Study and Simulation of A Solar System for Drying Purpose in Rwanda

To cite this article: P D Uwitije *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **462** 012001

IOP Conf. Series: Materials Science and Engineering 462 (2019) 012001 doi:10.1088/1757-899X/462/1/012001

Study and Simulation of A Solar System for Drying Purpose in Rwanda

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Abstract. This study aims to simulate and present the hourly thermal analysis of a forced convection solar dryer along with the parametric analysis of the drying process made using the drying characteristics of green pepper. Under the consideration of Rwanda weather condition on August 21st, the designed solar collector shows low performance before noon and high-performance afternoon. It generates output air temperatures above 50^0C from 12:00 until 19:00 with the highest value of 74^0C generated at 15:00. In the drying chamber, the green pepper drying time shows dependence on the air temperatures obtained from the solar collector and on the tray positioning number. The graphical results show that the products dried in the first tray dries quickly compared to those in the last trays, the effect of drying at high temperatures lead to the reduction in the drying time. The obtained results are confirmed by their similarities in curves trends with those of results diagrams in related literature studies.

1. Introduction

In the confrontation of the immense population increase and resource challenges facing humanity, sufficient provision in the food supply and renewable energy exploitation will take up vital importance. To cope up with current and future food supply, preservation techniques that optimise transport cost and reduction in food losses are required. An excellent and most applicable way to preserve products and to facilitate their transportation is the drying process. By reducing product moisture content, drying helps in the impediment of the microbial actions that are responsible for food spoilage and in the reduction of their weight. Unfortunately, mechanical thermal dryers are more energy intensive, have a high initial and fuel running cost and are the harmful impact on the environment. On the other hand, the traditionally used open sun drying is slow and fails in drying some particular products requiring intense energy. In Rwanda, the loss arising from products deterioration can be substantial especially for products such as fruits and vegetables deteriorating quickly. The use of solar drying in enclosed thermal systems becomes a very ideal and cost-effective alternative especially in the rural locations with non-existent grid connections [1]. Establishment of modelling techniques and simulation programs have been very useful in analysing and optimising the drying systems performance and in the forecasting of components temperatures and drying mechanism of different products [2]. Elaborated numerical studies for various solar dryers working in different locations have been carried out to study the system performance and drying process of different products. Dilip in India used a transient analytical model along with the drying characteristics of onions to evaluate the system's drying performance a solar crop dryer [3]. Using the drying characteristics of potatoes, Nasri and Belhamri in Algeria simulated an indirect forced convection solar dryer for drying agriculture products [4]. In their calculations, algorithm and code programs were established to solve the energy balance equation to calculate the hourly air temperatures of various components making the drying system. In Rwanda, the first study on drying mango slices in domestic solar dyer ascertained the promising application of reducing food spoilage [5]. The purpose of this study is to simulate a forced convectional solar dryer for drying the excess or non-sold out products fruits and vegetable in the local markets of Rwanda.

2. Materials and Methods

2.1. System Design

The drying system used in this present study is a typical indirect convection dryer designed to dry fruits and vegetables. It consists of two main parts, a double glazed conventional solar air heater and a drying chamber. The collector is tilted at 15° concerning the horizontal. On the top, it consists of two glass covers spaced by 15 mm with a thickness of 10 mm. In the middle, a galvanised sheet painted black of thickness 1 mm is used as an absorber whereas at its bottom it has polystyrene insulation of 4 cm thick. The drying chamber is a cubic box having a side length of 1 m walls. This consists of a 10 cm layer made up of brick and with external insulation of 4 cm thick layer of polystyrene. Inside the drying chamber, there are ten wired mesh racks separated by 10 cm in between on which 2.5 kg of products is laid. On the top, it is equipped with an extractor fan to ensure forced convection as shown in Figure 1. During the working time with bad weather conditions, the system is considered to have a backup air heater.

2.2. Theoretical Approach

In modelling the drying chamber, we have adopted the step by step mathematical model proposed by Danguent. This model accounts for the evolution of temperatures of all solar dryer elements in time and space. Much more it involves the effects of mass and system thermal inertia [4]. It consists of taking the drying chamber and cutting it into some fictitious slices in the direction of airflow. The obtained slice sections are delimited by two racks and the walls of the chamber as shown in Figure 2. The equations governing thermal and mass exchanges at the level of each tray section are written based on the energy and heat balance as follows:

Exchange at the external polystyrene wall face

$$\frac{m_{Pp}C_{Pp}}{4}\left(\frac{dT_{pe}}{dt}\right) = h_r.S_v\left(T_c - T_{pe}\right) + h_{am,pe}.S_v\left(T_{am} - T_{pe}\right) + k_p.S_v\left(T_p - T_{pe}\right) \quad (1)$$

