Modeling of a solar dryer for fruit preservation in developing countries

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Abstract

About 25,3 % of the Mozambican population is suffering from undernourishment even though a sufficient amount of food and specifically fruits are produced. Post-harvest losses are estimated to 25 % to 40 % and part of the production is not even harvested due to a short season. A solution has to be found to improve fruit preservation and allow the population to consume what is harvested later. Drying fruits is a solution to preserve them. However, juicy fruits are harder to dry than other fruits since they contain more water. One small-scale solution is drying juicy fruits in a specific membrane which allows water vapor to escape from the fruit and the fruit juice to dry. It is possible to couple these membranes with solar dryer technology to control parameters such as temperature, relative humidityand air velocit) in order to improve the drying process

Two types of solar dryers are tested and preseted in this paper: an indirect and a direct dryer. Both solar dryers are modeled using a CFD tool (COMSOL Multiphysics) and the modeling work is based on former research to elaborate a mathematical model of the dryer physics. The simulations results produced by COMSOL allow to study the influence of several parameters such as geometry of the solar dryers, ambient conditions and solar dryer materials in order to improve the design of the dryers. The results from the modeling are compared to on-site measurements, in Mozambique, in order to calibrate and validate the models. The models estimated temperatures and relative humidity with an average relative error inferior to 20 %.

Keywords: solar dryers, modeling, CFD, indirect solar dryer, direct solar dryer, fruit preservation

1. Introduction

1.1 Food insecurity and fruit preservation

Mozambique is a developing country which presents a high rate of undernourished people. Around 6,9 million inhabitants are undernourished which represents 25,3 % of the total population in Mozambique (Food Agricultural Organization of the United Nations, 2016). The situation is even more concerning for children since 43 % of the children under 5 years old suffer from chronic malnutrition and 6 % are considered as sharply malnourished (Instituto Nacional de Estatística, 2012).

Although an acceptable amount of food is grown, a significant part is not consumed due to harvest losses or spoilage before it can be consumed. Post-harvest losses are estimated between 25 % and 40 % in Mozambique and a large part of the fruit production is not even harvested due to a short season (Phinney, R. et al. , 2015).

A solution to cope with this issue is to provide a fruit processing technology to safely and cost-efficiently preserve fruits when they can be harvested in order to consume them later. Large-scale solutions such as canning or aseptic processing are economic but they also require a considerable amount of resources (clean water, energy, transport facilities) which are not necessarily available in developing countries like Mozambique.

1.2 Solar-assisted pervaporation

A small-scaled solution, solar-assisted pervaporation, is used to dry fruits in this work. It consists in putting fruit juice or fruit purée in a semipermeable membrane bags which allow water vapor to escape the bags but prevent it to enter back in it. A minimum temperature of 50 °C is required in order to avoid bacterial growth. The temperature also has to stay below 70 °C to avoid the degradation of acid ascorbic (Vitamin C) (Paul and Ghosh, 2011).

The criteria used to determine if a product has been dried enough and is suitable for conservation at room temperature is the water activity level a_w . The water activity corresponds to the ratio between the vapor pressure

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of the food, P_w, to the vapor pressure of water at the same temperature and pressure, P_{ws} (Phinney et al., 2015) and can also be expressed as the equilibrium relative humidity of the product divided by 100 (Singh, P. and Heldman, D.R. 2013). This relation is found in equation 1.

$$a_w = \frac{P_w}{P_{ws}} = \frac{RH}{100} \text{ (eq. 1)}$$

According to Phinney et al. (2015), several conclusions can be made concerning solar-assisted pervaporation pouches :

- The drying process using SAP-pouches allows to reach water activities below 0,7. For instance, the water activity in mango purée went from 1,0 to 0,48 after 45 hours of drying.
- Ambient relative humidity is a key parameter in the drying process and is related to the temperature. A lower relative humidity will provide a higher evaporation rate of the product inside the pouch.
- Ambient wind velocity that is the velocity of the air flow around the pouch decreases the drying time.

Given these conclusions, it is interesting to combine these SAP pouches with solar dryers.

1.3 Solar drying

Several types of solar dryers exist and this work aims to model two different types of them :

- A direct active solar dryer (Fig. 1)
- A tilted passive solar dryer (Fig. 2)

In a direct solar dryer, the drying product receives directly the solar radiations. In an active solar dryer, the heated fluid (air in this case) is forced to circulate by a fan, a blower or any equivalent. On the opposite, the drying product is not directly exposed to solar radiations in an indirect solar dryer and a passive solar dryer only relies on natural convection due to the temperature difference between the absorber and the air circulating in the solar dryer.

