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Study of the Thermo-hydric Behavior of an Indirect Tunnel-type Forced Convection Dryer and the Drying of Meat Slices in the Form of Kilishi

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Abstract The quality of a dried food product depends on the drying conditions and the technique used. A solar dryer of tunnel type has been designed for the drying of certain food products. We will evaluate in this work, the thermo-hydric behavior of this dryer in a first phase with no load and in a second phase, filled with slices of meat in thin strips during the drying. The drying kinetics of the thin strips of meat slices obtained experimentally are compared with a drying characteristic curve model (DCC). The comparison of the results of the drying characteristic curve model (DCC), and those found experimentally is satisfactory, with R2 is close to 1, MSE and RMSE are low values near 0.

Keywords: *solar drying, indirect forced convection dryer, drying kinetics*

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1. Introduction

There is no need to justify the need for food processing in Africa because for decades, solar drying has been used for the processing of some agro-food products [1]. There are several studies in the scientific literature on food drying and solar dryers. However, very few of these studies have dealt with the drying of kilishi (a food product derived from meat processing, which is very popular throughout sub-Saharan Africa). Among the studies that have presented solar dryers for kilishi drying, we can cite a few examples. Thus, the work of Yahaya Yaou, et al (1986) on the SAHEL 50 dryer [2]; the work of Hassan Mahaman Rabiou (1995) on the "shell" dryer and the "tent" dryer [3]; the work of Bechis S. et al (1996) on natural and forced convection dryers [4]; the work of Stefano Bechis, Federico Barigazzi et al (2013) on the Icaro dryer [5]; the work of Ahmat Tom (2015) on a dryer adapted for tropical countries [6] etc. To date, despite these proposed dryers in the literature; kilishi continues to be dried by the traditional drying process. The slices of meat are dried in the open air directly in contact with sunlight on a drying mat [7]. The objective of our work is to study the thermo-hydric behavior of an indirect tunnel-type forced convection dryer and to experiment with the drying of kilishi meat slices using this dryer.

2. Materials and Methods

2.1. Dryer Presentation

The dryer we are studying is a tunnel-type indirect forced convection solar dryer (see Figure 1 and Photo 1). It is a rectangular parallelepiped frame made of 1mm thick steel sheet. It is painted black to enhance the capture of solar radiation. It is 210 cm long and 45 cm wide. On one of these lateral faces on the width side is fixed a fan which makes the air pass inside the dryer. On the other side face opposite it is dimensioned the exit of the air of the dryer. One of these side faces, on the long side, has three (3) doors, each of which gives access to the compartments of the dryer. The interior of the dryer has trays with a surface area of 490 cm2. Each compartment can have six trays spaced 10cm apart.

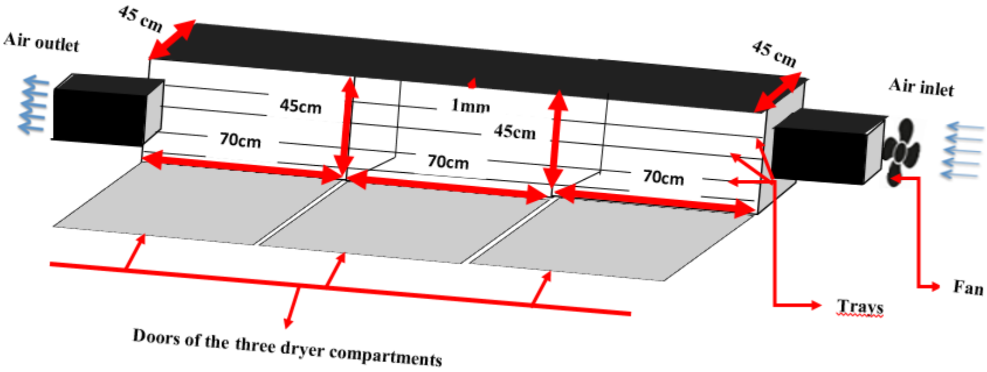


Figure 1. Schematic representation of the dryer studied

Picture 1. Photo of the dryer studied

2.1.1. Equipments Used

The main equipment used for the realization of our experimental tests are the following ones

- thermocouple type temperature probes, coupled with a data acquisition system (JINKO-JK804), to follow the evolution of the temperatures of the slices of meat, the walls of the dryer and the drying air of the dryer;
- thermo-hygrometers for monitoring the temperature and relative humidity of the air at the entrance and exit of the dryer;
- an electronic balance to follow the evolution of the mass loss of the slices of meat;
- a laboratory oven (PROLABO), which is used to determine the dry mass of the product.

