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RESEARCHARTICLE

STUDY OF THE SOLAR DRYING OF BOVINE MEAT: DRYING KINETICS AND TEMPERATURE PROFILES IN A MIXED TUNNEL SOLAR DRIER

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ABSTRACT

This work concerns an experimental study of beef drying with a mixed tunnel solar dryer with forced convection. Drying experiments were carried out at the Centre for Study and Research on Renewable Energies (CERER). The evolution of air and product temperatures as a function of irradiance and the position of the racks was studied, as well as the effect of treatment and air temperature on drying speed. The experimental curves presented in terms of reduced moisture content as a function of drying time are approximated by mathematical models of existing drying kinetics. The effective diffusion coefficients of the different samples with their treatment were determined essentially based on an approximation of the logarithm of the reduced humidities by the solution developed by Cranck on the diffusion equation. The values found for the effective diffusivity are 2, $666910^{-ᄇ}$, 2, $963021010^{-ᄇ}$ and 3, $4011510^{-ᄇ}$ respectively for the samples with peanut paste, with spices and without pre-treatment. The analysis of these results allowed to conclude on the thermal performance of the dryer but also that the "Henderson and Pabis", "Midilli et al" and "Logarithmic" models can be proposed respectively as the most reliable models to describe the evolution of the reduced moisture content as a function of time of the sample without treatment, with peanut paste and with spices.

INTRODUCTION

The conservation of meat remains a problem in countries with hot climates because the latter being very perishable; therefore requires adequate means of preservation to preserve its microbiological and organoleptic stability (1).Solar drying, which is already widely used, in the open air, by the populations and which is defined as being an operation which consists in extracting a quantity of water impregnating a product using as energy source solar energy, can therefore be, if well controlled from an energy and health point of view, a good solution for these countries where solar energy is abundant and where its populations do not have access to cold storage. The lowering of this content makes it possible to reduce the activity of enzymes and the rates at which undesirable chemical changes occur in order to ensure their conservation for a relatively long period or to facilitate their transformation (2).Physically, drying most often results from a simultaneous transfer of heat and mass within the product to be dried and at the interface between this product and the drying environment (3, 4, and 5).However, given the complexity of the transfer mechanisms and the diversity of the products, knowledge of the basic data, in this case the kinetic curves are necessary.
Research has been done on the drying kinetics of meat (6, 7, 8, and 9) as well as its diffusion coefficient (10, 11, and 12), all of these results lead us to think that it is necessary to study experimentally and model the drying kinetics of beef, in particular for different treatments during drying.Several empirical or semi-empirical models have been developed to account for the drying kinetics and to understand the physical laws that control transfers.

This is the logic behind this study, which aims at studying:

The thermal performance of the solar dryer used,the effect of the treatment with spices or peanut paste on the drying kinetics

Determine the empirical or semi-empirical models suitable for predicting the drying kinetics of beef, as well as the diffusivity.

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Mathematical formulation

Dry base water content (13)

It is the ratio of the variation between the wet mass M $_h$ (t) of the product and the dry mass m$_s$over the dry mass, it is defined by equation (1).

$$W_t = \frac{m_{h(t)} - m_s}{m_s} \quad (1)$$

Reduced humidity (14): It is defined as the ratio of the variation of the moisture content at time t and that of equilibrium over the variation of the initial content and that of equilibrium given by equation (2).

$$w_r = \frac{w(t) - w_e}{w_0 - w_e} \quad (2)$$

Modeling of drying kinetics

The data from the experimental results made it possible to determine the reduced water content, and the representation of this content as a function of time will allow the aid of an empirical model to predict the drying of the beef.We will use six models taken from the literature whose sintering will allow thanks to the statistical results to know the constants of the models which depend on the drying conditions. These models of drying kinetics are shown in Table 1 (15, 16).

