Mitigating Post-Harvest Losses in Bhutan through Solar Food Drying: Optimization and Analysis

Thesis for the degree of Master of Science in Environmental Engineering
Division of Energy and Building Design
Department of Building & Environmental Technology

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Abstract

Bhutan is the world’s most mountainous country which comes with some logistical difficulties. Due to slow transportation times and lackluster food preservation are the post-harvest losses high which especially affects the rural parts of Bhutan negatively. Solar Food: Reducing post-harvest losses through improved solar drying, is a project set out to design a low-cost solar powered food dryer to improve the quality of food preservation in the Himalayan region and is funded through Swedish Research Council.

This project analyzes the temperature changes seen in each component of the solar dryer, such as the heat exchanger, absorber, heat storage and the drying chamber at different air flows. The collected data is utilized to calculate the different efficiencies and heat fluxes. Furthermore, the drying rate was measured for each experiment to determine which flow performs optimally for drying. Thus, getting a good transparency of the system which in turn will assist in identifying potential areas for improvement.

The heat exchanger shows a decrease in performance with increasing flow, however, the heat flux between its sides remains fairly constant regardless of flow. In contrast to this shows the absorber an increase in performance with higher flows, and it plateaus after 10 l/s. The remaining energy in the heat storage at the end of each experiment peaked when the flow was 6 l/s, and 10 l/s short thereafter. The drying chamber had the highest temperatures in experiments with 10 l/s. The drying rate increased with increasing flow and showed no end to this trend.

The results indicate that a larger absorber would likely be the most beneficial modification in a future design. Additionally, a larger more powerful fan would likely result in better drying rates, however this would increase the overall cost and power consumption and the availability of such equipment might be low.

Table of Contents

1 Introduction

1.1 Project Background and Goals

This report is part of an ongoing project, Solar Food: Reducing post-harvest losses through improved solar drying, which aims to improve the quality and decrease post-harvest losses of food in rural Bhutan and Nepal through low-cost efficient solar powered food dryers. The project was made possible through the cooperation between Lund University and the Royal University of Bhutan and was funded through Swedish Research Council.

In this project, a solar dryer was evaluated by drying ginger and logging the temperature changes before and after each dryer component, and the solar irradiance at intervals of 30s. The data was then used to analyze the performance of each component under different air flows with the goal of getting a deeper understanding of the dryer and its limitations. The experiments were run with the following questions in mind:

- Is there an optimal air flow and why is it optimal?
- How does air flow affect each component?
- How can the dryer be improved?

1.2 Project Introduction

Food is a fundamental necessity that is taken for granted in many parts of the world. It is readily available and affordable for most; however, this would perhaps not be possible without the availability of various preservation methods. The food we grow is like us living organisms, and once harvested, it is severed from its source of water and nutrients and thus the deterioration process begins. Since most types of food can only be harvested during certain seasons, preservation is required for a steady supply of food all year round. Most preservation methods aim to slow down or completely stop the growth of microbials and slow down chemical and physical deterioration that occur naturally within the food (Singh 2022). A longer lifespan of food allows for longer transport, which is beneficial in e.g. mountainous areas where small roads meander between the mountains making it much less accessible for large-scale transport. Some common methods of food preservation are lowering the temperature of the food either through refrigeration or freezing, but other methods such as chemical preservatives, packaging, fermentation are also commonplace. Another widely used method is through dehydration, which means a large portion of the water is removed from the food creating a less favorable environment for microbials to grow thus prolonging the lifespan of the food (Singh 2022). Open air food drying is regularly used in Bhutan due to its low cost and accessibility to farmers, however, depending on the drying process, the quality of the finished product will vary due to nutrient degradation that can occur from direct sun light (Ndawula 2004). Bhutan is currently facing nutrient deficiencies in parts of its population (WFP 2020). Therefore, by improving the methods used for food preservation to maintain nutrient content, increase efficiency, and reduce spoilage with high reliability. This will hopefully help in improving the situation while increasing the profitability for farmers, as less food goes to waste.

2 Background

2.1 Bhutan

Bhutan is the most mountainous country in the world by two metrics, by coverage and by average height above sea level. In terms of area is Bhutan covered up to 98.8 % by mountains, which is likely the reason its average height above sea level is as high as 3280 m (World Population Review 2022). The country is on the southern slopes of the Himalayas which means the north part of the country is at a higher altitude than the south, resulting in different climate regions within the country. A humid tropical climate is found in the south, a more temperate climate is found in the central parts, and a cold and polar type climate is found in the highest northern regions of Bhutan. (Climate Research Unit of University of East Anglia 2020)

2.1.1 Economics

Before the pandemic, Bhutan experienced a fast economic growth and more than doubled its GDP per capita in 13 years. In 2019 its GDP was per capita 3 323 USD compared to 1 331 USD in 2006 (The World Bank 2022) which drastically reduced poverty from about 8 % down to 1.5 % (The World Bank 2022). However, despite these improvements, rural poverty, food insecurity, and malnutrition are still prevalent issues in Bhutan prompting the World Bank to provide aid to help improve the situation (Ishihara 2021). As a result, cost effectiveness is one of the top priorities for this solar dryer design. Because if it is too expensive to build, then it will not be accessible to the people who could benefit from it the most.

2.1.2 Agriculture

Bhutan is in general a quite agrarian country where about 57 % its people depend on farming (Chhogyel 2018). The mountainous and difficult topography does not only act as a physical hinderance for farming, but it also creates a more sensitive climate. Thus, the rapid change in climate we see today and in the foreseeable future is expected to have a large impact on the agriculture of Bhutan (Chhogyel 2018). The emerging problems this may cause increase the need for a better food preservation system since a reduction in post-harvest losses would increase the yield which could help buffer the eminent losses of a harsher climate.

2.2 The Food Dryer

The dryer that was used in this project consists of a heat exchanger, an absorber, heat storage, a drying chamber with six shelves, an internal fan, and an external fan.

The dryer can be seen in Figure 1 where the numbers appear in the order of occurrence, 1 is the inlet and 9 is the outlet. Additionally, the direction of the air flow is also visualized in the figure with arrows. The colors of the arrows indicate air temperature, where blue is colder and red is warmer.

Firstly, ambient air enters a circular inlet, passes over a flat piece of aluminum sheet that serves as a heat exchanger before moving across the absorber, which further heats it. After this the heated air passes through the heat storage into the drying chamber where it is mixed with cooler more humid recirculated air from the internal fan. Finally, the air passes along the other side of the heat exchanger before it is let out into the ambience through the outlet.

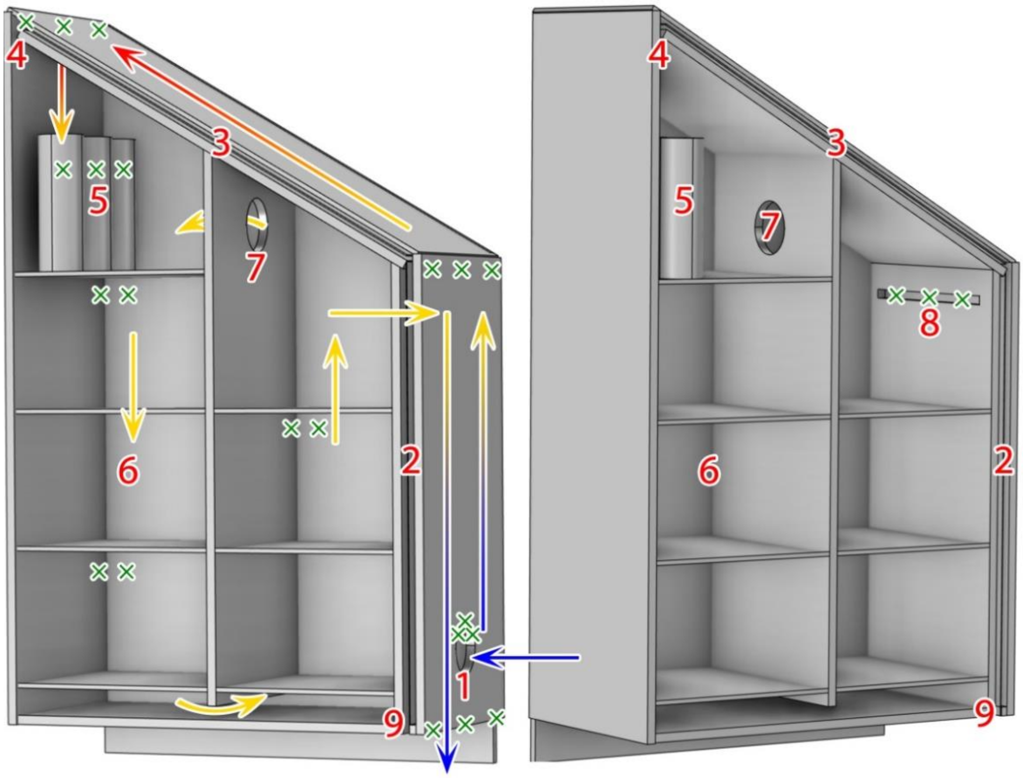

Figure 1: A 3D model of the food dryer as viewed from two angles. The numbered parts depicted in the figure appear in sequential order based on the air flow through the dryer and encompass the following components: 1. Dryer inlet; 2. Heat exchanger; 3. Absorber; 4. Absorber outlet; 5. Heat storage; 6. Drying chamber; 7. Internal fan; 8. Drying chamber outlet; 9. Dryer outlet. Each of the green crosses indicate the location of one thermocouple, all displayed in the left image except for the three by the drying chamber outlet which are displayed in the right image. The arrows point in the direction of the air flow while the color indicates its temperature, where blue is the coldest and red is the warmest.

2.2.1 Heat storage

The heat storage is an implementation which evens out the temperature over the day. In theory will it prevent the dryer from becoming too warm during peak sun hours, which in turn protects the food from the degradation caused by overheating. Additionally, the storage warms up the air later in the day when the sun is unable to do so sufficiently, resulting in a more stable and reliable drying process (Karlsson 2022). The storage is simple and consists of a few plastic water bottles placed by the inlet of the drying chamber. The size of the storage is modular and can be changed depending on what type of food is dried. Three bottles of one liter each were used in this project. However, the dryer's structure also provides some natural heat storage and retention capabilities, meaning the bottles are only supplementary.

2.2.2 Internal fan

In Figure 1 noted by the number 6, can a small hole be seen in the middle wall. This is where the internal fan is and will serve two purposes. Firstly, it will homogenize the air in the chamber, providing even drying regardless of food placement in the chamber. Without recirculation would there be a noticeable gradient in relative air humidity and temperature between the inlet and the outlet in the drying chamber. Meaning that the food closest to the inlet would receive significantly better drying conditions than the food closest to the outlet. Secondly, it increases the convection affecting the food without increasing the flow through the entire dryer. More convection usually means faster drying times, but that goes for higher temperatures as well. Regulating the flow passing over the food by only changing the flow through the entire dryer could lead to a situation where the optimal flow for the dryer might sacrifice temperature for convection, thus, decreasing the potential optimal drying rate while still giving uneven results. The recirculation fan solves this with only a small increase in price and power usage.

2.2.3 Absorber

The absorber used consists of half a square meter of flat sheet metal painted black covered by a glass pane. Air can travel in 1 cm narrow ducts on both sides of the absorber, maximizing the surface area available for heat transfer to the flowing air.

Black paint was used because it increases absorbance, however, it also increased the emittance of the absorber. Although there are surface treatments available that can increase the absorbance of the absorber while minimizing its emittance, these treatments are typically less readily available and more expensive. Thus, it is unlikely that such treatments would be utilized by farmers in Bhutan, which is why they were not used in this project. However, it should be noted that previous research has demonstrated that the use of low-emittance, high-absorbance surface treatments can significantly improve the performance of absorbers (Moore 1985).

2.3 Heat transfer and losses

There are three main methods for heat to be transferred: radiation, conduction, and convection. For a system in a state of energy equilibrium is the added energy equal the lost energy. This implies that if the energy lost through the three previously mentioned methods are added up, the sum will equal the total energy added to the system, which in this case is the sunlight absorbed by the absorber. Therefore if e.g. radiative losses of the absorber are reduced the absorber will reach a new equilibrium where its temperature and the ratio between the different transfer methods are likely different from before. However, since the energy input has not changed the total energy lost will also be the same as before. Each method affects the performance of the dryer differently and mitigation of unwanted heat transfer will result in higher internal temperatures and likely improving the performance as well.

