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Numerical simulation of drying under variable external conditions: Application to solar drying of seedless grapes

Lyes Bennamoun [a,*], Azeddine Belhamri [b]

[a] *Département de Physique, Institut des Sciences exactes, Centre Universitaire Larbi Ben M'hidi, Oum El Bouaghi 04000, Algeria*
[b] *Département de Génie Climatique, Faculté des Sciences de l'Ingénieur, Université Mentouri, Constantine 25000, Algeria*

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Abstract

The aim of this work is to study the drying kinetic behavior with respect to the variation of the external conditions. Diffusion model based on Fick's law is used. The heated air thermo-physical properties variation and shrinking effect are taken into consideration. The coefficient of diffusion is calculated based on experimental data and presented as a function of temperature and velocity. The numerical resolution of the mass transfer equation allows the calculation of the distribution of moisture inside the product, at any time. Sudden and progressive augmentation of temperature and velocity are simulated; the drying kinetic answers by changing its behavior with a non-instant response. Solar drying was investigated through the study of a flat air collector. The ambient air velocity considerably influenced the outlet temperature of the collector air which reverberates on the drying kinetic.

Keywords: Diffusion; Shrinking effect; Sudden augmentation; Progressive augmentation; Inertia; Air collector

1. Introduction

Sun natural drying is one of the most common traditional preservation methods used, in particular in non industrialized countries. Grapes, figs and olives as an example are commonly placed on the ground in order to be exposed to sun light and wind for drying purpose. Besides being a slow process, this method is subject to the deterioration of a part of the exposed harvest, caused by microbial attacks with change to its organoleptic characteristics. To limit this, many studies of solar dryers have been developed. Gallali, Abujnah, and Bannani (2000) presented a detailed experimental work, dealing with chemical analysis and sensory evaluation during natural and solar drying of some fruits and vegetables. It was found that the quality of the products solar dried was superior to ones naturally dried. Tiris, Tiris, and Dincer (1996) showed the importance of solar drying compared to the natural one. The products were dried in a small scale dryer doted with an electrical and a solar air heater. An improvement in the quality of the dried products and reduction in the drying time were observed during solar drying. An important review regarding various details such as design, construction and operational principles of practical solar dryers is reported by Ekechukwu and Norton (1999). Bennamoun and Belhamri (2002a, 2002b) presented a design and a study, based on heat and mass transfer applied to the collector air and drying chamber, of a solar dryer for agriculture products. The drying chamber was composed of ten trays. The collector was used to heat ambient air using free solar energy. A heater was added for the unfavorable climatic conditions. In a different way, Ratti and Mujumdar (1997) developed a model and simulation code of a solar dryer, using heat and mass balances, applied to solid and gas phases with time

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[*] Corresponding author. Tel./fax: +213 31 81 90 12.
E-mail addresses: lyes_bennamoun@yahoo.ca (L. Bennamoun), belhamri@altern.org (A. Belhamri).

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Nomenclature

a_w	water activity
C_p	specific heat (J/kg °C)
D	coefficient of diffusion (m^2/s)
D_V	diffusion of vapor in the air (m^2/s)
h	coefficient of heat transfer by convection (W/m^2 °C)
h_m	mass transfer coefficient (m/s)
h_r	adapted radiative exchange coefficient (W/m^2 °C)
k	adapted conductive exchange coefficient (W/m^2 °C)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
r	Product radius (m)
r^*	dimensionless radius ($r^* = \frac{r}{R}$)
R	overall product radius (m)
surf	surface (m^2)
T	temperature (°C)
t	time (s)
V	air velocity (m/s)
X	moisture content (kg/kg)
X^*	dimensionless moisture content ($X^* = \frac{X - X_{eq}}{X_0 - X_{eq}}$)

Greek symbols

μ	viscosity (kg/m s)
ϕ	relative humidity
ρ	density (kg/m^3)

Dimensionless numbers

Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number

Subscripts

A	absorber
ach	heated air
ah	wet air
am	ambient air
as	dry air
c	skier vault
dry	dry matter
e	external
eq	equilibrium value
f	product
fld	fluid
I	insulator
i	internal
moy	mean value
p	polystyrene
s or sol	ground
v	glass
vap	vapor
vsat	saturated vapor
0	initial value

varying air conditions. The results compared well with experimental ones. The effect of several parameters and shrinking were presented. Pangavhane and Sawhney (2002) have given technical and economical results on the use of solar drying for grapes. It was found that the use of a solar dryer is feasible. However, its acceptance by the farmers was limited due to its small capacity and too long a pay back period.

