Revue des Energies Renouvelables Vol. 19 N°2 (2016) 251 - 264
DOI: https://doi.org/10.54966/jreen.v19i2.565

Experimental analysis of solar drying kinetic of Algerian bay leaves (*Laurus nobilis L.*)

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(reçu le 26 Juin 2016 - accepté le 30 Juin 2016)

Abstract - *In this work, we present an experimental study of thin layer solar drying kinetics of Algerian bay leaves. The experiments were carried out in an indirect solar dryer operating in forced convection fitted with an auxiliary heater with aero controlled conditions. Bay leaves were dried at a relative intervals of relative air humidity, the air temperatures and air velocities ranging from 21 to 40 %, 40 to 60 °C and 0.25 to 0.8 m/s, respectively. 95 % of the water content of the product was reduced for a temperature of 60 °C. The experimental curves obtained show the presence of a decreasing drying rate. This drying rate increases with the increase of air temperature and varies inversely with the drying time. Five empirical mathematical models were used to analyze experimental data of moisture ratio over time. The model of Wang and Singh was the best prediction of drying curves with a correlation coefficient, chi-square, and an average relative error ranging respectively from 0.993 to 0.999, from 0.011 to 0.042 and 2.748 to 16.472 %. The curves obtained for all drying conditions were used for the determination of the drying characteristic curve. This latter has allowed us to empirically determine the equation of bay leaves drying rate which has been interpreted by a three degree polynomial. In addition, the diffusivity of the moisture content of bay leaves was determined from the analytical solution of the Fick's equation. The values range from* 0.9×10^{-9} *to* 6.1×10^{-9} m^2/s *with an activation energy that varies from 47.015 to 64.957 kJ/mole.*

Résumé - *Dans ce travail, nous présentons une étude expérimentale de la cinétique de séchage solaire en couche mince des feuilles de laurier algériennes. Les expériences ont été réalisées dans un séchoir solaire indirect fonctionnant en convection forcée équipé d'un chauffage auxiliaire à condition aérodynamique. Les feuilles de laurier ont été séchées à des intervalles relatifs d'humidité relative de l'air, les températures de l'air et les vitesses d'air allant de 21 à 40%, de 40 à 60 °C et de 0.25 à 0.8 m/s, respectivement. 95 % de la teneur en eau du produit a été réduite pour une température de 60 °C. Les courbes expérimentales obtenues montrent la présence d'une vitesse de séchage décroissante. Ce taux de séchage augmente avec l'augmentation de la température de l'air et varie inversement avec le temps de séchage. Cinq modèles empiriques mathématiques ont été utilisés pour analyser les données expérimentales du taux d'humidité dans le temps. Le modèle de Wang et Singh était la meilleure prédiction des courbes de séchage avec un coefficient de corrélation, le chi carré, et une erreur relative moyenne allant de 0.993 à 0.999, de 0.011 à 0.042 et de 2.748 à 16.472%. Les courbes obtenues pour toutes les conditions de séchage ont été utilisées pour la détermination de la courbe caractéristique de séchage. Cette dernière a permis de déterminer empiriquement l'équation de la vitesse de séchage des feuilles de laurier, qui est réalisée avec un polynôme à trois degrés. De plus, la diffusivité de la teneur en eau des feuilles de laurier a été déterminée à partir de la solution analytique de l'équation de Fick. Les valeurs vont de* 0.9×10^{-9} *à* 6.1×10^{9} m^2/s *avec une énergie d'activation qui varie de 47.015 à 64.957 kJ/mole.*

Keywords: Indirect solar dryer - Mass transfer - Drying kinetics - Modeling - Characteristic curve.

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1. INTRODUCTION

Nowadays, aromatic and medicinal plants are experiencing significant evolution on the international level. The bay leaves are aromatic plants used by the Algerian population as a spicy aroma and flavour in traditional dishes (Dias *et al.*, 2014). They are also used as a cure due to their medicinal properties: anti parasitic, stimulating, anticonvulsant, stomachic, pedicle (Ben Jemaa *et al.*, 2012).

The laurel is a shrub that can exceed 2.15 meters high, its persistent foliage is composed of lanceolate leathery leaves with wavy edges, and they are dark green. This tree belongs to the family of Lauraceae, it hails from the southern Mediterranean region (Sellami *et al.*, 2011) and widely cultivated in Europe and the United States as an ornemental, and in the northwest of African countries (Tunisia, Algeria, Morocco) (Ben Jemaa *et al.*, 2012).

Drying can lighten the products to allow their conservation, facilitate transportation and reduce the risk of post-harvest losses and especially broaden marketing by making them available throughout the year. The traditional drying technology creates various problems, among them the drying time and the exposition of the product to dust, insects and sunlight (Akpinar, 2008).

