Evaluation of an Indirect Solar Dryer with Integrated Heat Exchanger

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Abstract

Solar drying, utilizing solar energy to extract moisture from foodstuff, is a highly effective method for extending the shelf life of for instance fruits and vegetables. The utilization of solar dryers brings numerous benefits, e.g., it reduces reliance on fossil fuels and electricity and establishing an environmentally sustainable and relatively cheap option for food preservation. In this research we present key findings from measurements perform on a solar dryer with a built-in heat exchanger. Our solar dryer was constructed with the goal to keep it both as simple and as cheap as possible. The results show that the dryer outperforms open sun drying while simultaneously protecting the food stuff from the surrounding environment. Filling the dryers with more trays, and consequently more food, increases the difference in drying rate between the trays, which could be a concern for the end user as more attention needs to be paid to the drying process. This problem clearly indicates where future research must be carried out, i.e. in reducing this uneven drying. Future testing using multiple mixing fans or altering the airflow direction created by the internal fan could lead to a more even drying process.

Keywords: solar drying, measurements, indirect solar dryer

1. Introduction

Solar drying, utilizing solar energy to extract moisture from foodstuff, is a highly effective method for extending the shelf life of fruits. The utilization of solar dryers brings numerous benefits. It reduces reliance on fossil fuels and electricity, establishing an environmentally sustainable option. Solar drying preserves the natural qualities of fruits, including flavour, colour, and nutrient content, enhancing their nutritional value. Implementing solar dryers has the potential to significantly reduces post-harvest losses and boosts farmers' income. This paper presents measurements of a solar dryer with a built-in low-cost heat exchanger. Incorporating a heat exchanger along with the solar collector has potential to improve the dryer's efficiency. The heat exchanger preheats the incoming air, using the heat from the outgoing moist air from the dryer. Using heat recovery for small scale solar dryers is not common in the literature. However, it has been mentioned in earlier work, for instance in (Ghasemkhani et al., 2016) or in (Atalay et al. 2017) where external heat exchangers were used. However, these heat exchangers are more complex and would increase the price of the solar dryer. Adding complex heat exchangers also increases the risk of high pressure drop which in turn leads to larger and more expensive fans for the dryer. It ‘s therefore of great importance to try to use simple, low cost heat exchangers with a relatively low pressure drop.

Traditionally, open sun drying is used to dry for instance fruits and vegetables. However, this method has several disadvantages such as long drying time (Singh, 2011), dust contamination and losses related to animal

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intrusion (Moses et al., 2013). Furthermore, the texture and colour of the product may also change (Chaatouf et al., 2021). Solar drying using various kinds of protecting structures where the food is placed can result in a safer drying process. These dryers are often divided in two different categories, direct dryers, and indirect dryers. The direct type dryers are built in such way that the food stuff is directly hit by the solar radiation while the indirect dryers use the principle of heating the air indirectly and then transferring the heated air to some type of drying chamber where the food is placed (Aacharya, 2024).

One of the main limitations in this work is that the dryer has only been tested indoors using a solar simulator. Thus, effect from wind, varying solar irradiation, dust accumulation etc. is not included in this research. Furthermore, drying has only been carried out using apples as produce. Fruit or vegetables with lower moisture content, such as leafy greens, could show somewhat different results as the temperature in the dryer will be slightly higher.

2. Method

The constructed solar dryer is illustrated in Fig 1. The incoming fresh air, forced through the dryer using an external fan, comes in from below (1) and passes through the heat exchanger (2) placed at the bottom of the dryer. After the heat exchanger the air is passed through the absorber (3) and further into the drying chamber passing through water bottles (4) used for storing heat. Storing heat gives the possibility to prolong the drying time even after the sun has set. The heated air is then passed over the different trays (5) in the dryer before it is let out at via the chamber exhaust (6) and finally to the hot side of the heat exchanger with the exhaust at the back of the dryer (7). An internal fan (8) between the two sections of the dryer moves air in the same direction as the external fan. This fan is set for maximum airflow at all times. Figure 2 shows a photo of the solar dryer. The two chambers and the placement of the fruit are shown in the figure. The intention with the internal fan is to increase the airflow in the drying chamber without increasing the net flow through the entire dryer. This is done in order to increase the convective heat transfer from the air to the foodstuff at the same time as a high airflow will reduce temperature differences inside the dryer. Without the internal fan the risk is higher to have hot dry air from the absorber hitting the first tray, while as the air moves over the different trays it picks up moisture and consequently drops in temperature. This leads to the last tray, in the airflow direction, getting cold moist air and thus consequently low drying rate. This uneven drying rate can cause difficulties for the user as the food is not dried to desired levels all at once.

