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Development of a System Model for an Indirect Passive Solar Dryer with Experimental Validation

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Development of a System Model for an Indirect Passive Solar Dryer with Experimental Validation

by

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

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Abstract

Solar crop drying is a cheap and effective way to preserve food material, especially in developing countries where fuel and electricity are expensive or unavailable. Some tropical fruits are difficult to transport and store leading to significant spoilage. Without access to fuel and large drying systems, preserving fruits for later use is challenging or not possible for the rural farmer. Developing low-cost, easily assembled locally and low maintenance fruit drying systems would improve access to off-season and distant markets. A mathematical model of an indirect passive solar drying system was developed to design and optimize drying systems for use in developing countries and was validated through experimental testing.

The prototype drying system consisted of a transpired solar absorber, drying chamber, and chimney. The transpired solar collector allows for indirect heat gain using cheap materials, specifically landscape fabric. The drying chamber houses fruit on eight screen trays and the chimney induces airflow through the system without a power source. The novel collector efficiency regularly exceeded 50% with an average temperature rise over 20°C. Bananas were dried over a two day period from an average moisture content of 73% to 8%. A total of 4kg of banana slices per square meter of absorber area were dried over the testing period.

The mathematical model uses solar irradiance, ambient relative humidity, ambient temperature, and initial fruit moisture content to predict the fruit drying curves. The predicted average final moisture content of the bananas starting at 73% was 9% over the two day test period, indicating the model predicts performance reasonably well. Results from the system model highlight the need for additional experimentation to determine parameters such as the diffusivity of bananas and the mass transfer coefficient independently of experimental setup before it can be used as a tool to simulate drying performance for different environmental conditions and dryer system configurations.
Acknowledgements

I thank my family and friends for supporting me throughout my college career; the RIT machine shop staff for helping me accomplish my experimental setup in time for testing before winter; Sarah Brownell for sparking my interest for projects in Haiti and continuing to support me as I navigate my career options as an engineer; Dr. Steven Weinstein for his efforts to develop a model for mass transfer in fruit material to be used within the system model; and Dr. Rob Stevens, my advisor, for helping me develop a thesis on a topic I am passionate about, and for the continuous support and encouragement throughout my research.
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NOMENCLATURE

Abbreviations:
KGPB = Kolaborasyon Gwoupman Peyizan O’Boy
RIT = Rochester Institute of Technology

Variables:
\( a \) = Thermal diffusivity (m\(^2\)/s)
\( A \) = Area (m\(^2\))
\( b \) = Half the total thickness of banana slice for Karim model (m)
\( c \) = Constant in Van Decker Model
\( C \) = Concentration of diffusing substance (kg/kg)
\( C_b \) = Constant for GAB Equation, relates to sorption enthalpy
\( C_L \) = Langmuir’s Constant
\( C_p \) = Specific heat (J/kg-K)
\( d \) = Diameter (m)
\( D \) = Diffusion Coefficient (m\(^2\)/s)
\( D_{ban} \) = Diameter of banana slice (m)
\( D_{eff} \) = Effective Diffusion Coefficient (m\(^2\)/s)
\( ERH \) = Relative Humidity for Henderson Model (decimal)
\( f \) = Friction coefficient
\( F_R \) = Collector heat removal factor
\( g \) = Gravitational constant (9.81 m/s\(^2\))
\( h \) = Height of banana slice (m)
\( h_{cph} \) = Convective heat transfer coefficient (W/m\(^2\)K)
\( h_{in} \) = Enthalpy entering the control volume (J/kg)
\( h_m \) = Mass transfer coefficient (m/s)
\( h_{out} \) = Enthalpy leaving the control volume (J/kg)
\( h_r \) = Radiative heat loss Coefficient
\( H \) = Height of chimney (m)
\( i \) = Time iteration
\( I_c \) = Solar flux or Insolation (W/m\(^2\))
\( j \) = Space iteration
\( J \) = Mass flux (kg/s)
\( k \) = Page model constant or mass transfer coefficient multiplied by air density
\( K \) = Constant in Henderson Model
\( K_{GAB} \) = Constant for GAB Equation, relates to sorption enthalpy
\( l \) = Gap in mesh (m)
\( L \) = Total thickness of banana slice (m)
\( m \) = Mass (kg)
\( \dot{m} \) = Mass flow rate (kg/s)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$M$</td>
<td>Moisture Content, dry basis (kg/kg)</td>
</tr>
<tr>
<td>$M_{wb}$</td>
<td>Moisture Content, wet basis (kg/kg)</td>
</tr>
<tr>
<td>$MC$</td>
<td>Moisture Content (kg/kg)</td>
</tr>
<tr>
<td>$n$</td>
<td>Page Model Constant</td>
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<tr>
<td>$p$</td>
<td>Partial Pressure (Pa)</td>
</tr>
<tr>
<td>$P$</td>
<td>Pressure (Pa)</td>
</tr>
<tr>
<td>$Pr$</td>
<td>Prandlt Number</td>
</tr>
<tr>
<td>$q$</td>
<td>Heat energy (W)</td>
</tr>
<tr>
<td>$q_{loss}$</td>
<td>Heat lost in drying chamber zones (W)</td>
</tr>
<tr>
<td>$Q_u$</td>
<td>Useful heat gain by collector (J)</td>
</tr>
<tr>
<td>$R$</td>
<td>Thermal resistance (K/W)</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number (s = suction, w = wind, h = hole, b = back)</td>
</tr>
<tr>
<td>$RH$</td>
<td>Relative Humidity (%)</td>
</tr>
<tr>
<td>$S$</td>
<td>Shape Factor</td>
</tr>
<tr>
<td>$Sc$</td>
<td>Schmitt Number</td>
</tr>
<tr>
<td>$Sh$</td>
<td>Sherwood Number</td>
</tr>
<tr>
<td>$t$</td>
<td>Time (s)</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature ($^\circ$C)</td>
</tr>
<tr>
<td>$u$</td>
<td>Shrinkage velocity (m/s)</td>
</tr>
<tr>
<td>$U_L$</td>
<td>Overall heat loss coefficient for collector (W/m$^2$K)</td>
</tr>
<tr>
<td>$v$</td>
<td>Mean velocity (m/s)</td>
</tr>
<tr>
<td>$\dot{V}$</td>
<td>Specific volume (m$^3$/kg)</td>
</tr>
<tr>
<td>$\dot{V}$</td>
<td>Volumetric flow rate (m$^3$/s)</td>
</tr>
<tr>
<td>$V_s$</td>
<td>Suction velocity (m/s)</td>
</tr>
<tr>
<td>$w$</td>
<td>Wet basis air moisture content (kg/kg)</td>
</tr>
<tr>
<td>$x$</td>
<td>Direction of moisture flow within banana slice</td>
</tr>
<tr>
<td>$X$</td>
<td>Humidity Ratio (kg$<em>{water}$/kg$</em>{air}$)</td>
</tr>
<tr>
<td>$z$</td>
<td>Direction of moisture flow within fruit slice for Weinstein model</td>
</tr>
</tbody>
</table>

Greek Letters:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_s$</td>
<td>thermal diffusivity (m$^2$/s)</td>
</tr>
<tr>
<td>$\alpha_w$</td>
<td>water activity (dimensionless)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>coefficient for cubical expansion (K$^{-1}$)</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>effectiveness</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>emissivity</td>
</tr>
<tr>
<td>$\eta$</td>
<td>collector efficiency</td>
</tr>
<tr>
<td>$\eta$</td>
<td>collector efficiency</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stefan-Boltzmann Constant (W/m$^2$K$^4$)</td>
</tr>
<tr>
<td>$\sigma_p$</td>
<td>porosity (m$^2$/m$^2$)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density (kg/m$^3$)</td>
</tr>
</tbody>
</table>
\( \bar{\rho}_{ch} \) = average air density in chimney (kg/m\(^3\))
\( \omega \) = moisture content on a wet basis for Weinstein model
\( \infty \) = infinity (surrounding environment)
\( (\tau \alpha)_e \) = effective transmittance-absorptance product for collector

\textit{Subscripts:}

a or air = air
amb = ambient
ban = banana
banana = refers to banana slices
c = collector
ch = chimney
cham = dryer chamber
chim = chimney
ci = collector inlet
co = collector outlet
coll = collector
d = dry content
db = dry basis
dc = drying chamber
eff = effective
eq = equilibrium
exposed = exposed area
i = initial or time iteration
j = space iteration
mon = mono-layer
p = plate
ref = reference
sc = solar collector
sys = system
t = tray
tb = tray with bananas
total = sum or all of a specific unit
tray = references the tray that holds the specimen in the drying chamber
w = water
wa = water in air
wb = wet basis or weight of bananas
Chapter 1: Introduction to Food Drying

1.1 Solar Drying as Food Preservation

Solar drying of food is an effective means of food preservation and is especially useful in developing areas where fuel resources are scarce. Food drying preserves food by slowing down the action of enzymes, bacteria, yeasts, and molds [1]. Solar drying has been used since prehistoric times to dry foods such as vegetables, fruits, fish, and meat as well as other items like animal skins and soil bricks to build homes [1]. Conventional drying methods were developed around the 18th century and are still utilized in industry today [1]. Today, crop drying is mainly done at industrial levels in large food driers for mass markets. Common dried food items include cereal grains, fruits, and grapes. Drying can also help prevent waste by drying the parts of the plant thrown out during cooking and turning them into animal feed [2].

Tropical fruits can be preserved through solar drying in areas like Haiti, where sun is abundant but conventional fuel resources are scarce [3]. Breadfruit, a large starchy fruit that grows in these areas, is a particular food of interest. It is a nutrient dense food that is cited as a food source with great potential to end hunger in the areas it grows. However, breadfruit is one of the most wasted foods in Borgne, Haiti according to the KGPB farmers group. Once harvested, it only lasts 1-3 days before spoilage. During the harvest season, the markets are flooded with breadfruit which drives down prices and leads to a lot of wasted breadfruit. One way to solve this problem is to preserve the breadfruit by turning it into flour. This will increase the shelf life and make transportation easier. In order to turn the breadfruit into flour, the fruit needs to be dried which increases shelf life and makes it easier to grind into small particles [4]. The farmers group also cited other tropical fruits, such as bananas and mangoes, as a source of food waste. Drying can also help preserve these fruits for farmers in the area.

1.2 Dryer Classification

Basic drying physics is the same for all types of dryers, conventional or solar. Figure 1 is a schematic showing a typical breakdown of dryer classification. Figure 2 shows an example of
each type of solar dryer described. Some terminology varies from author to author, but the general concepts are the same.

Figure 1: Dryer Classification

Types of conventional dryers, those that use electricity or fuel to power heaters and fans, include both high temperature, fast drying methods and low temperature, bulk storage methods. High temperature dryers need controls to monitor the timing and temperature, because temperatures can easily over dry products if left in contact with the food until the equilibrium moisture content is reached [5]. Also, if high temperatures are used too early in the drying process, some foods will harden/cook on the outside and trap the remaining moisture on the inside [6]. Low temperature methods are used for bulk storage, often with grains, and when the color and certain nutrients need to be preserved in the food. [5]

Solar drying can be broken down into three sub categories: open (or natural), active, and passive. Open drying involves exposing the crop to the natural environment and sun exposure with no cover or protection from the elements. Open drying can be done on the branch (like grapes) or after harvest on open ground, mats, or cement. This is a very common method of drying in tropical areas [7]. According to Murthy, 80% of food produced by small farmers in developing countries is dried by open sun drying [8]. In Haiti, it is very common to see cocoa or coffee beans lying out on sheets to dry in the sun. Open sun drying is the cheapest method of drying,
having almost no capital cost and very low running costs (labor to move the sheets in and out each day). Most importantly, solar drying does not involve the use of fuels which can be very expensive in developing areas and in Haiti, where deforestation is a major issue [4].

Active and passive dryers require the use of a drying structure with multiple components. Figure 2 shows schematics of typical types of both active and passive dryers. Active solar dryers utilize fans to induce convection across the product. These fans (or blowers) require electricity to be powered. Active solar dryers are more common in developed areas where electricity is easily accessed. Passive dryers use natural convection, using wind pressure and buoyancy forces from solar-heated air to drive air flow [9]. This is the method of interest because the low cost and lack
of moving parts makes the drying system more robust. Chimneys are often used to improve natural-convection in the dryer [1], [8], [9]. Both active and passive dryers can be described further based on the how solar energy is captured.

The first solar category, direct (integral) sunlight occurs when solar radiation passes through a transparent surface and is directly absorbed at the surface of the fruit. For some crops, direct sunlight is considered key to developing flavors and allow color enhancement in fruits that need further ripening. However, in some cases direct drying can cause discoloration and be harmful to the product depending on the type of fruit and amount of sun exposure [6], [9]. Ideal materials include glass and acrylic because of their ability to allow light to pass through but trap infrared radiation. These transparent materials can be difficult to find in developing countries, as witnessed during a Haiti trip in January 2015 [3]. In areas that have materials available, the simple design makes these driers easier and cheaper to build than their indirect counterparts. When comparing drying rates between direct and indirect, direct can be slower because of poor ventilation [9].

For indirect (distributed) type solar dryers, thermal energy is collected in a solar collector and then the heated air is moved past the fruit. Indirect dryers are a relatively new technique for drying crops and have not been widely commercialized [1]. Some advantages over direct-type solar dryers include: larger crop capacity per surface area, no caramelization or heat damage due to radiation, preservation of nutritional value and color of sensitive crops, and flexibility of crop type that can be dried [1], [9]. However, due to complexity in design, indirect dryers can have a higher capital cost. There may also be a need for semi-skilled workers to load and shift product in dryer [1], [9].

