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Research Article

Numerical Simulation of Convective Drying of Mangoes (*mangifera Indica L.*) Under Variable Thermal Conditions

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Abstract

This work is interested in the modeling and numerical simulation of some drying rate during the drying process of mangoes under variable thermal conditions. The work was carried out based on a thermally thin layer of products in a parallel air flow type dryer. The numerical solution of heat and mass transfers' equations using a time-dependent air temperature was used to obtain a model that predicts the précised drying kinetics of mangoes under variable external conditions. The simulation of mangoes dried through temperature steps of (60°-50°-40°C) considerably modified the drying rate compared to drying at 60°C. The quality of dried products was improved as the energy efficiency of the drier.

Key words: *Modeling, kinetics, drying, variable thermal conditions*

1. Introduction

Drying is one of the most important operation units in the processing of fruits and vegetables. The main objective of any drying process is to produce a dried product of desired quality at minimum cost and maximum throughput, and to consistently optimize these factors. Drying is an energy intensive operation that easily accounts for up to 15% of all industrial energy usages, often with relatively low thermal efficiency in the range of 25–50%. Thus, to reduce the energy consumption per unit of product moisture, it is necessary to examine different methodologies to improve the energy efficiency of the drying equipment. Drying is a complex mechanism which involves the simultaneous heat and mass transfer between the air and products. With the help of some assumptions, transfer equations have been solved and several models of the kinetics have been proposed to predict and describe the drying process (Janjai *et al.*, 2008; Villa-Corrales *et al.*, 2010; Barati *et al.*, 2011). However, there are mathematical models that take into account the internal transfer (Kuitche *et al.*, 2007), whereas others take into account the transfer between the air and products. In the particular case of mangoes, several authors have proposed/or not mathematical models which predict as well as possible the drying kinetics of mangoes (Janjai *et al.*, 2008; Villa-Corrales *et al.*, 2010; Barati *et al.*, 2011). These studies were carried out in order to contribute to the reduction of the post-harvests losses which in southern countries are estimated at appoximately 40% of the production (Edoun *et al.*, 2010), and are generally undertaken with the constant air properties during the drying process. Moreover, models presented in the literature did not take into account the Dufour and Soret effects. However, the analysis of drying kinetics reported that the temperature has a significant influence on the drying kinetics, especially at the beginning of drying process, and at the constant rate throughout (Bennamoun, 2006).

Preliminary work relating to convective time-dependent drying scheme was reported (Giowacka & Malczewki, 1986; Lavialle, 1993; Chua *et al.*, 2001; Jannot, 2006; Bennamoun, 2006), and indicated that the final products obtained was improved while the energy requires was reduced. These works was unfortunately not formalized, since no model able to rationally describe the behavior of the product using a time-varying inlet air temperature was revealed, especially for products with high water content.

In the present work, a theoretical model for simulation of the drying kinetics using a time-varying inlet air temperature for mango is developed. The aim is to put throughout the parameters and the constraints piloting the drying of mangoes under variable air temperature conditions. Results of the present simulation could subsequently be used by drying engineers to provide a better understanding of the drying process.

Description

Principle of drying

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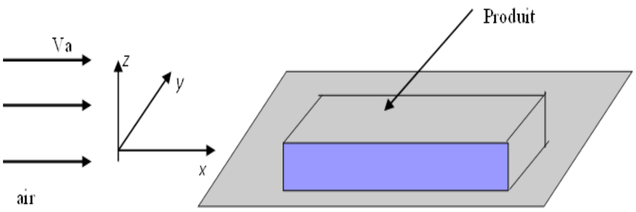
The product is dried in a parallel flow type dryer, as indicated below. The dryer is equipped with inlet and outlet air drying channels, an electric heater, adjustable forward curved centrifugal fan. The product is placed on a plastic mesh as a thin layer (Figure 1).



Mathematical model

The mathematical model used is a drift of the simultaneous heat and mass transfers. In developing the model, the following common assumptions are made:

- One-dimensional mass transfer in the food by diffusion.
- Lumped capacitance method for heat transfer within the food.
- Negligible shrinkage or deformation of food during drying.
- Constant physical and thermal properties of food during various time increments.
- Homogenous food.
- Convective heat and mass transfer at food surface.
- Constant air properties.

