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Experimental Study of a Modified Icaro Solar Dryer: The Case of Coffee Drying

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Abstract

Food losses in the developing country are thought to be 50% of the fruits and vegetables grown and 25% of harvested food grain. Food preservation can reduce wastage of a harvest surplus, allow storage for food shortages, and in some cases facilitate export to high-value markets. Drying is one of the oldest methods of food preservation. Drying makes produce lighter, smaller, and less likely to spoil and helps to minimize the moisture content in coffee beans as high moisture content during storage is certain to ruin the taste and appearance of coffee. This work presents the results of an experimental study of forced convection drying of coffee cherries in a modified Icaro solar dryer. The study aims to validate the numerical models developed for further research. The experimental tests envisaged also aim to determine the mass loss curves of the product by fixing or calculating its initial mass (1 kg), its initial water content (70%), the ambient temperature, the drying airflow (0.02 $m^3 \cdot s^{-1}$ to 0.09 $m^3 \cdot s^{-1}$) and the exchange coefficients. The influence of these aerothermal parameters on the drying time of a most commercialized coffee variety (Robusta) was studied. Finally, the results revealed an increase in the efficiency of the heat transfer air and a reduction in the water content of the coffee cherry from 70% to 9.87%, after 30.2 hours.

Keywords

Solar Dryer, Icaro, Experimental Validation, Moisture Content, Coffee, Temperature

1. Introduction

This work deals with the experimental study using the modified Icaro solar dryer implemented for coffee drying. The design and realization of this dryer were possible based on the authors' previous work [1] [2]. The choice and modification of the old Icaro dryer must meet the requirements of the target product, the availability of technology, manufacturing materials and climatic conditions. For these reasons, replacing the photovoltaic (PV) module with a 12-volt battery, changing the location of the glass at the sensor and modifying the arrangement of the racks inside the drying cabin can help to obtain the required temperatures for coffee drying. There are many methods of drying coffee cherries, the most commonly used of which are: wet drying and open air drying. The wet process requires significant investments in materials and water, with significant costs (depreciation, maintenance).

The drying of agricultural products, such as coffee, cocoa and cassava produced in hot and humid equatorial zones, is often difficult and imperfect. Many farmers use sun drying to reduce the moisture content of coffee beans. It is the most common traditional drying method in Central African Republic because of its low cost compared to mechanical drying. It requires little investment and is environmentally friendly since it uses the sun as the heat source and therefore produces no CO_2. However, sun drying tends to be labor intensive and has limited capacity. Temperature control is also difficult in this method and grains can easily be overheated, causing cracked grains which lead to low milling quality. In addition, the product has an altered taste, due to the smell of the soil, the drying method used and above all, the makeshift devices [3]. To overcome this, coffee must be subjected to treatments during which the nutritional and sensory quality of the coffee does not deteriorate, mainly due to the drying method used. The Central African Republic (CAR) is a country with a large solar resource averaging 4.8 kWh/m^2/day, over the year [4] favorable for the development of solar drying system. This work presents the results of an experimental study of forced convection drying of coffee cherries in a modified Icaro solar dryer. The influence of the aerothermal parameters on the drying time of a most commercialized coffee variety (Robusta) is investigated. The study aims to validate the numerical models developed for further research. The experimental tests envisaged aim to determine the mass loss curves of the product.