Measurements were carried out using an indoor solar simulator at Lund University in Sweden. The irradiation, at approximately 900 W/m², from the simulator can be considered to be parallel light due to reflectors arrangement in the simulator. No diffuse radiation hit the dryer during the experiments. Airspeed was measured using a Testo 416 with a precision of 0,1 m/s. The airspeed, and thus also the airflow, was measured in a long duct connected to the inlet of the dryer. Temperatures were measured using thermocouples connected to a Campbell Scientific Cr 1000 logger and an AM 16/32 multiplexer. Three thermocouples were placed at the inlet to the dryer (inlet cold side of the heat exchanger), inlet to the absorber (outlet at the cold side of the heat exchanger), absorber outlet, heat storage, drying chamber outlet (inlet at hot side of the heat exchanger) and at the dryer outlet (outlet at the hot side of the heat exchanger). Five thermocouples were installed at the different trays in the drying chamber. Experiments were carried out using five or nine trays of food. All measurements were performed using apples as drying object. All sensors were tested in boiling water and at ice/water mixture to discard faulty sensors. Measurements were taken every 30 seconds and averaged to minute values stored in the logger and downloaded to a computer for data treatment.

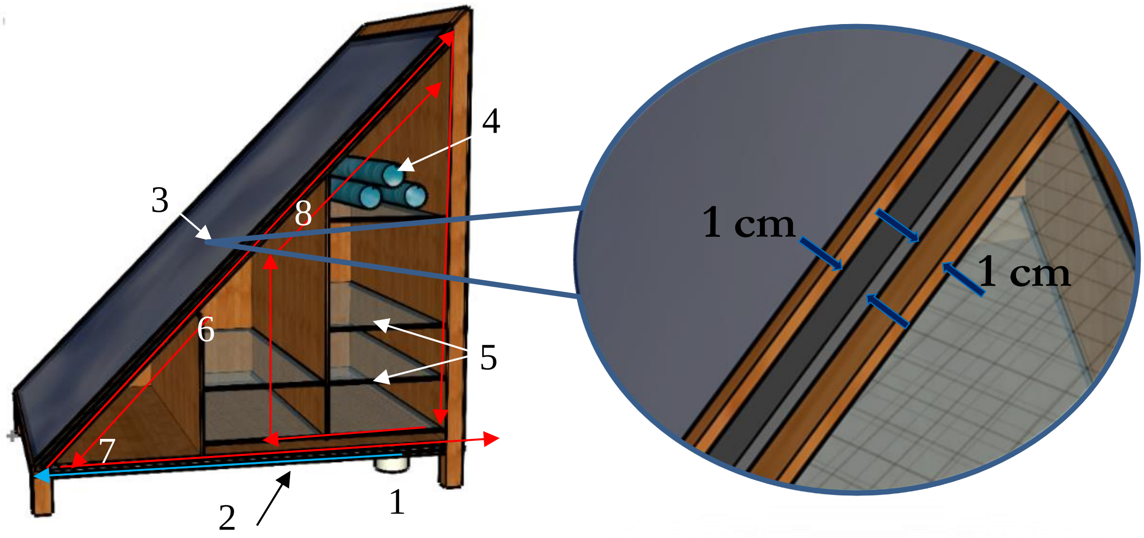

Fig. 1: Illustration of the solar dryer. The heat exchanger is placed at the bottom of the dryer. Airflow is indicated by the arrows. Blue arrows indicate cold air while the red arrows indicate warmer air. The zoom-in to the right shows the absorber separated 1 cm both to the glass cover and to the wooden backside.