Generally, the diffusion model based on Fick's law describes well the variation of the moisture during drying of foodstuffs. This is confirmed by the studies done by Chirife (1983), Bruin and Luyben (1980), where the coefficient of diffusion is considered as a function of temperature. Di Matteo, Cinquanta, Galiero, and Crescitelli (2000, 2003, 2002); Cinquanta, Di Matteo, and Esti (2002) studied drying of seedless grapes and plums and the coefficient of diffusion was considered constant. While, Azzouz, Guizani, Jomaa, and Belghith (2002) studied drying of grapes and the coefficient of diffusion was proposed to be a function of air temperature and product moisture. Toğrul and Pehlivan (2003) showed that there was variation in this coefficient with air velocity and air temperature during apricot drying.

Also, shrinking is an important aspect to be taken into consideration when developing a model describing the drying of foodstuffs. Youcef-Ali, Messaoudi, Desmons, Abene, and Leray (2001), Bennamoun and Belhamri (2003), Ratti and Mujumdar (1997) and Ratti and Crapiste (1992) introduced the shrinking phenomenon by letting the physical characteristics of the product vary with its moisture content.

In some non-developed countries, even though grapes are widely cultivated, there is no strategy for producing dried ones for internal consumption and thus avoiding costly importation. The objective of this paper is to study, by simulation, the behavior of seedless grapes during solar drying using a diffusion model with the introduction of shrinking and the determination of the most influential parameters in order to optimise the process.

2. The mathematical model

In this respect, the product is simulated as a spherical shape; the equation of the mass transfer, based on Fick's law, is written in spherical coordinates. The diffusion is considered as radial and the coefficient of diffusion as invariable with time and position

$$\frac{\partial X(r,t)}{\partial t} = \frac{D}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial X(r,t)}{\partial r}\right) \tag{1}$$

The model is treated with the following initial and boundary conditions:

$$\text{At } t = 0 : X = X_0 \tag{2}$$

$$\text{At the kernel; } r = 0 : \frac{\partial X}{\partial r} = 0 \tag{3}$$

At the surface, convective drying is affected by external conditions; the following condition is used:

$$r = R : -D\frac{\partial X}{\partial r} = h_{\mathrm{m}}(X - X_{\mathrm{eq}}) \tag{4}$$

Practically, the dimensionless form is used. Thus Eq. (1) is written

$$\frac{\partial X^*}{\partial t} = D\left(\frac{\partial^2 X^*}{(R\partial r^* + r^*\partial R)^2} + \frac{2}{r^* R}\frac{\partial X^*}{R\partial r^* + r^*\partial R}\right) \tag{5}$$

The initial and boundary conditions become

$$t = 0 : X^* = 1 \tag{6}$$

$$r^* = 0 : \frac{\partial X^*}{R\partial r^* + r^*\partial R} = 0 \tag{7}$$

$$r^* = 1 : -\frac{\partial X^*}{R\partial r^* + r^*\partial R} = \frac{Sh}{2R}X^* \tag{8}$$

(Sh) is determined from the equations (Daguenet, 1985)

$$Re < 350 : Sh = 1.82Re^{0.49}Sc^{0.33} \tag{9}$$

$$Re > 350 : Sh = 0.99Re^{0.59}Sc^{0.33} \tag{10}$$

The Sherwood number (Sh) depends on the wet air characteristics which are presented in the appendix.

2.1. Determination of the coefficient of diffusion

Commonly, the coefficient of diffusion is calculated by comparing experimental results and theoretical ones, such as analytical solutions given by Crank (1975).

The coefficient of diffusion of seedless grapes is determined from the experimental results presented by Berna, Rosselo, Cañellas, and Mulet (1991). In their paper, a presentation of the drying system is described. Then, two series of experiments were carried out to study the influence of air velocities and moderate temperatures (for application to solar drying) on the moisture content. The coefficient of diffusion is deduced from comparison of the moisture content experimental results and those given by Fick's law using variable separation.

The coefficient of diffusion is strongly affected by the air temperature. It increases with the dry bulb temperature increase. The following equation can represent the coefficient:

$$D = \left(-0.00067T_{\mathrm{ach}}^2 + 0.29300T_{\mathrm{ach}} - 7.30833\right)10^{-10}\ (\mathrm{m}^2/\mathrm{s}) \tag{11}$$

In the same way, it is found that increasing the air velocity increases the coefficient of diffusion. However, it is observed that at high velocities (provides a mean for 3 m/s) the influence is less important. The coefficient of diffusion can be given by the equation

$$D = (-0.04304V_{\mathrm{ach}}^2 + 0.39068V_{\mathrm{ach}} + 5.90529)10^{-10}\ (\mathrm{m}^2/\mathrm{s}) \tag{12}$$

The two last Eqs. (11) and (12) present a correlation coefficient equal to the unity.