Exchange through the wall between polystyrene and brick faces

$$\frac{m_{Pp}C_{Pp}}{4}\left(\frac{dT_p}{dt}\right) + k_pS_v\left(T_p - T_{pe}\right) = \frac{m_{Pb}C_{Pb}}{4}\left(\frac{dT_p}{dt}\right) + k_bS_v\left(T_p - T_{pi}\right) \quad (2)$$

Exchange at the internal surface of the brick wall

$$\frac{m_{Pb}C_{Pb}}{4}\left(\frac{dT_{pi}}{dt}\right) = k_bS_v\left(T_p - T_{pi}\right) + h_{ash,pi}.S_v\left(T_{ach} - T_{pi}\right) \quad (3)$$

The exchange between the product, internal wall face and the drying air at the internal wall face of the brick

$$\dot{m}_{ach}C_{Pair}(T^{\star}_{ach} - T_{ach}) = h_{ach,f}\,S_f\,(T_{ach} - T_f) + 4.\,h_{ach,pi}.S_v\left(T_{ach} - T_{pi}\right) \quad (4)$$

Exchange between the product and the drying air

$$m_fCp_{pf}\left(\frac{dT_f}{dt}\right) = h_{ach,f}\,S_f\left(T_{ach} - T_{pi}\right) - P_{ev} \quad (5)$$

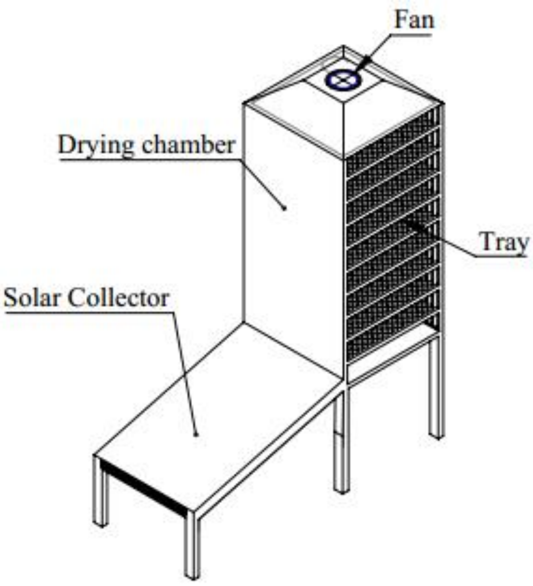

Figure 1. Diagram of the studied forced convection indirect solar dryer.

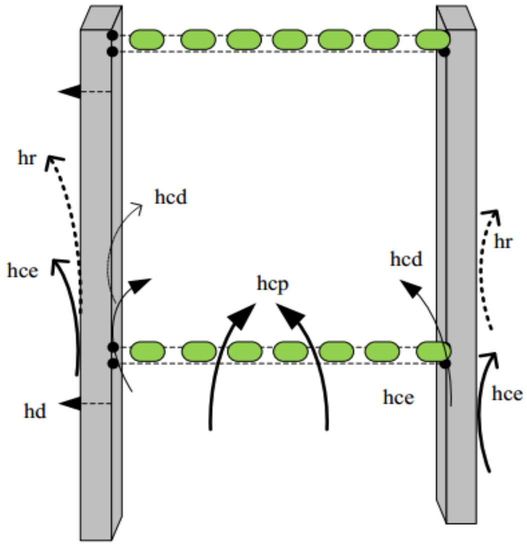

Figure 2. Energy balance on the tray inside the drying chamber.

2.3. Drying Kinetics

The kinetic model used to simulate the behaviour of the moisture transfer within the green pepper is the first order empirical model written as [6]:

$$\frac{dX}{dt} = -K(X - X_e) \quad (6)$$

With Xe representing the equilibrium moisture content for green pepper and K is a drying constant found in the experimental work for drying green pepper [7]. This constant K ensures the falling rate slope of the drying curve due to drying condition such as product diameter, drying temperature, air velocity and absolute humidity determined by:

$$K = K_0 D^{KD} T_{ach}^{KT} W_{ach}^{KW} U_{ach}^{KU} \quad (7)$$

Taking the moisture content $X = X_i$ at t=0 the solution is found for the moisture content at any time as in the following expression [6]:

$$\frac{X_t - X_e}{X_i - X_e} = e^{-Kt} \quad (8)$$

2.4. Numerical Approach

To solve numerically the set of equations obtained for the drying chamber, an implicit finite difference method is chosen and applied to discretise each equation in time and space. After, we are lead to resolve the set of obtained equations into a matrix system of $[A][T] = [B]$ in which the vector $[T]$ represents the vector of unknown quantities. Later a Matlab program is developed for the drying chamber in which an iterative Gauss-Seidel method is used to solve the system of equations. At the beginning of this simulation program, we assign at the beginning of the simulation arbitrary values at temperatures, which are equal to ambient temperatures, then heat exchange coefficients are calculated and injected into the system of equations above. After the resolution of the latter, the values of the temperatures calculated in this way are compared to the previous values. The calculations are considered complete when the desired precision is obtained. Otherwise, the calculated values are taken as arbitrary values, and the calculation is resumed to the desired precision.

