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Mass Transfer modeling in Date palm *(Phoenix dactylifera)* during hot air convective drying

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ABSTRACT

Quality of food during drying can be affected by a wide range of parameters such as temperature, relative humidity, air velocity and internal mass transfer coefficient. Mathematical modeling of moisture transport during drying is one powerful tool for understanding and control of drying process. In this research, date palms (V. Barhee) in khalal stage were dried as single layer at different temperatures (60, 70 and 80°C) with air velocity of 1.5 m^2/s in a cabinet dryer. A numerical model was developed to describe two-dimensional moisture transfer during drying of dates in the base of Fick's second law of diffusion by finite difference method on MATLAB software. The predicted model was validated by comparison with the experimental values. The predicted results by model showed good agreements with experimental data.

Keywords: Barhi variety, Date Palm, Drying, Modeling, Moisture Transport.

INTRODUCTION

Date palm (Phoenix dactylifera L.) is a monocotyledon of the family of the Palmae. Botanically, date fruit is a berry consisting of a single seed surrounded by a fibrous parchment like endocarp, fleshy mesocarp and the fruit skin (pericarp) and a rich source of carbohydrates comprising mainly of sugars and a good source of vitamins and macro elements like phosphorous, iron, potassium and a significant amount of calcium [1,2]. The production of date fruits in the world is estimated at 6.7 million tons [3]. Dates pass through four stages during their growth and ripening. The first stage is''Kimiri'', refers to young, green-colored dates followed by ''khalal'' stage where the fruit may be yellow, pink, red, or scarlet, or yellow spotted with red, depending upon cultivar. At ''rutab'' stage the fruit starts to soften and loses most of its astringent flavor, with the color changing into yellowish- brown. From there the fruit merges into the final ''tamr'' stage [3]. Most varieties of dates are generally consumed at rutab and tamr stage because of their maturity and desirable flavor. Barhee is one of soft type varieties that is most preferred by consumers, it varies from light yellow at khalal stage to light brown at mature stage and is one of varieties that is suitable for drying at khalal stage.

The moisture content of the fruit vary from 60% at the mature to about 25% at the dried stage [4], safe moisture content for storage of date is between 24% and 25%. Drying of fresh dates is necessary because it contains high moisture (about 60%) which limits the shelf life. Drying is one of the most important post-harvest operations for agricultural products. It is mainly aimed in reducing the moisture content of a product to a level below which deterioration does not occur and the product can be stored for a definite period [5]. Dehydrated dates are used in food preparations like sweets, snacks, confectionery, bakery products and health foods [6]. Commonly agricultural products are dried in open sunlight, which is extremely weather dependent and also exposure to microbial and other contamination [7]. To achieve consistent quality dried product industrial dryers should be used which are rapid and provide uniform and hygienic dried products [8, 9, 10]. The drying kinetics of food is a complex phenomenon and requires simple representations to predict the drying behavior, and for optimizing the drying parameters. A few studies have been conducted to drying of dates and influence of parameters such as temperature, variety, drying rate, etc on date. Kechao et al. (1997) empirically studied drying kinetics of dates [11]. Hassan and Hobani (2000) obtained drying rate of two different date fruit cultivars at three different temperatures and evaluated three empirical drying models [12]. Falade and Abbo (2006) investigated the effect of variety and drying temperature range of 50-80°C on air-drying pattern of date palm fruits [13]. But, no studies were found in literature on drying modeling of dates. The objectives of this study were: (i) to study the drying kinetics of dates in a cabinet dryer at 60, 70 and 80°C and (ii) to evaluate a suitable thin layer drying model.

Mathematical modeling
When the sample is placed into the hot air drier, the sample surface, directly exposed to hot air, is warmed up by convective and evaporation and the surface water evaporate. This results in moisture diffusion toward the product surface. In addition, during drying, moisture transfer creates a water gradient, which is at the origin of another driving force behind the moisture diffusion process and causes moisture profile redistribution.

