Estimation of the Diffusivities and Mass Transfer Coefficients for the Drying of D. Joaquina Pears

Raquel P. F. Guiné and Maria João Barroca

***Abstract*—Portugal is a tropical country with a long tradition of drying fruits, among which stand the pears. The design of the proper operating conditions relies on the knowledge of the transfer phenomena happening during drying. Hence, the present work aimed at determining the mass transfer properties of pears for convective air drying, based on the diffusion model. The values of the diffusion and mass transfer coefficients for the drying of pears of the variety D. Joaquina were determined for two drying temperatures, 60 ºC and 70 ºC, and the results obtained showed an increase of 38 % in diffusivity and an even more pronounced increase in the mass transfer coefficient, 56 %. Regarding the dimensionless numbers, Biot number ncreased 13 % while Dincer number decrease 28 %.**

***Index Terms*—diffusivity, mass transfer coefficient. pear drying**

I. Introduction

DRYING of foods is an important method of preservation and can be applied to a wide range of products. In countries where the climatic conditions allow it, foods are often dried by open-air sun exposure. However, and despite being a cheap method, it has some important disadvantages, like the dependency on the weather conditions and the problems that may arise from contaminations, infestations and microbial attacks. Additionally, the drying times can be quite long if the quantities to be dried are relatively high [1], [2].

The pear (*Pyrus communis* L.) is a fruit original of temperate zones and is cultivated in Europe. The flavor of the pears is influenced by the volatile aromatic compounds present and by the contents in sugars and organic acids (mainly citric and malic acids). Their bitter taste is normally associated with the phenolic and polyphenolic compounds. The color of the peel depends on the amount and type of pigments present, being mainly chlorophyll (green) and carotenoid (yellow) [3].

The design of driers is often done empirically, by extrapolation of knowledge existing for other cases. For reliable process modeling is very important a profound knowledge of the physical and chemical behavior of the food, as well as its drying kinetics, which accounts for the mechanisms of water removal [4], [5].

From the engineering point of view it is very important to understand the complex processes that occur during drying, being this achieved through modeling. Many mathematical models have been used to describe drying processes, being quite common the use of the diffusion laws. During drying many changes take place inside the foods [6], and these modifications affect the product mass transfer properties such as the mass diffusion and mass transfer coefficients.

The present work aimed at determining the mass transfer properties of pears of the variety D. Joaquina for hot air drying performed in a convective drier.

II. Experimental Procedure

A. Materials

Pears of the variety D. Joaquina were used in this study. The pears of this variety are very sweet and quite small (about 4 to 5 cm diameter maximum) and exhibit good drying features [4].

of optimal operating parameters for this type of food.

B. Methods

The pears were dried in a drying chamber with ventilation (WTB-Binder) at constant temperature, but with trials done at different temperatures (60 and 70 ºC). The air flow was 300 m^3/h. The drying time was 225 and 360 minutes respectively for 70 and 60 ºC.

Periodically the samples were removed in order to measure their average water content with a Halogen Moisture Analyzer, model HG53 from Mettler Toledo, which was previously calibrated in terms

III. Mathematical Modeling

For the mass transfer in one direction in non-steady state the moisture diffusion in the pears, assuming that they can be approximated to spheres, can be expressed by the Fick's second law [6]:

$$\frac{\partial W}{\partial t} = \frac{1}{r}\left\{\frac{\partial}{\partial r}\left(D_e r \frac{\partial W}{\partial r}\right)\right\}, \tag{1}$$

where W(r,t) is the dry basis moisture content in kg

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water/kg dry solids, t is time in seconds, D_e is effective diffusivity in m^2/s and r is the sphere radius in meters.

Assuming that the initial moisture content is uniform in the whole pear and that the sample presents central symmetry, the initial and boundary conditions are given by the following Equations:

for t = 0: $W(r,0) = W_0$, (2)

for r = 0: $\frac{\partial W(0,t)}{\partial r} = 0$, (3)

for r = R: $-D_e \frac{\partial W(R,t)}{\partial r} = h_m [W - W_a]$,

(4)

where W_0 is the initial product moisture content, W_a is the surrounding air moisture content (all dry basis) and h_m is the convective mass transfer coefficient.