Fig. 1 shows a zoom in on the absorber. The distance between the absorber and the glazing as well as the distance to the wooden structure of the drying chamber is 1 cm per side, see Fig 1. Allowing double passage, both front and back of the absorber results in a larger heat transfer surface and thus a higher heat transfer. The heat exchanger in the bottom of the dryer has the same measurements, 1 cm per side of the separating plastic sheet. The trays are made from simple mosquito net on a wooded frame. The heat storage bottles are old, recycled soda bottles. The entire dryer is made using as cheap material as possible in order to achieve a low production cost. All edges that could result in air leakage was sealed using duct tape.

Fig. 2, left, shows a photo of the solar dryer. The two chambers are indicated. The right side in Fig 2 shows a photo of apple slices to be dried in the drier.

Fig. 2: Left: Photo of the solar dryer. The two chambers are indicated in the photo. Right: Photo showing the placement of apples on the trays.

Measurements were taken with the external fan producing different airflows into the dryer in the range of 10 l/s to 20 l/s. The built in heat exchanger was evaluated by measuring the temperatures in and out at the cold and the hot side. The average of cold and hot side temperature heat recovery efficiency, η_{cold} and η_{hot} was investigated. Eq. 1 and Eq 2. was used for the calculations regarding temperature heat recovery efficiency.

$$\eta_{cold} = \frac{T_{out,cold} - T_{in,cold}}{T_{in.hot} - T_{in,cold}} \qquad \text{(eq. 1)}$$

and

$$\eta_{hot} = \frac{T_{in,hot} - T_{out,hot}}{T_{in.hot} - T_{in,cold}} \qquad \text{(eq. 2)}$$

where T is the temperature. The subscript *in* and *out* is used for inlet and outlet temperature while the subscript *cold* and *hot* is used to indicate the cold side and the hot side of the heat exchanger.

The efficiency of the absorber was calculated using Eq. 3.

$$\eta_{abs} = \frac{f_m \cdot C_p \cdot \Delta T}{I \cdot A} \qquad \text{(eq. 3)}$$

where f_m is the mass flow, C_p is the specific heat for air, ΔT is the temperature increase for the air in the absorber section, I is the radiation and A is the glazed area for the absorber. The absorber efficiency was measured as an average over the first three hours of operation. This means that the initial time when the absorber, the glazing and the solar drying construction is heating up, parts of the solar heat is used for this. Thus, the maximum efficiency is higher than the average efficiency stated in the result section.

For comparative reason, simultaneous measurements were carried out where trays with apples were placed outside the dryer, one in the radiation from the lamp and one tray in the shade. All experiments were carried out inside a laboratory. Thus, no wind was present during the experiments. One investigation was carried out where the average weight of a drying tray with fruit was measured every hour for eight hours straight. Another investigation looked at the ratio of drying rates between the highest and lowest drying rates among the different trays. For this, two different internal fans were used, a smaller and a larger fan. The exact flow from the two fans is now known. It should be noted that it is difficult to determine the airflow inside the drying chamber as the flow profile is far from well established. Experiments were carried out using the standard five trays and one set with an increased number of trays. In this case nine trays were used.

3. Results and discussion

Fig. 3 shows the efficiency of the heat exchanger for different flows. As can be seen the efficiency higher for the low airflows. The efficiency for the low flow is around 70 % and reduces to approximately 50 % for the higher flow around 20 l/s.