2. Materials and Method

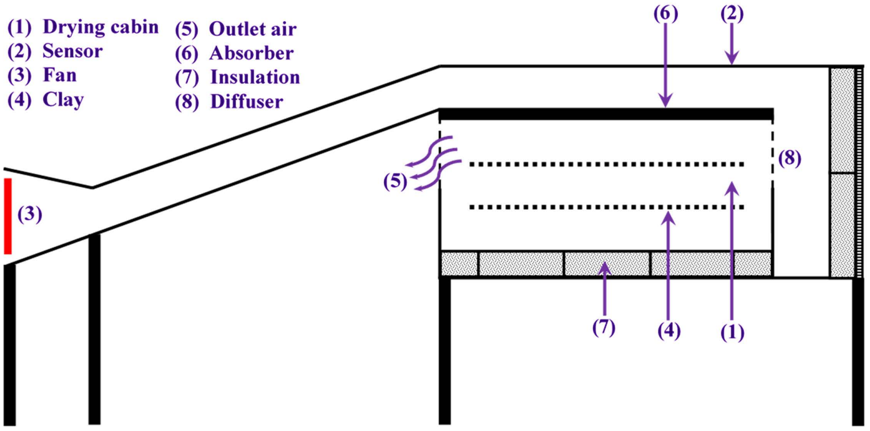
2.1. Drying Materials and Equipment

The coffee dried during the experimentation of our dryer is of the Robusta variety Coffea canephora shown in **Figure 1**. It comes from Boukoko, in the sub-prefecture of M'baïki, a town in the Central African Republic.

In this study, we used an indirect solar dryer with forced convection. It is designed and built at the *Laboratoire d'Energétique Carnot*. Measuring devices such as the Vantage Pro 2 for solar radiation measurement is used. Other measuring devices such as the Oregon platinum probe thermometers and the 425 tests are placed at different points of the solar collector and also in the drying chamber. These are also used to measure temperatures. The measurement of wet and dry mass is done by the use of an electronic balance, brand Sartorius and an oven, brand Memmert.

The modified ICARO dryer is an indirect forced convection dryer with a maximum storage capacity of 2 kg of fresh product. It has two racks, each with a maximum capacity of 1 kg. Figure 2 shows the modified ICARO dryer.

Figure 1. The robusta coffee variety (Canephora).



(a)

(b)

Figure 2. Modified Icaro solar dryer. (a) Picture; (b) Schematic diagram.

2.2. Experimental Method

The solar radiation values are obtained by averaging the solar fluxes recorded at each hour of the day to obtain the monthly and annual radiation. Our data are obtained from a program written in MATLAB and Excel.

For the evolution of the mass of the products, we used a Sartorius balance (capacity 1 kg, accuracy 0.001). The coffee cherries are placed on racks. On one rack, a quantity of 1 kg of coffee cherry is placed as a control sample, which is weighed every hour. The mass weighing is done by removing the sample from the drying chamber.

The temperatures were measured with a platinum probe thermometer (Oregon, 0.01) and testo 425 (precision, 0.01). The temperature probe and the testo 425 were placed at different measuring points for the temperature development. The same measurements were carried out first in the dryer without load and then with a load, from 6:00 a.m. to 6:00 p.m. during each hour of time.

To determine the dry mass of the product, two samples at the end of the drying process are taken and placed in a Memmert-type oven (30˚C to 200˚C) for 24 hours, at a constant temperature of 105˚C. The dry mass is obtained by making the difference between the masses before and after being placed in the oven. Finally, the data of two samples are averaged to obtain their final water content.

3. Estimation of Characteristic Parameters

The mass of water to be removed during the drying process, M_e, is given by Equation (1)

$$M_e = \frac{MR_i - MR_f}{100 - MR_f}. \tag{1}$$

The equilibrium water contents are calculated using Equation (2)

$$MR_s = M_c - M_b. \tag{2}$$

The evaluation of the dry mass allowed the determination of the initial water content in dry and wet basis by Equations (3) and (4) respectively:

$$MR_s = \frac{M_i - M_c + M_b}{M_c - M_i}. \tag{3}$$

$$MR_h = \frac{M_i - M_c + M_b}{M_i} \times 100. \tag{4}$$

The moisture content of the coffee bean is determined by the following Equation.

$$MR_s = 100 - MR_h. \tag{5}$$

Dry base water contents (MRs) using the following correlation.

$$MR = \frac{M(t) - M_{sec}}{M_{sec}} \times MR. \tag{6}$$

The reduced water content (RWC), is obtained using the relation (7)

$$MR_r = \frac{MR(t) - MR_{eq}}{MR_s - MR_{eq}}. \tag{7}$$

Where the drying rate is calculated from the following Equation (8):

$$\frac{dMR}{dt} = \frac{MR_{t+\Delta t} - MR_t}{dt}. \tag{8}$$

Where t is the drying time, $MR_{t+\Delta t}$ and MR_t indicate the water content at times $t + \Delta t$ and t, respectively.

