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Modeling convective and intermittent drying of agricultural products

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Abstract - *The purpose of this work is to quantify the energetic interest of convective and intermittent drying process of natural products. This drying mode has been achieved within a climatic blower. This laboratory device permitted us to achieve several tests for different conditions of drying for apples, carrots and peppers. This study permitted to appreciate the capacity of the model to describe the different drying periods. In the continuous case, a variation of the air velocity permitted us to find the most economic velocity for the drying of thin layer products. In the intermittent case, the numerical simulation profiles give us more information on what happens really to the product during periods of stop. Besides, the drying kinetics at the retaking increases with the air temperature. Then, we gain in energy and in global drying time.*

Résumé - *Le but de ce travail est de quantifier l'intérêt énergétique de convection et intermittent processus de séchage des produits naturels. Ce procédé de séchage a été effectué dans une soufflerie. Cet appareil de laboratoire permet de réaliser de nombreux tests et essais de séchage pour différentes conditions sur les pommes, les carottes et les poivrons. Cette étude a permis d'évaluer la performance du modèle sur différentes périodes de séchage du produit. Dans le cas continu, une variation de la vitesse de l'air a permis également de connaître la vitesse la plus économique pour le séchage de produits en couche mince. Dans le cas de séchage intermittent, les profils de la simulation numérique nous donnent des informations sur le produit pendant les périodes d'arrêt. D'ailleurs, la cinétique de séchage est intimement liée à la température de l'air. Puis, on gagne en énergie et en durée de séchage.*

Keywords: Convective and intermittent drying - Heat and mass transfer - Drying kinetic - Numerical simulation.

1. INTRODUCTION

The drying of a granular product layers is very important in the food-processing industry. In the past decades, considerable work has been done on the development of theory and mathematical models for drying processes [1-4]. The challenge for the engineering designer is now to define optimal dryers, which provide a product of constant good quality.

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Solar crop drying can thus offer a major energy saving technique, especially for developing countries where solar energy is generally abundantly throughout the year but intermittent along the day.

Climatic data for the site of INRST institute show that the mean daily solar radiation exceeds 7.7 kWh/m^2 in the summer. The mean daily sunshine ranges from 5 hours per day in December to 12 hours per day in July. Food quality is another important factor to be considered simultaneously with energy saving [5].

The absence of control over drying temperature was actually felt in open sun drying and the passive solar dryer, and then the later research tended to have a preference to the use of forced and intermittent air circulation solar dryer. Several designs of forced convection solar dryers have been recently proposed drying applications in developing countries and still a good deal of work is continuing in this direction [1.7].

Active solar dryers are designed incorporating external means like fans or blowers, for moving the solar energy in the form of heated air from the collector area to the drying beds.

Simulation models are helpful in designing new or in improving existing drying systems or for the control of the drying operation. Modeling drying of crops under solar energy is a complex problem involving simultaneous heat and mass transfer in a hygroscopic nature of crop.

The drying rate depends on a number of external variable parameters (solar irradiation, ambient temperature, relative humidity and wind velocity) and internal parameters (initial moisture contents, type of crops, crop absorptive, mass of product per unit exposed area, etc.)

The purpose of the present work is to extend our study on the intermittent drying process through a fixed granular bed [6]. The used method is adapted from the general porous medium theory of Whitaker [7]. The thermal and mass transfer description in the granular environment and the multiple interactions air-product are studied by a mathematical model [7, 8].

The air product mass transfer is described with a kinetic equation based on experimental data, which expresses the evaporation flow rate in relation to the characteristics of air and the state of the product along the drying [8].

The developed numerical model permits to study the effects of the drying air conditions on the drying time, to follow the displacement of the drying front for different operative conditions and therefore to optimize the considered dryer.

2. EXPERIMENTAL STUDY

In a preliminary study, the drying kinetics and the product characteristics were studied in the laboratory by means of a specific apparatus [6]. We consider a thin product layer with thickness between 0.8 cm and 1.0 cm, put on the insulating flat plate (25 cm length x 10 cm width) inside the vein of the specific apparatus.

An electronic balance of 0.01g accuracy is used to measure the weight of the drying products.

Air velocity V_a, temperature T_a and relative humidity H_r are closely controlled.