As a remediation to these drawbacks, solar dryers, an alternative option, have been designed to improve the quality of the finished product (Bekkiou *et al.*, 2009). Algeria has plenty of sun throughout the year, it enjoys an average annual sunshine duration of about 2650 hours per year for coastal regions and can reach 3500 hours per year for Sahara (Bennamoun, 2011) this leads to a daily average solar energy received from 16.2 to 27 MJ/m^2 on the horizontal plane (Bennamoun *et al.*, 2007).

This energy is sufficient enough, especially in summer, to meet any demand for energy in drying agricultural products. Solar energy reduces drying costs and certainly offers environmental friendly option and a viable economic alternative to other energy sources (Akpinar, 2006; Bekkioui *et al.*, 2011). This renewable energy source can be used directly or indirectly in drying applications. Experimental and mathematical studies on thin layer solar drying of products are required in order to understand and evaluate the characteristics of the process, on one hand and to estimate the equilibrium time, to determine optimal conditions of conservation and to generalize the characteristic curves of the products (Boudhrioua *et al.*, 2008), on the other hand.

The drying kinetics of food products depends on the physical properties of air drying used (temperature, relative humidity, flow) and the characteristics of the product to dry (Siles *et al.*, 2015). Given the complexity of mechanisms and product diversity, a single model cannot reflect all situations. For this reason, a number of empirical and semi empirical mathematical models with two or more parameters have been applied in the literature to describe drying curves of thin layer product (Ozbek *et al.*, 2007; Doymaz, 2006). Over the past years, the drying of the various products has been studied by many authors; for instance Coriander (Panwar, 2014); Alfalfa (Siles *et al.*, 2015); Thymus and mint (El-Sebaii *et al.*, 2013); Eucalyptus Globulus (Kouhila *et al.*, 2002). Regarding the study of bay leaves (Gunhan *et al.*, 2005), it was performed in a scale dryer.

In this work, an experimental study of the drying kinetics of bay leaves was conducted using an indirect solar dryer equipped with an electric auxiliary and operating in forced convection. The drying kinetics of bay leaves was carried out for three temperatures and three air velocities. These drying curves were tested by five mathematical models to select a model that best explains the drying mechanism. The overall results led to the presentation of the drying characteristic curve of bay leaves. Furthermore, the effective diffusivity and the activation energy were calculated.

2. MATERIALS AND METHODS

2.1 Experimental setup

To study the drying kinetics of bay leaves, an indirect convection solar dryer was designed in the Renewable Energy Development Centre or "Centre de Développement des Energies Renouvelables, CDER", at Bouzareah, Algiers, Algeria. The experimental setup is shown in Figure 1. A single-glazed solar collector (2.5 m × 1 m) was used to produce thermal energy for drying; it is inclined by 38° relative to the horizontal plane facing south. The cover of the solar collector is made of ordinary glass with a 0.5mm thickness. The absorber of the solar collector is made of galvanized sheet metal with a 0.5 mm thickness and painted in black. The back thermal insulation is provided by polystyrene plates of 6 cm thickness. The device also consists of an auxiliary heating (auxiliary heater), which is used to control the temperature from the drying air and a fan to ensure the circulation of air.

The size of drying cabinet (0.6 × 0.8 × 0.5 m) is composed of three separate shelves; each tray has an inlet and an air outlet. The air flow through each tray is 1/3 of the total input air to the drying cabinet. This one ends with a chimney for discharging moist air from the dried products. The outer faces of the drying cabinet are painted black to absorb the maximum amount of sunlight.

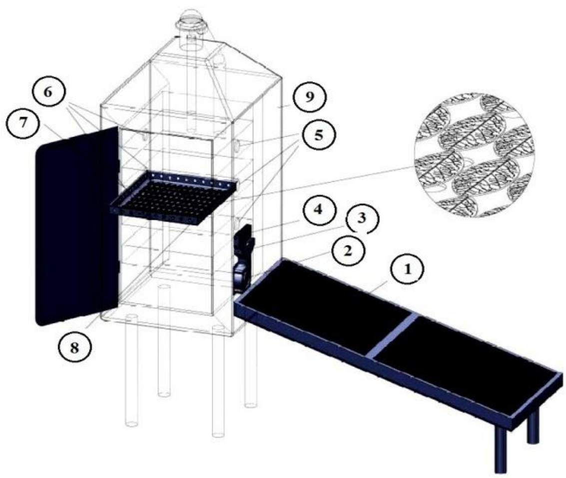

Fig. 1: Schematic representation of the solar dryer

(1) Solar collector; (2) Fan; (3) Air diffuser; (4) Auxiliary heating system; (5) Inlet air; (6) Outlet air; (7) Bay leaves; (8) Tray; (9) Drying cabinet.