Table 1. Specifications of Multichannel portable temperature meter (JINKO-JK804) with thermocouples

B Display:	5 digits
Min and Max Reading:	-200.0°C to 1800.0°C
Interface:	USB, MICRO SD, PC
Thermocouple Type:	T, K, J, N, E, S, R
Thermocouple Accuracy used	±0.5°C

Table 2. Specifications of thermo-hygrometers

Relative Humidity range	0 to 100% ± 2.5% with a resolution of 0.1%
Temperature range	-30 to 105°C ± 0.4°C with a resolution of 0.1°C
Dew point range	-60 to 80°C ± 1.5°C with a resolution of 0.1°C
Data storage capacity (auto mode)	Up to 8124 records
Software	Compatible with Windows OS
Relative Humidity range	0 to 100% ± 2.5% with a resolution of 0.1%
Temperature range	-30 to 105°C ± 0.4°C with a resolution of 0.1°C

Table 3. Specifications of Electronic scale (PRECISA-205 A)

Capacity	0.0001
Range (g/cm³)	205g
Scale Accuracy	±0.1

Table 4. Specifications of Laboratory oven (PROLABO FD 115)

Internal dimensions:	500 x 510 x 415 mm
Temperature range:	Ambient to +70°C

(a) (b) (c) (d)

Picture 2. (a), (b), (c) and (d) respectively the main equipment used

2.1.2. Experimental Processes

The tests aiming at apprehending the thermo-hydric behavior are carried out initially in vacuum and with the product. For all these tests we are interested in parameters such as the evolution of the temperature of the drying air inside the dryer; the evolution of the temperature of the walls of the dryer; the evolution of the temperature and the relative humidity at the entry and the exit of the dryer and finally the evolution of the temperature of product on racks. We also monitored the loss of mass of the product on different configurations of the arrangement of racks in the dryer. To determine the mass of dry matter of the product at the end of the drying process, the dried meat slices were weighed and placed in an oven at 105°C for 24 hours.

2.1.3. Estimation of the Characteristic Parameters of Drying

The dry base content (kg water /kg dry mass) of the product is expressed by the following formulation [8] :

$$X(\mathrm{t}) = \frac{m_{(t)} - m_s}{m_s} \tag{1}$$

Where $X(\mathrm{t})$ and $m_{(t)}$ are respectively the water content in dry basis and the mass of the sample at the time t of drying and m_s its dry mass.

The drying rate in terms of mass flow density is estimated from the rate of change of water content with time according to [9]:

$$\varphi_m = -\frac{m_s}{s}\frac{X}{\Delta t} = -\frac{m_s}{s}\frac{X_{(t)} - X_{(t+\Delta t)}}{\Delta t} \quad (2)$$

Where φ_m is the water flux per unit exchange area of the product (kg water /s.m^2); t the drying time (s) and Δt the time step between two consecutive measurements.

2.1.4. Theoretical Model of Drying Characteristic Curve

To describe the drying kinetics of meat slices, we used the VAN MEEL principle [10]. The drying characteristic curve corresponds to the expression of the variation of the reduced drying rate as a function of the reduced water content [11]. Thus, we are looking for an expression of the type [12]:

$$\frac{-\frac{dX}{dt}}{\left(-\frac{dX}{dt}\right)_0} = f(Xr) \quad (3)$$

With, The drying speed at time t:

$$-\frac{dX}{dt} \quad (4)$$

The speed of the first drying phase taken equal to the drying speed value at point $Xr = 1$:

$$\left(-\frac{dX}{dt}\right)_0 \quad (5)$$

Xr is the reduced water content defined by [13]:

$$\begin{cases} Xr = \dfrac{X - X_{eq}}{X_0 - X_{eq}} \approx \dfrac{X}{X_0} \\ X_0 = X_{cr} \end{cases} \quad (6)$$

The coefficients of a polynomial function of degree 4 fitted to the experimental points are determined according to the following relation:

$$C_i = \frac{1}{n}\sum_{j}^{n} C_{ij}, \; 0 \le C_i \le 4 \quad (7)$$

With n representing the number of tests performed, j the test number and C_i the coefficients of the functions $f(Xr)$.

