OPTIMIZATION OF HYDRATION PROCESS OF DATE PALM FRUITS FROM EXPERIMENTAL AND NUMERICAL APPROACHES

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ABSTRACT

This study focuses on the hydration process of dates from experimental and numerical investigations. Dry Tunisian Deglet Nour dates were hydrated at a laboratory scale by using saturated air. A theoretical model based on a finite element scheme was developed to describe mass transfer phenomena that occur during the hydration process. This model considers the real shape of dates with a 2D axisymmetric analysis. Both moisture diffusivity and convective mass transfer coefficient of dates were estimated by using an optimization algorithm based on a least square approach from experimental and numerical average moisture contents. Overall, the experimental moisture contents as a function of hydration time were found in good agreement with the simulated values for various operating conditions. Such a methodology can now be used as a predictive tool to simulate the hydration of dates in order to improve the quality of final product and reducing processing time.

Keywords: Dates hydration, modeling, moisture diffusivity, convective mass transfer coefficient

1. INTRODUCTION

In Tunisia, date palm (Pheoenix dactylifera L.), especially the Deglet Nour Cultivar, constitutes an important food and financial source. The chemical composition, in particular moisture content, of Deglet Nour date palm fruits can vary depending on agronomic practices, climatic conditions as well as ripening stage (El Arem et al. 2010). During last years, there has been an increase in the proportion of dry dates in annual crops. These dry dates are processed in the industry in order to obtain fruits similar to those labeled as Extra category dates. Hydration represents the key unit operation of this process. Therefore, the control of this operation is of paramount importance especially when excessive times of hydration could reduce the shelf stability of dates and induce a waste of energy whereas insufficient hydration durations lead to non acceptable final product quality.

2. MATERIAL AND METHODS

2.1. Raw material

Deglet Nour dates were harvested in 2014 and stored at 4°C and 65% of relative humidity.

2.2. Experimental procedure

Hydration experiments were conducted at laboratory scale approaching industrial conditions by placing dates in a closed environment at atmospheric pressure and where air reaches relative humidity of 100% and inner temperatures between 50 and 65°C. To achieve this, a metallic enclosure was filled with water and heated with a temperature controlled hot plate. Dates were placed in the head space of the enclosure without any contact with the water. The level of heating was set in such a way that temperatures of surrounding air medium, which are recorded by thermocouples placed near the dates, remain in the range of desired temperatures during each experiment. The experimental system designed is presented in Figure 1. Average moisture contents of dates flesh were measured at regular intervals during hydration by a method modified from Singh et al. (2013) which consists of drying 3 g of dates in an oven at 105°C for at least 18h.

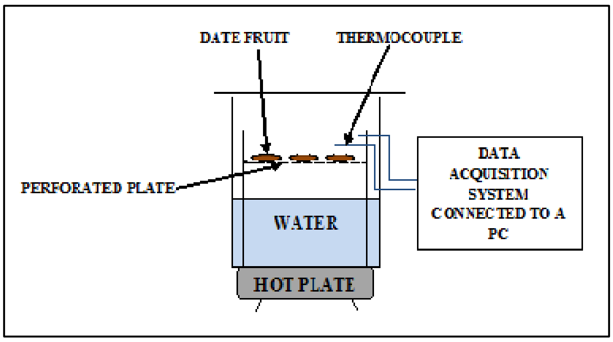

Figure 1: Laboratory Experimental System Designed for Dates Hydration

2.3. Modeling of hydration

Prior to modeling, monitoring of the temperatures within the dates flesh for the range of hydration times used for undertaking experiments showed that the temperature can be considered as homogenous. Therefore a theoretical model based on a finite element scheme was developed to describe only mass transfer phenomena during the hydration operation based on Fick's law according to Eq.(1).

$$\frac{\partial C}{\partial t} = \nabla.(D\nabla C) \quad (1)$$

Where C and D are the instantaneous molar concentration (mol/m^3) and the diffusivity (m^2/s) of moisture within the date flesh. Since that the transport phenomena are symmetric, a 2D axisymmetric domain was considered to represent date flesh as shown in Figure 2.

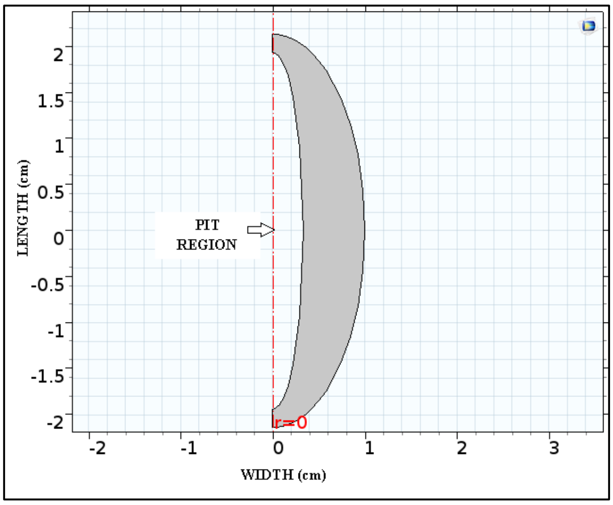

Figure 2: 2D Axisymmetric Domain

The initial and boundary conditions are as follows:

1. Uniform initial moisture molar concentration C_0 which is calculated from Eq.(2).

   $$C_0 = \frac{X_0 \rho_0}{M_w} \quad (2)$$

   Where X_0 , ρ_0 and M_w are the initial average date flesh moisture content on humid basis (kg/kg) , initial density of date flesh (kg/m^3) and the molecular mass of water (kg/mol) .
   ρ_0 is determined using Eq.(3).

   $$\rho_0 = \frac{m_0}{V} \quad (3)$$

   Where m_0 and v are the initial mass (kg) and the volume (m^3) of date flesh.
2. Null mass flux at the surface in contact with the date pit.
3. Natural mass convection at the outer surface in contact with the saturated air. The mass flux $N(mol.m^{-2}.s^{-1})$ of moisture inward date flesh is given by Eq. (4).

$$N = k_c(C_b - C_s) \quad (4)$$

Where k_c , C_b and C_s are convective mass transfer coefficient (m/s), bulk molar water vapor concentration (mol/m^3) and molar water vapor concentration in the air adjacent to the outer surface (mol/m^3).
C_b and C_s are determined using respectively Eq.(5) et Eq.(6).

$$C_b = \frac{P_{vs}}{RT} \quad (5)$$

$$C_s = \frac{P_{vs}}{RT} a_w \quad (6)$$

Where P_{vs} , R and a_w are saturated vapor pressure at the average absolute temperature T (K) of the air, ideal gas constant $(8.314\, J.mol^{-1}.K^{-1})$ and water activity of date flesh. Neglecting sorption hysteresis phenomenon, a_w was defined using the GAB model in Eq.(7) (Kechaou and Mâalej 1999; Kechaou and Mâalej 2000).

$$X = \frac{X_m C k a_w}{(1-ka_w)(1-ka_w+Cka_w)} \quad (7)$$

Where X is the instantaneous moisture content on dry basis(kg/kg). X_m , C and k are the constants of the model.
k_c is determined initially using the correlation for natural mass transfer coefficient around a sphere according to Eq.(8) (Cussler 2009).

$$\mathrm{Sh} = \frac{\mathrm{kcD_{eq}}}{\mathrm{D_{w,a}}} = 2 + 0.6(\mathrm{Gr})^{\frac{1}{4}}(\mathrm{Sc})^{\frac{1}{3}} \quad (8)$$

Where Sh, Gr and Sc are Sherwood, Grashof and Schmidt numbers. D_{eq} is the surface-equivalent sphere diameter of the date (m). $D_{w,a}$ is the diffusivity of the water vapor in air (m^2/s) which is estimated using Eq.(9) (Bolz and Tuve 1976).

$$\mathrm{D_{w,a}} = -2.775 \times 10^{-6} + 4.479 \times 10^{-8}\mathrm{T} + 1.656 \times 10^{-10}\,\mathrm{T}^2 \quad (9)$$

The model was implemented in the software COMSOL®MultiPhysics release 5.1 which solves partial differential equations by using the finite element method. The computational domain is meshed using triangular elements. Date flesh moisture distribution is computed during hydration and the average moisture concentration is calculated as a function of time with the average coupling operator.
Then, by using the optimization module from COMSOL®, both moisture diffusivity and convective mass transfer coefficient at the surface were estimated by minimizing the least-square objective function

calculated from experimental and numerical mean moisture contents. Experimental values were implemented in COMSOL® using equations Eq.(10) and Eq.(11) similar to Eq.(2) and Eq.(3).

$$C_t = \frac{X_t \rho_t}{M_w} \quad (10)$$

Where X_t and ρ_t are the instantaneous average date flesh moisture content on humid basis (kg/kg) and density of date flesh (kg/m^3) . ρ_t is determined using Eq.(11).

$$\rho_t = \frac{m_t}{V} \quad (11)$$

Where m_t and v are the instantaneous mass (kg) and the volume (m^3) of date flesh which is considered constant and equal to the arithmetic mean of initial and hydrated date.

3. RESULTS

Although experiments were conducted for several types of Deglet Nour dates, only results for one type of dates which are slightly harder and drier than labeled Extra category dates are presented. The molar moisture concentration distribution is computed at times when average moisture contents were measured experimentally. Figure 3 illustrates molar moisture profile within the flesh of one date after 14640s (≈ 4h) of hydration at the average temperature of the air during hydration.