2.2 Experimental procedure

Laurel leaves used in drying experiments were harvested from heights of Algiers (Bouzareah), Algeria. The mass of the product used in drying experiments was 60 ± 0.001 g per tray. The temperature measurement was made by thermometers (± 0.5 °C) and relative humidity was measured by thermo hygrometers (± 1%). The loss of product mass during the drying process has been determined using an electronic balance (± 0.001 g). In each experiment, the product weight was measured each 15 minutes for the beginning of the drying and each 60 minutes at the end of drying.

2.3 Determination of moisture ratio and dimensionless drying rate

To describe the drying kinetics into thin layer and determine the drying characteristics curves of bay leaves, the concept Meels Van (1958) (Van Meel, 1958) was applied. The moisture ratio (MR) of bay leaves obtained at any time of solar drying experiment is calculated by equation (1) (Ait Mohamed *et al.*, 2008).

$$MR = \frac{X(t) - X_{eq}}{X_0 - X_{eq}} \tag{1}$$

Where, X_0, is the initial water content (kg water/kg dry basis (db)); X_{eq} is the equilibrium moisture content (kg water/kg (db)); MR is the moisture ratio. The content of the X_{eq} is determined from desorption isotherms for bay leaves (Ouafi *et al.*, 2015). The dimensionless drying rate (f) was determined for each experiment by the relation (2)

$$f = \frac{\left(-\frac{dX}{dt}\right)_t}{\left(\frac{dX}{dt}\right)_0} \tag{2}$$

Where, $\left(\frac{dX}{dt}\right)_0$, the initial drying rate.

The shape of the characteristic curve of drying in a thin layer is given by the relation $f = f\ (MR)$.

2.4 Mathematical modeling of solar drying curves

Semi empirical mathematical equations commonly used in the literature were tested on the experimental results of the moisture content versus time $MR = f(t)$ aiming to select the best model and represent the curve of the drying kinetics of thin layer bay leaves. The five chosen mathematical models are given in **Table 1**.

The method of nonlinear regression Levenberg-Marquardt was used to obtain the various constants of each model using the Curve Expert software. The correlation coefficient (R), the chi-square (x^2) and the average relative error ($P\%$) are necessary to evaluate the quality of the fit. These parameters are determined from the relations (3-5) (Boudhrioua *et al.*, 2008):

$$P = \frac{100}{N} \sum_{j=1}^{N} \frac{MR_{jcal} - MR_{jexp}}{MR_{jexp}} \tag{3}$$

$$x^2 = \frac{\sum_{i=1}^{N} \left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - p} \tag{4}$$

$$r = \sqrt{1 - \frac{\sum_{j=1}^{N} \left(MR_{jcal} - MR_{jexp}\right)^2}{\sum_{j=1}^{N} \left(\overline{MR} - MR_{jexp}\right)^2}} \tag{5}$$

Where, $\overline{MR} = \frac{1}{N} \sum_{j=1}^{N} MR_j$

Where, $MR_{i,cal}$ and $MR_{i,exp}$ are the calculated and experimental values respectively, N the number of data points and p is the number of constants in the regression model.

Table 1: Mathematical models given by various authors for the drying curves

	Model equation	References
Newton	$MR = \exp(-k\,t)$	(Lewis, 1921)
Henderson and Pabis	$MR = a\exp(-k\,t)$	(Henderson and Pabis, 1961)
Logarithmic	$MR = a\exp(-k\,t) + c$	(Akgun and Doymaz, 2005)
Two term	$MR = a\exp(-k_0\,t) + b\exp(-k_1\,t)$	(Noomhom and Verma, 1986)
Wang and Singh	$MR = 1 + a\,t + b\,t^2$	(Wang and Singh, 1878)

Where a, b, k_0, k_1, g, h, b are parameters of the equations, t is time (min), MR is moisture ratio.

3. RESULTS AND DISCUSSION

During drying experiments, the temperature of the drying air, the relative air humidity and the air velocity vary from 40 to 60 °C, 21 to 40% and 0.25 to 0.8 m/s, respectively. The initial moisture content of bay leaves 2.49 kg of water per kg of dry basis was reduced to the final moisture content that varies from 0.22 kg to 0.35 kg water per kg of dry basis (**Table 2**).