The thermal efficiency η of the solar collector is defined by the Equation (9)

$$\eta = \frac{Q_u}{S_c I_r}. \tag{9}$$

The useful power recovered by the fluid is determined by the Equation (10)

$$Q_u = D \times Cp_{air}\left(T_s - T_e\right). \tag{10}$$

4. Results and Discussion

The curves for the temperature profile, the reduced water content, the drying rate and the variation of the thermal efficiency are shown in Figure 3.

Temperatures are measured at the different points of the collector. These are: the ambient temperature *Ta*, the absorber temperature *Tabs*, the fluid temperature *TF* and the sky temperature *Tc*. It is remarkable to see in Figure 3 that the temperature of the absorber *Tabs* is the highest, which can be explained by its solar absorption factor (black painted aluminum absorbers). Its maximum value is 95.8˚C at 12 o'clock.

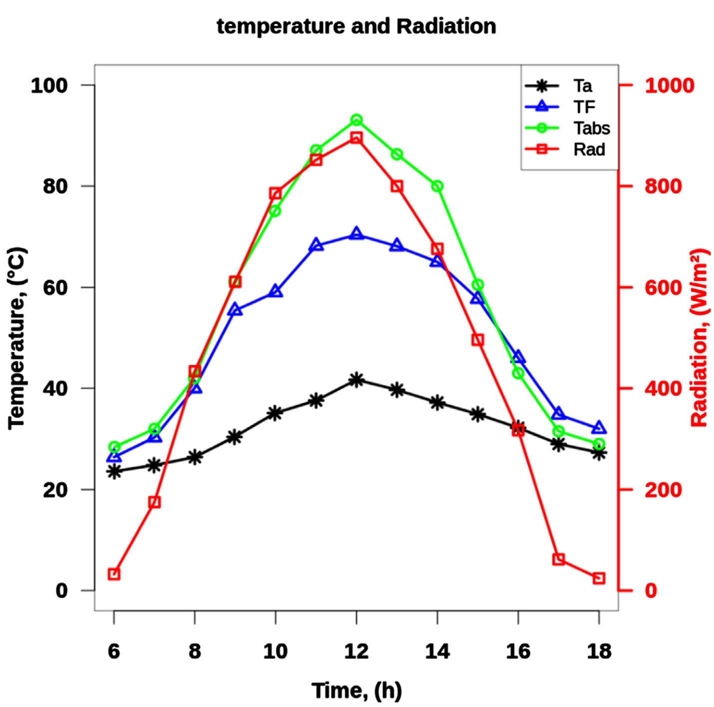


Figure 3. Curve of different temperatures at the sensor.

The temperature of the fluid *TF*, has a maximum value of about 74.4˚C at 12:00. The temperature levels of the drying fluid are well within the recommended range for quality coffee drying [5] [6]. The maximum ambient temperature is above 40˚C. The maximum temperature difference between the ambient value and the temperature of the heat transfer fluid at the collector outlet can reach 30˚C at around 12:00 p.m. (what explains this difference?). Note that the temperature pattern is similar to that of the solar radiation. From these curves, it is clear that the highest temperature is that of the absorber, resulting from the high power it has absorbed. A difference of 19.4˚C separates the temperatures of the absorber and the heat transfer fluid, which is due to the low absorption coefficient of the glass (0.06).