In transient conditions, the solution of Fick's Law can be approximated by an infinite series, of the form [6], [7]:

$$MR = \frac{W - W_e}{W_0 - W_e} = \sum_{n=1}^{\infty} \frac{6}{\pi^2} \exp\left[-D_e \frac{\pi^2 t}{r^2}\right] \quad (5)$$

where MR is the moisture ratio, dimensionless, and W, We and W_0 are, respectively, the moisture content at time t, the equilibrium moisture content and the initial moisture content, all expressed in dry basis (g water/g dry solids). Taking into account that the terms of the series after the first are relatively insignificant and can therefore be ignored, then the solution of the Fick's Equation is given by:

$$MR = \left(\frac{6}{\pi^2}\right) \exp\left[-D_e t \left(\frac{\pi^2}{r^2}\right)\right] \quad (6)$$

The thin-layer models assume that the moisture evolution along drying is related to some parameters, such as the drying constant, k (1/s), or the lag factor, k_0 (dimensionless), that account for combined effects of various transport phenomena during drying [8]. The Henderson and Pabis model is an example of such models, and is expressed through the following Equation [9]:

$$MR = k_0 \exp(-kt) \ . \quad (7)$$

The convective mass transfer coefficient, h_m (m/s), and the diffusivity coefficient, or effective diffusivity, are correlated by the dimensionless Biot number for mass transfer [10]:

$$Bi_m = \frac{h_m r}{D_e} \ , \quad (8)$$

where r is the sphere diameter (m). Equation (8) is valid for Bi greater than 0.1 [11], and allows the estimation of h_m, if the Bi_m is known.

Dincer and Hussain [11] report the equation that correlates the Biot number with the dimensionless Dincer Number:

$$Bi_m = \frac{24.848}{Di^{0.375}} \ , \quad (9)$$

with,

$$Di = \frac{u}{kr} \ , \quad (10)$$

where u is the flow velocity of drying air (m/s), k the drying constant and r the radius.

The determination of the mass transfer properties of the pears was done following the steps:

1. Estimate MR from the experimental drying data for every time t;
2. From a plot ln(MR)=f(t) estimate D_e from the slope through (6) (slope = $-D_e \pi^2/r^2$);
3. Estimate k and k_0 by combining (6) and (7);
4. Calculate Di, Bi_m and h_m from (10), (9) and (8), respectively.

IV. Results and discussion

Fig. 1 shows how the moisture content of the D. Joaquina pears, expressed as percentage wet basis, varied along drying for the two temperatures tested. At each measurement interval several measurements were made and some variability can be observed for the values of moisture determined for different samples, all taken from the drier at the same time. This is natural, since some variations in the sample volume or even properties, may influence the removal of the water from the food, therefore originating different values for moisture content. Furthermore, the pears before drying also presented some variability in their moisture content, which can be attributed to different slight difference in the ripening state of the pears. The pears were dehydrated to a very high extent, in order to obtain a crispy snack.

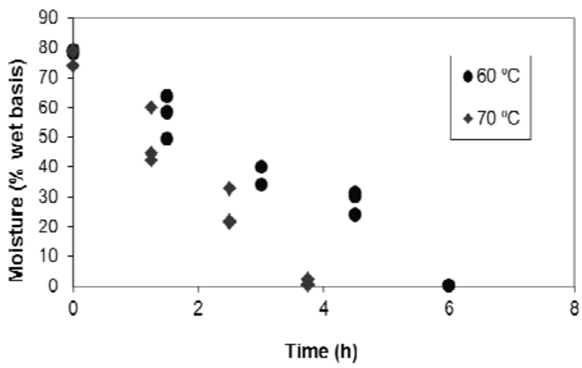

Fig. 1. Variations of the pears moisture content along drying for different drying temperatures.

The graph in Fig. 2 reveals the fast diminish in the values of the moisture ratio, as defined in equation (5), starting with 1 initially and tending to approach zero as the drying proceeded.

Fig. 3 shows the linearization of the functions ln(MR)=f(t) for the two temperatures tested, being the results corresponding to the equations obtained presented in Table 1. In the two cases both the slope and intercept are slightly different, and it is also visible that the fitting was not so good. The values of R2 found were 0.7782 for the drying at 60 ºC and 0.8321 for the drying at 70 ºC.