The mathematical model used to simulate the drying process that takes place in the falling rate period, is two-dimensional Fick's law of mass diffusion. In order to develop the model, we assumed the geometric shape of the samples as a cylinder with constant radius, uniform initial moisture distribution, and symmetrical radial and axial diffusion with constant value of the diffusion coefficient (D_{eff}) throughout drying process. The mathematical equation governing the drying process in a two-dimensional cylindrical object with the appropriate boundary conditions is given as Eq (1) where W is the moisture content of sample and D is diffusion coefficient:

$$[1] \quad \frac{\partial W}{\partial t} = \frac{D}{r}\frac{\partial}{\partial r}\left(r\frac{\partial W}{\partial r}\right) + D\left(\frac{\partial^2 W}{\partial z^2}\right)$$

Nomenclature	RH relative humidity (kg/kg_{db})
M moisture content (kg/kg dm)	t time (s)
D moisture diffusivity (m^2/s)	T temperature (°K)
D0 pre-exponential factor of Arrhenius equation(m^2/s)	
Km moisture transfer coefficient at surface (m/s)	**Greek symbol**
Kg moisture transfer coefficient at surface (Kg/Pa.S.m^2)	ρ density (kg/m3)
H height (m)	**Subscripts**
R radius (m)	d date
r radial coordinate	st stone
z axial coordinate	i initial
n number of nodes in r-direction	m moisture
m number of nodes in z-direction	a air
	s saturation
	app apparent

With the following boundary conditions:
The equations of boundary conditions have been followed as:

$$[2] \quad z = \frac{H_{st}}{2} \Rightarrow -D_{st}\frac{\partial W(r, H_{st}/2, t)}{\partial z} = -D_d\frac{\partial W(r, H_{st}/2, t)}{\partial z}$$

$$[3] \quad z = \frac{H_d}{2} \Rightarrow -D_d\rho_{app,s}\frac{\partial W(r, H_d/2, t)}{\partial z} = k_g(P_s(T_s) - P_a(T_a))$$

[4] $$r = r_{st} \quad \Rightarrow \quad -D_{st} \frac{\partial W(r_{st}, z, t)}{\partial r} = -D_{d} \frac{\partial W(r_{st}, z, t)}{\partial r}$$

[5] $$r = r_{d} \quad \Rightarrow \quad -D_{d} \rho_{app,s} \frac{\partial W(r_{d}, z, t)}{\partial r} = k_{g}(P_{s}(T_{s}) - P_{a}(T_{a}))$$

Eq. (6) describes the diffusion that controls the drying behavior assuming a constant radius R throughout the drying process, and correlates the experimental data by non-linear regression to obtain an effective diffusion coefficient D_{eff}. Effective diffusivity thus obtained can be expressed by using an Arrhenius type equation [14, 15] in the form:

[6]
$$D_{d} = D_{0} \exp\left(-\frac{E_{a}}{RT}\right)$$

where D_0 is the pre-exponential factor (m^2/s), E_a is the activation energy (kJ/mol), T is the temperature of air (°K) and R is the gas constant (kJ/mol °K). E_a and D_0 values are determined by plotting ln (D) as a function of 1/T where the slop of the curve equals –Ea/R and the intercept of the curve indicates ln (D_0).

[7] $$D_{st} = 1e^{-12}$$

[8] $$P_{s}(T_{s}) = a_{w} P_{sat}(T_{s})$$

[9] $$P_{a}(T_{a}) = RH_{a} P_{sat}(T_{a})$$

[10] $$k_{g} = \rho_{air} \frac{M_{w}}{M_{air} P_{atm}} k_{m}$$

K_m is calculated by means of dimensionless numbers method as followed equations:

[11] $$Sh_{x} = 0.332 \; Sc^{1/3} \; \mathrm{Re}_{x}^{1/2}$$

[12] $$Sh_{x} = \frac{K_{m} x}{D}$$

[13] $$Sc = \frac{\nu}{D}$$

Where ν the cinematic viscosity of hot air and D is equals 0.0000159 m^2/s.