Table 2: Drying conditions during experiments in the indirect solar dryer

Test	V (m/s)	T ± 0.5 (°C)	Rh ± 1 (%)	M_0 (kg/kg db)	M_e (kg/kg db)	M_f (kg/kg db)	T (min)
1	0.25	40	38.9	2.4893	0.184	0.2905	1065
2	0.25	50	28.3	2.4904	0.075	0.3473	360
3	0.25	60	22.4	2.4904	0.051	0.3447	270
4	0.5	40	36.8	2.4873	0.187	0.2823	1020
5	0.5	50	27.2	2.4904	0.08	0.3447	330
6	0.5	60	22.8	2.4901	0.052	0.2856	240
7	0.8	40	31.7	2.4883	0.171	0.2216	900
8	0.8	50	25	2.4904	0.071	0.2798	300
9	0.8	60	21	2.4890	0.056	0.2217	150

Figures 2-4 illustrate the variations of the moisture ratio as a function of drying time for three temperatures (40, 50 and 60 °C) and three air velocities (0.25, 0.5 and 0.8 m/s). It is clear from these figures that the moisture content has an exponential decrease; it decreases continuously with the drying time.

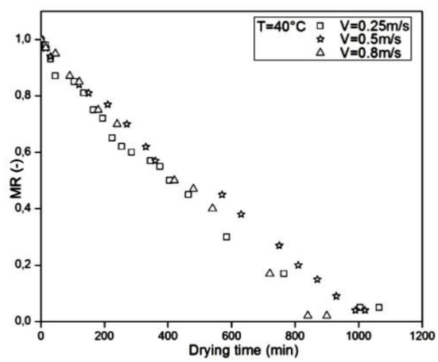

Fig. 2: Thin-layer drying curves of bay leaves at T= 40°C

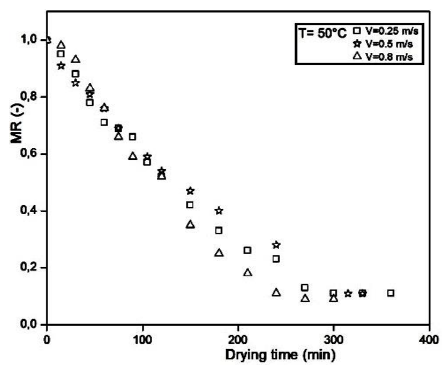

Fig. 3: Thin-layer drying curves of bay leaves at T= 50°C

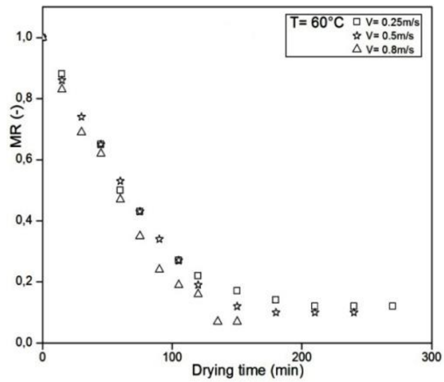

Fig. 4: Thin-layer drying curves of bay leaves at T= 60°C

The drying time in these experiments ranged from 150 to 1065 minutes. This figure also shows that at low temperatures (T= 40 °C), the product takes much more time to reduce the water content of the vegetable material compared to higher temperature (T= 60 °C). This can be explained by the small amount of heat given by the lower temperatures which is insufficient to accelerate the diffusion of water from the inside of the product to its surface.

The curves of drying rates, depicted in figures 5-8, were determined from the curves of the moisture content. These figures show the experimental curves of drying rate as function of the moisture ratio and drying time, respectively.

These curves have a decreasing shape; the drying rate decreases continuously with the moisture content as well as with the drying time. We note an absence of the heat-up (phase 0) which corresponds to the period of increasing the rate of drying, where the product temperature is increased without significant loss of water, even for phase at a constant drying rate (phase 1). These curves are characterized by the presence of only the falling drying rate period (phase 2).

Bimbenet *et al.*, (1984) reported that phase 0 disappears in practical when the product to be dried takes the form of particles or leaves and the constant rate period is not observed in the case of vegetable products. Diamond *et al.*, (1993) pointed out that during the phase 2, the product surface is no longer saturated with water, which means that diffusion is the dominant physical mechanism governing the movement of moisture from the interior of product on its surface.

This result is similar with those obtained in several studies such as *Chenopodium ambrosioides* (Ethmane Kane *et al.*, 2008), *Eucalyptus Globulus* (Kouhila *et al.*, 2002), *Citrus aurantium* (Ait Mohamed *et al.*, 2005), Verbena (Belghit *et al.*, 2000).

The curves show, also, the influence of temperature and air flow on drying. For a constant air velocity (V=0.8 m/s) (figure 5), the drying rate decreases with the decrease of moisture content and increases with increasing temperature. Higher temperature of the drying air produces a higher rate and hence a faster movement of water molecules which are inside the product (Lahsasni *et al.*, 2004).