The final solar dryer category, mixed-mode, utilizes both direct and indirect sunlight [9]. A solar collector is used to heat drying air that flows through the drying system while the drying chamber, the area housing the crop of interest, is made of transparent material to allow for direct sunlight to come in contact with the material. The crop material is then heated from the top by the direct radiation as well as from the bottom by the heated air through convection. Mixed-mode dryers are common because of their fast drying rates but have the same draw backs as direct solar dryers mentioned above [9], [10].
Figure 3 shows the typical layout for an indirect passive solar dryer. The three main components are the solar collector, drying chamber (drying bin), and a chimney. This type of dryer was chosen for research due to its many benefits and potential to aid the KGPB farmers in Borgne, Haiti.

1.3 Solar Collector Review

Traditional solar collectors consist of an absorber plate/surface that absorbs the solar radiation and radiates infrared energy back into the drying air. The change in density of the heated air causes the air to flow up into the drying system often guided by a casing to contain the heated air. Bare-plate collectors, shown in Figure 4, are the most basic of commonly used collectors. Bare-plate collectors have high thermal losses through the exposed surface and are generally low in thermal efficiency at high temperature differences and increase in efficiency as the temperature difference decreases [11].

Figure 3: Indirect passive solar dryer. This design was used for corn drying. [9]
Covered plate solar collectors utilize a transparent cover above and parallel to the absorber plate and therefore, increase efficiency. The cover reduces convective and radiative heat losses and protects the absorber plate from the environment. Cover materials should allow for a high transmittance of visible light and low transmittance of infrared radiation. Glass is often thought of as a good cover material. Another appropriate material is acrylic (Plexiglass) [11]. Covered-plate solar collectors have many configurations including front-pass, back-pass, suspended-plate, and perforated-plate covered solar collectors.

These traditional solar collectors can be costly in developing areas. Fortunately an alternative approach to the bare-plate and covered collectors is to use an unglazed transpired collector. Figure 5 shows a typical unglazed transpired solar collector. This collector is oriented vertically, as it would be on the outside wall of a building, to preheat ventilation air going into the building [12].

Transpired collectors have negligible convective losses to the atmosphere, due to the suction created by the system [12]. Therefore, convective heat transfer will be modeled differently in the model than for a traditional collector, though some of the traditional theory still applies. The theory will be explored further in Chapter 2 and 4.
1.4 Background and Theory of Drying

In general, food drying is defined as the process of removing moisture from an agricultural product until a desired amount of moisture is left in the product [1]. The desired moisture content varies depending on the fruit properties, initial moisture content, and the final use of the product, i.e. replanting of grains or drying fruit for consumption [5].

There are four different types of drying methods: convection, conduction, radiation, and excitation. These different methods are based on the type of energy used to do the drying. Convection uses warm air to transfer heat to the material and evaporate moisture and is the most common method. Conduction uses a heated surface to conduct heat to the material and induce evaporation of the moisture. Radiation uses infrared energy to heat the material and is most commonly used in vacuum dryers and, in the case of solar radiation, direct solar dryers. Excitation uses polarized molecules to absorb the energy and heat the material. Excitation can be used to quickly dry liquids, pastes, or milled material without degrading the material [6].

Indirect solar drying uses a convective drying method where heated, low moisture air is used to transfer heat to the product and evaporation takes place at the product surface [1], [6]. Moisture
within the material moves through diffusion to the surface as the fruit continues to dry (see Figure 6).

![Figure 6: Convective drying of a fruit sample. The red, solid arrows indicate heat transfer and the green, dotted arrows indicate mass transfer.](image)

Although there are different methods for drying, the basic principles remain the same. The moisture needs to move through the material and evaporate at the surface [6]. Moisture content is a way to measure the dryness of the material. Moisture content can be described on a wet basis or a dry basis. Wet basis moisture content is defined as:

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

(1)

where \(m_w\) is the mass of the water in the material and \(m_d\) is the mass of the dry material. Wet basis moisture content is commonly used in agriculture and described as a percentage. Because the total mass of the crop changes as drying continues due to the mass of the water changing, dry basis moisture content is more common in the engineering calculations [1]. Dry basis moisture content is defined as:

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

(2)

In drying, the final moisture content occurs when drying can no longer take place in the existing environmental conditions. This final moisture content is known as the equilibrium moisture content. Equilibrium moisture content is defined as the point where the vapor pressure on the surface of the product is equal to the vapor pressure of the surrounding air and no absorption or
desorption is taking place. The equilibrium point can also be described as the moisture content of a fruit after it has been exposed to a certain environment for an extended period of time [1], [5].

The equilibrium point can also be defined by the water activity of the product. The water activity is the ratio of the partial pressure of water within the crop to the partial pressure of pure water at the same temperature, such that:

\[ \alpha_w = \frac{p_w}{p_w^*} \]

where \( p_w \) is the partial pressure of the water solution of the product and \( p_w^* \) is the partial pressure of pure water, at the same temperature. The water activity is approximately equivalent to the relative humidity of the surrounding air of the material at a specific temperature when the product is at thermodynamic equilibrium [1], [6], [13]. The activity limit describes the point that microorganisms stop growing, therefore, is used in industry when drying food. In terms of moisture content, food products typically need to be dried to 5%-25% (wet basis) to reach the desired activity limit [14]. The activity limit varies depending on the food.

Many empirical and some theoretical models for determining the drying rate of fruits rely on the equilibrium moisture content as a known variable [15], [16]. Sorption isotherms are used to find the equilibrium moisture content. These isotherms show the relationship between moisture content and water activity at a constant temperature [1], [6]. Figure 7 shows a sample of a sorption isotherm, specifically for carrots used by A. Kaya to complete a theoretical model for drying carrots [17].

There are two widely accepted equations for finding the sorption isotherms of crops. These include the BET and GAB equations, both which are based off of the theory of Langmuir’s multi-layer absorption [1]. The BET equation is described as [1]:

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

where \( M_{mon} \) is the mono-layer moisture content and \( C_L \) is the Langmuir’s constant. The GAB equation is expressed as:
\[
\frac{M_{eq}}{M_{mon}} = \frac{C_b K_{GAB} \alpha_w}{(1 - K_{GAB} \alpha_w) * (1 - K_{GAB} \alpha_w + C_b K_{GAB} \alpha_w)}
\] (5)

where \(C_b\) and \(K_{GAB}\) are constants related to the sorption enthalpies.

Finding the drying rate of a specific crop and dryer is desirable when designing and implementing a system. It is important to know how long it will take to dry a product for practicality and economic reasons. The drying rate is represented as the moisture content over time. The rate is determined by the product properties such as temperature and initial moisture content as well as the properties of the drying air, specifically temperature, relative humidity, and air flow/velocity. Drying rates also vary by fruit type and fruit specimen, even under the same initial and drying conditions. Drying rates have two distinct periods for hygroscopic materials: the constant drying rate period and the falling drying rate period, see Figure 8. Hygroscopic materials have bound moisture within the product, such as fruit and other food items, while non-hygroscopic materials only have unbound moisture, such as wet paper or cloth.

The constant drying rate period occurs when the moisture evaporating from the surface of the product is the limiting factor driving the drying process and not the mass transport in the fruit. This is shown as Phase I in Figure 8. The amount of energy needed to enter this phase is determined by the latent heat of vaporization which is defined as the amount of energy required to be absorbed by the product in order to vaporize moisture from it [5].

The falling drying rate period can be broken down into two separate stages. The first, represented as Phase II in Figure 8, occurs when the surface of the fruit is no longer saturated and is limited
by moisture evaporating from the unsaturated surface. The drying rate decreases as less and less moisture is available at the surface to evaporate. The second stage, represented as Phase III in Figure 8, occurs when the moisture diffusing from within the fruit to the surface is the limiting factor driving the drying process. This phase continues until the fruit reaches equilibrium with the surrounding environment.

The critical moisture content, indicated by point “C” in Figure 8, is the point when crop drying transitions from the constant drying rate period to the falling drying rate period. This point is where the moisture being evaporated is equal to the rate moisture migrates to the surface. Some mathematical models for fruit drying begin at this point since the first phase is nonexistent or negligible, depending on the fruit [1], [16].

Chapter 2: Mathematical Modeling and Experimentation Theory Review

2.1 Mass Transfer Through Food Material

There is an enormous amount of research about the drying kinetics of different types of food products. Models have been generated to predict drying curves for food material. These models focus mainly on the falling drying rate period where the diffusion of moisture in the material is
the governing process instead of the constant rate period where moisture evaporation at the surface is driving the system. Models include characterization of grains, fruits, and vegetables.

Early models mainly focused on cereal grains [5]. O.V. Ekechukwu summarizes these early models in his review of solar-energy drying systems. The Kelvin model (1871) focuses on capillary condensation within pores of a material. This model is limited by the relative humidity range where capillary condensation occurs (>95%) and relies on a lot of information to be known about the capillary action in the food, such as the capillary radius and the angle of contact of moisture and the capillary wall [5].

In 1949, the Page model was developed for the drying of shelled corn in thin layers [15]. This model is the basis for many empirical thin layer models currently used. The Page model is:

$$\frac{M - M_{eq}}{M_i - M_{eq}} = e^{-kt^n}$$

(6)

where $M$ is the moisture content at any given time, $M_{eq}$ is the equilibrium moisture content, $M_i$ is the initial moisture content, $k$ and $n$ are measured constants, and $t$ is time. Many researchers have characterized foods using the Page model by conducting experiments to find the $k$ and $n$ constants of specific food materials [18]–[21].

There are several other more complex and empirically based models used that are derivatives of the Page model. Togrul et al. analyzed fourteen different models to find the best fit for apricots, a fruit that previously had not been widely explored [20].

Not all models are empirically based. Many theoretical models exist; the most common utilize Fick’s Second Law of Diffusion. There have been adaptations to the basic diffusion model, normally to account for shrinkage of the material [16], [18], [22]. Fick’s Second Law is expressed as [23]:

$$\frac{\partial C}{\partial t} = D \left( \frac{\partial^2 C}{\partial x^2} \right)$$

(7)

where $C$ is the concentration of water within the material and $D$ is the diffusion coefficient of the
material and is typically empirically determined. $D$ is often not constant and can be dependent on temperature and moisture content. Porciuncula (2013) and Baini (2008) review several different forms of diffusivity models [24] [25].

Karim’s theoretical model adapts Fick’s Law and corrects for shrinkage [16]. Karim’s model is expressed as [16]:

$$\frac{\partial M}{\partial t} = D \left( \frac{\partial^2 M}{\partial x^2} \right) - u \left( \frac{\partial M}{\partial x} \right)$$  (8)

where $u$ is the shrinkage velocity. Figure 9 shows the entire banana slice being modeled and Figure 10 shows the control volume used for Eq. (8) in Karim’s model. Note that the moisture generation term does not show up in Eq. (8) because it is assumed there are no chemical reactions happening during the drying process. This assumption is consistent with other research [26], [27].
Other models that use Fick’s law include 2D rectangular models (for more accurate predictions on rectangular slices) and 2D cylindrical models (for foods like carrots) [17], [26].

Assumptions for the Karim model include: no chemical reaction takes place, drying air is distributed uniformly through the dryer [16]. Assumptions made for a similar model include: constant thermophysical properties of the specimen (thermal conductivity, density, and specific heat), negligible radiation effects, and moisture evaporation only at the upper surface and diffusion only inside the specimen [26]. The difference in assumptions results in slightly different boundary and initial conditions.

Equation 9 shows the boundary condition at the line of symmetry of the Karim setup, or when \( x = 0 \):

\[
\frac{\partial M}{\partial x} \bigg|_{x=0} = 0
\]  \quad (9)

Equation 10 shows the boundary condition at the surface of the banana for the Karim model. This applies at \( x = b \) and \( x = -b \), both the top and bottom surfaces:

\[
-D_{\text{eff}} \frac{\partial M}{\partial x} \bigg|_{x=b} + uM \bigg|_{x=b} = h_m (M - M_{eq}) \bigg|_{x=b}
\]  \quad (10)

where \( D_{\text{eff}} \) is the diffusion coefficient of the banana and \( h_m \) is the mass transfer coefficient. The diffusion coefficient is not constant; it varies with moisture content. Karim accounts for this by accounting for shrinkage of the banana material. Equation 11 shows the relationship between shrinkage and the diffusion coefficient:

\[
\frac{D_{\text{ref}}}{D_{\text{eff}}} = \left(\frac{b_0}{b}\right)^2
\]  \quad (11)

\( D_{\text{ref}} \) is the variable being solved for and represents the diffusion coefficient at a specific point in time where the banana surface is at point \( b \). \( D_{\text{ref}} \) is a constant and is determined through analysis of experimental data. To extract \( D_{\text{ref}} \) from the data, Karim utilizes a widely used expression derived from Fick’s Law [28], [29]:


\[ \ln \left( \frac{M}{M_i} \right) = \ln \left( \frac{8}{\pi^2} \right) - \frac{\pi^2 D_{ref} t}{L^2} \]  

(12)

where \( L \) is the thickness of the drying specimen, \( t \) is time, \( M \) is the moisture content of the fruit at a specific point in time and \( M_i \) is the initial moisture content of the fruit. Experimental values were plugged into \( \ln \left( \frac{M}{M_i} \right) \) and plotted on the y-axis and \( \frac{t}{L^2} \) was plotted on the x-axis. According to Karim, the slope of the straight portion of the curve is a measure of reference diffusivity for a particular set of drying conditions [16]. Figure 11 shows an example curve used by Karim to find the reference diffusivity. The slope needs to be divided by \( \pi^2 \) to determine the coefficient. Equation 12 is invalid for varying environmental inputs, specifically changing air temperature and relative humidity.

![Figure 11: Karim diffusivity curve. Note that the y-axis should be ln(M/Mi).][28]

To find the mass transfer coefficient, \( h_m \), Karim used the Sherwood number (\( Sh \)) for a flat plate. The Sherwood number is analogous to the Nusselt number in heat transfer problems [30]. The equations used by Karim solved for the local \( h_m \) coefficient. Using the model for the average mass transfer coefficient across a plate may improve the model. Equations 13 and 14 show the relationships used in the Karim model for laminar and turbulent flow, respectively:

\[ Sh = \frac{h_m L}{D_0} = 0.332 Re^{\frac{1}{8}} Sc^{\frac{1}{3}} \]

(13)
where $D_0$ is the diameter of the fruit slice, $Re$ is the Reynolds number, and $Sc$ is the Schmidt number.