[14] $$z = 0 \Rightarrow \frac{\partial W(r, 0, t)}{\partial z} = 0$$

[15] $$r = 0 \Rightarrow \frac{\partial W(0, z, t)}{\partial r} = 0$$

The initial condition is: $W(r, z, 0) = W_{0}$

Numerical method

To describe moisture transfer during drying of dates, each date was considered as a cylinder with measured dimensions. Because of symmetrical transfer of moisture, we solved the equations for half of a date. To facilitate the solutions, equations were solved for a platform by dividing the domain of solution to a grid of points in the form of mesh. r-direction was divided into N-1 space steps using N nodes. Node 1 was the center, and node N the radial surface. Z-direction was divided into M-1 space steps using M nodes. Node 1 was the center, and node m the axial surface. At each node, the moisture transfer equations were applied. In addition, at node 1, N and node M, the boundary conditions for the center and for the surface apply, respectively.

The moisture content values for central nodes were estimated by the following solved equation:

[16]
$$\begin{aligned} W(i,j,t+1) &= W(i,j,t) + dt((D(Wi+1,j,t) - W(i,j,t))((i-1/2/)(i-1))/dr^{2}) \\ &+ (D(W(i-1,j,t) - W(i,j,t))((i-3/2)/(i-1))/dr^{2}) \\ &+ (D(W(i,j+1),t) - 2W(i,j,t) + W(i,j-1,t))/dx^{2})) \end{aligned}$$

The procedure outlined above was implemented using a computer program written in MATLAB language.

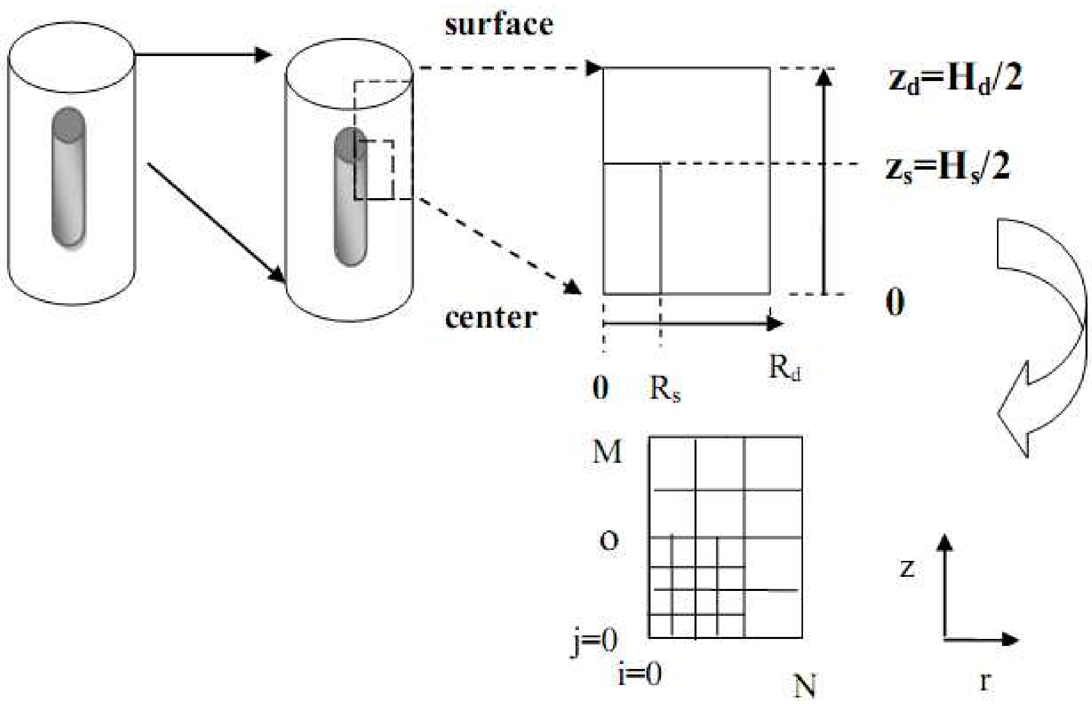

Fig 1. Schematic description of the system model

Parameters used during calculations

The mathematical proposed model can describe the moisture content as a function of time and position, water activity at surface, moisture profiles at axial and radial surfaces and total water loss during drying of dates based on input values of model. These inputs are: characteristics of dryer hot air, sample dimensions, physical properties of sample, initial temperature and moisture content of sample, and the number of nodes in the radial and axial directions and total time of drying. Table (1) shows the Sample physical properties and drying operation conditions.