Moreover, the temperature of the drying air has a significant effect on the drying time (figure 7). From the experiments, there is a drying time reduction of more than 70% between 40 and 60 °C. Arslan *et al.*; (2010) noted that, when the drying temperature is high, the vapor pressure of water within the leaves increases, it creates a pressure gradient between the surface and interior of the sample that will generate the rise of the drying rate and the diffusion of water outwards. According to figures 6 and 8, the air velocity does not have much effect on the drying kinetics and does not affect the development of the moisture content in the process.

Madamba *et al.*, (1996) explained this fact by the negligence of the resistance of the moisture on the surface of the product compared to the internal resistance. This indicates that the drying limiting factor is the transfer of water to the interior of the product (Ben Haj Said *et al.*, 2014). Similar results have been reported by many authors, for instance: parsley leaves (Doymaz *et al.*, 2006), *Eucalyptus* Globulus (Kouhila *et al.*, 2002), bay leaves (Gunhan *et al.*, 2005).

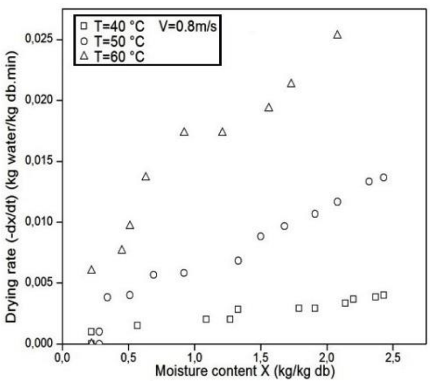

Fig. 5: Variation of drying rate versus moisture content at different temperature and fixed air velocity of 0.8 m/s

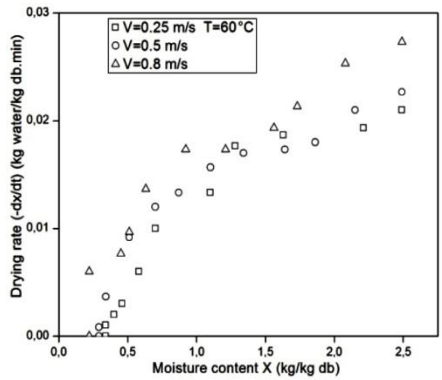

Fig. 6: Variation of drying rate versus moisture content at different air velocity and T= 60°C

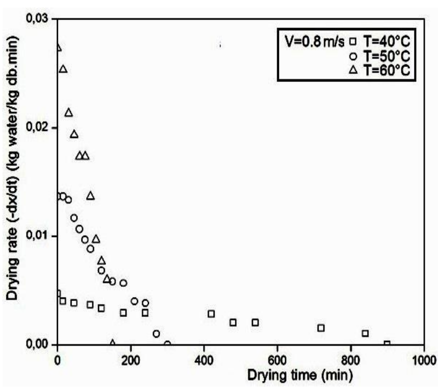

Fig. 7: Variation of drying rate versus drying time at different temperature and air velocity 0.8m/s

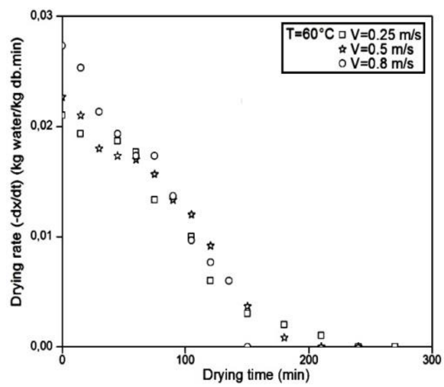

Fig. 8: Variation of drying rate versus drying time at different air velocity and T=60°C

3.1 Modeling of the kinetics of drying

To standardize the drying curves, data concerning the content of moisture have been converted into a dimensionless parameter called moisture ratio (MR). The experimental data of the moisture content as a function of time were fitted with five mathematical models to determine the equation of the suitable drying curve. The coefficients of each model were evaluated by nonlinear regression analysis (method of Marquart) that allows proper adjustment for any proposed model. The best model is characterized by the highest value of the correlation coefficient (r) and by the lowest value of chi-square (x^2) and average relative error (P%).

The determined coefficient values of each model along with the corresponding values of correlation coefficients (r), chi-square (x^2) and average relative error (P%) are listed in **Tables 3**.

These results show that the model of Wang and Singh was found to be the appropriate equation to describe the thin layer drying curves of bay leaves, in all solar drying conditions investigated. This model has the highest r value, and the lowest value of x^2 .

The values of correlation coefficients (r) and chi-square (x^2), the average relative error (P%) vary from 0.993 to 0.999, from 0.011 to 0.042 and from 2.748 - 16.472 %, respectively. The experimental results and those predicted by the selected best model (Wang and Singh) is shown in figure 9.