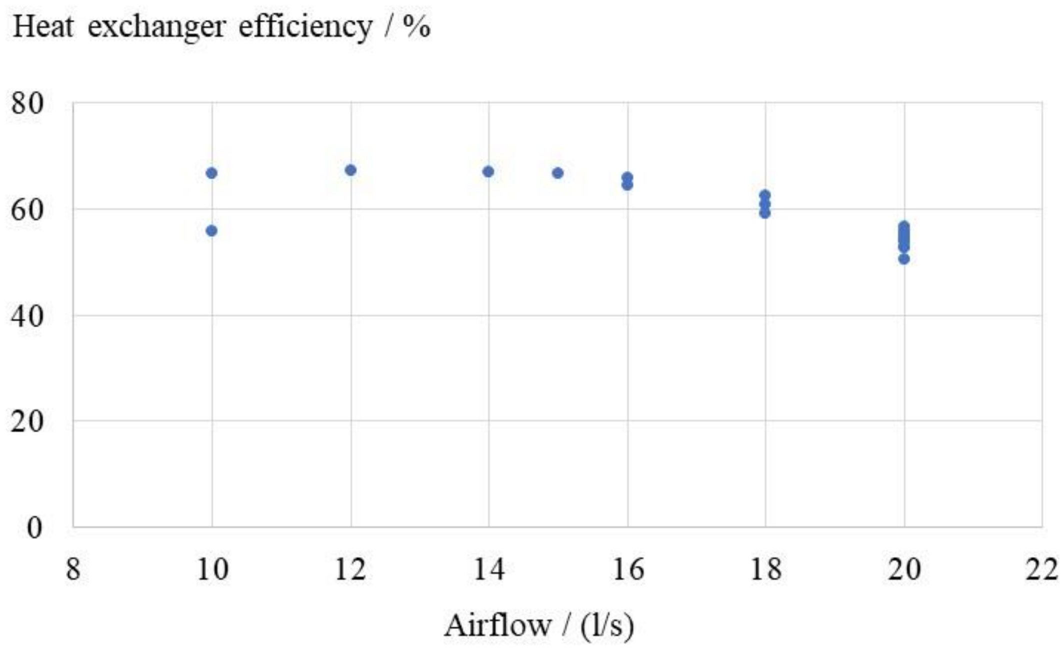

Fig. 3: Heat exchanger efficiency as a function of airflow to the dryer.

Fig. 4 shows the absorber efficiency for two different airflow settings, 10 l/s and 20 l/s. After approximately one hour the absorber efficiency is stable around 60 % for the 20 l/s airflow and somewhat below 40 % for the 10 l/s airflow. The increase in efficiency over the first hour is explained by solar drier heating up from a cold initial condition. As parts of the heat is used to heat the drier less heat is available for heating the air and thus the efficiency of the absorber appears low in the beginning of the day.

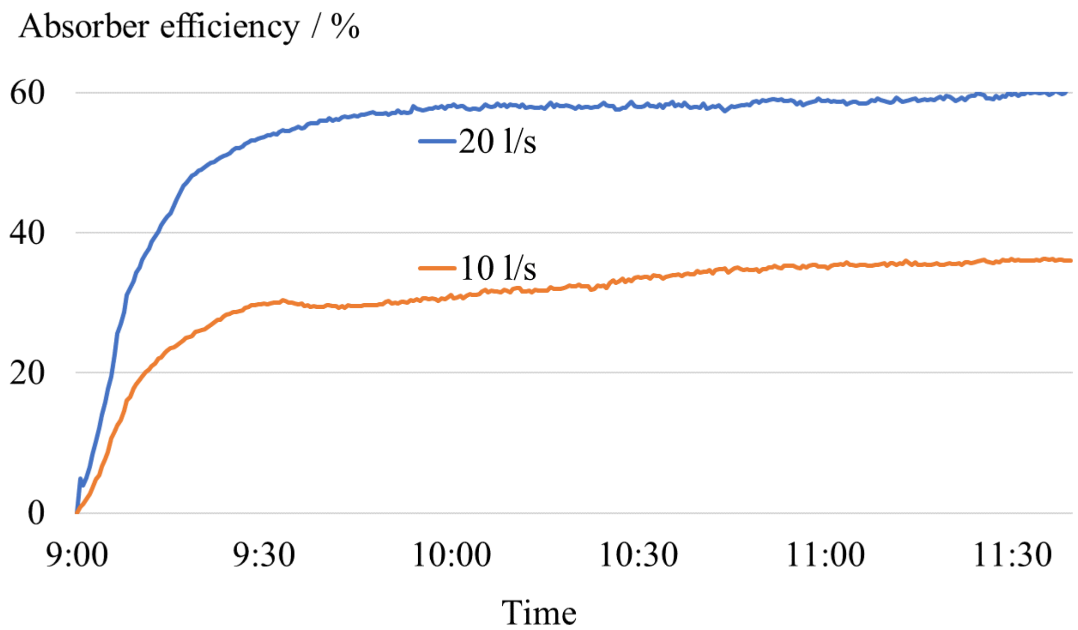

Fig. 4: Absorber efficiency as a function of time. The orange line is for 10 l/s airflow through the dryer and the blue line is for 20 l/s.