Table 1. Sample physical properties and the conditions of drying operation

Surface temperature(˚k)	313.15
Air flow rate(m/s)	1.5
Weight of dates(kg)	0.330
Density (kg/m^3)	1151
Volume (m^3)	Density/weight
Temperature of dryer air(˚k)	313.15
Radius(m)	0.0134
Number of radial nodes (m)	15
Number of axial nodes	18
Initial moisture content(kg/kg)	1.857
Height of date(m)	0.0344
Height of stone(m)	0.0184
Radius of stone(m)	0.0041
Drying time(s)	2150
Activation energy(kj/mol)	45.2
D0(m^2/s)	0.0223

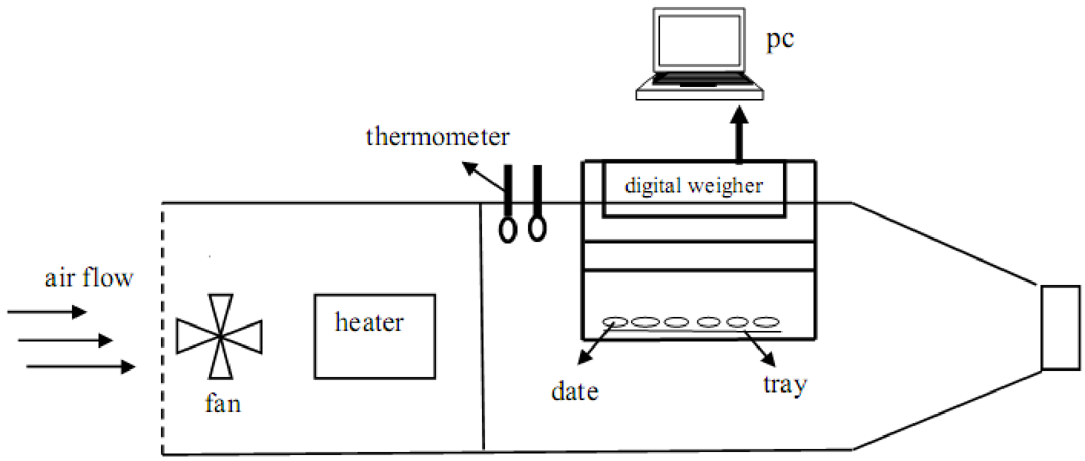

Fig 2. Scheme of Cabinet dryer

MATERIALS AND METHODS

Sample preparation
Dates of Barhee variety at khalal stage were obtained from the palm grove in ABADAN. They were stored at -20°C until they were dried. One hour before drying, they were defrosted by microwave.

Method
Thin-layer drying experiments were conducted at 60,70 and 80°C drying air temperatures in cabinet dryer as shown in (fig2). Each experiment was replicated three times and the average values were used for analysis. Three hundred gram of dates was spread on the tray in the drying chamber .The tray was connected to a weighing machine linked to the computer. Drying was carried out at an air flow rate of 1.5 m/s and the dates' weights were recorded every time. The initial moisture content of dates was determined according to the method of AOAC (1996).

Model Validation
Developed numerical model validation was conducted by checking the agreement between experimental data, obtained under operating conditions and model predictions.

RESULTS AND DISCUSSION

Model validation
As we described, validation of model conducted by comparing between experimental and model predicted datas. Fig. (3) shows plotting experimental data as a function of predicted average water loss from developed model during drying for 70˚C. When the date sample is placed in the dryer, the moisture content decreases and the total water loss increases. if the slope of plot tend to 1 and the ordinate tend to zero, it is indicating good adjustment between experimental and predicted data. As could be seen, the correlation between experimental and predicted water loss values is very well and the root mean square of errors is 0.002, so the results show good agreement between simulation and experimental data.