Weight loss data allowed the moisture content to be calculated as follows: $X(t) = m(t)/ms$, where ms is the weight of dry mass obtained after a long stay in a vacuum at 95 °C and $m(t)$ the weight of the evaporated moisture.

The values of $\dot{X}(t) = dX/dt$ were obtained by derivation of a polynomial expression identified for five experimental points. For the convective and intermittent case, the sudden change of operative conditions has been achieved of a way that permitted the continuous acquisition of the mass loss and the temperature profiles.

Temperature evolutions on the grape layer during the drying process were registered at regular intervals with K thermocouples. These registers were located on the bottom, top, and centre of the packed layer. Dry-bulb and wet-bulb temperatures of environmental air were taken.

A preliminary analysis of the characteristic drying curves of apples (Fig. 1) shows that the drying operation may be divided into three periods:

- A short period with constant drying rate (CDRP).

- A second period with decreasing drying rate (DDRP) dominated by the internal diffusion of humidity. The drying process becomes faster.

- A third period (falling rate period, FDRP) dominated by the slowness of the drying rates.

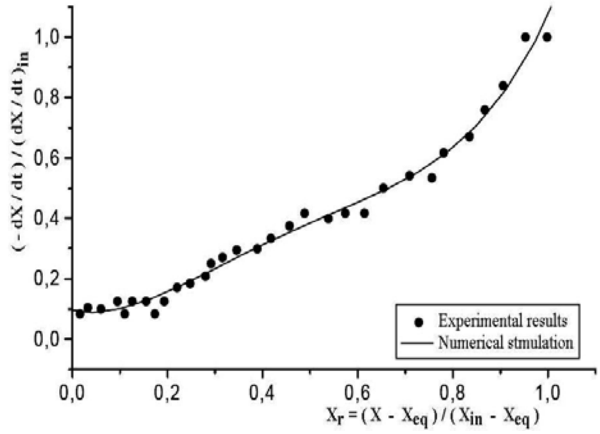

Fig. 1: Characteristic drying curves of apple slices

The evolution of the drying kinetics according to the reduced and normalized moisture content of the product has been studied for different airflow parameters [10].

Moreover, a numerical procedure had been applied to establish the characteristic drying curves as:

$$\dot{X}/\dot{X}_{in} = f\left(X_r, T_a\right)$$

where X_{eq} is the equilibrium moisture content determined by the adsorption curves.

Statistical treatment of large number of points gives also the reliable results for $X(t)$, $\dot{X}(t)$) and $\dot{X}(X)$.

Van Meel [9] proposed a characteristic drying curve assuming the following form $f\,(X_r)$:

$$\frac{\partial X}{\partial t} = \dot{X}_{in}\,.f\,(X_r)$$

$$\text{with} \quad X_r = \frac{X - X_{eq}}{X_{in} - X_{eq}} \tag{1}$$

$$f\left(X_r\right) = 0.09328 - 0.28857\,X_r + 4.3161\left(X_r\right)^2 - 7.2438\,(X_r)^3$$

3. THEORETICAL APPROACH

The problem under investigation is forced convection of air over thin product layers (apple slices, grapes, peppers, corn, hazelnuts, and pea) in a tunnel dryer. The schematic configuration is a thin layer product placed under fixed air flow conditions.

This is well adapted, in a first approximation, to classic tunnel dryers, which are widely used for dehydrating fruits and vegetables in Mediterranean countries. The medium is discontinuous and the macroscopic equations, which govern heat and mass transfer, are generally obtained by the method of scale changing from a one grain scale to a macroscopic one which includes several grains.

Throughout this study, we will use the same definitions and notations as described in [10]. The resulting equations follow from mass and energy balances relating to an elementary control volume [11, 12]:

$$\rho_a\left[\varepsilon\frac{\partial Y}{\partial t} + V_a\frac{\partial Y}{\partial x}\right] = -\dot{m} + \frac{\partial}{\partial x}\left[\rho_a\,D_e\frac{\partial Y}{\partial x}\right] + \frac{\partial}{\partial y}\left[\rho_a\,D_e\frac{\partial Y}{\partial y}\right] \tag{2}$$