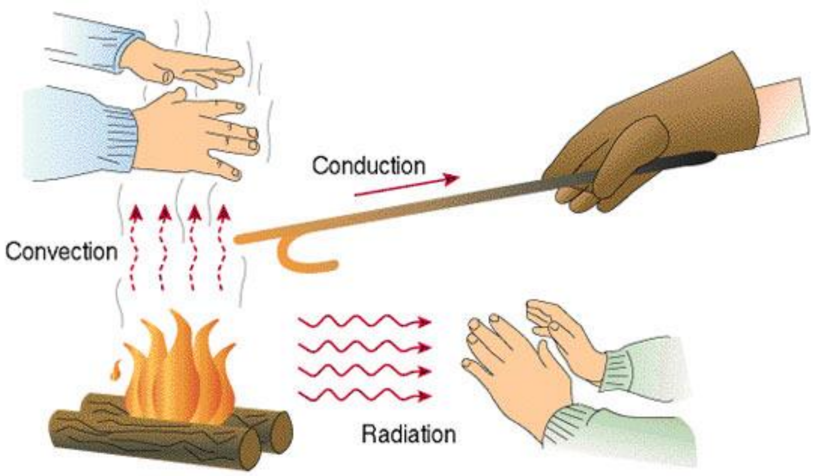

Figure 2: An illustration on the three main methods heat is transferred. (Image by: Kmecfiunit. Image License: https://creativecommons.org/licenses/by-sa/4.0/deed.en.)

2.3.1 Radiative

Radiative heat transfer is the energy that is radiated out from a body of mass with a temperature above 0 K in the form of electromagnetic radiation. The wavelength of the waves radiated from the object depend on the temperature but is in general within the infrared range for normal applications (Engineering ToolBox 2003). The equation for the rate in which energy is radiated from a body is as follows:

$$q = \varepsilon \, \sigma \, T^4 A \qquad \text{Eq. 1}$$

The surface of the object affects the rate of radiation in two ways, firstly by the total external area, seen as A in equation 1, where more area gives the object a greater surface in which to radiate from, thus increasing the output. Secondly, by the emissivity of the surface, seen as ε in equation 1, where some surfaces have a greater ability to radiate than others. A body with a surface with maximum emissivity is considered a black body and has an emissivity of 1. The worse the emitter a surface is the closer to 0 is the emissivity. Stefan-Boltzmann's constant, seen as σ in equation 1, is $5.67 \cdot 10^{-8}$ W/(m^{2}K^4) regardless of surface.

The dryer in Bhutan has a sheet of glass above the absorber, this prevents some of the radiation emitted from the absorber from escaping the system. The glass reflects or re-emits parts of the radiation back, thus reducing the radiative losses of the system. Due to this effect will more layers of glass prevent more thermal radiation from leaving the system. However, it will also reduce the amount of sunlight that reaches the absorber. Which is why more layers of glass could have a negative effect on a system unless the radiative thermal losses are high (Davidsson 2021).

2.3.2 Conductive

Heat can also be conducted, which is heat flux through a solid material. Different materials have different conductivities, meaning some materials will transfer heat faster than others. In the case of the dryer is heat conducted through the wooden walls and insulation separating the ambience from the internal volume. The rate in which heat is conducted through a wall scale linearly to the temperature difference between the two sides. The equation explaining this heat flux is as follows (Engineering ToolBox 2003):

$$q = A \left(\frac{k}{s}\right) \Delta T \qquad \text{Eq. 2}$$

Where k is the material constant for conductivity, s is the thickness of the wall and ΔT is the temperature difference between the two sides of the wall. Thus, will thicker walls with a low conductance reduce thermal losses from conductivity, which is why several layers of insulation was adhered to the exterior of the dryer used in this project.

2.3.3 Convective

The speed at which heat is transferred through convection, much like conductive heat transfer, increases proportionally with temperature. But instead of heat being transferred through a solid, convection is the heat that is transferred via a liquid or gas. This makes it significantly more complicated to predict as fluid masses usually have internal motion which depends on several factors, such as small differences in temperature and pressure. However, it can in many cases be simplified down to the following equation (Engineering ToolBox 2003) :

$$q = h_c A \Delta T \qquad \text{Eq. 3}$$

Where h_c is the convective constant of the system and ΔT is the temperature difference between the surface in contact with the fluid and the average temperature of the fluid.

2.3.4 Heat flux and Density of Air

Heat flux is heat energy transferred per second and can be calculated for air flow by multiplying the mass flow F_m, specific heat of air C_p and the temperature difference over one second ΔT

$$q = F_m C_p \Delta T \qquad \text{Eq. 4}$$

The mass of air that passes through the system every second can be determined by taking the average inflow velocity multiplied the cross-sectional area of the inlet for the volumetric flow, then multiplied by the density of the air which results in the mass flow.

$$F_m = V_{air} A_{cross} \rho_{air} \qquad \text{Eq. 5}$$

Thus, the flux can be derived by combining Eq. 4 and Eq. 5 as:

$$q = V_{air}\, A_{cross}\, \rho_{air}\, C_p\, \Delta T \qquad \text{Eq. 6}$$

The isobaric specific heat of air is about 1.01 kJ/(kg·K) for the relevant temperatures (Engineering ToolBox 2004). The density of air at 1 atm pressure and 25 °C is about 1.17 kg/m^3 (Engineering ToolBox 2003). However, the density and pressure of air changes with altitude and the dryer was situated about 900 m above sea level (JNEC u.d.). The density of air can be calculated by first finding the air pressure at 900 m using the following equation (Engineering Toolbox 2003):

$$p = p_{atm}\,(1 - 2.25577 \cdot 10^{-5}\, h)^{5.25588} \qquad \text{Eq. 7}$$

Where p_{atm} is 1 atm in pascal and h is the altitude in meters. Thus, at our altitude of 900 we get a local pressure of 0.91 Bar. The density can then be calculated using the ideal gas law:

$$pV = RT \qquad \text{Eq.8}$$

By rewriting volume as weight divided by density and solving for density we get

$$\rho = \frac{p \cdot m}{RT} \qquad \text{Eq.9}$$

Dividing both sides with the same equation but for standard density and pressure found at sea level with the same mass and temperature we get:

$$\frac{\rho}{\rho_{atm}} = \frac{p}{p_{atm}} \qquad \text{Eq.10}$$

From this we can solve that the density of air at 900 m altitude is approximately 1.05 kg/m^3 which can be used in the heat flux equation for more correct energy and efficiency calculations.

2.4 Heat exchanger

The heat exchanger used in the dryer works with a counter-flow, which means that the flow on one side goes in the opposite direction compared to the other, allowing for maximum potential heat transfer. In theory could the entire difference in heat energy be transferred from the hot side to the cold side using this method, but in practice are there always some heat losses lowering the efficiency. As a point of reference could a modern counter flow heat exchanger operate at about 90 % efficiency (J. Kragh 2007).

Figure 3: A visualization of a counter flow heat exchanger. The top half feeds in a cold fluid and the bottom half feeds in warm. The gray area in between is a thin metal plate conducting heat between the fluids.

The equation for heat exchanger efficiency, assuming equal mass flow on both sides, is the following (Cengel 2002) :

$$\eta = \frac{T_{out\_c} - T_{in\_c}}{T_{in\_h} - T_{in\_c}} \qquad \text{Eq. 11}$$

The efficiency is the ratio between the difference across one side, in this case the cold side, against the difference between the inlets on both sides. To achieve an efficiency of 100 %, a complete transition in temperature between the sides is necessary. Meaning that the outlet of the cold side is same temperature as the inlet of the hot side.

The heat exchanger can also be used as an indicator for potential leakage issues. In the absence of any leakage, conservation of mass dictates that an equal amount of air will flow on both sides of the heat exchanger. Assuming no change in heat capacity, should the temperature changes seen across both sides of the heat exchanger, due to the conservation of energy, be identical. For instance, if the cold side is heated 5 °C, then the hot side should get cooled 5 °C. However, in the presence of leakage will the mass flow on the hot side reduce while conservation of energy still holds, and as seen in Eq. 6, this will result in a greater temperature change across the hot side. Thus, a continuous comparison between the two sides will provide valuable transparency to the system.

2.5 Drying

2.5.1 Temperature

Appropriate temperature is an important part in drying food and is generally around 60 °C. The faster food can be dried the smaller the risk for spoilage is (Schmutz 1999). If the temperature is too low, the time it takes to dry the food will increase while failing to directly prevent microbial growth (Döhlen, o.a. 2016). However, if the temperature is too high, the food will be cooked. A cooked surface can change structure in ways that create a barrier preventing internal moisture from escaping, thus, slowing down the drying and increasing the risk of spoilage (Schmutz 1999). Additional to this would cooking the food lead to deterioration of nutrients and discoloration of the food which is often used as a quality indicator (Ndawula 2004) (Mystayen, Mekhilef and Saidur 2014).

2.5.2 Physics

There are several factors affecting drying rate other than temperature, some of the more important are the humidity of the air, flow, the amount of available surface area and the water volatility of the food (Dryden 1982).

Air drying is in essence a stream of air warmer than the surface of the food resulting in a constant heat transfer to the food, where both a higher flow and temperature will increase the rate in which energy is transferred. This in turn increases the rate at which water is evaporated. Since it takes a considerable amount of energy to evaporate water, a lot of the energy transferred from the air will be used for this purpose, thus, leading to a decrease in temperature of the air and also a small change in temperature of the food (Narayanan 2017). This can be compared with the cooling effect sweat has on our bodies, where the evaporation of sweat keeps us from overheating. Due to this effect will tests done on an empty dryer show higher temperature readings than ones filled with food since none of the heat energy is used for evaporation. The temperature of an object being cooled by evaporating water is known as the wet bulb temperature. A higher relative humidity of the air leads to slower evaporation, thereby reducing its cooling effect and resulting in a higher wet bulb temperature. Eventually will air get saturated with vapor and little to no evaporation will happen. At this point will the wet bulb temperature be the same as the surrounding air (Engineering ToolBox 2004). What this means for the dryer is that the temperature while drying food will be reduced more if dry air is used due to the food drying faster, and the opposite for humid air (Dryden 1982). However, the amount of vapor that air can hold is significantly increased with higher temperature, thus, heating the air before it enters the drying chamber will make sure it is capable of absorbing moisture.

Evaporation takes place from the food's surface. Thus, drying time is affected by the ratio of the total surface area of the food being dried to the total mass of water being evaporated.. This also means that the rate in which moisture can travel from within the food to the surface will matter (Dryden 1982). This rate varies for different types of food implying that evaporating 1 kg of water from apple slices may not necessarily have the same drying time as evaporating 1 kg of water from mangoes, even if their surface areas are identical.

2.5.3 Drying Rate and Surface Area

One of the key units used in this report is drying rate, which describes how many grams of water evaporates each hour per square meter of surface area.

$$Drying\ Rate = \frac{\Delta m}{t_{drying} \cdot A} \qquad \text{Eq.12}$$

Ginger has a density of 423 kg/m^3 (Shirsat, o.a. 2019) which can be used to calculate the total volume of the used ginger based on its weight. Assuming that the entire volume of ginger is contained within a cylinder with the same height as the width of a single slice. Then, if the thin curved area of the side is neglected, can the total area be approximated by dividing the volume with the height of said cylinder and multiplying by two. The curved surface area of the cylinder will be neglected since the slices are so narrow and would complicate calculations and likely not affect the final result significantly. Also, the radius of the ginger slices varies greatly making such an estimation likely to be inaccurate. Thus, was this method of estimating surface area deemed sufficient and used in this report.

3 Method

3.1 Preparations and Calibrations

Firstly, before departing to Bhutan, some thermocouples were connected to a Campbell Scientific Multiplex 16/32 which in turn was connected to a Campbell Scientific CR1000 Data Logger. The logger was left running for a full night in a room of about 25 °C to validate the reliability of the results for an extended time. Additionally, another test was conducted by submerging the thermocouples in boiling water for a few minutes to verify the readings were also accurate in higher temperatures. A similar test was later conducted with ice-water to test the thermocouples in colder conditions as well. This entire process was repeated later with all thermocouples used in Bhutan before installing them in the dryer.

In Bhutan, the dryer underwent inspection for flaws, such as unnecessary pressure drops, potential leakages and functionality. Once the dryer was up to standard and had all the predetermined functionalities, both the external and internal fan were installed, and the glass cover for the absorber glued and sealed to the dryer.

Twenty-four thermocouples were measured to appropriate lengths, cut, and labeled before attached in the dryer at the locations indicated by the green crosses in Figure 1. Each section was fitted with three thermocouples: one in the middle and two on the sides. The placement of the thermocouples allowed for temperature readings before and after each side of the heat exchanger and the absorber. Furthermore, thermocouples were also positioned inside the heat storage and drying chamber. However, for the chamber, six thermocouples were placed in pairs rather than groups of three: one pair in the beginning, one pair in the middle, and one pair close to the outlet.

To prevent faulty readings from the thermocouples, all of them were prepared accordingly. A length of 4 mm - 5 mm of insulation was removed from the ends, and the wires were separated and connected with a small amount of soldered at the very tip. The attachment of the thermocouples in the dryer was deliberately chosen to ensure that no exposed part of the thermocouple touched any surface or was directly exposed to thermal radiation from the absorber or the sun. Consequently, the most significant and only heat source in direct contact with the end of the sensor was the flowing air in the dryer.

