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RESEARCH ARTICLE

EXPERIMENTAL STUDY OF AN INDIRECT SOLAR DRYER USING NATURAL CONVECTION: CHANGES IN THREE PHYSICAL PARAMETERS

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ABSTRACT

An experimental study was carried out on an indirect solar dryer operating with natural convection. The study focused on the behavior of three parameters over time. Solar radiation at the measurement site, the temperature of various elements of the collector and of the air at four precise locations inside the dryer, and the velocity at its outlet were measured. The results of the five-day average measurements showed that the solar dryer has a uniform temperature profile inside the drying chamber. The average values for solar radiation, air temperature in the chamber and air velocity at the chimney outlet are $505.4 W/m^2$, 50.7°C and 0.8 m/s respectively. Added to these are the average temperatures of some of the collector's components and of the air leaving the collector. In view of the temperature levels reached in the dryer, drying operations can be carried out.

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INTRODUCTION

Solar energy is an abundant resource distributed throughout the world (Tiwari, Arvind, and Shyam 2016), (Badescu 2008). Numerous studies have been carried out to estimate its potential for various applications (Coulibaly and Ouedraogo 2016), (Hafez, Shazly, and Eteiba 2015), (Nébon *et al.* 2019), (Dumka, Kosmopoulos, Ningombam, and Masoom 2021), (Guengane *et al.* 2020), (Goumwêndkouni Gilbert *et al.* 2022), (Korachagaon and Bapat 2012). Among the potential applications of solar energy (Fischer 1987), (Ouédraogo *et al.* 2022), (KY *et al.* 2018) is solar drying, Solar dryers are devices used to ensure more hygienic drying. Solar dryers are devices used to extract part of the water contained in a product [10]. When the amount of water remaining in a product reaches a certain value, the product can be preserved over time. In this way, various agricultural products, which rot because of their high water content, can be preserved when they undergo drying operations. Numerous studies have been carried out on solar dryers around the world (Dissa *et al.* 2009), (Boureima 2016), (Pakouzou, Ouédraogo, and Bokoyo 2022), (Sikoudouin *et al.* 2021), (Chaudhari and Salve 2014), (Musembia, Kiptoo, and Yuichi 2016). There are several different types and sizes, depending on the field of application. The choice of a dryer for drying a given product depends on a number of parameters.

The type, nature and geometry of the product on the one hand, and the temperature, speed and drying time of the product on the other, are the criteria to be taken into account when drying (Lankouande *et al.* 2021), (Boureima 2016), (Pakouzou, Ouédraogo, and Bokoyo 2022) With the aim of making efficient dryers available to the public, various prototypes have been developed (Pangavhane, Sawhney, and Sarsavadia 2002). With regard to the class of indirect solar dryers operating with natural convection, notable advances have been observed (Ky, Dianda, Ouedraogo, Ouedraogo, *et al.* 2018). Indirect dryers are equipped with a solar collector to heat the air entering the drying chamber. This is a key element of a solar dryer. As drying chambers are generally insulated, heat loss is minimized. Consequently, improving the thermal performance of a solar collector (NDIAYE 2018) that can be attached to an insulated drying chamber will be facto improve the thermal performance of the dryer. A number of researchers (Lankouande *et al.* 2021), (Ky, Dianda, Ouedraogo, Ouedraogo, and Bathiebo 2018), have improved dryer performance by proposing different models of solar air collectors. The method generally used consists in increasing the collector's useful energy by increasing either the absorber temperature, the exchange surface or the air velocity in the collector. Since convection is natural, only the first two parameters can be increased. The exchange surface between the air and the absorber is increased by means of fins (Bhattacharyya, Anandalakshmi, and Srinivasan 2017), (Pakdaman, Lashkari, Tabrizi, and Hosseini 2011), (Ouedraogo, Dianda, Palm, and Bahiebo 2015), (Gopi 2017). The temperature of the absorber is raised by intensifying solar irradiance using reflectors, concentrators or even lenses. Temperature is maintained by keeping the absorber in an insulated greenhouse with or without energy storage (Musembia, Kiptoo, and Yuichi 2016). The use of reflectors and concentrators requires a certain delicacy, not forgetting the need for solar tracking. As for the phase-change material, monitoring and expertise are required to ensure its effectiveness and durability over time. In addition, the solar collectors are inclined at an angle close to the latitude of the location where the system is installed. The solar dryer tested in this paper has a cylindrical collector that cannot be oriented on a horizontal plane, and an absorber heated by a greenhouse without energy storage. The aim of this work is to set up an autonomous solar dryer. As the collector is horizontal, solar tracking is no longer necessary. The experimenter must ensure that there are no masks (shadows) when the device is exposed to the sun.