The temperature T_{ach} is presented in (°C) and the velocity V_{ach} in (m/s).

2.2. Modeling solar drying

Solar drying was performed using an air flat collector. In this way, it is necessary to present the equations governing its behavior, based on heat transfer.

The collector is composed (from the exterior to the interior) of a plate Pyrex glass used as a cover, an aluminum paper painted black as the absorber and polystyrene as an insulator. The air flows between the absorber and the polystyrene. The equations, governing the behavior of the air flat collector, are:

Exchange external glass surface—ambient medium

$$\frac{m_{\mathrm{v}} \cdot C_{\mathrm{p_v}}}{\mathrm{surf}}\left(\frac{\mathrm{d}T_{\mathrm{ve}}}{\mathrm{d}t}\right) = P_{\mathrm{v}} + h_{\mathrm{r_{v,c}}} \cdot (T_{\mathrm{c}} - T_{\mathrm{ve}}) + h_{\mathrm{v,am}} \cdot (T_{\mathrm{am}} - T_{\mathrm{ve}}) + k_{\mathrm{v}} \cdot (T_{\mathrm{vi}} - T_{\mathrm{ve}}) \tag{13}$$

In the glass

$$\frac{m_{\mathrm{v}} \cdot C_{\mathrm{p_v}}}{\mathrm{surf}}\left(\frac{\mathrm{d}T_{\mathrm{vi}}}{\mathrm{d}t}\right) = h_{\mathrm{r_{v,A}}} \cdot (T_{\mathrm{A}} - T_{\mathrm{vi}}) + h_{\mathrm{v,A}} \cdot (T_{\mathrm{A}} - T_{\mathrm{vi}}) + k_{\mathrm{v}} \cdot (T_{\mathrm{ve}} - T_{\mathrm{vi}}) \tag{14}$$

Exchange absorber—internal glass surface—internal insulator surface

$$\frac{m_{\mathrm{A}} \cdot C_{\mathrm{p_A}}}{\mathrm{surf}}\left(\frac{\mathrm{d}T_{\mathrm{A}}}{\mathrm{d}t}\right) = h_{\mathrm{v,A}} \cdot (T_{\mathrm{vi}} - T_{\mathrm{A}}) + P_{\mathrm{A}} + h_{\mathrm{r_{v,A}}} \cdot (T_{\mathrm{vi}} - T_{\mathrm{A}}) + h_{\mathrm{r_{A,I}}}.(T_{\mathrm{I,i}} - T_{\mathrm{A}}) + h_{\mathrm{fld,A}} \cdot (T^*_{\mathrm{ach}} - T_{\mathrm{A}}) \tag{15}$$

In the insulator

$$\frac{m_{\mathrm{I}} \cdot C_{\mathrm{p_I}}}{\mathrm{surf}}\left(\frac{\mathrm{d}T_{\mathrm{Ii}}}{\mathrm{d}t}\right) = h_{\mathrm{r_{A,I}}} \cdot (T_{\mathrm{A}} - T_{\mathrm{Ii}}) + k_{\mathrm{I}} \cdot (T_{\mathrm{Ie}} - T_{\mathrm{Ii}}) + h_{\mathrm{fld,Ii}} \cdot (T^*_{\mathrm{ach}} - T_{\mathrm{Ii}}) \tag{16}$$

Exchange external insulator surface—ground

$$\frac{m_{\mathrm{I}}\cdot C_{p_{\mathrm{I}}}}{\mathrm{surf}}\left(\frac{\mathrm{d}T_{\mathrm{Ie}}}{\mathrm{d}t}\right) = k_{\mathrm{I}}\cdot(T_{\mathrm{Ii}}-T_{\mathrm{Ie}}) + h_{r_{\mathrm{s,I}}}\cdot(T_{\mathrm{sol}}-T_{\mathrm{Ie}}) + h_{\mathrm{v,am}}\cdot(T_{\mathrm{am}}-T_{\mathrm{Ie}}) \qquad (17)$$

In the heat carrier

$$\dot{m}_{\mathrm{am}}\cdot C_{p_{\mathrm{air}}}\cdot(T_{\mathrm{ach}}-T^{*}_{\mathrm{ach}}) = \mathrm{surf}\cdot h_{\mathrm{fld,A}}(T_{\mathrm{A}}-T^{*}_{\mathrm{ach}}) + \mathrm{surf}\cdot h_{\mathrm{fld,Ii}}(T_{\mathrm{Ii}}-T^{*}_{\mathrm{ach}}) \qquad (18)$$

P_{v} is the absorbed energy flux by the glass.