The term, $M_{eq}$, in Equation 10 represents the final moisture content of the banana slice if it was held at constant conditions until equilibrium. In Karim’s model, this moisture content is found through empirical data where bananas were dried at constant environmental conditions to find $M_{eq}$ in each scenario. When environmental conditions are not constant for this system, the equilibrium moisture content needs to be found theoretically. This can be done through the sorption isotherm models such as the BET and GAB equations reviewed in Chapter 1 (Eqs. 4-5). Not every model fits all food products, therefore different models are used depending on the type of food being studied.

According to a publication by the American Society of Agricultural and Biological Engineers (ASABE), the Henderson equation is most suitable for bananas [31]. Equation 15 shows the Henderson model used and Table 1 shows the coefficient values for bananas. As shown in Table 1, this equation only predicts well in the middle of the relative humidity range. Also, coefficients $K$ and $N$ are only reported for a temperature of 25°C.

$$ERH = 1 - e^{-KtM_{eq}^N}$$  \hspace{1cm} (15)

<table>
<thead>
<tr>
<th>Product</th>
<th>Temperature</th>
<th>$r!h$ range</th>
<th>Equation</th>
<th>$K$</th>
<th>$N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple</td>
<td>30°C</td>
<td>0.10 - 0.75</td>
<td>10.05</td>
<td>0.1091</td>
<td>0.7535</td>
</tr>
<tr>
<td>Apple[a]</td>
<td>19.5°C</td>
<td>0.10 - 0.70</td>
<td>10.04</td>
<td>4.4751</td>
<td>0.7131</td>
</tr>
<tr>
<td>Banana</td>
<td>25°C</td>
<td>0.10 - 0.80</td>
<td>10.05</td>
<td>0.1268</td>
<td>0.7032</td>
</tr>
<tr>
<td>Chives</td>
<td>25°C</td>
<td>0.10 - 0.80</td>
<td>10.04</td>
<td>11.8931</td>
<td>1.1146</td>
</tr>
<tr>
<td>Grapefruit</td>
<td>45°C</td>
<td>0.10 - 0.80</td>
<td>10.05</td>
<td>0.1519</td>
<td>0.6645</td>
</tr>
<tr>
<td>Mushrooms</td>
<td>20°C</td>
<td>0.07 - 0.75</td>
<td>10.04</td>
<td>7.5335</td>
<td>1.1639</td>
</tr>
<tr>
<td>Mushrooms[a]</td>
<td>25°C</td>
<td>0.10 - 0.80</td>
<td>10.04</td>
<td>11.5342</td>
<td>1.1606</td>
</tr>
<tr>
<td>Peach</td>
<td>20 - 30°C</td>
<td>0.10 - 0.80</td>
<td>10.05</td>
<td>0.0471</td>
<td>1.0096</td>
</tr>
<tr>
<td>Peach</td>
<td>40°C</td>
<td>0.10 - 0.80</td>
<td>10.05</td>
<td>0.0440</td>
<td>1.1909</td>
</tr>
<tr>
<td>Peach</td>
<td>50°C</td>
<td>0.10 - 0.80</td>
<td>10.05</td>
<td>0.0477</td>
<td>1.3371</td>
</tr>
<tr>
<td>Pear</td>
<td>25°C</td>
<td>0.10 - 0.80</td>
<td>10.05</td>
<td>0.0882</td>
<td>0.7654</td>
</tr>
<tr>
<td>Tomato</td>
<td>17°C</td>
<td>0.10 - 0.80</td>
<td>10.04</td>
<td>10.587</td>
<td>0.9704</td>
</tr>
</tbody>
</table>

[a] Desorption isotherm data. All other data is for sorption (moisture addition) measurements.
2.2 Heat Transfer through Food Material

Heat transfer within the material can be similarly modeled based on Fourier’s Law [30]. The Karim model for heat transfer is expressed as [16]:

$$\frac{\partial T}{\partial t} = a \left( \frac{\partial^2 T}{\partial x^2} \right) - u \left( \frac{\partial T}{\partial t} \right)$$

(16)

where $T$ is the temperature of the specimen at a given time and $a$ is the thermal diffusivity. Thermal diffusivity for bananas can be found in the ASHRAE Handbook on Refrigeration [32].

Models often assume the food material is in thermodynamic equilibrium with the drying air. Because it reaches equilibrium much faster than the moisture part of the model, this assumption is often true and was confirmed through preliminary modeling.

2.3 Drying Chamber Review

Although there are many models for the characterization of drying rates in the specimen, few researchers have created a system model of the drying chamber. Karim and A.O. Dissa have similar drying chamber models of a solar dryer, one for bananas and the other for mangoes, respectively [16], [27].

Karim used an energy balance throughout the dryer to model the heat transfer which took into account the latent heat of vaporization, the amount of energy needed to evaporate moisture from the material. Karim simultaneously used a moisture balance throughout the chamber to solve for the chamber conditions [16]. A.O. Dissa took a similar approach, however, modeled the heat transfer in the chamber using electric diagrams and thermal resistances [27].

C. Ratti and A.S. Mujumdar also used mass and energy balances, however, they modeled a packed bed dryer common for grain drying instead of a shelved dryer [7]. Packed bed drying relies heavily on the size of the grain and the porosity of the bulk mass.
2.4 Chimney Review

Generally, there is a lack of focus on chimney modeling for indirect passive solar dryers [33]. Many natural circulation solar dryers suffer from inefficient chimney design. Some are constructed from metal material with no insulation which allows for little solar heating to take place within the chimney and high heat losses through the walls. Though many designs have been reported, there is a lack of optimization of this subsystem of the solar drying system [33].

To generate air flow, there needs to be a buoyancy force. This is created by differences in the air density in the chimney and ambient air. The pressure drop through a chimney can be described as [33], [34]:

\[ \Delta P_{ch} = gH(\rho_{amb} - \bar{\rho}_{ch}) = \beta gH\bar{\rho}_{ch}(T_{ch} - T_{amb}) \]  \hspace{1cm} (17)

where \(g\) is the gravitational constant, \(H\) is the height of the chimney, \(\rho_{amb}\) is the density of the ambient air, and \(\bar{\rho}_{ch}\) is the average density of the chimney air. The density of the chimney air between the temperature range of 25-90 °C can be expressed as [33].

\[ \bar{\rho}_{ch} = 1.11363 - 0.00308T \]  \hspace{1cm} (18)

The temperature range is valid for the typical range of indirect passive solar drying operating temperatures. The losses due to friction in a cylindrical chimney can be expressed as [33]:

\[ \Delta P_{ch} = 0.03\bar{\rho}_{ch}\left(\frac{v^2}{2d}\right) \]  \hspace{1cm} (19)

where \(v\) is the mean velocity of the air and \(d\) is the diameter of the chimney. Combining Eqs. (17), (18), and (19) the velocity in the chimney can be determined as [33]:

\[ 0.03\bar{\rho}_{ch}\left(\frac{v^2}{2d}\right) = 0.0308g(T_{ch} - T_{amb}) \]  \hspace{1cm} (20)

From Eq. (20) the function of the mean velocity versus the temperature in the chimney can be determined [33].

The equations above are for a chimney system and do not take into account pressure drops that will occur throughout the other subsystems of the full solar dryer system. When air flow is
determined throughout the system the pressure drop across the solar collector and the drying chamber will need to be considered. The total system pressure drop can be described as [35]:

$$\Delta P_{sys} = \Delta P_{sc} + \Delta P_{dc} + \Delta P_{ch}$$

(21)

where $P_{sc}$ is the pressure drop across the solar collector and $P_{dc}$ is the pressure drop across the drying chamber.

O.V. Ekechukwu and B. Norton [33] attempted to improve the chimney by testing a solar radiation absorbing surface around a solar chimney. The intention was to create a “greenhouse effect” within the chimney to keep the air heated and above ambient temperature, which would keep the chimney working properly and enhance the buoyancy induced air flow. They concluded that with having a well-designed chimney, it is possible to keep chimney air temperatures above the ambient air temperature.

J.K. Afriyie et al. [36] characterized a direct passive solar dryer as one large chimney. They treated changes in size and bends as losses in the system and attempted to discover the effect of the dryer roof angle on the ventilation of the system. They concluded that the chimney should cover the entire width of the dryer and be combined with an appropriate angle to improve the ventilation for a direct type solar dryer.

2.5 Collector Review

Traditional solar collectors for dryers are well characterized and can be evaluated by their useful heat gain. Performance curves are obtainable for commercially available types of solar collectors including bare plate, single cover, double cover, and triple cover collectors. Properties of materials for absorber plates and covers have been well documented and can be used when designing a solar collector [11]. The useful heat gain for a collector is given by:

$$Q_u = \dot{m}C_p(T_{co} - T_{ci}) = A_cF_R[I_c(\tau \alpha)_e - U_L(T_{ci} - T_{amb})]$$

(22)

where $Q_u$ is the useful heat gain by the collector, $\dot{m}$ is the mass flow rate of the air through the collector, $C_p$ is the specific heat capacity of air, $T_{co}$ is the collector outlet temperature, $T_{ci}$ is the
collector inlet temperature, $A_c$ is the area of the collector, $F_R$ is the collector heat removal factor, $I_c$ is the solar insulation, $(tα)_c$ is the effective transmittance-absorptance product for the collector, $U_L$ is the overall heat loss coefficient for the collector, and $T_{amb}$ is the ambient temperature.

The collector efficiency is stated as:

$$\eta = \frac{Q_u}{I_c A_c}$$  \hspace{1cm} (23)

The characteristics needed to evaluate traditional solar collectors can be found in typical performance curves (ex: Figure 12) [11]. Singh characterized the convective heat transfer coefficient, $h_{cpf}$, of the absorber late to the flowing air for direct, indirect, and mixed-mode type solar dryers [37]. The characterization was done through experimentation and the collector consisted of a glass cover and an aluminum absorber plate.

Velmurugan conducted an exergy analysis for four different types of solar collectors, all containing at least a cover plate and absorber plate [38]. Fudholi et al. also used exergy in their study of solar dryers. Their main focus was the difference between a transpired solar collector, open sun drying, and shaded drying [39].
A transpired solar collector design was chosen for this prototype to experiment with low cost materials that are accessible in Haiti. Transpired collectors are a once-through solar energy heating system generally used to preheat air for systems like ventilation and crop drying [40]. Figure 13 shows a typical transpired solar collector. It consists of a perforated absorber plate and plenum, which is the space or box behind the plate. The outlet is at the top of the collector for vertical collectors. Figure 14 shows a more detailed look at the perforated plate. The pitch of the holes refers to the distance between each hole, and can be in square or diamond patterns. The diameter of the hole is also important and is a big factor in determining the efficiency of the collector.

Research and modeling has been conducted on transpired collectors to discover the most critical factors affecting its efficiency [41]. Kutscher et al. looked into heat losses associated with transpired collectors and found that natural convection losses are negligible on large collectors when the pressure drop is high enough [40]. In other work, Kutscher looked into the importance
of the heat transfer coefficient in low flow rate transpired collectors and showed that flow rate, crosswind speed, hole pitch, and hole diameter are major factors [12]. Other work include modeling of a transpired collector with experiment validation [41], [42].

The Van Decker Model focused on the heat exchange effectiveness of the collector through the front of the absorber plate, through the holes in the plate, and the back of the plate [43]. This model will be further explored in Chapter 4.

![Figure 13: Unglazed transpired solar collector, vertical orientation, for preheating ventilation air.][12]

![Figure 14: Schematic of Absorber plate for Van Decker Model][43]
2.6 Review of Drying Systems

Typically, when characterizing dryers, one is built, tested and then characterized. Hachemi built an indirect dryer (with no chimney) and tested multiple types of solar collectors [44] while Hassanain and Alonge built, tested, and compared three separate drying systems [14], [45].

Hassanain looked at open solar drying, indirect active system with a transpired solar collector, and an indirect passive system with an externally powered blower and no collector (shaded drying house) [45].

Alonge examined three main types of solar dryers: indirect, direct, and mixed-mode type dryers (all passive). His studies found mixed-mode drying was the most efficient, however, nutrient degradation was not considered [14]. Gbaha created and experimented with a direct passive solar dryer to dry tropical fruits. The experimental data was fit to empirical equations (similar to the Page model) [46].

Simate created a system model for an indirect and mixed-mode dryer. Neither models included a chimney; however, pressure drop throughout the system was calculated to determine the velocity of the air. An empirical thin-layer model was used for the grain drying and parameters were determined from other sources. The collector included a glass cover and absorber plate. [10]

Creating a system model to characterize an indirect passive solar drying system with a chimney will add to existing literature as well as expand the expertise of the Sustainable Energy Lab.
Chapter 3: Problem Statement

The focus of this research was to develop and experimentally validate a model of an indirect passive solar dryer system for the drying of tropical fruits. There are models available for individual subsystems of the drying system, however there currently is no complete system model for passively driven, transpired solar drying system for tropical fruits. Also, this system uses non-conventional materials, such as landscape fabric for the absorber plate of the collector, which had not been used in a system model before.

The objectives of this research were:

- Design an indirect passive solar drying system using low cost collector system
- Develop a prototype of the system for experimentation
- Develop a mathematical model for the system
- Preliminary validation of the model using experimental data

The system consisted of a transpired solar collector, drying chamber with eight screened drying trays, and a chimney. A prototype was built and tested using bananas. Figure 15 shows a simple schematic of the prototype setup. Measurements of the ambient and environmental conditions were taken for inputs to the system model. Temperatures, relative humidity, and air flow were monitored within the dryer to help with validation of the mathematical model.

