectors rather than one larger collector needs to be considered with respect to transportation, availability of materials, and user interest. In the consideration of the dryer as an industrial process, space requirements and mobility of the system will be ignored. Drying performance has been shown to increase with higher flowrate and larger collectors, but whether these changes are economically sensible is unclear. To support the statements made above, a simple economic model is proposed.

The specific results of using this model and conclusions stated herein are wholly based on the preliminary assumptions made for the economic costs and the collector model chosen for this study: an unglazed transpired solar collector. Based on personal visits to Haiti and collaboration on developing low cost dryers with Dr. Robert Stevens at RIT, an economic model is drafted from prototyping done in Borgne, Haiti. Based on purchases made for prototypes created in Haiti, the
cost of an unglazed transpired collector drying system can be calculated as follows.

\[
\text{Cost} = 156.81 \frac{\$}{m^3/s} \dot{V} + 3.26 \frac{\$}{m^2} A_c + $22 f(\dot{V}) + $25 \quad [\$] \quad (43)
\]

This model considers only the fans, photovoltaics, collector material, and wood needed to extend the frame of a rectangular collector. The construction of the drying chamber is assumed to be insignificant and the cost of the metal trays in Haiti is represented by the fixed cost value of $25. \dot{V} \text{ is the volumetric flowrate of the system in } m^3/s, A_c \text{ is the total collector area, and } f(\dot{V}) \text{ is the cost of the photovoltaic. For up to every additional } 0.071 \frac{m^3}{s} \text{ of airflow another } $22 \text{ PV is needed. For this simple application } f(V) \text{ is a discrete function such that flowrates } 0-0.071 \frac{m^3}{s} \text{ need } $22 \text{ in PV, } 0.072-0.144 \frac{m^3}{s} \text{ needs } $44 \text{ in PV and so on. The output of this model is the total cost of the system in USD with assumptions made in Appendix C. Table 13 shows the the cost breakdown and cost per kilogram of mango dried for various system designs.}

<table>
<thead>
<tr>
<th>Case</th>
<th>(A_c [m^2])</th>
<th>(\dot{V} [\frac{m^3}{s}])</th>
<th>Fan $</th>
<th>Collector $</th>
<th>PV $</th>
<th>Total Cost $</th>
<th>Cost per kg $ \frac{s}{day/kg}</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5</td>
<td>0.142</td>
<td>22.20</td>
<td>16.30</td>
<td>44.00</td>
<td>107.50</td>
<td>N/A</td>
</tr>
<tr>
<td>B</td>
<td>2.55</td>
<td>0.071</td>
<td>11.10</td>
<td>8.31</td>
<td>22.00</td>
<td>66.41</td>
<td>N/A</td>
</tr>
<tr>
<td>C</td>
<td>5</td>
<td>0.047</td>
<td>7.40</td>
<td>16.30</td>
<td>22.00</td>
<td>70.70</td>
<td>23.1</td>
</tr>
<tr>
<td>D</td>
<td>2.55</td>
<td>0.024</td>
<td>3.70</td>
<td>8.31</td>
<td>22.00</td>
<td>59.01</td>
<td>43.39</td>
</tr>
<tr>
<td>E</td>
<td>2.55</td>
<td>0.047</td>
<td>7.40</td>
<td>8.31</td>
<td>22.00</td>
<td>62.71</td>
<td>26.35</td>
</tr>
</tbody>
</table>

The cost to increase daily output by a kilogram of mango is not linear with collector area or flowrate. Considering that case D dried four stacks and case E dried seven stacks, the cost per kilogram dried per day is clearly not off by a factor of 2 ($43.39 \text{ vs. } $26.35 \text{ per stack}). Looking at case C where the collector is double that of case D, a cost of $23.10 per kilogram is even better. This is consistent with the analysis of the drying performance presented in Figure 50. Increasing the flowrate has a much larger influence on the performance over the collector area. For case A and B to be viable in this analysis, they would have to cost less than $23.10 to increase output by 1kg of mango. The performance of case A would have to be extraordinary to compensate for the
jump in photovoltaic costs (at least 4.7kg of mango dried per day). Looking at all the collector area and flowrate combinations from this section, a contour of the cost to increase daily output by one kilogram is shown in Figure 51.