P_{A} is the absorbed energy flux by the absorber.

*: represents the precedent step.

P_{v} and P_{A} change with time and position of the collector emplacement. Also, they are functions of glass and absorber properties (Bennamoun & Belhamri (2003) and Daguenet (1985)).

Heat transfer coefficients are calculated with classical formulas (Daguenet (1985)).

2.3. Characteristics of the dried product

As the physical and biological characteristics of the product change during overall drying process; it is important to know and study these characteristics. The initial ones are shown in Table 1.

The specific heat is expressed (Singh, 1996)

$$C_{p_{\mathrm{f}}} = 1.424m_2 + 1.549m_4 + 1.675m_3 + 0.837m_5 + 4.187m_1 \qquad (19)$$

Also, the density of the product is expressed as a function of the product components as follow (May & Perré, 2002):

$$\rho_{\mathrm{f}} = \frac{\sum_{i=1}^{5} X_{\mathrm{i}}}{\sum_{i=1}^{5} \frac{X_{\mathrm{i}}}{\rho_{\mathrm{i}}}} \qquad (20)$$

X_{i} is the constituent proportion relative to the dry mass of the product.

The mass of the product is equal to

$$m_{\mathrm{f}} = (X_1 + 1)m_{\mathrm{dry}} \qquad (21)$$

Table 1
Composition of the grapes components of 1 cup (92 g) (Source: USDA Nutrient Database for standard reference, release 12 March 1998) and their density (Source: May and Perré, 2002)

i	Components	Percentage (%)	Density (kg/m^3)
1	Water	81.3000	1000
2	Carbohydrate	17.1500	1500
3	Fat	00.3500	930
4	Protein	00.6304	1400
5	Ash	00.5696	1850

The dry mass of the product can be deduced from its initial composition and using Eq. (21).

Thus the radius can be calculated and presented as a function of the product moisture content. It is equal

$$R(X_1) = \left(\frac{3}{4\pi}\frac{m_{\mathrm{f}}(X_1)}{\rho_{\mathrm{f}}(X_1)}\right)^{\frac{1}{3}} \qquad (22)$$

This allows the shrinking effect to be taken into account.

Azzouz et al. (2002) have given the equilibrium moisture content of grapes which is presented as a function of water activity (function of the temperature) written in the form

$$1 - a_{\mathrm{w}} = \exp(-B(X_{\mathrm{eq}})^{c}) \qquad (23)$$

B and C are coefficients which vary with temperature.

Fig. 1 shows variation of the density and radius of the dried product. It shows a contraction of the dimension of the product as being around 50%. However, an increasing of the density was observed as a result of the water evaporation which makes the product more concentrated.

A comparison between two calculus operations has been performed; one with introducing shrinkage and the second without, as illustrated in Fig. 2. The importance of introducing shrinkage is clear and neglecting it brings about erroneous results.

2.4. Resolution method

Eq. (5) is a parabolic partial-differential equation. Its discretization, using finite difference method, converts it into a system of equations. This is rewritten into a matrix in the form

$$[a][X] = [b] \qquad (24)$$

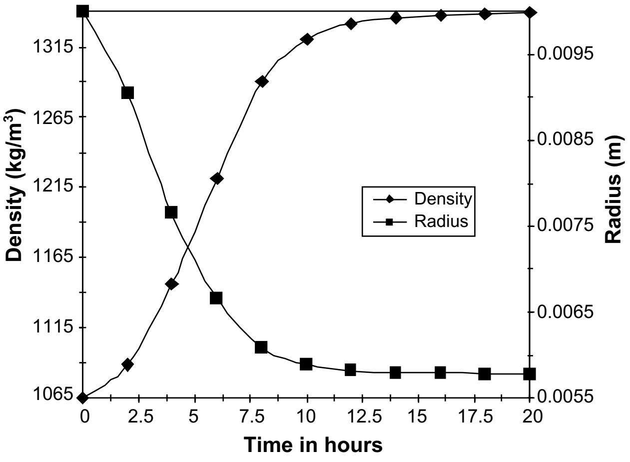

Fig. 1. Effect of the shrinkage on the density and the radius of the dried product ($T_{\mathrm{ach}} = 55$ °C; $V_{\mathrm{ach}} = 4.75$ m/s; $\Phi = 10\%$).