Figure 4 shows a comparison between the different variations of ambient and sky temperatures as a function of time. The sky temperature is given by the Swinbank relation [7]. It is calculated as a function of the ambient temperature of the experimental site.

We can notice in **Figure 4** that the ambient and sky temperatures have almost the same pattern and reach their maxima between 12:00 and 2 pm, a period when the heat flow is important. This behavior confirms the Swinbank relationship in which the sky temperature depends on the ambient temperature.

The variation of the average inlet and outlet temperatures of the collector over the course of a day are shown in **Figure 5**.

It can be seen from these curves that at the beginning of the exposure, the temperatures are almost the same. After some time has elapsed (8.00 hrs), the air temperature at the sensor outlet increases very rapidly and reaches its highest

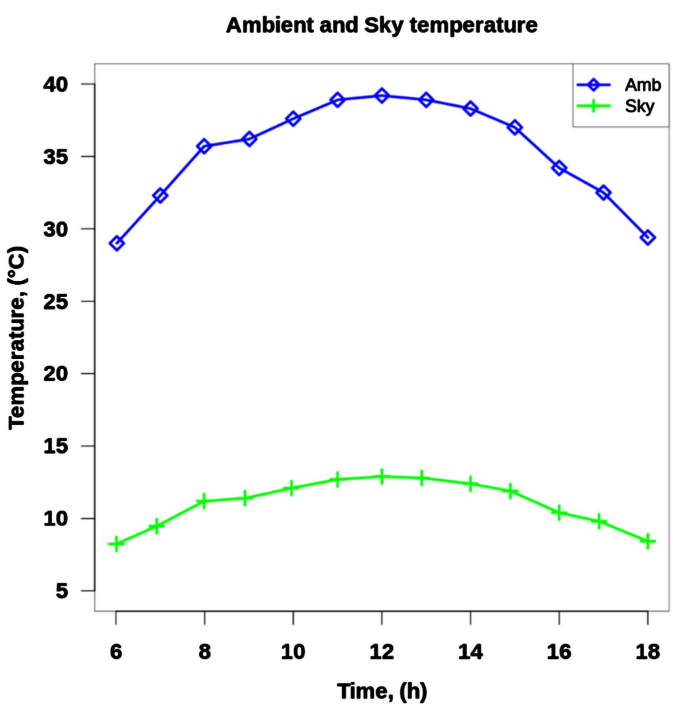


Figure 4. Temporal variation of ambient and sky temperatures.

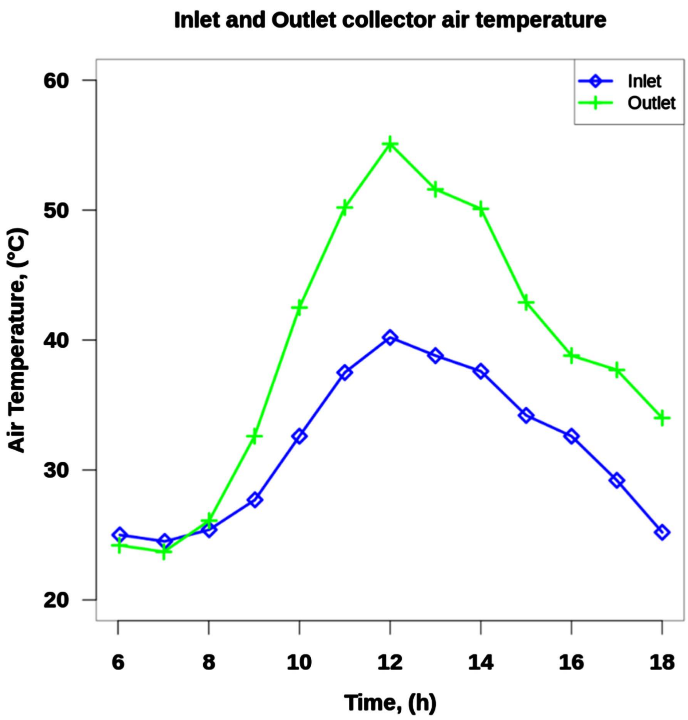


Figure 5. Evolution of air temperatures at the inlet and outlet of the collector.