Figure 15: Simple schematic of Indirect Dryer prototype
The system model created in MATLAB allows the user to predict the drying curves of the fruit on each of the trays in the dryer. A separate model was developed for the collector, drying chamber, fruit drying model, and the chimney. This allowed each piece of the system to be isolated and checked using experimental values to better validate the model.

This first generation model of the dryer prototype will provide a tool for predicting performance of a crop drying system in different climates, optimizing design and operation of indirect passive solar dryers, and exploring alternative concepts throughout the system, such as alternative collector designs. The model is a starting point for further research of the crop drying field in the Sustainable Energy Lab.
Chapter 4: Development of the System Model

The system model was developed in MATLAB using multiple sub-functions to break the system into its main subsystems. The main program reads environmental inputs and calls each sub-function to simulate drying of a particular fruit. The system outputs conditions such as temperature, humidity and flow rate over time to indicate the conditions within the dryer. The moisture content of the fruit is solved for within the system to model the drying curves. The main program stores output data from each time step to the next. The system time set is user defined and was set up to iterate every 5 minutes. Figure 16 shows a general layout of the system model approach.

![System Model Coding Schematic](image)

In Figure 16, each box represents a separate subsystem of the drying system. The largest box symbolizes the main program which stores the data for the entire drying system and therefore, contains all other subsystems.

The main program inputs data from text files specified by the user. Main variables are initialized at the start of the program to be used throughout the system, such as the fruit and air properties. Fruit and air properties are stored in structures, which allow multiple properties of each material to be stored within one variable. The structures allow information to be moved through the system efficiently and organized. The variable names can be redefined within each sub-function which enables naming conventions to be easily managed and understandable to an outside user. The main program built an array of structures to track the variables through space and time.

A loop configuration is used in the main program to step through time at the system level. Each system time step was set to 5 minutes, though this can be changed by the user to match the
The first sub-function called simulates the solar collector. The solar flux, ambient temperature, and ambient relative humidity are input to the sub-model and the outputs are the collector outlet temperature and relative humidity. The outputs are stored in the main program as variables, $T_2$ and $RH_2$ respectively. The humidity ratio, kilograms of water per kilograms of dry air, is tracked through the drying system requiring a conversion of the collector outlet relative humidity to the humidity ratio using the collector outlet temperature. This variable is stored as $X_2$.

$T_2$, $RH_2$, and $X_2$ become inputs to the next sub-function which simulates the drying chamber subsystem. The drying chamber model is separated into zones, one corresponding with each tray. The number of trays is user defined and independent of the drying system experiment. The drying chamber sub-function steps through space, or each zone, using a loop configuration. The output from each zone becomes the input to the next. After the final zone, the outputs are sent back to the system model as $T_3$, $RH_3$, and $X_3$ to be tracked. The fruit and air structure variables allow the conditions for each zone to be stored over time.

Within the drying chamber sub-function, fruit drying takes place. This is modeled in separate sub-functions. By creating a separate sub-function for the fruit, the overall model is independent of the type of fruit used in the experiment and the fruit can be user defined. The fruit drying sub-functions input initial fruit and air conditions and output a mass flux of moisture into the air. This allows for the relative humidity to be updated as it moves through each zone and is critical in correctly modeling the drying curves of each tray. The fruit and air structure variables are input to the fruit drying sub-function to track the moisture content of the fruit on the tray and the surrounding air properties throughout the fruit slice, over each zone, and over time.

The outputs from the drying chamber and fruit drying sub-functions are stored in the main program. Next, $T_3$, $RH_3$, and $X_3$ become the inputs the chimney model sub-function. The chimney model uses the buoyancy forces and pressure drops from the entire drying system to solve for the volumetric flow rate of the system. The initial flow rate must be assumed for the first time step of the model since the first three sub-functions depend on the volumetric flowrate to solve for their respective outputs. The initial flowrate from the experimental setup data was used to start this model. The chimney model outputs the flowrate using data from the current
time step to predict the flow rate for the next time step. This flowrate is stored in the main program and utilized for the next system time step in the loop.

Two MATLAB functions were developed to convert the humidity ratio into relative humidity (or vice versa) when needed for calculations based on equations developed by Vaisala [47]. These functions were utilized in multiple sub-functions as well as the main program.

Each subsystem model is detailed in the next several sections.

4.1 Fruit Drying Model

During the early stages of drying, the moisture transfer at the surface of the fruit limits the overall transport from the fruit material. However, mass diffusion within the fruit is the limiting process for most of the drying time, as discussed in Chapter 2. The following subsection contains the theory of diffusion for a non-dilute system. Earlier models and textbook cases usually assume there is a dilute system (i.e. when the solid has very little moisture). The implementation of this theory will also be discussed.

4.1.1 Governing Equations

The goal of the fruit drying model is to determine the rate of evaporation at the surface of the fruit when exposed to surrounding air at a given temperature and humidity ratio for each specified zone in the drying chamber. The model also needs to determine the local moisture content and density changes throughout the fruit and track these properties for each zone. The governing equations used in previous work for drying often neglected the small velocity or assumed a constant velocity for both the water and solid (dry fruit material), throughout the drying process. Many of the models found in the literature rely on model specific material properties, which have limited predictive capabilities when a system is operated under different conditions, such as different product thicknesses, different drying air conditions, and flow rate around the drying product. A model developed through ongoing research at RIT by Weinstein is used to simulate moisture transport within and from the surface of a fruit [48]. The model accounts for the high mass fraction of water in the banana material (a non-dilute system), which is typically not accounted for in many models. Other assumptions include: fruit can be modeled as a flat plate with 1D mass transport, no chemical reaction is occurring during the drying
process, the banana surface is in thermodynamic equilibrium with the immediate surrounding air, symmetry in the fruit system such that mass transfer at the bottom of the fruit slice is equal to the mass transfer at the top, and the banana is in thermal equilibrium with the air at all times. The final assumption is reasonable since the thermal energy transport to raise the fruit 10-20°C is negligible compared to the energy required for mass transport. Also, the temperature time response to reach equilibrium is on the order of minutes compared to hours for the mass transport response.

Figure 17 shows a schematic of the 1D fruit plate system to be modeled.

![Schematic for mathematical model of moisture in fruit drying system. Note that A, or Air Phase, is the immediate surrounding air of the fruit product and B, or Solid Phase, is the fruit material. Also, the T(z,t) term is not modeled because of the assumption that the fruit is in thermal equilibrium with the surrounding air. The dashed line is the plane of symmetry through the center of the fruit. [48]](image)

To model the transport of moisture and solid material in the fruit system, mass continuity and diffusion of moisture in the solid is assumed using Eqs. (24-25). Equation 24 accounts for transient mass continuity, often seen in fluid mechanics, or the conservation of total mass in the system, which accounts for both the water and solid mass.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z}(\rho u_z) = 0$$  \hspace{1cm} (24)
The variable \( \rho \) is the density of the banana for a specific time, \( \omega_1 \) is the mass fraction of the water in the solid material, \( z \) is the vertical space unit, \( u_z \) is the average velocity of the banana material.

Equation 25 accounts for the mass flux of the moisture (subscript 1) in the system. It is assumed that water mass is conserved as it diffuses through the system, which is shown on the left hand side of Equation 25. The average velocity term, \( u_z \frac{\partial \omega_1}{\partial z} \), is usually neglected in cases of dilute systems (most common types of problems seen in textbooks). The right hand side demonstrates Fick’s law of diffusion which is widely used in literature.

\[
\rho \left[ \frac{\partial \omega_1}{\partial t} + u_z \frac{\partial \omega_1}{\partial z} \right] = \frac{\partial}{\partial z} \left( \rho D \frac{\partial \omega_1}{\partial z} \right) \tag{25}
\]

The variable \( \omega_1 \) is the mass fraction of the water in the solid material, \( z \) is the vertical space unit, and \( D \) is the diffusion coefficient of water through the solid material. The mass fraction, or moisture content on a wet basis, varies with space and time. Diffusivity of the solid material is a function of both the temperature and moisture content of the fruit being used, therefore it is also a function of location and time. Further exploration of the diffusion coefficient will be detailed in section 4.1.2.

Finally, in Equation 26, Amagat’s law is used to relate the specific volume of the system components, water and solid banana, to the density of the system. This assumes volume additivity.

\[
\rho = \frac{1}{\tilde{V}_2 + (\tilde{V}_1 - \tilde{V}_2)\omega_1} \tag{26}
\]

The variable \( \tilde{V}_2 \) is the specific volume of pure solid material and \( \tilde{V}_1 \) is the specific volume of pure water. The bulk transport equations, Eqs. (24-26), leave us with 3 equations and 3 unknowns, \( \rho \), \( \omega_1 \), and \( u_z \), which are all a function of time and temperature [48].

The boundary conditions for the system at the center of the banana, where \( z \) is equal to zero are:

\[
\frac{\partial \omega_1}{\partial z} = 0 \tag{27}
\]
showing that the moisture gradient and bulk average velocity are equal to zero. At the fruit surface, when \( z = h(t) \), the moisture diffusion in the fruit at the surface is equivalent to the mass convecting from the fruit surface to the bulk fluid so that:

\[
\rho D \frac{\partial \omega_1}{\partial z} = k(\omega_{A1,\infty} - \omega_{A1,S})(1 - \omega_1)
\]

(29)

where \( k \) is the mass transfer coefficient and in the air times the density of the air, \( \omega_{A1,\infty} \) is the moisture content of the surrounding air on a wet basis and is an input from the drying system, and \( \omega_{A1,S} \) is the moisture content of the air directly next to the surface of the banana and is a function of the wet basis moisture content of the fruit and temperature. \( \omega_{A1,S} \) is determined from the GAB equation described in Chapter 1 and will be further explained in section 4.1.2. This expression is analogous to Newton’s Law of Cooling for convection. The far right term and denominator of the right hand side of Equation 29 is due to the fact the system is a non-dilute system. Note, this is a general system of equations for a non-dilute system. For the special case of dilute systems where \( \omega_{A1,S} = 0 \), the boundary condition shown in Eq. (29) reduces to the simple case of diffusion in the solid equals the convection in the gas.

Also at the surface \( (z = h(t)) \), the rate change of the fruit half thickness, \( h \), is equal to the average velocity of the total mass minus the moisture diffusion at the surface, so that:

\[
\frac{\partial h}{\partial t} = u_z - \left( -\frac{D}{1 - \omega_1} \frac{\partial \omega_1}{\partial z} \right)
\]

(30)

In other words, the velocity of the surface of the banana as it shrinks during drying is \( \frac{\partial h}{\partial t} \). The initial conditions, where time equals zero, are:

\[
\omega_1 = \omega_{10}
\]

(31)

\[
h = h_o
\]

(32)
where \( \omega_{1o} \) is the initial wet basis moisture content of the fruit and assumed to be uniform throughout the fruit and \( h_o \) is the initial half thickness of the banana slice. The diffusivity of banana, mass transfer coefficient, and \( \omega_{A1,5} \) are all inputs to the banana model. The model outputs the moisture content of the banana, the mass flux (amount of water added to the air), and the temperature of the air.

4.1.2 Fruit Input Parameters

The coefficients \( D \), \( k \), and \( \omega_{A1,5} \) are defined within the sub-function \textit{fruit\_properties} of the banana model. \( \bar{V}_1 \) and \( \bar{V}_2 \) were also input using the sub-function, though these are constant values. \( \bar{V}_1 \), the specific volume of pure water, is assumed to be \( 0.001 \) m\(^3\)/kg and \( \bar{V}_2 \), the specific volume of solid banana (without moisture), is assumed to be \( 0.000909 \) m\(^3\)/kg.

The diffusion coefficient is not constant, but is assumed to vary with moisture content. The coefficient is also highly dependent on the material and will change from one banana to the next. This is especially prevalent in non-ripe vs ripe bananas and has been studied by Nguyen [49]. For this model, a linear relationship was assumed shown in Eq. (33). After testing several possible models for the diffusion coefficient, using curves studied by Baini (2008), it was determined that the linear model resulted in values closest to those seen in other literature [25] [50].

\[
D = a \omega_1 + b
\]  

(33)

The equation was fit by adjusting overall moisture content of the first tray of bananas on the first day of testing to find coefficients \( a \) and \( b \), where \( a = 0.89 \times 10^{-10} \) m\(^2\)/s and \( b = 0.39 \times 10^{-11} \) m\(^2\)/s. Ideally, this coefficient should be determined from an independent measurement.

To find \( k \), which is equivalent to the product of the mass transfer coefficient and local air density, \( h_m \times \rho_{\text{Air}} \), several analogies to the heat transfer convection coefficient correlations were considered such as those used as Karim explained in Chapter 2. However, the system assumptions did not allow for any of the analogies to be used successfully.
The first analogy considered was the flat plate relationship used by Karim [16]. This correlation, shown in Chapter 2, assumed the air flow was parallel to the plate and solved for the local mass transfer coefficient. To adjust this model, the equations were changed to solve for the average mass transfer coefficient across the plate [30]. This model was also insufficient for the system. Because the air flow is perpendicular to the banana slice, Table 7.3 of the 7th edition textbook by Bergman et. al. was considered [30]. Unfortunately, the Reynolds number was not in the valid range for this correlation.

Other considerations utilized the drag coefficient to model the friction factor of the perpendicular air flow to a round disk plate [51]. First, the Reynolds analogy was considered, however the assumption that the Prandlt number is approximately equal the Schmidt number is not valid for the system being modeled. Next, the Chilton-Colburn Analogy was considered. This analogy also used the drag coefficient to find the friction factor and assumed the Prandlt number to be between 0.6-60 and the Schmidt number to be between 0.6-3000. Although our system seemed to fit these assumptions, the mass transfer coefficient was still an order of magnitude higher than expected.

Finally, a model presented by Kobus and Shumway of heat transfer from a stationary isothermal circular disk (very similar to a banana slice in the dryer) was also considered, however, the coefficient calculated was also too high to match the experimental data [52].