Figure 51: Cost per kilogram of mango dried daily for various collector areas and flowrates $\frac{\text{S}}{\text{kg}}$.

In the range of the space explored, increasing the flowrate and increasing the collector area reduces the effective cost of the system. Increasing flowrate for collector areas close to $2.55m^2$ has the largest gradient in performance change until around $0.030 \frac{m^3}{s}$, at which point the flowrate must be increased to almost $0.040 \frac{m^3}{s}$ before a significant change in cost occurs. Increasing collector area for most flowrates has limited reduction in the overall cost per kilogram dried as shown by the vertical gradient lines. It is unclear from the region explored whether the top right corner of Figure 51 is a maximum, further testing in flowrates up to $0.071 \frac{m^3}{s}$ and collector areas up to $8m^2$ would need to performed to verify this.
5.6.4 Model Reflections

The scope of this model investigation has been limited to small standalone systems powered by a single PV. Flowrates between $0.016 \frac{m^3}{s}$ and $0.037 \frac{m^3}{s}$ were investigated in a controlled lab setting. The results from these tests fed the model exploration in this section for flowrates between $0.016 \frac{m^3}{s}$ and $0.047 \frac{m^3}{s}$ - with the understanding the upper limit is an extrapolation of model trends. The model is only simulated for a single day of drying where trays are considered dried once below 82% moisture content on a dry basis. Increasing flowrate had a larger influence in the range as compared to increasing collector area. By assuming a simple economic model, this comparison is validated for small dryer systems. Maximizing collector area and flowrate in the range of values tested yields the most effective drying and economic yield. These metrics set requirements for higher flowrate and collector area combinations to be viable options.
6 CONCLUSIONS

6.1 Study Summary

Solar dryers are a tool to preserve large amounts of fruits/agricultural products by dehydration. There are many types and classifications of solar dryers based on how thermal energy is provided to the fruit and how the drying chamber is designed. Typical testing of these systems involves varying test conditions due to local weather and substantial material to construct each dryer design. This thesis has developed a robust experimental teststand to produce consistent testing conditions for any indirect drying chamber design. The system simulates the conditions of air exiting any collector design for a given set of ambient conditions and then passes this air to the attached drying chamber. This creates numerous opportunities for testing various drying chamber designs, exploring controlled dehydration of a range of tropical fruits, and investigating the impact of external/internal conditions on the drying process.

6.1.1 Importance of Small Changes to Overall Heat Transfer

During testing in this study, a change between wooden trays and metal trays was made. For a 2mm thick mango film under airflow at $0.022 \frac{m^3}{s}$, 50.8°C, drying time was reduced by 1.5 hours by simply swapping from wooden to metal trays. This improvement is attributed to additional heating on the bottom surface by reducing the thermal resistance of the tray. Also when testing multiple stacks of trays under the same conditions, bottom trays experienced considerably longer drying times as compared to trays above them. Bottom trays only have one channel of air adjacent to them while all other trays have two. This exemplifies the importance of heat transfer from beneath the mango film despite no mass transfer occurring across the bottom of the plate. Providing thermal energy from both sides of the 2mm film significantly improves drying performance.

6.1.2 Teststand Provides Consistent Testing to Explore Design Choices

This teststand provides the ability to consistently test the drying performance of various collector areas and system flowrates for a fixed drying chamber design. Conditions between each test can be replicated in a controlled manner or varied with confidence. This teststand is able to simulate
flows between $0.016 \, \text{m}^3 \, \text{s}^{-1}$ to $0.037 \, \text{m}^3 \, \text{s}^{-1}$ and temperatures between 30°C and 60°C at a constant moisture ratio of $0.0216 \frac{\text{kg}_{\text{wet}}}{\text{kg}_{\text{air}}}$. This range of parameters corresponds to the thermal output of an unglazed transpired solar collector of up to 5$m^2$ under typical Haitian conditions. While simulating tropical conditions we recorded the fruit mass throughout the entire testing period so moisture content and moisture removal can be calculated accordingly. This indoor teststand significantly reduces noise compared to outside testing by creating controlled testing conditions, allowing us to explore the impact of dryer design conditions on fruit drying. The conclusions and observations made can be attributed to design changes and are not influenced by effects from varying ambient conditions. We found that higher flowrates for a fixed collector area and larger collector areas for a fixed flowrate generally improve performance. To determine whether these increasing trends continue or reach a peak point, more stacks of fruit (a larger drying chamber) and/or larger teststand system components to reach higher temperatures and flowrates would be needed.