The absorber efficiency is shown in Fig. 5. The y-axis shows the efficiency as a function of airflow. As can be seen the efficiency is higher for the higher flows. The experiments performed with the larger internal fan are indicated with red circles. The lower efficiencies might depend on a change in airflow due to higher pressure in the drying chamber. This was however not investigated. The results from the different heat transfer processes, i.e. the heat transfer in the heat exchanger and from the absorber, are contradicting in how the flow to the dryer should be controlled. High flow leads to an effective heat transfer from the absorber to the air but a lower heat recovery rate in the heat exchanger.

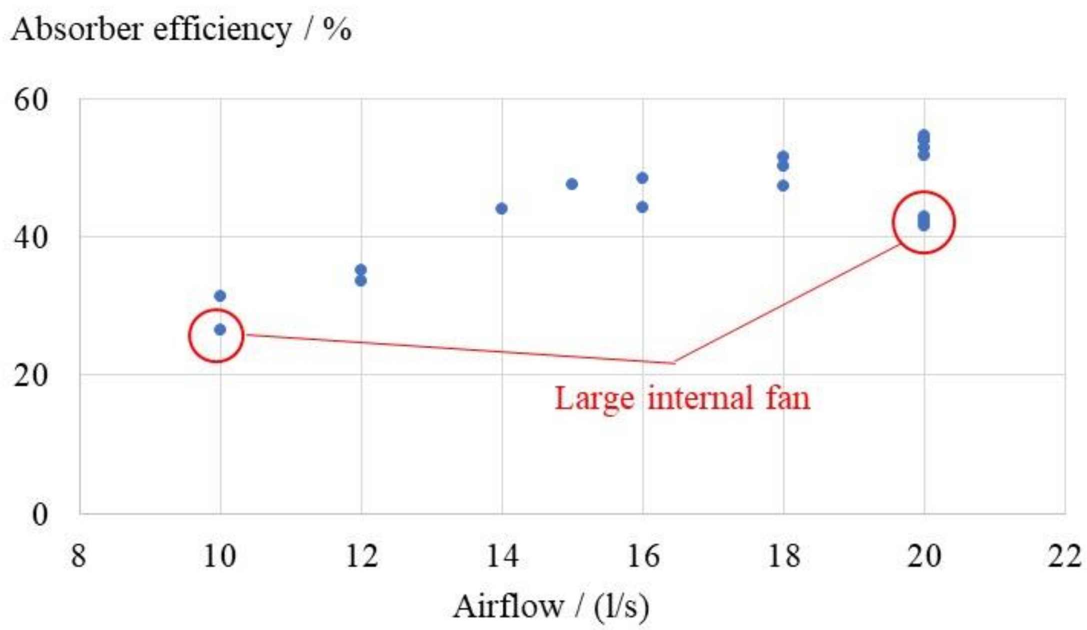

Fig. 5: Absorber efficiency as a function of airflow to the dryer.

Results from apple drying are shown in Fig 6. The y-axis shows the total weight of the fruit. For the solar dryer cases using different airflow from the external fan the average weight of the trays is used to represent the weight. The red, grey, and yellow lines show the weight measured every hour for different external flows, 10 l/s, 15 l/s and for 20 l/s. The difference in drying rate between the different airflows are small. The weight of the fruits using open solar drying with the fruits under the solar simulator lamp is shown in green colour while open drying where the fruit was placed in shade is shown in blue colour. The largest difference in drying rate is for the open drying placed in shade. However, also the open drying placed in the radiation shows significantly lower drying performance compared to the solar dryers. It should be noted that the open solar drying placed in the radiation from the lamp, appears to flatten out at a significantly higher moisture content. This phenomenon was not further evaluated. It should be noted that one possible measurement mistake was removed from the analysis for the “Open sun drying”. The point is indicated in Fig 6 with a green star.