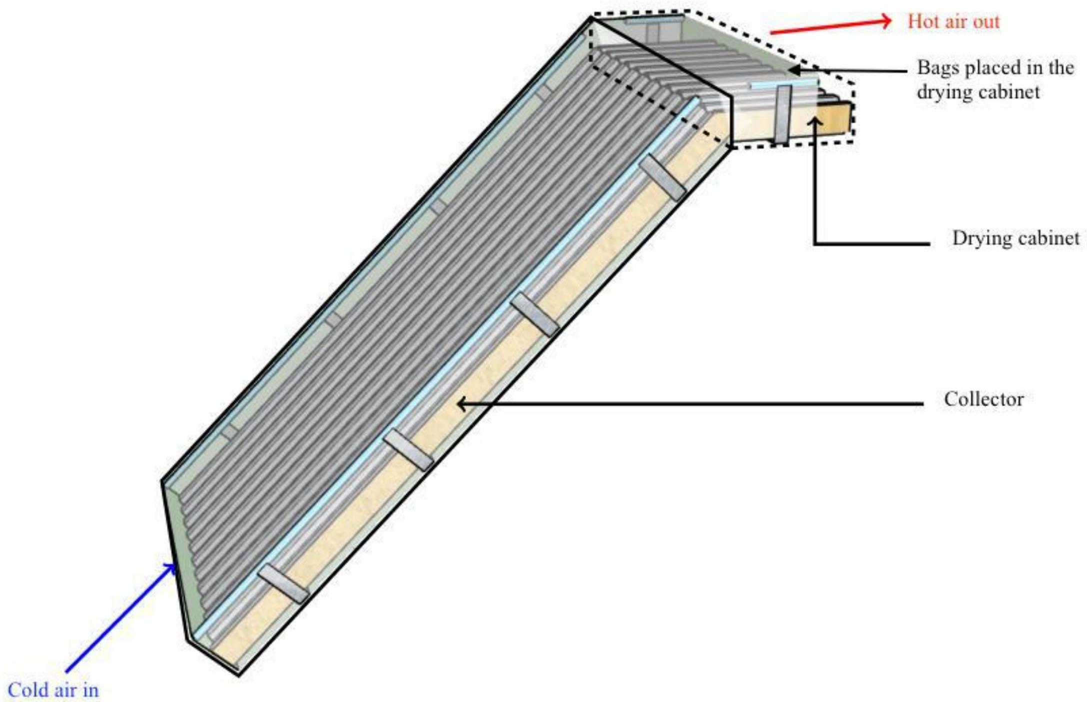

Figure 1 : Tilted passive solar dryer

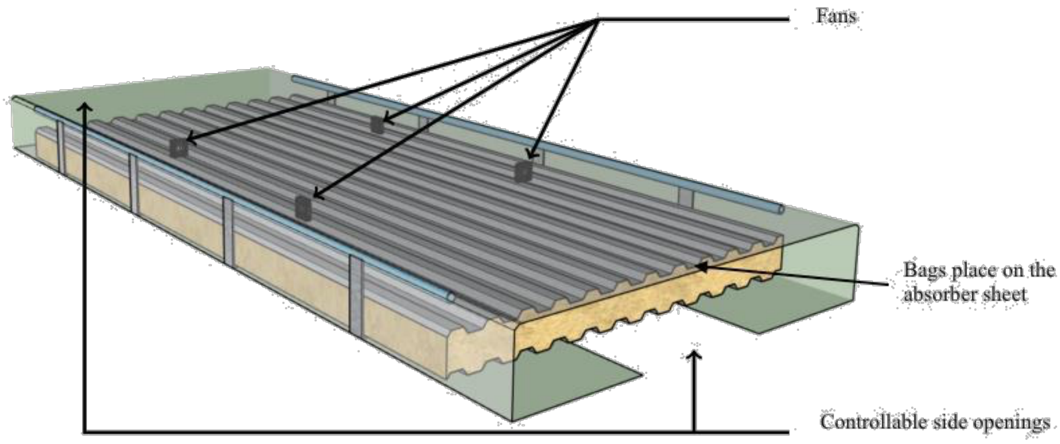

Figure 2 : Active direct solar dryer

2. Theory

The heat transfer exchanges in a solar dryer are presented on Figure 3. The solar radiation (1) is transmitted through a plastic sheet and absorbed by the absorber plate or on the fruit itself. Once the radiation is absorbed, part of it is emitted back to the plastic sheet. The rest is used to heat the air by convection on the absorber plate and the inner sides (4). The role of the absorber is thus to convert radiation in heat, by absorption and emission. Convection also happens on the plastic sheet (3) and the outer sides with the ambient air. Losses occur by radiation (2) from the plastic sheet from the sides of the solar dryer to the sky and from the bottom sheet of the collector to the ground. Finally, heat is transferred by conduction in the different materials.

