Mathematical Modelling and Simulation of the Mass and Heat Transfer of Batch Convective Air Drying of Tropical Fruits

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ABSTRACT

In the present study, a mathematical model capable of predicting the instantaneous moisture and temperature distribution inside fruit and vegetable material undergoing shrinkage during drying process has been developed. The model takes into account moisture content and shrinkage of material as well as shrinkage dependent effective diffusivity. The mass transfer and heat equations were solved using a numerical technique. For evaluation and validation purposes, the model was applied to drying data obtained from the drying tests carried out on banana slices. An oven dryer was used to conduct the test. Banana slices of approximately 5 mm thickness and 30 mm diameter were dried over a temperature range of 50 ^{o}C and 70 ^{o}C for 6 hours. The predicted results compared favourably with the experimental results. Thus, the experimental results validated the model developed. In addition, empirical drying rate equations are developed. The model is therefore capable of predicting dynamic behaviour of drying of fruits undergoing shrinkage and, as such, it can be used as a design tool.

Keywords: Drying; Mathematical modelling; Shrinkage; Simulation; Moisture diffusivity

1.0 INTRODUCTION

Losses of fruits and vegetables in developing countries are estimated to be about 30-40% of production (Jayaraman and Gupta, 1995). The need to reduce post-harvest losses is of paramount importance for these countries. Drying processes has been one of the oldest technologies among the industrialized processes in the preservation of agricultural food materials or products. This is gaining forces as one of the promising techniques and thus become an object for research studies. It is defined as a process of moisture removal due to simultaneous heat and mass transfer (Ertekin and Yaldiz, 2004; Waewsak et al., 2006). Dried fruits and vegetables have gained commercial importance and their growth on a commercial scale has become an important sector of agricultural industry. The most significant reason for the popularity of dried products is that in dehydrated foods, microorganisms practically do not grow due to the presence of a minimum amount of water and thus they are immune to chemical or enzymatic reactions that could provoke alterations or spoilage in the food. This confers on the dried food longer shelf-life (Agarry and Owabor, 2012). Other reasons include substantial volume reduction as well as product diversity.

Fruits are generally characterized by high initial moisture content, high temperature sensitivity (i.e. colour, flavour, texture and nutritional value subject to thermal deterioration), and shrinkage of materials during drying. The required amount of thermal energy to dry a particular product depends on many factors, such as, initial moisture content, desired final moisture content, temperature and relative humidity of drying air, and air flow rate. Thus, several researchers in recent times have investigated the drying characteristics or behavior of different food materials including fruit and vegetables, sea food products using different drying methods such as open sun drying for grapes ((Togrul and Pehlivan, 2004), banana (Agarry and Owabor, 2012), fish (Jain and Pathare, 2007), and onion slices (Arslan and Ozcan, 2010); solar drying for green pepper (Akpinar and Bicer, 2008), strawberry (Beltagy et al., 2007), Brook mangoes (Dissa et al., 2011), banana (Agarry and Owabor, 2012), and okra (Doymaz, 2011; Ismail and Ibn Idriss, 2013)); and hot air drying for red pepper (Simal et al., 2005), okra (Doymaz, 2005), tomato (Doymaz, 2007), and carrot (Zielinska and Markowski, 2010), respectively.

Many mathematical models have been proposed to describe the drying processes of most of these food materials such as the Newton model (O'Callaghan et al., 1971), Page model (Akpinar et al., 2003), Henderson and Pabis model (Karathanos and Belessiotis, 1999), logarithmic model (Yaldiz et al., 2001), two term exponential model (Akpinar et al., 2003). The drying models are generally classified into three categories which are: the empirical, the semi-empirical and the theoretical models (Toure, 2012). Modeling is essentially a mathematical way of representing processes or phenomena to explain the observed data and to predict behaviour under different conditions (Hadrich and Kechaou, 2004). Mathematical models are very useful in the design and analysis of simultaneous heat and moisture transfer processes. The existing mathematical models are either too simplistic and, hence, deviate significantly from real processes or too complex to have any practical application. It is thus essential to develop a model which should not only be meaningful and relatively simple to use, but also significantly accurate to predict temperature and moisture distribution during drying. Considerable studies have been performed on the drying of agricultural products; however, reliable simulation models to aid the design of cabinet or tray dryers for fruits are few.

