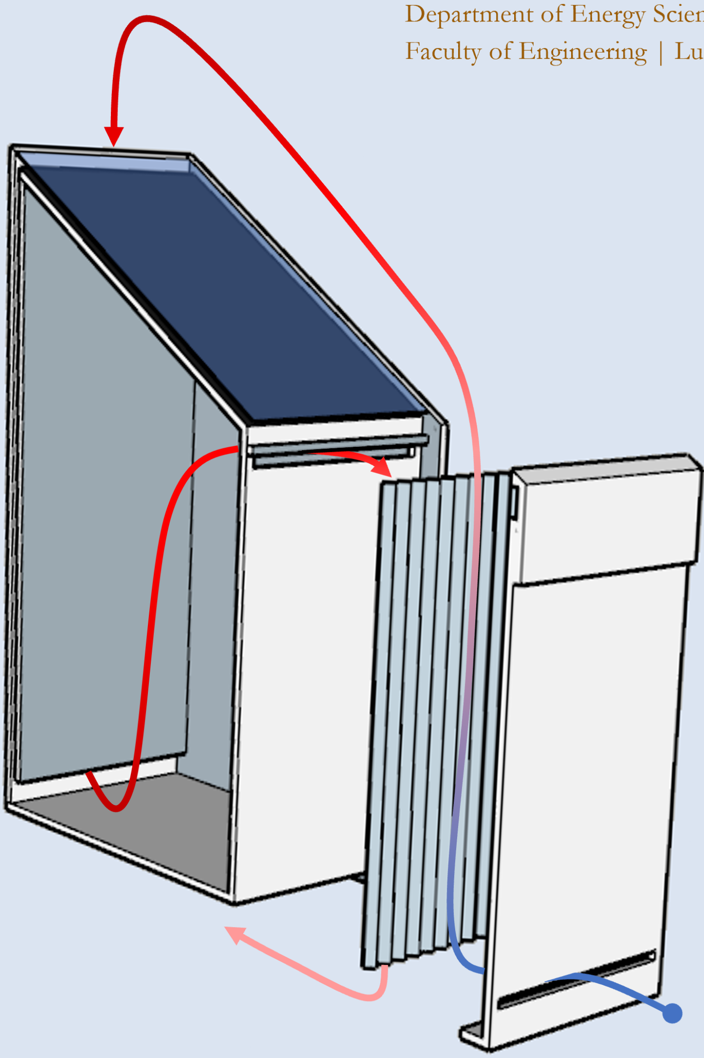
Development and Testing of a Novel Solar Dryer Design with an Incorporated Heat Exchanger

For use in the Himalayan regions

Adam Probert

Thesis for the degree of Master Science
in Engineering
Division of Heat Transfer
Department of Energy Sciences
Faculty of Engineering | Lund University



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March 2022, Lund

Abstract

Post harvest losses is a major concern for farmers in the Himalayan regions of Nepal and Bhutan. The lack of modern preservation methods, like refrigeration and controlled atmosphere, result in most farmers relying on open air sun drying to preserve their product. This method is outdated with many drawbacks. One suggested solution has been to introduce solar dryers to increase drying performance and increase food security. In this study a novel solar dryer design has been presented that will increase the drying performance further. The design includes a heat exchanger that preheats the incoming air. Tests were carried out on a prototype that was constructed at Kathmandu University. The results show that the incorporation of a simple heat exchanger can increase the drying temperature in a solar dryer by 10 °C. Issues regarding the door construction and the forced convection was highlighted during the tests. The design needs to be further developed before a final product can be presented.

Preface

This master thesis is a part of the project *SolarFood: Reducing post-harvest losses through improved solar drying* (VR-2020 -04071). The project is a collaboration between Lund University, Kathmandu University, Royal University of Bhutan and Ruralis - Institute for Rural and Regional Research. The project will span over the course of three years and is funded by the Swedish Scientific Council in collaboration with the Swedish International Development Cooperation Agency. The project is being coordinated by Dr Martin Andersson and Dr Henrik Davidsson at Lund University.

Acknowledgement

I would like to start by thanking Dr. Bivek Baral and everyone in the Energy lab at Kathmandu University. Together you welcomed me with open arms from the first day and made my stay in Nepal truly amazing. I will never forget all the adventures you brought me on! I would also like to thank my supervisors and examiator in Sweden who have answered my emails day and night and helped me when all hope seemed lost. Thank you Dr. Martin Andersson and thank you Dr. Henrik Davidsson for being there at all times and guiding me through the project! Finally I would like to thank my family and my friends who have helped and motivated me throughout this project and my entire time at University. Most of you are great and nearly all of you are at least above average. You have no idea how utterly lost I would be without you!

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1 Introduction

Within most agricultural activities the annual yield will be harvested during only a few months of the year. This yield then needs to be preserved and stored for up to twelve months until the next harvesting season. The preservation of grain crops during this period can be achieved with cheap and easily available materials (Mobolade, Bunindro, Sahoo and Rajashekar, 2019). Most fresh fruits and vegetables however, consist of over 80 % water and are classified as highly perishable commodities and deteriorate rapidly without proper handling (Hasan et al., 2019). For rural and small scale farmers in the Himalayan regions this is a major concern as modern preservation methods such as refrigeration and controlled atmosphere is not yet available or affordable (Ministry of Agriculture, 2018), (The World Bank, 2017, (Hasan et al., 2019). The only available option is often sun drying where the fruit or vegetable is placed directly in the sun to dry (Udomkun et al., 2020). This method leaves much to be desired as a significant share of the yield is spoiled during this stage. Due to a lack of studies the exact size of these post harvest losses in the Himalayan regions are not fully known. One estimate in the south Asian regions suggests the post-harvest losses to be between 25 % and 40 % and a second report on maize in Bhutan determine a post harvest loss of 26 % while a third report found drying losses of apples in Nepal to be between 40 % and 44 % (Faqeerzada et al., 2018), (Dorjiq, Tsheringq and Lhamoq, 2020), (National Agriculture Research Institute, 2019).

One suggested solution to decrease the post harvest losses in the Himalayan regions has been to introduce solar dryers. A solar dryer still relies on the radiation from the sun to dry the fruit, but unlike traditional open sun drying it does so in a more controlled way. By installing a black plate, called an absorber, in the bottom of a transparent and insulated chamber the solar radiation will be absorbed by the absorber and heat will be radiated to the chamber. The result is an increased temperature, a drastic decrease in drying time while the drying chamber also protects the product throughout the drying period (Mustayen, Mekhilef and Saidur, 2014). Many different designs for solar dryers have been suggested and tested with promising results. Dryer products such as leafy herbs, bitter gourd and lemon balm leaves can already be dried in under one day in good natural conditions (Kumar and Singh, 2020). However, for fruit and vegetables of higher moist content the drying time exceeds one day and can be as high as seven days (Kumar and Singh, 2020). There is thus a need to further improve the design and thermodynamics of the solar dryer to allow for even higher drying rates and lower drying times.

1.1 Project introduction

This master thesis is a part of the project *SolarFood: Reducing post-harvest losses through improved solar drying*. The final goal with the project is to improve farmers' livelihoods and contribute to rural development and local food security by developing a locally adapted solar dryers for crop drying with short drying times.

1.2 Aim and research questions

This report is the first in a series of reports focusing on the thermodynamics and performance of the solar dryer. The aim with this report is to develop and test a novel solar dryer design with an incorporated heat exchanger to increase performance. The solar dryer will be adapted towards use in the agricultural sector of the Himalayan regions of Nepal and Bhutan. This report hopes to present a novel solar dryer design and answer the following research questions:

- By how much can a heat exchanger increase the performance of a solar dryer?
- Could a heat exchanger be incorporated in such a way that the overall affordability of the solar dryer is kept?
- Could a heat exchanger be incorporated in such a way that the solar dryer can still be constructed locally without imported materials or skills?

1.3 Limitations

As this report is a part of multi-year project, the aim is in no way to present a finalized product. The aim is rather to prove or disprove the concept of incorporating a heat exchanger in a solar dryer. The scope of this report is also limited to designing the solar dryer. Other factors such as market analysis, receptivity, health and food safety etc. are handled by other parties within the project.

2 Background

2.1 Nepal

Agricultural sector

In Nepal more than two thirds of the countries population of 30 million, are employed within the agricultural sector. Still, the sector only contributes to one third of the countries GDP (Moody's Analytis, 2021a). The Nepalese agriculture sector is characterised by great diversity due to the varying terrain and climate. Some general problems include lacking irrigation systems, harsh terrain for transport and machinery and natural disasters such as flooding and erosion (Ministry of Agriculture, 2018). The majority of farmers grow rice or other grain crops. It is only in central parts of the country close to Kathmandu and in the very western parts where fruit and vegetable farms are dominant (Ministry of Agriculture, 2018). In the western parts a lack of post, harvest handling is stated as a main concern (Ministry of Agriculture, 2018). The average farm size in Nepal is 0.7 ha and the most grown fruits and vegetables are in falling order of yield; Cauliflower, Cabbage, Mango, Tomato, Onion, Banana, Raddish, Cucumber and Mandarin (Central Bureau of Statistics, 2019), (Ministry of agriculture & Livestock, 2021).

Food insecurity and nutrient deficiency

The rural areas of Nepal is heavily poverty stricken. In a economic survey the Ministry of finance estimate that 18.7 % of the population live below the poverty line of 1.9 $ per day (Government of Nepal Ministry of Finance, 2019). Further, the Asian Development Bank estimated the poverty in the rural areas of Nepal to be nearly twice that of the urban areas (Asian Development Bank, 2013). In a report published by the Ministry of Health and Population in Nepal only 59 % of households stated that they were food secure. 34 % of household stated that they were mildly or moderately food insecure while 7 % were severely food insecure (Nepal Ministry of Health and Population, 2016). The same report shows that Nepal faces an extensive micro-nutrient deficiency as less than half the population consumed the minimum dietary diversity (Nepal Ministry of Health and Population, 2016). The most immediate cause of micro-nutrient deficiency in Nepal is a lack of dietary diversification with low consumption of fruit, vegetables and different animal produce (Bhandari and Banjara, 2015). Diversification of crop cultivation and increased intake of nutrient-rich fruits and vegetables is highlighted as an efficient measure to battle the micro-nutrient deficiency (Bhandari and Banjara, 2015).

2.2 Bhutan

Agricultural sector

The agricultural sector in Bhutan employs more then half the countries population of 800 000, while only contributing to 17 % of the GDP (Moody's Analytics, 2021b). It is characterised by low product qualities, high post harvest losses and low food security. Some general problems include poor soils, harsh terrain for transport and machinery, outdated technology and natural disasters (Moody's Analytics, 2021b) (The World Bank 2017). As the road network is under-developed in most regions, many farms lack a secure market access and limits transport and access to storage facilities (The World Bank, 2017). The sector is dominated by small scale and family-run farms where subsidence farming is the main activity (The World Bank 2017). The average farm size in the country is 1.2 ha (The World Bank, 2017). Cereal grains and potatoes make up half the agriculture sector whereas fruits and vegetables make up about 40 % (Royal Government of Bhutan Ministry of Agriculture and Forests, 2020). The most grown fruits and vegetables in Bhutan are in falling order of yield; Mandarin, Arecanut, Turnip, Pumpkins and Squash, Cabbage, Chilli, Apple, Raddish, Cucumber, Cauliflower, Beans, Bananas, Pear, Peach and Guava (Royal Government of Bhutan Ministry of Agriculture and Forests, 2020).

Food insecurity and nutrient deficiency

For farmers in rural Bhutan, where almost 17 % lived below the poverty line of 1.9 $ per day in 2014, decreasing post harvest losses is of great importance (Moody's Analytics, 2021b). Although hunger is no longer considered a national issue nearly one third of the population suffer from food insecurity (The World Bank, 2017). Bhutan still receive humanitarian aid from the UN world food program due to malnutrition (Moody's Analytics, 2021b) (World Food Programme, 2020). In a 2017 report it was concluded that 35 % of Bhutanese households face food shortages yearly, half of which face food shortages at least 4 months per year (The World Bank, 2017). Further more 44 % of children aged 6 to 59 months suffer from anaemia which is a a proxy indicator for micro nutrient deficiencies (World Food Programme, 2020). In a risk factor survey from 2019 it was concluded that 86 % of the Bhutanese did not consume adequate amounts of fruit or vegetables (World Food Programme, 2020).