Table 3: Statistical analyses on the modeling of moisture contents and drying time

Model	V(m/s)	T(°C)	Parameters								
			a	b	c	d	e	f	r	x^2	P
Newton	0.25	40	0.117	-	-	-	-	-	0.988	0.047	25.634
		50	0.354	-	-	-	-	-	0.992	0.039	12.464
		60	0.665	-	-	-	-	-	0.993	0.037	14.109
	0.5	40	0.107	-	-	-	-	-	0.980	0.059	38.337
		50	0.323	-	-	-	-	-	0.994	0.031	11.347
		60	0.698	-	-	-	-	-	0.993	0.036	14.442
	0.8	40	0.116	-	-	-	-	-	0.971	0.079	96.693
		50	0.396	-	-	-	-	-	0.978	0.072	25.809
		60	0.855	-	-	-	-	-	0.988	0.049	23.483
Henderson and Pabis	0.25	40	1.026	0.122	-	-	-	-	0.989	0.046	23.898
		50	1.049	0.377	-	-	-	-	0.994	0.034	9.512
		60	1.025	0.686	-	-	-	-	0.993	0.037	14.473
	0.5	40	1.040	0.113	-	-	-	-	0.983	0.057	35.709
		50	1.023	0.334	-	-	-	-	0.994	0.030	10.694
		60	1.034	0.726	-	-	-	-	0.994	0.035	13.793
	0.8	40	1.052	0.124	-	-	-	-	0.974	0.076	90.345
		50	1.106	0.449	-	-	-	-	0.988	0.056	18.293
		60	1.044	0.894	-	-	-	-	0.989	0.048	20.952
Logarithmic	0.25	40	1.413	0.0645	-0.429	-	-	-	0.997	0.022	6.343
		50	1.162	0.291	-0.138	-	-	-	0.996	0.027	8.787
		60	0.985	0.800	0.060	-	-	-	0.995	0.032	8.606
	0.5	40	2.386	0.031	-1.405	-	-	-	0.998	0.016	6.889
		50	1.316	0.198	-0.331	-	-	-	0.998	0.016	4.448
		60	1.039	0.714	-0.008	-	-	-	0.994	0.036	14.067
	0.8	40	4.783	0.015	-3.793	-	-	-	0.998	0.023	18.350
		50	1.377	0.276	-0.313	-	-	-	0.994	0.039	11.976
		60	1.286	0.555	-0.279	-	-	-	0.996	0.028	10.961
Two term	0.25	40	0.513	0.122	0.513	0.121	-	-	0.989	0.048	23.897
		50	0.524	0.376	0.525	0.377	-	-	0.994	0.036	9.511
		60	0.0007	-1.040	1.039	0.724	-	-	0.996	0.027	5.518
	0.5	40	0.520	0.113	0.520	0.112	-	-	0.982	0.059	35.709
		50	0.511	0.333	0.512	0.334	-	-	0.995	0.033	10.693
		60	0.517	0.726	0.517	0.726	-	-	0.994	0.038	13.793
	0.8	40	0.526	0.124	0.526	0.124	-	-	0.974	0.081	90.362
		50	0.553	0.449	0.553	0.449	-	-	0.988	0.061	18.289
		60	0.522	0.895	0.522	0.893	-	-	0.989	0.054	20.959
Wang and Singh	0.25	40	-0.090	0.002	-	-	-	-	**0.997**	**0.021**	**5.410**
		50	-0.288	0.023	-	-	-	-	**0.998**	**0.020**	**6.005**
		60	-0.539	0.079	-	-	-	-	**0.996**	**0.030**	**5.179**
	0.5	40	-0.077	0.001	-	-	-	-	**0.998**	**0.017**	**6.779**
		50	-0.258	0.018	-	-	-	-	**0.999**	**0.011**	**2.748**
		60	-0.564	0.086	-	-	-	-	**0.998**	**0.015**	**6.818**
	0.8	40	-0.074	0.0005	-	-	-	-	**0.998**	**0.023**	**16.472**
		50	-0.303	0.022	-	-	-	-	**0.993**	**0.042**	**11.808**
		60	-0.649	0.109	-	-	-	-	**0.998**	**0.023**	**8.505**

P is average relative error; x^2 chi-square; *r* is correlation coefficient; a, b, c, d, e, f are parameters of the equations.