Table 1. Mathematical models of drying curves

Model	Equation
Page	W_r(t)=exp (-kt^n)
Logarithmic	W_r(t)=aexp (-kt) +b
Henderson and Pabis	W_r(t)=aexp (-kt)
Midilli and al	W_r(t)=aexp (-kt^n) +bt
Wang Singh	1+at+bt^2
Newton	W_r(t)=exp (-kt)

The choice of the model that can describe the drying of beef is made using the following statistical criteria (17):
A high correlation coefficient (r²) (tending towards 1) and a Chi-square (χ2) and minimum ESM (tending towards 0), Given by equations (3), (4), and (5)

Correlation coefficient (r^2) given by equation (3).

$$r^2 = \frac{\sum_{i=1}^{N} (W_{r,i} - W_{re,i})^2}{\sum_{i=1}^{N} W_{r,i}^2} \quad (3)$$

Mean systematic error (ESM) defined by equation (4).

$$E = \frac{1}{N} \sum_{i-1}^{N} (W_{r,i} - W_{re,i}) \quad (4)$$

χ - Reduced square given by equation (5).

$$\chi^2 = \frac{\sum_{i=1}^{N} (W_{r,i} - W_{re,i})^2}{N-Z} \quad (5)$$

Calculation of the effective diffusion coefficient

Water migrates from the interior to the surface of the product under the action of various mechanisms which can be combined. In this analysis, the main mechanism for transporting water in meat strips is diffusive in nature.The diffusion equation, based on Fick’s second law, shows the evolution of the diffusion coefficient.

It is expressed by the following relation (18):

$$\frac{\partial w}{\partial t} = D_m \frac{\partial w}{\partial x} \quad (6)$$

This equation is based on the following assumptions

- water migration is only through diffusion;
- the water content on the external surface of the product is equal to that at equilibrium;
- the diffusion coefficient and the temperature of the product are considered constant;
- and the shrinkage of the sample is negligible.

On the basis of these hypotheses, the analytical solution of Fick's second law, developed by Crank, 1975, (19), can be expressed by:

$$W_r = \frac{8}{\pi^2} \sum_0^\infty \frac{1}{(2n+1)^2} \exp\left[-(2n+1)^2 D_m \frac{\pi^2}{e^2} t\right] \quad (7)$$

Only the first term can be used to estimate the effective mass diffusivity at the long drying time which leads to equation (8)

$$W_r = \frac{8}{\pi^2} \exp\left(-\pi^2 \frac{D_e \; t}{e^2}\right) \quad (8)$$

The values of D_e are generally determined by the graphical method by representing the experimental drying data in terms of lnWr as a function of the drying time (t) (20).

$$\ln w_r = \ln\left(\frac{8}{\circledR^2}\right) - \frac{\circledR^2}{e^2} \frac{D_{eff} \circledR^2 t}{e^2} \quad (9)$$

The result is a straight line with slope $\left(\left(\frac{D_{eff} \circledR^2}{e^2}\right)\right)$ which allows to calculate the effective diffusion coefficient (21)

$$D_{eff} = \frac{k e^2}{\circledR^2} \quad (10)$$

MATERIALS AND METHODS

Experimental device: The mixed tunnel solar dryer used is composed of a 50 Wp 12 volt photovoltaic module, two 12V fans, an aluminum absorber painted in matt black with a surface area of 1.5 m² and a 2 m² drying cabin with four horizontal racks located on the same level. The solar radiation arriving on the surface of the dryer is converted at the level of the module into electrical energy to operate the fans, these send air to the level of the absorber which is responsible for storing the heat that it will give up to the fluid. This heat-charged fluid enters the drying cabinet and is in contact with the product before being discharged outside the dryer.

Figure 1: Mixed Tunnel Solar Dryer

Devices and Measures: The table below gives us all the devices used with their characteristics

Experimental Protocol: The tests were carried out at CERER (center for study and research on renewable energies) during the month of December 2019.Control samples were obtained by cutting the meat into twelve small strips 5mm thick.

Table II.4 Characteristics of measuring devices

Désignation	Model	Measuring range	Accuracy
Thermochrons	DS1922T	0 125 C	0,5C 0 ,0625C
Thermocouple	PCE-T390	- 100 1370 C	0,2 %
Solarimeter	PYR13O7	0 1999 W/m^2	±5 %
Electronic Balance	CX 265	0 60g	0 ,01mg
oven	BINDER	0 250C	-