Because all models considered above seemed to greatly overestimate the mass transfer coefficient, the limiting case of diffusion in a semi-infinite material with no convection was assumed. The limiting case assumed there was no air movement around the banana and the gradient in moisture content was the only factor driving evaporation from the surface of the banana slices. The heat transfer energy balance is expressed as [30]:

\[ q = S\lambda\Delta T \]  

where \( q \) is the heat rate due to conduction, \( S \) is the shape factor, and \( \lambda \) is the thermal conductivity. Similarly, the mass rate can be described as:

\[ m = SD_{wa}\rho_{ban}\Delta MC_{wb} \]  

where \( D_{wa} \) is the diffusion coefficient of water vapor in air, \( \rho_{ban} \) is the density of banana, \( \Delta M \) is the change in moisture content, and \( C_{wb} \) is the water vapor concentration at the surface.
where $D_{wa}$ is the diffusivity of water in air and $MC_{wb}$ is the wet basis moisture content of the banana. Each equation can be divided by the surface area of the banana slice to find the heat or mass flux. The shape factor for a disk exposed to a semi-infinite medium is expressed as [30]:

$$S = 2D_{ban} \quad (36)$$

where $D_{ban}$ is the diameter of the banana slice. The mass flux can also be stated as:

$$J = \rho_{ban} h_m \Delta MC_{wb} \quad (37)$$

It is assumed that Eqs. (34) and (35) are analogous and equation (36) is substituted for the shape factor. Finally, equating Eqs. (35) and (37) the mass transfer coefficient is determined as:

$$h_m = \frac{8D_{wa}}{\pi D_{ban}} \quad (38)$$

This value was added to the resistance created by the mesh on the bottom of the banana. Figure 18 shows the dimensions of the mesh screen used for the drying trays.

![Figure 18: Dimensions of the screen mesh used for they trays in the drying chamber](image)

The resistance caused by the screen mesh is:

$$R_{mesh} = \frac{l}{D_{wa} \left( \frac{A_{exposed}}{A_{total}} \right)} \quad (39)$$

where $l$ is the thickness of the gap created by the mesh, $A_{exposed}$ is the open area of a single square in the screen (for this case: $(1.68 \text{mm} - 0.3 \text{mm})^2$), and $A_{total}$ is the total area of a single
square of screen (for this case: 2.8 mm²). Equation 40 shows the effective mass transfer coefficient in terms of resistance:

$$h_{\text{m eff}} = \frac{1}{\frac{R_{\text{mesh}}}{2} + \frac{1}{h_m}}$$ (40)

The moisture content of the air directly next to the surface of the banana, $\omega_{A1,S}$, is needed to solve for the moisture transfer at the surface of the banana. To solve for this input variable, the GAB model (Eq. 5 from Chapter 1) was assumed to relate the surface moisture content on both sides of the fruit surface [53]. The GAB constants were found by fitting the model to Kiranoudis experimental data where the water activity rate and dry moisture content for bananas was measured at two different temperatures [54]. Alternative models that could be used can be found in Section 4.4 of work by Delgado and de Lima [55]. Further exploration into these models is needed to determine what is best for banana material [50].

4.1.3 Implementation of the Banana Model

In order to implement the equations into the MATLAB function, the equations needed to be non-dimensionalized in space. This allowed for the problem to be easily discretized without needing to re-mesh the problem for every iteration as the banana thickness changed. The spatial dimension can be non-dimensionalized by:

$$\eta = \frac{z}{h(t)}$$ (41)

Substituting Eq. (41) into the governing equations of the system, the surface of the banana can be easily located in space and will be between the values of 0 to 1.

To solve the system of equations, an implicit finite difference approach was coded into a MATLAB function by Stevens from the Sustainable Energy Lab at RIT to be used in the system model[50]. This model is detailed in Figure 19. The sub-function drymaster defines the parameters input from the system model and cycles through for the system time step. This sub-function can be run at intermediate time steps, if needed. The parameters from the drymaster
function are combined with those of the `fruit_properties` function to input to the `dryfruit` sub-function. The main equations from Weinstein are modeled in `dryfruit`. This sub-function discretizes the banana slice within one system time step and solves for the local moisture content and local average velocity. The `drymaster` sub-function uses the `fsolve` tool to solve the equations outlined in the `dryfruit` function. These equations solve for the mass flow rate of water vapor in the air due to evaporation, moisture content, average velocity, and height of the bananas to the drying chamber model. Data stored from the previous time step to input as the initial conditions into the next time step [50].

![Figure 19: Fruit Model System Coding Schematic](image)

### 4.2 Dryer Model

The dryer model receives inputs from the collector model (sent in through the main program) and interacts with the fruit drying model internally. The outputs feed into the chimney model through the main program. Figure 20 shows a general layout of the drying chamber MATLAB code.
Each tray makes up its own zone in the system. For instance, zone one contains the first tray and receives inputs from the solar collector and outputs to zone two. By breaking the system into zones, the moisture content for the bananas on each tray can be determined.

As moisture leaves the bananas and enters the air, the new humidity ratio of the air is calculated as:
\[
X_{(j+1)} = X_{(j)} + \frac{\dot{m}_w(j)}{\dot{m}_a}
\] (42)

where \(X_{(j+1)}\) is the humidity ratio leaving the zone, \(X_{(j)}\) is the humidity ratio entering the zone, \(\dot{m}_w(j)\) is the water vapor mass flow rate due to evaporation at the surface of the fruit and is determined by the fruit drying model, and \(\dot{m}_a\) is the mass flow rate of the dry air (not including water vapor). The humidity ratios output from this equation are on a dry basis. To get to the wet basis humidity ratio, Equation 43 is used:

\[
w_{(j+1)} = \frac{X_{(j+1)}}{1 + X_{(j+1)}}
\] (43)

The wet basis is solved for because it is an input to the fruit drying model and will be saved in the main program using the air variable structure and used to solve the next system time step. Heat energy is used during the evaporation process and causes the temperature across the zone to decrease. Because the enthalpy is constant across the zone, the system can be represented as the following energy balance for a steady state system:

\[
\dot{m}_a(h_{in} - h_{out}) = q_{loss}
\] (44)

where \(h_{in}\) represents the enthalpy into the zone, \(h_{out}\) is the enthalpy leaving the zone, and \(q_{loss}\) represents heat losses in the zone. Enthalpy can be expressed in terms of temperature and humidity ratio as [47]:

\[
h = T(1.01 + 1.89X) + 0.0025X \left[\frac{kJ}{kg}\right]
\] (45)

Combining Eqs. (44) and (45) the outlet temperature of the zone can be solved as:

\[
T_{A_{(j+1)}} = \frac{T_{A_{(j)}}(1.01 + 1.89X_{(j)}) + 0.0025(X_{(j)} - X_{(j+1)}) - \frac{q_{loss}}{\dot{m}_a}}{1.01 + 1.89X_{(j+1)}}
\] (46)
where $T_{A(j+1)}$ is the temperature leaving the zone, $T_{A(j)}$ is the temperature entering the zone, $C_p$ is the specific heat of air. The losses as assumed to be zero, however will be explored further in Chapter 6.

4.3 Solar Collector Model

The solar collector model determines the collector outlet temperature and relative humidity based on incident solar radiation, ambient temperatures, and relative humidity. Figure 22 shows the layout of the MATLAB code in more detail.

![Figure 22: Solar Collector Coding Schematic](image)

The Van Decker model was used to calculate the collector efficiency and outlet air conditions [43]. The expression for the steady state efficiency of a transpired solar collector was developed by Kutscher [56] and is shown as:

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

(47)

where $\alpha_s$ is the solar absorptivity of the absorber surface, $h_r$ is the radiative heat loss coefficient from the absorber surface to the surroundings, $\epsilon$ is the collector surface heat exchange effectiveness, $V_s$ is the suction velocity, $\rho$ is the density of air, and $C_p$ is the specific heat of air.

The equation for suction velocity is:

$$V_s = \frac{\dot{V}}{A_c}$$

(48)
where $\dot{V}$ is the volumetric flow rate of the system and $A_c$ is the collector surface area. The equation for $h_r$ is:

$$h_r = \epsilon_p \frac{\sigma (T_p^4 - T_\infty^4)}{T_p - T_\infty} \quad (49)$$

where $\epsilon_p$ is the emissivity of the absorber plate, $\sigma$ is the Stefan-Boltzmann constant, $T_p$ is the temperature of the plate, and $T_\infty$ is the temperature of ambient air. The solar absorptivity of the plate and the emissivity of the plate are typically determined by an independent measurement or experimental data is fitted to the model (Eq. (47)). By fitting the experimental data to the efficiency model, the estimated values are: $\alpha_s = \epsilon_p = 0.687$ for the landscape fabric used in the system described in Chapter 5 [50]. Extensive testing of the absorber material is needed to have more confidence in the material properties. The temperature of the plate is also not known for this system. In order to solve for the temperature, an initial temperature was assumed to be approximately 50°C above ambient and a loop iteration was used until the temperature converged. The model for the plate temperature is assumed to be a set temperature above collector outlet temperature (around 10°C). The model started with the assumed initial absorber temperature and iterated until the change in absorber temperature between iterations was less than 0.01°C. The convergence criteria is user defined to allow for a variable degree of accuracy depending on model demands.

To develop a model for the effectiveness, Van Decker breaks the total effectiveness into three components: the effectiveness at the front of the plate, through the holes in the plate, and at the back of the plate. Equations (50-53) show the definition for each effectiveness:

$$\epsilon \equiv \frac{T_o - T_\infty}{T_p - T_\infty} \quad (50)$$

$$\epsilon_f \equiv \frac{T_{o1} - T_\infty}{T_p - T_\infty} \quad (51)$$

$$\epsilon_h \equiv \frac{T_{o2} - T_{o1}}{T_p - T_o} \quad (52)$$
\[ \epsilon_b \equiv \frac{T_o - T_{o2}}{T_p - T_{o2}} \]  

where \( T_{o1} \) is the bulk mean temperature of the air as it enters the hole, \( T_{\infty} \) is the temperature of ambient air, \( T_p \) is the temperature of the absorber plate, \( T_{o2} \) is the bulk mean temperature of the air as it exits the hole, \( T_o \) is the bulk mean temperature of the inside of the collector, \( \epsilon_f \) is the effectiveness for the front of the plate, \( \epsilon_h \) is the effectiveness through the holes, and \( \epsilon_b \) is the effectiveness at the back of the plate. Figure 14 in Chapter 2 shows a detailed schematic of these temperatures. By combining Eqs. (50-53), the total effectiveness is:

\[ \epsilon = 1 - (1 - \epsilon_f)(1 - \epsilon_h)(1 - \epsilon_b) \]  

Van Decker models each effectiveness based on Reynolds number of the velocity at each stage of the absorber. The model is empirically based and constants are solved for by fitting the model to experimental data taken from many different plate configurations. For the effectiveness at the front of the plate:

\[ \epsilon_f = \frac{1}{1 + Re_s \min \left[ a * \frac{Re_w}{PrRe_h}, f \right]} \]  

where \( a \) and \( f \) are constants and equal to 1.733 and 0.02136 respectively, \( Re_s \) is the Reynolds number based on the suction velocity and \( Re_w \) is the Reynolds number based on the wind velocity [43]. A value for the wind velocity was assumed since there was not experimental data for the wind speed on the day of testing.

The effectiveness through the hole in the plate is shown as:

\[ \epsilon_h = 1 - e^{-4\left(\frac{P}{D} + \frac{3.66}{PrRe_h D}\right)} \]  

where \( P \) is the pitch of the holes and \( D \) is the diameter of the holes (as explained in Chapter 2), \( Pr \) is Prandlt’s number of air, \( Re_h \) is the Reynolds number based on the velocity through the holes, and \( t \) is the thickness of the plate [43]. The term \( \frac{P}{D} \) accounts for the non-uniform
temperature across entering the hole in the absorber plate. However, because the transpired collector being modeled is significantly smaller and thinner than those tested by Van Decker, the constant \( c \) was set to zero. The thickness of the landscape fabric is so small, the effectiveness of the hole is negligible.

Finally, the effectiveness at the back of the plate is shown as:

\[
\epsilon_b = \frac{1}{1 + e \times Re_b^{\frac{1}{3}}}
\]  

(57)

where \( e = 0.2273 \) and \( Re_b \) is based on the suction velocity divided by the porosity of the plate [43]. Combining Eqs. (55-57) with Eq. (54) gives the total collector effectiveness, which is used to determine the efficiency of the collector using Eq. (47).

To solve for the temperature leaving the collector, the useful heat gain was found by:

\[
Q_u = \eta I_c A_c
\]  

(58)

where \( I_c \) is the solar insulation. Finally the outlet temperature was found using:

\[
T_{out} = \frac{Q_u}{mC_p} + T_\infty
\]  

(59)

Equations (58) and (59) are widely used to find the useful energy and outlet temperatures of solar collectors.

### 4.4 Chimney Model

The chimney model is used to determine the volumetric flow rate through for the system. The chimney is the driving force behind the air flow in the system. The buoyancy forces and pressure losses throughout the entire system need to be accounted for.