2.3 The demand for improved drying techniques

The agricultural sectors of Nepal and Bhutan have many similarities and are subjected to many of the same difficulties. The rural areas of both countries are poverty stricken with extensive food insecurity and nutrient deficiency as a result. Due to a harsh terrain and lacking infrastructure the modern preservation methods like refrigeration and controlled atmosphere are scarcely available or affordable. Many farmers are therefore forced to resort to open air sun drying where the commodity is placed in direct sunlight to dry up (Udomkun et al., 2020). Although this method is cheap, it is technically outdated and has many drawbacks. The drying process is slow and some commodities require up to seven days of drying before being sufficiently preserved (Kumar and Singh, 2020). As all drying parameters are also weather dependent there is no way to control the temperature in the process (Mustayen, Mekhilef and Saidur, 2014). This is a major concern as different products require different drying temperatures in order to be regarded as safe (Kumar and Singh, 2020). A too high temperature will burn the product and decrease the nutrient values whereas a too low temperature will only incubate the product and speed up microbial growth.

The drying process is also labour intensive as constant care is required to rotate, protect and cover the commodities during bad weather and during night hours. Throughout the drying process the commodities are subjected to dust, insects, bacterial growths and fungi infections which causes large losses and lower the quality (Mustayen, 2014). Ultimately issues related to this drying method can cause a large loss of income for the farmers (Udomkun et al., 2020). These losses are especially prevalent for fruit- and vegetable farmers as these commodities deteriorate rapidly without proper handling (Hasan et al., 2019). Due to a lack of studies the exact size of the losses emerging from post harvest handling are not fully known but estimates has put them in the span of 25 % to 45 % (Faqeerzada et al., 2018), (Dorjiq, Tsheringq and Lhamoq, 2020), (National Agriculture Research Institute, 2019). It is thus apparent that there is a demand to improve the current drying methods in rural Nepal and Bhutan.

2.4 Cabinet dryers

One suggested way of improving the drying performance and decreasing the post harvest losses has been to introduce different solar dryers. A solar dryer still relies on the radiation from the sun to dry the fruit, but unlike traditional open sun drying it does so in a controlled chamber. With the addition of an absorber chamber that absorbs the solar radiation and an insulated drying chamber, the drying time drastically decreases while also protecting the product throughout the drying period (Mustayen, 2014). During the past decades efforts has been made to develop a solar powered drying system that can increase drying rate and product quality. Many different designs have been suggested and tested with promising results (Kumar and Singh, 2020) (Mustayen, 2014).

Although size, design and materials varies greatly between proposed systems many of the most promising and widely tested solar dryers are categorised as cabinet dryers. In a cabinet dryer glass or transparent plastics is utilized together with an absorber to absorb the solar radiation and and insulated chamber to create a protected drying cabinet (Kumar and Singh, 2020) (Mustayen, 2014). The cabinet results in a drastic increase in drying temperature and drying rate. Dryer products such as leafy herbs, bitter gourd and lemon balm leaves can already be dried in under one day in good natural conditions (Kumar and Singh, 2020). However, for fruit and vegetables of higher moisture content the drying time most often exceeds one day and can be as high as seven days (Kumar and Singh, 2020). There is thus a need to further improve the design of the cabinet solar dryers to allow for even higher drying rates and lower drying times. Cabinet solar dryers can be categorized as either direct or indirect.

Direct solar dryers

A direct solar dryer consists of only one combined absorber- and drying chamber. The absorber is installed in the bottom of the chamber and the product is placed on treys above it (see figure 2.1) (Kumar and Singh, 2020). These dryers are simple, cheap and easy to construct (Mustayen, 2014). Some drawbacks however, include a limited drying capacity and and uneven product quality (Kumar, Sansaniwal and Khatak, 2016). The product that is dried in a direct solar dryer can also be damaged by the direct sunlight causing a drastic decrease in nutrition values (Kumar and Singh, 2020).

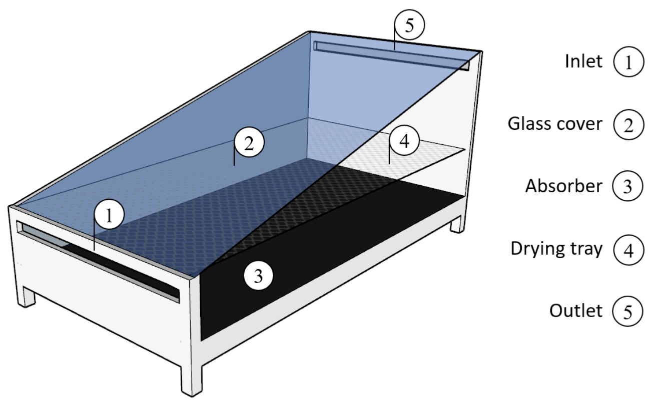

Figure 2.1: A schematic view of a direct cabinet solar dryer (Probert A, 2021)

Indirect solar dryers

An indirect solar dryer consists of two separated chambers. The absorber chamber is designed to collect the solar radiation and to heat an airflow. This air is then lead in to the second adjacent drying chamber where the fruit is dried (Kumar, Sansaniwal and Khatak, 2016). The system is more expensive but in return delivers higher drying rates, higher temperatures and a more even drying process (Kumar, Sansaniwal and Khatak, 2016). Since the fruit are not subjected to direct sunlight they also retain more nutrients than would be the case if they would be dried in a direct solar dryer (see figure 2.2) (Udomkun et al., 2020).

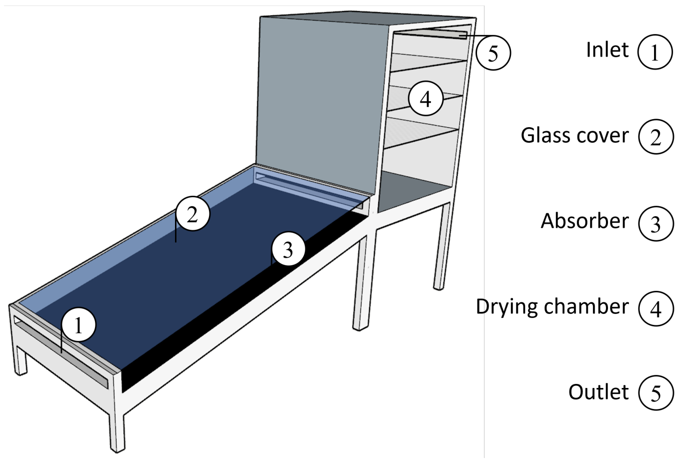

Figure 2.2: A schematic view of an indirect cabinet solar dryer (Probert A, 2021)

Choosing solar dryer type

Although the solar dryer types are clearly distinguishable in design, previous research has shown that the performance varies greatly even within these categories (Kumar and Singh, 2020). Early reviews on the subject prefer direct and passive solar dryers to a greater extent due to their simpler and cheaper design and independence of electricity (Ekechukwu and Norton, 1999). As designs became more efficient and solar panels became cheaper the preference shifted and later reviews has to a larger extent concluded that indirect and active solar dryers reach a lower drying time and increased fruit quality which out weighs the increased costs (Kumar, Sansaniwal and Khatak, 2016) (Paul and Singh, 2021). Direct solar driers are generally only efficient for smaller quantities of products with low moisture content while the indirect and active solar dryers are preferred for larger quantities or more moist products (Kumar, Sansaniwal and Khatak, 2016).

The Bhutanese and Nepalese agricultural sector is dominated by small scale and family-run farms. Although these farms do not produce a high yield in comparison to more developed farms the yields are still counted in tons per hectare (Food and Agriculture Organization of the United Nations, 2012). With an average farm size of 0.7 ha in Nepal and 1.2 ha in Bhutan this places the yield well above the limit that would favour indirect solar dryers (Kumar and Singh, 2020). The most commonly grown fruits and vegetables in Bhutan and Nepal are also of higher moisture contents that have been proven challenging to dry in a direct solar dryer (Kumar and Singh, 2020). The profound nutrient deficiencies in Bhutan and Nepal would further strengthen the case of a solar dryer where the product is protected from the sun. In regards to this an indirect solar dryers would be considered more suitable for this task.

2.5 Heat exchanger

All cabinet dryers have in common that they have one air inlet where cold air is brought in to the dryer and one outlet where the heated air is released. As the outgoing air has passed the drying chamber it is partly, or fully, saturated with moisture and is unable to dry any more product. It is however still significantly warmer than the inlet air raising the possibility of introducing a heat exchanger.

A heat exchanger is technically a device which aims to increase the heat transfer between two bodies. In this case these bodies are the two air streams, the outlet air and the inlet air. By incorporating a heat exchanger the excess heat could be used to preheat the incoming air before it reaches the absorber. By doing so the thermal energy would be recycled within the dryer, ultimately leading to reduced heat losses, increased thermal efficiencies and an increased drying temperature.

There is not much existing research combining heat exchangers and solar dryers. The author of this report has not been able to find any previous prototypes where heat exchangers has been installed in cabinet solar dryers. However there is proof that air-air heat exchangers can be efficiently implemented at these relatively low temperatures to improve efficiency without negatively impacting the drying process (Ghasemkhani et al., 2016).

2.6 Heat transfer

As the performance of a solar dryer is ultimately dependent on energy balances, an understanding of heat transfer is key in further developing the design. Although radiative heat transfer is central in the absorber, it is the convective heat transfer forces that are of most interest when redesigning the solar dryer. These forces are the dominating factor in the heat exchanger and for the heat losses through the walls of the solar dryer. The convective forces between two mediums is expressed by equation 2.1.

$$\dot{Q} = h \cdot A \cdot \Delta T(t) \tag{2.1}$$

Where $\dot{Q}$ denotes the convective heat transfer, h denotes the heat transfer coefficient, A denotes the surface area where the heat transfer takes place and ΔT(t) denotes the temperature difference between the two mediums. While the two latter parameters can be altered directly, the heat transfer coefficient is more complex. For compact surfaces the heat transfer coefficient can be expressed by introducing Nusselts number in equation 2.2.

$$Nu = \frac{h \cdot D_h}{\lambda} \tag{2.2}$$

Where Nu denotes Nusselts number, λ denotes the thermal conductivity and D_h denotes the hydraulic diameter which can be further calculated through equation 2.3.

$$D_h = \frac{4A}{P} \tag{2.3}$$

Where A is the cross sectional area of the surface and P denotes the wetted perimeter in direct contact with the other medium.

Nu is a dimensionless number relating the conductive and convective heat transfer in a boundary layer. This relation is dependant on the geometry of the boundary layer as well as the behaviour of the flow. An approximation of *Nu* in triangular ducts is shown in equation 2.4. Empirical studies have found that this equation leaves an error margin of below 10 %. (Shah, London and White, 1978)

$$Nu = 2.15 + (2.31)(10^{-3}Re + 1.25(10^{-7})Re^2 - (9.6)(10^-12)Re^3 \tag{2.4}$$

A simplified version of the equation, with an error margin below 15 %, is shows in equation 2.5 (Shah, London and White, 1978).

$$Nu = 2.15 + 0.00245Re \tag{2.5}$$

Here Re denotes the dimensionless Reynolds number which is the ratio of inertial and viscous forces in a flowing fluid. The definition of *Re* is shown in equation 2.6.

$$Re = \frac{uD_h}{\nu} \tag{2.6}$$

Where u denotes the mean velocity of the fluid and ν denotes the kinematic viscosity. If a flowing fluid has high inertial forces and low viscous forces a turbulent flow will arise characterised by random and chaotic movements with whirls. This is often the case when *Re* has a value above 2300. If *Re* is low, with high viscous forces and low inertial forces, the flow will be laminar with a uniform flow pattern. A high *Re* will result in a turbulent flow and through equations 2.5, 2.4 and 2.2 an increased *Nu* and heat transfer coefficient.

