

HEAT AND MASS TRANSFER DURING AIR DRYING OF FRUITS

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ABSTRACT

This study included air drying of a single le kernel of fruits (apple, apricot or grape) which is taken as a sphere. Convective heat and mass transfer takes place between the sample surface and its drying environment; while, unsteady heat conduction and moisture diffusion take place within the drying body without phase change for liquid (evaporation occurs at the surface only). The mass, energy conservation equations was solved by using the finite difference technique. A set of empirical correlations have been employed to determine the product properties which assumed to be changed during drying process like (thermal conductivity, specific heat and coefficient of moisture diffusion) and other properties was assumed to be constant through the process as (the coefficients of heat and mass transfer and the density). The results showed that the product temperature is increased and its moisture content will decrease during the drying process. The numerical results were compared with experimental results and showed good agreement.

Key words:Heat and mass transfer, Convective drying, Conduction, Diffusion, Apple, Apricot, Grape.

الخلاصة:

تضمنت هذه الدراسة استخدام الهواء كوسيط تجفيف لعينة مفردة من الفاكهة (تفاح،مشمش،عنب) ذات شكل كروي. يحصل انتقال حرارة بالحمل بين سطح العينة ومحيط تجفيفها بينما يحصل انتقال حرارة بالتوصيل ورطوبة بالانتشار داخل العينة بدون حدوث تغير بالطور للسائل الرطوبي (التبخر يحصل على السطح فقط). تم حل معادلات حفظ الطاقة والكتلة باستخدام طريقة الفروقات المحددة. استخدمت في هذا البحث مجموعة من المعادلات التجربية لحساب بعض خواص المنتج التي افترضنا انها تتغير خلال عملية التجفيف مثل(الموصلية الحرارية،الحرارة النوعية،معامل الانتشار الرطوبي) والبعض الاخر افترضنا قيمته ثابته خلال العملية مثل(معاملي انتقال الحرارة والكتلة بالحمل ،الكثافة). بينت النتائج زيادة درجة حرارة المنتج ونقصان محتواه الرطوبي خلال عملية التجفيف قررنت النتائج مع التنائج وبينت توافق جيد.

INTRODUCTION:

Drying, in general, usually means removal of relatively small amounts of water from material. The purpose of drying food products is to allow longer periods of storage with minimized packaging requirements and reduced shipping weights .In the chemical industries, Drying or dehydration is one of the most important processes used in the processing of food and in the storage of grains [Nalaini 2005].

Food have a high moisture contents which are lost during the drying process this water can be produce important change in size that hinder the analysis of heat and mass transport, so the shrinkage may not be considered[Wu and Yang2004].

Mass transfer can be subdivided into molecular mass transfer and convective mass transfer. Convective mass transfer involves the migration of matter from a surface into a moving fluid or a stream of gas while diffusion deals with the random molecular migration of matter through a medium. Diffusion may be subdivided into molecular diffusion, capillary diffusion. Molecular diffusion is analogous to the

conductive transfer of heat. In heat conduction; energy is transferred from a region of high temperature to a region of low temperature due to the random motion of gas or liquid molecules or the vibration of solid molecules. Similarly, in molecular diffusion, matter is transferred from a region of high concentration to a region of low concentration [Raisul and Mujumdar 2005].

Water moves through the interior of the foodstuff as a liquid or water vapor through various air passageways in the cellular structure of foodstuff and through the cell walls. Water moves by two main mechanisms: capillary action (liquid) and diffusion of bound water (vapor).capillary action causes free water to flow through the cell cavities and pits. Diffusion of bound water moves moisture from zones of high concentration to zones of low concentration caused by differences in moisture content and relative humidity [Edgar Deomano 2001].

MATHEMATICAL MODEL:

The goal of the present model is to describe the drying process for a single kernel of fruits (apple, apricot and grape) fig.(1). This model is based on the fact that during the single kernel drying processes, moisture diffusion and heat conduction dominate inside the kernel and convective heat and moisture transfer take place on the surface.

Geometry and Coordinates System

The geometry under consideration is an isotropic sphere fig. (1), with the drying air flow along the sphere. The radius of the sphere is (R). The coordinate, which is used, is the spherical coordinate (r).

Assumptions

To solve the heat and mass transfer equations some assumptions should be taken to fit this case which is under study, these assumptions are:

- 1. Heat and mass transfer is one dimensional, unsteady state in the radial direction.
- 2. The kernel is considered to be single with spherical object.
- 3. Moisture diffusivity of the kernel was assumed as known function of moisture content and temperature of the product, while thermal conductivity and specific heat as a known functions of the compositions of the food.
- 4. Mass transfer from the kernel is due to concentration gradients.
- 5. Shrinkage may not be considered.
- 6. No chemical reaction.
- 7. No heat generation.