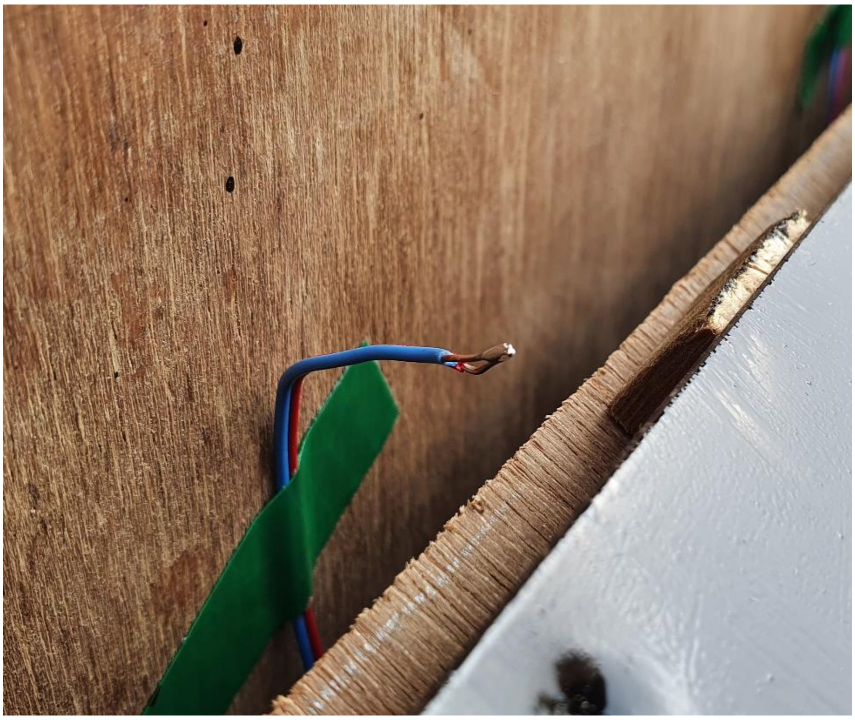

Figure 4: A thermocouple with a soldered tip placed by the outlet of the absorber. It has been placed next to the absorber to avoid excess heat radiation from the absorber.

A reliable connection to ground is necessary for the datalogger to function properly. However, due to issues with the building’s ground, a proprietary solution was devised. A metal pipe was driven into the soil and watered once a week to ensure a good connection. A copper wire was then tightly wound around the part of the pipe above ground and connected to the ground lug in the datalogger.

A 3-meter-long duct with a diameter of 160 mm was connected to the inlet of the dryer, and a shorter duct measuring 1 meter in length with a diameter of 50 mm was attached to the end of the larger duct. These ducts are not intended to be included in the final design but are being used solely for the flow measurements needed for the experiments.

3.2 Flow Measurements

The air flow was measured using a standard method described in the book “Metoder för mätning av luftflöden i ventilationsinstallationer” (Johansson and Svensson 1999). According to this method, the point of measurement should be located at least a distance equal to two times the diameter of the duct away from the fan, and at least five times the diameter away from the air intake. In the setup used for this report, these requirements were exceeded with ample margin. To measure the flow, two holes were drilled in the duct at the appropriate location: one on the top and one on the side. These holes allowed for insertion of a hot wire anemometer from two perpendicular directions, and for each direction, the anemometer was inserted first 46 mm and then 114 mm deep into the duct. In a duct, the air close to the center moves faster than the air close to the wall, creating a gradient of varying air speeds in between. This means that there is a point in this gradient where the air speed is equal to the average speed of the entire duct, and for a duct with a diameter of 160mm, this point can be found at the depths previously mentioned (Johansson and Svensson 1999). The average air speed of these four points, combined with the cross-sectional area of the duct, was used to calculate the volumetric flow.

Since no standard method was found for measuring air velocity in the smaller duct, the flow was first measured using the standard method explained above in the larger duct. Then, the flow was measured once at a depth of approximately 3.5 mm in the smaller duct to test its viability for flow measurements. Due to the conservation of mass and negligible pressure differences is the volumetric flow expected to be about the same. It was confirmed for several flows that multiplying the air velocity measured in both ducts with their corresponding cross-sectional areas gave the same volumetric flow. As a result, the smaller duct was deemed a better measuring point because small changes in volumetric flow led to much greater differences in air velocity than seen in the larger duct. However, the smaller duct was removed for flows above 10 liters per second due to its constriction of the flow.

3.3 Ginger Preparation

The appropriate amount of ginger needed per experiment was determined by preparing an abundance of ginger and filling the dryer as much as reasonably possible for the first few experiments and then deciding on a set amount.

To prepare the ginger for each experiment, approximately 8 kilograms of ginger was peeled in bulk. Before the start of each experiment, 2.5 kilograms of the peeled ginger was weighed and sliced to a consistent width using a mandolin slicer. Ten to twelve slices were randomly selected, the total thickness was measured using measuring tape, and the average thickness per slice was then estimated by calculating the average thickness of the selected slices.

The ginger was evenly distributed inside the dryer by placing piles on each shelf until all piles were roughly equal. Then ginger was spread out on each shelf carefully to avoid any overlapping.

3.4 Drying and Data Collecting

The experiments started at 8:00 in the morning by turning on the internal fan, data logger and the external fan through a voltage regulator. The voltage for the external fan was adjusted to achieve the desired flow, and the flow was tested using the method described earlier. If the flow differed from the desired level, then the voltage was adjusted accordingly. This loop of setting voltage and testing the flow was repeated until the desired flow was achieved. This process was repeated around noon to correct any changes that might have occurred after the initial set up. On exceptionally windy days the process could be repeated up to three times, usually around 10:00, 12:00 and 14:00. Once the time reached 17:00 the fans were turned off and the data from the logger saved to a computer as an excel sheet.

Once all equipment was shut off, the ginger was collected from the dryer and weighed. The weight of the ginger before and after was noted in an excel sheet together with date and flow.

3.5 Constant Drying Rate Verification

Since the weight of the ginger was only measured before and after drying and a constant drying rate calculated based on that, therefore, there was a need to verify that assuming a linear decrease in weight is a good approximation. The linearity of the weight reduction over time was verified twice: once with a flow of 2 l/s and once with a flow of 10 l/s. The experiments were set up in the same manner as the previously described experiments, but with the weight of a specific shelf recorded every hour during the drying process. This shelf was removable and positioned in the middle of the drying chamber relative to the path of the air, away from both the inlet and outlet. The recorded weight was later plotted against time with a linear fit, along with an R2 value, to confirm the linearity of the weight reduction over time.

3.6 Open Air Drying

As a comparison to the dryer, six open-air drying experiments were conducted: three in shade and three in direct sunlight. This experiment was conducted in a similar way to the experiments done with the dryer, with ginger prepared in the same way and same drying time. However, less ginger was used for these experiments with around 500g of prepared ginger per run. The weight was measured before and after the experiment and used for determining the drying rate.

3.7 Excel and calculations

Each experiment was processed with the same script to minimize manual labor and mistakes. The script was coded using Visual Basic for Applications in excel, and organized the data, giving each component its own page and graphs accordingly. It was also designed in a way to make it compatible with other computers with only minor changes, thus, hopefully saving future projects some time in data analysis.

For ratios and efficiencies some filtering was necessary due to unreasonably large values obtained when division close to zero happened, this was done to prevent these large values from distorting the calculated average efficiencies for the day. These large values typically appeared in the morning when the dryer was cold from the night, causing it to cool the air to a temperature sometimes lower than the ambience.

To help future projects, most of the graphs have been fitted with polynomial approximations, accompanied by their respective equations and R2-values. This could prove valuable for simulations or comparisons with similar dryers.

3.7.1 Absorber efficiency

The efficiency of the absorber could be derived through the division of two separate energy transfers: the total solar flux available over the heat absorbed by the air. The heat absorbed by the air was obtained through Eq. 6, while the solar flux by multiplying the measured irradiance with the surface area of the absorber, which is 0.5 m^2.

3.7.2 Heat storage

The heat flux of the heat storage was calculated using an altered version of Eq 6. Since the total mass of water and the heat capacity is known could the heat flux at a given time be approximated by comparing the temperature of the water with its temperature 20 minutes earlier. Thus, determining the change of heat energy contained in the storage over that time. Thereafter dividing it with the number of seconds passed gives the change in energy per second, which represents the average heat flux to or from the storage at a that time window. This method was then used as a rolling average and plotted in excel.

4 Results

4.1 Hourly Weight Measurement

The hourly weight measurements used for verifying that the drying rate is constant gave results closely following a linear pattern. Both linear fits have R^2-values exceeding 0.99 which strongly supports the assumption of constant drying rate. One data point for 10 l/s at around 2 hours drying time was removed due to a mistake made in the weighing process.

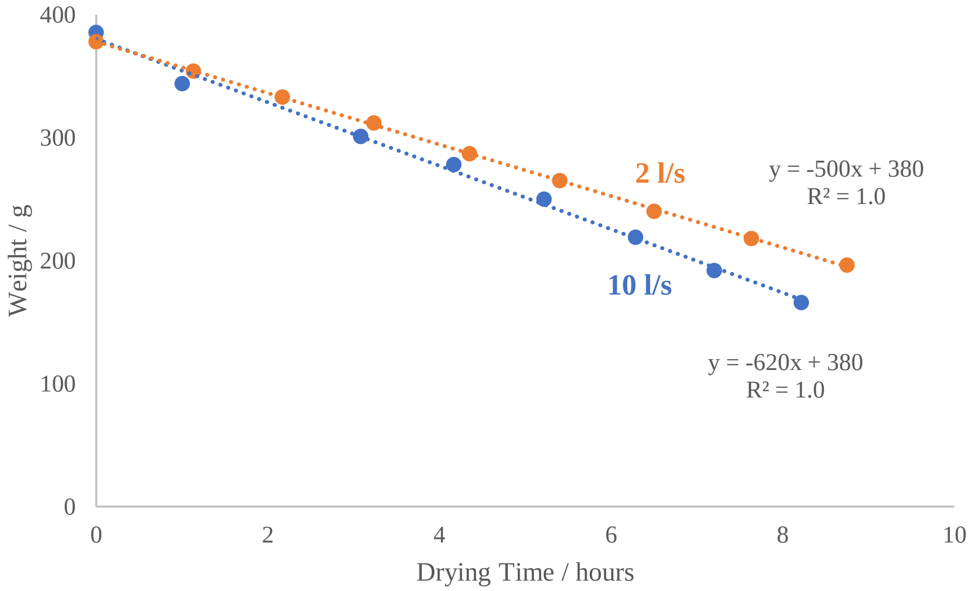

Figure 5: Hourly weight measurements of ginger over time for two separate experiments, one with a flow of 2 l/s (orange) and one with 10 l/s (blue). The upper equation and R^2-value is regarding the linear fit of the 2 l/s (orange) experiment and the lower is regarding the other experiment.

4.2 Combined Data from Multiple Experiments

4.2.1 Drying Rate

Changes in air flow affect both temperature and drying rate. There is a continuous increase in both temperature and drying rate when the flow is increased from 4 l/s to 10 l/s. However, further increases to the flow resulted in a gradual decrease in temperature but a small increase in drying rate. The differences in drying rate and temperature between 14 l/s and 18 l/s are rather small which indicates a pattern of diminishing returns. The lowest flows show a different pattern where an increase from 2 l/s to 4 l/s has a significant increase in temperature but no noticeable change in drying rate.

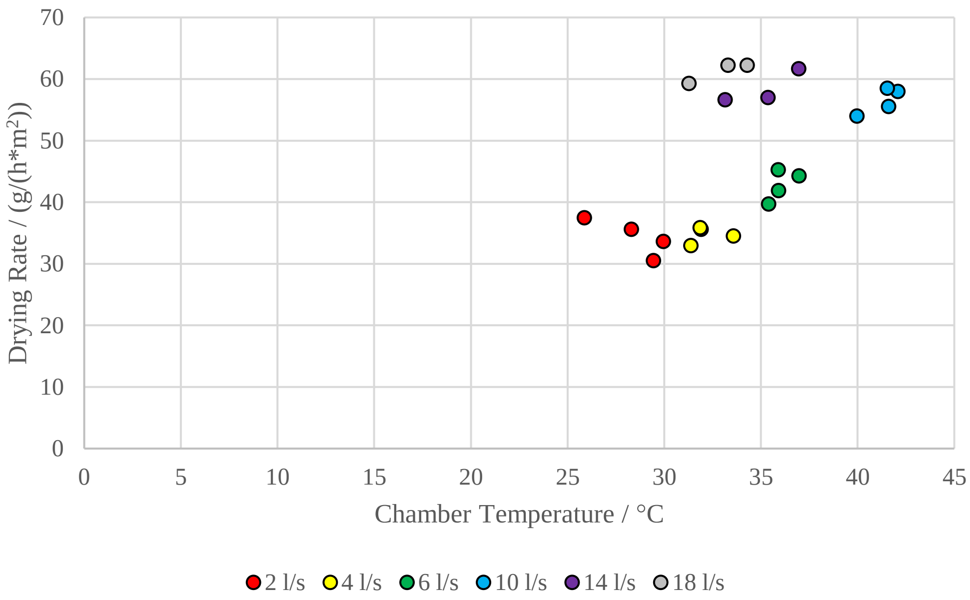

Figure 6: Drying rate plotted over average chamber temperature. Each dot is the result of one experiment and the color of the dot indicates what flow was used.