value of 55.3˚C. This can be explained by the fact that the absorbed energy is used to heat the collector elements; thus the fluid in its flow under the absorber receives heat from it. There is also a difference between the ambient temperature (collector inlet), the temperature at the inlet of the drying chamber and the temperature at the racks. This difference is due to the heating of the absorber in the solar collector. The temperature of the ambient air at the collector outlet increases due to solar radiation. We deduce that the collector outlet temperature is an important parameter for the drying operations. The experiment carried out shows that the average temperature gradient of the air between its inlet and outlet of the collector during the peak hours (12.30 - 14.30) is about 13.8˚C, with an average velocity at the collector inlet of 1.5 m/s. These results are consistent with those obtained by [8] [9].

Figure 6 shows the evolution of the average temperature of the 2 drying racks for 3 days.

It can be seen from **Figure 4** that the average temperature of the two racks during the three days of the experiment has the same pattern. However, the average temperature of the first rack reaches its maximum value of 75˚C for the three days of the experiment, while the average temperature of the second rack reaches its highest value, 65˚C, at around 12 hours during the "no-load" test days. It is also important to note that the closer the rack is to the absorber, the hotter it gets, because as the hot air moves away from the source, it cools down, due to the convective transfers that take place between the air, as it moves, and the furnace walls.

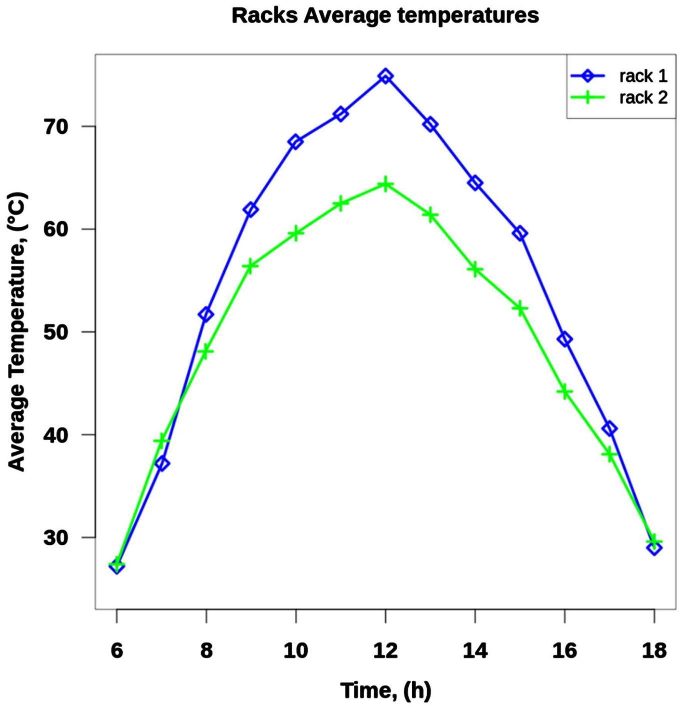


Figure 6. Average temperatures of the racks for three days.

Figure 7 shows the temperature variation of the first loaded experiment (1000 mg) during the drying of the coffee cherry.

Here the temperature increases in the drying cabin from 32˚C to 62˚C on the first day, from 62˚C to 67.8˚C on the second day, from 73.3˚C to 74.1˚C on the third day and on the fourth day at the end of the drying process. As a first approximation, we can say that the temperature variation is a function of the global irradiation. It can also be seen in Figure 6 and Figure 7 that the temperature of the drying air at the first rack remains close to the temperature of the absorber. This can be explained by the fact that the drying air exchanges with the inner wall of the kiln as it rises. This regularly lowers its temperature from the first rack to the next! Also, there was heat exchange between the air and the product spread on the first rack.