GOVERNING EQUATIONS

Unsteady heat transfer is that phase of the heating and cooling when the temperature changes as a function of location and time. In food process operations, the unsteady state period is an important component of the process. Analysis of temperature variations with time during the unsteady-state period is essential such process Temperature is a function of two independent variables, time and location; hence, the following partial differential equation is the governing equation for a one dimensional case [Frank and David 1996]

Energy equation

$$\rho c_p \frac{\partial T}{\partial t} = k \left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} \right)$$
(1)

Mass transport equation

If the diffusion of moisture is radial, the diffusion equation in spherical system takes the form of:

$$\frac{\partial M}{\partial t} = \left(\frac{D \ \partial^2 M}{\partial r^2} + \frac{2 \ D \ \partial M}{r \ \partial r}\right)$$
(2)

The moisture and heat diffusion equations were solved simultaneously to obtain the distribution and gradients of moisture and temperature developed inside the sphere. The model was then applied to the study of the kernel during the drying process.

Initial and boundary conditions

The initial temperature and moisture distribution are assumed to be uniform; the initial condition for the distribution of temperature is specified as [Frank and David 1996]:

$$T(r, 0) = T_{\circ}$$

The boundary conditions are specified at the center and the surface of the kernel at (r=0), (r=R) for a two dimensional system.

Due to the symmetry, there is no temperature / concentration gradient at the product center (r = 0); therefore, at this boundary the following conditions exist [Moreira 2005]:

$$\frac{\partial T}{\partial r}\Big|_{r=0} = 0 \tag{3}$$

Due to heat transfer at the surface of the kernel by convection and to the geometric center of the kernel by conduction the boundary condition for heat transfer is given by the following equation at (r = R, t > o) [Frank and David 1996]:

$$k A \frac{\partial T}{\partial r}\Big|_{r=R} = h A (T_R - T_\infty)$$
⁽⁴⁾

The initial and the boundary condition for the movement of moisture are given as [Frank and David 1996]:

 $M(r, 0) = M_{\circ}$

Because of the symmetry, also there is no moisture concentration gradient at the product's center; therefore the boundary conditions will be [Moreira 2005]:

$$\frac{\partial M}{\partial r}\Big|_{r=0} = 0 \tag{5}$$

Due to diffusion inside the kernel and convection at the surface, the boundary condition at (r = R, t > 0) [Frank and David 1996]:

$$D\left(\frac{\partial M}{\partial r}\Big|_{r=R}\right) + h_m \left(M_R - M_\infty\right) = 0 \tag{6}$$

THERMAL PROPERTIES CALCULATION:

Thermal properties include specific heat, thermal conductivity and thermal diffusivity, so the methods of calculation for these properties were as follows:

Specific heat calculation:

specific heat is essential part of the thermal analysis of food processing or of the equipment used in heating or cooling of foods. An empirical equation proposed by [Choi and Okos 1983] to calculate specific heat which takes into account the composition of food is:

$$C_{P} = 4.18 W_{W} + 1.711 W_{P} + 1.928 W_{F} + 1.547 W_{C} + 0.908 W_{A} \qquad (kJ/kg K) \qquad (7)$$

Where:

W= mass or weight fraction of each component. The subscript denotes the following component: W = water, P = protein, F= fat, C = carbohydrate, A = ash.

These components were available in the literature by [Desrosier1985] as shown in Table (1).

Thermal Conductivity Calculation:

An empirical equation developed by [Sweat 1986] is for solid and liquid foods to calculate thermal conductivity :

$$k = 0.58 W_W + 0.155 W_P + 0.16 W_F + 0.25 W_C + 0.135 W_A$$
(W/m K) (8)

Most high moisture foods have thermal conductivity values close to that of water. On the other hand, the thermal conductivity of dried foods is influenced by the presence of air with its low thermal conductivity value [Frank and David 1996].

Moisture Diffusivity Calculation:

An empirical equation proposed by [Kiranoudis 1995] to calculate moisture diffusivity for all types of fruits and vegetables is as follow:

$$D = a \exp\left(-\frac{b}{M}\right) \exp\left(-\frac{c}{T}\right)$$
(9)

Where: M = moisture content (kg of water/ kg of dry solid). T = temperature (°C). $a = 1.29 \times 10^{-6}$ b = 0.0725 c = 2044hould be noted that D shares with largel temperature

It should be noted that D change with kernel temperature and moisture content and k, C $_{P}$ change with the compositions of the material while h,h $_{\rho}$ were assumed to be constants.

Calculations of Mass Average Moisture and Temperature content:

 (\overline{M}) and (\overline{T}) can be calculated from the equation below [Haghighi 1988]:

$$\overline{M} = \frac{\int_{V} M_{(r)} dV}{\int_{V} dV}$$
 For every time step
$$\overline{T} = \frac{\int_{V} T_{(r)} dV}{\int_{V} dV}$$
 For every time step

These can be used by using numerical integration (Simpson Rule).