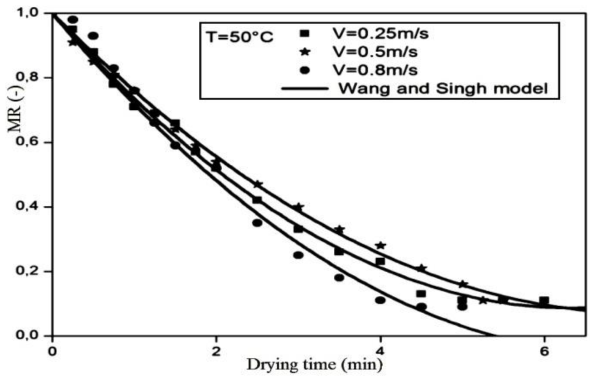

Fig. 9: Experimental and predicted (Wang and Singh model)
moisture ratio versus drying time of Algerian bay leaves

3.2 Drying characteristic curve (CDC)

Figure 10 illustrates the variation of the dimensionless drying rate as function of the moisture ratio which fall into a tight band indicating that the effect of air temperature on these curves could be described by a single equation in the examined solar drying conditions.

A smoothing of the CCD allowed identifying a model that best fits the experimental data of bay leaves. This is a third order polynomial model whose coefficients are given by {Eq (7)}:

$$f = -0.0658 + 2.3536\,MR - 2.8667\,MR^2 + 1.5261\,MR^3 \qquad (7)$$

The criteria used to assess the validity of adjustment was the standard error (S = 0.09) and the correlation coefficient (r = 0.93).

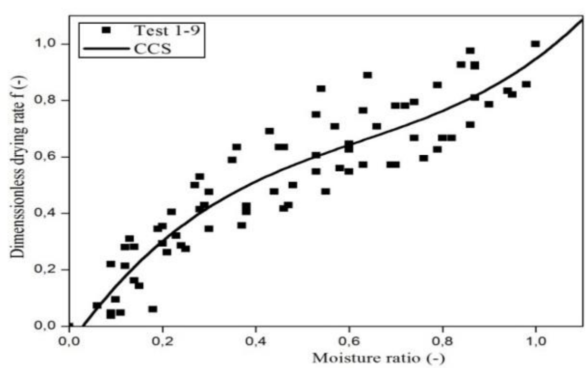

Fig. 10: Dimensionless drying rate
versus moisture ratio of bay leaves *(Laurus nobilis)*

3.3 Determining the effective diffusion coefficient and the activation energy

The result obtained in this work shows that the drying of the bay leaves occurs only in the period of falling drying rate which means that the diffusion of water in the solid is the mechanism that controls the process (Kane *et al.*, 2008). Fick's second law can be used to interpret experimental results of the drying process. The analytical solution of the second Fick law developed by Crank (1979) {Eq (8)} into an infinite plate geometry was used to estimate the diffusivity of moisture of bay leaves from the drying kinetics. (Boudhrioua *et al.*, 2008).

$$\mathrm{Ln}(\mathrm{MR}) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}\, t}{(e/2)^2}\right) \quad (8)$$

Where: MR, is the moisture ratio, D_{eff} is the effective diffusion coefficient (m^2/s), t is the drying time (s) and e is the thickness of the bay leaves (m).

This equation was applied, assuming that the movement of moisture is one-dimensional, without volume change; a constant diffusivity, a uniform distribution of moisture and an outer negligible resistance (Boudhrioua *et al.*, 2003).

The effective diffusion coefficient was calculated by plotting $\mathrm{Ln}(\mathrm{MR})$ as a function of time as shown in {Eq (8)} The plot of $\mathrm{Ln}(\mathrm{MR})$ as a function of time (t) gives a straight line with a slope given by {Eq (9)} (Ait Mohamed *et al.*, 2008).

$$\mathrm{Slope} = \frac{\pi^2 D_{eff}}{(e/2)^2} \quad (9)$$

The variation of the effective diffusion coefficient D_{eff} for each air temperature and drying air velocity is shown in **Table 4**.

Table 4: Values of the D_{eff} of *Laurus nobilis* leaves

Test	V(m/s)	T(°C)	D_{eff} (m^2/s)
1	0.25	40	0.9939×10^{-09}
2	0.25	50	2.2065×10^{-09}
3	0.25	60	2.8824×10^{-09}
4	0.5	40	0.9940×10^{-09}
5	0.5	50	2.3059×10^{-09}
6	0.5	60	3.7174×10^{-09}
7	0.8	40	1.3915×10^{-09}
8	0.8	50	3.0216×10^{-09}
9	0.8	60	6.1426×10^{-09}

The effective diffusivities of the product dried at 40-60 °C vary in the range of 0.9×10^{-9} to 6.1×10^{-9} m^2/s. The temperature effect on the diffusivity of moisture is considerable. Indeed, D_{eff} of values increase with increasing temperature. Similarly, for a given temperature, D_{eff} increases with increasing the air velocity. Several authors have also reported the influence of temperature on the diffusivity of moisture (Boudhrioua *et al.*, 2008; Ruiz Celma *et al.*, 2008, Akgun *et al.*, 2005).