3. Results and Discussion

The hourly distribution temperatures for different elements of the solar air heater and the output air temperatures are presented in Figure 3. The maximum fluid output temperatures above 50°C are generated from 12:00 up until 19:00 with the highest value of 74°C generated at 15:00 owing to maximum radiation and high ambient temperatures input at this time. It is observed that before 8:00, both temperatures do not increase much even though they are exposed to solar radiation for 3 hours. This is explained by the effect the received energy is used to warming up the system. Another remarkable observation is the high collector output temperature fluid at 19:00 despite sunlight absence. This is due to the logic of mass inertia for system cooling [4].

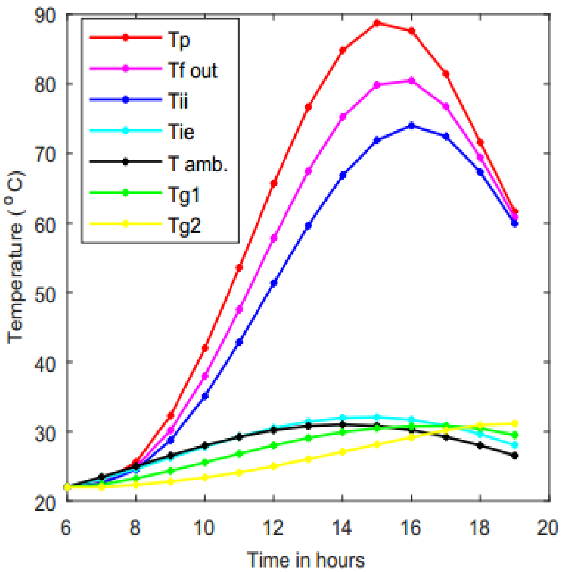

Figure 3. Variation in temperatures for different air collector elements

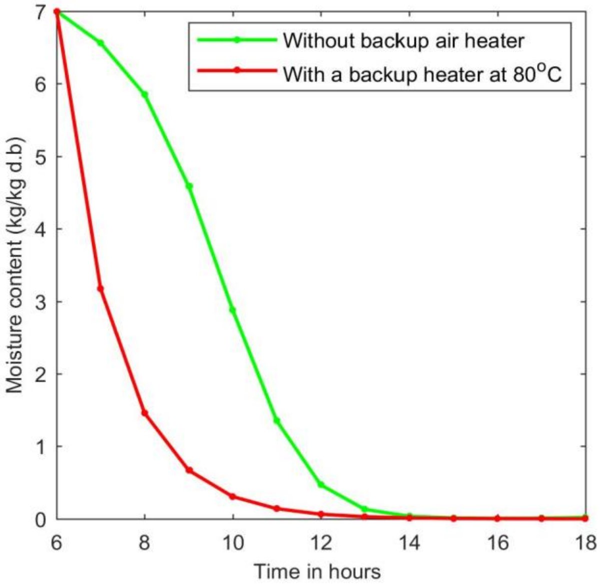

Figure 4. Effect of drying at constant and varying temperatures on the moisture content reduction

The performance of the drying chamber is evaluated by the decreasing product moisture content concerning the drying time. In Figure 4, the influence of drying with constant fluid temperatures at 80°C when the backup heater is added is shown in red curve whereas the influence of using varying air temperatures when there is no heater is depicted by the green curve. When drying at constant temperatures, product water removal is high at the beginning of the drying process owing to the quick evaporation of product moisture content in external layers of product. The moisture content reduction for the green curve represents the reduction due to collector air temperatures varying hourly depending on the radiation intensity reaching on the solar air heater. The reduction goes slow first in the morning but later is accelerated when much radiation intensity is gathered and after the ambient temperature has increased. Drying at a controlled constant temperature of 80°C insured by the solar collector with the addition of heating results in short drying of six hours from 6:00 am to 11:00 am compared to 8 hours needed when using solar air heater only. Similar results in curves shape are found for drying onions [6].