Under these conditions, the simplified diffusive models always satisfactorily describe the data experimentally (Pavon-Melendez *et al.*, 2002). The effective diffusivity is an empirical parameter obtained starting from the experimental data. In addition, Ruiz-Lopez *et al.*, (2004) compared experimentally the effect of the variable physical properties on the kinetics of drying. They arrived at the conclusion whereby for reasons of research, it is desirable to use the variable physical properties.

Moisture distribution

Moisture, in the vapor state leaves the surface of the product. The liquid water which arrives at the surface is initially evaporated and then carried away by the hot air. The associated equation of mass derived from the diffusive model is written as:

$$\frac{\partial X}{\partial t} = D\frac{\partial^2 X}{\partial^2 z} \quad (1)$$

The boundary and initial conditions are written as follows:

$$D\rho_s \frac{\partial X}{\partial z}\Big|_{z=\delta} = -h_m\rho_a(X_s - H_a) \quad (2)$$

$$\frac{\partial X}{\partial z}\Big|_{z=0} = 0 \quad (3)$$

$$X(z,0) = X_0 \quad (4)$$

The mass transfer coefficient of mangoes for slab is computed using the following relationship (Janjai *et al.*, 2008).

$$h_m = \frac{D_a}{L}(2 + 0{,}522Re^{0{,}5}Sc^{0{,}33}) \quad (5)$$

Heat Transfer

The transfer of heat occurs because of the existence of the variation in temperature between the product and the air:

$$\rho\delta C\frac{\partial T}{\partial t} = h(T_{air} - T) - h_m H_v \rho_a (H_a - X_s) \quad (6)$$

Where heat transfer coefficient for forced convection is calculated on the basis of well-known semi-empirical correlation expressing the dependence of Nusselt number up on Reynolds and Prandtl numbers (Perry and Green, 1997).

$$Nu = \frac{hL}{K_a} = 0{,}664Re^{0{,}5}Pr^{0{,}33}$$

Resolution Method

Moisture distribution

To solve the transfer equations, when consider that the geometry of the slabs of products is regular, we chosed a diagram of the finite difference (Patankar, 1980). Thus, a size X will be discretized, then it follows that: i translate the step of space and j the step of time, we have:
Thus, in the center of our section, the equation (3) becomes:

$$X_0^{j+1} = X_1^{j+1} \quad (7)$$

With the external border, the equation (2) leads to:

$$X_n^{j+1} = \frac{D\rho_s}{D\rho_s + h_m\Delta z\rho_a}X_{n-1}^{j+1} + \frac{h_m\Delta z\rho_a}{D\rho_s + h_m\Delta z\rho_a}H_a \quad (8)$$

For the internal nodes, equation (1) is written as:

$$-\frac{D\Delta t}{(\Delta z)^2}X_{i-1}^{j+1} + \left[1 + 2\frac{D\Delta t}{(\Delta z)^2}\right]X_i^{j+1} - \frac{D\Delta t}{(\Delta z)^2}X_{i+1}^{j+1} = X_i^j \quad (9)$$

One leads to an overall system of linear equation which is solved by the matrices method.

Heat Transfer

After discretization, equation (8) becomes:

$$T^{j+1} = \left(1 - \frac{h\Delta t}{\rho\delta C}\right)T^j + \frac{h\Delta t}{\rho\delta C}T_a - \frac{h_m H_v \rho_a \Delta t}{\rho\delta C}(H_a - X_s) \quad (10$$

Results and Discussion

Simulation

The reduced moisture content of the product is obtained by determining the moisture content of each point and for each step of time and by making the average, and then divided by the initial moisture content of the product. While incrementing time, one arrives at a certain number of points which are joined to obtain the graph giving the evolution of moisture content within the product.