There are several studies in the literature that have chosen the polynomial model for the smoothing of the drying characteristic curve, including [14-20].

For the case of the slices of meat that we study, we obtained by modeling the experimental points the following characteristic function [21]

$$f(Xr) = -1.875Xr^4 + 4.932Xr^3 - 5.014Xr^2 + 2.700Xr + 0.019 \quad (8)$$

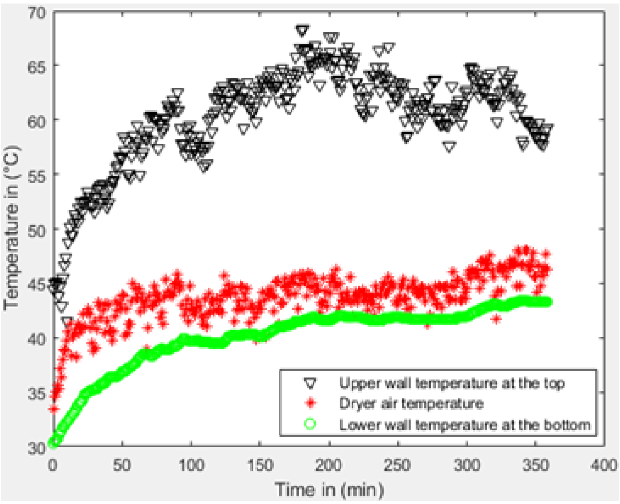
With,

$$R^2 = 0.994$$

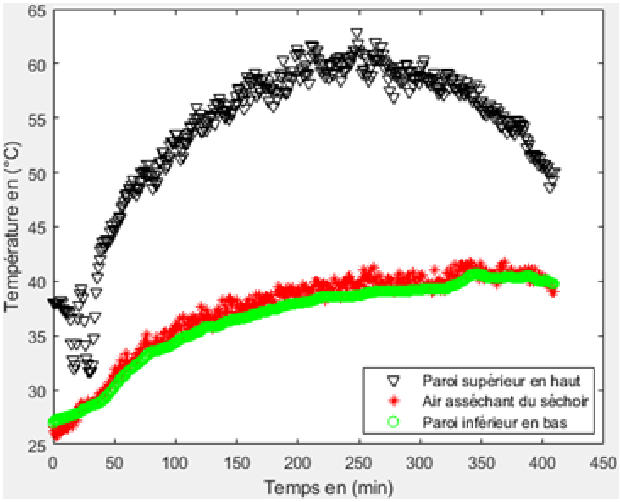
2.1.5. Results and Interpretations

2.1.5.1. Evaluation of Experimental Temperatures

The figures (Figure 2 A and Figure 2B) show respectively the evolution of the temperatures obtained experimentally during the drying tests in vacuum (in natural convection dryer mode and in forced convection dryer). We have respectively at the level of the legend of the figure: the evolution of the temperature of the wall of the dryer at the top which receives the solar radiation; the evolution of the temperature of the drying air inside the dryer and the evolution of the temperature of the bottom wall of the dryer in contact with the ground.