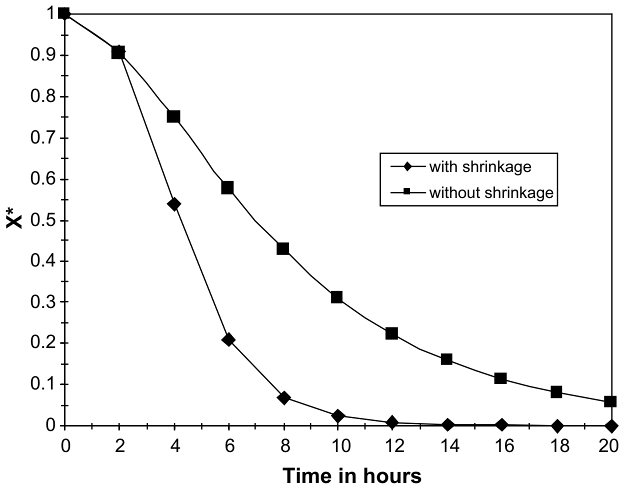

Fig. 2. Shrinkage effect on the calculus of the kernel product moisture ($T_{ach} = 55$ °C; $V_{ach} = 4.75$ m/s; $\Phi = 10\%$).

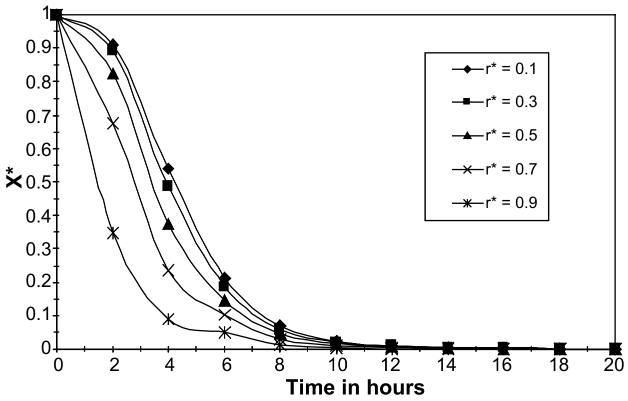

Fig. 3. Distribution of the moisture content inside the dried product ($T_{ach} = 50$ °C; $V_{ach} = 4.75$ m/s; $\Phi = 10\%$).

As [*a*] contains many sparse coefficients (equal to zero), an iterative method may be more rapid and more economical in memory requirement of a computer, also a self correcting is an advantage (Gerold & Wheatly, 1989). The Gauss–Seidel iterative method was adopted.

A sufficient condition, to converge to the solution, is the diagonal dominance. This is insured by the existence of the source represented by the matrix [*b*] which contains non-zero coefficients. A simulation code was developed. To introduce the shrinkage effect in the calculation, the characteristics of the product (included in the coefficients of the matrices [*a*] and [*b*]) were recalculated for each time step and for each space step. The presented results were calculated with a relative error less or equal to 10^{-3}%.

A second calculation code is used to study the behavior of a flat air collector, in order to simulate solar drying. A second system is obtained and the same method is used.

3. Results and discussion

The considered product is simulated as a sphere, with an initial radius 0.01 m. The simulation displays that relative humidity has a less effect than the other external conditions. This was similar to the remarks presented in the experimental work of Kiranoudis, Maroulis, and Marinos-Kouris (1992) dealing with drying of foodstuffs. In this context, the relative humidity is considered as constant and equal to 10%. Thus, the study of the external conditions is limited to the effect of air temperature and air velocity.

Drying is translated by the decreasing of the moisture content of the product, which is the look of all the curves of Fig. 3. The model shows the absence of a constant drying period, as the experimental works done by Ratti and Crapiste (1992), Lahsasni, Kouhila, Mahrouz, and Jaouhari (2004). As a result of water evaporation taking place at the surface of the product; drying of the kernel of the product takes more time than its surface (Fig. 3). It can be deduced that increasing the characteristic dimension of the dried product leads to an increase in the drying time, as found by Kiranoudis et al. (1992), Bennamoun and Belhamri (2003), Ratti and Mujumdar (1997), Ahmet Tütüncü and Labuza (1996). Nevertheless, a time of 20 h is still sufficient to dry all parts of the product as confirmed by Berna et al. (1991). Azzouz et al. (2002) has found the same drying time for other varieties of seedless grapes.