Empirical studies have however shown that this direct link between *Re*, *Nu* and the heat transfer coefficient in reality is more complex. For starters equation 2.5 is only valid in systems where $Re < 2200$ and the ratio of the length and diameter of the duct is above 50 ($L/d > 50$) (Shah, London and White, 1978). Further, equation 2.6 is only directly valid for circular ducts. A non-circular duct, with sharp corners give rise to fluctuating and unpredictable flows that will behave differently within different parts of the duct. The result being that turbulent and laminar flows will coexist requiring further modifications to the equations (Hesselgreaves, Law and Reay, 2016b). For this report the exact heat transfer coefficient is however not necessary. As the aim is not to optimize the heat exchanger it is deemed sufficient to only determine what factors influence the heat transfer coefficient.

Influencing the Heat transfer

Through equations 2.5, 2.4 and 2.2 it is now clear that the heat transfer coefficient can be increased by increasing *Re*. According to equation 2.6 this is achieved either by increasing D_h or the mean velocity of the fluid. By increasing D_h, *Re* would increase but as D_h is present in the numerator in equation 2.2 the heat transfer coefficient would remain unchanged. The possibility of increasing D_h is also limited as it would require larger ducts, effectively decreasing the effective area and the total heat transfer according to equation 2.1.

An increase of mean velocity is therefore easier to achieve. The unit of the heat transfer coefficient is however $W/(m^2K)$ and if studied it is apparent that an increase in mean velocity is not necessarily desired. As the unit is time dependent, an increased flow rate will result in less energy per volume air. Thus if the increase in mean velocity also increase the flow rate two contradicting effects on the heat transfer will arise. On one hand the *Re* increases but on the other, the transferred heat would be shared by more air. If the mean velocity could be increased without also increasing the flow rate, for example by designing a thinner and longer heat exchanger, the effect of the heat transfer would be only positive.

It is also apparent from equation 2.1 that an increase in the surface area of the heat exchanger or an increase of $\Delta T(t)$ would result in an increased heat transfer between the two mediums. This can be achieved for example by adding heat fins.

3 Method

The method for this study has been divided into two sections. The first section aims to derive and present a new solar dryer design whereas the second section consists of field tests where two prototypes will be built and tested.

3.1 Designing the Solar dryer

A design criteria for the solar dryer design was established to ensure that the design would be adapted to its task. A review of the current situation in the agricultural sector of Nepal and Bhutan was carried out in order to list and highlight the most crucial requirements that the new solar dryer design would face.

With the design criteria in place a literature study was conducted in order to decide on the most appropriate solar dryer design as described in section 2.4. Strengths and weaknesses of the different designs were highlighted and the overall suitability for the task was evaluated using the design criteria. Lastly, different opportunities for the incorporation of the heat exchanger in the solar dryer design were evaluated. Different placements and heat exchanger types were discussed. From this last step the overall design and characteristics of the solar dryer design came together and was presented.

3.2 Field test

The field tests included the construction of two solar dryers. A first prototype was constructed at Lund University in Sweden. Here the design was tested with the help of a controlled environment and a solar lamp. The aim with the first prototype was to assert that the design worked as intended and to highlight any challenges in the construction of the design. The solar dryer was tested with the solar lamp set to 900 W/m and the flow set to 32 l/s.

The insight gathered from the first prototype was incorporated in a second dryer that was built at Kathmandu University in Nepal. Here the dryer was placed outside on a terrace without any shading, and tested in ambient conditions. Tests were conducted to optimize the flow rate and heat exchanger geometry. The construction process was outsourced to a local carpenter in order to test the complexity of the construction process and to highlight any uncertainty in the drawings.

Construction

The second solar dryer prototype was constructed and assembled by locally available materials and by local business. The report author gave detailed instructions and was available to answer any questions from the craftsmen.

Flow optimisation

Multiple full-day measurements were conducted with the fan set to each of the following voltages; 16 V, 12 V, 8 V and 4 V. The measurements were repeated for each voltage until data from a clear day with stable solar radiation was collected. The solar radiation, flow rate and temperatures were measured according to the measuring plan in section 3.3 and the data was processed in excel.

Optimising the heat exchanger

During the tests two heat exchangers were tested. The heat exchangers consisted of one single piece of metal. The first heat exchanger was folded in V-shapes with a V-height of 1.5 cm and a V-width of 2 cm (see figure 3.1). The second heat exchanger was a flat metal sheet without any folds. The total width and length of both heat exchangers were 50 cm and 102 cm respectively.

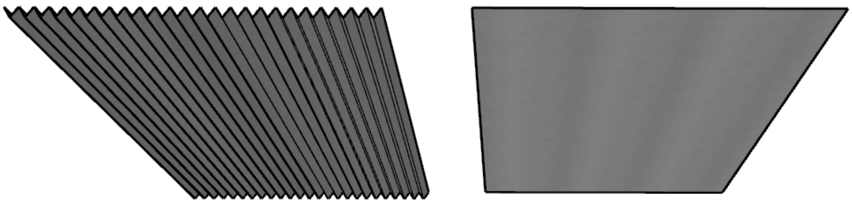

Figure 3.1: A schematic view of the two heat exchangers (Probert A, 2021)

The first heat exchanger was tested through multiple full-day measurements with the fan set to each of the following voltages; 16 V, 12 V, 8 V and 4 V. The measurements were repeated for each voltage until data from a clear day with stable solar radiation was collected. The efficiency of the heat exchanger was measured as the quotient of the theoretical maximum temperature increase of the inlet air, denoted as AMT for arithmetic mean temperature, and the actual temperature increase according to equation 3.1 (Fakheri, 2014).

$$\eta = \frac{\Delta T}{\Delta T_{max}} = \frac{\Delta T_{actual}}{AMT} \tag{3.1}$$

Where AMT is the theoretical maximum heat transfer where both air flows reach the same temperature defined by equation 3.2.

$$AMT = \frac{T_{in} + T_{out}}{2} \tag{3.2}$$

Where T_{in} is the temperature of the cool air entering the heat exchanger and T_{out} is the temperature of the hotter air exiting the drying chamber.

After the flow measurements were completed the second heat exchanger was installed instead. This setup was tested during multiple full-day measurements with the fan set to 8 V. The efficiency of the second heat exchanger was monitored and compared to the first heat exchanger.

3.3 Measuring plan

A system of instruments were used to measure and log the solar radiation, flow rate and multiple temperatures within the dryer during the experiments. A total of 35 type T thermocouples and a CR11 pyranometer were connected to a Campbell Scientific CR1000 logger and an AM16/32 multiplexer. The logger read the instruments every 30 seconds and every minute the mean value of the two last measurements were stored on the logger and later transferred to a computer. The flow rate was measured once per day with a hand held anemometer following the protocol described by the former Swedish Council for Building Research (Byggforskningsrådet, 1999). The flow was measured in a pipe connected to the solar dryer whereas the pyranometer was placed on top of the protective glass. The ambient temperature was measured in shaded place in close proximity to the solar dryer. The rest of the thermocouples were installed according to figure 3.2 where each temperature measuring point had five thermocouples installed for increased certainty (see section 4.1 for details of the solar dryer design).

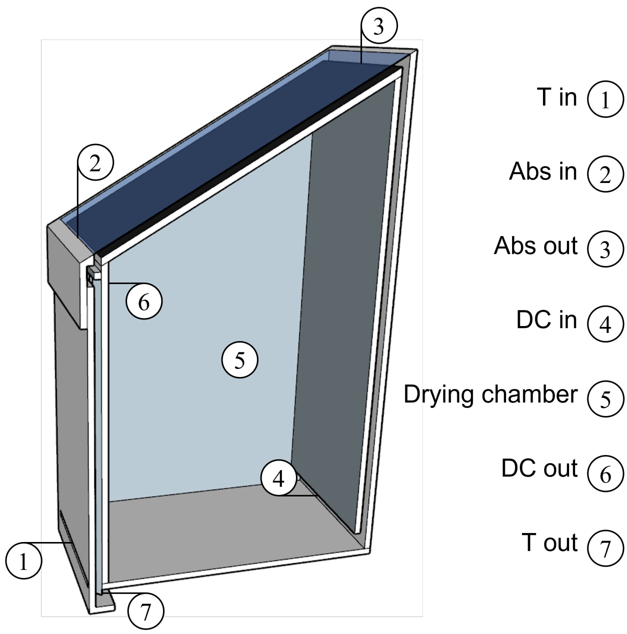

Figure 3.2: A schematic view of the placement of thermocouples within the solar dryer. In each measuring point there are five thermal couples installed evenly through the depth of the dryer (Probert, 2021)

4 Results

4.1 Designing the Solar Dryer

In a performance study reviewing previous solar dryer designs Mustayen et al. concluded that different solar dryer designs have different strengths and weaknesses making them suitable for different tasks and applications (Mustayen, Mekhilef and Saidur, 2014). To make sure that the design is adapted towards the task at hand it is crucial to specify the challenges the solar dryer will face. This is ensured by establishing the *design criteria*. In the design criteria the most crucial factors for the success of the design are highlighted so that the design will fit its context. The importance of each factor is also ranked from high to low so priorities can be made. The level of importance was based on the literature study. The most important factors were found to be Performance, Affordability, Flexibility, Complexity and Sustainability. See table 4.1 for a summary of the design criteria.

Performance
The main concerns raised with open sun drying is the low drying rates and long drying times (Lhendup, 2021) (Kumar and Singh, 2020). During the drying process the product is subjected to pests, dust, insects, rain, fungi and bacterial growth which together causes large losses and lowers the product quality (Lhendup, 2021) (Kumar and Singh, 2020). Therefore a substantial decrease of drying time is needed in order for the solar dryer to present itself as a viable alternative to traditional open air sun drying. The quality of the dried fruit also need to be maintained at the very least, but an increase of quality would be desired for example by achieving more evenly dried product. Especially maintaining the high nutrient values of the fruit is of importance to battle the nutrient deficiencies in both countries (World Food Programme, 2020) (Nepal Ministry of Health and Population, 2016).

Affordability
The target group of the solar dryer is mainly farmers in the poor rural regions where more modern conservation methods such as refrigeration or controlled atmosphere, are not available or affordable (Hasan et al., 2019). The rural regions of Bhutan and Nepal are heavily poverty stricken so a low-cost design that is affordable by the farmers is an absolute necessity for the solar dryer to be an option. The cost needs to be kept low throughout installation, management and maintenance.

Flexibility
Most farmers in both Nepal and Bhutan farm a large variety of crops, grains fruit and vegetables. Therefore it is of importance that the dryer is flexible and can be used for the whole variety.

Complexity
As the solar dryer will be a reasonably heavy and large construction it will not be possible (or economically feasible) to transport it from afar. The final design needs to be simple and should to the largest extent only consist of materials that are readily available in the rural areas. Complexity also implies that the final design needs to be user-friendly and easy to operate regardless of experience and prior knowledge.

Sustainability
The ultimate solar dryer would solely be driven by sunlight both for heat and electricity. However as Nepal and Bhutan has a renewable energy mix based of hydropower and has nearly universal electricity coverage an active solar dryer with a electric fan connected to the grid would still be deemed sustainable.

Table 4.1: This tasks design criteria and the priority of each criteria

Factor	Description	Priority
Performance	A substantial decrease of drying time is required as well as maintaining quality.	High
Affordability	The design is required to be affordable by farmers in the poverty struck rural areas.	High
Flexibility	The design should be able to dry a variety of products and be implemented in different places.	Medium
Complexity	The design needs to be easy to construct locally and easy to operate regardless of experience and prior knowledge.	Medium
Sustainability	There should be no use of bio- or fossil fuels involved in the design.	Medium

4.1.1 Incorporating the Heat Exchanger

There are multiple options and alternatives for incorporating a heat exchanger into an indirect solar dryer. The aim is to find a solution which has a high performance while still being simple and cheap to construct. One option would be to connect an external heat exchanger to the solar dryer. An external heat exchangers could be efficient but would come at a high cost. The external heat exchangers could also be harder to construct locally as some parts would likely need to be outsourced from elsewhere. The connection to the external heat exchanger could also be material-heavy and would result in channels further increasing heat losses and flow resistance. Another option would be to redesign the solar dryer and fit the heat exchanger inside the design. This has the potential to decrease the material usage and would be more flexible in the choice of heat exchanger materials. A complete rework of the design could also benefit other aspects of the design as it allows for a comprehensive overview of the whole system.