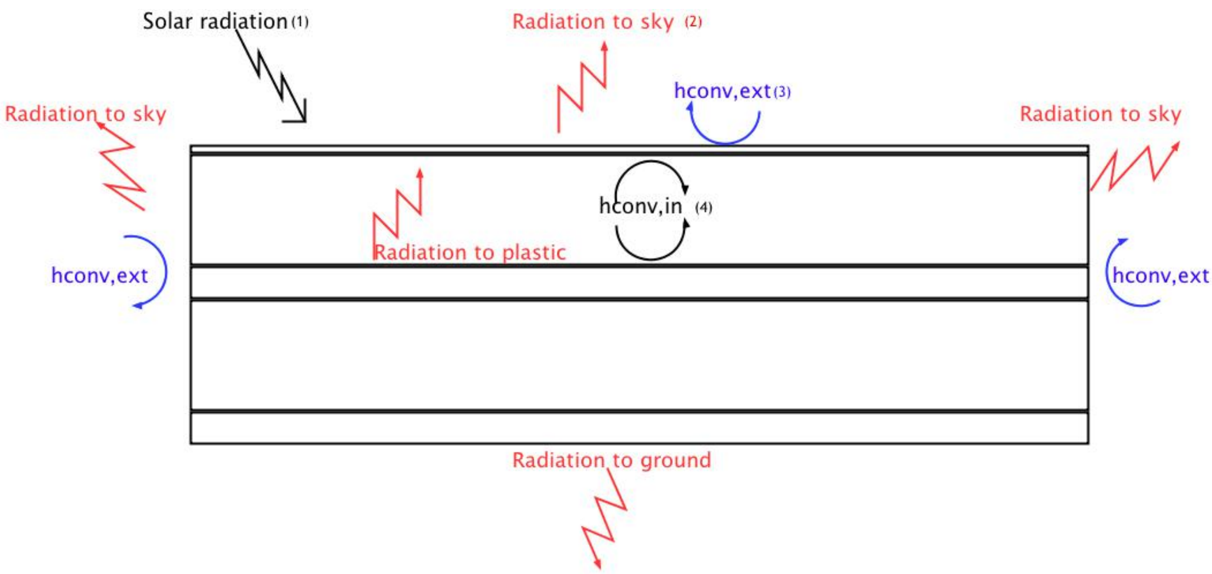

Figure 3 : Heat transfer in a solar dryer

3. Method

3.1 Models' description

The aim of this work is to model two types of solar dryers using the software COMSOL. The two main parameters taken into account in the studies are temperatues of the different elements of the solar dryers and relative humidity of the air circulating in the solar dryers.

A first model, referred as Model 1, aims to represent the tilted collector, Figure 3, with a tilt angle of $\theta = 45°$. The computer model of this solar dryer enables to quantify heat transfer. In this model, the air inlet velocity is set to a constant value. This value is kept in the whole collector. In this model, the study focuses on the air characteristics circulating in the collector (temperature distribution, relative humidity). The velocity profile is not modeled using fluid dynamics equation. The airflow velocity value is used to calculate the Nusselt number and deduce the convective heat transfer occurring on the absorber plate.

A second model, referred as Model 2, represents an active flat dryer (Fig. 2) containing bags full of water. To create this model, the Heat Transfer Module is used in COMSOL. In this model, the solar dryer is the same as the indirect solar dryer, except that the direct solar dryer is flat and the bags are put directly in the solar dryer. The temperature distribution in the dryer and the relative humidity are the two main parameters studied.