The average drying rate increases as flow increases but with diminishing returns. The highest drying rate achieved in the dryer was measured using a flow of 18 l/s, resulting in a drying rate of 60 g/(h·m^2) which is slightly faster than shaded open air drying. However, open air in direct sunlight is significantly faster still. A flow of 2 l/s or 4 l/s gives the slowest drying rates with around 35 g/(h·m^2) which is a little more than half the rate achieved with 18 l/s. Each dot in Figure 7 is the average of several experiments with similar conditions. The open-air drying experiments have no set flow and are therefore placed close to zero and excluded from the trend line.

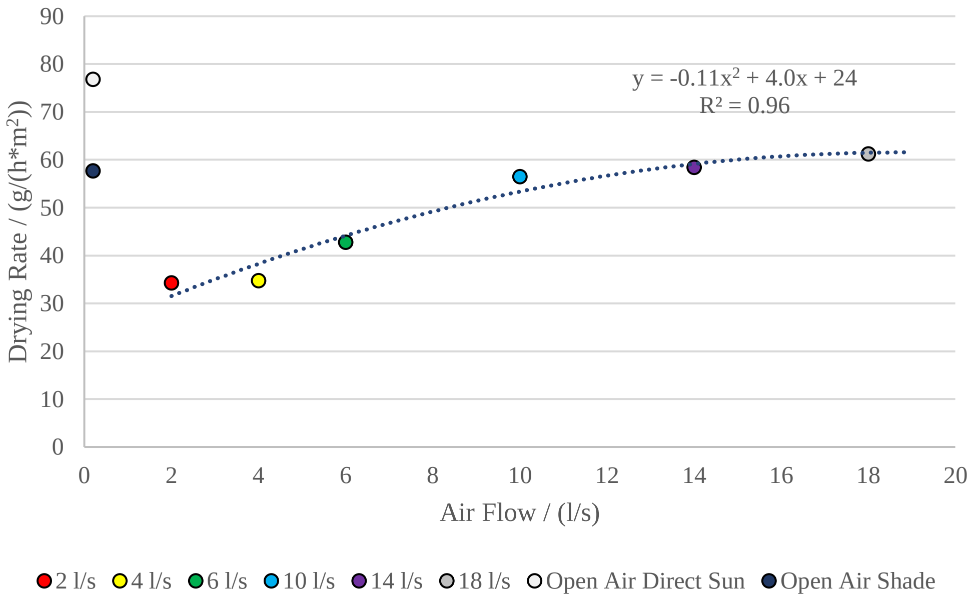

Figure 7: The average drying rate plotted over flow. The trendline does not include the open-air drying experiments.

4.2.2 Heat Exchanger

The efficiency of the heat exchanger was calculated using Eq. 11 and decreases as the flow increases, and this pattern seems to closely follow a second-degree polynomial with an R^2-value of almost 1. The highest measured efficiency was found for 2 l/s which reaches as high as 77 %. The drop in efficiency is quite linear until the flow exceeds 10 l/s, beyond which the efficiency seems to level off at around 30 %.

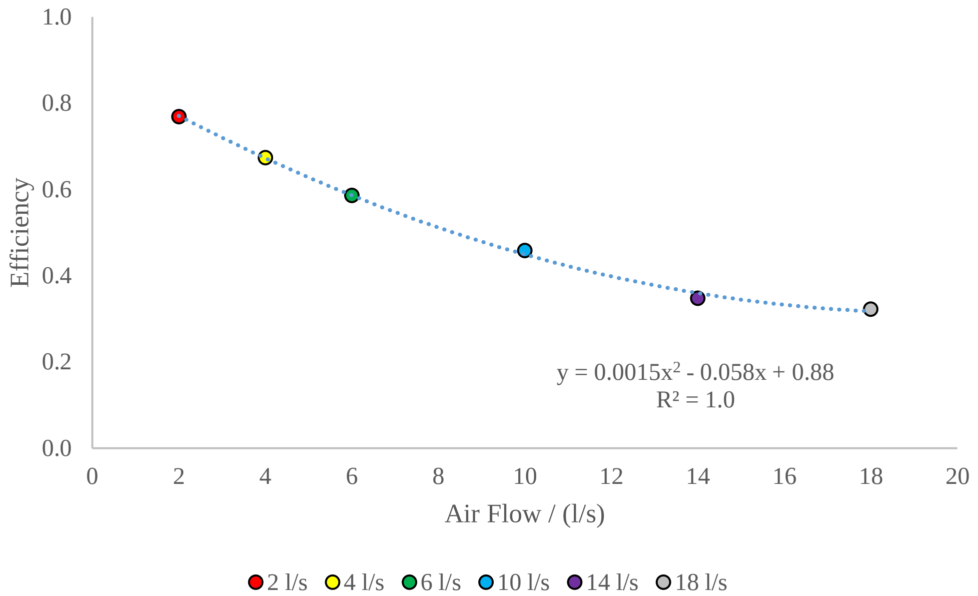

Figure 8: The average efficiency of the heat exchanger plotted over flow. Each dot is the average of several experiments. The trendline is a dotted blue line and is of the 2nd order and based on the average values seen in the plot.

The heat flux from the hot side to the cold side of the heat exchanger appears to be relatively consistent across different flows. The linear trendline based on all flows except for 2 l/s shows no slope, which indicates that flow has no significant effect on the energy performance of the heat exchanger. At a flow of 2 l/s, the heat flux deviates from the trend, measuring only 9 W compared to all other measured flows which showed heat fluxes around 17 W. This deviation is the reason for the exclusion from the trendline. The highest observed average heat flux seen in 10 l/s at 19 W.

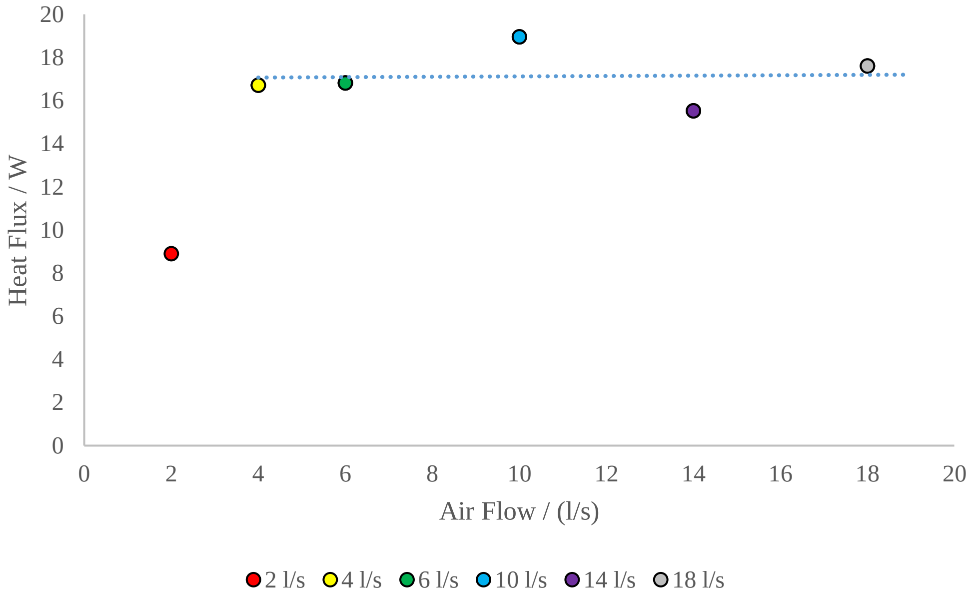

Figure 9: Average heat flux in the heat exchanger from the hot side to the cold side at different flows. The trend line is linear and displayed as a dotted blue line, and does not include the data from 2 l/s. Each color represent a different flow spanning from 2 l/s to 18 l/s and is the average of several experiments each.

4.2.3 Absorber

The efficiency of the absorber increases with an increasing flow and levels out once the flow exceeds 10 l/s. The calculated efficiency of the absorber reaches almost 100 % for the higher flows, and gets as low as 6 % for 2 l/s. The trendline best suited for this data is of the second order and follows the data closely with an R^2-value of 1. However, to simplify the equation, the trendline only includes the flows where substantial change is observed.

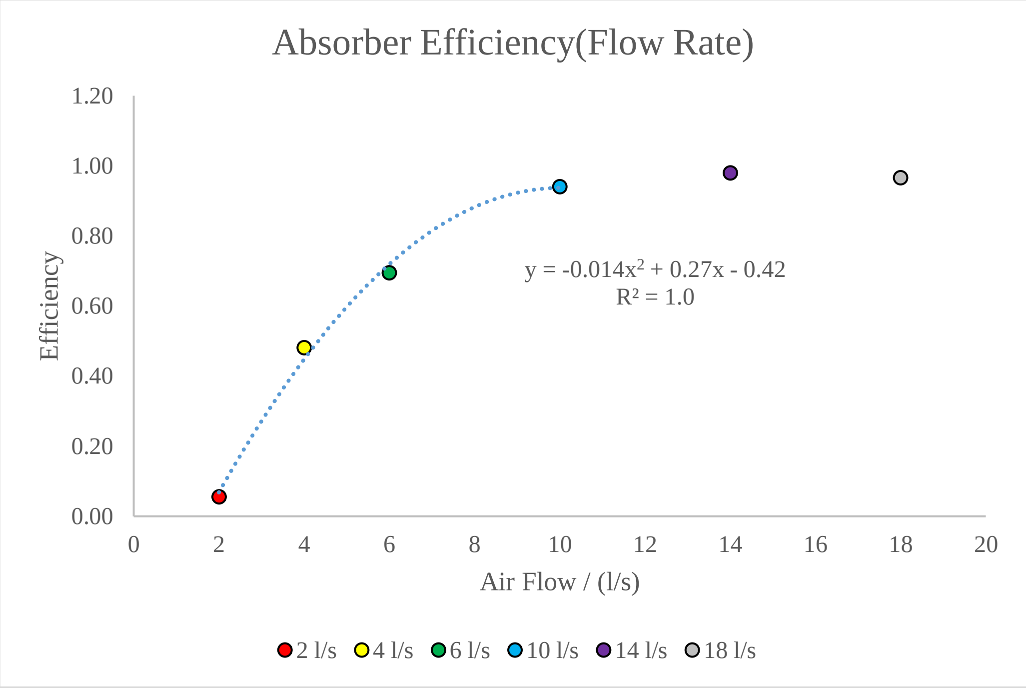

Figure 10: The average efficiency of the absorber plotted over flow. Each dot is the average of several experiments. The trendline is a dotted blue line and is based on the values seen in the plot.

4.2.4 Heat Storage

The average heat flux of the heat storage, which depends on the temperature difference between the water inside the bottles and the air leaving the absorber, followed a linear pattern. For each flow, the average line showed that there was negative heat flux (i.e., heat leaving the storage) when there was no temperature difference between the water inside the bottles and the incoming air, except for 2 l/s. The slope of the lines varied across different flows, which implies that a sudden change in temperature for incoming air will affect the heat flux more if the flow is higher.

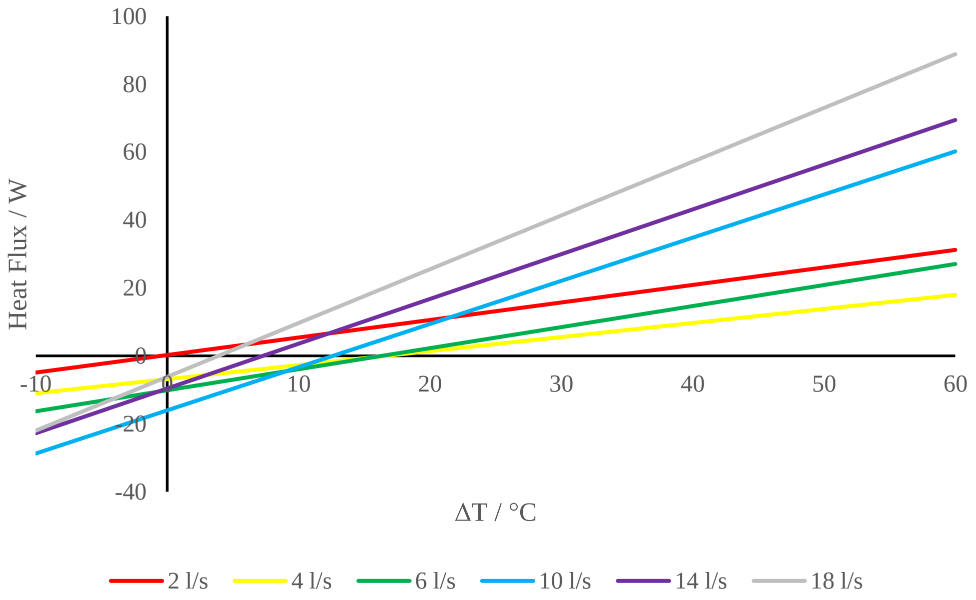

Figure 11: A line plot of the heat flux between the air entering the drying chamber from the absorber and the water in the heat storage over the temperature difference between them. Each line is the average of several experiments.