4.1.2 The Novel Solar Dryer Design

Below the novel solar dryer design is presented. The predominant features of the solar dryer is the introduction of an incorporated heat exchanger and the fact that the absorber is placed on top of the drying chamber rather than beside it. For traditional solar dryers this switch would result in a higher energy usage as warm air needs to be forced downwards. However, for the heat exchanger to work efficiently a counter-flow is needed and thus this vertical air movement is unavoidable. This more compact design aims to decrease the material usage and thus production cost, as the top and front sides of the drying chamber are shared with the absorber chamber and heat exchanger respectively. This increase the thermal efficiency by allowing some of the heat losses to be re-circulated. Any heat losses from the bottom of the absorber chamber will for example just end up inside the drying chamber and would still contribute to the drying process. Likewise heat escaping from the front of the drying chamber would be recycled through the heat exchanger. The drying chamber would be better insulated as the top part would even have a positive heat transfer as the warmer air from the drying chamber would result in a net movement of heat inwards towards the drying chamber. The incorporated design also minimizes the necessary heat losses associated with the air movement from the outlet to the inlet as this movement is now locked inside the drying chamber. In figure 4.1 the schematics for the second prototype can be seen.

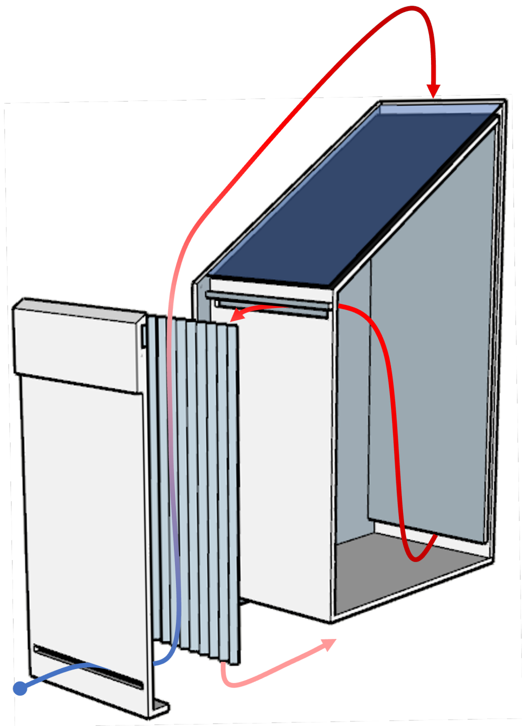

Figure 4.1: A schematic of the second solar dryer prototype constructed in Kathmandu. Note that this is a experimental prototype only (Probert. A. 2021).

Note that the schematic in figure 4.1 is an experimental prototype and not a commercial product. It is in fact the second prototype which was built in Kathmandu. Here the heat exchanger is installed by clamping it in place between the wooden stick fastened above the air outlet of the drying chamber and the wooden piece attached at the bottom of the front piece. The reason for this is to enable easy access and be able to change the heat exchanger. This is only necessary for experimental purpose and thus a commercial design would have a different solution to this. Further design details are presented below.

Heat exchanger

The proposed design has been shaped around making the heat exchanger as simple and cheap as possible. The heat exchanger is placed inside a thin compartment and consists of a single piece of waved metal. The waved form increases the surface area and aims at creating a turbulent flow. It also increases the constructions stability. The metal sheet can be constructed from a variety of readily available metals and the waved form can be made locally.

Drying chamber
The drying chamber is located below the absorber. This eliminates any heat losses from the top as the temperature is warmer in the absorber chamber. Any heat losses through the front plate would be recycled through the heat exchanger and would heat the incoming air. The wooden wall towards the back of the solar dryer aims to lead the air downwards to ensure that the heat will be evenly distributed in the drying chamber. By leading this air on the inside of the dryer the heat losses are minimized as any heat leaking inwards would be reused in the drying chamber.

Fan connector
The fan connector is a piece that connects the fan to the rectangular inlet slit in the solar dryer. It is designed to minimize resistance and lead the air smoothly. A schematics of the fan connector is shown in figure 4.2 below.

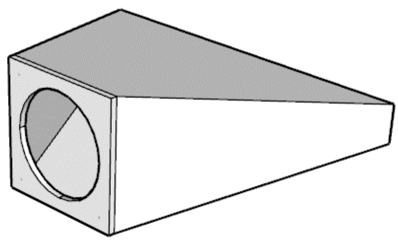

Figure 4.2: A schematic of the fan connector that is installed on the front piece and acts as a bridge between the fan and the inlet slit of the solar dryer (Probert. A. 2022).

Absorber chamber
The absorber chamber has studs installed which aim to lift the absorber from the bottom of the absorber chamber. By creating a one centimeter gap below the absorber, the surface area of the absorber in contact with the airflow in increased. The heat losses are also decreased as there is no direct conduction between the warmer absorber and the bottom plate.

Materials
The solar dryer has been designed with the possibility of local construction in mind. Thus the materials are all readily available in most parts of the world. Plywood is predominantly used for the main construction of the dryer. For the absorber one sheet of metal is needed and a glass sheet is needed to cover the absorber chamber. A variety of insulation materials can be used to cover the dryer. In this report a low emitting absorber will be used. This could be exchanged for a sheet of metal or wood which is painted black however this would result in a lower efficiency.

4.2 Lund University Laboratory Tests

Construction

A first prototype of the solar dryer was constructed at Lund University. The construction process indicated that the design was, in most parts, simple and straight forward to assemble. The wood pieces were sawed by a wood worker using precise tooling. The heat exchanger was made by a sheet-metal worker also using precise tooling. The dryer was assembled by the report author without previous experiences of wood working. The door construction was fastened through a set-up consisting of one screw and eight rubber straps. The insulation consisted of foam plastic screwed in place on all sides. Challenges were found in the installation of the heat exchanger as the top and bottom part of the heat exchanger needed to be sealed with joint foam not to leak. The door system was also hard to fasten and seal after each opening. The first prototype can be seen in figure 4.3.

Figure 4.3: The first prototype constructed at Lund University (Probert. A. 2021).

Performance test

As a reminder the temperature measurement were taken according to figure 3.2. For full explanation of the measurement points see section 3.3.

The performance of the first prototype was measured when the lamp was set to 900 W/m and the fan set to 12 V, measuring a flow of 32 l/s. The prototype was tested during a run of nearly 6 hours. The results of the test is shown in figure 4.4.

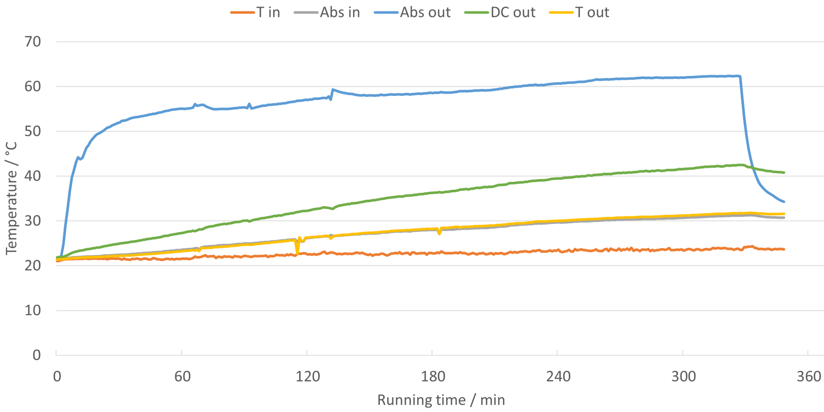

Figure 4.4: The performance of the solar dryer with an irradiation of 900 W/m and a measured flow of 32 l/s.

The temperature of the air leaving the drying chamber reached a maximum of 42 °C at the end of the measurement. The temperature directly after the absorber was shown to be substantially higher than at any other place of the dryer, above 60 °C. The temperature decreased nearly 20 °C from the absorber to the heat exchanger. Note that the solar lamp was turned of at t=330 minutes resulting in the sudden drop of temperatures as the dryer cooled down. In the first prototype the temperature was not measured at the entrance nor inside the drying chamber.

The performance of the heat exchanger was calculated through the temperature difference of the inlet air. In figure 4.5 the heat exchangers performance is shown.

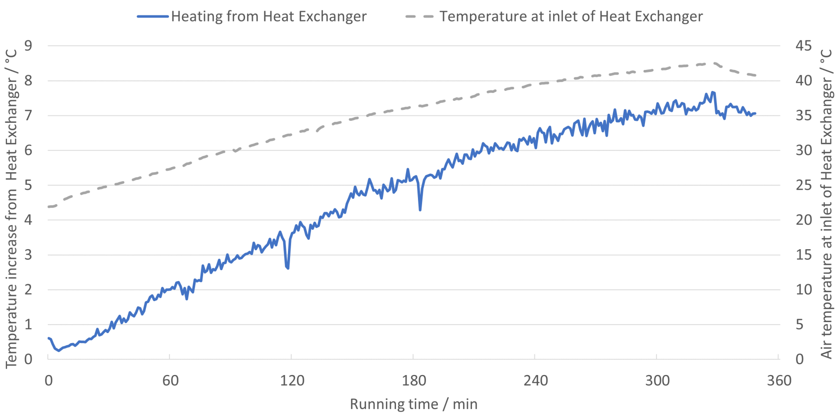

Figure 4.5: The temperature increase of the inlet air passing through the heat exchanger as well as the temperature of the air entering the heat exchanger.

The performance of the heat exchanger is seen to steadily increase throughout the experiment reaching a maximum of about 7 °C at the end of the experiment. The temperature of the air entering the heat exchanger is also shown for reference and is likewise increasing throughout the experiment.

From the data collected during the test a volumetric loss of flow was noted. The temperature difference on the two sides of the heat exchanger differed from each other denoting different flows as the heat capacity of the air volumes are comparable. The estimated volumetric losses from the prototype are presented in figure 4.6 below.

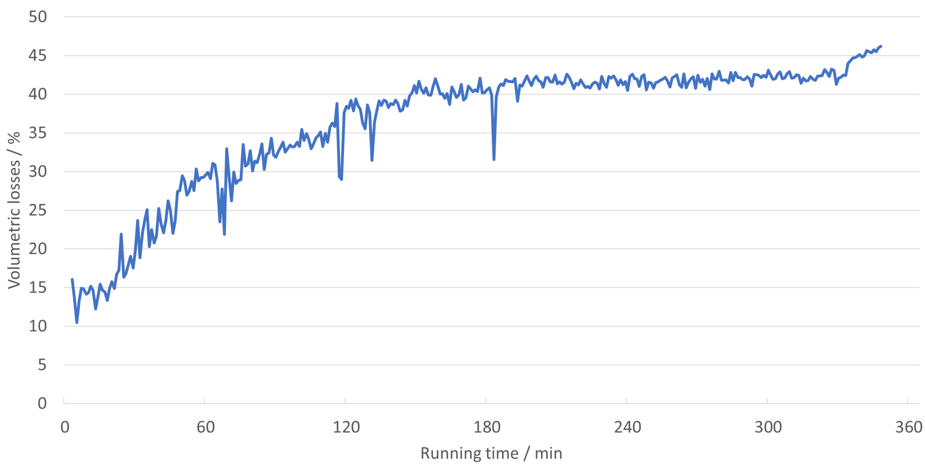

Figure 4.6: The volumetric flow rate losses as indicated by the difference in cooling and heating on the heat exchanger

The volumetric losses through the solar dryer were observed to start at 10 % but grew as the dryer heated up. After three hours the losses stabilised at around 40 %.

4.3 Kathmandu University Field Tests

Construction

The second prototype was constructed and assembled entirely by a local carpenter after receiving detailed instructions. The heat exchanger was likewise made by a local sheet-metal worker using only basic tools. All materials used were readily available at the market in Banepa, a suburb of Kathmandu. Due to the leakage observed in the first prototype the door construction was changed slightly to be fastened with 12 screws. The design of the front piece was also changed to allow for a easier access to the heat exchanger and allow for it to be changed. The insulation consisted of Styrofoam available at the local market. The second prototype can be seen in figure 4.7.

Figure 4.7: The second prototype constructed at Kathmandu University (Probert. A. 2021).

Data processing

Due to a malfunction in the data logger some of the collected data from the measurements in Nepal needed to be processed. In figure 4.8 raw data from a measurement is shown as an example of the data handling process.