First, the effect of influential parameters is studied by inspecting the drying time at various drying temperature. In Figure 5 the effect of drying at various constant temperatures (40, 60 and 80°C) of air on the drying time of products in the last tenth tray is illustrated. Drying at 80°C occurred 3 hours earlier compared to the drying time at 60°C happening after ten hours whereas drying at 40°C requires more than fifteen hours of drying time. Similar findings in the graph trends are obtained when drying onions in the previous work [6]. At last, the performance of the drying chamber is evaluated by studying the reduction in product moisture content in different trays. The difference in drying time is illustrated in Figure 6 for trays 1 and 10. The drying time for products placed in the first tray is short compared to the product dried in the last tenth tray. The explanation might be based on the fact that the air temperature at the entrance of the drying chamber decreases as it moves from tray to tray. Another reason would be the decrease in the drying air capacity to take up water as it moves from tray to tray fixing more water vapour. The observed graphic trends are similar to the work of D. Jain in his work concerning a solar crop dryer [3].

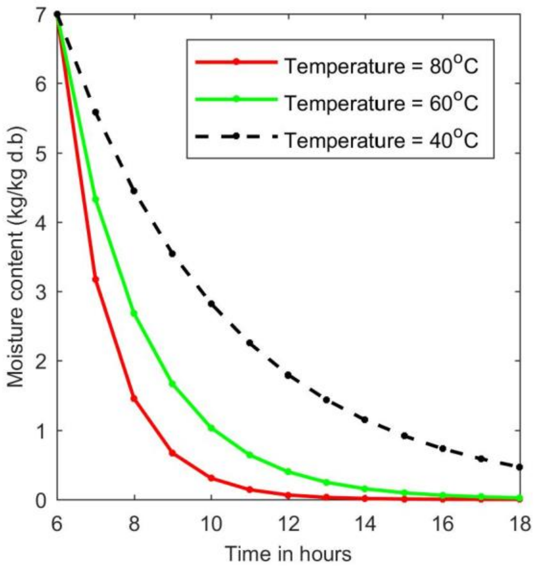

Figure 5. Effect of drying temperature on the moisture content reduction.

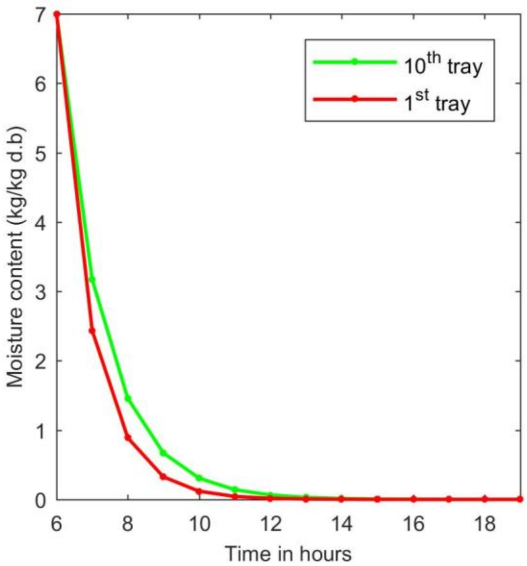

Figure 6. Variation in moisture content in the first and last tray.

4. General Conclusion

In this paper, we study the behaviour of an indirect forced convection solar dryer by the use of numerical modelling. The developed Matlab program fits perfectly for studying the thermal performance of the solar collector and drying chamber in Rwanda. To do this, we proceeded to the mathematical simulation of our dryer by developing and solving the respective mass and heat transfer mathematical models to reflect the physical reality of the working mechanism of a forced convection indirect solar dryer. The results showed that the designed solar collector generates high air temperatures capable of shortening the drying process and that using a backup heater increases the system performance, especially in the morning time. In the parametric study, the drying rate is much influenced by the drying temperature. It is also observed that products in different trays have different drying time. The graphical results obtained using the drying kinetics of green pepper presented similarities in the curve trends occurring in the diagrams of related work. This comparison allowed us to conclude that our simulations are valid. Using the developed code program will help in choosing appropriate measurements and in decision making during system design.

Nomenclature

C_p	:	Specific heat (J/kg K)
D	:	Characteristic dimension (m)
hr	:	Coefficient of heat exchange by radiation (W/m^2K)
j	:	Section number
K	:	Coefficient of heat transfer by conduction (W/m^2K)
$\dot{m}$	:	Mass flowrate (kg/s)
T	:	Temperature (K)
X	:	Moisture content (kg/kg d. b)

Subscripts

a	:	Ambient
ach	:	Heated air
b	:	Brick
f	:	Air fluid
f	:	Product
e	:	External
g_1	:	First glass cover
g_2	:	Second glass cover
ii	:	Internal part of the insulation
ie	:	External part of the insulation
p	:	Absorber plate
s	:	Sky
t	:	Time

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