The multiplier which determines the slope of the lines in Figure 11 increases with flow, and as seen in the figure below, this increase follows a linear pattern.

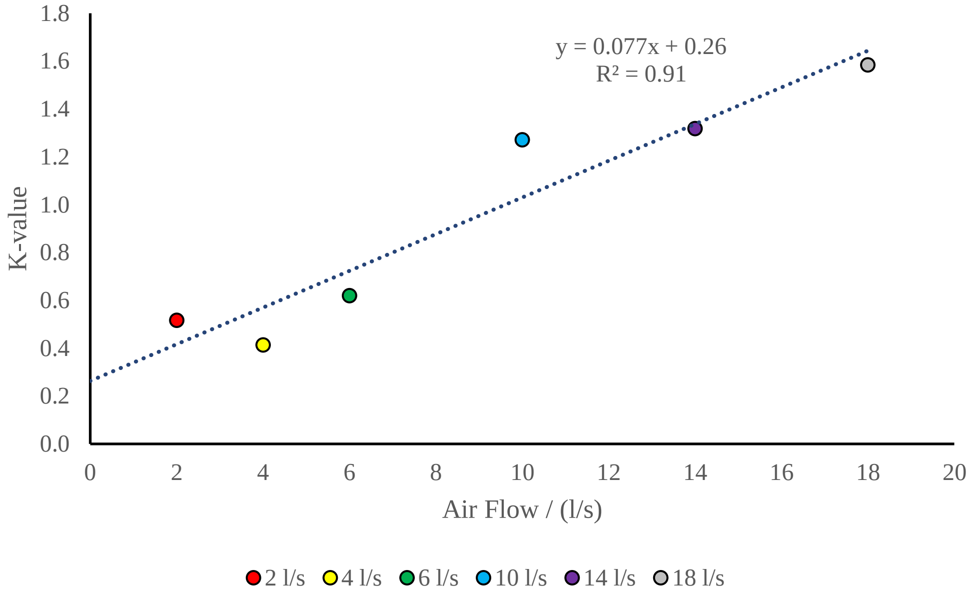

Figure 12: The multipliers which determines the slope of the lines seen in Figure 11 (i.e., the number which is multiplied with the variable in the line equation) plotted over flow.

The average amount of remaining heat energy at the end of the experiments, which indicates the potential heating for operation after sunset, shows an initial increase as the flow is increased from 2 l/s to 6 l/s, followed by a decrease at higher flows. The decrease is small between 6 l/s and 10 l/s but becomes significant between 10 l/s and 14 l/s, after which the rate of decrease appears to slow down. Notably, the flow resulting in the most amount of energy stored by the end of the day was 6 l/s, while the flow resulting in the least amount of energy stored was 18 l/s.

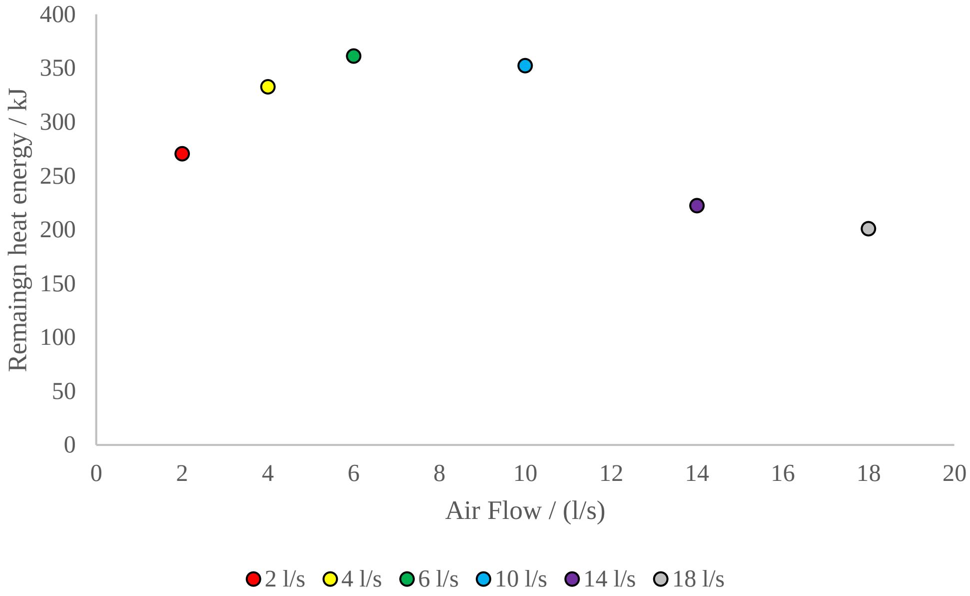

Figure 13: The average remaining heat energy stored in the heat storage at the end of the experiments plotted over flow.

4.2.5 Drying Chamber

The average temperature in the dryer appears to reach its peak at approximately 42 °C for a flow of 10 l/s and is lowest at around 28 °C for a flow of 2 l/s. The trendline used is of the second order and follows the data reasonably well with an R^2-value of 0.86, indicating that the estimate is rather good but with some deviations.

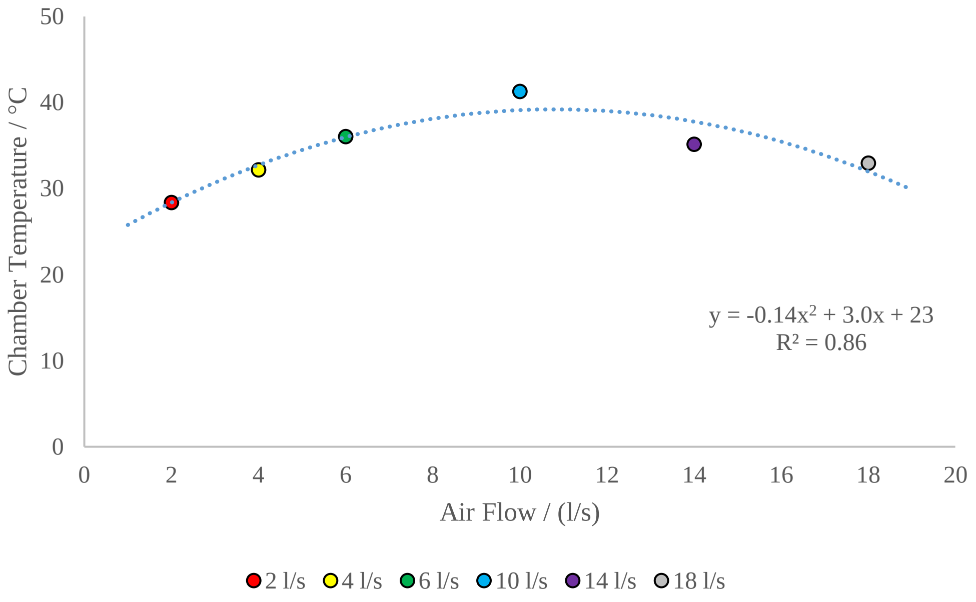

Figure 14: The average chamber temperature plotted over flow. Each dot is the average of several experiments. The trendline is a dotted blue line and is based on the average values seen in the plot.

4.3 Individual Experiment Analysis

4.3.1 Absorber

In most experiments, the absorber efficiency exhibits different results in efficiency earlier in the day compared to later, even if the temperature difference between the absorber and the ambient temperature are the same. With significantly lower efficiency before noon, and higher after. An example of this can be seen in the figure below which corresponds to one of the experiments with a flow of 6 l/s.

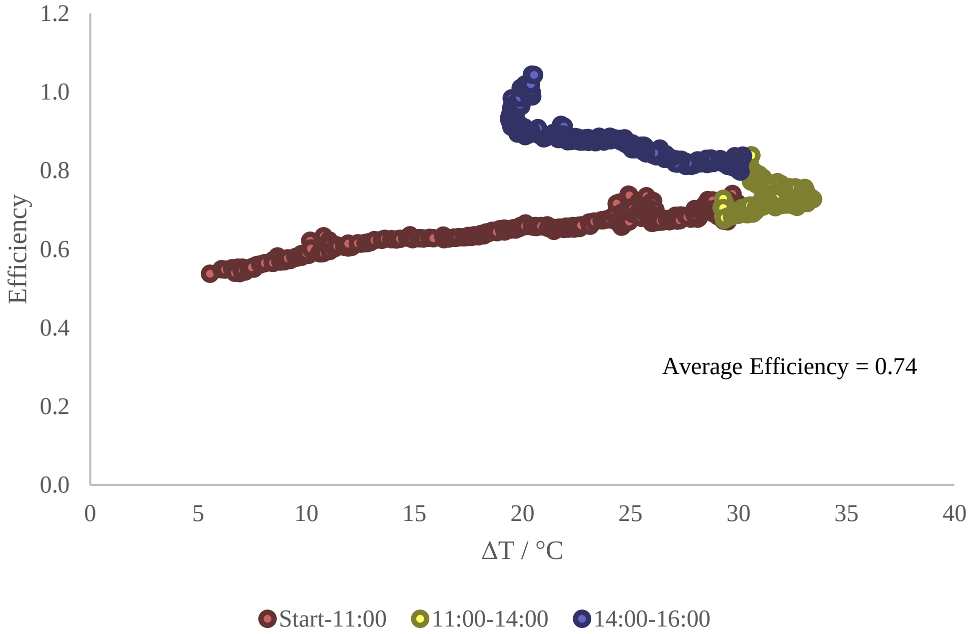

Figure 15: All absorber efficiencies measured in the experiment conducted the 19/11 – 2022 with a flow of 6 l/s. The average efficiency that day was 74 %. The red dots are data from before 11:00, the yellow dots are data measured between 11:00 and 14:00 and finally the blue dots are measurements between 14:00 to 16:00.

4.3.2 Heat Exchanger

The heat exchanger required some time to give stable results. The gray line shows the ratio between the temperature difference seen across the cold side over the difference seen across the hot side. The ratio tended to gravitate towards 1.0, some days a bit below, and others a bit above, nothing consistent enough to indicate leaking issues. The results came back more stable for the more moderate flows and very unstable for the highest and lowest rates. The drop seen for the temp ratio and the efficiency for the cold side between 10:00 and 11:00 is due to division close to 0, which were filtered out.

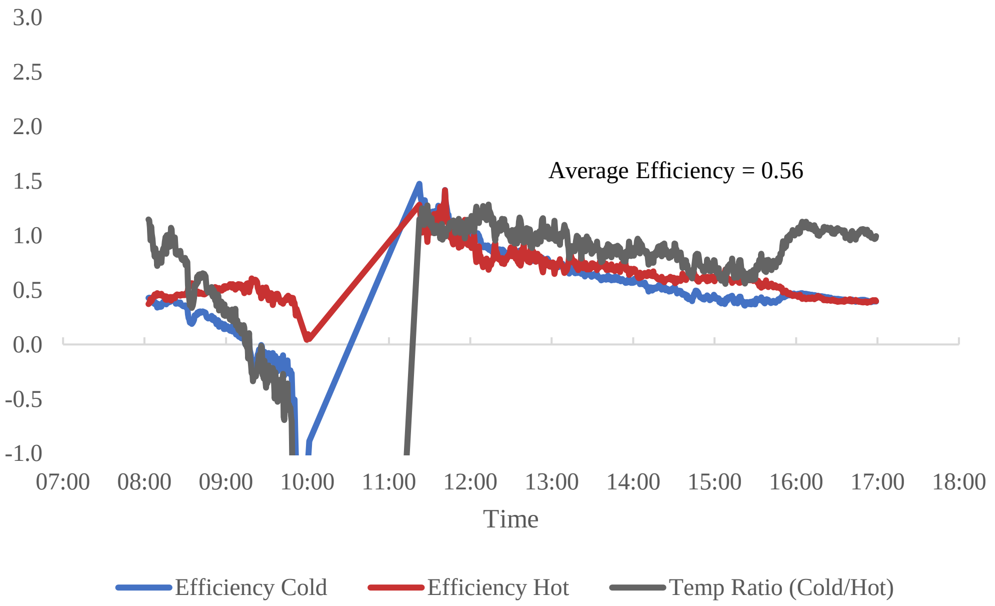

Figure 16: The heat exchanger efficiencies and temperature difference ratio measured the 8/12 – 2022 in an experiment using 6 l/s. The blue line is the efficiency measured over the cold side and the red line is the efficiency measured over the hot side. The gray line is the ratio of the temperature difference seen across the cold side divided by the difference seen across the hot side.