Generally speaking, it can be seen that on the first day of the experiment the coffee cherry contains enough water. After the first day, there is a rise in temperature for the rest of the days. This aspect shows that for each day of the experiment a certain amount of water is evaporated. It can be also observed from Figure 7 that the coffee is already dry on the third day, because on the fourth day there is no resistance to the temperature increase.

We calculate the mass of water to be removed, the dry masses and the time taken for the coffee to dry in the dryer and in the open air. The values of the water contents are shown in Table 1.

We note that the dry-base water content for the sample dried in the dryer is lower than that of the air-dried product. This shows that the coffee dried in the dryer is better appreciated than that dried in the open air. Furthermore, we have shown that coffee cherries dry about 12 times faster in a solar dryer than in the open air, and that the final drying levels are achieved in 30.2 hours cumulated in the solar dryer, while this time is about 380 hours in the open air.

Figure 8 shows the typical evolution of the water content of coffee as a function of time during drying.

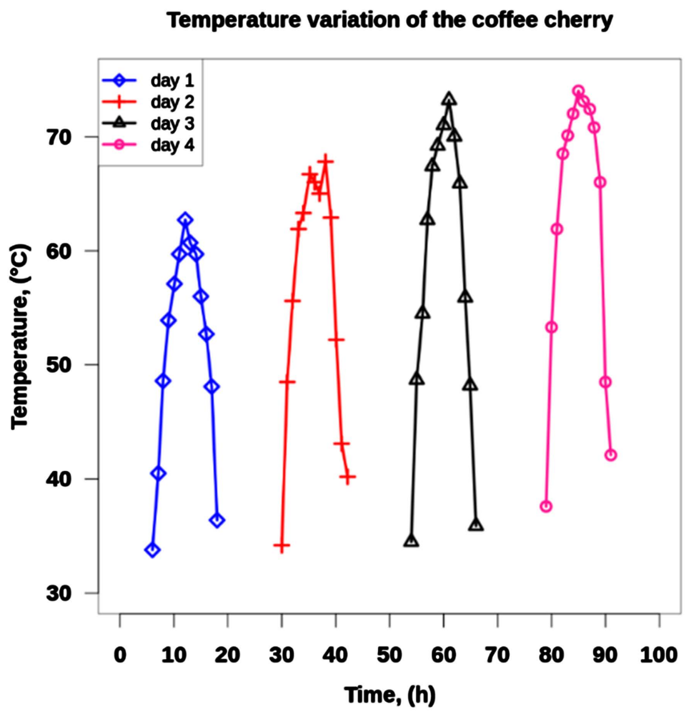


Figure 7. Temperature variation of the coffee cherry on the first rack.

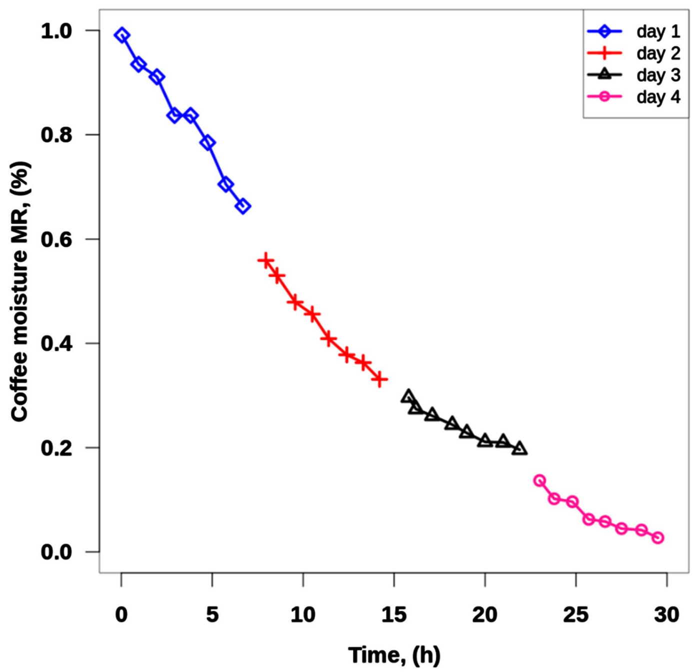


Figure 8. Variation of coffee moisture content with time during drying.