Bananas are one of the world most traded fruit in both fresh and processed form (Dandamrongrak et al., 2003). Few researchers have studied the drying of this fruit either as untreated or pretreated form using natural convection and forced air convection (hot air drying) (Sankat et al., 1996; Dandamrongrak et al., 2003; Agarry and Owabor, 2012). At present, there are very few simulation models that represent the batch drying of tropical fruits. As shrinkage in fruits is an observable phenomenon that has a strong influence on the drying rate (Lima et al., 2002), it must be taken into account in order to obtain reliable predictions of performance. Few researchers such as Gekas et al. (1988), Jomma and Puiggali (1991), Clara et al. (1995), and Karim and Hawlader (2005) have considered shrinkage of material during drying in their drying models.

The objective of this study is to develop a mathematical drying model that takes into account uncoupling of heat and mass transfer phenomena and the unidirectional shrinkage of the material to predict the temperature and moisture profiles inside the material. The effect of temperature on the moisture diffusion coefficient in banana drying was also investigated.

2.0 MATHEMATICAL MODELLING

2.1 Material Model

In the present model, the drying material is considered as a thin slab of thickness $L = 2b$ at a uniform initial temperature T_0 and moisture content M_0. The two sides are exposed to an air flow at temperature T_a and relative humidity RH, as shown in Fig. 1. Shrinkage of agricultural products during drying is an observable physical phenomenon, which occurs simultaneously with moisture diffusion and may have a significant effect on mass diffusivity and the moisture removal rate, hence, it is necessary to take into account the effect of shrinkage (Mulet et al., 1987). In vegetables and fruits, the volume of shrinkage is very close to the volume of water loss by dehydration (Suzuki et al., 1976). To simplify the model, the following assumptions were made (Karim and Hawlader, 2005):

(1) Moisture movement and heat transfer are one dimensional (i.e. from the interior to the air–sample interface, and evaporation takes place at the interface).

(2) No chemical reaction takes place during drying, i.e. thermal and chemical properties of material, air and moisture are constant within the range of temperatures considered.

(3) The material undergoes shrinkage as drying progresses.

(4) Uniform distribution of air through the dryer.

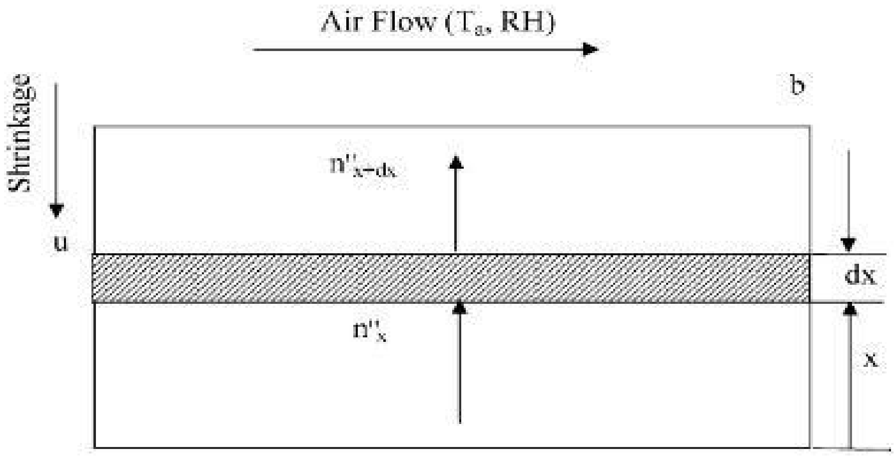

Fig. 1: Elemental control volume in the material sample

It is evident from the schematic representation of the process above that the hot air and the moisture removed from the sample are in a counter current motion.

Modelling from first principle mass conservation equations can be written using Fick's second law

2.1.1 Moisture Transport

Input - output =Accumulation

$$0 - \frac{\partial j}{\partial x}(Ax) = (u\frac{\partial M}{\partial x} + \frac{\partial M}{\partial t})(Ax) \qquad (1)$$

Dividing through by Ax gives

$$-\frac{\partial j}{\partial x} = u\frac{\partial M}{\partial x} + \frac{\partial M}{\partial t} \qquad (2)$$

Recall that flux $J = -D\frac{\partial c}{\partial x}$ (mass transfer flux)

Where C = concentration and M = moisture content

Substitute j into Equation (2)

$$u\frac{\partial M}{\partial x} + \frac{\partial M}{\partial t} = D\frac{\partial^2 M}{\partial x^2} \qquad (3)$$

2.1.2 Mass Transfer Equation

In a macroscopic description, the medium is considered to be the superposition of two continuous interaction media, a solid matrix and a liquid diffusing within the matrix. Thus, in the conservation of the entire mass of the medium during a transformation, two phases are considered (Hadrich and Kechaou, 2004):