3.2 Assumptions

The following assumptions are made to model the active direct solar dryer and the passive indirect solar dryer :

- The solar dryers' studies are steady state for a constant solar irradiation. This is an approximation since the solar irradiation varies with time and weather conditions (clouds).
- The calculations can be run on half of the solar dryer without affecting the accuracy of the results given the symmetry of the considered geometry.
- The solar dryers which are modeled are built with a black net put on top of the absorber. This net is neglected.
- The plastic sheet does not absorb visible radiation, $a_p = 0$.
- The outward radiation from the sides is assumed to be radiated toward the sky while the radiation from the bottom goes to the ground.
- The heat radiation between the absorber and the plastic sheet is taken into account and a view factor is calculated for this.
- The inner sides are assumed not to reflect radiation
- There are no air leakages

3.3 Model validation method

In order to validate the models created for the two solar dryers, the results obtained through the model calculations are compared to field measurements. The values compared are five temperatures, plastic sheet, inlet air, outlet air, absorber plate, rock-wool insulation, bottom sheet and the relative humidity of the outlet air. The experimental set-up is presented in Section 3.3.

The mathematical tool used to compare the values from the model and from measurements is the relative error, defined by equation 2.

$$\varepsilon = \frac{x_{model} - x_{measured}}{x_{measured}} \text{ (eq. 2).}$$

3.4 Experimental set-up

The measurements collected are temperatures and relative humidity at chosen points on the solar dryer (Figure below).

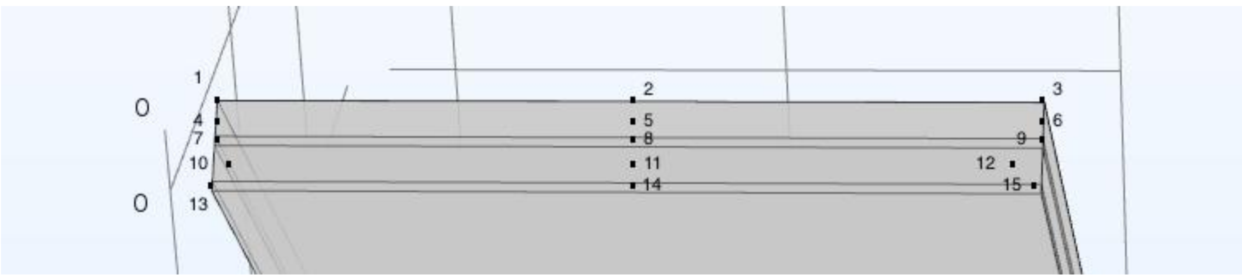

Figure 4 : Measurement points on the air outlet of the collector

The measurements collected are temperatures and relative humidity at chosen points on the solar dryer. To do so, two measurements tools have been used :

- four Vernier© sensors patched on strategic points on the solar dryer
- a Testo probe connected to a Testo435-2 logger, able to measure temperature and relative humidity

The measurements were taken during 30 minutes to reach stable values. The logs were stored on the Vernier© device and then transferred to a computer to be exploited on Excel. Each measurement has been done twice to deal with the repeatibility aspects of the experiments.

The ambient conditions were measured during 3 hours. Then, an average of the ambient temperature, ambient relative humidity and ambient solar irradiation has been done and used as intial values in the COMSOL models.

4. Results

4.1 Input data

The input data used for both the tilted passive and the flat active solar dryers is presented in the following table (Tab.1).

Tab. 1 : Input data

Parameter	Value	Unit
Collector width	1,1	m
Collector length	1,8	m
Insulation thickness	0,05	m
Global solar irradiation	916	W/m^2
Ambient temperature	31,6	°C
Ambient relative humidity	34,4	%

4.2 Model 1 : Tilted passive collector

The results from the computer model give the temperatures of the different elements of the solar dryer are given in Table 1 below. Here are presented the average temperature for each component of the tilted passive solar dryer.

Tab. 2 : Temperatures of the different elements of the titled passive solar dryer

Element	Temperature / (°C)
Plastic sheet	55,2
Outlet air	59,7
Absorber sheet	76,0
Insulation	43,0
Bottom sheet	33,2

The air temperature is above 50 °C and below 65 °C which means that the drying is performed in the correct range of temperatures to ensure the quality of the drying product, as shown on Figure 4. Less than 15 % of the collector length is necessary for the different elements to reach 80 % of the outlet temperature.

The value measured on-site for the ambient relative humidity is 34,4 % and is the one used in simulations. The calculations done by COMSOL show that at the outlet of the collector, the relative humidity drops to 10,1 % at the center of the air outlet surface.

4.3 Model validation

In order to validate Model 1 (resp. Model 2) for the tilted passive (resp. flat active) solar dryer, the temperatues values and the relative humidity value of the air obtained through COMSOL calculations are compared to the measurements of the same values, done on-site.