3.1. Influence of the air temperature

Fig. 4 shows that the air temperature is an influential parameter, as was the case in works presented by Azzouz et al. (2002), Laguerre, Lebert, Trystram, and Bimbenet (1991). Increasing the air temperature gives the air

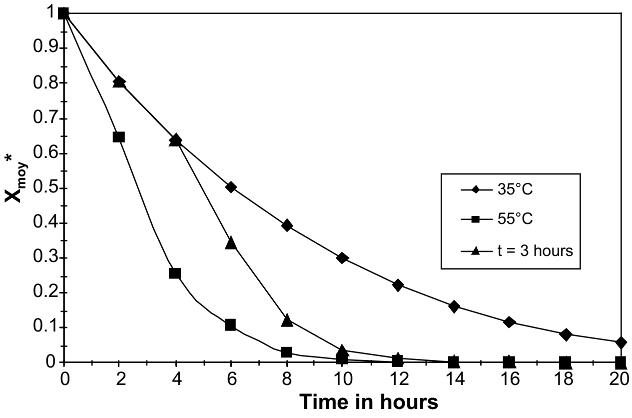

Fig. 4. Influence of the sudden augmentation of the air temperature ($V_{am} = 4.75$ m/s; $\Phi = 10\%$).

more evaporative power which is reflected in the drying time by making it shorter.

A sudden augmentation of the air temperature is started just after $t = 4$ h. At $t = 6$ h the air temperature is equal to 55 °C. It is observed that the drying kinetics adapts and changes its behavior. However, at the same time ($t = 6$ h), the drying kinetics has not attained the one at 55 °C, it is reached at $t = 18$ h. Indeed, a time of response of about 12 h was registered. It can be said that the operation presents inertia to a sudden augmentation of the temperature. The same phenomenon is observed by Fohr, Arnaud, Ali Mohamed, and Benmoussa (1990), in an experimental work of construction materials. The augmentation of the temperature does not present an instant reaction of the product.

In Fig. 5, a progressive augmentation of the air temperature, started at $t = 4$ h, is now simulated. The augmentation is about 5° each 2 h. This means that the air temperature attains 55 °C at $t = 12$ h. Of course, the drying kinetics changes its behavior and moves to the one at 55 °C. Really, it is reached at $t = 19$ h, which presents a time of response of about 7 h. The time of response at the progressive augmentation is then lower than the sudden one. Increasing the temperature 5° each 2 h is around one degree every 30 min. The adaptation of the product to the new conditions, of course, takes place more easily than during sudden augmentation.

3.2. *Influence of the air velocity*

The air temperature is kept constant at 55 °C and the humidity at the constant value of about 10%.

As confirmed by the experimental studies done by Toğrul and Pehlivan (2003), Azzouz et al. (2002), Sanjuán, Lozano, Clemente, Garcia-Pascula, and Mulet (2002), Fig. 6 shows that the air velocity is not as influential a parameter as the temperature and, moreover, the influence decreases with drying process increasing.

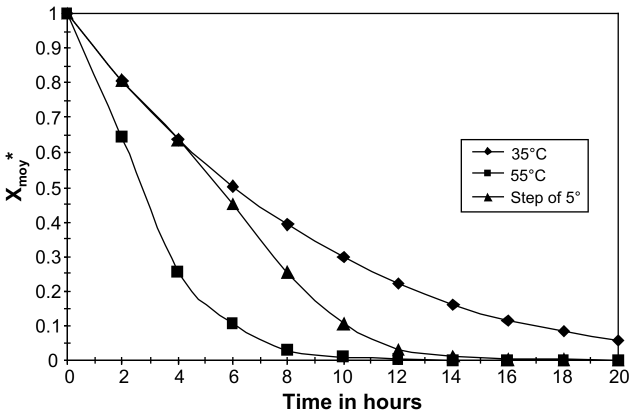

Fig. 5. Influence of the progressive augmentation of the air temperature ($V_{am} = 4.75$ m/s; $\Phi = 10\%$).

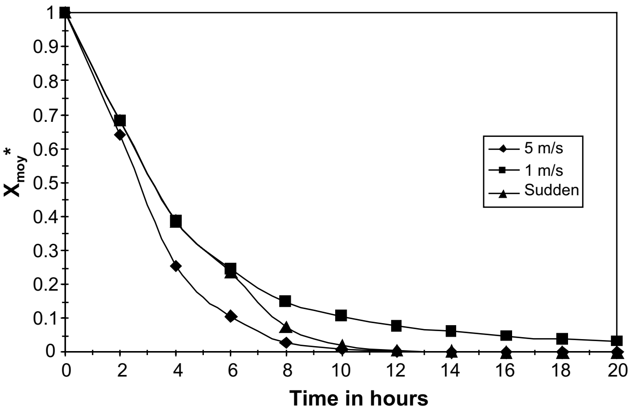

Fig. 6. Influence of the air flow rate on the moisture content during sudden augmentation ($T_{am} = 55$ °C; $\Phi = 10\%$).

A sudden augmentation of the air velocity is effectuated just after $t = 4$ h and at $t = 6$ h the air velocity is equal to 5 m/s it is observed that the drying kinetic manages its behavior by directing it to the curve of $V_{am} = 5$ m/s and attains it around $t = 15$ h. The response of the product was not an instant one as it takes around 9 h.

