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Experimental determination of the drying characteristics and the effective moisture diffusivity of the Dandelion leaves undergoing convective solar dryer

H. Moussaoui[1], M. Kouhila[1], N. Abdenouri[2], Y. Bahammou[1], Z. Tagnamas[1], A. Idlimam[1], A. Lamharrar[1]

[1]*Team of Solar Energy and Medicinal Plants, Teacher's Training College, Cadi Ayyad University, BP 2400 Marrakesh*
[2]*FSTG, Department of Applied Physics, Cadi Ayyad University, Abdelkrim Elkhattabi, BP 549 40010 Marrakesh, Morocco*

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haytem.moussaoui@gmail.com
Phone: +212676556667;

Abstract

Preserving food products through solar drying is a promising application. It is an efficient friendly environment technique to conserve food. The contamination of food is actually due to the presence of certain harmful microorganisms that deteriorate the products. Indeed, water activity in the product is one of the major causes of this problem. The solution must include a shelf life-prolonging food process that can only be obtained by both reducing water and microbiological contamination. Hence, the need for the solar dryer. This paper tackles the impact of certain drying parameters on the water loss of dandelion leaves. The drying kinetics at different temperatures (50, 60, 70 and 80°C) together with two airflows (150 and 300 m3.h-1) of this plant were studied in a convection solar dryer. The drying curves and the Effective moisture diffusivity are the major results found and analyzed in the study.

1. Introduction

The Dandelion leaves is used as a special ingredient in soup, green salads, teas and wine. Hence, the growing need for its conservation represents a major concern in the field of food industry. In addition to its taste qualities, dandelion is known for its detoxifying properties. In Phytotherapy, it is often recommended to promote digestion and detoxification of the liver. Dandelion can grow in extreme weather conditions, both hot and intense frost [1].

Indeed, the conservation of food presents one of the main pillars of scientific research. It has several benefits in terms of costs at regional, national and global scales. In this respect, several techniques and methods are elaborated in order to conserve food in optimal conditions at the lowest cost [1, 2].

Throughout history, several civilizations have used solar drying as a useful solution to protect food from contamination. It is a free effective moisture-reducing technique. However, it is still unable to protect the product from dust, rain, insect, rodents, and other sources of contamination; hence, degrading the food quality which may lead to unpredicted serious economic effects on the domestic or even the international market [2]. Thereby, a solar alternative is needed.

The convective solar dryer is a non-contaminating tool and an economically beneficial solution that can ensure a better-quality product with a low energy demand.

The study of the drying kinetics is based on determining heat and mass transfers that take place at level of food product and air exchanges. These phenomena are characterized by very complex transfer mechanisms [3]. Indeed, this complexity is due to the thermophysical properties of mass transfer as well as that of heat transfer that are affected by temperature and moisture content of the product.

A convective solar dryer is used in this experiment in order to study the drying kinetics of the dandelion leaves as well as its drying characteristics. Therefore, the variation of moisture content and the drying rate for several aero-thermal parameters can be deemed of as the main pillars in analyzing the product drying behavior during the drying process [4].

The understanding of the drying characteristics of agricultural materials is made clearer by thin layer drying modeling. These types of models are part of three categories that are theoretical, semi-theoretical as well as empirical [5]. As for the theoretical type, it concerns the diffusion equation or the simultaneous heat and mass transfer equation. On the other hand, the semi-theoretical approach deals with the approximated theoretical equations. Finally, the empirical equations are easily applied to the drying simulation since they depend on experimental data. While the theoretical approaches account for only the internal resistance to moisture transfer, semi-theoretical and empirical approaches consider only the external resistance to moisture transfer between the product and air [6].