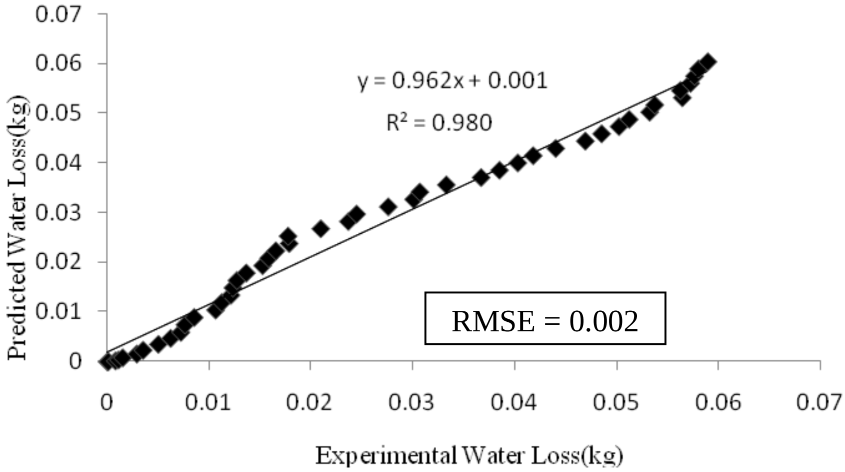

Fig 3. Comparison of predicted water loss with experimental results

Total water loss and moisture profiles

Total predicted water loss of dates during drying process at 60, 7o and 80$^{℃}$ are shown in fig.4. As temprature increases, water loss and water loss rate of dates increases, too. Fig.5 shows profile of the moisture content in the center at axial direction and fig.6 at radial direction. As can be seen, the moisture content of the date at the end of drying is lower at the surface in two directions due to the evaporation on surface because of direct contact with hot air, but moisture content at center decreases rarely due to low moisture diffusion coefficient of date and distance from surface.