The buoyancy force for each component of the prototype: solar collector, drying chamber, and chimney, was calculated using the same basic equation:
\[ \Delta P = gH\Delta \rho \tag{60} \]

where \( \Delta P \) is the pressure difference across a component, \( g \) is the standard gravitational acceleration constant, \( H \) is the vertical height of the component, and \( \Delta \rho \) is the difference in air density between the air in each component and the air outside the system. Eq. (60) can solved for each component and summed to determine the total pressure driving flow, which ban be set equal to the pressure losses of the system to determine the flow rate. The pressure loss for the collector was modeled as after Kutscher (1994) [12]:

\[ \Delta P = \frac{1}{2} f_{coll} \rho V^2 \tag{61} \]

where \( \rho \) is the density of air, \( V \) is the suction velocity and \( f_{coll} \) is determined by an empirical fit [12]:

\[ f_{coll} = 6.82 \left( \frac{1 - \sigma_p}{\sigma_p} \right)^2 R_{cham}^{0.236} \tag{62} \]

where \( \sigma_p \) is the porosity of the absorber plate and \( R_{cham} \) is defined as before in the collector model. The pressure loss across the each tray in the drying chamber used Cengel’s model [57]:

\[ \Delta P = \frac{f_{cham} \rho_{cham} \dot{V}^2}{2A_{Avail}^2} \tag{63} \]

where \( \rho_{cham} \) is the average density of the air in the drying chamber, \( A_{Avail} \) is the space available for air to move through the tray, \( \dot{V} \) is the volumetric flow rate of the system, and \( f_{cham} \) is defined as [58]:

\[ f_{cham} = \frac{22}{R_{cham}} + 1.3(1 - \sigma_{psc}) + \left( \frac{1}{\sigma_{psc}} - 1 \right)^2 \tag{64} \]

where \( R_{cham} \) is the Reynolds number based on the air flow through the drying chamber and \( \sigma_{psc} \) is the porosity of the screen material used for the drying trays. This model assumes the
screen is not contaminated, made of circular metal wire that is not corroded, and the Reynolds number is less than 50.

Finally, the losses in the chimney were modeled for the sudden change from a rectangular duct of the drying chamber to the small circular duct of the chimney and the friction of the air flow through the chimney itself [34]. The velocity in each pressure loss term was converted to volumetric flow rate and set equal to the total buoyancy force of the system. The volumetric flow rate was solved and output to the system model.

Since all the subsystem models rely on the volumetric flow rate, an initial value was assumed using the experimental data found during the experiment detailed in Chapter 5. The chimney model was used to predict the flow rate for the next time step in the system based on the conditions for the current time step. This means the volumetric flow rate is a time step behind the rest of the model and is an area for future improvement. Figure 23 shows the general layout of the MATLAB code.

![Figure 23: Chimney Coding Schematic](image-url)
Chapter 5: Experimental Setup

The experimental dryer setup was designed to validate and troubleshoot the mathematical model and serve as a first generation prototype. This setup would not be ideal for use in Haiti because of material cost and difficulties maneuvering the dryer in a rural landscape. However, suggestions for dryer material and construction will be given in Chapter 8 of this thesis. The experimental setup consist of a solar collector, drying chamber, chimney, and data acquisition system, which is depicted in Figure 24 and Figure 25.

![Experimental Setup](image)

Figure 24: Experimental Setup

The transpired solar collector absorber is made from black landscape fabric. The absorber was made by stretching the fabric over a wooden frame using screen spline to keep it in place. Then, a small finishing nail was heated and pressed to the fabric to melt the holes. The absorber is approximately 0.71m by 1.17m with a total area of approximately 0.83m². The average hole pitch is 0.47in (0.0119m) and average hole diameter is approximately 0.09in (0.0023m). Figure 26 is a general schematic showing the absorber plate as well as hole pitch and diameter. The plenum frame is made of wood with a layer of 1in insulation covering all inside walls, so walls...
were assumed to be adiabatic. Wheels are attached to the bottom for easier transport. When attached to the drying chamber, the collector slope is approximately 38° from the horizontal.

Figure 25: Experimental Setup Sensor Schematic. Thermocouples 5 and 6 appear above trays 3 and 8, respectively.

Figure 26: Absorber plate and general dimensions definitions.
The frame for the drying chamber is made of t-slotted extruded aluminum bars with wheels attached at the bottom for transportation. The main body is made from steel sheet metal with the sides and bottom being insulated. The front and back faces of the drying chamber were not insulated to allow the largest possible tray size. The edges of the dryer were sealed with caulk to minimize air infiltration. The total height of the chamber is 27in, from the floor panel where the collector outlet rests to the last point before the taper to the chimney. The top of the first tray sits 7.25in from the bottom, each tray is spaced approximately 2.25in, and there is 3.625in above the top of the eighth tray. The trays are accessible from the back of the dryer and numbered from 1 to 8 starting from the bottom. The trays consist of a wooden frame with a standard window screen material to allow air to flow around the bananas. The effective area of the tray, the area inside the wooden frame, is approximately 31in (0.7874m) by 15in (0.381m) or 465in² (0.3m²). Figure 27 shows a tray after bananas have been loaded for drying. Approximately 1.5 average sized bananas sliced at 0.2in thick, was placed on each tray, or approximately 30% capacity (Banana surface area/Total Area available).

Figure 27: Loaded tray with banana slices

The collector-chamber connection was sealed by using a piece of weather stripping. The collector was tilted and set on the edge of the chamber frame. A piece of insulation covered the top to minimize heat loss from the outlet of the collector to the inlet of the chamber. This set up would potentially allow for different angles of the solar collector to be tested.
The chimney base is screwed onto the top of the dryer and is made of stainless steel. The chimney has a robust base to insure it would not fall over due to wind. A galvanized steel 6” round duct was used for the chimney itself. The chimney extends 5ft from the top of the dryer for a total system height of approximately 11.7ft.

Each main component is separate to allow for easier transportation. Figure 24 shows the actual dryer system set up for testing. Figure 25 is a schematic of the system to better show where each sensor was placed.

Preliminary calculations on the moisture carrying capacity of the air in the dryer allowed a preliminary mass of bananas suitable for the dryer to be found. Approximately 5kg of bananas per meter squared of solar collector was suitable for a 3 day drying period. This would use approximately 9 trays. This calculation assumed there would be no drying during the night while the dryer was inside. The final dryer set up had 8 trays and approximately 4kg of bananas per meter squared of solar collector for a two day test period.

The collector absorber plate was expected to cause approximately 1Pa of pressure loss in the system at a flow rate around 0.02 m$^3$/s. The plenum is a minimum source of pressure loss in the system, causing around 0.003Pa of loss.

Preliminary calculations assumed a 10-20°C rise in temperature and 0.005-0.02 m$^3$/s volumetric flow rate to check for pressure loss and buoyancy force through different chimney diameters and heights. The diameters checked were 6in and 4in and the heights were 60in and 40in. To minimize pressure loss in the chimney, a duct of 6in was chosen over a 4in duct. The 6in duct had an approximate pressure loss of 0.2Pa compared to the 0.9Pa for the 4in duct. A 60in chimney height provided 1.5 Pa of pressure where a chimney of 40in only produced around 1 Pa. The taller chimney was needed in order to pump air through the system.

5.1 Equipment Specifications and Orientation

Figure 25 above shows the general layout of all the sensors used in the experiment. The sensors were mounted throughout the system while the data acquisition devices were attached to the frame of the dryer and connected to a laptop. LabVIEW was used to collect the data and
MATLAB and Excel were used for data processing. Moisture content of the bananas, temperatures throughout the system, ambient temperature and relative humidity, relative humidity at the outlet of the dryer, solar insulation, and flow rate through the chimney were all measured during the experiment to compare to the theoretical model.

The main sensors consisted of thermocouples, relative humidity sensors, a pryanometer, and a flow meter. The thermocouples, used to measure temperature, were logged using a USB-TC logging system that can handle a maximum of 8 thermocouples at a time. The relative humidity sensors, used to measure the relative humidity of air, and pryanometer, used to measure solar insulation, were logged using an NI-6008 USB data logger. The pryanometer also required a signal conditioner to convert amperage to voltage. Both data loggers were connected to a laptop and synced with LabVIEW to record the data. This data was recorded every 30 seconds. The flow meter averaged the flow data internally over a 30 second period and the data was recorded manually by entering the reading from the flow meter screen into the LabVIEW code. The LabVIEW data was stored in a text file for later analysis using Excel and MATLAB.

To track the moisture content of the bananas over time, each tray weight was recorded using an LCT Counting Scale periodically throughout the experiment. For the first day, the weight was recorded every 30 minutes and on the second day, every 60 minutes.

A pressure sensor was used to validate preliminary calculations but was not used during the experiments. The pressure sensor data was viewed through NI MAX and stored manually by writing measurements by hand.

**Error! Reference source not found.** lists the equipment and their specifications used in the experiment.
Table 2: List of Equipment with corresponding parameters. Refer to Figure 25 for the location each parameter was measured at for the experiment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Equipment</th>
<th>Model</th>
<th>Additional Equipment</th>
<th>Uncertainty</th>
<th>Parameters measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Thermocouple</td>
<td>Type-K</td>
<td>USB-TC logging system</td>
<td>±0.3 °C</td>
<td>$T_1, T_2, T_3, T_4, T_5, T_6, T_7, T_8$</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>Relative Humidity Sensor</td>
<td>OMEGA – HX71-V1</td>
<td>12V Power supply</td>
<td>±4%</td>
<td>$RH_1, RH_{amb}, RH_3$</td>
</tr>
<tr>
<td>Solar Insulation</td>
<td>Pyranometer</td>
<td>LI-200/R</td>
<td>Li-Cor 2420 Light Sensor</td>
<td>±1% of reading</td>
<td>$I_C$</td>
</tr>
<tr>
<td>Air flow</td>
<td>Flow meter</td>
<td>Velocicalc 9535</td>
<td>AA batteries</td>
<td>±3% of reading or 0.015m/s</td>
<td>$v_{air}$</td>
</tr>
<tr>
<td>Mass</td>
<td>Scale</td>
<td>LCT - 50000 Counting Scale</td>
<td>Adapter 10-12V/500mA, baking sheet</td>
<td>±0.0023</td>
<td>$m_{tray_n}$, where n=1-8, $ΔP_{coll}$</td>
</tr>
<tr>
<td>Pressure</td>
<td>Pressure sensor</td>
<td>OMEGA Px278-0.1D5V</td>
<td>12V Power supply</td>
<td>±1% of reading</td>
<td>$ΔP_{coll}$</td>
</tr>
</tbody>
</table>

Thermocouple 1, recording $T_{amb}$, and Relative Humidity sensor 1, recording $RH_{amb}$, were placed underneath the dryer, to avoid direct radiation from the sun. There was a layer of insulation between the drying chamber and the sensors to ensure they were not affected by the heat of the dryer.

The pyranometer was mounted on the frame of the absorber plate to ensure it had the same orientation same as the collector absorber. Three thermocouples (numbers 2-4) were placed in the outlet of the collector. Thermocouple 2 was placed on the side wall, thermocouple 3 was in the center of the absorber plate and center of the plenum, and thermocouple 4 was in the center of the absorber plate and set closer to the absorber plate. Figure 25 shows the collector thermocouples’ orientation. The average of these temperatures were taken to be used as the experimental value for the collector outlet temperature. Further investigation into the temperature profile at the outlet is needed in order to have a more accurate picture of the temperature entering the drying chamber.
Thermocouple 5 was placed in the center of the drying chamber, between trays three and four or approximately 1in above the third tray. The sensor was placed on the sunny side, or front, of the dryer (opposite of the tray handles, see Figure 25 for clarity) and measured temperatures 6in in from the wall. Thermocouple 6 was placed approximately 1in above tray eight in the center of the drying tray and measured temperatures 6in in from the front wall. These temperatures were monitored for comparison to the model as well as live feedback during testing. The temperature was observed to decrease from tray one to tray eight as energy was transferred to the banana slices for evaporation.

Thermocouple 7 and relative humidity sensor 2 were placed at the inlet of the chimney. This allowed validation of the chimney model separately (using experimental data only) as well as provided insight into where the model may need to be modified. Also, having a temperature reading in the same place as a relative humidity reading enabled an easy conversion from relative humidity to humidity ratio of the drying chamber exiting air and chimney inlet air.

The eighth and final thermocouple was place at the top of the chimney along with the flow meter. Since the model assumes the chimney is not gaining any heat, this temperature was not used in the comparison but did validate the assumption of no heat gain. The average change in temperature measured from thermocouple 7 to 8 was 4.7°C, which would result in a 2% density change of dry air and would not greatly impact the model. Also, the reading may have been skewed by the solar radiation at the top of the chimney. Changes in the setup will be discussed later to address this issue. The Velocicalc 9535 flow meter was placed in the center of the chimney approximately 6in (0.15m) from the top. Further experimentation to understand the velocity profiles exiting the collector will help achieve a more accurate reading.

All thermocouples are logged using a USB-TC system and all data is recorded using a data acquisition program developed with LabView.

5.2 Uncertainty of Measurements

Thermocouples were validated using an OMEGA TrueRMS Supermeter indoors. All thermocouples were within 0.3°C of each other at room temperature. This uncertainty will propagate through to the collector efficiency equation. Because the collector outlet temperature
was averaged, ±5°C was used as the uncertainty of this variable because of the average difference between the measured temperatures.

The relative humidity sensors were new and calibrated before they were sent. The sensor was recorded using the NI-USB-6008 data logger. The relative humidity sensor has 4% accuracy according the manufacturer.

The pyranometer was calibrated by Li-Cor Incorporated in June 2015, a few months before testing. The pyranometer outputs milliamps and is connected to a Li-Cor 2420 Light sensor amplifier. The gain amplifier can be adjusted and was set to a 0-5VDC range, such that the solar flux is linearly proportional to the voltage output of the amplifier. Voltages are recorded using a NI-USB-6008 data logger which uses the LabVEIW code to store data. The uncertainty of the pyranometer was assumed to be approximately 10% of the reading based on manufacturer data and accounting for having the sensor at an angle instead of directly facing the sun.

To avoid constantly measuring the unknown velocity profile in the system chimney to determine the volumetric flow rate of the system, the Velocicale flow meter velocity was calibrated to a known volumetric flow rate using an OMEGA FTB-900 precision turbine flow meter. Although the precision turbine flow meter would have been easier to use during the drying testing, it was not sued because it would have induced a large pressure drop in the system and therefore impacting the overall system performance. The calibration was done by using a small blower to move air through the turbine flow meter and then through the drying chamber and chimney. The Velocicale flow meter was placed in the chimney with the same orientation as it was for the drying experiments. This allowed a known volumetric flow rate to be related to the air velocity. This was used to convert the velocity to volumetric and mass flow rates during data processing. Figure 28 shows this relationship in more detail.
The uncertainty of the volumetric flowrate was assumed to be 10% of the reading based on equipment precision and confidence of measurements taken.