A: natural convection dryer mode

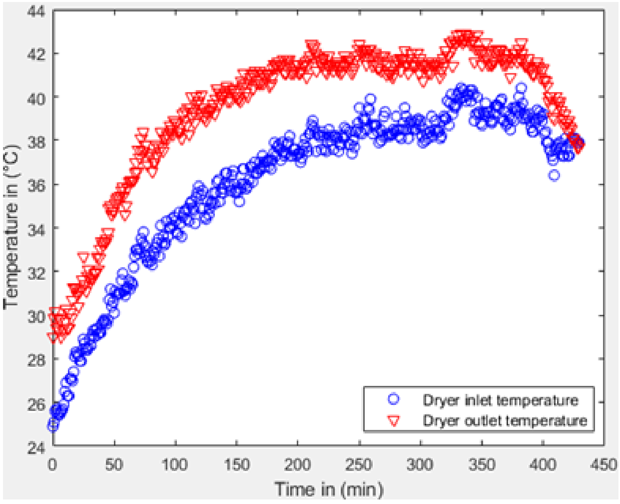


B: forced convection dryer mode

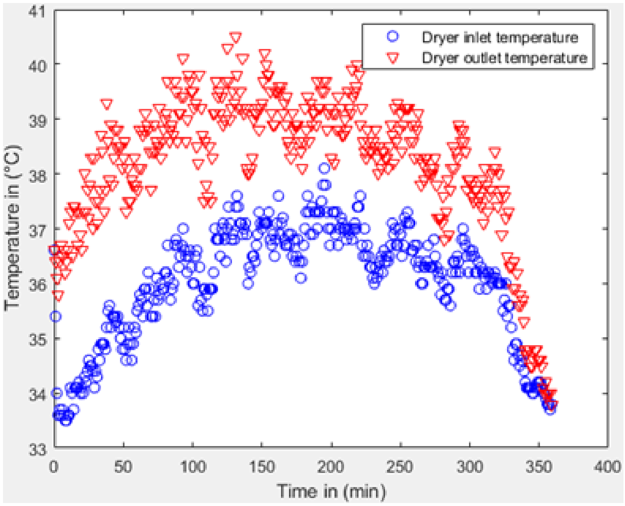
Figure 2. A and **B**: Experimental curves of the evolution of the temperatures, at the level of the vacuum dryer in natural and forced convection dryer mode

Two tests were carried out during the day between 9am and 4pm. We notice for these tests a difference of temperature between the various places of the dryer. We also notice that the temperatures in natural convection dryer mode are higher than those in forced convection dryer mode. In forced convection the air does not have time to take temperature, this shows the influence of the speed of the drying air on the different temperatures of the dryer.

The figures (Figure 3 A and Figure 3B) show respectively the evolution of the temperatures of the inlet and outlet of the dryer in vacuum and with the product.



A: natural convection dryer mode



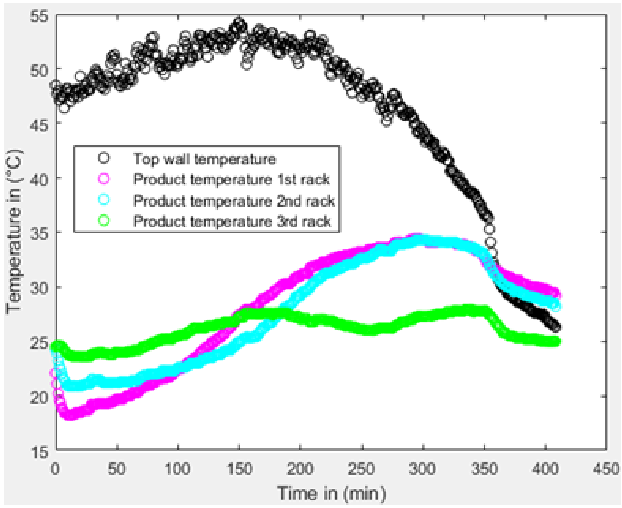
B: forced convection dryer mode

Figure 3. A and **B**: Experimental curves of the evolution of temperatures at the entrance and exit of the dryer

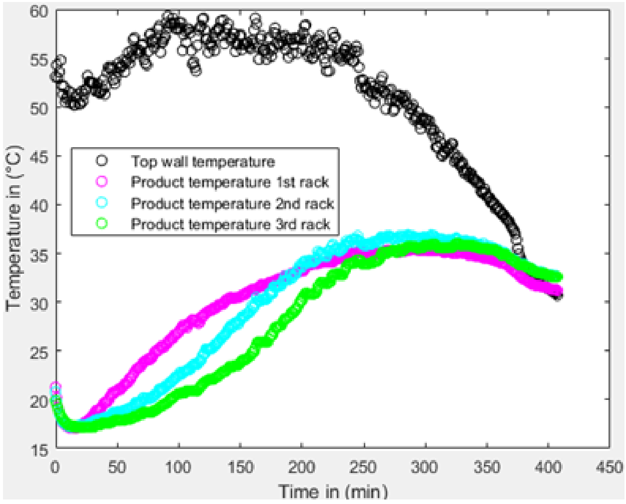
It appears from the tests that the air temperature at the dryer inlet is lower than the air temperature at the dryer outlet. The air trapped inside the dryer is heated by convection with the walls of the dryer. These walls have accumulated heat through the absorption of solar radiation.