Experiments with unstable results were typically conducted on windy days with low flow rates or in experiments with high flow rates. In experiments with high flow rates, the temperature difference was very low, and as a result, even small changes in temperature had a significant impact on the ratio, leading to large fluctuations. One example of this is shown in the figure below.

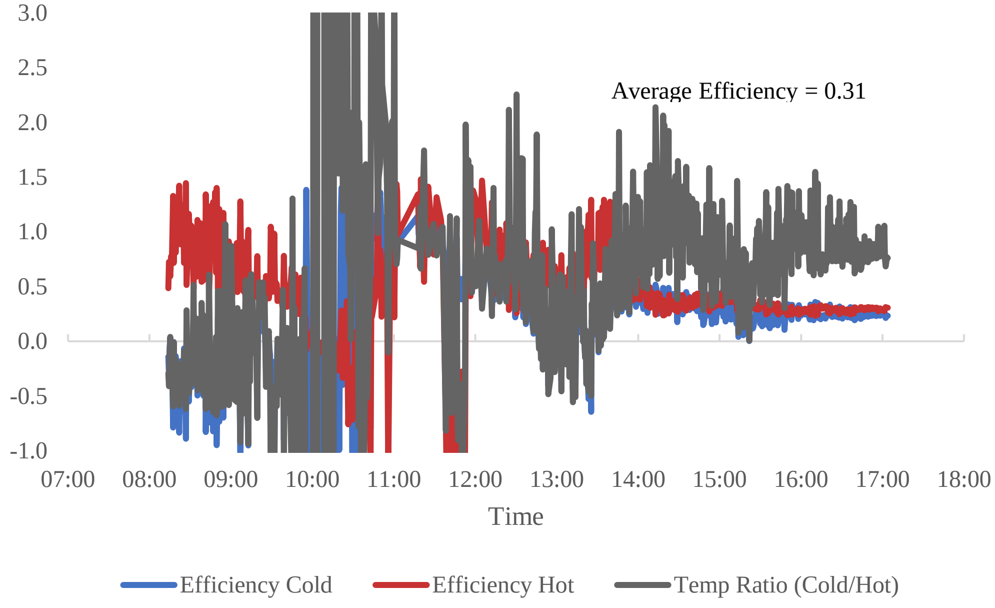

Figure 17: The heat exchanger efficiencies and temperature difference ratio measured the 14/12 – 2022 in an experiment using 18 l/s. Same as above but a different experiment with less clear data.

At higher flows, there is a minimal temperature difference observed across either the hot or cold side of the heat exchanger, whereas lower flows result in larger temperature differences. The gap seen between 10:00 and 11:00 is as previously mentioned due to filtering out unreasonably large values in efficiency due to division close to zero.

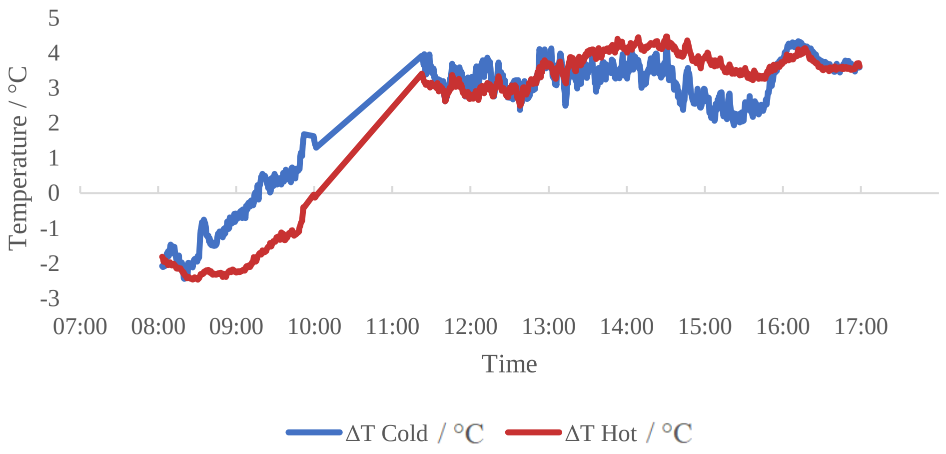

Figure 18: The temperature difference seen across the cold side is represented by the blue line and the hot side by the red line. The data displayed is from the same experiment as Figure 16 where the flow was set to 6 l/s.

An example of an experiment with a high flow and a low temperature difference can be seen in the figure below which shows data from an experiment with the flow set to 18 l/s, where the temperature difference rarely exceeds 2 °C.

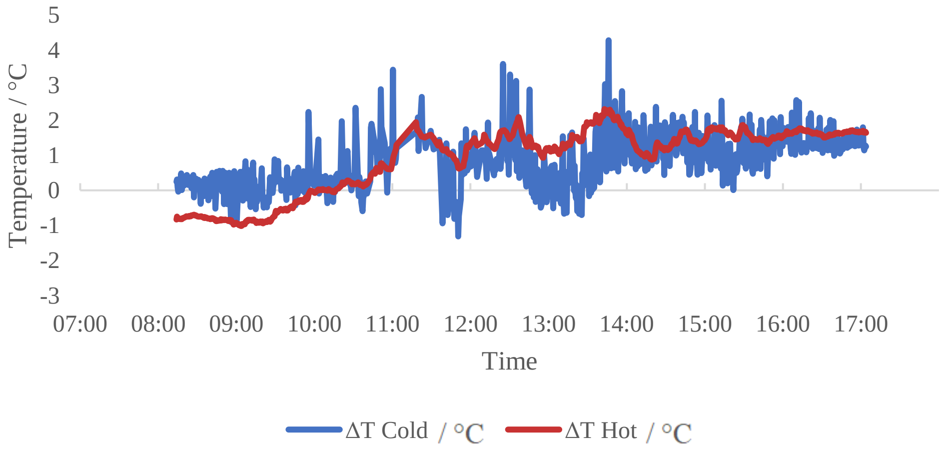

Figure 19: Temperature difference seen across both sides of the heat exchanger. Same as above but this shows the data from the same experiment showed in Figure 17 which has a flow of 18 l/s.

4.3.3 Heat Storage

The heat flux of the heat storage gave varying results with predictable patterns shown some days, and larger variations on others. However, even experiments with erratic data showed a trend of the bottles being heated in the morning and cooled in the evening.

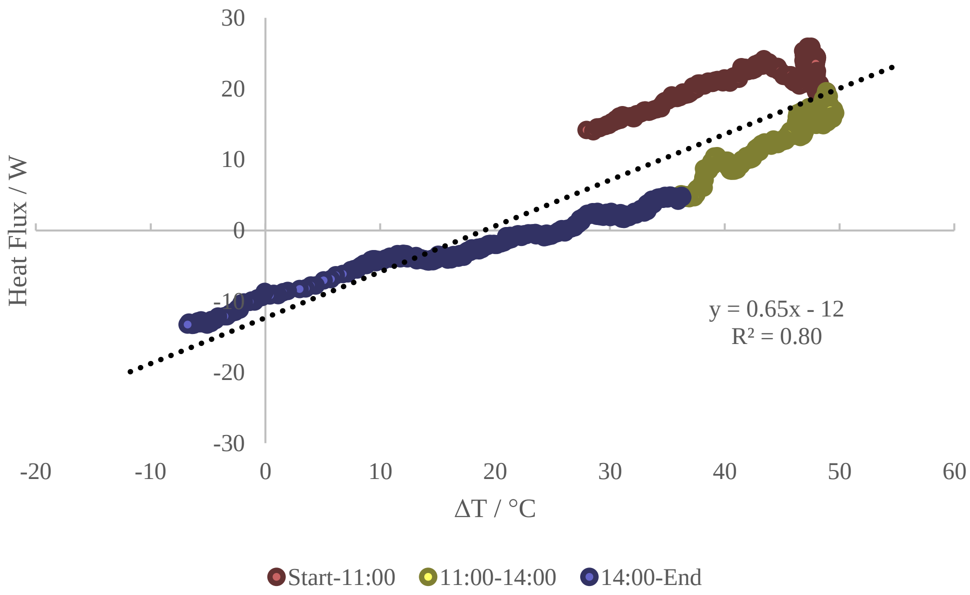

Figure 20: The heat flux between the water in the bottles and the air leaving the absorber plotted over the difference in temperature between them. The red dots are data from before 11:00, the yellow dots are data measured between 11:00 and 14:00 and finally the blue dots are the measurements done after 14:00. The data is from the experiment conducted the 24/11 – 2022 whit a flow set to 6 l/s.

An example of an experiment with highly unstable data can be seen below. Negative heat flux, i.e., the bottles losing heat, could even be seen where the inlet air was 25 °C warmer than the water, indicating that more factors have an effect on the result than intended.

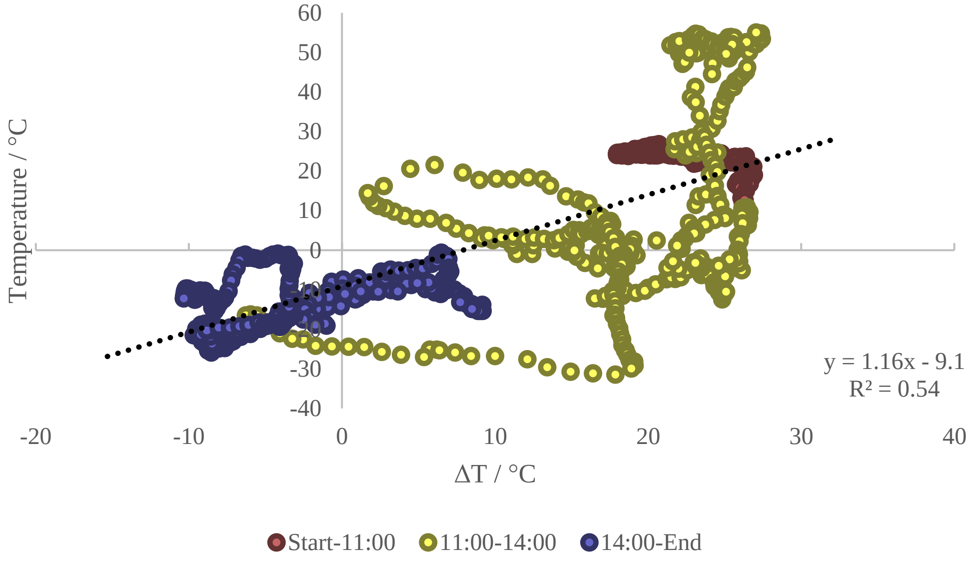

Figure 21: The heat flux between the inlet air and the water plotted over the temperature difference. Same as above but from a different experiment with less clear data conducted the 11/12 – 2022 with a flow of 14 l/s.

4.3.4 Drying Chamber

The temperature seen inside the drying chamber shows a gradual increase in temperature throughout the morning, with a sharp increase in the temperature of the incoming air. Between 11:00 and 14:00 the input air is stable at around 77 °C while the chamber temperature increases significantly. After 14:00 we see a substantial decrease in the incoming air temperature, however, the chamber temperature remains relatively stable at around 45 °C with only a very gradual decrease towards the end. The temperature seen inside the chamber varies greatly depending on what flow was used, however, the same pattern as described above can be seen, albeit with different temperatures.

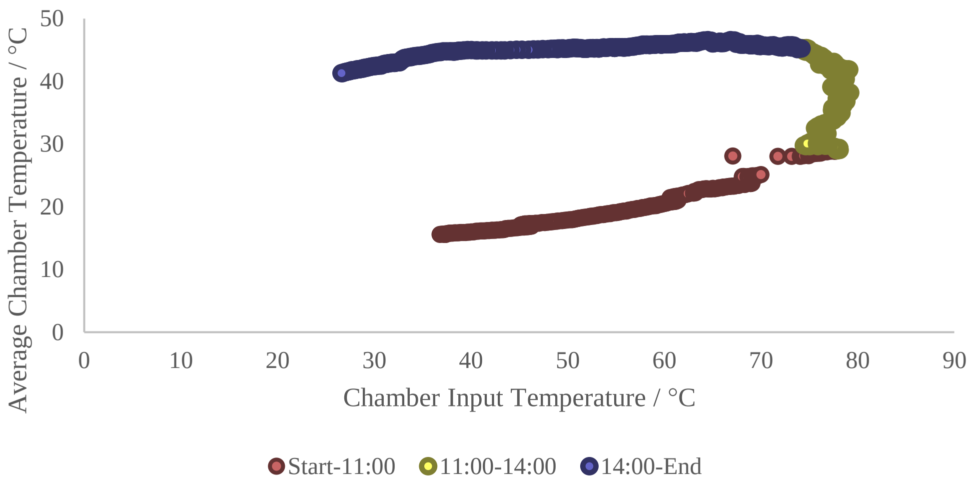

Figure 22: The drying chamber temperature plotted over the chamber input temperature, the air leaving the absorber. The red dots are data from before 11:00, the yellow dots are data measured between 11:00 and 14:00 and finally the blue dots are the measurements done after 14:00. The data is from the experiment on the 8/12 – 2022 using the flow of 6 l/s.