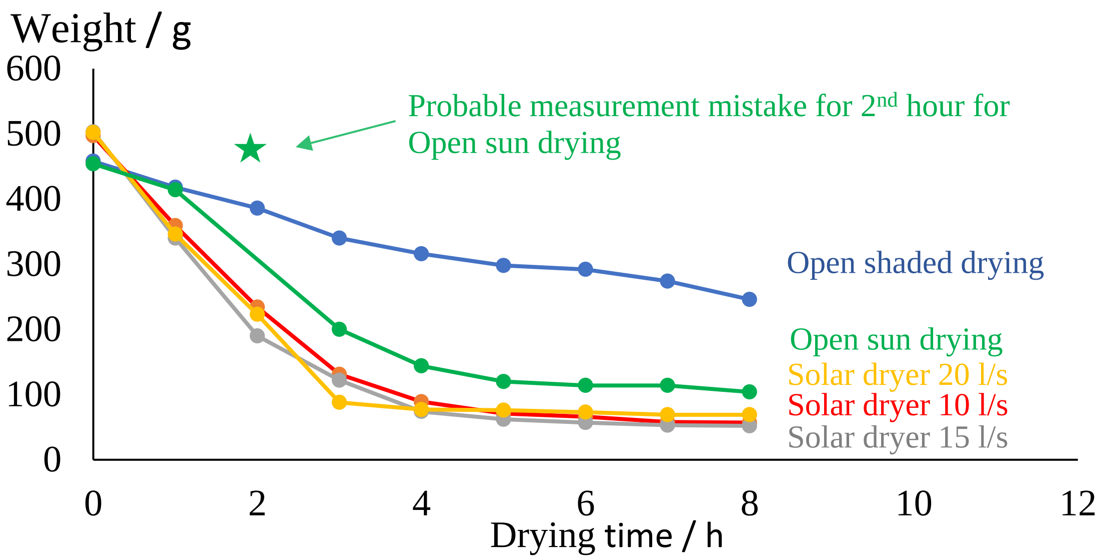

Fig. 6: Drying rates for different types of solar drying and different airflows. The green line is for open sun drying, the blue line is for open shaded drying while the red, grey and yellow lines are for different airflows, 10 l/s, 15 l/s, and 20 l/s.

Fig. 7 shows the variation of drying rate among the different trays inside the dryers. The blue bar shows the highest drying rate during a specific set-up while the red bar shows the lowest drying rate for the same set-up. Using a larger internal fan reduces the difference between the trays. When more trays are introduced into the dryer the difference between the highest and lowest drying rate increases significantly.

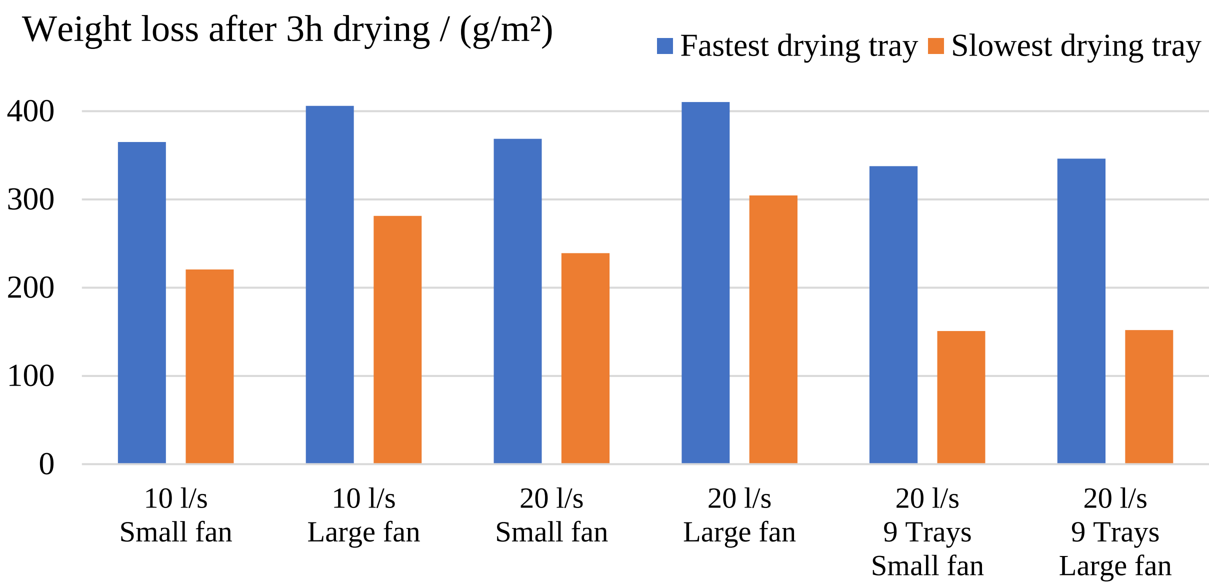

Fig. 7: Total drying during 3 h. In blue is the total weight loss for the fastest drying tray and in orange is the total weight loss for the slowest drying tray.