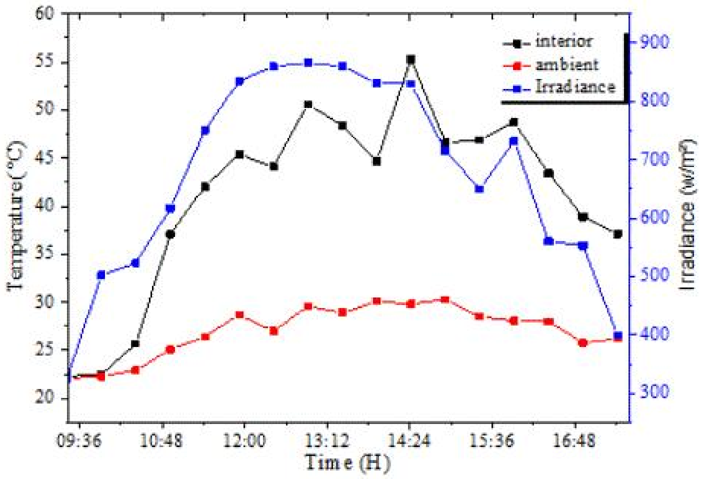

Figure 2: Influence of irradiance on air temperatures

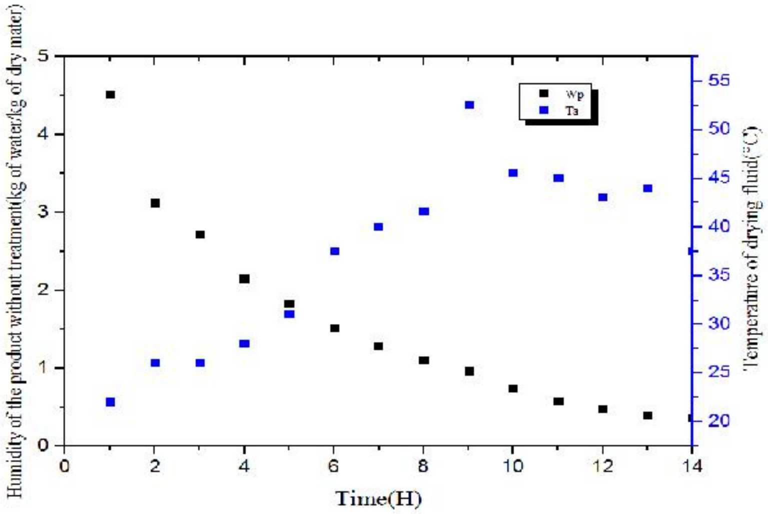

Figure 3: Influence of air temperature on drying speed

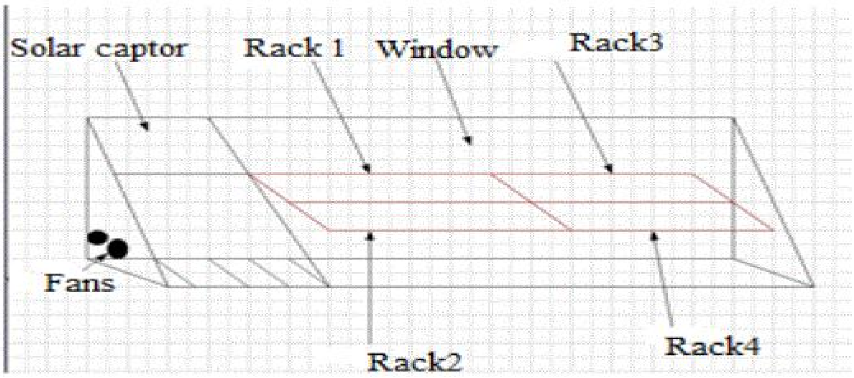

Figure 4: Illustration of the position of the dryer racks

Two treatment solutions were prepared with local spices to coat some of these samples after four hours of drying.Stainless steel knives are used for trimming and cleaning, that is to remove the fat, and tendons.The drying racks are numbered 1 to 4, including racks 1-2 and 3-4 located respectively at the entrance and exit of the cabin.The drying took place in two phases; first the product was dried in the dryer for four hours, then it went through the seasoning (treatment) phase.Twelve samples are used as controls:

four samples were treated with peanut paste (E1, E2, E3, E4), four others with spices only (E7, E8, E9, E12), and the remaining four are without processing (E5, E6, E10, E11) and are arranged on the shelves respectively E1, E2, E3, on the first rack, E4, E5, E6 on the rack 2 and E7, E8, E9 on the rack 3, E10, E11 E12 on rack 4, weighings are carried out before the start of drying and then during drying over time intervals of 1 hour. Finally, after drying, the samples are introduced into an oven at a temperature of 105 ° C for 24 hours. Thus the final product obtained is weighed in order to determine the anhydrous mass of the samples.