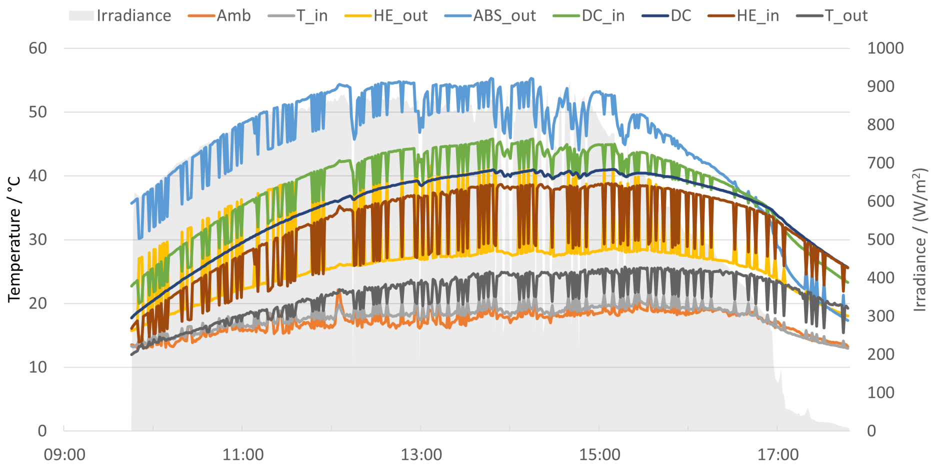

Figure 4.8: An example of how the malfunctioning logger stored data. The graph is chosen only to highlight the problems in data storage.

The errors effected every measurement connected to the multiplexer, leaving the values of T_in, T_amb and the pyranometer as these were connected directly to the logger and were unaffected. In order to correct the errors the faulty values were removed and replaced with a linear regression connecting the last and first affirmed values. In figure 4.9 the same data is shown after data processing.

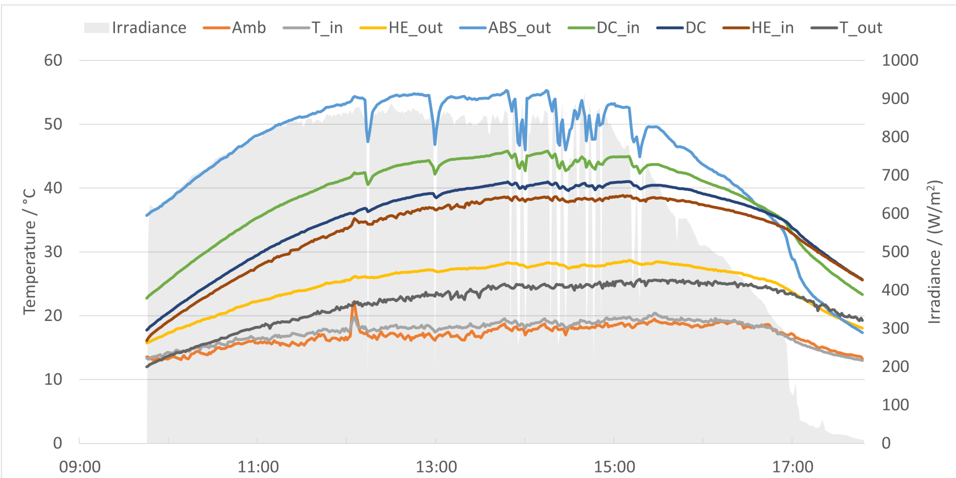

Figure 4.9: An example of how the data looks after being reworked through a linear regression connecting the last and first affirmed values. The graph is chosen only to highlight the problems in data storage.

The impact of flow rate on the performance

Due to a rapid shift in weather the flow rate measurements were carried out in two separate groups. The first group consisted of 16, 12 and 8 V and were measured during a warmer period with a higher ambient temperature. The second group consisted of 8 V and 4 V and was measured during a colder period. There was also a smaller modification which was carried out on the door system between the two measurements. This is assumed to have minimum impact on the measurements as they are based on the temperature entering the drying chamber. The measurements of the second group was started one hour later than the first group due to a limited access to the solar dryer was placed. In figure 4.10 the temperature entering the drying chamber is shown for the fan set to 16, 12 and 8 V, correlating to 32, 24 and 16 l/s respectively. The average solar radiation for the full set of measurements are also plotted (dark gray) along with the complete interval span within which the solar radiation was kept through all days (light gray). Note that the plotted temperatures are a mean value of multiple measurements. Three measurements were carried out on 8V, two were carried out on 12 V and one measurement was carried out on 16 V.

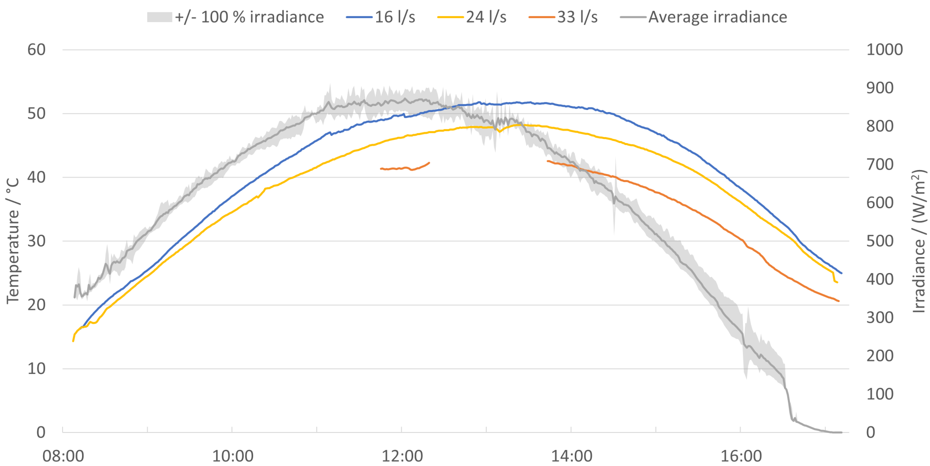

Figure 4.10: The mean temperature of the air entering the drying chamber for flow rates of 33, 24 and 16 l/s.

The results from the first group indicate that the lowest flow of 16 l/s resulted in the highest temperature, reaching a maximum of 52°C. The medium flow of 24 l/s resulted in a maximum temperature of 48°C while the highest flow of 33 l/s resulted in a maximum temperature of about 44°C. Two power cuts during the measurement of 33 l/s resulted in some of the data missing.

The result from the second group is shown in figure 4.11. Three measurements were carried out for the flow of 16 l/s whereas two were carried out with the flow set to 7 l/s. Note that the measurements started one hour later in the morning and that the ambient temperature was lower for the second group than the first group.

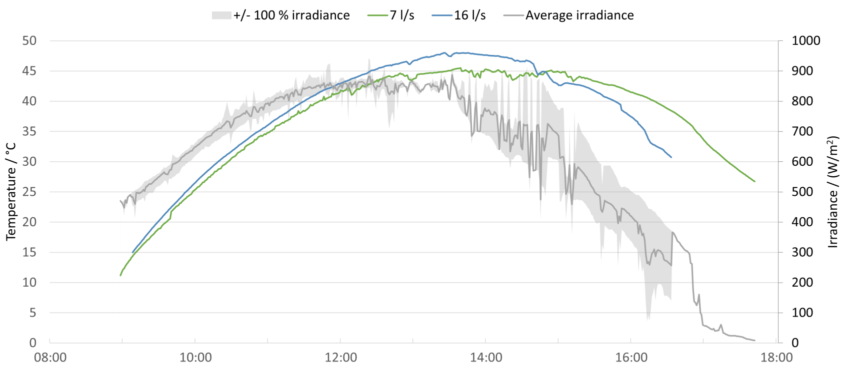

Figure 4.11: The mean temperature of the air entering the drying chamber for flow rates of 16 and 7 l/s. Note that the measurements started one hour later in the morning and that the ambient temperature was lower for the second group than the first group.

The results from the second group indicate that the higher flow of 16 l/s resulted in the highest temperature reaching a maximum of 48°C. The lower flow of 7 l/s resulted in a maximum temperature of 46°C. Due to unstable weather the solar radiation did fluctuate a lot in the afternoons. The measurements with the higher flow was observed to cool more rapidly than the higher flow rate.

Throughout all tests the highest temperatures were observed directly after the absorber. Figures 4.12 and 4.13 show the mean temperatures of the air leaving the absorber for the different flow rates.

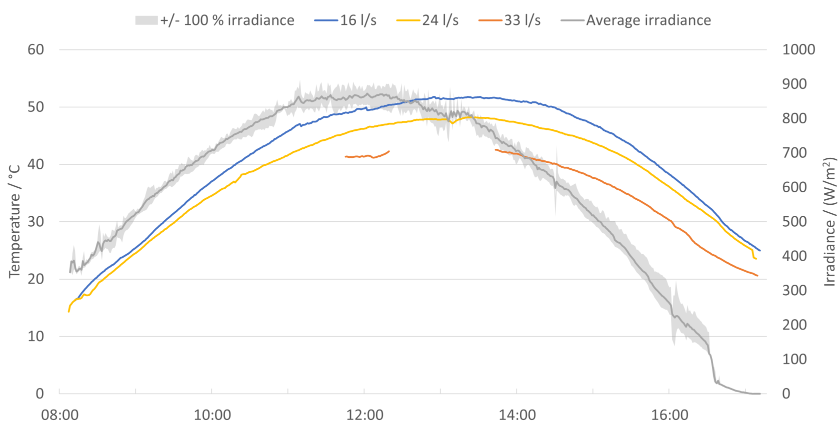

Figure 4.12: The mean temperature of the air leaving the absorber at flow rates of 33, 24 and 16 l/s.

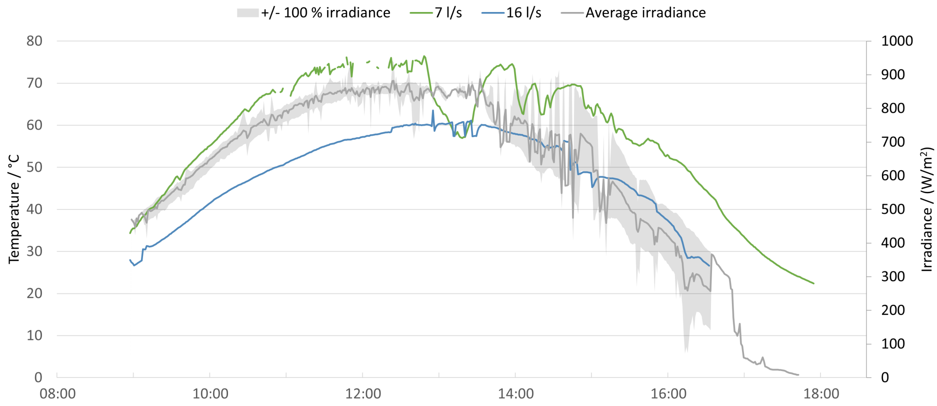

Figure 4.13: The mean temperature of the air leaving the absorber at flow rates of 16 and 7 l/s.

The results indicate that the temperature after the absorber is higher when the flow is low. The maximum temperature is observed at a flow rate of 7 l/s where the temperature reaches above the maximum measurable temperature of the thermocouples which is 76°C. The temperature is observed to be lowest for the highest flow rate of 33 l/s. For this flow the temperature barely reaches 50°C.

The impact of flow rate on the performance of the heat exchanger

During the flow measurements the efficiency of the folded heat exchanger was measured. The results from the first group can be seen in figure 4.14.