Table 1 shows the ratio between the fastest drying tray and the slowest drying tray. Having a larger internal fan both increases the drying rate at the same time as it reduces the difference in drying rate between the trays. Increasing the number of trays makes the difference in drying rate worse. Furthermore, using the larger fan does not offset the drying rate difference when loading the dryer with nine trays rather than only five.

Table 1. Ratios between fastest and slowest drying trays in the drying chamber.

Flow / (l/s)	Internal fan size	Number of trays	Ratio of drying rate (Fastest / Slowest)
10	Small fan	5	1,65
10	Large fan	5	1,44
20	Small fan	5	1,54
20	Large fan	5	1,35
20	Small fan	9	2,24
20	Large fan	9	2,28

Fig. 8 shows a typical temperature distribution in the dryer during drying. The specific temperatures captured in the figure is from a drying case using 20 l/s. The measurement was taken at 12:00 midday. The incoming air is at 22 °C. After passing the heat exchanger the temperature has increased to 28 °C. After passing the absorber the temperature reaches 52 °C. Inside the dryer temperature drops as moisture is removed from the food stuff. The average temperature in the dryer is between 32 °C to 37 °C. The temperature at the outlet from the drying chamber, i.e. the inlet to the hot side of the heat exchanger is at 36 °C. After passing the heat exchanger the temperature is at 28 °C. The higher temperature drop on the cold side of the heat exchanger could be due to leakage in the dryer, resulting in lower outlet flow from the dryer compared to inlet flow. This would then lead to a higher temperature drop on the hot side of the heat exchanger. Using Eq. 1 and Eq. 2 gives an average temperature efficiency of 50 % for the heat exchanger. This is almost as high as the efficiency for the absorber as presented in Fig. 4. However, the actual temperature gain, and thus energy gain, is much higher for the absorber than for the heat exchanger. This is partly an effect of the rather efficient drying inside the drying chamber. The higher the drying rate is the colder outlet temperature from the drying chamber and thus less heat to recover in the heat exchanger. The results could differ depending on what type of food is being dried. Fruit and vegetables that dries slower, for instance due to skin or shell on the fruit, could then result in a higher outlet temperature. This could in turn be interpreted as the heat exchanger being more effective.

Fig. 8: Temperature distribution in the dryer.

4. Conclusions

Increasing the airflow through the dryer has mixed consequences for the different parts in the dryer. The heat exchanger works less optimal for higher flows. However, the absorber parts work better for higher flows as the higher airflow through the absorber moves the heat from that section into the drying chamber. Furthermore, the measurements show that varying the external fan between 10 l/s to 20 l/s only has a smaller effect on the actual drying rate. However, the drying rate is higher when using a solar dryer compared to open sun drying. Running the dryer with the external fan at 20 l/s slightly reduces the difference in drying rate between the trays compared to using only 10 l/s from the external fan. Using a larger internal fan also reduces the difference. However, filling the dryers with more trays, and consequently more food, increases the difference in drying rate between the trays. This could be a large concern for the end user as more attention needs to be paid to the drying process. This problem clearly indicates where future research must be carried out, i.e. in reducing this uneven drying. Furthermore, the dimensions for the heat exchanger and the solar absorber have potential for future improvements. Other techniques for enhancing the heat transfer rate such as introducing a non smooth surfaces on the absorber could also lead to higher efficiency for the absorber.

The low heat transfer from the heat exchanger is mainly due to temperature loss inside the drying chamber. As the energy in the dryer is used for drying the food the temperature is reduced. This effects the heat transfer in a negative way for the heat exchanger, even if the efficiency in relative terms is high. However, a deeper test of the dryer should be carried out using leafy vegetables and fruits and vegetables with skin or shell. The slower drying in terms of moisture supply to the drying air could lead to a higher temperature in the drier. In such cases the heat exchanger might be more suitable as part of a solution.

5. Acknowledgments

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