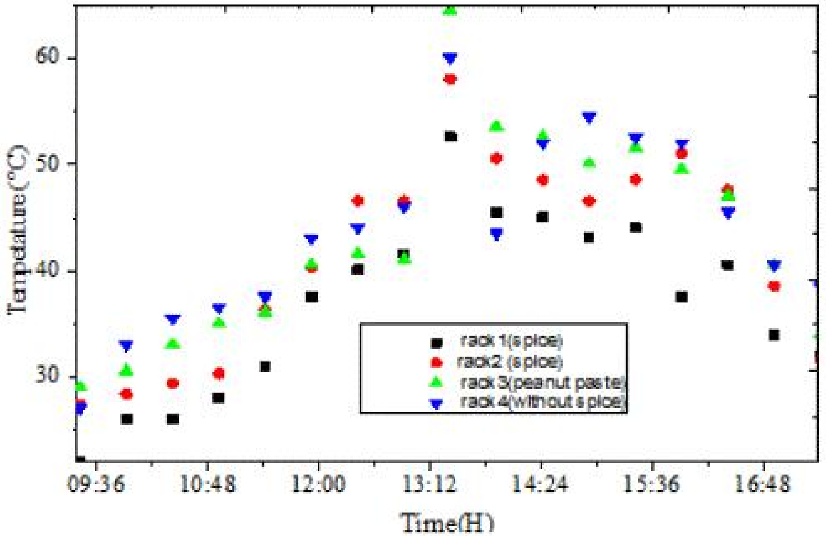

Figure 5: Influence of the greenhouse effect and the thermal conversion of the dryer on the product temperature depending on the racks