MATERIALS AND METHODS

Equipment: The device used in this experimental study is an indirect solar dryer operating by natural convection. The dryer consists of a solar collector containing cylindrical tubes attached to a flat absorber in the form of an annular disk. Fins are attached radially to the underside of the plate to create identical horizontal ducts with variable cross-sections. It was designed at the Renewable Thermal Energy Laboratory at the Joseph. KI-ZERBO University in Ouagadougou, Burkina Faso. Figure 1 shows a photo of the device. The special feature of this model is the horizontal shape of its collector, making it more suitable for regions with relatively low latitudes and high levels of sunshine.

Figure 1. Photo of experimental set-up

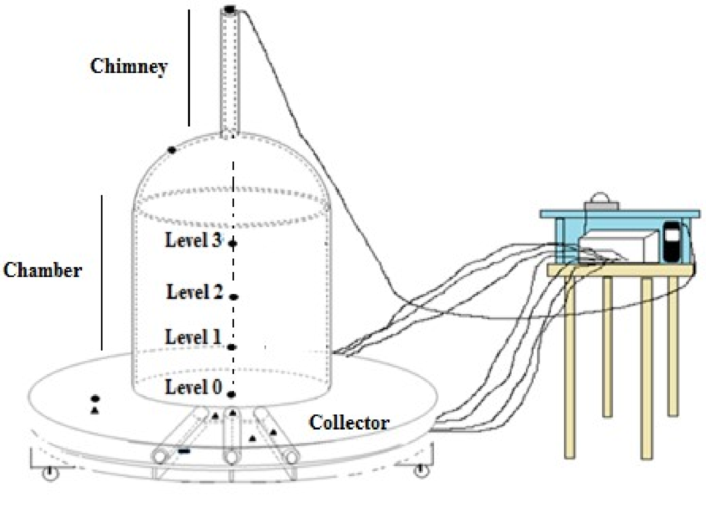

Figure 2. Measurement probe locations

Table 1. Accuracies of the instruments used for the experimentation

Instruments	Measuring range	Accuracy
A pyranometer (SR03-05 from Hukseflux brand), sensibility $S=9.58\mu V/(Wm^{-2})$,	0 to 2000 Wm^{-2}	$\pm 15\,W.m^{-2}$
Thermocouples of K-type	-200 to 1370 °C	$\pm(0.3\,°C + 0.1\%\ \text{of m.v})$
A hot wire anemometer (Testo 480)	0 to 20 m/s	$\pm(0.03\,m/s + 5\%\ \text{of m.v})$

The instruments used to measure the device are a pyranometer (SR03-05 from Hukseflux brand),, a midi-Logger (GL220) and a hot-wire anemometer (Texto 480). K-type thermocouples were used. The relative uncertainties of these instruments are given in Table 1.