The purpose of this work is to study the drying kinetics of the dandelion leaves as well as analyzing the impact of the temperature and the airflow rate on the drying kinetics of the samples. Additionally, it seeks to fit the drying curves by using several models in order to select the most suitable one along with determining the thermo-physical properties. According to literature, there are a large number of physical and thermal properties of heat and mass transfer of food product. In this regard, the moisture diffusion and the energy of activation are selected as ideal properties thanks to their utility and convenience to the drying food in a thin layer [6,7].

2. Material and Methods

2.1. Experimental set-up and procedure

The experimental system is an indirect forced convection solar dryer, as shown in Figure 1, composed of several parts that ensure the proper running of the system. The main components are [8]:

- A simple glazing and a circulation solar captor with a surface of 2.5 m^2 inclined from 31 ° to the horizontal level and oriented southward.
- A centrifuge ventilator (0.083 m^3/s, 80 mm CE, 220 v, and 0.1 kW).
- Thermo-regulator (0-100°C with a 1°C precision)
- An auxiliary source (4kW Electrical resistances)

The solar rays heat the airflow upward the samples; they enter below the trays in the drying cabinet below. To keep a constant air-drying temperature; the use of an auxiliary heater is necessary and unavoidable. The calculation of the mass loss of the product on the tray during the experiment is done via a (±0.001 g); the weight was measured by removing the product from the drying cabinet each 10 min until the weight becomes stable. The moisture content is then calculated by taking the difference between the mass before (M_h) and after drying (M_d) in a 105 °C oven for a period of 24.

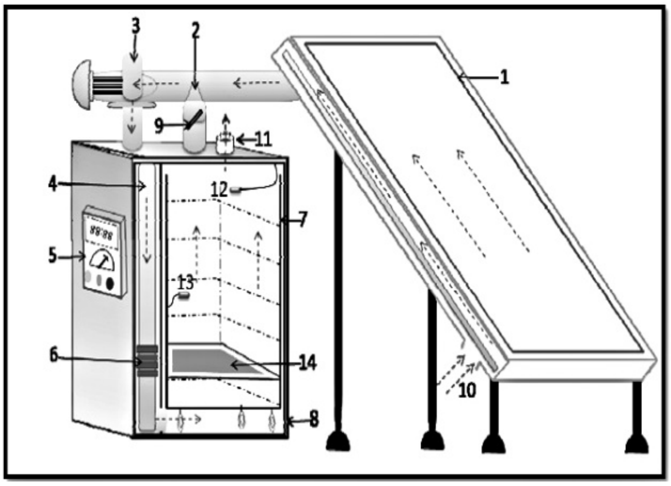

Figure 1: Schematic representation of the solar dryer : (1) solar collector; (2) circulation fan; (3) fan; (4) airflow direction, (5) control box; (6) auxiliary heating system; (7) shelves; (8) drying cabinet; (9) recycling air; (10) control foot; (11) exit of air; (12) humidity probes; (13) thermocouples.

Finally, the expression of the Moisture Content MC (t) is represented by the equation below [3, 5]:

$$MC(t) = \frac{M_h(t) - M_d}{M_d} \tag{1}$$

2.2. The drying curves and the influence of drying parameters on the drying rate of dandelion leaves

In order to understand the drying behavior of the dandelion leaves, it is of extreme significance to determine the drying curves. They represent the changes in masses so that the analysis of the mass transfers with the environment under different conditions can be possible together with the influence of the temperature and humidity on the drying behavior of the plant. Thus, it is indispensable to plot the variations of the moisture content MC in function of the drying time. Furthermore, the curves should represent the variation of the drying rate (DR (t)) in function of the moisture ratio (MR) as well as the moisture content. The eq. (2) and eq. (3) illustrate the relationship between each one and the moisture content respectively [8,9]:

$$DR(t) = \frac{dMC(t)}{dt} \tag{2}$$

$$MR = \frac{MC - MC_e}{MC_0 - MC_e} \tag{3}$$

Where:

MC_e refers to the equilibrium moisture content

MC_0 refers to the initial moisture content at time (t=0)

2.3 The characteristic drying curve

The characteristic drying curve method entails describing the drying kinetics of the samples using an empirical equation obtained by adjusting the drying experimental data. Moreover, it aims at collecting the overall experimental results obtained on a product and for various aero-thermal conditions on a single base curve called drying characteristic curve (CCS) [10].