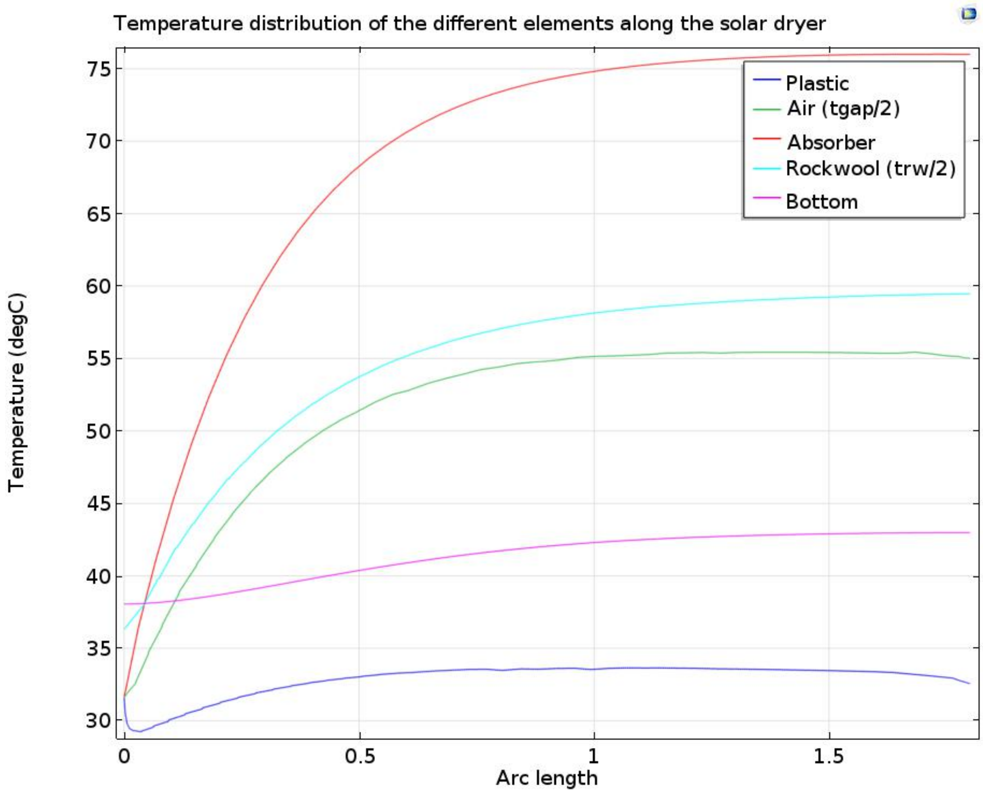

Figure 5 : Temperature of the different elements along the tilted passive solar dryer

For Model 1, the relative error for the temperatures given in Celsisus degrees varies from 2,6 % to 29,2 %. The average relative error for each element of the collector is given in Table 3 below, showing that the temperatures calculated by the model can be considered as accurate, except for the plastic sheet. For the relative humidity, a relative error of 8 % is obtained when the outlet air relative humidity measured is compared to the estimation from the computer model.

Tab. 3 : Relative errors for the temperature and relative humidity values – Model 1

Element	Average temperature measured on-site (°C)	Average temperature calculated by the model (°C)	Relative error on temperature
Plastic sheet	46	34	24 %
Outlet air	58	52	10 %
Absorber sheet	61	67	10 %
Insulation	61	55	11 %
Bottom sheet	40	41	3 %

The same is done with Model 2 and the relative error for the temperature values varies from 2,7 % to 33,2 %. The average relative error for each element of the collector is given in Table 4 below, showing again that the temperatures calculated by the model can be considered as accurate, except for the plastic sheet. For the relative humidity, a relative error of 8 % is obtained too when the outlet air relative humidity measured is compared to the estimation from the computer model.

Tab. 4: Relative errors for the temperature and relative humidity values – Model 2

Element	Temperature measured on-site (°C)	Temperature measured on-site (°C)	Relative error on temperature (°C)
Plastic sheet	41	28	32 %
Outlet air	49	43	12 %
Absorber sheet	44	51	17 %
Insulation	45	43	4 %
Bottom sheet	38	35	8 %

4.4 Parametric studies

The influence of the following parameters is studies through parametric studies in which all the parameters are fixed except the one studied.