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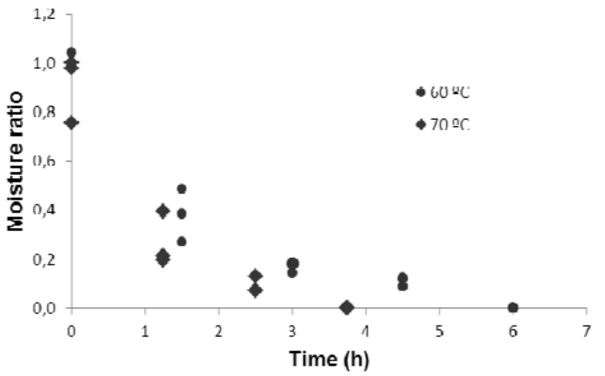

Fig. 2. Decrease in moisture ratio of the pears for the temperatures tested.

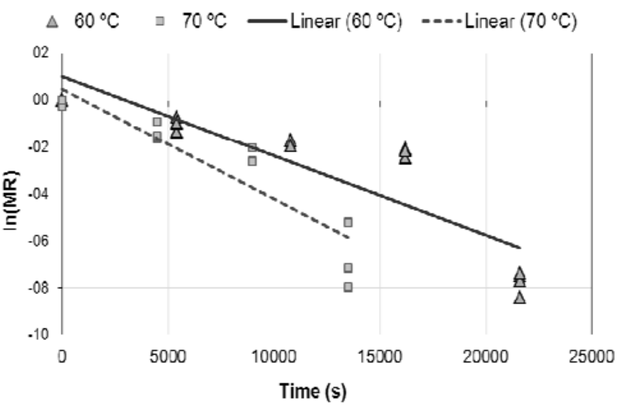

Fig. 3. Linearization of the functions ln(MR)=f(t) for the different temperatures. (Results of the fits presented in Table I).

TABLE I
PARAMETERS FOR LINEARIZATION OF THE FUNCTION LN(MR) = F(T), FOR THE TWO TEMPERATURES TESTED

Drying temperature	Slope	Intercept	R^2
60 ºC	$-3.397x10^{-4}$	1.038	0.7782
70 ºC	$-4.692x10^{-4}$	0.496	0.8321

The values of the drying constant and lag factor were calculated from equation (7). The values obtained for the drying constant were $3.3970x10^{-4}$ s^{-1} and $4.6920x10^{-4}$ s^{-1}, respectively for 60 and 70 ºC. These values are higher than those reported by Roberts et al [12] for the convective hot air drying of grape seeds in the range of temperatures from 40 to 60 ºC and with air velocities above 1.5 m/s. This is expected, having in consideration that the temperatures used in the present study are also higher, and the products are different. Furthermore, the values found by Guiné et al [13] for the solar drying of pears of the variety S. Bartolomeu, ranging between $5.7188x10^{-6}$ s^{-1} and $1.1037x10^{-5}$ s^{-1}, are also inferior to those found in the present work, because the drying conditions were variable. Nevertheless, the values found for the two temperatures clearly indicate an increase in the drying constant as the temperature raised from 60 to 70 ºC.

As to the values fund for the lag factor, they were 2.8236 and 1.6418 respectively for the temperatures 60 and 70 ºC. Dincer and Hussain [10], for the drying of potatoes at 40 ºC, with an air velocity of 1 m/s and a characteristic dimension of 0.09 m, report a value for the lag factor of 1.0074, which is just slightly lower than those in the present study. The values found by Guiné et al [13] for the S. Bartolomeu pears varied from 0.6658 to 2.2538, depending on the drying system, and stand in the same range as those found for the D. Joaquina pears.

Table II shows the values obtained using the methodology explained previously for the different mass transfer properties based on the experimental data obtained for the two temperatures. The values of the effective diffusion coefficient or diffusivity, De, are $8.6047x10^{-10}$ m^2/s and $11.8850x10^{-10}$ m^2/s, for the temperatures 60 and 70 ºc, respectively. These stand in the same range of the values found by Guiné et al [13], $1.4218x10^{-10}$ m^2/s to $2.7439x10^{-9}$ m^2/s, and they are also of the same magnitude of that reported by Dincer and Hussain [10] for the air drying of cylindrical okara, $5.6752x10^{-10}$ m^2/s. However, the values found for the D. Joaquina pears are inferior to those reported by Dincer and Hussain [10] for the air drying of spherical potatoes, $9.4259x10^{-7}$ m^2/s, or those of Tripathy and Kumar [8], which vary from $3.28x10^{-8}$ to $6.09x10^{-8}$ m^2/s, for cylindrical potato samples for temperatures in the interval 33.74 - 47.70 ºC, or stand in the range $2.43x10^{-8}$ - $4.18x10^{-8}$ m^2/s for sliced potato samples at temperatures between 35.55 ºC and 49.88 ºC.