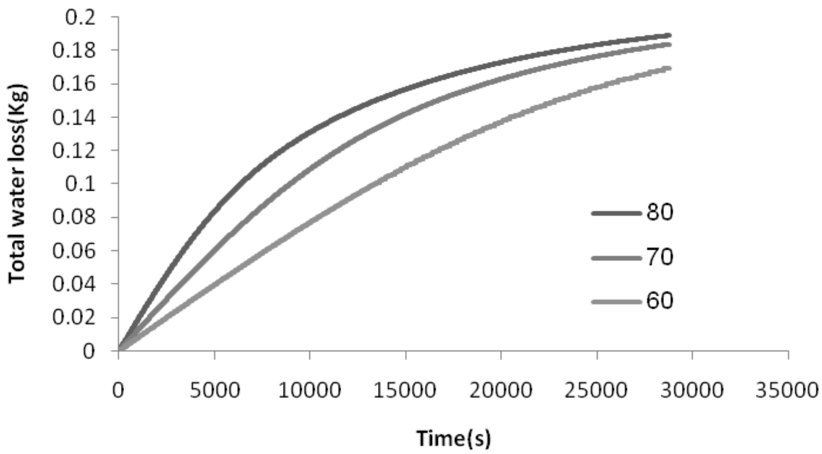

Fig4. Total water loss at 60, 7o and 80$^{℃}$

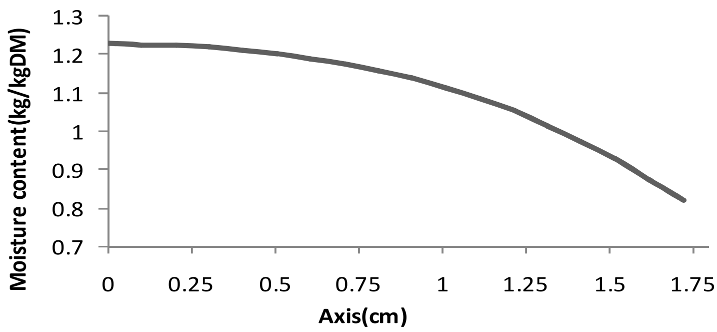

fig.5. Predicted moisture content distributions at center at axial direction

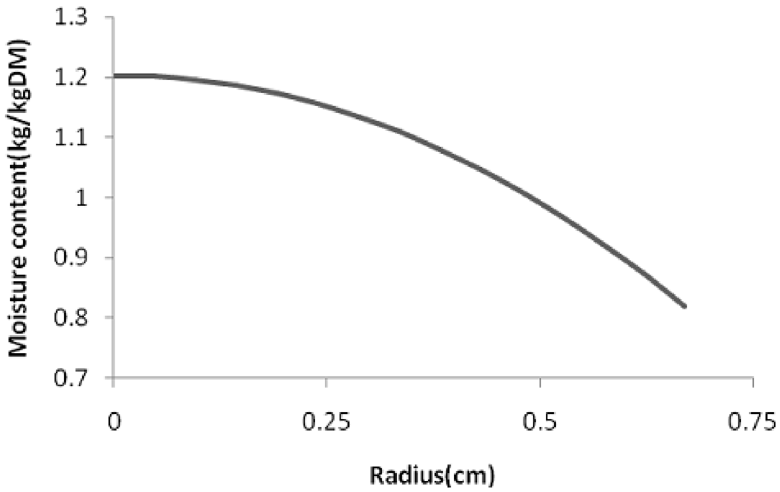

Fig.6. Predicted moisture content distributions at center at radial direction

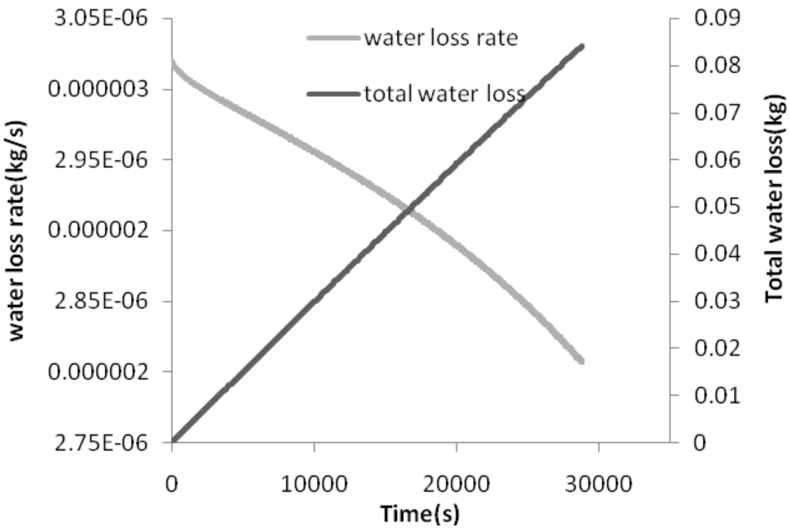

Fig7. Predicted water loss rate and total water loss throughout the drying process

The water loss rate and total water loss obtained from developed model are shown in fig. 7. The water loss rate is highest at the beginning of the drying process because of moisture gradient at the beginning of process. As the total water loss increases, the water loss rate decreases gradually with the time.

Moisture diffusivity and activation energy

The effective moisture diffusivity, D_{eff} of dates increased from $2.1351E^{-09}$ to $72.065E^{-09}$ m^2/s for dates with skin and from $6.4338E^{-09}$ to $1.23633E^{-08}$ m2/s for dates without skin as drying air temperature of a thin-layer dryer increased from 60 to 80°C.

CONCLUSIONS

A numerical model was developed to simulate two-directional moisture transfer in a finite cylinder in the base of Fick's second law of diffusion during drying of dates. The predicted results showed good agreements with experimental results in term of weight loss: the RMSE between experimental results and model predictions is 0.002 for total water loss. It can be concluded that this model, firstly, describes well the mechanisms of moisture diffusion in a two-dimensional moisture transfer during drying of date palms and, secondly, it is appropriate to applied for prediction of moisture profiles and water loss during drying and for better controlling the process and high quality production.

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