6.1.3 Bulk Diffusion Models Predict Majority of Drying Process for Thin Film Mango

Choosing a thin 2mm layer of mashed up mango has allowed for fast drying times that occur within a single day. This moisture removal rate for a thin film is readily influenced by changes in external conditions and appears to minimize internal diffusion effects until the removal of the last 15% of fruit moisture at which point moisture removal is not significantly affected by drying air properties. This led to the development of a shrinking thin film drying model that assumes a bulk moisture content for the fruit. This semi-empirical model is fit using both tests where the inlet conditions are held constant and those where the inlet conditions varied with typical meteorological data for the region. The initial fit using the variable conditions was only able to predict the first stack moisture content. Further analysis of the potentially developing flow led to a proposed correction to the amount of air mixing with the evaporated fruit moisture. Due to the developing hydrodynamic boundary layer, it is proposed that only 40% of the air is mixing with moisture removed from the mango film over the length of the chamber. This value is based on optimizing a proposed system model to the multiple stacks of weight data recorded for each test. This fitted model combined with a modified system model allows for the exploration of drying performance of the 2mm mango film in dry basis moisture content ranges of 0.82 to 5.25 (45% to 84% wet basis). This simple approach provides a starting point for the exploration of the influence of external conditions on drying performance.

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6.1.4 Simple Economic Model Coupled with Bulk Model Verifies Design Choices

Using this semi-empirical system model, typical weather conditions are explored in Borgne, Haiti for July 1st by varying collector areas of 1 – 5 m$^2$ and volumetric flowrates of 0.016 – 0.047 m$^3$/s. A fixed drying chamber with ten stacks of fruit with 340g of fruit per stack was simulated under these conditions with the developed model. Combining the results of the drying performance with a simple economic model based on prototyping done by the lab in Borgne, generic guidelines for small standalone solar dryers are proposed. In general, increasing the system flowrate at a specific collector area yielded the most reduction in the cost per kilogram of mango dried as compared to increasing the collector area for a specific flowrate. Performance increases with flowrate and collector area over the range tested. The optimum design point in this study lies on the edge of the region explored. Whether this is the best design combination or if points outside of the testing range are better is unknown, the implication of which will be discussed in Section 6.3. The best case simulated by this study found an expected cost of $23.10 to increased daily output by 1 kg of mango with a collector area of 5 m$^2$ and flowrate of 0.047 m$^3$/s. This suggests that for every $23.10 spent on this solar dryer, one additional kilogram of raw mango will be dried on a typical day. This cost includes tray material, basic structure material for the collector including wood and plastic, fans, and PV modules. If other drying chamber, collector, or flowrate designs are developed - they need to have an expected cost per kilogram dried lower than this to be a viable alternative. This metric is meaningful for applications in developing countries where the best performing solar dryer design may not be affordable. Minimizing the cost to dry fruit per capital spent is a first step to developing better dryer designs.

6.2 Research Contributions

The conclusions and data presented in this work have led to the following advancements in the drying field that support better design of solar dryers.

1. Constructed a teststand that simulates air from solar collectors in tropical environments for controlled testing of drying chambers

2. First controlled study to use real variable conditions for exploring the influence of external parameters on drying
3. Demonstrated the importance of external heat transfer in drying performance during the falling rate regime for thin mango pulp

6.3 Future Work

This study has produced many insights that need further investigation. These questions stem from both the exploration of experimental trends and the derivation of the semi-empirical model.