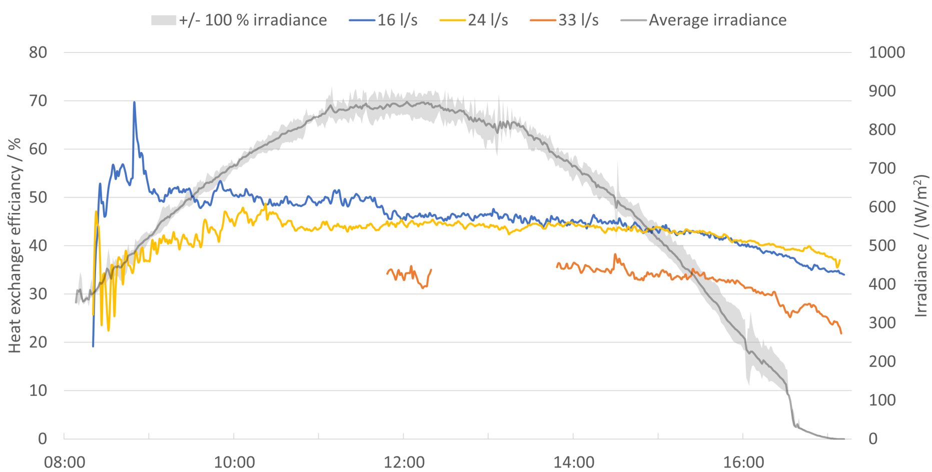

Figure 4.14: The efficiency of the heat exchanger measured over different flow rates.

During the first hours of the measurements the lower flow of 16 l/s showcase the highest efficiency of around 50 %. At noon the efficiency decreases to 45 % and there is no longer an observable difference from the efficiency of 24 l/s. The highest flow rate of 33 l/s showcase the lowest efficiency throughout the measurements, reaching a maximum of about 35 %.

In figure 4.15 the heat exchanger efficiencies of the second group is presented. Note that the measurements for this group started an hour later than the first group, resulting in the ambient temperature being substantially higher than the cooler air in the insulated drying chamber. This results in the heat exchanger working the opposite way while the air is warming up resulting in a efficiency of above 100 % in the morning.

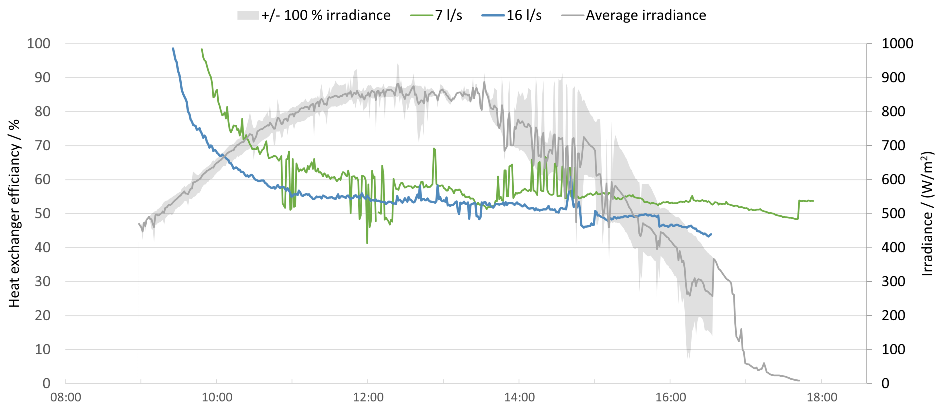

Figure 4.15: The efficiency of the heat exchanger measured over different flow rates. Note the later start which results in the the incoming air being substantially warmer than the cooler air leaving the insulated dryer.

The results indicate that the lower flow of 7 l/s results in the highest efficiency of around 55 %. For the higher flow of 16 l/s the efficiency is observed to be steadily about 5 % lower.

The temperature difference on the two sides of the heat exchanger was observed to differ from each other denoting a volumetric flow loss. The estimated volumetric losses from the first group are shown in figure 4.16.

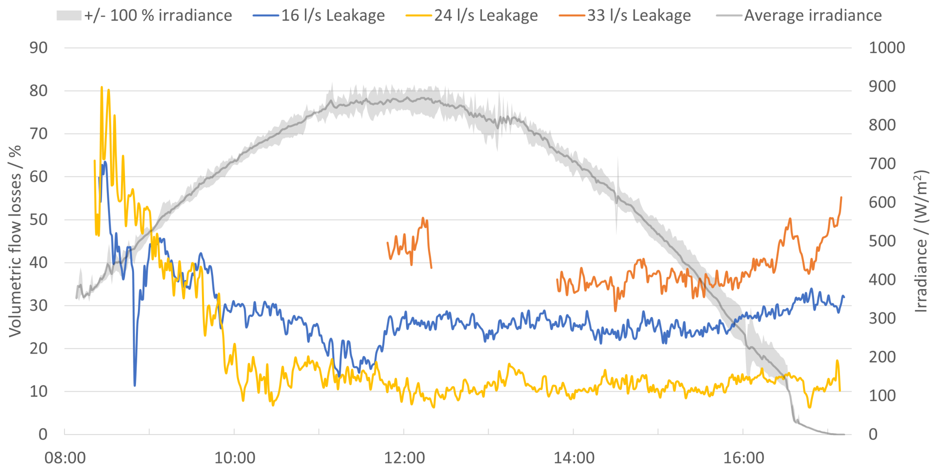

Figure 4.16: The volumetric flow losses for the tests as indicated by the difference in cooling and heating on the heat exchanger.

For the first group the volumetric losses are observed to vary heavily. The highest losses are observed for the highest flow of 33 l/s. Here the losses reached around 40 %. The lowest losses were observed for the measurements conducted with a flow of 24 l/s. Note the order in which the tests were carried out. The tests with a flow rate of 24 l/s were conducted first, followed by the tests with 16 l/s and concluded with the tests with 33 l/s.

In figure 4.17 the volumetric losses observed for the second group are presented. Note that a rework of the door was carried out between the first and second group due to an increased leakage.

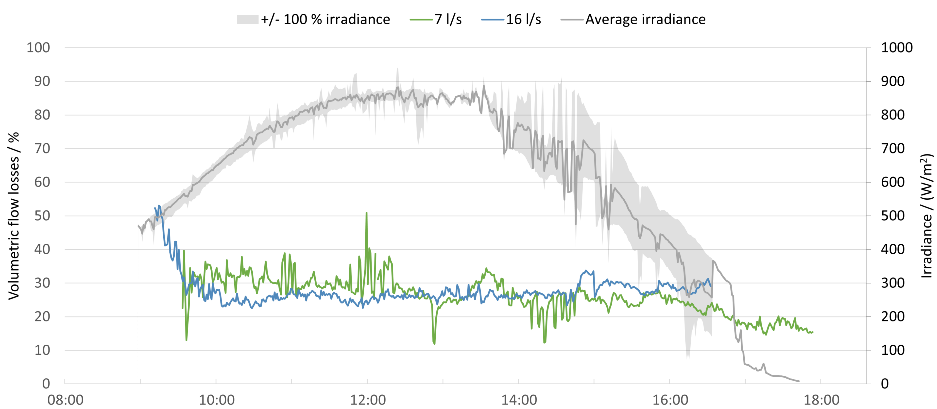

Figure 4.17: The volumetric flow losses for the tests as indicated by the difference in cooling and heating on the heat exchanger.

For the second group the flow losses was found to be more steady. There was no observable difference in flow losses between the tests carried out with a flow rate of 7 l/s and 16 l/s.

The impact of the heat exchanger geometry on it's performance

In figure 4.18 the heat exchanger efficiencies for the two tested heat exchangers are compared when run on 16 l/s. Note that the data shows the mean value of multiple full-day tests. Three measurements were carried out for 24 l/S while two measurement were carried out on 16 l/s.

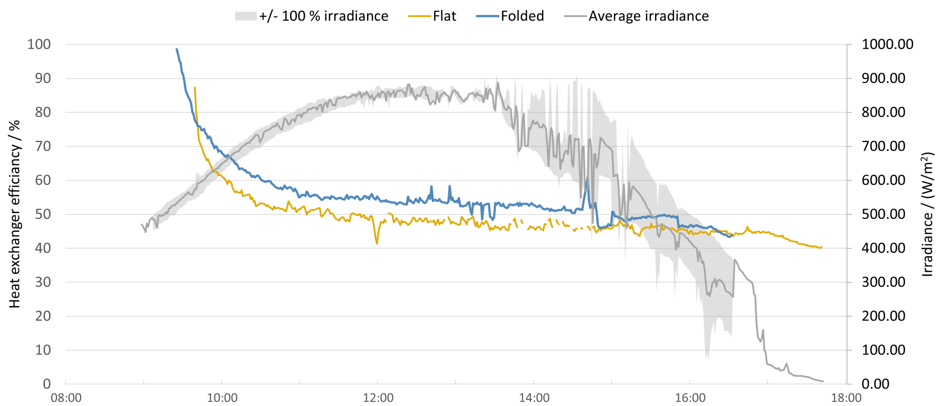

Figure 4.18: A comparison of the efficiencies of the two different heat exchangers when run on 16 l/s

The results indicate that the folded heat exchanger has a higher efficiency throughout the measurement as compared to the flat heat exchanger. The folded heat exchanger has an efficiency of between 40 and 50 % whereas the efficiency of the flat heat exchanger is around 40 %.

Lastly the Reynolds number for the folded heat exchanger was calculated at the different flow rates through equation 2.6. The results are presented in table 4.2 below.

Table 4.2: The Reynolds number of the folded heat exchanger at different flow rates

Flow rate	7 l/s	16 l/s	24 l/s	33 l/s
Reynolds number	384	877	1315	1809

5 Discussion

It is important to keep in mind that the aim with this report has not been to construct a finalized and optimized solar dryer. The aim has only been to develop and present a new conceptual solar dryer design and to prove or disprove it. With this in mind the overall performance of the solar dryer prototype in this report is not of direct interest and should not be directly compared to other reports. All the tests in this report have been conducted during mid-winter where the solar radiation has been at a local minimum. The prototype was not optimized for these conditions as it was constructed with year-round tests in mind. The fixed angle thus increase radiation losses and ultimately decreases the performance. Further, the availability of the solar dryer prevented the measurements to be commenced at sunrise. As a result up to three hour of potential drying time was missed in the morning. Lastly the constructed prototypes showcased a large volumetric loss of between 15 and 50 %. Together these factors decreased the performance substantially and any direct comparisons will thus be misleading. The concept provided by this report will need to be developed further and reconstructed before any direct comparisons can be made.

Design

The presented solar dryer design has many conceptual improvements that, if constructed correctly, should increase the thermal efficiency. The most notable concept would be the incorporated heat exchanger which is observed to increase the inlet temperature by up to 10 °C. Although this report did not review the heat losses in depth it is assumed that the redesign would result in lower heat losses as compared to a indirect solar dryer due to the more compact design. The more compact design also leads to a lower material usage.

On the backside of the design the dependence of the fan should be highlighted. Although a traditional indirect solar dryer often uses a fan to increase the air flow, it is also capable of running solely on natural convection. This is not the case for the presented design as the heat would be trapped at the top of the dryer, directly after the absorber. This issue became clear during the tests as the temperature after the absorber was significantly higher than the air entering the drying chamber. The results indicates that the warm air was trapped and could not be pushed down to the entrance of the drying chamber. This is perhaps the most apparent weakness of the design as it increases heat losses and decreases the performance. The issue became clearer as the flow decreased, further strengthening the hypothesis of there being a heat lock. Other challenges with the prototypes was the complexity in the construction. Although not overwhelmingly complicated, the front part with the heat exchanger is more complex than the relatively easy parts in a traditional indirect solar dryer. In commercial prototypes this design could however be simplified further. The complexity in the prototypes presented in this report were there to enable the exchange of heat exchanger, this would not be needed in a final design. The major leakages found in this report where to a large extent connected to the door design. This is a major issue with the constructed prototype but it is not connected to the design concept. With a better door design these losses could be eliminated.

Heat exchanger

The basic heat exchanger presented in this report was shown to reach a maximum efficiency of about 50 %. This correlates to an increase of the inlet air temperature by up to 10 °C. During the tests involving different flow rates an increasing leakage was discovered that makes it hard to quantify any results. They did however indicated that a decreased flow, and increased contact time, resulted in a higher heat exchanger efficiency. If the leakage was solved the performance of the heat exchanger would likely also increase as less energy would leave the drying chamber and the temperature of the exhaust would be higher.

The tests involving the flat metal sheet indicate that an increase of surface contact area by 50 % results in a 5 % increase in heat exchanger efficiency. The installation was also more complicated for the flat heat exchanger as there was no stability and wood pieces were needed to keep the heat exchanger in place.

