Experimental study of a direct solar drying process with a thermal storage System using latent heat

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Abstract

In this study, we designed a direct solar dryer at the Research and Development Unit for Renewable Energies in Ghardaia to dry tomatoes. A phase change material was used to store excess heat and utilize it when the sun was absent to increase the dryer's efficiency. The obtained results from the drying kinetics were modeled. The results showed that the Page model was the best model to predict the drying kinetics of tomatoes in the studied dryer ($R^2 = 0.99946, RMSE = 0.00911, \chi = 8.2914E - 5$). Additionally, the use of the phase change material increased the dryer's temperature in the absence of sunlight compared to the dryer without the phase change material. The effective moisture diffusion value in the tomato slices was $5.12586^{-9}(m^2/s)$.

Keywords: Solar Drayer; PCM; Drying Kinetics. Tomatoes;

1. Introduction

Drying is an ancient preservation technique that reduces the moisture in products to prevent the growth of microorganisms and harmful chemical reactions [1]. It also decreases mass and volume, thus reducing storage and transport costs [2]. However, it is an energy-intensive process, often powered by LPG, coal, biomass, or solar energy sources. Traditional solar drying is economical but has drawbacks like contamination, difficulty in control, and product losses. To address this, modern solar dryers allow for more efficient drying under controlled conditions (45°C to 60°C) [3]. Nevertheless, their reliability is limited by the intermittent nature of solar radiation, which has led to the integration of auxiliary heat sources and thermal storage systems, either by sensible heat (stones, water) [4-6], or latent heat (paraffin wax, calcium chloride) [7, 8]. These systems optimize energy conservation to maintain drying during low sunlight. Air circulation, natural or forced, helps remove moisture, especially for products with low internal resistance [9, 10]. Simple fans can improve this process for small-scale production [11]. In this context, the present work is based on the development of a direct solar dryer capable of processing fruits and vegetables on a small scale, targeting family farmers or small producers.

2. Materials and Methods

The experimental prototype is a direct solar dryer with a thermal energy storage system using paraffin wax for latent heat storage. Built by the Applied Research Unit in Renewable Energies (URAER), it has a trapezoidal steel structure measuring 2.20 m wide. The front is polycarbonate, and two rear doors allow access. Inside, products can be placed on perforated metal shelves or the lower surface. A thermal storage system with paraffin wax and aluminum powder is located above the trays, and a 35W fan aids air circulation.

2. 1. Drying experiments

2.2. Moisture content

The initial moisture content of the tomatoes was identified to be 93.5% on a wet basis. The removal in moisture content during the dehydration was calculated using the subsequent formula (Eq. (1)):

$$X = \frac{M_t - M_s}{M_s}$$ **Error! Reference source not found.**

2.3. Drying kinetics

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The moisture content of the drying sample at time ‘‘t’’ is characterized by a moisture ratio (MR), which serves as a key parameter in elucidating the drying kinetics of the product. This moisture ratio, denoted as MR was expressed as the following formulas:

Fig. 1 Direct solar dryers with MCP

$$XR = \frac{X_t - X_e}{X_0 - X_e}$$ **Error! Reference source not found.**

2.4. Effective moisture diffusion

The rate of mass transfer by diffusion is corresponding to the moisture level. The determination of the effective diffusion coefficient is needed to characterize the mass transfer, by using the equation of Fick that is:

$$\frac{\partial XR}{\partial t} = D_{eff} \nabla^2 XR$$ **Error! Reference source not found.**

Assuming the slab is an infinite, undeformable geometry (with negligible shrinkage or expansion), Crank [12] developed Fick's method, which is expressed as follows:

$$\frac{\partial XR}{\partial t} = D_{eff} \nabla^2 XR$$ **Error! Reference source not found.**

After simplifying equation 2, it becomes

$$\ln(XR) = \ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{eff}}{4L^2}$$ **Error! Reference source not found.**

The drying kinetics are characterized using thin layer drying models. To identify the most suitable model, seven different proposed models, as outlined in Table 1, will be evaluated. The selection of the best model to represent the drying curves is primarily based on the coefficient of determination (R^2). Along with R^2, additional statistical criteria, including the reduced chi-square (χ^2) and root mean square error (RMSE), were also employed to determine the best fit.

Table 1: The mathematical models and statistical values for drying tomato slices.