The temperature seen inside the dryer compared to the ambience shows a similar pattern as seen in Figure 22, however, instead of having a small decline in the evening there is a small increase instead. From about 11:00 the incoming air temperature will gradually approach the chamber temperature until later in the evening when it eventually becomes cooler, thus causing the dryer to cool down.

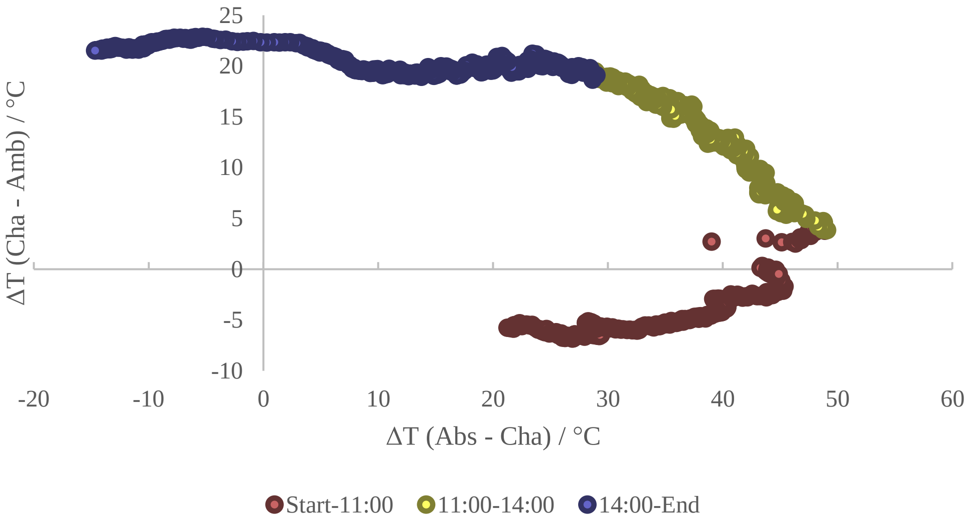

Figure 23: Relative drying chamber temperature. Similar to the graph seen in Figure 22 but both axis are exchanged for temperature differences instead. Where the Y-axis is the difference between the chamber and the ambiance, and the X-axis is the difference between the air leaving the absorber and the chamber temperature. The data is from the same experiment as Figure 22.

5 Discussion

5.1 Results

5.1.1 Drying rate

The results suggests that a higher flow is better, however, the external fan in the current system limits the possibility of further increases. Even the higher tested flows are unsustainable since they required a higher than rated voltage to achieve. It is worth noting that without a duct for measuring flow there will be less resistance pushing air through the dryer, which could result in higher flows. Thus, if the dryer is to be used for drying and not experimentations in the future is it recommended to run both the internal and external fans at their rated max speed.

It is possible that a system with a larger absorber and a higher temperature increase could yield different results, where there is a peak drying rate within the achievable flows. A point where the flow is sufficient to provide plenty of dry air and convection without compromising the temperature too much. Alternatively, it is possible that flow is simply a more critical factor to consider when drying. However, it is important to consider that the availability of more powerful fans may be limited and increasing the airflow would require a higher energy input. Consequently, if the dryer were to be redesigned to increase the flow, then it is important take into account the limitations imposed by availability, cost, and energy consumption. Thus, might a larger absorber still be a more cost-effective improvement while using resources more available in rural Bhutan.

Humidity of air also effects drying rate, and increasing the temperature of air increases its capacity to carrying moisture, thereby reducing its relative humidity. Days or seasons with high humidity might have different optimal flows for drying as the increase in temperature might be more or less essential. On a day with 100 % relative humidity would drying be impossible without increasing the temperature first.

5.1.2 Heat exchanger

In contrast to the absorber, the heat exchanger's efficiency decreases with an increase in flow, though, the heat flux between the sides seem to remain relatively constant. This suggests that the decrease in efficiency to some extent cancels the increased temperature difference obtained from the increase in absorber performance. However, even at flows above 10 l/s when the absorber efficiency plateaus will the heat flux remain, which indicates that there are other factors at play beyond just comparing efficiencies. In any case, the actual energy performance of the heat exchanger does not seem to be overly sensitive to changes in flow as the heat flux remains constant in all flows, except for the anomaly at 2 l/s. This anomaly is likely caused by the low flow and poor utilization of the absorber, which creates a bottleneck in the system by lowering the temperature difference between the sides of the heat exchanger to such extents that the heat flux goes down significantly.

The heat exchanger recycled on average 17W of heat energy. This is not a very significant amount; therefore, the question arises: is the heat exchanger cost effective enough to justify its existence in a low-cost food dryer? Or could the resources used for the heat exchanger be better utilized on other components, such as the absorber or a better fan? Although, the heat exchanger might be more important in a system with higher internal temperatures. Further research is needed to determine if the gains in performance justify the extra cost.

5.1.3 Absorber

The trendline used to estimate the efficiency of the absorber does not incorporate flows exceeding 10 l/s. This exclusion is justified by the fact that flows above 10 l/s exhibit a consistent pattern, rendering the need for an equation to predict them redundant when no variation is observed. Moreover, including them meant an equation of a higher order was needed for acceptable accuracy. Hence, it was deemed better to use a simpler equation for the flows of 10 l/s and below.

5.1.4 Heat storage

The heat flux from the air to the heat storage is more effected by temperature differences at higher flows, which can be attributed to the bottles having more air to interact with every second if the flow is high. Thus, when the sun goes down and the air gets cold, the excess heat stored in the bottles will deplete faster for higher flows. This can be seen in Figure 13, where the higher flows have the lowest amount of remaining energy at the end of each experiment, which concluded around 17.00. Another pattern is the increase in energy when the flow increases 2 l/s to 6 l/s which is likely due to the increased convection.

If the experiments were to be extended beyond sunset and run for a longer duration, there is a possibility that the relative performance of the more moderate flows would improve. This can be attributed to the fact that these flows retained more residual heat at the end compared to higher flows. As a result, the extended runtime would allow full utilization of the heat storage, both bottles and structure, which would have the greatest benefit to the flows with the most retained heat at the end of the experiments showed in Figure 13.

The bottles account for a relatively small portion of the thermal mass in the dryer. However, in the case of this dryer there was no indication of the drying chamber ever getting too warm, meaning the storage is not protecting the food by absorbing excess heat. Therefore, the inclusion of additional storage is questionable, as it takes up a full shelf in the dryer, meaning there is a chance that this space is sacrificed for no substantial boost in dryer performance. However, all experiments in this report concluded around 17.00 which means that the experiments ended before the storage is needed the most. Thus, further experiments with longer run-times are needed to verify if heat storage is beneficial and worth sacrificing space for.

5.1.5 Drying chamber

Figure 22 displays the temperature inside the dryer during an experiment using a flow of 6 l/s. The data shows a gradual increase in temperature during the first half of the day, followed by relatively constant temperatures during the latter half. However, the temperature never reaches the generally considered optimal drying temperature of to 60 °C which is a problem as the higher temperatures help in eliminating microbes. The chamber was the warmest at flows of 10 l/s, and even then the temperature barely gets above 50 °C. This reinforces the notion that a good improvement to the dryers design would be a larger absorber.

5.2 General Discussion

5.2.1 Risks of pushing the system to higher flows

The initial plan for the experiments was to only test the flows of 2 l/s, 4 l/s, 6 l/s and 10 l/s. However, the pattern that emerged in several of the graphs indicated that even higher flows could yield better drying rates and more interesting results which would add to the overall conclusion. With the current air duct set up, the small duct attached to the larger duct glued to the inlet, allowed for 10 l/s with a voltage close to the external fans rated maximum of 12V. Thus, was it deemed to unsafe to push the system to even higher flows without altering the system, as it would risk fan failure which if it were to happen before all initial experiments were completed would be devastating for the project. To achieve higher flows, the smaller duct was removed as it became a significant bottle neck at flows above 10 l/s. The experiments with 14 l/s were conducted after completing all initially planned experiments, and the experiments with 18 l/s being the final ones. To run the experiments of 18 l/s, the fan was overvolted to about 15 V, significantly more than what the fan is built for, however, since these were the final experiments would the project not be compromised in case the fan broke under theses extreme conditions.

5.2.2 Surface area calculation for open-air drying

The ginger dried using the open-air method was, unlike the ginger inside the drier, placed on cardboard and not a mesh. But the same formula was used for calculating the surface area of the ginger in both systems even though the side of the ginger facing down had significantly less exposure to air. However, cardboard can absorb some of that moisture compensating a bit for that loss in air exposure. The method used for calculating surface area was not changed as the ginger was still prepared in the same way and it was deemed a better comparison if the data was processed and treated equally.

5.2.3 Neglected surface area

The surface area of the ginger was estimated as described in the method section. However the sides of each slice, the sides not cut by knife, were neglected. As a result, the surface area of the ginger in the calculations was smaller than its actual area. The magnitude of this error varies and may impact the conclusions and patterns observed in the results. A more accurate method of estimating surface area could potentially affect the overall findings of the study, however, it is likely this change would be insignificant.

5.2.4 V-shape of the absorber efficiency

Figure 15 shows that the graph takes the shape of a “v” or an arrow, which was not what was expected. The hypothesis was to see a linear shape with a negative slope, meaning that the efficiency decreases with a larger temperature difference since it leads to greater heat losses. It is likely that the V-shape is caused by heat absorption in the walls and interiors of the dryer. In the earlier half of the day when there is a positive slope, the structure of the dryer is gradually getting warmer to a point close to equilibrium, thus slowly allowing more heat to be absorbed by air instead, which increases the efficiency of the dryer. Around noon, the efficiency stabilizes, and in the afternoon, a negative slope with a very high efficiency is observed. This can be attributed to the same effect as in the morning but in the opposite direction. In other words, the structure of the dryer is now cooling and providing additional heat to the air, leading to increased efficiency. Since the temperature inside the dryer is not the same at the beginning and the end of an experiment, meaning there is still available energy stored in the system, will this in theory have some impact on the average measured efficiency. However, the magnitude of this error is debatable and since all experiments were run with fairly similar weather conditions and during the same time of day, is the error likely similar between experiments. Though it should be noted that the temperature inside the dryer differs between flows which means that different amount of heat gets stored in the structure and might therefore have some impact on the comparison between these experiments, though likely not enough to have a large impact on the conclusion.

5.2.5 The effects of temporary shading

The effect described above can also have short-term effects on the data. If a thick cloud suddenly blocks the sun around noon, the solar flux will decrease to a small fraction of what it was moments before, and this change can be very sudden. In this case the dryer will be very warm compared to the sudden small solar flux, putting the system in a state far from equilibrium causing the dryer to emit more heat than what is being absorbed. Thus, a significant portion of heat that is transferred to the air will be from the structure, resulting in a unreasonably high measured efficiency sometime far above 150 %.

5.2.6 Seasonal temperature shift and chamber temperature approximation

The relationship between the average drying chamber temperature and flow, as depicted in Figure 14, follows a quadratic pattern. However, the R2-value is below 0.9, which could be attributed to several factors, including the possibility that a quadratic approximation may not be suitable. However, this graph does not account for ambient temperature, which may vary on different days, leading to lower chamber temperatures on days with lower ambient temperatures. Since the experiments with 14 l/s and 18 l/s were all done closer to winter when the ambient temperature was noticeably lower, it will likely affect the results thus lowering the accuracy of an otherwise potentially good approximation.

5.2.7 Flow and chamber temperature relationship

The peak measured chamber temperature occurs at 10 l/s, likely due to two factors: absorber efficiency and the rate of air mass passing through the dryer. When more air that passes through, more energy is needed to heat it. Meanwhile, higher absorber efficiency results in more energy being captured. At flows below 10 l/s, the increase in absorber efficiency provides a greater increase in energy input than the additional mass requires to reach the same temperature as a lower flow. Therefore, the temperature increases. However, after 10 l/s, absorber efficiency can no longer increase and thus any further increase in flow will decrease the temperature.

5.2.8 Filtering irregular logger errors

Not all data that was collected could be used. An irregular error occurred in the logger, causing it to temporarily go out of sync with the multiplex. As a result, some of the data shifted i.e., the readings for the inlet were displayed as the absorber temperature, and the absorber temperatures were labeled as chamber temperatures, etc. Fortunately, these errors were easily identified as they always left at least one empty value, since if the data is shifted, then there is no data for the inlet as there are no earlier sensor's data that could shift to its place. Thus, all these errors could be filtered out by simply removing every row with at least one empty cell. Luckily, this had little impact on the final data as there was still an abundance of data remaining, even after removing several rows in particularly bad days. One row only account for 30s of drying time over a total of 9h, and the errors appeared to occur randomly, some bad days with about 50 deleted rows and some with none. Since the errors were spread out randomly in each day were no large continuous segments deleted. Consequently, the graphs that emerged, even on bad days, still followed a continuous pattern.