This shows the efficiency of the dryer to raise the temperature of the air trapped inside.

The figures (Figure 4 A and Figure 4B) show respectively the evolution of temperatures obtained experimentally during the drying tests with the product. For these tests, we were interested in the behavior of the three (3) racks of the dryer. We observed in the figure (Figure 4 A), three (3) racks arranged on the same horizontal plane in the dryer, one rack in each compartment of the dryer. We observed in the figure (Figure 4 B), three (3) racks arranged on the vertical plane in the dryer. Here the racks are in only one (1) compartment of the dryer. For both figures, we have respectively the evolution of the temperature of the wall of the dryer, the evolution of the temperature of the product placed on each rack.



A: Racks in each compartment of dryer



B: Racks in a single compartment of dryer

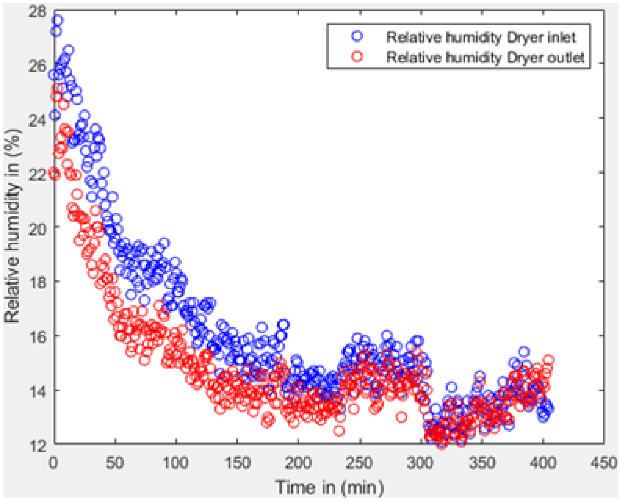
Figure 4. A and B: Experimental curves of the evolution of temperatures, drying with the product on three (3) racks

It can be seen in the figure (Figure 4 A), during a first phase (from 0 to 150 min), corresponding to the beginning of the drying, the temperature of the product of the 1st compartment is lower than that of the 2nd and 3rd. This phenomenon is explained by the fact that the temperature of the drying air at the entrance of the dryer is less hot compared to the exit. In addition to this, the product of the 1st rack (of the 1st compartment) receives more air speed compared to that of the 2nd and 3rd rack. In the second phase (from 150 to 450 min) when the drying process continues, the air becomes more and more loaded with moisture from the inlet to the outlet due to the evaporation of the product from the different compartments. This explains the rise in temperature of the product of the 1st compartment compared to those of the 2nd compartment and the 3rd compartment, until the uniformity of temperatures towards the end of the drying.

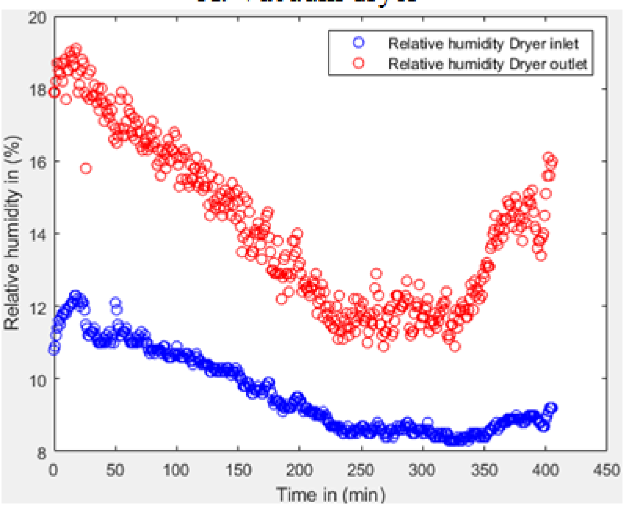
We can see on the figure (Figure 4 B), when the products are in the first compartment on three successive trays, at the beginning of drying and after a very short time (from 0 to 25 min), the same evolution of temperatures of products receiving the same heat flow. When drying continues, the temperature of the product on the first rack, which is positioned upwards, rises more than that of the product on the second and third racks. Indeed, the air in contact with the wall of the dryer is warmer. This situation highlights a stratification of the temperature from the top to the bottom..