The Arrhenius equation is generally used to model the effect of temperature on the effective diffusivity as follows:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{R\, T_k}\right) \quad (10)$$

Where: D_0 is the Arrhenius factor (m^2/s), E_a is activation energy (kJ/mol), T is the absolute temperature of the air (K), and R is the universal gas constant (8.314J / mol K). Equation (10) can be rearranged in the form of:

$$\mathrm{Ln}\left(D_{eff}\right) = \mathrm{Ln}\left(D_0\right) - \frac{E_a}{R\,T_k} \tag{11}$$

The activation energy E_a was determined from the slope of $\mathrm{Ln}\left(D_{eff}\right)$ as function of (1/T), while the ordinate at the origin represents $\mathrm{Ln}\left(D_0\right)$ (figure 11). The values of the activation energy of bay leaves for air velocities 0.25, 0.5 and 0.8 m/s are respectively 47.015, 57.873 and 64.957 kJ/mol.

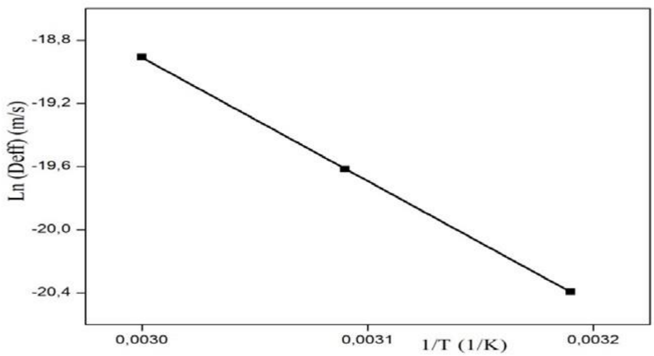

Fig. 11: Arrhenius-type relationship between effective diffusivity and temperature at V=0.8 m/s

4. CONCLUSION

The thin layer drying kinetics of bay leaves has been established experimentally in an indirect convection solar dryer for different climatic conditions. The drying rates are characterized by the absence of the period (0) and (1) which corresponds to the period of drying at increasing rate and at a constant rate respectively and the presence of the single period of the decreasing rate.

During drying of the bay leaves, 80 to 95 % of the water content has been reduced. Diffusion is the mechanism involved in the drying process of the product. The air velocity has a negligible effect on the drying process and the main influencing factor is the drying air temperature. In order to explain the behavior of drying of bay leaves, five different thin layer drying models were compared according to their coefficients of correlation (R), chi-square (x^2) and average relative error ($P\%$).

The model of Wang and Singh best describes the thin layer drying curves of bay leaves with a correlation coefficient ranging from 0.993 to 0.999 and a chi-square (x^2) ranging from 0.011 to 0.042 and average relative error ($P\%$) ranging from 2.748 - 16.472 %.The drying curve was interpreted by a polynomial 3rd order that allowed generalizing the data of drying kinetics of bay leaves.

Moisture diffusivity values were calculated using the analytical solution of Fick's equation. They vary from 0.9×10^{-9} to $6.1 \times 10^{-9} m^2/s$. In addition, the temperature dependence on the coefficients of diffusivity has been described by the Arrhenius relationship. Finally, we note that the activation energy varies from 47.015 to 64.957 kJ/mole.

Acknowledgement: Authors would like to thank Dr. Ramdane Younsi from Polytechnic Montreal for his support and contributions.

NOMENCLATURE

CDC	characteristic drying curve
f	dimensionless drying rate at any time of drying
MR	moisture ratio
X_{eq}	equilibrium moisture content [kg water / (kg db)]
X_0	initial water content [kg water / (kg dry basis (db)]
r	correlation coefficient
x^2	chi-square
P	average relative error
N	number of data points
$MR_{j,cal}$	calculated values of moisture ratio
$MR_{j,exp}$	experimental value of moisture ratio
p	number of constants
V	air velocity [m/s]
T	temperature [°C]
D_{eff}	effective diffusion coefficient [m^2/s]
t	time [s]
e	thickness [m]
E_a	activation energy [kJ/mol]
D_0	Arrhenius factor [m^2/s]
T_k	temperature [K]
R	universal gas constant [8.314 Jmol^{-1} K^{-1}]
$(-\frac{dMR}{dt})$	Drying rate at any time of drying [kg water / (kg dry basis (db).min]
$\left(-\frac{dMR}{dt}\right)_0$	initial drying rate

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