In addition, since the equations are coupled, with each step of time one calculates the average temperature of the product which is consigned in a table of value then used to obtain changes in average temperature within the product for various values of the air properties and size of the product. It is summarized in the flow chart below:

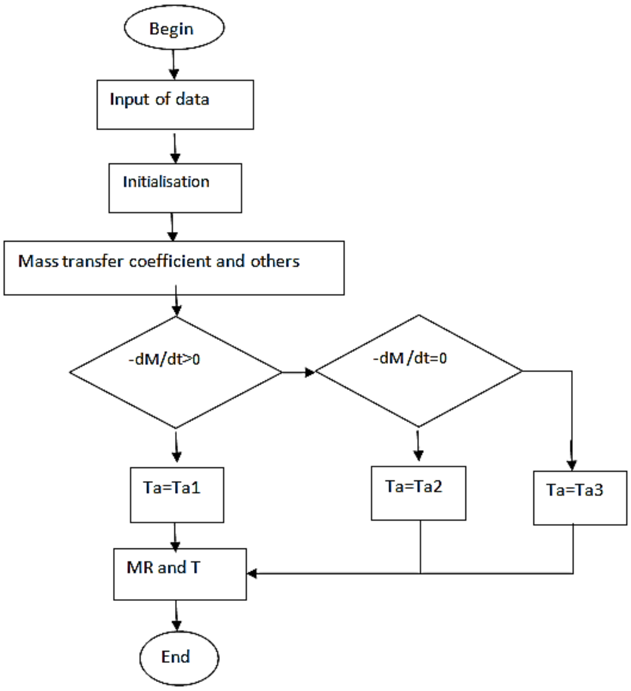


Figure 2: Algorithm

Results analysis

Figure 3 represents the kinetic evolution of water lost at three temperatures. These results were obtained by considering the samples of dimensions 40 x 40 x 15 mm and 40 x 40 x 12 mm, the air velocities of 0.2m/s, 0.5m/s and 0.8m/s, a relative humidity of 0.8 and 0.6 and three temperatures of air drying say 40°C, 50°C and 60°C.

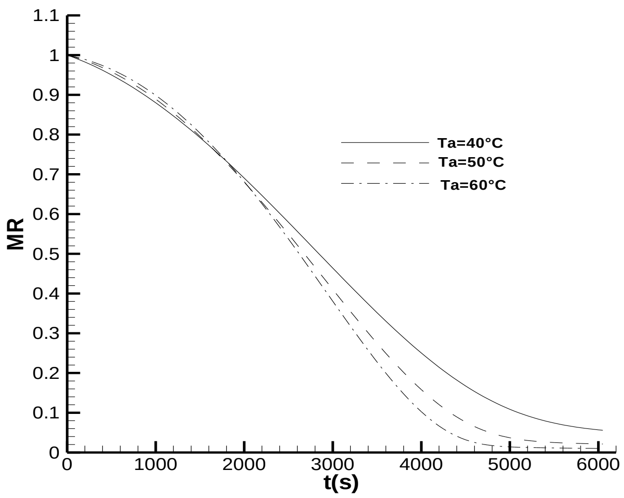


Figure 3: Time-evolution of the moisture content of product at 40, 50 and 60°C (with e=12mm, Va=0.2 m/s, Hr=0.8)

It is observed in Figure 3 an inverse relationship between the drying time and the air drying temperature. It is also observed that increasing the air drying temperature reduces the drying time, which agrees with others studies of mango drying (Pavon *et al.*, 2002; Corzo *et al.*, 2008 and Janjai *et al.*, 2008). To reach the reduced moisture content of 0.1, it requires approximately 5340s for 40°C, whereas it takes practically 3000s for a drying carried out at 60°C. This simulated result is in agreement with other results on the drying of other foodstuffs (Moreira *et al.*, 2005*;* Fernando *et al.*, 2008; Villa-corrales *et al.*, 2010).

Figure 4 represents the evolution of average moisture content using a time-varying inlet air temperature. We observed that when one dries by using sudden variation of temperatures from 60°C, 50°C to 40°C, one needs around 3700s to reach the value of MR of 0.1, whereas approximately 3800s is needed to reach the same MR with 60°C. Therefore, drying using a time-varying inlet air temperature improves the energy efficiency of the drier, which agrees with the works done by several authors during drying of other products (Chua *et al.*, 2001). It is also observed that during drying using a time-varying inlet air temperature, maximum temperature reached by the product was around 44°C, whereas during drying at 60°C the temperature of products at the same time went down to 49°C, and this product would have been during the 5000s exposed to drying air this temperature (Figure 5). Previous works Lavialle, (1993); Chua *et al.*, (2001) have revealed that there is certainly a profit in quality related to the fact that during the drying under variable air temperature products are not exposed for a long time to the temperature of 60°C.