2.1.5.2. Evaluation of the Relative Humidity

The figures (Figure 5 A and Figure 5B) show respectively the evolution of relative humidity at the entrance and exit of the dryer. We have in the figure (Figure 5 A), the results of the test with no load and in the figure (Figure 5 B), those of the test with the products in the dryer.



A: Vacuum dryer



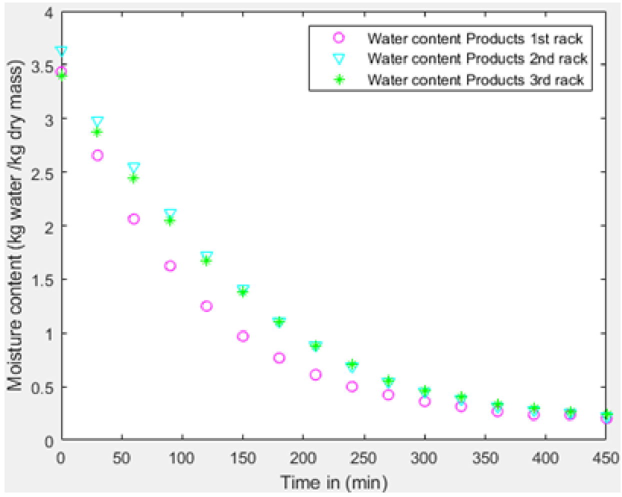
B: Dryer with product

Figure 5. A and B: Experimental curves of the evolution of the relative humidity of the vacuum dryer and the dryer with the product

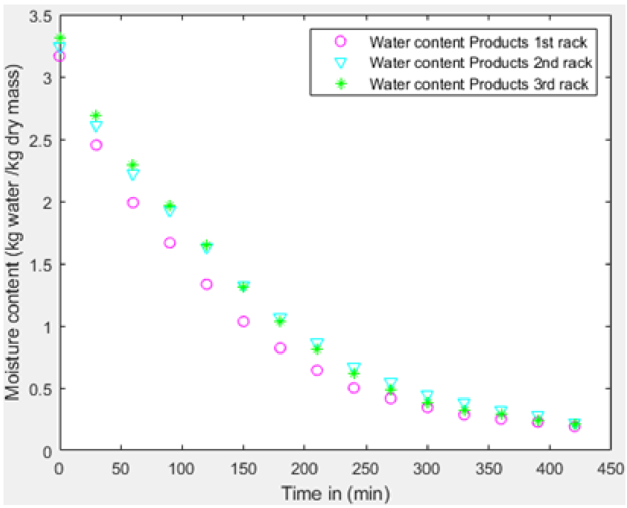
The examination of these curves shows two (2) phenomena. For vacuum drying, the relative humidity at the inlet is slightly higher than at the outlet of the dryer. This illustrates the efficiency of the drying chamber to dry a product. For drying with the product, the opposite effect can be observed. The relative humidity at the outlet is strictly higher than at the inlet of the dryer, this is caused by the evacuation of water from the product in the dryer to the outlet of the dryer. This phenomenon was observed by Moussa Na Abou Mamouda et al for the drying of tomatoes, okra, potatoes and mangoes [22].

2.1.5.2. Evaluation of the Water Content of Products

The figures (Figure 6 A and Figure 6B) show respectively the evolution of the water content as a function of time during the drying tests with the product on three (3) racks of the dryer. The figure (Figure 6 A) presents the evolution of the water content of the product placed on a rack of each compartment of the dryer. The figure (Figure 6 B) presents the evolution of the water content of the product arranged on three (3) racks in one (1) compartment of the dryer. We have respectively on the two figures, the evolution of the water content of the product of the 1st, 2nd and 3rd rack.