The rationale behind the characteristic drying curve as developed by Van Meel [11] is to quest for a normalized single curve through the representation of the drying rate ratio to the rate of the first phase as it is shown in the eq. 4 in function of the moisture ratio.

It is necessary to note that the characteristic drying curve must verify the properties demonstrated in the equation system eq. 5 in order to attain a reasonable range of constant experimental conditions namely that of drying airflow, temperature, as well as the dimensions of the dried samples [12].

$$f=\frac{\left(-\frac{dMC(t)}{dt}\right)_t}{\left(-\frac{dMC(t)}{dt}\right)_I}=\frac{\left(-\frac{dMC(t)}{dt}\right)_t}{\left(-\frac{dMC(t)}{dt}\right)_0} \tag{4}$$

$$\begin{cases} f=0 & for & MR=0 \\ 0\le f\le 1 & for & 0\le MR\le 1 \\ f=1 & for & MR\ge 1 \end{cases} \tag{5}$$

2.4 The effective moisture diffusivity

During the drying process, water migrates from the inside of the product towards its surface prompted by a combination of various mechanisms that act together. It is taken for granted that a particular capillary-porous plant that is replete with water facilitates water transport. In the same token, the transport of the food product water is often attributed to the liquid water diffusion resulting from the impact of the concentration gradient [13]. The evolution of water content can be described as a function of the water content gradient along with a global diffusivity that combines various transport phenomena according to the second law of Fick:

$$\frac{\partial MR}{\partial t}=D_{eff}\nabla^2 MR \tag{6}$$

Where D*eff* refers to the effective moisture diffusivity of the sample whose unit is termed as m2.s-1. This later is affected by the degree of temperature, the product moisture content of the product as well as the retraction of the solid matrix.

In this respect, Crank suggested an analytical solution notably that of the second law of Fick in case of an infinite dimension plate [14]. This solution can be obtained according to certain specific conditions: the initial distribution of water in the plate is uniform, the shrinkage of the product is negligible, and the diffusion coefficients are invariable.

$$MR=\frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\frac{\pi^2 D_{eff}t}{4L^2}\right] \tag{7}$$

While the drying time is big and considerable, we can note that all terms in the series are negligible in front of the first term; therefore, the eq. 18 is obtained [15]:

$$MR=\frac{8}{\pi^2}exp\left[-\frac{\pi^2 D_{eff}t}{4L^2}\right] \tag{8}$$

Where L (in m) is the half thickness of the samples used.

Establishing effective moisture diffusivity (D_{eff}) is typically carried out through using the graphical method. This later involves a representation of the moisture ratio (MR) natural logarithm as a function of the drying time (t) as displayed in eq. 19. The outcome is a linear regression (A×t+B) where the term A correlates with $\left(-\frac{\pi^2 D_{eff}}{4L^2}\right)$.

$$Ln(MR) \cong Ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{eff} t}{4L^2} \tag{9}$$

The effective diffusivity (D_{eff}) is calculated via the graphical method by representing the experimental drying data in terms of the natural logarithm of the moisture ratio MR as a function of the drying time.

3. Results and discussion

3.1 Drying curves

Figure 2 displays the eight experimental drying tests. It presents the variation of moisture content as a function of time for different drying air conditions for these eight tests.

According to Figure 3, the increase in the drying temperature causes the airflow rate as well as the drying rate of dandelion leaves to increase. Therefore, it can be easily deduced that the drying kinetics of the dandelion leaves are strongly influenced by the drying air temperature. This significant outcome is also illustrated in several papers and studies [16, 5].