6.3.1 Expansion of Testing Matrix for Larger Collector Flowrates and Areas

First and foremost is the extension of the upper range of flowrates tested. This study did not discover a definitive peak point in performance when increasing the flowrate for a given collector area. Further testing would be required to determine at which point performance decreases with flowrate due to reduction in drying temperatures caused by increasing flowrate. To reach the suggested range of flowrates up to $0.071 \text{ m}^3/\text{s}$ and collector areas up to $8 \text{ m}^2$, a fan capable of inducing that amount of flow and a heater providing up to 3000W of thermal energy is needed. From the variation of model fits seen for constant and variable condition tests in Section 5.5.4, it is advised that all further testing be done with variable conditions. Exploration of flowrate could be accomplished by fixing a flowrate for the entire variable condition day or scaling it with solar flux similar to this study. When comparing this data, attention should be focused on how the performance of stacks further into the drying chamber is impacted by design choices rather than the inlet stacks.

6.3.2 Exploration of Different Drying Chamber Designs

Now that the teststand has been constructed, a change in the design of the drying chamber opens up many opportunities. Extending the length of the existing chamber from this experimental study would allow additional stacks to be measured. This would help improve/adjust the simple system level model proposed in this paper. All drying scenarios explored in Section 5.6.2 predicted the first two stacks drying regardless of the collector/flowrate configuration, thus emphasis should
be placed on modeling the deep layer aspect of drying. This could be accomplished by using the shrinking film model proposed in Section 5.3 with an updated system level model based on experimental insights gained from that study. Alternatively a completely different drying chamber design could be connected to the test stand such as a vertical chamber, which is common in many past studies. This would be challenging with the mango pulp but could be done for thin samples of other fruits. This potentially would allow for further review of the influence of heat transfer from both sides of a sample on drying performance. Continuing with a tunnel style dryer either taller, longer, or wider in size would allow for investigation of the proposed drying model in a different configuration.

6.3.3 Exploration of Model for Larger Film Thicknesses

Validating the proposed model in this study is certainly of interest if different thicknesses of mango films are tested. A major assumption made in this study is that internal diffusive effects are negligible and that a bulk moisture content can be assumed. By mashing up the mango into a thin film, this assumption is most likely valid for the range the model is fit in. Whether this model can continue to be used for thicknesses of 4mm or 6mm and how the model fit parameters change with these film heights is of interest. This can help define boundaries for simple, external condition based models that can predict drying performance for the majority of the drying process. Understanding the change in fit parameters may also prompt other simple modeling of how the larger film thickness impacts moisture removal.

6.3.4 Verification of Equilibrium Modeling for High Moisture Contents

Lastly exploration of the equilibrium modeling for dry basis moisture contents above $1 \frac{kg_{wat}}{kg_{dry}}$ is needed for understanding fruit surface relationships. The GAB equation defines the boundary relationships between the relative humidity of the air layer directly adjacent to the fruit surface and moisture content at the fruit surface. Nearly 85% of the fruit’s moisture is removed before most GAB model fits are valid. It may be the case that air at the fruit surface is nearly fully saturated for high moisture contents as predicted by extending the GAB model fit from Talla et al. into higher moisture contents [60]. Modeling of the moisture equilibrium in a sealed environment as typical for most GAB fits could be done with the teststand. Likewise modeling for a varying
equilibrium such as the variable condition testing in this study could also be explored. A simple model to predict moisture removal could be chosen that utilizes an equilibrium moisture content alongside measurable parameters such as fruit temperature and fruit moisture content. Tracking how the moisture equilibrium changes with external conditions would help define the influence of the equilibrium on drying performance. It may be possible that for thin films, heat and mass transfer coefficients at the surface are more important in the drying process than the moisture equilibrium at the surface. This would be an argument for why higher flowrates, despite lower drying temperatures, yield higher moisture removal rates in this study.
APPENDIX A - Flowrate Error Calculation

Volumetric flow rate through the system is calculated using Eq. (13), repeated here as Eq. (44), where $Q$ is the thermal energy provided by the heaters as calculated by measuring the voltage and current via the shunt resistor and voltage transducer, $C_P$ is the specific heat of air, $\Delta T$ is the temperature rise across the heater and $\rho$ is the density of air.

$$\dot{V} = \frac{Q}{C_P \Delta T \rho} \quad (44)$$

The uncertainty in the flow measurement can be calculated using the following equation:

$$\delta \dot{V} = \dot{V} \sqrt{\left(\frac{\epsilon Q}{Q}\right)^2 + \left(\frac{\epsilon C_P}{C_P}\right)^2 + \left(\frac{\epsilon \Delta T}{\Delta T}\right)^2 + \left(\frac{\epsilon \rho}{\rho}\right)^2} \quad (45)$$