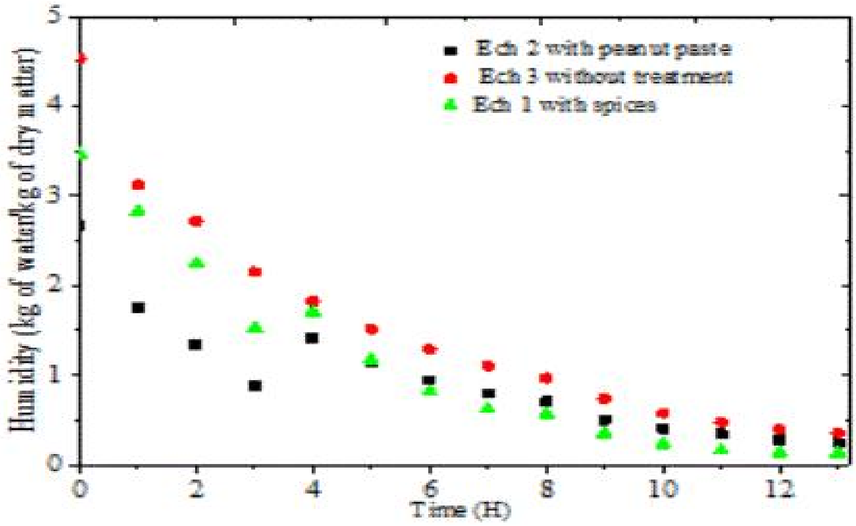

Figure 6:Effect of the treatment on the drying of the product

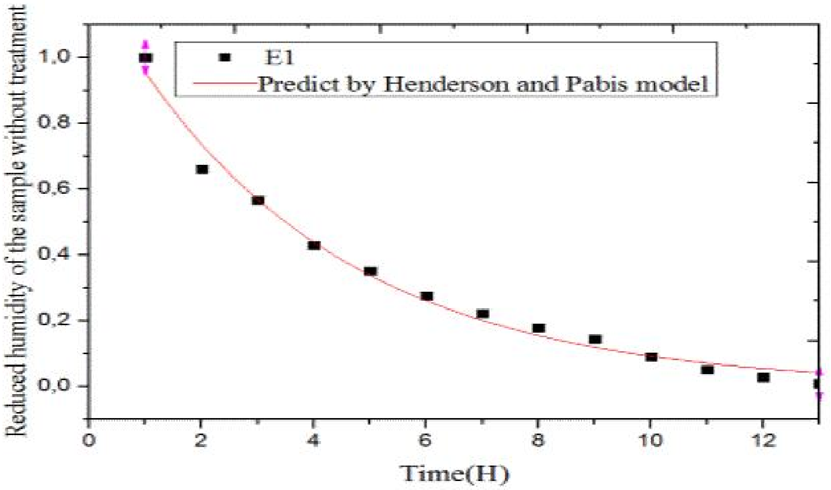

Figure 7: Reduced humidity of the sample without treatment as a function of time

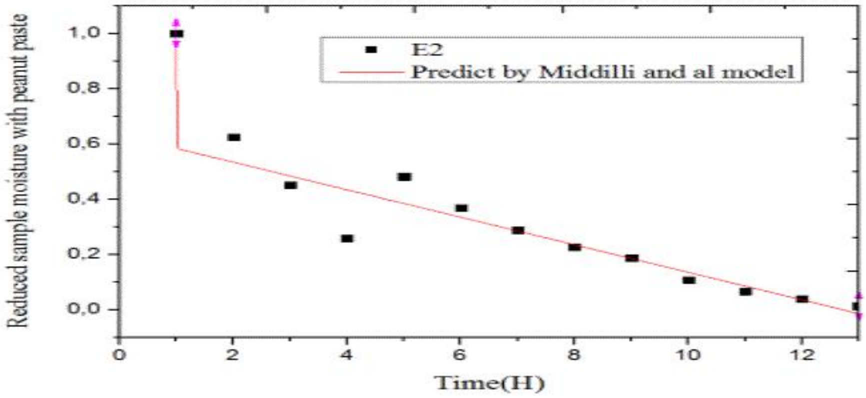

Figure 8: Reduced humidity of the sample with peanut paste as a function of time

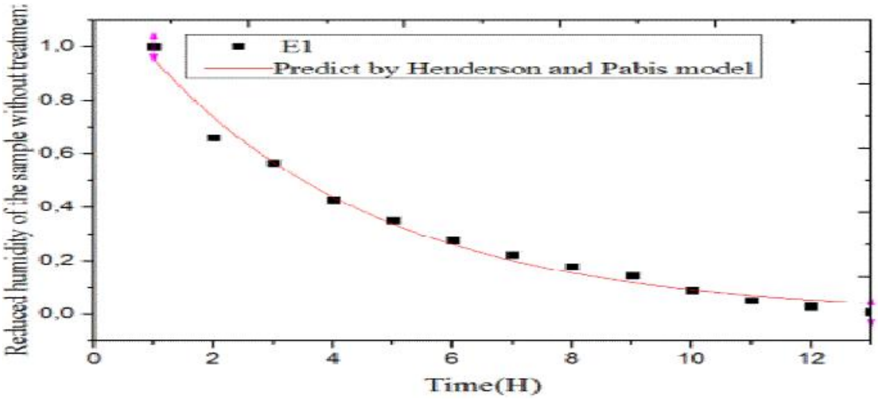

Figure 9: Reduced humidity of the sample with spices as a function of time

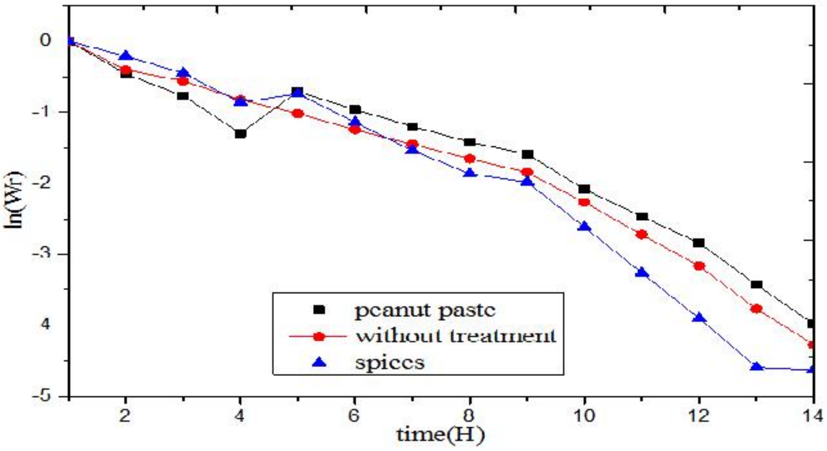

Figure 10: Variation in the log of reduced humidity as a function of time

Table 2: Parameters of the six models of beef drying kinetics

Model	Samples	Treatment	Model coefficients	χ^2	r^2	ESM
Page	E_1	Without treatment	k= 0,13456n= 1,26517	0,00214	0,97477	0,02356
	E_2	Peanut paste	k=0,18998n=1,0433	0,00983	0,87068	0,10812
	E_3	Spices	k=0,07754n=1,54106	0,00219	0,97917	0,02404
Logarithmic	E_1	Without treatment	a=1,23481b=-0,01663 k=0,24684	0,00117	0,98626	0,01167
	E_2	Peanut paste	a=1,1113b=0,03005k=0,25193	0,01009	0,86717	0,10095
	E_3	Spices	a=1,35541b=1,35541k=0,19972	0,0015	0,98575	0,01495
Henderson and Pabis	E_1	Without treatment	a=1,23638k=0,25922	0,00109	0,98719	0,01196
	E_2	Peanut paste	a=1,10657k=0,22764	0,00923	0,87856	0,10153
	E_3	Spices	a=1,33333k=0,25956	0,00232	0,97786	0,02555
Middilli and al	E_1	Without treatment	a=0,68153b=-0,05736k=-0,43919n=-93,7826	0,00341	0,95981	0,0307
	E_2	Peanut paste	a=0,6337b=-0,0498k=-0,50478n=-157,7322	0,0058	0,92365	0,05222
	E_3	Spices	a=0,83714b=-0,07401=-0,25846	0,00901	0,91413	0,08109

			n=-34,85794			
Wang Singh	E_1	Without treatment	a=-0,156b=0,0063	0,00291	0,96574	0,03199
	E_2	Peanut paste	a=-0,15278b=0,00621	0,01165	0,84672	0,12814
	E_3	Spices	a=-0,14282b=0,00498	0,0036	0,96573	0,03955
Newton	E_1	Without treatment	k=0,21047	0,00385	0,95465	0,0462
	E_2	Peanut paste	k=0,20473	0,00908	0,88058	0,10891
	E_3	Spices	k=0,19816	0,00838	0,92014	0,10055

RESULTS AND DISCUSSION

Variation of air and irradiance: Figure 2 shows the influence of irradiance on air temperatures.Ambient air and drying fluid temperatures vary approximately in the same way as irradiance.There is also a very large temperature difference between the ambient temperature and that of the interior of the dryer, at the time of strong sunshine.For low irradiance, this difference is not too large (Tamb is practically identical Tint.)The temperature dependence on the irradiance proves that the thermal efficiency of the dryer depends on the irradiance of the medium. This strong temperature gradient between the interior and the exterior of the dryer is explained by the fact that the latter is mixed, in fact, in addition to the thermal conversion rate of the absorber, the interior air is heated so directed by Greenhouse effect.