METHODOLOGY

The pyranometer was set up on the experimental site, ensuring that it would not be affected by shade throughout the day of measurement. K-type thermocouples were attached to the solar collector and to the drying chamber. At the collector, the thermocouples were used to determine the temperatures of the plate, a tube and a fin, as well as the air temperatures at the collector inlets and outlets. As for the drying chamber, temperatures were obtained by means of four thermocouples arranged along the vertical center line from the bottom to the top of the chamber. The positions of the thermocouples, as shown in figure2, were numbered in levels starting from the bottom of the drying chamber: level o (5 cm), level 1 (20 cm), level 2 (35 cm) and level 3 (50 cm). The anemometer probe was positioned just outside the chimney. The instruments were set up to record in five (5) minute time steps. The instruments were switched on and off simultaneously for each measurement day. The measurement period covered the days of March 10, 11, 12, 13 and 24, 2022. Solar irradiance, temperature and speed were averaged.

Calculation of physical quantities: Irradiance data were obtained in voltage form. Global solar irradiance values were deduced from equation (1).

$$G = U/S \qquad \text{equation (1)}$$

G: global solar radiation in W/m^2, U: voltage in mV and S: sensitivity in μV //(Wm^{-2})

Estimation of the averages of the physical quantities $Q_{j,i}$ (radiation, temperature or velocity) at a given instant of a day during the measurement period was carried out by applying equation (2)

$$\bar{Q}_i = \frac{1}{N}\sum^{j=N_j} Q_{j,i} \qquad \text{equation (2)}$$

The averages of these physical parameters were calculated using equation (3)

$$\bar{Q} = \frac{1}{N}\sum_{i=1}^{i=N}\bar{Q}_i \qquad \text{equation (3)}$$

N is the total number of measured values

Calculation of the overall average temperature in the drying chamber is given by equation (4):

$$\bar{T}_c = \frac{1}{4}\sum_{i=1}^{i=4}\bar{T}_{cl_i} \qquad \text{equation (4)}$$

$\bar{T}_{cl_i}$ is the mean temperature per level in the drying chamber. The values of drying chamber temperature and stack exit velocity were statistically calculated to determine the equations that best represent their evolution over time. The convergence criteria used were: sum of squared errors (SSE), coefficient of determination (R^2), adjusted R^2 and root mean square error (RMSE).

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(Q_{p,i} - \bar{Q}_{e,i}\right)^2}{\sum_{i=1}^{n}\left(\bar{Q}_{e,i}\right)^2} \qquad \text{Equation (5)}$$

$$SSE = \sum_{i=1}^{n}\left(Q_{p,i} - \bar{Q}_{e,i}\right)^2 \qquad \text{Equation (6)}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(Q_{p,i} - \bar{Q}_{e,i}\right)^2}{n}} \qquad \text{Equation (7)}$$

RESULTS AND DISCUSSION

Results: During the measurement campaign, the data obtained was processed and the results presented in graphical form.

Solar radiation: The figure shows the overall solar irradiance profile at the measurement site.

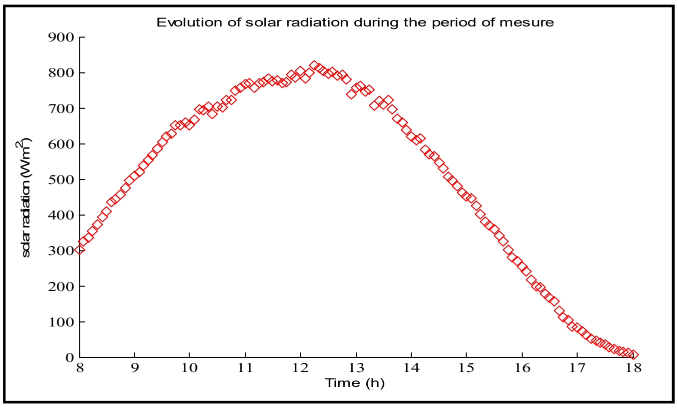

Figure 3. Solar radiation profile during the period of experimentation

Temperature profiles: The temperature trends over time for some elements of the solar air collector are shown in the Figure 2.