The first parameter studied is the airflow velocity, which is constant in the solar dryer. The influence of the airflow velocity on the outlet temperatures, the internal convective heat transfer coefficient and the energy losses is studied. Six values of airflow velocity are studied : 0,1 ; 0,5 ; 1,0 ; 1,5 ; 2,0 ; 2,5 m/s. The higher the velocity, the lower the air temperature will be at the outlet. The same is observed for the absorber temperature at the outlet. This is due to the increased convection effects when increasing the airflow velocity. The air circulates faster in the absorber sheet and the heat will leave it faster. The relative humidity does not vary much as well and remains at about 10 % varying from 5 % for the lowest velocity to 12 % for the highest. Since the relative humidity depends on the temperature value, it is normal that a higher speed induces a higher relative humidity rate, because a higher airflow velocity is responsible for a lower temperature in the air. The internal convective heat transfer coefficient is affected by a change in the inlet airflow velocity. It is higher when the velocity is higher as shown on Figure 5. The range of values for this coefficient remains around [0,5; 2,0] $W/m^2/K$.

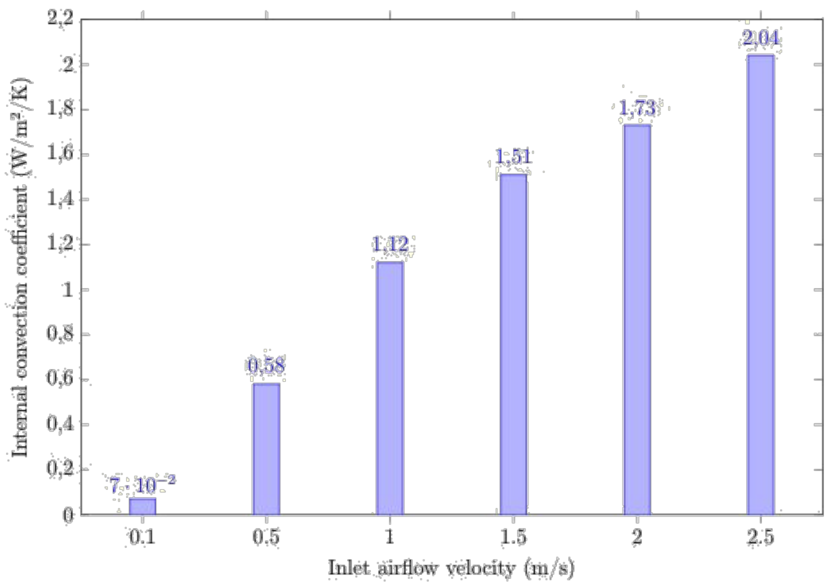

Figure 6 : Internal convection coefficient depending on the airflow velocity - Tilted passive collector

Then, the influence of the internal convection coefficient on the absorber plate is studied. The internal convective heat transfer coefficient on the absorber has a major influence on the outlet air temperature, the relative humidity and the outlet absorber temperature. When increasing the internal convective heat transfer coefficient on the absorber, the air at the outlet is at a higher temperature. For a constant velocity, increasing the internal convection coefficient on the absorber results in a lower relative humidity for the outlet air. The graph of the evolution of the outlet air temperature depending on the internal convective heat transfer coefficient is shown on Figure 6.

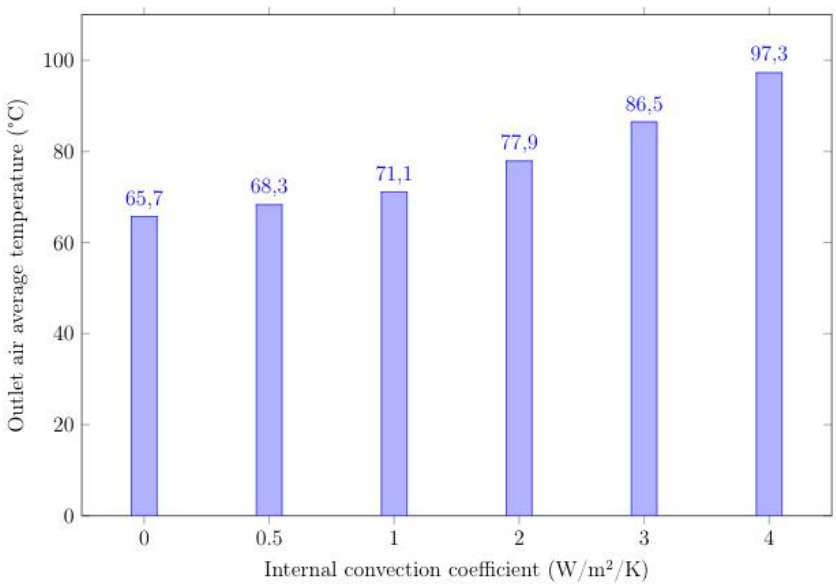

Figure 7 : Evolution of the outlet average air temperature depending on the internal convection coefficient for the tilted passive solar dryer