TABLE II
MASS TRANSFER PROPERTIES OF PEARS CALCULATED FOR THE TWO TEMPERATURES STUDIED

Drying temperature	D_e (m^2/s)	Di	Bi	h_m (m/s)
60 ºC	$8.6047x10^{-10}$	116820	0.3126	$5.3795x10^{-8}$
70 ºC	$11.8850x10^{-10}$	84575	0.3528	$8.3870x10^{-8}$

The values of the Di number in Table II decrease from 116820 at 60 ºC to 84575 at 70 ºC. These values are higher than the value presented by Dincer and Hussain [10], which was 12356 for potatoes of spherical geometry dried with air at 1 m/s and 40 ºC. On the contrary the values in the present work are considerably lower than those found by Guiné et al [13], varying from 371350 to 2317400 for the drying of S. Bartolomeu pears in different systems.

The Biot numbers are very similar for both temperatures, being 0.3126 for 60 ºC and 0.3528 for 70 ºC. Both values are higher than 0.1, thus allowing the use of Equation (8) for the estimation of the mass transfer coefficients. These values are higher when compared to those reported by Guiné et al [13] ranging between 0.1020 and 0.2026, according to the drying system. However, for the convective drying of spherical potatoes at 40 ºC Dincer and Hussain [10] reported a value of 0.3119, which is very similar to those in this work.

The convective mass transfer coefficient, h_m, varied from $5.3795x10^{-8}$ m/s to $8.3870x10^{-8}$ m/s, respectively for 60 ºC and 70 ºC. These values stand in the same range of the values encouneterd by Guiné et al [13] for pears of a different variety and submitted to varied drying systems, $3.5040x10^{-9}$ m/s - $1.1222x10^{-8}$ m/s, and they are also similar to that for the convective drying of cylindrical okra

(1.6098×10^{-8} m/s) at 80 ºC, as reported by Dincer and Hussain [10]. On the other hand, the present values are considerably smaller than those found by Dincer and Hussain [10] for the convective drying of spherical potatoes (3.2665×10^{-5} m/s). Tripathy and Kumar [8] determined the convective mass transfer coefficients for potato elements in cylindrical and sliced shapes, and their results lead to h_m ranging from 1.61×10^{-7} m/s to 4.17×10^{-7} m/s in the range of temperatures from 33.74 ºC to 47.70 ºC for the cylindrical shape and from 1.70×10^{-7} m/s to 3.21×10^{-7} m/s for temperatures between 35.55 ºC to 49.88 ºC for the sliced shape.

Fig. 4 shows the effect of the temperature raise on the mass transfer properties of the D. Joaquina pears. Regarding the diffusivity, D_e, the increase of 10 ºC originated a raise of 38 % in the effective diffusion coefficient, corresponding to about 14 m^2/s per ºC. The mass transfer coefficient increased very pronouncedly, 56 % for the 10 ºC raise. As to the dimensionless numbers, the Biot number increased 13 % while the Dincer number decreased 28 %.

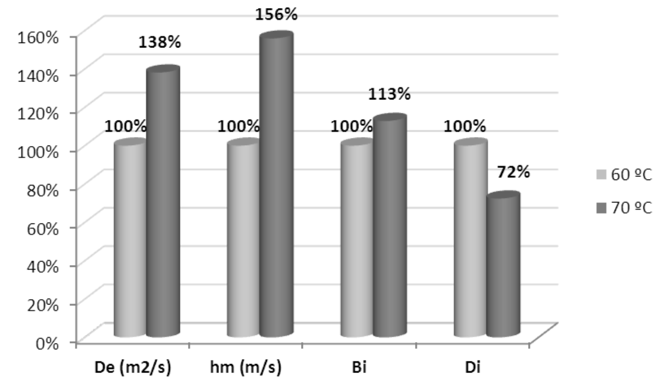

Fig. 4. Variation of the thermo physical properties of D. Joaquina pears with drying temperature.

V. Conclusion

The values of the diffusion and mass transfer coefficients for the drying of pears of the variety D. Joaquina were estimated in this work for two drying temperatures, 60 and 70 ºC. The results obtained enabled to conclude that the raise in temperature originated an important increase in the value of the diffusivity, demonstrating the effect of temperature on the efficiency of the internal mass transfer. Also the mass transfer coefficient suffered a very important increase with temperature, owing to a higher efficiency of the moisture transfer at the surface of the pears.

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