Thus, to carry out drying in accordance with the theory of the maximum admissible temperature of the product, it is recommended to start drying after the temperature setting phase of the dryer.

Mass and thermal variation of the product: In Figure 3, at low temperatures (20 ° C to 35 ° C), there is a rapid decrease in the humidity of the product (from 4.5 to 2 kg of water / kg of dry matter); beyond 4 hours, despite higher temperatures, the decrease in humidity is slower.The first observation corresponding to the very rapid drying of the product is explained by the phase of removal of its free water. Indeed, the free water of the product is a water to which its activity (a_w) is equal to 1, therefore very easy to release.The slow decrease in humidity results in the removal phase of the bound water.Generally, in a wet product water is found under three types of bonds (free, weakly bound and strongly bound). These bonds of water to the flesh of the product, very difficult to break explains the slowing down of the drying speed corresponding.These results show that the drying speed does not increase as a function of temperature in a linear fashion. And even it is often recommended to lower the temperature in the last phase of drying to avoid the phenomenon of crusting.

Variation of product temperatures according to the drying racks: As a reminder, the number 1 and 2 racks are closer to the solar collector. The rack number 2 is closer to the glass surface than the rack 1. This is explained by the inclination of the glass relative to the surface of the racks.The number 3 and 4 screens located in the other compartment of the cabin are further from the sensor and undergo the same tilting effect of the window.Thus the racks 2 and 4 aligned in the direction of the hot air are closer to the glass surface than the racks 1 and 3 aligned on the other hand.The control products placed on rack 1 and 2 underwent the same treatment after 4 hours of drying, the product on rack 3 was treated with peanut paste and that found on rack 4 was dried without treatment.