A typical case for a flowrate calculation is as follows:

Table 14: Appendix A flowrate error calculations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal Value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$</td>
<td>900W</td>
<td>50W</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>25°C</td>
<td>2°C</td>
</tr>
<tr>
<td>$C_P$</td>
<td>1008 J/kgK</td>
<td>1 J/kgK</td>
</tr>
<tr>
<td>$\rho$</td>
<td>1.225 kg/m³</td>
<td>Vary by 10%</td>
</tr>
</tbody>
</table>

Using these values yields the following:

$$\frac{\delta \dot{V}}{\dot{V}} = 0.140 \quad (46)$$

This corresponds to a flowrate of $0.029 \pm 0.004 \text{m}^3 \text{s}^{-1}$. 
APPENDIX B - Moisture Removed Calculation

The percentage of the initial amount of water removed can be calculated by the following expression:

\[
\frac{m_{w,o} - m_{w,f}}{m_{w,o}}
\]  
(47)

The initial mass of water, \(m_{w,o}\), and final mass of water, \(m_{w,f}\), can be replaced by multiplying their respective dry basis moisture content and dry mass as below:

\[
\frac{m_d X_o - m_d X_f}{m_d X_o}
\]  
(48)

This can be simplified into the following expression:

\[
1 - \frac{X_f}{X_o}
\]  
(49)

Using a value of \(X_o = 5.25\) and \(X_f = 0.82\) yields a percent removed of roughly 84%.
APPENDIX C - Economic Model Assumptions

This appendix details the assumptions taken to form the economic model from Eq. (43), which is restated below:

\[
\text{Cost} = 156.81 \frac{\$}{m^3} \dot{V} + 3.26 \frac{\$}{m^2} A_c + $22 f(\dot{V}) + $25
\]

The case study dryer features a solar collector shaped like a long, flat box. The box is a "fixed" 7ft on one side and can be extended in the other direction. The hollow frame of the box is made from wood to create a supporting structure that is wrapped entirely in plastic. Based on purchases made for that project, the following assumptions are formulated.

1. Cost per Volumetric Flowrate
   (a) Small 12 volt, 118mA axial fans from www.Mouser.com were bought at a cost of $2.37 per fan with each fan having a no pressure flow rating of 0.0175 \(\frac{m^3}{s}\).
   (b) The value of 156.81 per \(\frac{m^3}{s}\) of airflow is the division of those two numbers.
   (c) Reduction in price from buying in bulk is not considered

2. Cost per Collector Area
   (a) A 93 \(m^2\) roll of High Density Polyethylene was bought from InternationPlastics for $80, giving an average cost per unit area of material of $0.86 per \(m^2\).
   (b) Original design features a hollow frame completely wrapped in the plastic, only the top surface area is considered in this analysis. Realistically the amount of plastic needed per unit length is constant and overall price of the plastic is small compared to the fan cost such that cost of the side plastic can be ignored.
   (c) Eight 16ft one by fours were bought at $50 in Cap-Haitien, Haiti. The collector it is designed for is 7ft wide with a box style frame, so the cost per increasing the length of the collector to accommodate an increase in area is \(\frac{\$50}{(8\times16ft)(0.3048\frac{m}{ft})^2\times7ft}\times4boards\), $2.4 per every \(m^2\) of collector area.
   (d) This contributes to a total of $3.26 per \(m^2\) of collector

3. Cost per Solar Panel

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(a) A $22 12\text{ volt, 10 watt solar panel was purchased from WindyNation. With a peak amperage rating of }560\text{ mA, it can run roughly five of the axial fans for a total airflow around }0.071\frac{m^3}{s}.

(b) Thus for every additional $0.071\frac{m^3}{s}$ of airflow desired, an additional solar panel must be purchased at $22.

4. Fixed Cost

(a) A thin sheet of aluminum (of unknown grade) was purchased in Cap-Haitien, Haiti for $25 and cut into metal sheets the approximate size of the trays used in this investigation.
Figure 52: Detailed wiring diagram of setup
REFERENCES