$$\begin{aligned}\rho_a\left(C_{p_a} + Y.C_{p_v}\right)\left[\varepsilon\frac{\partial T_a}{\partial t} + V_a\frac{\partial T_a}{\partial x}\right] &= \dot{m}\,C_{p_v}\left(T_s - T_a\right) + \xi\,h_{as}.\left(T_s - T_a\right)\\ &\frac{\partial}{\partial x}\left[\varepsilon.\lambda_{ae}.\frac{\partial T_a}{\partial x}\right] + \frac{\partial}{\partial y}\left[\varepsilon.\lambda_{ae}.\frac{\partial T_a}{\partial y}\right]\end{aligned} \tag{3}$$

$$\begin{aligned}\left(1-\varepsilon\right)\rho_s\left(C_{p_s} + X.C_{p_l}\right).\frac{\partial T_s}{\partial t} &= -\dot{m}.\Delta H_{vap} + \xi\,h_{as}.\left(T_a - T_s\right)\\ &\frac{\partial}{\partial x}\left[\left(1-\varepsilon\right).\lambda_{se}.\frac{\partial T_s}{\partial x}\right] + \frac{\partial}{\partial y}\left[\left(1-\varepsilon\right).\lambda_{se}.\frac{\partial T_s}{\partial y}\right]\end{aligned} \tag{4}$$

$$\dot{m} = -\left(1-\varepsilon\right).\rho_s.\frac{\partial X}{\partial t} = \left(1-\varepsilon\right).\rho_s.\dot{X} \tag{5}$$

Where $\dot{m}$ is the evaporation rate and ΔH_{vap} is the latent heat of vaporization:

$$\Delta H_{vap} = \Delta H^{o}_{vap} + \left(C_{p_v} - C_{p_l}\right).T_s \tag{6}$$

The thermal conduction in air and between slices is expressed with the coefficients of equivalent thermal conductivities of the solid product and the fluid (air) supposed to be isotropic. The thermal dispersion effect is treated as a diffusive term added to the air thermal conductivity [12].

The above-developed model requires the knowledge of an important number of parameters. Porosity, specific area and mass concentration of the granular product were estimated from geometrical measurements of the bed particles.

External energy and mass transfer are dependent on air flux properties, but there are a limited number of reports dealing with heat and mass external transfer in a gas flow surrounding a foodstuff [13]. As a consequence, different expressions were employed to calculate the external transfer coefficients.

4. NUMERICAL APPROACH

The equations are solved by an implicit method of finite differences using the control volume approach as described by Patankar [14]. In order to look for the optimum values of temperature and velocity of the drying air, we started with temperature increases at constant velocity, then with speed reductions at constant temperature.

Finally, we have simulated the experiences conditioned by velocity reductions coupled to temperature increases. For continuous drying, the time step, chosen initially very small, increases progressively to follow the drying kinetics of the product. For intermittent drying, we opted for a regular thin spatial mesh.

5. RESULTS AND INTERPRETATIONS

In order to analyse the influence of input air properties on drying, we studied the evolution of the product moisture content $X(x,t)$, the solid product temperature $T_s(x,t)$, the air temperature $T_a(x,t)$ and the air absolute humidity $Y(x,t)$ as a function of time and bed length.

The results of the numerical simulation are presented as a curve giving the spatial evolution of these variables at different times. The presented model has been validated by previous numerical and experimental work achieved on Tunisian grape samples [15, 16].

The comparison with other recent studies is satisfying [17]. The concordances of confrontations justify choices and hypotheses made for the development of this numerical procedure.

Figures 2 and 3 show respectively the evolution of the air temperature and the moisture content at different times. The product layer thickness is of 1.0 cm and air inlet conditions of 3 m/s and 60 °C and 40 °C were used.

During a time stop (20 min), there are to relaxation of the internal gradient of temperature and moisture content through the product sample. It drags an increase of the water activity toward the surface of the product layer as well as a reduction of the temperature gradient.

The tunnel has variable length, L = 6 m and 10 m. It is crossed by an air flow which has, at the inlet, constant physical characteristic temperature, velocity and humidity. The tunnel lateral area has been considered adiabatic. The products are put on a fixed-bed to allow heat transfer through the whole product surface.

Figures 4 and 5 show experimental and simulated evolution of the product moisture content and the average product temperature in the fixed-bed layer with slabs thickness of 0.8 cm. Air flow of 0.5 m/s to 7 m/s and air inlet temperature of 60 °C were used.