Table 1. Coffee cherry drying results.

Experiment	Set temperature	Dry mass	$MR_f = 0.01$	time
coffee inside the dryer	105˚C	15.97	0.0987	30.2
coffee in the open air		6.76	0.1099	380

The evolution of the water content during drying shows a slowing down of the drying process, although there is no systematic stop. Indeed, these curves of reduced water content do not show phase 0 during the drying process. The absence of phases 0 and 1 in food products in general is due to the fact that they are not saturated with water, *i.e.* they do not contain free water. We see that at the end of each day of drying, the remaining water content is 42.19%, 23.23%, 13.93% and 8% of the initial water content on a dry basis, respectively. From **Figure 8**, we can deduce that most of the drying takes place on the first and second day. This result leads us to say that the quantity of water evaporated during these first two days corresponds to the free water of the coffee, which is easy to eliminate. This observation has been made in several studies, in particular that of A. O. Dissa *et al.* [10]. From the third day onwards, the drying process starts to be slowed down, due to the shrinkage of the product. During the fourth day, the water content at the end of drying is lower (8%) due to the higher temperatures in this drying mode. From all these tests, we can conclude that drying in the modified Icaro dryer gives satisfactory results both in terms of drying time and final moisture content value.

The evolution of the drying rate of coffee as a function of the water content is presented in **Figure 9**.

Figure 9 shows that the drying speed is most marked between 97.8% and 67% of the water content. It becomes average between 60% and 20% and gradually decreases to stabilize from 10%. In fact, the more the drying process evolves, the more the quantity of water decreases from day to day. This shows that during the drying process, free water is evaporated while bound water is maintained. **Figure 9** also provides information on the characteristic coffee drying curve described by our model, which can be validated for drying rates ranging from 0.01 $kg \cdot kg^{-1}$. Ms to 0.13 $kg \cdot kg^{-1}$ Ms. This result is similar to that obtained by A. O. Dissa [10] for the drying of the Amélie mango variety and after by Lankouande *et al.* [11].

Figure 10 shows the evolution of the thermal efficiency of the solar collector as a function of time.

It can be observed that the collector's efficiency depends on the period of time the collector is exposed to the sun. It can be seen that the efficiency of the collector for the day of 20 December 2020 reaches the maximum value equal to about 47.53%. A similarity is noted between the experimental curves carried out by many preview works on the variation of the thermal efficiency of the collector.

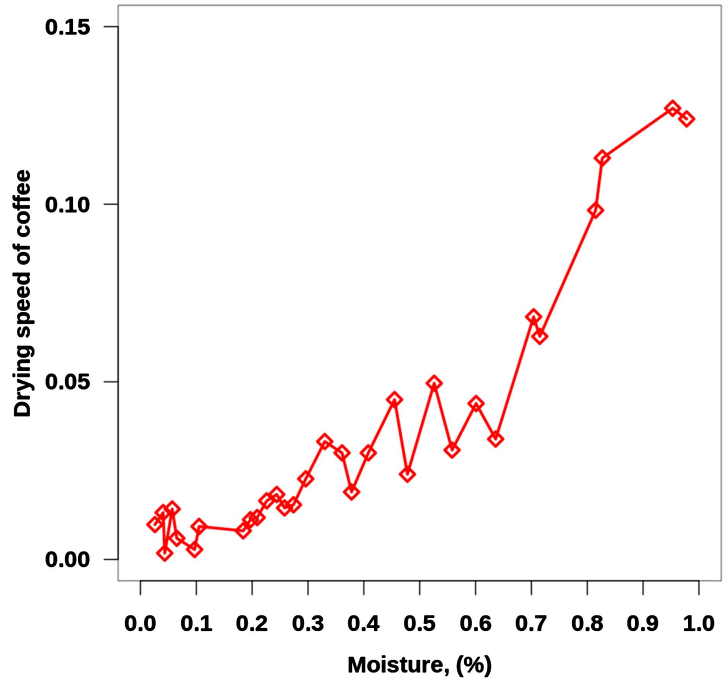


Figure 9. Variation in drying speed of coffee as a function of moisture content.