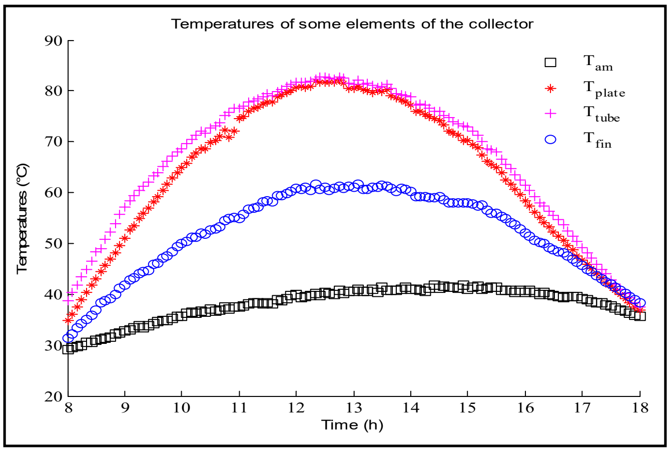

Figure 4. Temperatures profiles of plate, tube, fin and ambient air

Collector outlet temperature profiles are shown in Figure 5. The temperature trend at the tube outlet (blue curve) remains above that at the variable-section channel outlet (red curve).

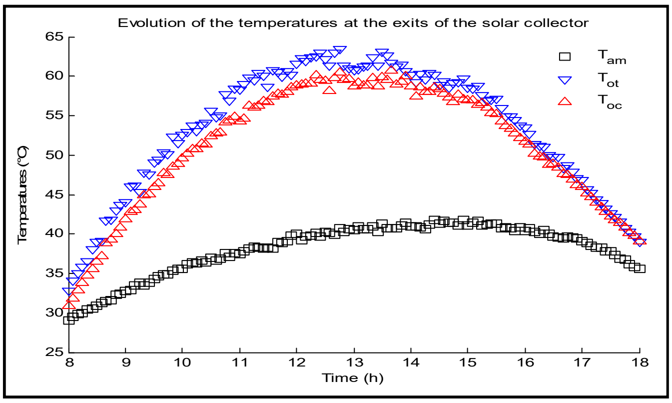

Figure 5. Ambient temperature and collector outlet temperature profiles

Temperature trends in the drying chamber were determined using four thermocouples arranged vertically along the centerline of the chamber, from bottom to top, as shown in figure 2. These trends are shown in Figure 6.

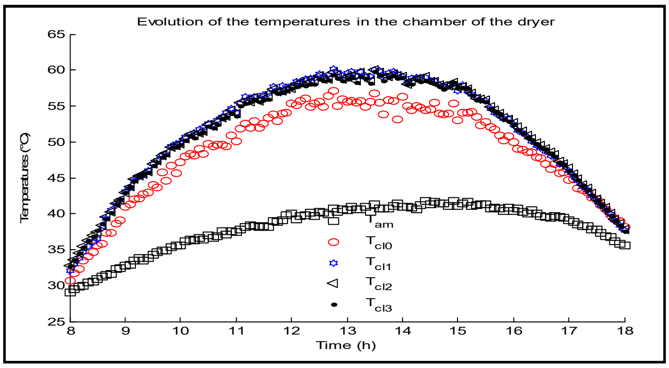

Figure 6. Temperature profiles inside the dryer at four different points following the center line

Average values for chamber levels 0, 1, 2 and 3 are shown in Figure 7.

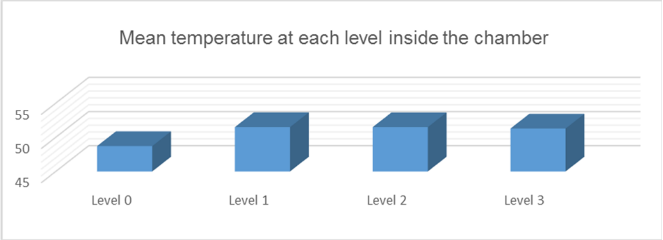

Figure 7. Average temperature values for the four chamber levels

The average temperature profile in the drying chamber is represented in the Figure 8.