Fig. 7 illustrates the influence of a progressive augmentation of the air velocity. The augmentation is about 1 m/s every 2 h, started just after $t = 4$ h. In this way, the air velocity $V_{am} = 5$ m/s is attained at $t = 12$ h. it is observed that adjusted drying kinetics reaches the one at 5 m/s around $t = 17$ h which represents a time of response of about 5 h.

3.3. *Study of solar drying*

It was found that 3 m^2 surface collector is an optimum parameter (Bennamoun & Belhamri, 2003) with 10° inclination angle (Percebois, 1975) (this study is valid for Constantine region which is located east of Algeria, Capderou, 1986).

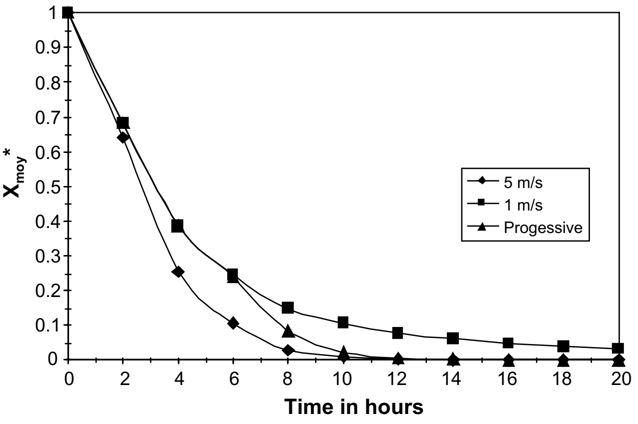

Fig. 7. Influence of the air flow rate on the moisture content during progressive augmentation ($T_{am} = 55$ °C; $\Phi = 10\%$).

Generally, before 8 a.m., it is not of interest to start the drying process; the received energy being used to warm up the collector. Otherwise, the received energy is used to increase the collector air temperature. The outlet collector air temperature has the form of the ambient one and the received radiations. For these two last parameters, the maximum is reached at 12 a.m. However it can be seen in Fig. 8, that the maximum is after 1 p.m. Also, there is no received radiations after 7 p.m. and it is seen that the temperature is higher than the ambient one. It can be concluded that a time of response or inertia exists for the collector.

The roll of the ambient air velocity is a dissipative parameter. Increasing the ambient air velocity leads to a decrease in the outlet collector air temperature. This result surely has repercussions on the drying kinetics and it is seen in Fig. 9 that increasing the ambient air velocity leads to increase in the drying time. To eliminate water from the product and attain the equilibrium value, almost two days were needed, especially at high air velocities. A dead time is observed from 9 p.m. to 8 a.m. of the next day ($t = 32$ h), where drying is not performed. Adding a heater (it works when the outlet collector air temperature is less than 50 °C) helps to eliminate this zone. It allows drying in unfavorable climatic conditions; also it allows reducing the effect of the external conditions as shown in Fig. 10.

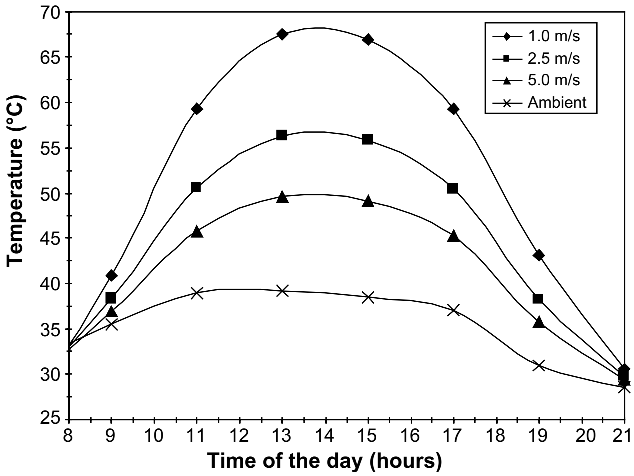

Fig. 8. Inlet and outlet collector temperatures and influence of the ambient air velocity.

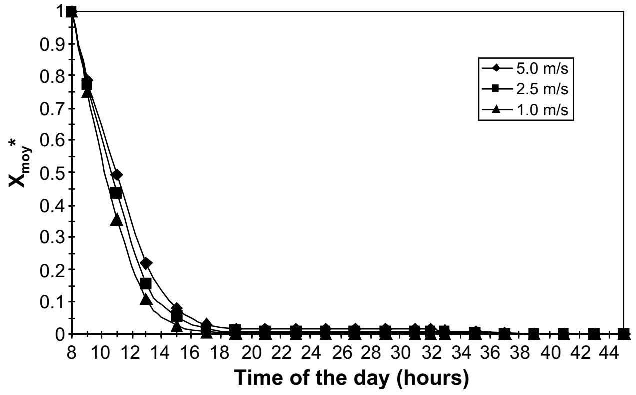

Fig. 9. Influence of the ambient air velocity on the moisture content of the product during solar drying.