Before the seasoning phase, the products being on racks 3 and 4 have high drying temperatures than racks 2 and 1. In addition, racks 2 and 4 have respectively higher temperatures than those of the rack 1 and 3.Immediately after the treatment of the products, a temperature overshoot of the product of rack 3 (seasoning with peanut paste) compared to those of rack 2 and 4 is noted.After the various treatments of the control samples, the observation is the same as in the first hours of drying.The greenhouse effect at the level of the drying cabin is not the same as at the level of the four racks. Racks 2 and 4 being closer to the glass surface have higher temperatures. In addition, racks 4 and 3 benefit much more from the thermal conversion effect of the drying cabinet than the other racks.The return to the same behavior as in the first hours of drying can be explained by a temporal effect of the peanut paste on the product. The effect of the glass which is the cause of these temperature differences can be eliminated by tilting the racks of the dryer at the same angle as the glass.To avoid the crusting phenomenon, it is necessary to take into account the drying time before pasting the peanut paste.

Variation in the humidity of the product over time: We averaged the water content of the four samples for each pretreatment to observe their variations over time (Figure 6).We note that before the treatment, a very marked drop in the humidity of the product is observed. On the other hand, after treatment of certain samples, the humidity decreases slowly.Sample 3 produced without treatment has a slower drying kinetics than the two samples with treatment. In addition, sample 2 treated with peanut paste despite its low water content has a lower drying speed than that of sample 1 with spices (higher water content after treatment).This very rapid decrease observed before treatment still confirms that we are in the phase of removing the free water observed in Figure 2-8.

The accelerating effect of the treatment on the drying speed explained by the phenomenon of osmosis which takes place there. In fact, when two media of different concentrations (product to be dried and the spices or peanut paste) are brought into contact, the water migrates from the least concentrated to the most concentrated, here therefore from the product to the treatment solution. The peanut paste solution being more viscous than the spicy solution, slows the extraction of water much more than that of the spices.

To have quick drying and an acceptable finished product, treatment is an essential step.

RESULTS OF THE MODELING

Beef drying kinetics: The representations of the reduced water content as a function of time for the different samples obtained from the drying experiment were adjusted by six models of drying kinetics using Levenberg-Marquardt nonlinear regression on OriginPro 9 .1 .The constants of the models and the statistical results such as r ^ 2, ESM and χ ^ 2 obtained are presented in table 2.The above results present the constants of the models which are parameters which depend on the drying conditions; as well as the statistical results. The criteria of high correlation coefficient (r^2), RSME and low presented in paragraph 3 made it possible to bring out for each sample a model which gives a good fit (Figures 7,8,9).The Anderson and Pabis model was chosen as the one that best describes samples 1, namely drying the meat without pretreatment r^2=0,98719, χ^2 =0,00109 and ESM = 0.01196.That of Midilli et al was chosen for the drying of sample 2, namely the drying of the meat pretreated with peanut paste for coefficients r^2=0,92365, χ^2=0,0058 and ESM = 0.05222.And finally the Logarithmic model to describe the drying of sample 3, the meat pretreated with spices with coefficients r^2=0, 98575, χ^2=0, 0015 and ESM = 0.01495.

Effective mass diffusivity of the different samples: The diffusion coefficients of the samples according to their treatment during drying were obtained graphically by plotting the logarithm of the reduced humidities as a function of time for the three samples represented by figure 10.The values of the diffusion coefficients of the different samples as well as the statistical results obtained are recorded in the table below. The results show a lower diffusivity for the sample with peanut paste D_{eff} =2, 666910^{-8}, followed by the sample without treatmentD_{eff}= 2, 96302 $10^{-8}$and samplewhich spices has the greatest diffusivity D_{eff} =3, 4011510^{-8}
.

These results are consistent with the diffusivity coefficients found in the literature, which is in the diffusivity range between 10^{-1} and 10^{-8} in the context of the drying of food products(22)(23)(24).

Conclusion

The experience in this work of studying the solar drying of beef has produced several results. Indeed, this study made it possible to judge the performance of the mixed solar drier, in order to see the influence of air temperature on drying, and the effect of the treatment on the drying speed of the meat. The study of the drying kinetics made it possible to note the absence of the first drying phase, that is to say the period of warming up the meat. The numerical determination of the constants of the various empirical models studied makes it possible to conclude that the “Henderson and Pabis”, “Midilli et al” and “Logarithmic” models are respectively the most reliable models for describing the evolution of the reduced water content in time function of the sample without treatment, with peanut paste and spices. The values found for the effective diffusivity are 2.666910^{-8} , 2.9630210^{-8} and 3.4011510^{-8} for the samples with peanut paste, without treatment, and spices respectively.

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