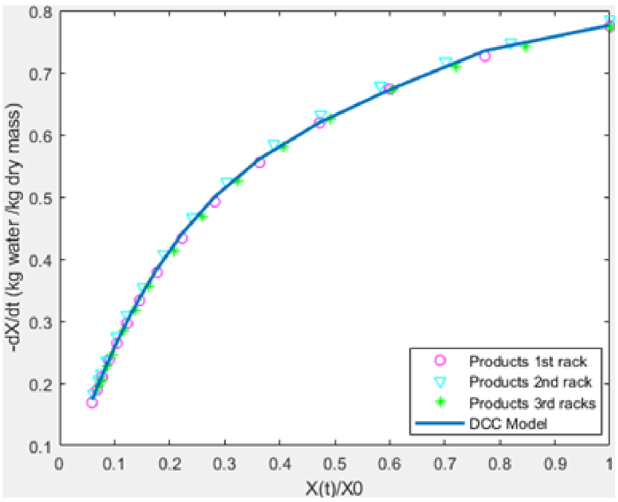
A: Racks in each compartment of dryer



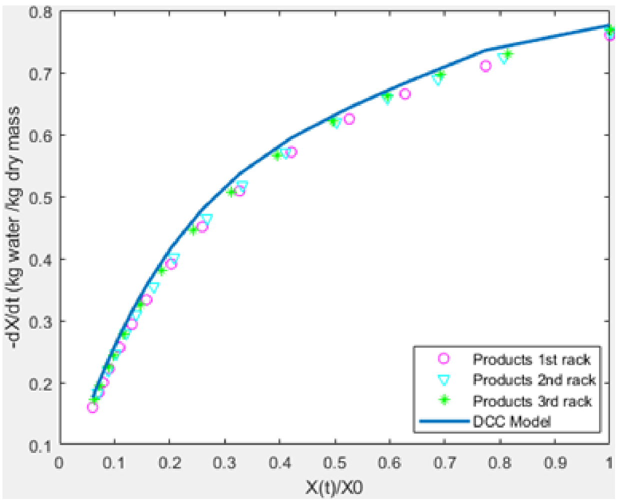
B: Racks in a single compartment of dryer

Figure 6. A and **B**: Experimental curves of the evolution of the water content of products on three (3) drying racks

The examination of these curves illustrated the influence of the position of the racks in the dryer, It varies with the position of the racks in the direction of the flow of air drying of the dryer. Thus, we see in the figure (Figure 6 A), the products placed in the first compartment of the drying unit, shows the lowest water content compared to those in the second compartment, and those in the second compartment are lower than those in the third compartment of the drying unit. The figure (Figure 6 B) shows a similar trend, when the products are in one (1) compartment on three successive racks. The 1st rack placed at the top of the unit, where the air is warmer, shows the lowest water content, compared to the 2nd and 3rd rack of the dryer compartment. These trends were observed by Dissa et al [23] for indirect solar drying of mange.



A: Racks in a single compartment of dryer



B: Racks in a single compartment of dryer

Figure 7 A and B: Validation of the drying characteristic curve model with the experimental curves

It is found that the experimental points agree with the characteristic curve model. The table below shows the statistical parameter values of the relative errors between the two results.

The examination of these values shows R2 close to 1 and MSE and RMSE are low values close to 0. We can conclude that the model is satisfactory.

Table 5. Statistical parameters

	R2	MSE	RMSE
Horizontally arranged racks			
Product racks N°1	0.9969	0.0012310	0.0111
Product racks N°2	0.8934	0.0045	0.0670
Product racks N°3	0.8858	0.0045	0.0671
Vertically arranged racks			
Product racks N°1	0.9990	0.00038440	0.0062
Product racks N°2	0.9468	0.0019	0.0439
Product racks N°3	0.9765	0.00096394	0.0310

3. Conclusion

This work has allowed us to evaluate the phenomena of thermal and mass exchange that takes place in the drying chamber of the dryer studied. We distinguished a difference of drying of the product being on the various racks of the dryer. The study also allowed us to validate a model of characteristic curve of drying (CCS). As a perspective to the study of this dryer, a numerical study via the computational fluid dynamics method (CFD), allows to have a better understanding of the distribution of heat flow inside this dryer.

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