Model	Equation	Constants	R^2	RMSE	χ
Newton	$MR = \exp(-kt)$	k=0.00205	0.99604	0.0242	5.268E-5
Page	$\mathbf{MR = \exp(-kt^n)}$	**k=8.91E-4; n=1.13889**	**0.99946**	**0.00911**	**8.2914E-5**
Modified Page	$MR = \exp(-(kt)^n)$	k=0.0021; n=1.13947	0.99946	0.00911	8.2906E-5
Henderson and Pabis	$MR = a\exp(-kt)$	k=0.00215; a=1.02947	0.99745	0.0198	3.92093E-4
Logarithmic	$MR = a\exp(-kt) + b$	k=0.04743; a=0.81495; b=-0.1794	0,99618	0,02385	5,6885E-4
Midilli-Kucuk	$MR = a\exp(-kt^n) + bt$	k=0.00312; n=1.06752; a=1.01568; b=4.202E-6	0,98586	0,03252	7,349E-4
Approximation of Diffusion	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	k=0.00398; a=1.04788; b=6234.81	0,99553	0,02582	6,6651E-4

Based on the obtained statistical values, it is evident that the Page model is the closest for predicting the drying kinetics of tomato slices in the studied solar dryer. The effective moisture diffusion value in the tomato slices is $5.12586^{-9}\frac{m^2}{s}$.

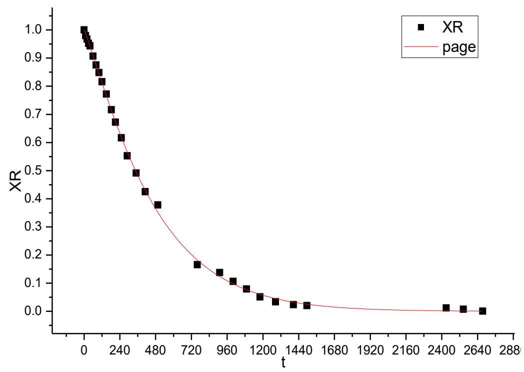

Fig. 2 Evolution de la cinétique de séchage

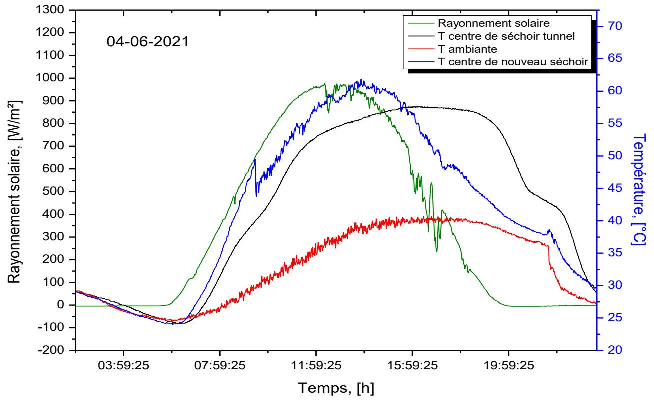

Fig. 3 Evolution of the ambient temperature and the air temperatures at the center of the dryer and solar radiation

2.5 Performance of Solar Dryer

Fig. 3 represents the temperature variations inside and outside the solar dryer, as well as the solar radiation intensity on 04/09/2024, during which the dryer was tested without any product. The ambient temperature changed from 25°C, reaching a maximum of 37°C at 3:00 PM. Meanwhile, the dryer's temperature rose from 25°C to a peak of 62°C at around 1:30 PM. As for the solar radiation intensity, it reached 1000 W/m².

Fig. 4 represents the temperature variations in the solar dryer with the presence of the product and the phase change material, which was filled in small containers. The maximum temperature inside the dryer reached 70°C at 2:00 PM, while the temperature of the phase change material reached 80°C at 3:00 PM. The solar radiation intensity reached 900 W/m².

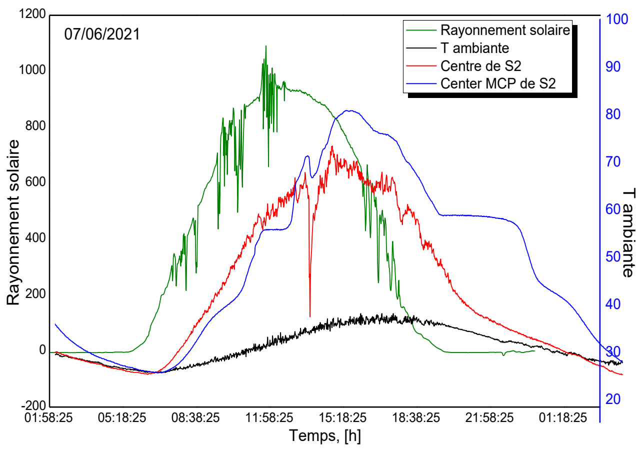

Fig. 4 Evolution of the ambient temperature and the air temperatures at the center of the dryer (with product and MCP) and solar radiation.

3. Conclusion

- The best model for predicting the drying kinetics is Page.
- The effective moisture diffusion value in the tomato slices is 5.1258E-9 m^2/s.
- The presence of the phase change material in the dryer extended the drying time in the absence of sunlight until 21:00 instead of 19:30.

Nomenclature

M_t:	The weight at t	X_t:	The moisture content at particular time
X_0:	Initial moisture content	X_e:	equilibrium moisture content
Ms:	Dry weight of the material		

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