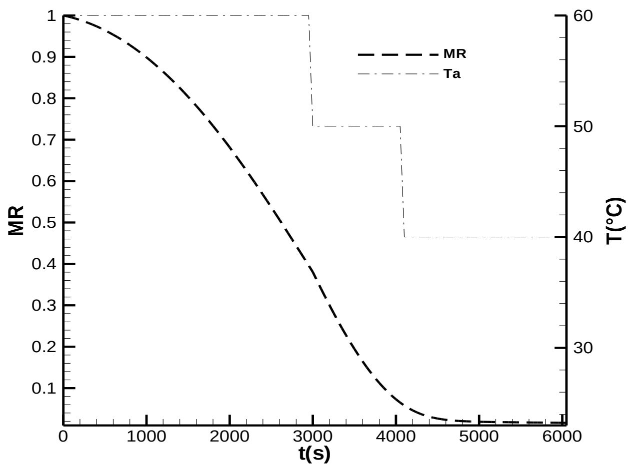


Figure 4: Time-evolution of moisture content of product for various drying temperature (with e=12mm, Va=0.2 m/s, Hr=0.8)

Generally the drying velocity increases up to a maximum of 2950s for the value 0.00027kg/kgdm/s and at the temperature of 60°C after the beginning of the operation (Figure 6). This occurs for the three temperatures corresponding to an average moisture content of 0.4% beyond which the rate starts to decrease. It has been reported that during the constant drying rate the properties of air considerably influence the drying kinetics

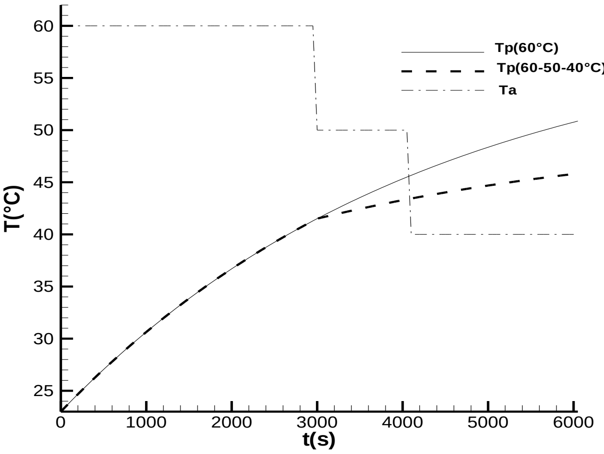


Figure 5: Comparison of time-evolution of product temperature at constant and various drying temperature (with e=12mm, Va=0.2 m/s, Hr=0.8)

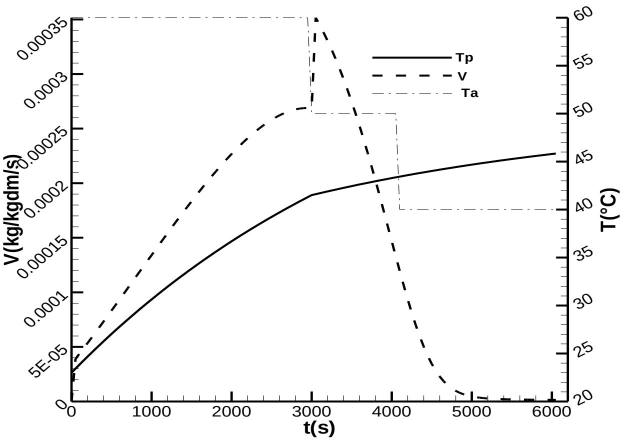


Figure 6: Time-evolution of drying rate of product for various drying temperature (e=12mm, Va=0.2 m/s, Hr=0.8)

(Bennamoun *et al.*, 2006). In order to maintain the high value of the drying rate, we changed the inlet air temperature from 60°C to 50°C. The effect of changes in temperature can be resumed by the sudden increase of the drying velocity to the value of 0.00035 kg/kgdm/s, followed by its decrease till the end of the drying process. This enables us to confirm that this reduction of temperature has contributed to accelerate drying, which can explain why this passage practically eliminated the Soret effect (Magherbi *et al.*, 2007), and this decreased rate was not so significantly after nearly 4600s.