The conclusions from these tests indicate that the impact of increasing the contact area and contact time outweighs the decrease of the Reynolds number. Judging from the calculated Reynolds number the flow in the heat exchanger is laminar at all flow rates. Although the heat transfer increases with increased Reynolds numbers the most significant increase is observed when the flow becomes turbulent at a Reynolds number of above 2300. Further tests are therefore needed to find the optimum balance of these parameters.

Note that tests were supposed to be conducted with a third heat exchanger with tighter folds and increased surface area. The aim was to further investigate the impact of surface area on the heat transfer and to increase the efficiency. These tests were however ruled out as the desired design could not be constructed locally by the sheet metal worker. Instead of importing the heat exchanger or getting it made elsewhere it was argued that if the heat exchanger can not be constructed locally it would decrease the availability and increase the cost of the solar dryer which was counter productive to the project goal.

Applications

In this report an attempt was made to develop a solar dryer which could meet the requirements of the agricultural sectors of Nepal and Bhutan. However the challenges lifted in the design criteria are of a more general nature and are expected to apply for many other regions as well. If the design criteria would be met than the solar dryer could have a much wider field of applications and could be usable in many other regions as well.

6 Further development

This study has only been the first step in a three year process to develop a commercial solar dryer design. Therefore multiple important aspects of the solar dryer has been left untouched for future reports. This chapter highlight some of the parameters that could require further research.

Introducing internal fans and overcoming the heat lock

The results from this report showed that a heat lock was created after the absorber where warm air got trapped. If a solution for this problem is found the performance of the solar dryer can be drastically improved as the temperature of the air entering the drying chamber could be drastically increased. One possible solution would be to replace the back panel with fans dragging the air downwards. Such a solution could also have a positive impact on the drying process due to increased air movement in the drying chamber. The increased movement in the drying chamber should result in a more rapid removal of saturated atmospheres around the drying product and thus increase drying performance. The removal of the back panel could also mean that the air would pass through the product both on the way down and on the way up further increasing this effect.

Heat exchanger

In this report the concept of creating a heat exchanger from a single sheet of folded metal was tested with promising results. The estimated Reynolds number did however indicate that turbulent flow was never reached limiting the heat transfer. With further optimisation the performance of the heat exchanger could increase if a turbulent flow is reached. This could be achieved either by a change in geometry, air speed, flow rate or size.

Thermal heat storage system

For a optimum drying process the temperature needs to be kept within a temperature span. A too high temperature will result in the product being burnt whereas a too low temperature will only incubate the product and actually decrease life time. Keeping the temperature within this span will be crucial in order to achieve a good dried product. Although the prototypes in this report did not reach the temperatures at which the product starts to burn, a new prototype very well could during mid day. The inclusion of a thermal heat storage system would thus be suitable to even out the temperature fluctuations and decrease the maximum temperature in exchange for increasing the drying temperature in the afternoon and thus increasing the active drying time per day. The placement of the heat storage system is suggested to be at the bottom of the drying chamber or directly below the absorber as this triangular room is not ideal for placement of product.

Temperature control

The results from the measurements carried out in this report indicate that the drying temperature can be partly controlled through changing the power of the fans. A lower flow results in a higher temperature directly after the absorber but due to the heat lock it results in a lower temperature entering the drying chamber in this experiment. This could be further investigated to achieve a more controllable temperature. Controlling the fan could also be used to increase the drying time per day. Although not apparent from the results in this report, if the drying chamber would be air tight and well insulated a lower air flow would result in less heat leaving the dryer and thus keeping the chamber warmer for longer.

Design and usability

In this study a major leakage was found in the door system of both prototypes. Therefore a rework of the mechanism will be crucial for the next prototype. Besides decreasing the leakage a general overview of the design should be done to make the design as easy as possible to construct and make it user friendly.

Other aspects

This report has solely focused on the performance and thermodynamics of a novel solar dryer design. In order to reach the set goal of a commercial product, further research is needed in other fields as well. This would include but not be limited to economics, susceptibility, sector integration, product placement, food- and health safety, production etc.

7 Conclusion

In this report a novel solar dryer design, with an incorporated heat exchanger, has been developed and tested. The results indicate that the incorporation of a simple heat exchanger can increase the inlet air temperature by up to 10 °C and reach an efficiency of 50 %. The heat exchanger tested in this report is deemed available at any sheet-metal workshop and is not expected to affect the affordability of the solar dryer substantially. The tests that were carried out in Nepal, highlighted problems in the forced convection and in the air tightness of the prototypes.

The novel solar dryer design presented in this report could potentially become a viable alternative for farmers in the Himalayan regions of Nepal and Bhutan. An increased performance was deemed the most crucial factor and with the heat exchanger installed the performance increased substantially. Further research is however needed to solve the highlighted problems and to further develop the performance of the solar dryer. In order to turn the prototype into a commercially available design, further research is also needed within other parts of the project such as for example economics, market analysis and receptivity.

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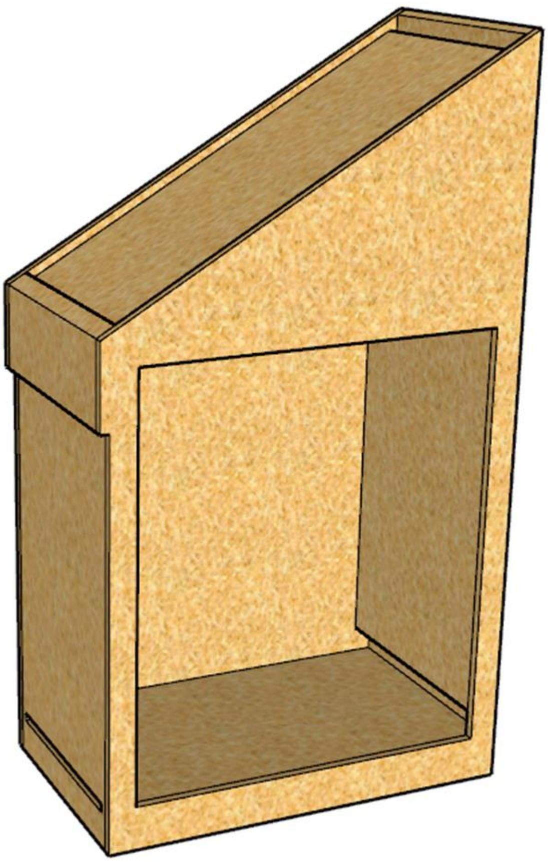
9 Appendix