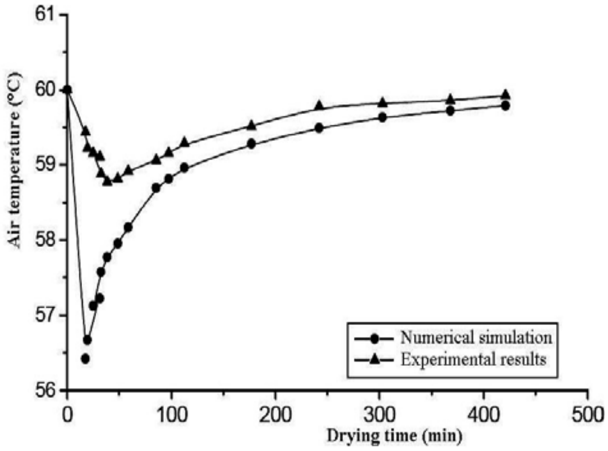

Fig. 2: Evolution of the air temperature according to the time (Ta = 60 °C, Va = 3 m/s)

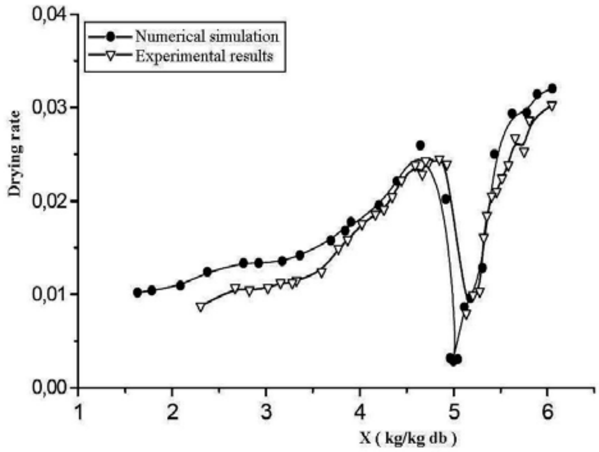

Fig. 3: Evolution of the drying rate during the time according to the moisture content (Ta = 40 °C, Va = 3 m/s)

Best reproduction of the experimental data was obtained with air velocity from 1.0 m/s to 5.0 m/s and air inlet temperature between 40 °C and 70 °C. The numerical simulation showed in Fig. 4 is made by taking the same conditions of those of the outdoor experiences ($T_{a0} = 30°C$, $H_r = 50\%$, $X_{in} = 4 kg/kg$).

Figure 6 shows the drying kinetics of a sample of apples slices spread out in a 6 m tunnel with sample thickness of 0.8 cm and operative conditions of 3 m/s and 60 °C.

The drying appears by the displacement of the drying front from the upstream toward the downstream of the outflow.

This drying front appears distinctly after some time steps of blowing ($\Delta t = 1 \text{hour}$). It is followed by a sudden increase in the product temperature. According to its initial value, the solid medium temperature starts to increase above $T_{a0} = 30°C$.

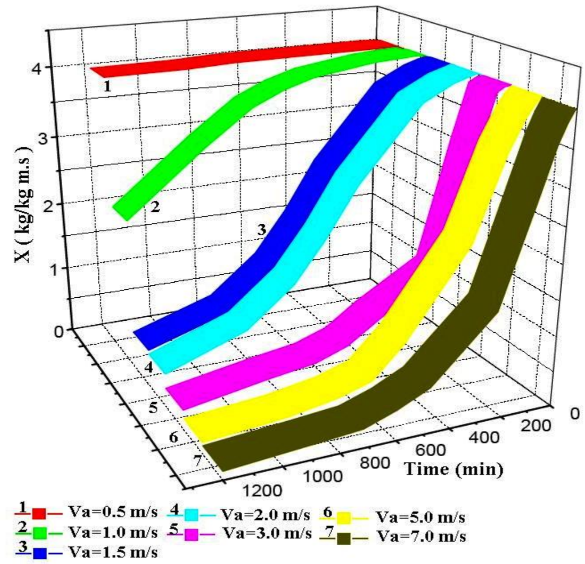

Fig. 4: Evolution of the product moisture content for different air velocity (Ta = 60 °C)