Properties Unused in the Model of Calculations:

Constant properties namely, the heat transfer coefficient, mass transfer coefficient, particle density, initial moisture contents and initial temperatures are calculated experimentally by [Chemkhi, Zagroba and Bellagi 2005] and [Bauman and Ukrainczyk 2005] as shown in Table (2).

NUMERICAL SOLUTION

Digital computers and developed numerical mathematics are widely used for the purpose of solving heat and mass balance equations[Raisul and Mujumdar 2005].most of studied are used numerical analysis to solve heat and mass transfer equations(1),(2),(3) and (4) by using computational methods. In numerical methods, the computational domain is divided into small regions called (meshes) and assuming that the system of the deferential equations is valid over the finite domain. Using some techniques, such as (finite

difference), the system of differential equations transforming into a system of algebraic equations, which are then, solved over the domain at each of the finite meshes. The grid generation can accomplish by using directory (j) in the direction of (R) so every nodes has the axis [()] and time divided into time steps, Δt , so that time can be written= i Δt fig(2). Where:

j is the radial grid index =1, 2, 3....,n

i is the time grid index =1, 2, 3....,m

The method of the numerical solution taken was the (implicit finite difference) technique to solve the transient behavior of the heat and mass transfer equations within the sphere. a one dimensional spherical finite difference framework, consisting of 10 concentric shells of equal thickness, was developed to model the heat and mass transfer in the drying object during the drying.

To convert the (Unsteady state term) which include $\left[\rho c_p \frac{\partial T}{\partial t}\right]$, (forward difference) may used to convert it to an algebraic equation as follows:

$$\rho c_p \frac{\partial T}{\partial t} = \rho c_p \frac{T_{i+1, j} - T_{i, j}}{\Delta t}$$
(12)

To get numerical stability for the (implicit finite difference technique) {which was more stable from another methods like (explicit) or (Crank Nicolson) differences by trying it in the computer program} it can be maintained over much larger values of Δt than for a corresponding explicit method; indeed some implicit methods are unconditionally stable, meaning that any value of Δt , no manner how large, will yield a stable solution [Anderson and Pletcher 1984].

To convert the (R.H.S) of energy equation k

$$k\left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r}\right)$$
 to algebraic terms,

(central difference) may be used as follows:

$$k\left(\frac{\partial^{2}T}{\partial r^{2}}\right) = k\left[\frac{T_{i+1, j+1} - 2 T_{i+1, j} + T_{i+1, j-1}}{\Delta r^{2}}\right]$$
(13)

$$\left(\frac{2}{r}\frac{\partial}{\partial}\frac{T}{r}\right) = \frac{2}{r_j} \left[\frac{T_{i+1,j+1} - T_{i+1,j-1}}{2\Delta r}\right] = \left[\frac{T_{i+1,j+1} - T_{i+1,j-1}}{j\Delta r^2}\right]$$
(14)

An implicit approach is one where the unknowns must be obtained by means of simultaneous solution of the difference equation applied at all grid points arrayed at a given time level, because of this need to solve large system of simultaneous algebraic equations, implicit method are usually involved with the manipulations of large matrices (Anderson and Pletcher 1984).

The (L.H.S) of the mass transport equation $(\partial M/\partial t)$ can be written in finite difference form in the same way of the (L.H.S) of energy equation Also the (R.H.S.) which represent

(Diffusion Term) in mass transport equation
$$D\left(\frac{\partial^2 M}{\partial r^2} + \frac{2}{r}\frac{\partial M}{\partial r}\right)$$
 can be converted to

an algebraic equation by (central difference).

Boundary Condition at the Center of the Kernel:

At (r = 0, t = 0) boundary condition eq. (3) can be converted to algebraic terms by using (forward difference technique) as follows:

$$\frac{T_{i+1, j+1} - T_{i+1, j}}{\Delta r} = 0$$

$$T_{i+1, j+1} = T_{i+1, j}$$

Also in the same way for eq. (5):

$$M_{i+1, j+1} = M_{i+1, j}$$

Boundary Condition at the Surface of the Kernel:

At (r = R, t > 0) boundary condition eq. (4) can be converted to algebraic terms by using both (back ward and forward difference techniques) as follows:

(15)

$$k \frac{T_{i+1,j} - T_{i+1,j-1}}{\Delta r} = h \left(T_{\infty} - T_{i+1,j} \right)$$

$$T_{i+1,j} - T_{i+1,j-1} = \frac{h\Delta r}{k} \left(T_{\infty} - T_{i+1,j} \right)$$

$$c_{1}T_{i+1,j} = c_{2}T_{i+1,j-1} + I \qquad (16)$$
Where:
$$c_{1} = \left(1 + \frac{h\Delta r}{k} \right)$$

$$c_{2} = 1$$

$$c_{3} = -\frac{h}{\Delta} \Delta r$$

$$c_{1} = \left(1 + \frac{h \Delta r}{k}\right)$$

$$c_{2} = 1$$

$$I = T_{\infty} \quad \frac{h \Delta r}{k}$$

At (r =R, t > 0) boundary condition eq. (6) can be converted to algebraic terms by using (back ward difference) as follows:

$$M_{i+1,j} - M_{i+1,j-1} = \frac{h_m \Delta r}{D} (M_{\infty} - M_{i+1,j})$$
$$d_1 M_{i+1,j} = d_2 M_{i+1,j-1} - H$$
(17)

Where:

$$d_{1} = \left(1 + \frac{h_{m}\Delta r}{D}\right)$$
$$d_{2} = 1$$
$$d_{3} = \frac{h_{m}\Delta r}{D}$$

$$H = \frac{h_m \Delta r}{D} M_{\alpha}$$

NUMERICAL ALGORITHM

The algebraic equations after the discretization by the finite difference method were solved iteratively by Tri-Diagonal Matrix Algorithm. The solution procedure contains the following steps:

- 1. Start form initial gauss values of temperature and moisture content distributions inside the kernel.
- 2. Solve the mass transfer eq.(2) to obtain the moisture distributions.
- 3. Solve the boundary condition eq.(6) to obtain the surface moisture content.
- 4. Solve the heat transfer eq.(1) to obtain the temperature distributions.
- 5. Solve the boundary condition eq.(4) to obtain the surface temperature of the kernel.
- 6. Calculate the thermal conductivity and specific heat that are taking into account the composition of food.
- 7. Calculate the mass diffusion coefficient that is dependent on the kernel temperature and moisture content.
- 8. Substituting all the calculated values for the initial ones, going back to step 2 and repeat the subsequent steps until convergence is reached. Convergence was assumed whenever any two successive iterations was less than 10.

RESULTS AND DISCUSSION

The finite difference equations of this study were solved on a digital computer using FORTRAN 95 program.

Figs (3, 6 and 10) show the temperature distribution as a function of radius and time inside the kernel. since the drying process took place from the outer to the center of the product, the temperature of product center is kept increasing gradually during the first hours of the total time of the drying process before it reaching to its equilibrium value after that time; while surface temperature almost change largely in comparison with center temperature during that period, so the smallest temperature values are found close to the center and the highest are found close to the surface.

It is clear that the temperature increase from the center to the surface of the kernel.

Figs (4,7 and 11) show that the moisture content decrease with time until it reaches its equilibrium value after 4.33 hours for apricot,10hours for apple and 16.66 hours for grape. Since the drying process took place from the outer to the center of the product, the moisture of product surface during the first hours decreased largely before it reaching gradually to its equilibrium value after that time; while center moisture change is kept relatively small in comparison with surface moisture during that period. The mass average moisture content decrease with time and a comparison with the excremental research [Raisul and Mujumdar 2005] show good agreement, and that is clear in figs.(5,8 and 12) for apricot, apple and grape respectively. Fig. (9) Shows that the diffusion coefficient increase with the moisture content and time for apple. The curves for apricot and grape coincide with that for apple.

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NOMENCLATURE

Symbol	Definition	Units	
А	Area	m^2	
CP	Specific heat of product at constant pressure	J/kg K	
D	Moisture diffusion coefficient in product	m^2/s	
h _m	Mass transfer coefficient of vapor in air	m^2/s	
h	Convective heat transfer coefficient in air	$W/m^2 K$	
k	Thermal conductivity	W/m K	
М	Moisture content	kg water/kg dry solid	
Mo	Initial moisture content	kg water/kg dry solid	
M∞	Air moisture content	Kg water/kg dry solid	
\overline{M}	Average moisture content	kg water/kg dry solid	
Т	Product temperature	K	
To	Initial temperature of the product	K	
T _R	Surface temperature of the product	K	
Τ∞	Drying air temperature	K	
\overline{T}	Average temperature	К	
t	Time	sec	
R	Radius of product	m	
r	Variable radius of product	m	

Table (1) approximates the composition of fruits and vegetables per (100) g.

Material	water	proteins	fat	carbohydrates	ash
Apple	23	1.4	73.2	1	1.4
Apricot	24	5.2	66.9	0.4	3.5
grape	24	2.3	71.2	0.5	2

Table (2) some properties of samples which are available in the literatures. [ASHRAE handbook 1998]

Material	Density	H.T.C.	M.T.C.	I.M.C.(Kg/Kg)	D.T.(°C)
Apple	840	30	0.029	4.4	60
Apricot	1688	24	0.023	4.7	70
grape	1161	27	0.021	6.6	65



Fig. (1) Mathematical model with initial and boundary conditions



Fig. (2) An implicit finite difference module