5.2.9 Varied stability of data

As is shown in the section Individual Experiment Analysis, the stability of the data varies greatly, where the most unstable results came either from 2 l/s or 18 l/s, and the most stable results from 6 l/s and 10 l/s. This is most apparent in the graphs showing the efficiency of the heat exchanger and can be explained by the fact that in both cases are the temperature differences throughout the heat exchanger very small. The efficiency is calculated by dividing the temperature difference on one side by the difference in temperature between the inlets on both sides. The problem occurs when these two temperatures are almost the same, thus, when calculating the efficiency will the denominator be close to 0, therefore, could a change as small as 0.1 °C have a large impact on the calculated efficiency. The cause for such a small temperature difference is likely different for the two flows. In the case of 2 l/s, the cause is most likely the extremely low utilization of the absorber, while for 18 l/s, it is due to the flow of mass that is too large for a high temperature increase with the current absorber.

An additional factor that may contribute to the instability seen in the case of 2 l/s is wind sensitivity. A sudden gust of wind could easily increase or reduce the flow temporarily with 1 l/s and sometimes even more. This change is less significant for higher flows but is a decrease or increase of 50 % for 2 l/s. In some extreme cases the wind was even strong enough to cause temporary back flow in the dryer, meaning the air is going in the opposite direction, which is why extra caution was used for experiments with 2 l/s. The wind tended to be the strongest around lunch, which had a noticeable effect on the flow, therefore was the flow checked several times a day to minimize the errors this might cause.

5.2.10 Challenges in measuring flow

Measuring flow can be challenging as readings often fluctuate, making it difficult to set a precise flow, and taking great precautions in this process does not necessarily increase the overall precision throughout the day. This is because the flow gradually decreases and was in most cases lower around lunch than it was set to in the morning. Therefore, even if it was adjusted and corrected several times a day, the fact remains that the flow was running lower than intended before the adjustment.

Overestimating the flow leads to a higher perceived mass flow, which in turn increases the calculated heat flux to the air. Accurately measuring heat flux to the air is crucial for calculating the efficiency of the absorber, as the efficiency is derived from the solar flux divided by it. Therefore, is the real efficiency of the absorber likely lower than what is presented in this report.

5.2.11 Lack of origin alignment and instability in data for heat storage

As seen in Figure 11, which describes the linear heat transfer to the heat storage based on the temperature difference between the water and the air leaving the absorber, almost none of the lines go through the origin. However, in theory should no heat be transferred if there is no difference in temperature between two interacting bodies. A similar error can be seen with the negative heat flux despite a large positive temperature difference in Figure 21. Though, these errors can be explained by the fact that the air leaving the absorber is not fully isolated on its path to the water bottles, thus having a short time to mix with the air in the drying chamber. Consequently, decreasing the temperature of the air before reaching the bottles, but after it has already been measured. This error should be more significant for lower flows due to a greater dilution of the warm air from the absorber. The mixing effect is also increased by fact that the bottles were placed next to the internal fan. However, a deflector was placed in front of the fan to direct the air downwards, thus reducing this error.

6 Conclusion

The efficiency of the absorber plateaus after reaching a flow of 10 l/s. Consequently, beyond this point, the internal temperature ceases to increase with increased flow and instead starts to decline. However, despite the decline in temperature, the drying rate continues to increase with a higher flow and this report managed to find no end to this trend. Therefore, if a high drying rate is the primary objective, maximizing the flow is advised, however, if high temperatures are prioritized, then a flow of 10 l/s is optimal.

The heat storage showed that 6 l/s and 10 l/s had most heat retained at the end of the experiments, thus, there is a chance that extended drying times where this energy can be utilized might change the results in favor of more moderate flows. However, the bottles used as storage take up internal space which could be used for food, and the structure of the dryer already functions as heat storage. Thus, it is debatable if the addition of water bottles is beneficial.

The heat exchanger displayed an inverse relation with flow, where an increase in flow resulted in lower efficiencies. For the highest tested flow, the efficiency was as low as 30 % with a temperature increase in the cold side of about 1 °C to 2 °C and a heat flux of about 17 W. It is debatable if the heat exchanger is worth the added complexity and cost with the dryer’s current design, but it might find more use in a design with higher internal temperatures.

In conclusion, a significant improvement to the dryer's design would be a larger absorber, and potentially a larger fan if the budget and availability allow. Additionally, the exclusion of a heat exchanger and heat storage from the dryer’s current design could be a valid approach to decrease the total cost and complexity of the system.

6.1 Future Works

The implications of the varying amount of heat retained in the storage, as discussed in *5.1.3 Heat storage,* require further research. The extent of these benefits are unknown but could be explored by extending the duration of the experiments with several hours. This will allow for a more comprehensive evaluation of whether the changes in relative performance resulting from the retained heat are significant enough to warrant the space required for storage.

The cost effectiveness of the heat exchanger, as mentioned in the section *5.1.2 Heat exchanger*, is questionable and needs further research. One approach to determine this could be to conduct an experiment where firstly one dryer with a heat exchanger is built, which establishes the budget for another dryer without a heat exchanger. The money saved from omitting the heat exchanger could then be used to build a dryer with a slightly larger absorber or buy a larger and more powerful fan. Though it should be mentioned that a larger fan will add long-term energy costs, and the exclusion of a heat exchanger will lower the resistance of pushing air through the dryer, which would yield higher flows even with an identical fan. The two dryers can then be tested side-by-side under equal conditions to determine the most cost-effective approach. Although, the heat exchanger might be more important in a system with higher internal temperatures, therefore will this experiment be more relevant once a design with higher internal temperatures is used.

The error described in the section *5.2.11 Lack of origin alignment and instability in data for heat storage* could be removed in future projects by attaching temperature sensors on the outside of the bottles, thus measuring the actual temperature of the air interacting with the bottles, after it has already been mixed. Another solution could be by giving the storage a space separate from the drying chamber and measuring the temperature of the air going in and out of this space, but this would add complexity to the building process and might not affect the overall performance of the dryer which would make such a change hard to justify.

As mentioned in the section *5.1.1 Drying rate*, relative air humidity greatly affects drying performance. Since the humidity in the ambient air varies greatly depending on seasons in Bhutan, further research could help investigate how this changes what flow performs optimally.

7 Bibliography

Cengel, Yunus A. 2002. *Heat Transfer - A Practical Approach.* 2. Mcgraw-Hill.

Chhogyel, Ngawang, Kumar, Lalit. 2018. "Agriculture and Food Security." *Climate change and potential impacts on agriculture in Bhutan: a discussion of pertinent issues.* BMC. Accessed 08 18, 2022.

Climate Research Unit of University of East Anglia. 2020. *Climate Change Knowledge Portal.* Accessed 08 23, 22. https://climateknowledgeportal.worldbank.org/country/bhutan/climate-data-historical.

Davidsson, Henrik. 2021. "Canvas." *Solar collector physics.* Accessed 08 31, 2022. https://canvas.education.lu.se/courses/14485/files/1675057?module_item_id=407937.

Dryden, I.C.G. 1982. "Chapter 9 - Drying, conditioning and industrial space heating." In *The Efficient Use of Energy (Second Edition)*. Butterworth-Heinemann.

Döhlen, Viktor, Gustaf Bengtsson, Ricardo L Bernardo, and Randi Phinney. 2016. "Performance Testing of a Solar Thermal Fruit Dryer – A Case Study to Reduce Food Waste in Mozambique." *ISES International Solar Energy Society.* Department oc Architecture and Built Environment, Lund University. 10 14. Accessed 09 01, 2022. https://proceedings.ises.org/paper/eurosun2016/eurosun2016-0169-Bengtsson.pdf.

Engineering ToolBox. 2003. *Air - Density, Specific Weight and Thermal Expansion Coefficient vs. Temperature and Pressure.* Accessed 08 31, 2022.

—. 2004. *Air - Specific Heat vs. Temperature at Constant Pressure.* Accessed 08 31, 2022. https://www.engineeringtoolbox.com/air-specific-heat-capacity-d_705.html.

Engineering Toolbox. 2003. *Atmospheric Pressure vs. Elevation above Sea Level.* Accessed 01 17, 2023. https://www.engineeringtoolbox.com/air-altitude-pressure-d_462.html.

Engineering ToolBox. 2003. *Conductive Heat Transfer.* Accessed 08 30, 2022. https://www.engineeringtoolbox.com/conductive-heat-transfer-d_428.html.

—. 2004. *Dry Bulb, Wet Bulb and Dew Point Temperatures* . Accessed 09 02, 2022. https://www.engineeringtoolbox.com/dry-wet-bulb-dew-point-air-d_682.html.

—. 2003. *Engineering ToolBox.* Accessed 09 04, 2022. https://www.engineeringtoolbox.com/convective-heat-transfer-d_430.html.

—. 2003. *Radiation Heat transfere.* Accessed 08 30, 2022. https://www.engineeringtoolbox.com/radiation-heat-transfer-d_431.html.

Esdras, Nshimyumuremyi, Wang, Junqi. 2018. "Thermal efficiency and cost analysis of solar water heater made in Rwanda ." (Sage journals) 37 (3).

Hall, Richard, Blower, John. 2016. "Low-emissivity Transpired Solar Collectors." (Energy Procedia) 91.

Hankins, Mark. 1991. "The Solar Resource." In *Small Solar Electric Systems for Africa: A Guide for Planning and Installing Solar Electric Systems in Rural Africa*, by Mark Hankins. CSC Technical Publication.

Ishihara, Yoichiro, Qian, Joe. 2021. *The World Bank.* 09 21. Accessed 09 01, 2022. https://www.worldbank.org/en/news/press-release/2017/09/21/partner-with-bhutan-improve-agriculture-productivity-food-security.

J. Kragh, J. Rose, T.R. Nielsen, S. Svendsen. 2007. "New counter flow heat exchanger designed for ventilation systems in cold climates." *Energy and Buildings*, 11 ed.

JNEC. n.d. *About the Collage.* Accessed 10 2022. https://www.jnec.edu.bt/en/our-college/.

Johansson, Per, and Anders Svensson. 1999. *Metoder för mätning av Luftflöden i ventilationsinstallationer.* Lund: Byggforskningsrådet.

Karlsson, Adam. 2022. "Low cost thermal storage for solar dryers in the Himalayas." *LUP Student Papaers.* Lund University. Accessed 08 24, 2022. https://lup.lub.lu.se/student-papers/search/publication/9085069.

Moore, Stanley W. 1985. "Solar absorber selective paint research." *Science Direct.* Accessed 03 10, 2023. https://www.sciencedirect.com/science/article/pii/0165163385900371.

Mystayen, A.G.M.B, S Mekhilef, and R Saidur. 2014. "Performance study of different solar dryers: A review." *ScienceDirect.* 06. Accessed 05 10, 2023. https://doi.org/10.1016/j.rser.2014.03.020.

Narayanan, R. 2017. "Chapter Seven - Heat-Driven Cooling Technologies." In *Clean Energy for Sustainable Development*, by Abul kalam Azad, Subhash C. Sharma Mohammad G. Rasul. Academic Press. Accessed 09 02, 2022. https://www.sciencedirect.com/science/article/pii/B9780128054239000077.

Ndawula, J. 2004. " Alterations in fruit and vegetable β-carotene and vitamin C content caused by open-sun drying, visqueen-covered and polyethylene-covered solar-dryers ." *African Health Sciences.* Accessed 08 16, 2022. https://www.ajol.info/index.php/ahs/article/view/6873.

Schmutz, Pamela, Hoyle, E.H. 1999. *Clemson Cooperative Extension - Home & Garden Information Center.* Accessed 09 01, 2022. https://hgic.clemson.edu/factsheet/drying-foods/.

Shirsat, Bhawna S., S Patel, Borkar P A, and Pramod Bakane. 2019. "PHYSICAL PROPERTIES OF FRESH GINGER (Zingiber officinale) RHIZOMES." *ResearchGate.* 07. Accessed 10 05, 2022. https://www.researchgate.net/publication/334623814_PHYSICAL_PROPERTIES_OF_FRESH_GINGER_Zingiber_officinale_RHIZOMES.

Singh, R. Paul and Desrosier, Norman Wilfred. 2022. *food preservation.* 31 07. Accessed 07 31, 2022. https://www.britannica.com/topic/food-preservation.

The Engineering Toolbox. 2003. *Emissivity Coefficients common Products.* Accessed 08 26, 2022. https://www.engineeringtoolbox.com/emissivity-coefficients-d_447.html.

The World Bank. 2022. *The World Bank.* Accessed 09 01, 2022.

WFP. 2020. "World Food Programme." *WFP's support to Nutrition in Bhutan.* Accessed 08 16, 2022. https://reliefweb.int/report/bhutan/wfp-s-support-nutrition-bhutan.

World Population Review. 2022. *Most Mountainous Countries 2022.* Accessed 08 17, 2022. https://worldpopulationreview.com/country-rankings/most-mountainous-countries.