Building instructions for solar dryer with incorporated heat exchanger

Adam Probert

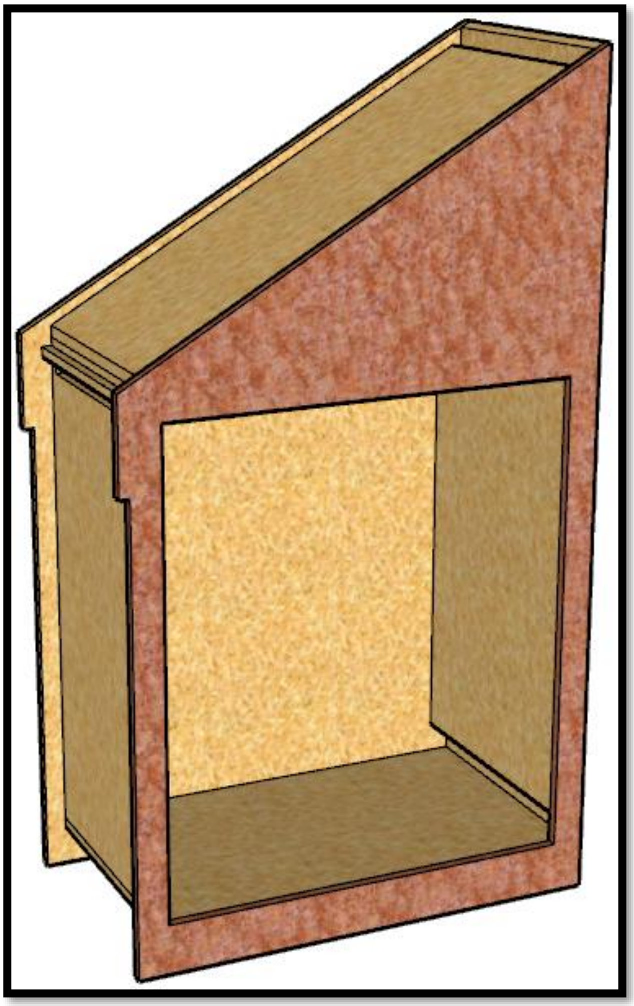
2022-02-23

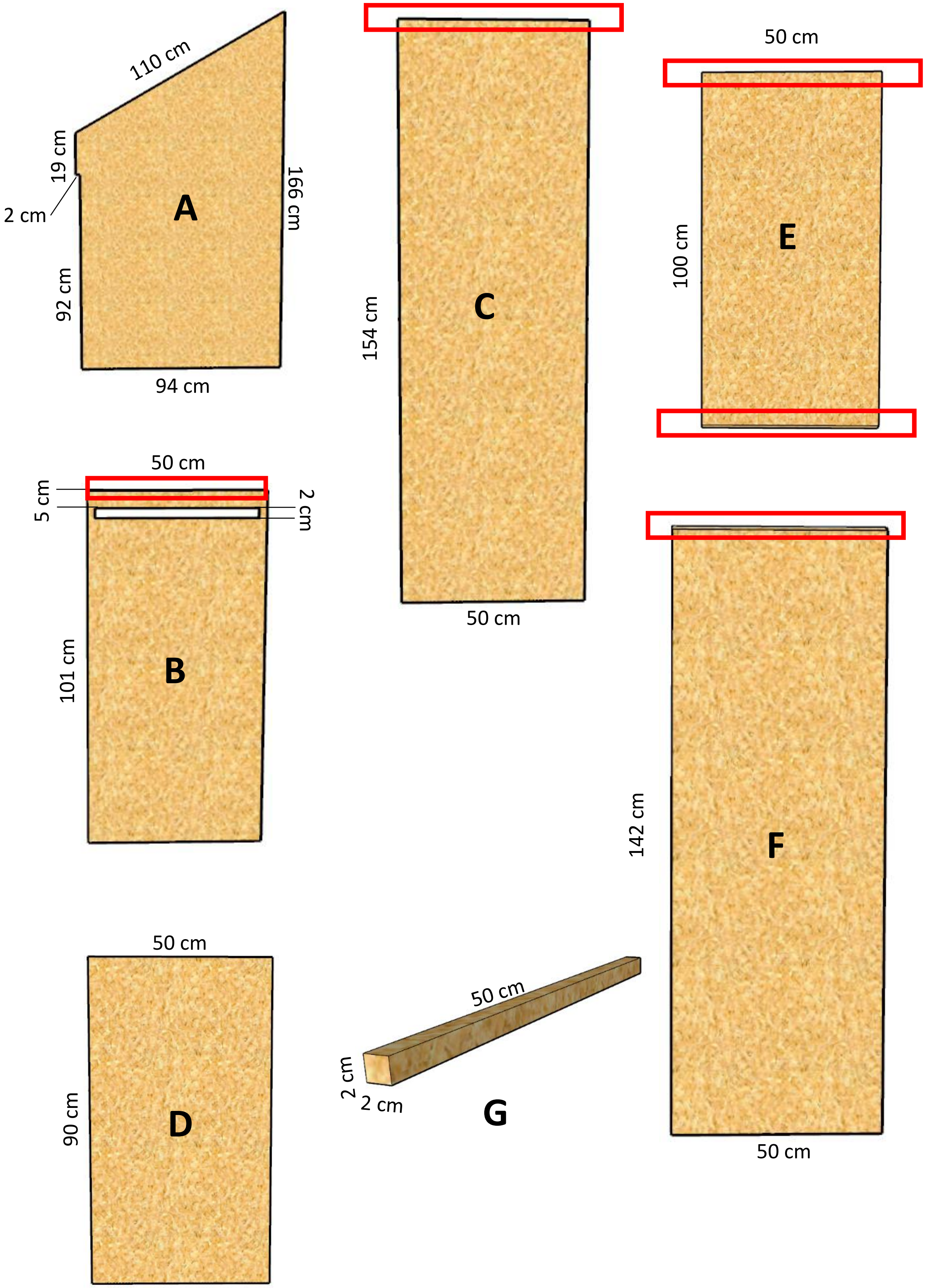


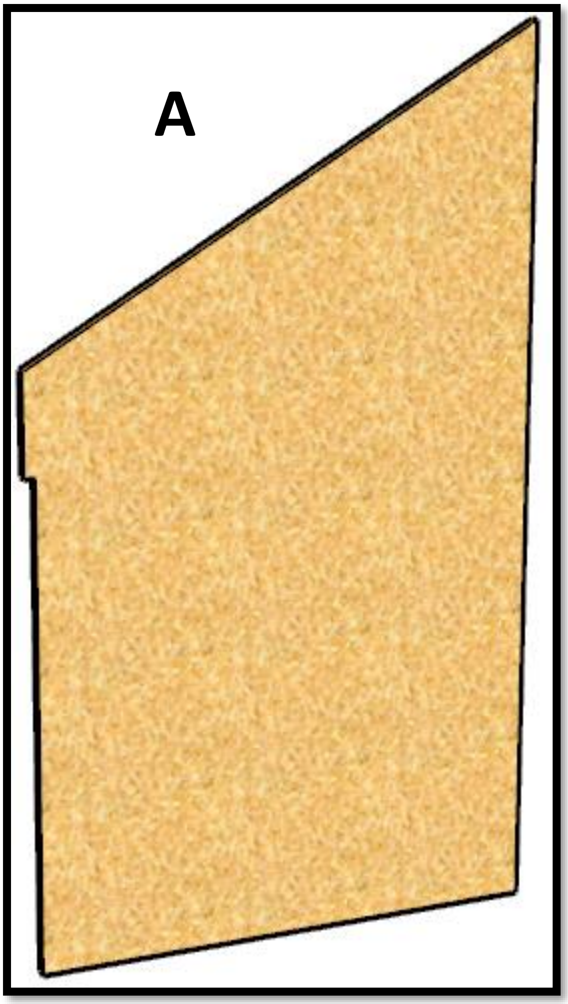
Main box

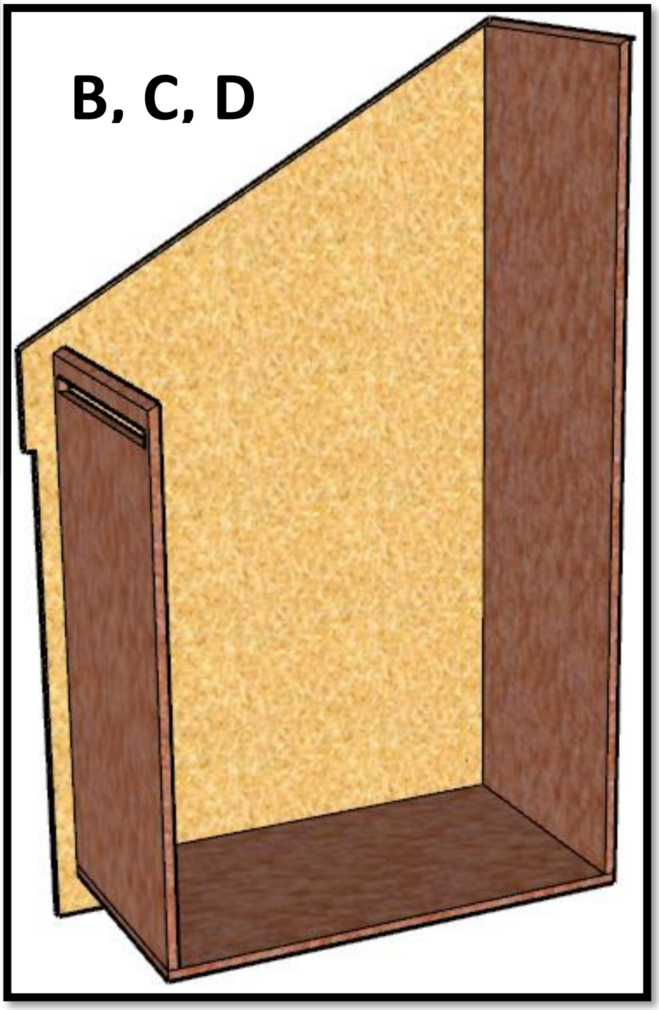
The main box is shown below. The easiest way to assemble it is to lay the backside (**A1**) on the floor and screw all other pieces onto it. Metal angles can be used to increases strength where needed. The space between pieces **C** and **F** should be 20 mm. The space above piece **E** and below the edges should also be 20 mm. Note that there should also be a lid on the outside so there needs to be two **A-**pieces (**A1, A2**)

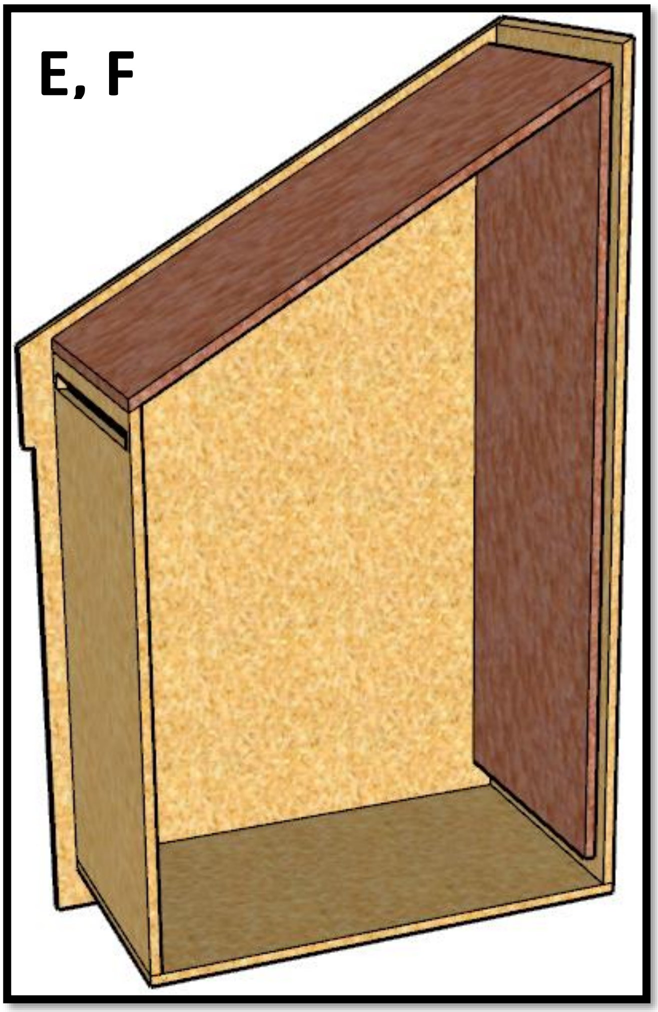
On the next page the sizes of all pieces can be seen. The thikness of all pieces should preferably be 20 mm but between 15 and 20mm should also be ok. The sides marked with a red square should be cut in a 30 degree angle (the same angle as desired inclination) as to fit with other pieces. In which case the written lengths are the length of the longer side. The top part (**E**) needs to be cut on both sides so the cut becomes parallel.

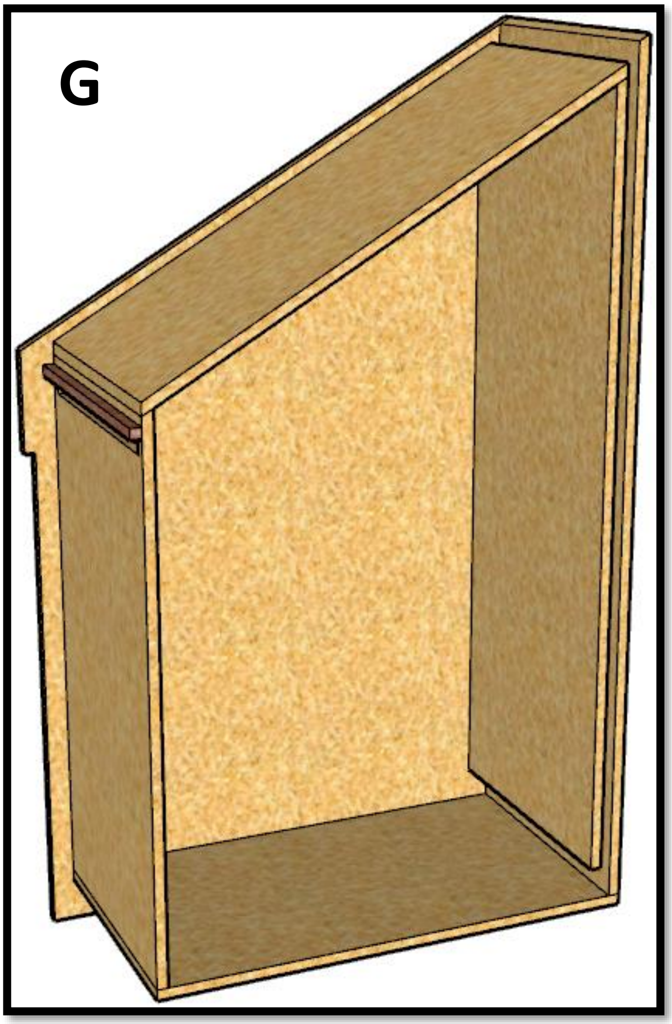


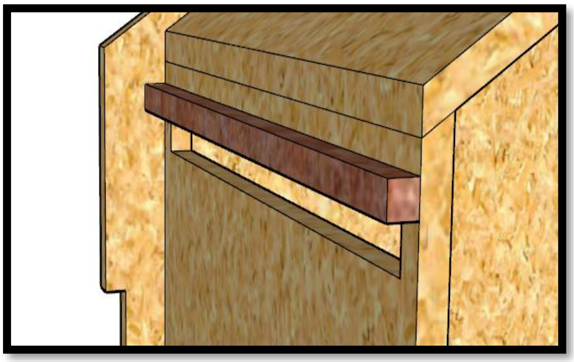

A
110 cm
19 cm
2 cm
92 cm
166 cm
94 cm
B
50 cm
5 cm
2 cm
101 cm
C
154 cm
50 cm
D
50 cm
90 cm
E
50 cm
100 cm
F
142 cm
50 cm
G
50 cm
2 cm
2 cm

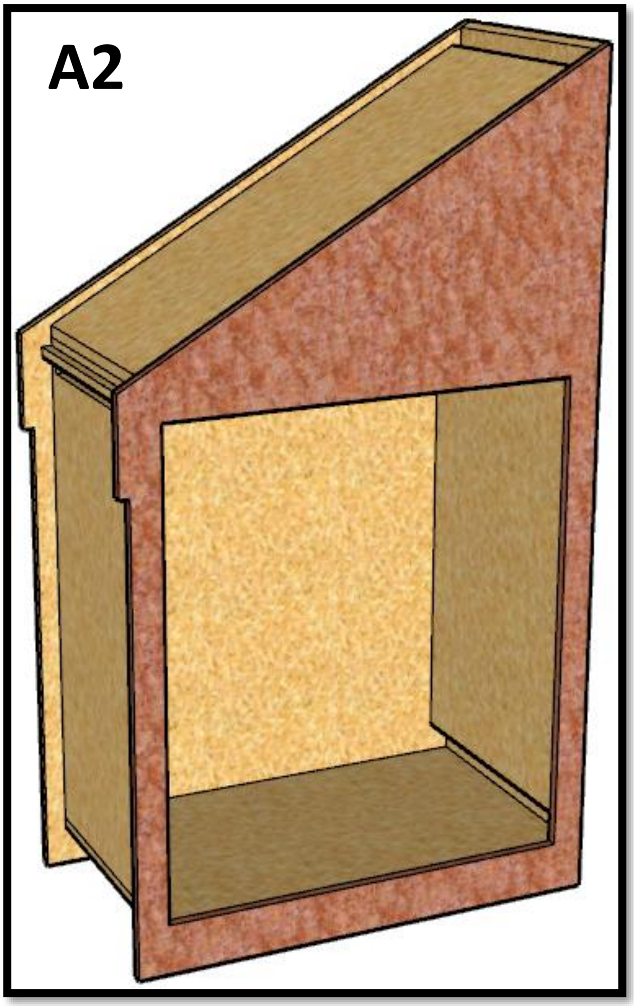

A


B, C, D


E, F


G




A2