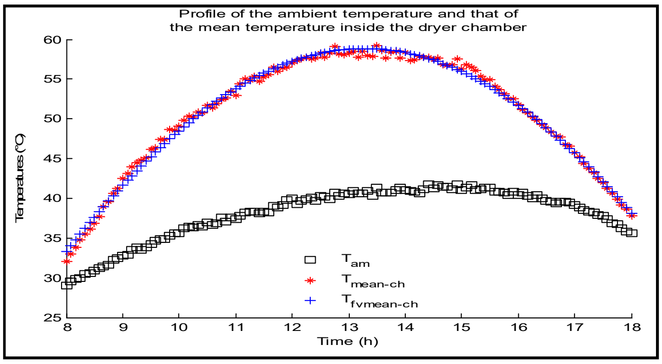

Figure 8. Mean temperature behavior inside the chamber during the period of experimentation

The average temperature profile in the drying chamber is represented in the figure 7by the red curve.in figure 8. The blue curve represents the evolution of the same average temperature obtained by smoothing the temperature values in the chamber given by equation 8.

$$T_{moy\_ch}(t) = a \cdot \sin(b \cdot t + c) \qquad \text{Equation 8}$$

where coefficients a, b and c are given: $a = 58.8; b = 0.2; c = -0.9$

Equation 8 was obtained by taking into account the validation criteria given by equations 5 to 7

Speed profile at chimney outlet: The measurement parameters are not only limited to solar radiation and temperature, but also to stack velocity. The values taken by the velocity are shown in the Figure 9.

This is generally true of March, one of the sunniest months in the country. With regard to the temperatures at the collector and inside the chamber, we note that the temperature profiles are similar. However, the highest temperatures are those of the tubes (66.5+/-0.4°C), followed by that of the annular plate (63.9 +/-0.4°C) to which the tubes are attached (see table2). This difference could be explained firstly by the fact that the tubes are housed in the greenhouse formed by the glass and the plate. Secondly, the proximity of the glass tubes to the plate. This raises the problem of optimizing the distance between the transparent cover and the absorber plate in a solar collector. Identical rectangular fins fixed radially to the underside of the annular plate were used to obtain identical pipes with a variable rectangular cross-section. These fins have an average temperature of 51.9 +/- 0.4°C, i.e. an average drop of 11°+/-0.4C compared with the temperature of the annular plate.

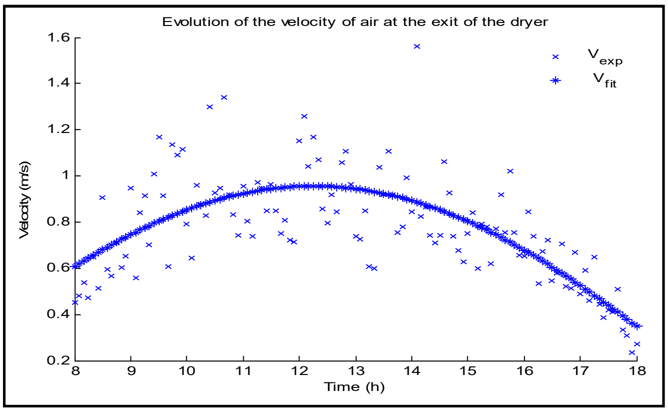

Figure 9. Stack exit velocity and its smoothing over time

Table 2. Average values of determined physical quantities

Parameters	Solar Radiation (Wm^{-2})	T_am (°C)	T_plate (°C)	T_tube (°C)	T_fin (°C)	T_ot (°C)	T_oc (°C)	T_c (°C)	V ($m.s^{-1}$)
Average values	505.4	38.1	63.9	66.5	51.9	53.3	51.3	50.7	0.8
Accuracy	±15	± 0.4	±0.4	± 0.4	± 0.4	± 0.4	± 0.4	± 0.4	± 0.1

Since velocity fluctuations are very pronounced, the values were smoothed to show the evolution of these velocities. This is shown by the bold curve in the figure 9. The velocity profile at the stack outlet can be approximated by a function of time given by the expression:

$$V(t) = a \cdot \sin(b \cdot t + c) \qquad \text{Equation (9)}$$

where coefficients a, b and c are given by: $a = 0.9; b = 0.2; c = -1.0$

The mean values of global solar radiation, various temperatures and velocity evaluated in this study are listed in Table 2.