Pressure drops were measured throughout the collector. The pressures were so insignificant, around 1Pa, the sensor was not able to read a difference. The precision on the OMEGA Px-278 sensor should have allowed for these measurements to be taken, however, no meaningful readings were obtained. The pressures did not seem to change significantly from top to bottom of the collector, with plenum depth, or flowrate.

5.3 Experimental Procedure

Multiple test runs were performed to check that all sensors were working properly. Once the equipment was working, two full experiments were performed. Each batch took 2 days to complete, for a total of approximately 12hrs in the sun and some drying indoors overnight per batch.

Each empty tray was weighed and recorded. To measure the trays, a large cooking sheet was placed on the scale for better balance and weight distribution. The trays were then placed on the sheet. Once the tray weights were recorded, bananas were measured with the peel and without the peel. This was used as a sanity check to make sure we were getting expected weights once the bananas were sliced and placed on the tray. The weight of the peel allowed us to gather an average banana weight to confirm preliminary calculations that estimated the number of bananas that could be dried.

<table>
<thead>
<tr>
<th>volumetric flow rate</th>
<th>chimney velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>m³/s</td>
<td>m/s</td>
</tr>
<tr>
<td>0.0208</td>
<td>1.44</td>
</tr>
<tr>
<td>0.0175</td>
<td>1.23</td>
</tr>
<tr>
<td>0.0155</td>
<td>1.1</td>
</tr>
<tr>
<td>0.0132</td>
<td>0.96</td>
</tr>
<tr>
<td>0.0083</td>
<td>0.63</td>
</tr>
<tr>
<td>0.0106</td>
<td>0.79</td>
</tr>
<tr>
<td>0.0067</td>
<td>0.54</td>
</tr>
<tr>
<td>0.00515</td>
<td>0.43</td>
</tr>
<tr>
<td>0.0023</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Figure 28: Flow rate calibration table
The specimen were prepared indoor before the system was moved outside. This was due to available space and equipment to prepare the specimen as well as the placement of the sun. Since the system needed to be connected to power, the testing spot shaded from a nearby building until around 10am in mid-September.

The bananas were sliced using a kitchen knife and cutting board to about equal thickness, approximately 0.2in (0.005m). The thicknesses of multiple specimen were measured with a small scale to find the average thickness as well as the range. The slices were then placed on the drying trays equal distance apart. The goal was to fill the trays to approximately 70% capacity and still allow airflow around the slices. Once the trays were filled they were weighed using the same steps as above and replaced in the drying chamber. The weight of the bananas were found by subtracting the weight of the trays. The time of the recording of this weight is used as time “0” seconds for the experimental data.

Once all the trays were filled the equipment was moved outside. This needed to be done with two people or multiple trips with one person. The entire set-up took approximately 20-30minutes to set up. First the computer was hooked up to a power source and started. While the computer started-up, the collector was placed into the drying chamber and oriented towards the sun. Material was placed in the outlet of the collector to prevent airflow into the system before the DAQ system was ready.

Next the chimney base was screwed into the top of the dryer and the flow meter was secured into place at the top of the chimney duct. Once everything was secure, the chimney was placed into the holder on top of the dryer.

Once LabVIEW was opened and all equipment attached to power and the computer, the material was removed from the collector outlet and the connection was sealed to the drying chamber. Finally, the data acquisition was started. The data was logged every 30 seconds.

The flow meter did not have data acquisition capability so data needed to be manually input into the LabVIEW recording code approximately every 5 minutes. The flow meter did have a running average capability and was set to an averaging time of 30 seconds.
During the first day, the trays were weighed every 30 minutes. This was majorly affected by any wind. To minimize wind uncertainty, the scale was placed behind the system and readings were taken when the air was stagnant whenever possible.

Periodically, typically every 1.5-2 hours, the system was turned to face the sun to maximize solar input, which was critical since solar resource in Rochester, NY was low during mid-September. This allowed for maximum temperatures to be reached throughout the day and better mimic conditions that would be seen in places closer to the equator, such as Haiti, where the system will be used.

Once the solar flux began to rapidly diminish at the end of the day, the collector was disconnected from the system, data acquisition stopped, and bananas weighed on last time. The bananas were left on the trays and the system was dismantled and taken indoors.

On the second day, the bananas were weighed before taking the system outside and directly after setup (same as the day before). However, on the second day, the trays were weighed every hour since less moisture was leaving the bananas. The experiment was stopped near the end of the second day when the moisture was not changing and within the precision of the scale used for weight measurements.

This process was followed for each of the two full experiments completed.

Once an experiment was complete, the specimen were placed in a convection oven at 60ºC until completely dry, approximately 12 hours. This allowed us to find the solid weight of the bananas and therefore find the moisture content on a dry basis for the bananas for each tray.

5.4 Data Processing

The data for the temperatures, relative humidity, and solar flux was measured every 30 seconds in LabVIEW. To make the data more manageable and reduce noise, MATLAB was used to average the data over 5 minute periods. Noise in the data most likely occurred due to wind gusts, shadows crossing the collector (people standing in front), and losses when measuring the mass of the trays. The collector outlet temperature was calculated as the average of the readings from thermocouples 2, 3 and 4.
The mass of the trays was recorded and processed in Excel. The weight of the tray was subtracted from the total weight to find the mass of the bananas. This mass and the final dry mass of the bananas were used to calculate the moisture content of the fruit over time using equation 2. Equation 1 and 2 were combined to convert the dry basis moisture content to a wet moisture basis content. Equations (65) and (66) were used to find the uncertainty of the moisture content measurements on a dry and wet basis, respectively:

\[ \Delta M_{C_{db}} = \sqrt{\left(\frac{1}{m_d}\right)^2 \Delta m_{tb}^2 + \left(\frac{1}{m_d}\right)^2 \Delta m_t^2 + \left(\frac{m_{tb} - m_t}{m_d^2}\right)^2 \Delta m_d} \]  \hspace{1cm} (65) 

\[ \Delta M_{C_{wb}} = \sqrt{\left(\frac{1}{m_{wb}}\right)^2 \Delta m_d^2 + \left(\frac{m_d}{m_{wb}^2}\right)^2 \Delta m_{wb}^2} \]  \hspace{1cm} (66) 

where \( m_d \) is the mass of the dry bananas, \( m_{tb} \) is the mass of the tray and bananas, \( m_t \) is the mass of the tray, and \( m_{wb} \) is equal to the difference between \( m_{tb} \) and \( m_t \).

The efficiency of the collector was calculated using Eq. (67). Note that for the temperature of the collector, the average outlet temperature was used.

\[ \eta = \frac{\dot{V} \rho C_p (T_{out} - T_{amb})}{I_c A_c} \]  \hspace{1cm} (67) 

Equation (68) shows the uncertainty for the collector efficiency:

\[ \frac{\Delta \eta}{\eta} = \sqrt{\left(\frac{\Delta \dot{V}}{\dot{V}}\right)^2 + \left(\frac{\Delta I_c}{I_c}\right)^2 + \frac{\Delta T_{out}^2 + T_{amb}^2}{(T_{out} - T_{amb})^2}} \]  \hspace{1cm} (68) 

where \( \dot{V} \) is the volumetric flowrate, \( I_c \) is the solar flux, \( T_{out} \) is the collector outlet temperature, and \( T_{amb} \) is the ambient temperature.
Chapter 6: Results and Comparisons

Two sets of experimental data were successfully obtained. Each set contained a full dryer of bananas that were dried over a two day period, one on September 18th and 22nd and the other on September 23rd and 24th. These days were relatively sunny with occasional small breezes. A longer period of cloud coverage and larger breezes occurred on September 22nd during testing. Error was introduced to the data because of breezes when measuring the mass of the trays. To minimize this error during the second experimental test, a heavy cooking tray was used as the base on the scale to make the trays sturdier during weighing. The first set of data is less informative because of how much drying occurred in the bananas while indoors between the 18th and 22nd.

The bananas were prepared as stated in Chapter 5 using the experimental procedure: sliced into 0.2in thick slices and placed onto trays while indoors. The initial mass and moisture contents for each tray can be found in Table 3.

Table 3: Initial Banana Mass and Moisture Content by tray

<table>
<thead>
<tr>
<th>Tray #</th>
<th>Initial Mass [kg]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/18-22</td>
<td>Initial MC_wb</td>
<td>73.2%</td>
<td>71.4%</td>
<td>71.7%</td>
<td>73.3%</td>
<td>73.0%</td>
<td>70.6%</td>
<td>72.4%</td>
<td>73.5%</td>
</tr>
<tr>
<td>9/23-24</td>
<td>Initial Mass [kg]</td>
<td>0.435</td>
<td>0.387</td>
<td>0.385</td>
<td>0.386</td>
<td>0.43</td>
<td>0.444</td>
<td>0.444</td>
<td>0.441</td>
</tr>
<tr>
<td>9/18-22</td>
<td>Initial MC_wb</td>
<td>72.9%</td>
<td>71.8%</td>
<td>71.9%</td>
<td>73.6%</td>
<td>72.8%</td>
<td>72.5%</td>
<td>73.0%</td>
<td>72.3%</td>
</tr>
</tbody>
</table>

Once experimental data was collected and processed and the modeling was complete, the results were compared to validate the model and highlight potential improvements in the system. Iterations were made on parameters to better fit the model to the data. Below are the final results for the experimental and model data.

6.1 Experimental Conditions and Dryer Performance

The first set of data collected had large uncertainties in the moisture content values due to the timing and less favorable weather conditions and therefore, was not fully analyzed. Figure 29 and Figure 30 show the temperature data collected during testing for both experiments. Figure 25 from Chapter 5 shows a schematic of the position of each temperature reading. The three collector temperatures were averaged to find the collector outlet temperature that was used in calculating the collector efficiency. The thermocouple after tray was directly after the tray while...
the inlet to the chimney was directly before the entrance to the round chimney duct. Note that the data is a set of discrete data points; connecting lines are used for clarity.

Note that T3 was the thermocouple closest to the absorber plate, thus it makes sense it is the highest temperature of the collector outlet temperature probes. For data comparison purposes T2-T4 were averaged to get a single collector outlet temperature.

In Figure 29 around 525 minutes into the drying time all temperatures experienced a “dip”. This is due to a decrease in solar irradiation at this time, as shown in Figure 31. Figure 31 shows the solar flux over time for each set of drying data. The collector outlet temperature was typically 20°C above ambient for the first set of data. Temperatures decreased as the air passed through the drying chamber. The chimney outlet temperature exceeded the chimney inlet temperature indicating some net solar gains or possible radiant gains from direct exposure at the top of the chimney. Drying chamber temperatures are higher on the second day relative to the ambient temperature. This is expected since less energy is going into evaporation as the banana slices are in a period of lower drying rates. The collector temperatures are generally lower on the second day which is likely due to the lower ambient temperature.
Figure 29: Measured temperatures for 9/18 and 9/22 drying test.

For Figure 30, the first few data points for T8 are outliers since the thermocouple was unplugged at the start of testing and reads a value of -9999 when this occurs. The same trends are seen in the second set of data as the first. The collector outlet regularly exceeded 20°C above ambient temperature.

Figure 31 shows the solar flux for both sets of data. The color of the dashed lines corresponds with the data to show the break between testing days. Day one of the second set of data is a good example of solar flux throughout the day, showing the lower intensity at the beginning and end of the day. The small jumps in the data, particularly at times 150 and 275 in the second set of data, indicate times of day when the dryer set up was turned to face the sun.
Figure 30: Measured temperatures for 9/23 and 9/24 drying test.

Although relative humidity was the actual measurement, humidity ratio is shows because there is no temperature dependence and gives a clearer picture of what is happening in the system. As shown in Figure 32, most of the drying happened during the first day and not much drying occurred on the second test day for the experiment conducted on 9/18 and 9/22. This is due to the long period the bananas spent indoors between testing days. Figure 33 shows the ambient humidity ratio and drying chamber exit humidity ratio over time for the data taken on 9/23 and 9/24. This data set shows a more gradual decrease of moisture in the drying air over time.
Figure 31: Solar Flux vs Time for both sets of testing data.

Figure 32: Humidity Ratios converted from measured relative humidity for data set 9/18 and 9/22
Figure 33: Humidity Ratios converted from measured relative humidity for data set 9/23 and 9/24

Figure 34 shows the wet basis moisture content of the banana slices over the drying period. The data is broken up by tray. Tray 1 was at the bottom of the drying chamber and therefore, expected to dry the fastest.

Bananas were dried over the two day period with an average initial moisture content of 73% and dried to an average of 8%. The bananas on the top tray did not dry as quickly as the bananas at the first tray. 4kg of banana slices per square meter of collector absorber area were dried with an average volumetric flowrate of between 0.015 - 0.020m$^3$/s. Figure 35 shows the volumetric flow rate over the testing period. The flowrate seems to correspond somewhat with solar flux (see Figure 31). There is an initial startup period at the beginning of the day and the flowrate tapers off with solar flux at the end of each day.
Figure 34: Moisture Content on a wet basis over time for testing period 9/23-9/24.

Figure 35: Volumetric Flow Rate of the drying system over time for the experiment conducted 9/23-9/24
Figure 36 shows the collector efficiency over time. The efficiency mainly stays between 40%-70%, however there are a few outliers. Most of these are due to the fact there is thermal storage in the system, but a steady state model was assumed. When a cloud or other object blocks the sun for a short period of time, the solar flux decreases very rapidly. However, the temperature in the system does not decrease as fast because of the thermal mass of the system. This results in high temperatures being reported for low solar fluxes. This especially explains the last point which goes above 100% efficiency. This also explains the low efficiencies during the couple of points during the warm-up period of each day.