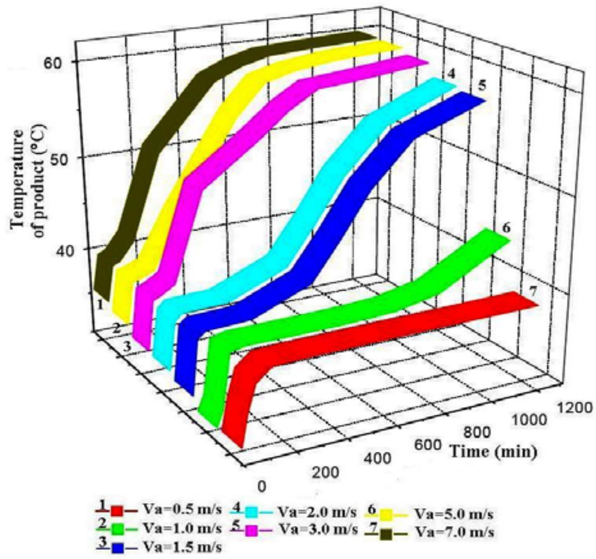

Fig. 5: Evolution of the product temperature through the tunnel dryer for different values of air velocity Va (Ta = 60 °C)

The drying front and the wet region appear sooner. We can notice that when the air velocity and the inlet temperature increase, the evaporation front moves more quickly and consequently the necessary time for drying decreases (Fig. 5 and 6).

Figure 7 shows the evolution of the air absolute humidity through 6 m tunnel length. The absolute humidity of the medium starts to increase at the permeable surfaces. It moves by gravity and entrainment to the tunnel exit.

The drying front starts at the tunnel inlet when the product temperature increases significantly within the medium. Moreover, the numerical simulation shows that the product bed overheats at the inlet and near the drying front interface. When time increases, the overheating propagates inside the medium. The product temperature and the moisture content tend to their final values in the entire medium, and the evaporation ceases.

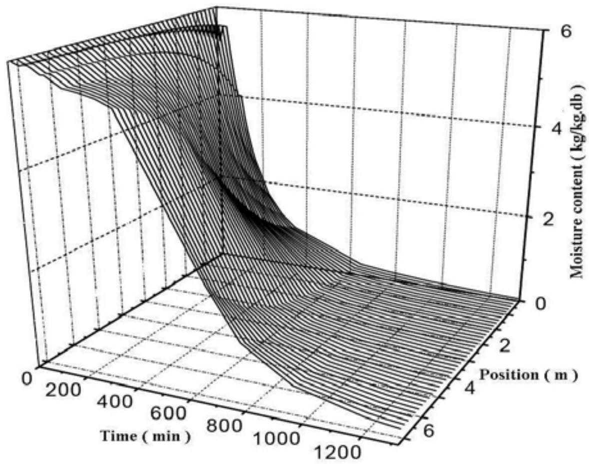

Fig. 6: Evolution of the average moisture content of the product samples through the tunnel dryer

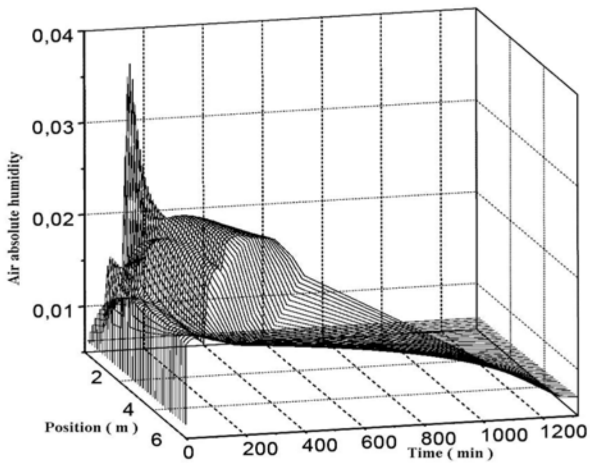

Fig. 7: Evolution of the air absolute humidity through the tunnel dryer

6. CONCLUSION

The mathematical model for a no steady-state drying process presented in this work involves heat and mass transfer properties in both air and product. Thermodynamic relationships for water equilibrium between air and product, physical proprieties of the solid particles and geometrical proprieties of the product layer were considered.

Convective and intermittent drying presents an energetic gain. A major gain of time and energy is gotten by an increase of the airflow temperature and a reduction of the air velocity.

The magnitude of the drying kinetic is more important for higher initial air temperature and velocity. Our model can be adapted to other products and dryers devices.

This mathematical model showed ability for fitting experimental drying data for various agricultural product layers. This study permitted to appreciate the capacity of the model to describe the different drying periods.

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