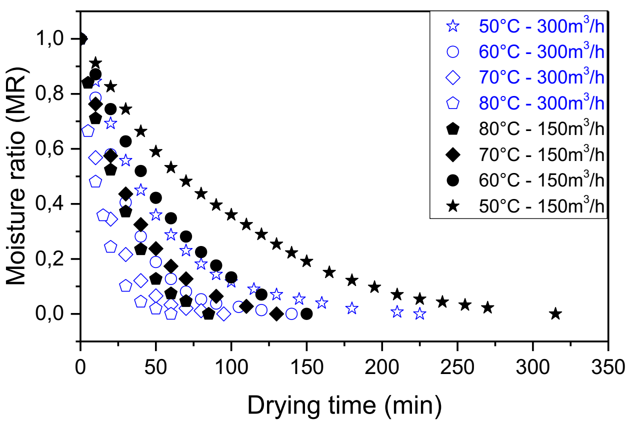

Figure 2: Variation of moisture ratio as a function of time.

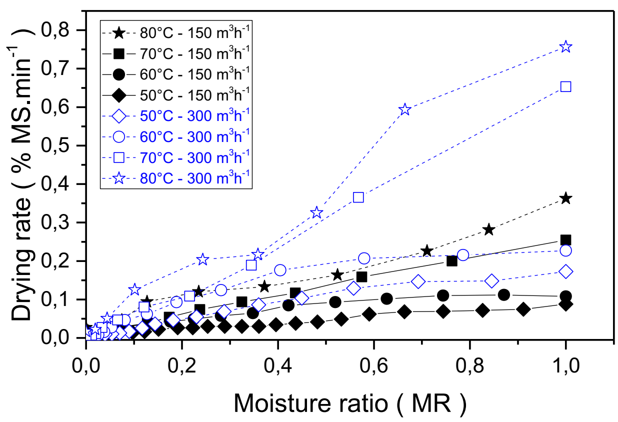

Figure 3: Variation of drying rate as a function of moisture ratio

3.2 Characteristic drying curve

Figure 4 shows the variation of the standardized drying rate f in function of the moisture ratio in different aero-thermal parameters (temperature and airflow). This representation refers to the characteristic drying curve that consists of normalizing the drying kinetics in a theoretical model from experimentations.

The polynomial in (MR) that correlates the relationship between the standardized drying rate of dandelion leaves and the moisture ratio was obtained from the several drying experimental data [9, 8]. In addition, they are established through using the Marquard-Levenberg's non-linear optimization method and the Origin 6.1 software. The best polynomial regression is obtained by selecting a high correlation coefficient r as a criterion of evaluation a as it is represented in the flowing equations:

$$f = 1.041MR \tag{10}$$

$$r = 0.98 \tag{11}$$

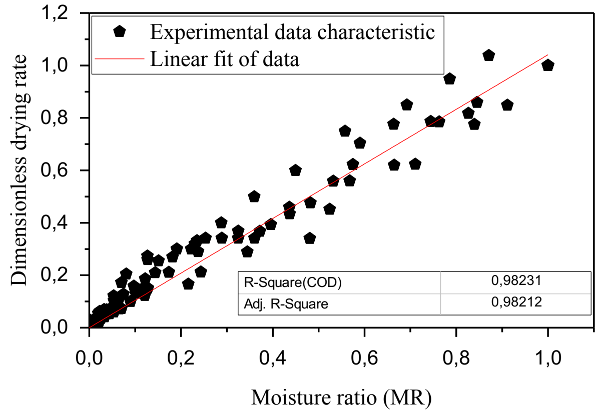

Figure 4: The characteristic drying curve of the dandelion leaves

3.3 Effective moisture diffusivity

The Figure 5 represents the variation of the natural logarithms of the moisture ratio in function of the drying time of the samples at different temperatures (50, 60, 70 and 80°C) and with different airflows (150 and 300 $m^3.h^{-1}$). What's more, it can be noted from the figure that the natural logarithm of the moisture ratio values decreases with the increase of the drying time, the temperature and the airflow. These finding has been widely emphasized in a large number of a research papers [15, 14].