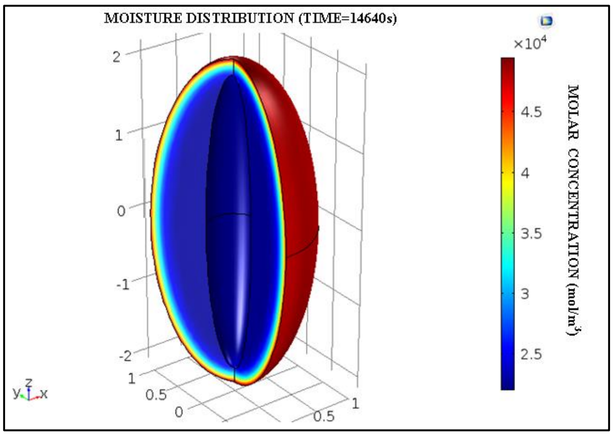

Figure 3: Moisture Concentration Distribution Within Date Flesh After 4h

As mentioned above, the mean water concentration is then computed. The estimation of both moisture diffusivity and mass transfer coefficient by minimizing the least square objective function using Levenberg-Marquardt optimization solver was undertaken as follows:

1. Effective mass diffusivity is estimated by taking initial mass transfer coefficient determined from the Eq.(8).
2. By considering the value of mass diffusivity found from the first run, a second optimization is performed to estimate the mass transfer coefficient.

Table 1 shows the estimated diffusivities and convective mass transfer coefficient for two dates from the considered type.

Table 1: Estimated Moisture Diffusivities and Mass Transfer Coefficients

Date Number	Date 1	Date 2
***D*(m²/s)**	5.54E-11	5.54E-11
***kc* (m/s)**	0.00123	0.00126

The values of estimated convective mass transfer coefficient which depend on the dimensions of dates are consistent with the values found using the correlation for natural convection (Eq.8).
Figure 4 and Figure 5 represent experimental and calculated moisture molar concentration data as a function of time using estimated mass diffusivity and convective coefficient.

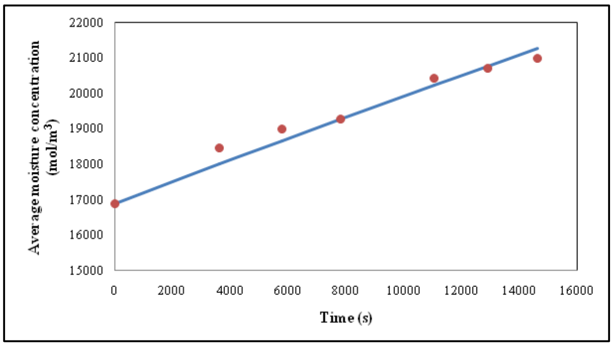

Figure 4: Experimental vs Calculated Average Moisture Concentration Of Date1

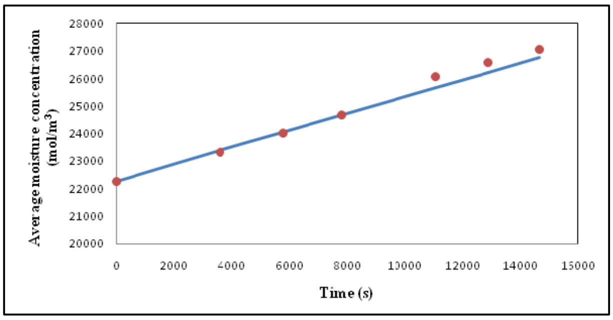

Figure 5: Experimental vs Calculated Average Moisture Concentration Of Date2

It is shown that there is a good agreement between calculated and experimental average moisture molar concentrations.
The root mean square difference (RMS) is also calculated from the Eq. 12 (Kechaou and Maâlej 2000).

$$RMS = \sqrt{\frac{\sum_i \left(\frac{Cav_{i,exp} - Cav_{i,cal}}{Cav_{i,exp}}\right)^2}{n-1}} . 100 \quad (12)$$

Where Cav_i is the average moisture molar concentration at the i-th experimental point.
Table 2 confirms the accuracy of the modeling since that root mean square differences (RMS) do not exceed the value of 1.39%.

Table 2: Root Mean Square Differences Between Experimental and Calculated Curves

Date Number	Date 1	Date 2
RMS (%)	1.39	0.97

It is also seen that the phase of decrease in moisture uptake rate is not observed. It could be explained by the relatively short times of hydration (in comparison to maximum processing times in industry).
The estimated moisture diffusivities and convective coefficients shown in Table 1, Figure 4 and Figure 5 indicate that these values do not vary greatly with the initial average moisture concentration. Therefore, this model can be used to predict times necessary to reach desired final moisture contents by taking into account the variability of raw material for this type of dates.

4. CONCLUSION

Hydration is the key unit operation in the industrial thermal process of dates. However there are a scarce data about the capacity of moisture uptake during hydration. In this work, a theoretical model was developed to describe mass transfer phenomena involved in this operation. The model enables to estimate moisture diffusivity and convective mass transfer coefficient using an investigation performed experimentally. This model can be used to simulate hydration of dates in order to predict and optimize this operation. In addition, the model could be used to optimize the maximum time of hydration. For current industrial applications, this operation often lasts during more than 4h. The proposed modeling approach may thus help for the optimization of this operation in order to enhance the mass transfer at the surface and to reduce the energy consumption during hydration.

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