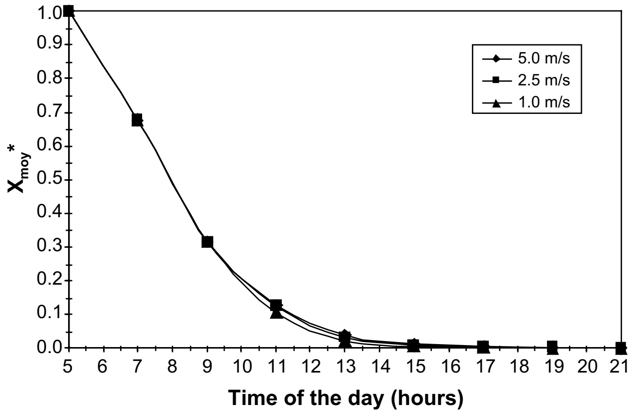

Fig. 10. Influence of adding a heater.

4. Conclusions

Many characteristics of foodstuffs change during drying, with the appearance of shrinkage. This latter is an important parameter to take into consideration; whereby false results can occur.

The study shows that air temperature is an influential external parameter which is not the case of air velocity and humidity. The simulation of sudden and progressive augmentations of the air temperature and the air velocity has shown that the reaction of the product during this augmentation is not instantaneously and a time of a response is registered. This last is less important during progressive augmentation than during sudden one. It can be concluded that during progressive augmentation, the product has got time to react and to adapt its behavior. From an energetic point of view, progressive augmentation can be benefit and a gain can be obtained. It is seen that the reaction of the product, to the variations of the influent parameters, takes a long time to establish the new drying conditions. In this way, it is indispensable to have a rigorous choice of these parameters, temperature in particular, and have a control of them.

The diffusion model can detect the variations in the drying kinetics during external condition changes. Therefore, it can be used to study solar drying. During solar drying, the ambient air velocity is an influential parameter. It influences the outlet collector air temperatures. The use of a heater can decrease this influence;

also it can allow the use of the dryer in unfavorable drying conditions.

Appendix

The characteristics of the wet air are calculated using the following equations (the temperature is given in Kelvin): Daguenet (1985) gives:

$$D_{\mathrm{v}} = 2.26 \times 10^{-5} \frac{1}{p} \left(\frac{T_{\mathrm{ach}}}{273}\right)^{1.81} \tag{25}$$

$$\rho_{\mathrm{as}} = \frac{\rho_{\mathrm{ah}}}{1 + W} \tag{26}$$

$$W = 0.622 \frac{\phi P_{\mathrm{vsat}}}{P_{\mathrm{ah}} - \phi P_{\mathrm{vsat}}} \tag{27}$$

P and P_{ah} are, generally, equal to the atmosphere

$$\rho_{\mathrm{vap}} = \rho_{\mathrm{ah}} - \rho_{\mathrm{as}} \tag{28}$$

$$P_{\mathrm{vsat}} = 10^{17.433 - \frac{2795}{T_{\mathrm{ach}}} - 3.868 \log(T_{\mathrm{ach}})} \tag{29}$$

The viscosity of the wet air is calculated using the following equations (Lampinen & Ojala, 1993):

$$\mu_{\mathrm{ah}} = \frac{\mu_{\mathrm{as}} \rho_{\mathrm{as}} + \mu_{\mathrm{vap}} \rho_{\mathrm{vap}}}{\rho_{\mathrm{as}} + \rho_{\mathrm{vap}}} \tag{30}$$

$$\mu_{\mathrm{as}} = \frac{1.448 \sqrt{T_{\mathrm{ach}}}}{1 + \frac{110.4}{T_{\mathrm{ach}}}} 10^{-6} \tag{31}$$

$$\mu_{\mathrm{vap}} = (0.0361 T_{\mathrm{ach}} - 1.02) 10^{-6} \tag{32}$$

Its density is calculated (Maake, Eckert, & Cauchepin, 1993)

$$\rho_{\mathrm{ah}} = \frac{348.3}{T_{\mathrm{ach}}} p_{\mathrm{ah}} - \phi p_{\mathrm{vsat}} \frac{131.6}{T_{\mathrm{ach}}} \tag{33}$$

Here the pressure is in atmosphere.

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