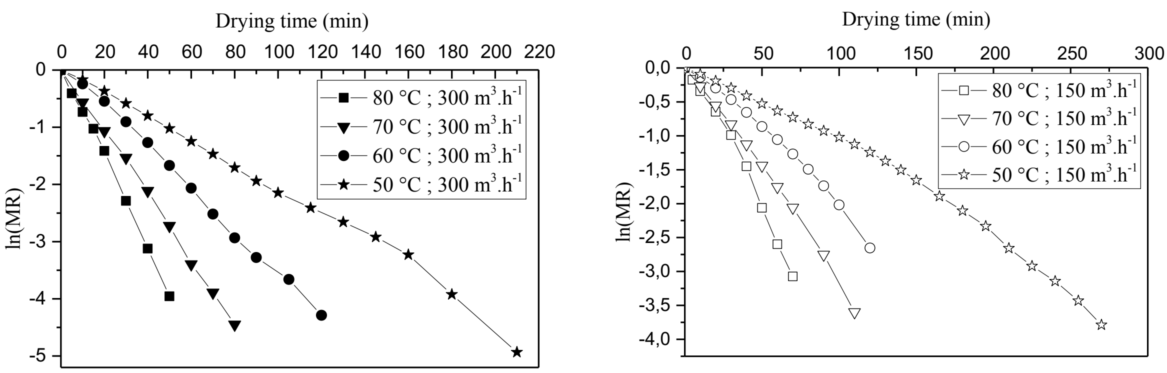

Figure 5: The effects of temperature and airflow on the effective diffusion coefficient of dandelion leaves

Table 1: The values of the effective moisture diffusivity of the dandelion leaves.

Exp	T (°C)	Airflow Dv($m^3.h^{-1}$)	Effective moisture diffusivity *Deff* ($m^2.s^{-1}$)	r
1	50	150	2.2819 10^{-11}	0.9866
2	60	150	3.6342 10^{-11}	0.9944
3	70	150	5.426 10^{-11}	0.985
4	80	150	7.4375 10^{-11}	0.9826
5	50	300	3.7525 10^{-11}	0.9913
6	60	300	6.2373 10^{-11}	0.997
7	70	300	9,4659 10^{-11}	0.9984
8	80	300	1,3387 10^{-10}	0.9974

The table 1 summarizes the values of the effective moisture diffusivity (D_{eff}) of dandelion leaves that are obtained based on the eq. 19 in different drying conditions. We can also observe that the values of D_{eff} decreases with decreasing the drying airflow together with the temperature. These results can be explained in one hand by the mass transfer that governs the moisture diffusion increase when the drying temperature rises, and which facilitates the removal of water within the product. In the other hand, when the flow rate increases, the convection of the drying airflow increases as well; therefore, the diffusion of water within the product accelerates. Finally, it is worth noting that in the literature several researchers found that the value of the effective moisture diffusion coefficient is in range of 10^{-8} to 10^{-12} $m2.s^{-1}$ for food in a drying process [5, 16].

4. Conclusion

The drying kinetics of the dandelion was experimentally investigated in this paper in a thin layer convective solar dryer in a Moroccan climate conditions (region of Marrakech). The obtained experimental drying curves obtained shows that the only existing rate is that of the drying rate period. Additionally, the drying air temperature appears to be the principal factor that influences the drying kinetics. The results allow us to determine both the drying curve and the drying rate equation. What's more, the effective moisture diffusivity values are determined using the Fick's diffusion model. They are established within the range of ($2.2819\ 10^{-11} - 1.3387\ 10^{-10}$). As mentioned earlier, the D_{eff} value increases with the increase of the temperature and the airflow.

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