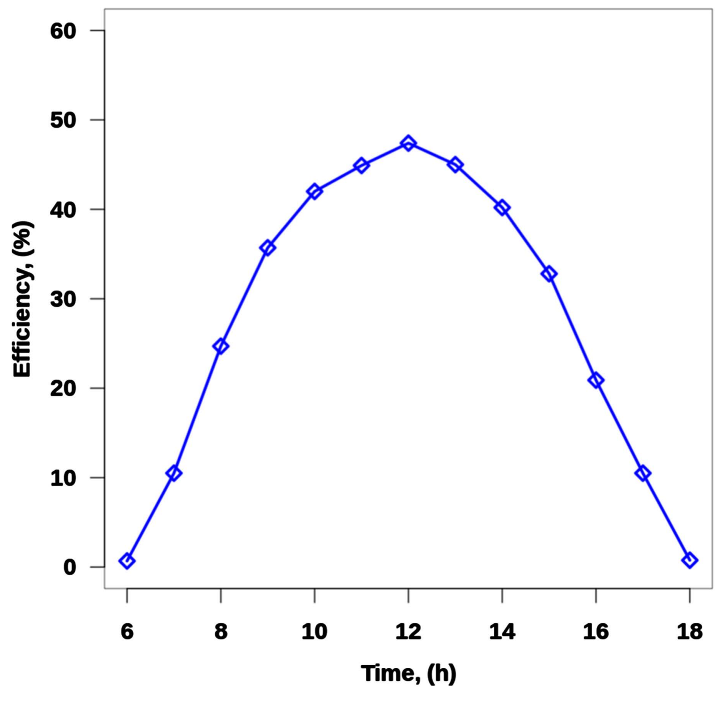


Figure 10. Variation of collector thermal efficiency.

5. Conclusion

The experiments carried out on the modified Icaro solar dryer model allowed us to determine the performance of this dryer: This dryer allowed to minimize the energy losses and to acquire a maximum of solar radiation transmitted inside the dryer. It appears from this study that the maximum temperatures are reached around 12:00. The performance of the solar dryer depends strongly on the climatic conditions and more particularly on the temperature and the sunshine. In our case, for variations of the average ambient temperature between 25˚C and 40˚C, we could obtain temperatures inside the dryer exceeding 70˚C in the middle of the day in different situations tested. The model is validated for the air speed of 1.5 m/s and for different test temperatures. Variations in coffee temperatures were taken into account in the model selected, so that they are consistent with the properties of the drying air. This dryer reduced the moisture content of the coffee from 70% to 9.87% during the 3 days of drying. The wet-base moisture content curve shows that coffee drying is valid for speeds ranging from 0.01 to 0.14 $kg \cdot kg^{-1}$ Ms for a moisture content range of 0.1% to 0.98%.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

Cp	Specific heat at constant pressure, (J/kg·K)
D	Diameter, (m)
Δt	Time variation, (s)
I	Solar radiation, (W/m^2)
M	Mass, (kg)
MR	Water content
S	Area, (m^2)
T	Temperature, (˚C)
Q	Heat, (W)
Greek letter	
η	Thermal efficiency of the solar collector
Subscripts	
b	beaker
c	sky/coffee
e	thickness/entrance
eq	equivalent
f	final state
I	initial state
h	sun's height
r	reduced
sec	dryer
u	useful