Figure 36: Collector Efficiency vs Time for 9/23 and 9/24

Overall, the collector efficiency regularly exceeded 50% with an average temperature rise over 20°C. The dryer was actively adding moisture throughout the drying process, seen through the rise in humidity ratio of the air. Because the first set of data did not have ideal environmental conditions and time between days of the experimental was significantly longer than an overnight period, the second set of data was the main focus for analysis and simulation. First day data can be found in Appendix A.
6.2 Simulation Comparison

In the following plots, all experimental data is from the experiment held on 9/23-9/24. The discrete data points represent experimental values while a continuous function shows the simulated data. Note that the simulation is technically discrete data at five minute intervals. The line is used for visual clarity.

Figure 37 shows a comparison of the experimental and simulated temperature data at the collector outlet.

![Figure 37: Collector Outlet Temperature Comparison.](image)

The collector model underestimates the collector outlet temperature according to our experimental data.

Figure 38 and Figure 39 show temperature points within the drying chamber. The simulated data is broken into two lines representing two different days during the testing period. The data was broken into two days in order to reset the initial moisture content values of bananas at the beginning of the second day of testing within the simulation. Figure 38 shows the temperatures after Tray 3 in the drying chamber. The theoretical appears to capture the temperature reasonably.
well at this point in the chamber. However, in Figure 39, the model overestimates the temperature after the eighth tray for the most part. In order to correct for the overestimated temperatures, a heat loss of 10W can be assumed in each zone of the drying chamber. The assumptions that the front and back walls of the dryer are adiabatic and not accounting for losses when weighing the trays during data collection could easily account for the 10W of lost heat. Figures Figure 40 and Figure 41 show the temperatures after Tray 3 and Tray 8, respectively, when 10W of heat loss is assumed. Note that the model better matches the temperature after the last tray in the drying chamber.

Figure 42 shows that the modeled humidity ratio at the outlet of the drying chamber has good agreement with the experimental data. The model does indicate a slightly higher dryer exit moisture content, indicating a slight over prediction in total moisture removal rate.

Figure 38: Drying Chamber Temperature, located after Tray 3.
Figure 39: Drying Chamber Temperature, located after Tray 8.

Figure 40: Drying Chamber Temperature after Tray 3 with 10W of heat loss per zone.
Figure 41: Drying Chamber Temperature after Tray 8 with 10W of heat loss per zone.

Figure 42: Humidity Ratio of Drying Chamber Outlet Air. Ambient humidity ratio is presented as a reference point.
Figures Figure 43 through Figure 50 show the drying curves by tray for the bananas, or the wet basis moisture content over time. The model fits the data better for trays closer to the bottom of the drying chamber, and over predicts drying more the further up the chamber the air travels. This reflects the same trend seen with the temperatures being simulated.

For the most part, the second day of drying is well predicted by the model within experimental error. The deviation in the first day is likely due to over estimation of temperature as well as inaccuracies in calculating parameters such as the diffusivity and mass transfer coefficient. The current model for the diffusivity relies on a curve fit using data for Tray 1 from the experiment. It is likely that this model is not independent of the setup.

The mass transfer coefficient was predicted by using the limiting case. Equation (69) was used to estimate the appropriate value for $k$ used in the governing equations of the fruit drying model:

$$k = h_{m_{eff}} \cdot 1.6 \cdot \rho_{Air}$$  \hspace{1cm} (69)

An increase of 60% of the limiting case for $h_{m_{eff}}$ was chosen by fitting the model to the data from Tray 1 of the experiment. Finding a model for this coefficient will be critical in future research. Chapter 7 discusses in more detail how to strengthen the model to better predict the drying curves and to feel more confident in the predicting abilities of the model under different conditions.
Figure 43: Drying Curve for bananas on Tray 1.

Figure 44: Drying Curve for bananas on Tray 2.
Figure 45: Drying Curve for bananas on Tray 3.

Figure 46: Drying Curve for bananas on Tray 4.
Figure 47: Drying Curve for bananas on Tray 5.

Figure 48: Drying Curve for bananas on Tray 6.
Figure 49: Drying Curve for bananas on Tray 7.

Figure 50: Drying Curve for bananas on Tray 8.
The chimney model predicts the volumetric flow rate of the system reasonably well. It slightly overestimates the flow rate which could be contributing to the overestimation in drying. Figure 52 shows the collector efficiency results.

Figure 51: Volumetric Flow Rate through Drying System.

Figure 52: Collector Efficiency.
The collector efficiency model predicts the efficiency well in regard to the average efficiency seen in the experimental data. It is expected that the efficiency would vary more with temperature and flowrate. When the experimental flowrate is used, the simulation shows more variance over time. Strengthening the flowrate model could greatly impact the entire system since every subsystem depends on the volumetric flow rate.
Chapter 7: Conclusion

7.1 Overview

A prototype indirect passive solar dryer was designed, built and tested. The prototype consisted of three subsystems: a transpired solar collector, a drying chamber, and a chimney. Preliminary modeling helped determine the height of the chimney and number of trays the system could handle. The transpired solar collector used cheap landscaping fabric for the absorber plate and still provided sufficient heat gain to the system. Experiments were conducted during September 2015 in Rochester, NY. Temperatures and relative humidity were monitored throughout the system to show dryer performance. After analysis, it was determined that the collector had an average efficiency above 50% and the system dried 4kg of banana per square meter of solar collector area with an average volumetric flow rate around 0.015 m$^3$/s. Bananas were dried from an average moisture content of 73% to 8% on a wet basis.

A mathematical model was developed to predict the drying rates of fruit. The model was broken into sub-functions so each subsection of the dryer could be modeled independently. A model typically used for commercial transpired solar collectors and that is based on the effectiveness of the absorber plate was used. Equations for a non-dilute mass transfer system were derived to model the amount of moisture leaving the fruit and added to the drying air. The drying chamber model was discretized into zones, each zone representing a tray of fruit in the drying chamber. As the air traveled through the drying chamber, more moisture was added to the air. The chimney was modeled by setting the buoyancy forces of the system equal to the pressure losses of the system to solve for the volumetric flowrate. Each subsystem depends on the flowrate making the chimney a critical component of the model.

Overall, the model was able to predict the general trends observed experimentally. The model tended to overestimate the flowrate and temperatures, causing a faster drying rate than actually occurred at the beginning of the drying period, specifically on the first day. The second day tended to under predict drying in first few trays while the later trays were still over predicted but with a smaller margin of error. This meant the model was able to predict the average moisture content of the bananas dried from 73% to 9% over the course of the two day test. By experimenting with varying parameters, the model was able to follow experimental curve trends
better with 90% flowrate, 12W of heat loss per zone in the drying chamber, and a lower mass transfer coefficient. This helped highlight areas of improvement in the model and experiment.

The model created will serve as a starting point for the Sustainable Energy Lab at RIT to further explore crop drying and provides a tool for researchers to use to predict the drying rates of various tropical fruits using their under varying environmental for their drying system. The model can be used to optimize a dryer for a specific set of environmental conditions and requirements. For example, the KGPB farmers in Haiti may need a drier that can dry 2 baskets of breadfruit in a 12 hour period. The model could utilize weather data available online to simulate a dryer in Haiti where temperature and relative humidity will typically be higher than the Rochester testing conditions and vary the system design parameters to find out how much collector area is needed per kilogram of breadfruit. Opportunities for further experimentation and improving the modeling to create a more robust and affective predicting and optimization tool are discussed in the following section. The ultimate goal is to create a model that can be confidently used with any tropical fruit and multiple dryer configurations by simply changing parameters such as fruit material properties and area/size or placement of a subsystem.

7.2 Further Research Opportunities

Future research opportunities are present in all aspects of the experiment and model. These opportunities can be broken down into model development and improvements and experimental improvements.

To better understand where improvements can be made, the model was adjusted to account for some of discrepancies in the simulated versus experimental data. As stated above, the temperature model was adjusted by accounting for 10W of heat loss. After further exploration into the experimental data and analyzing the difference of enthalpy entering and leaving the drying chamber, it was determined approximately 12W of heat loss occurred on average per zone. Next, the mass transfer coefficient was set to the limiting case, as discussed in Chapter 4.1.2, instead of adjusting it to fit the experimental data. Finally, the flowrate was adjusted to 90% of the current calculated value to better match the experimental data. The model assumed for the friction factor from Chapter 4.3 are experimental correlations that could be off by ±20%.
Increasing the overall pressure loss of the system by 20% decreases the flowrate to 90% of the original modeled value.

Accounting for some heat losses and overestimation of friction coefficients for the system appear to account for the discrepancies between the model and experimental data as shown in the following figures. Figure 53 shows the updated temperature after tray 8, Figure 54 and Figure 55 show the updated drying curves for tray one and tray five, while Figure 56 shows the updated flowrate. The adjustments are explored further in the following sections.

Figure 53: Temperature after Tray 8 with 12W of heat loss
Figure 54: Tray 1 Moisture Content (wet basis) after adjustments to model

Figure 55: Tray 5 Moisture Content (wet basis) after adjustments to model
7.2.1 Modeling Opportunities

For transpired solar collector model, the main modeling improvements are in independently measuring the material properties of the absorber plate for use in the simulation. The absorptivity and emissivity were found by fitting a model to experimental data. It was also assumed that the absorptivity and emissivity are equal, which is a reasonable assumption for non-selective surfaces. However, there are experiments and equipment available that could measure these parameters to get a more accurate absorber plate properties. Another way to improve the collector model would be to validate it independently through experimentation. Running a series of tests for the collector under varying flowrates, wind speeds, and solar insulations, as well as varying pitch and hole diameter dimension, would allow the empirical model used (fit for commercially available transpired collectors) to be better fit to a small scale transpired solar collector because the size of the collector could cause issues with current assumptions, especially with varying wind conditions.

The chimney model, which determines the flowrate, is dependent on the solar collector thermal performance and drying chamber drying performance. However, the subsystem performance of
these models are all dependent on the flowrate, creating an implicit system model. Because of this circular dependency, an initial volumetric flowrate needed to be assumed. The model uses the first experimental data point to do this, however, ideally the model should be solved without experimental data. Solving for the flowrate implicitly could greatly improve the model. Also, determining the sensitivity of the model to the friction coefficients for each component could help identify where more independent testing needs to be conducted to more accurately predict the pressure drops across components. The main pressure drop happens across the solar collector absorber plate. The current model assumes the absorber plate is a smooth surface, however, the landscape fabric has a texture due to the woven fibers, so the actual pressure drop may be higher than what is currently calculated using the smooth surface model. Other improvements to the model to improve flowrate include adding all minor losses, as some were assumed negligible for this model, and accounting for any heat gain through the chimney. Making these adjustments could account for the approximate 10% discrepancy between the experiment and model for the flowrate.

For the drying chamber part of the model, most of the improvements can be made within the sub-function for fruit drying. Currently, the diffusivity for the banana is determined by fitting tray one model data to the experimental data. Ideally, the diffusivity of bananas should be measured independently. However, it’s important to note that the coefficient can vary depending on banana ripeness and other factors that are not easily isolated. The mass transfer coefficient for bananas should also be measured independently. Analogies to the heat transfer coefficient and the drag coefficient may not be valid for the current flow configuration: perpendicular flow to the face of the banana slice. Further research into this area is needed to create a model to accurately predict this parameter. The third parameter to be measured is the $\omega_{A1.5}$ coefficient which was modeled using the GAB equation to relate the moisture content at the surface of the banana to the moisture content directly next to the surface of the banana as a function of temperature.

One assumption that can be evaluated in further research is the assumption that the fruit being dried is in thermal equilibrium with the inlet air in each zone of the drying chamber. Accounting for transient temperature variation in the fruit may improve the accuracy of the drying curves.
Although the model predicts the drying curves for the experiments reasonably well now, improvements in implementation and the parameters of the model could increase confidence in being able to predict curves under different conditions.

### 7.2.2 Experimental Opportunities

Since experiments were conducted during the fall in Rochester, the number of viable testing days were limited. Expanding on the experiments conducted and compiling more data for the drying system will be helpful in understanding the performance of the dryer.

Experimenting on the dryer chamber independently may help determine whether there is heat loss in each zone that is not account for currently. As shown above, there appears to be approximately 12W of heat loss in each zone that explain the discrepancies between the model and experimental data. Improving the seal of the trays on the back of the chamber could account for the discrepancies in temperature between the simulation and experiment. This would mean there is a lower flowrate than predicted across the solar collector resulting in increased temperatures there and cooler air being pulled into the system as it moves through the trays, explaining the over prediction occurring at tray eight.

Additional measurements that could help improve the uncertainty of the experiment are the wind speed and wind direction. The wind can have a huge impact on the collector efficiency and flowrate of the system. Also, using a radiation shield for the thermocouples may improve the accuracy of measuring the air temperature. This would be especially helpful for the chimney inlet and outlet because the end of the probe is much closer to the dryer walls than the thermocouples in the drying chamber. More temperature probes at the inlet to the collector would allow the temperature profile to be better understood. This will allow for a more accurate temperature calculation, as it could be different than the average of the three temperatures explained in Chapter 5.

Some variables that can be studied are specimen size and thickness, how tightly packed the specimen are on the drying trays, and how many trays have specimen on them. Also, the dryer could be tested under different types of environmental conditions. The dryer was only tested on
warm, sunny days. It would be interesting to study how the dryer performs on extremely humid
days, cloudy days, cool days, etc. The more conditions it is tested in, the more data there is to
validate that the mathematical model works under various conditions.

Areas that could be changed in the system include the collector and the chimney. The collector
angle can be modified as well as the absorber area. This would impact the inlet temperature to
the dryer and the flowrate of the system. The chimney height can also be varied to study the
effect it has on flowrate.

Overall, the experimental setup allows for more data to be recorded to help validate the
robustness and accuracy of an improved model.
Appendix A

Remaining Experimental Data for Testing Period 9/18 and 9/22
References


[18] A. O. Dissa, H. Desmorieux, J. Bathiebo, and J. Kouliadi, “Convective drying characteristics of