We equally noted in Figure 7 that the delay in the time response was approximately 400s for a change in temperature from 60°C to 50°C and 200s for a change from 50°C to 40°C. Hence, it can be concluded that this operation presents inertia to the sudden increase in temperature. The same phenomenon was observed by Fohr *et al*. (1990) during the drying of building materials. Thus, a sudden increase in the temperature does not present an instantaneous reaction in the product. When compared drying at 60°C and the model developed in this study, we noticed that using our model could reduce the drying time.

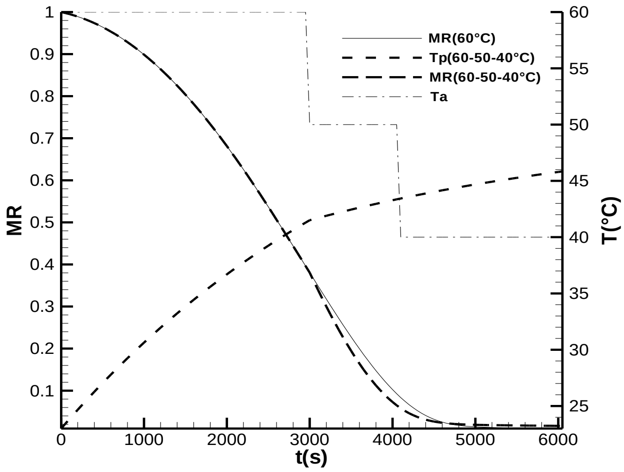


Figure 7: Time-evolution of the moisture content and product temperature for various drying temperature (Hr=0.8, Va=0.2 m/s, e=12mm)

Conclusion

This research has established a relevant and reliable mathematical model describing the transport phenomena involved in mangoes drying under the convective boundary conditions at the surface. The model provides information about drying using a time-varying inlet air temperature. The temperature and moisture content history of mango slice are introduced numerically at varying values of the drying air parameters including temperature, velocity, relative humidity, initial food temperature and its thickness. MR=0.1 is reached at 3900s value under drying at variable conditions, instead of 4100s at 60°C. This process results in a reduced drying time to obtain the desired product moisture. Thus, the thermal efficienty of such a process is high. This model could be useful in the conception phase of a drier adapted to this product to reduce post-harvest losses in tropical zones. Further works could be focused on the quality of final product during drying under variable conditions.

Nomenclature

aw: water activity (-)
C: product specific heat (J/kg/°K)
D : effective diffusivity (m^2/s.)
D_a : effective diffusivity of water in air (m^2/s.)
h : heat transfer coefficient ($W.m^{-2}.°K^{-1}$).
Ha : air moisture content (kg water vapour/kgdry air)
h_m : mass transfer coefficient ($m.s^{-1}$)
H_r : air relative moisture in %.
H_v : heat of vaporization of water (KJ/kg).
K_a : heat transfer coefficient in air($W.m^{-2}.°K^{-1}$).
L : length of food, parallel to air flow (m)
P_a : atmospheric pressure Pa.
P_{tot} : total pressure Pa
P_{vs} : saturate water vapor pressure Pa.
Ta: air temperature (°C)
Tp: product temperature (°C).

t : time (s).
V_a : air velocity ($m.s^{-1}$)
V : rate of drying (kg/kgdm/s)
X: food moisture content (kgwater/kgdry matter)
Xs : interface moisture content (kgwater/kgdry air).
z : spatial coordinate
Dimensionless numbers
Nu: Nusselt number
Pr: Prandtl number
Re: Reynolds number
Sc : Schmidt number
Greek symbols
ρ : density of food ($kg.m^{-3}$)
δ : half thickness of food (m)
ρ_s : density of drying product ($kg.m^{-3}$)
μ_a : kinematic viscosity (kg/m.s).

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