DISCUSSIONS

The measurement period was spread over five days in March 2022. Measurements were taken from 8 a.m. in the morning to 6 p.m. in the evening, without interruption. The graphs are based on the mean values of the five measurements taken on three physical parameters (global solar radiation, temperature and speed). The solar radiation curve shows a parabolic profile with a concave downward slope, reflecting an increase from the first hours of measurement until reaching a maximum value at around 12:30 pm, before gradually decreasing and levelling off at sunset. Radiation was 300 +/-15W/m^2 at the start of the measurements, reaching a value of 800 +/-15W/m^2 by the time the sun was at its zenith. The fact that the curve shows less fluctuation proves that the sky was relatively clear at the time of measurement.

This could be due to greater thermal resistance between the plate and the fin, caused by inefficient thermal contact (presence of interstitial resistance) and the fact that the material of the fin and plate (iron) have relatively low overall conductivities. The average fin temperature is close to the average air temperature (51.3 +/- 0.4°C) at the channel outlet between two adjacent fins. At lower duct outlets (ducts with variable rectangular cross-sections), the average temperature obtained is lower than that at tube outlets (upper ducts). This is due to the position of the fins in relation to the tubes, on the one hand, and to the fact that the mass of air to be heated by the tubes is less than that to be heated by the fins, on the other. A look at the temperature profiles in the drying chamber reveals similar patterns, although the temperature at the lowest level in the chamber is the lowest. Figure 8 shows the evolution of the average temperature value in the drying chamber over the experimental period. Equation (8) represents the evolution of this temperature over time. The drying chamber has a uniform temperature distribution over the experimental period. This temperature of 50.8 +/- 0.4°C is suitable for solar drying of many agricultural products. With regard to the velocities at the chimney outlet, we can see that they fluctuate considerably. Nevertheless, we can see that these clouds of points follow a curve with a profile similar to that of the radiation, as do the temperatures (see figure 9). The time evolution of the smoothing curve is given by equation (9). The average velocity value of 0.8 +/- 0.1 m/s proves that the air is moving in the dryer.

CONCLUSION

In this paper, we determined the changes over time in overall solar radiation at the site where the system was installed, as well as those related to temperature and speed. Temperatures are measured at various points in the dryer, while velocity is estimated at the chimney outlet. The evolution of these variables is based on average values over five days of measurements. It was found that the hottest temperatures in the dryer were at the collector level. In the drying chamber, temperatures in levels 1, 2 and 3 evolve in the same way over time. Level 0 is the lowest temperature in the drying chamber. This finding differs from what is generally found in the literature. In addition, the evolution over time of the average temperature in the drying chamber and the velocity at the chimney outlet were each approximated by a function of the form Q(t)=a.sin(b.t+c) where the coefficient a, depends on the physical quantity Q concerned while the other two b and c could be linked to solar radiation. It was also found that for the measurement period under consideration, average solar radiation of 505W/s would result in an average temperature of 50.8 +/-0.4°C in the drying chamber, and an average velocity of 0.8 +/- 01 m/s at the stack outlet. These temperatures are ideal for drying various agricultural products. It should also be pointed out that the proposed dryer is fitted with a horizontal collector, so it does not require solar traction, either manual or mechanical. Air movement is achieved without the introduction of mechanical means; convection is natural. The dryer could work best in regions with low latitudes and good solar potential. In regions where latitude is important, it can only really be used around local solar noon.

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Competing Interests: The authors declare that there were no competing interests.

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