The radiative properties such as the transparency of the plastic sheet and of the absorptance and the emissivity of the absorber are some other important parameters which influence is studied. Simulations were run with the following values for the absorber emissivity : 0,1 ; 0,3 ; 0,5 ; 0,7 ; 1. The value of 1 corresponds to an ideal black body. The lower the emissivity, the higher the absorber temperature will be and thus the higher the air will be. A low emissivity means that the absorber is loosing less heat by radiation since it emits less thermal radiation (visible and infrared). This parameter is material-dependent.

Finally, the last parameters which influence is studied is the insulation thickness. The insulation thickness values tested are: 0.1 cm, 1 cm, 3 cm, 5 cm, 10 cm, 15 cm, 20 cm. Increasing the insulation thickness allows to get higher outlet air temperature to a certain point as shown on Figure 7. After 15 cm, the gain in the outlet air temperature is less perceptible. The temperature of the bottom part of the solar dryer is highly impacted by the insulation thickness.

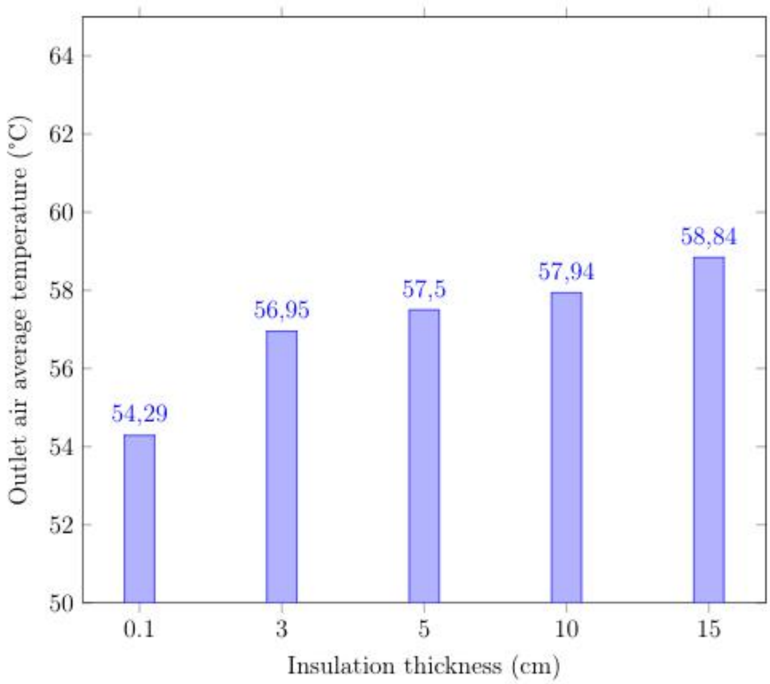

Figure 8 : Evolution of the outlet average air temperature depending on the insulation thickness for the tilted passive solar dryer

4.5 Design optimization

Some design optimization can be deduced from the previous parametrics. First of all, the insulation thickness needs to be chosen carefully. A too thick insulation layer is not useful but 5 cm seems to be a minimum value to limit the heat losses and keep the bottom part of the solar dryers at a reasonable temperature. Increasing the thickness of the insulation layer also increases the absorber temperature and in this case, even if more heat is transferred by convection to the air, the temperature difference between the absorber and the plastic sheet is higher and so are the radiative losses from the absorber to the plastic sheet. Finding the minimum thickness needed for the insulation layer allows also to reduce the price of the material needed.

The absorber material should be chosen carefully with the highest absorptance possible and the lowest emissivity. For this, low emitting coating absorbers would of course provide better drying performances. However, the quite high emittance of the absorber (0,8) used to build the solar dryers is sufficient to ensure an air temperature between 50°C and 65°C and thus food safety regarding the drying product. Since the solar dryers will be built and used in Mozambique, the emittance of the absorber is not a prior concern given the price difference between a classic corrugated metal sheet and a low-emitting coating. The plastic sheet material choice could be improved by choosing a more transparent material to increase the fraction of solar radiation transmitted to the absorber.

Then, increasing the convection on the absorber plate is a way of transferring more heat to the air. It can be done by increasing the surface of contact between the air and the absorber. Then, a better way of increasing the convective heat transfer is to increase the convective heat transfer coefficient, which means increasing the Nusselt number or the hydraulic diameter (the effective surface of the absorber). It could be possible to increase the natural convection thanks to a double-pass system with the air entering on the backside of the passive solar dryer and then going around the absorber plate and exiting the solar dryer on the opposite side to the one the air entered. The convection around the bags is also very important. As explained by Phinney and Tivana (2016), the higher the airflow velocity around the bags, the higher the drying rate. One idea to increase the amount of air passing around the bags could be to have air passing above and under the bags. In the passive solar dryer, the bags should be put higher in the drying chamber joined to the collector. However, a balance has to be found because the driest air is located close to the absorber plate. In the active solar dryer, the fans already provide a good circulation of air around the bags. The point in this is also to avoid the moisture to stay on the bag so the relative humidity does not increase too consequently around the bags.

5. Discussion and conclusion

The model validation has been done by comparing measurements to values calculated by COMSOL. However, the tools used to take measurements are a source of error. In both models (passive tilted and flat active), the plastic sheet temperature is underestimated. This is an example of the difficulty to measure temperatures on certain elements of the solar dryer. Also, the model used to represent the solar dryers used an internal convective heat transfer coefficient based on a Nusselt number calculated using correlations. This is another source of error. One approximation has been done regarding the absorber plate shape. The material used in the solar dyers is a corrugated metal sheet. To simplify the problem, it is modeled as a flat sheet which thickness is equal to half of the height of the bumps of the corrugated metal sheet. When measuring the absorber temperature, it is always the temperature at the top of the bumps which is collected. A difference of 2,5 to 4°C is observed between the temperatures on the bumps or the hollows.

The internal convection in the solar dryer is one of the most delicate point in this modeling task. There are several solutions to do so. One solution is to determine an equivalent conductivity to the convection phenomenon. For the solar dryer, convection in the fluid would occurs in the case of an "horizontal cavity heated from below". COMSOL requires to give the dimension of the cavity (distance plastic sheet - absorber) and the temperature difference between the air and the horizontal plate heating the air. This solution might not be the best, first because knowing the temperatures of the air and absorber are one of the goal of the study and are not meant to be set. Also, the software uses some correlations that are not easily accessible. Another solution is to use another module in the software to model the flow behaviour. Thanks to the Boussinesq approximation for instance, it would be possible to model the natural convection inside a passive solar dryer (Motte et al., 2011). However, in this case, it is time consuming and it could not have been possible to carry out parametric studies with such a model. Finally, the chosen solution was to calculate the Nusselt number and give it as a parameter in the software. COMSOL allows to determine the different elements of the Nusselt number formula (specific heat at constant pressure, density, etc) depending on the temperature in each cell of the mesh of the air domain.

Finally, it could have been possible to model the airflow using the Navier-Stokes equations in the Non-Isothermal Flow Module available in COMSOL. However, this method is time-consuming, even using simplifications such as symmetry in the geometry. Some models have been built taking into account the fluid behavior. The results for the temperature and the relative humidity were close to the results given by the model not including the fluid behavior modeling.

To conclude, the models created in COMSOL Multiphysics give sufficient information regarding the temperatures and air relative humidity in several parts of both a direct and indirect solar dryer. Even if the exact temperatures might not be found, the models give correct approximation of it. The main purpose of these models is to study the effect of different parameters variation. The main conclusions of this work are that:

- COMSOL is a sufficient tool to build models. It will also allow to improve the modeling by including more phenomena (water vapor transport for instance).
- The models give a sufficient estimation of the temperature and relative humidity in a direct and in an indirect solar dryer with a maximum relative error of 10% for the outlet air temperature.
- The calculations of the external convective coefficient can be done with different formulas without changing the results in a significant way. However, the calculation of the internal convective coefficient is more important and the formula used to calculate requires to be chosen carefully depending on the flow characteristics (Reynolds and Prandtl numbers).
- It is possible to increase the performance of the two solar dryers tested by reducing the space between the absorber and the plastic sheet and by using an insulation layer of at least 5 cm.

- The choice of a low-emissivity material for the absorber is not of prime importance. However, the plastic sheet could be of higher quality with a higher transparency.

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