- the liquid phase characterized by a velocity of the liquid diffusion $\overline{v}e$;
- the solid phase characterized by a velocity of the diffusion of the solid $\overline{v}s$

The mass balance equations are given as Equations (5) and (6) (Hadrich and Kechaou, 2004):

Liquid phase

$$\frac{\partial \rho_e}{\partial t} + div\,(\rho_e.\overline{v}e) = 0 \qquad (4)$$

Solid phase

$$\frac{\partial \rho_s}{\partial t} + div\,(\rho_s.\overline{v}s) = 0 \qquad (5)$$

In which ρ_e *and* ρ_s are respectively the apparent bulk mass densities of the liquid component and the solid component. The density of material (banana) is considered as $\rho = \rho_e + \rho_s$

If we consider that mass transfer follows Fick's law as given in Eq. (3), then Eqs. (4) and (5) becomes:

$$\frac{\partial \rho_e}{\partial t} + \overline{v}e\frac{\partial \rho_e}{\partial x} = D\frac{\partial^2 \rho_e}{\partial x^2} \qquad (6)$$

and

$$\frac{\partial \rho_s}{\partial t} + \overline{v}s\frac{\partial \rho_s}{\partial x} = D\frac{\partial^2 \rho_s}{\partial x^2} \qquad (7)$$

$D =$ is diffusion coefficient; $\partial t = \text{change in time}$ and $\partial x = \text{change in distance}$. In which moisture (M) is defined as $\frac{\rho_e}{\rho_s}$ *and* $\frac{\partial}{\partial t}$ is the time derivative following the movement of the solid.

The D can be determined experimentally using the following equation suggested by Hawlader et al. (1991)

$$\ln\frac{M}{M_o} = \ln\left(\frac{8}{\pi^2}\right) \quad \pi^2\frac{Dt}{L^2} \qquad (8)$$

When the experimental value of $\ln\frac{M}{M_o}$ is plotted against $\frac{t}{L^2}$, the slope D is our D_{ref}.

This approach is a simplified one and shrinkage is not considered. For the materials undergoing shrinkage, diffusion coefficient D in Eq. (7) and Eq. (8) is not constant (Gekas et al., 1988; Karim and Hawlader, 2005) but varies with moisture content. One way to solve the problem of the shrinkage effect is to incorporate the volume change into the diffusion coefficient. Therefore, to consider the real condition, an effective diffusion coefficient (D_{eff}) is introduced.

$$\frac{\partial \rho_e}{\partial t} + \overline{v}e\frac{\partial \rho_e}{\partial x} = D_{eff}\frac{\partial^2 \rho_e}{\partial x^2} \qquad (9)$$

and

$$\frac{\partial \rho_s}{\partial t} + \overline{v}s\frac{\partial \rho_s}{\partial x} = D_{eff}\frac{\partial^2 \rho_s}{\partial x^2} \qquad (10)$$

Fish (1958) and Crank (1975) have presented methods to determine the functional dependence of D_{eff} on moisture content

$$\frac{D_{ref}}{D_{eff}} = \left(\frac{b_o}{b}\right)^2 \qquad (11)$$

Where 'b' is the thickness of material (half of the length). The thickness ratio is obtained from Eq. (12) (Desmorioux and Moyne, 1992; Qing, 1997):

$$b = bo\left(\frac{\rho_e + \overline{M}\rho_e}{\rho_e + \overline{M}_o\rho_s}\right) \qquad (12)$$

To solve the governing equations, it is necessary to determine the shrinkage velocity. At present, as the shrinkage velocity cannot be predicted and experimental determination is also difficult, Qing (1997) assumption on shrinkage velocity has to be made. This study assumes a linear distribution of shrinkage velocity. Thus at any point in the sample, shrinkage velocity can be expressed as

$$u(x) = u(b)\frac{x}{b} \qquad (13)$$

and velocity at the exposed surface is

$$u(b) = \frac{b - b(old)}{\Delta\tau} \quad (14)$$

Where 'b (old)' is the half thickness of the sample at the previous time step. The density of the specimen is assumed to be uniform at the beginning of drying. In the middle of the specimen, the density gradient is considered zero (x = 0). The initial and boundary conditions of Eqs. (7) and (8) can be written as:

The initial conditions are $\rho_e|_{t=0} = \rho_o$, $\rho_s|_{t=0} = \rho_s$, boundary conditions:

$$\text{At } x = 0,\ \frac{\rho_e}{\partial x}\Big|_{x=0} \text{ and } \frac{\partial \rho_s}{\partial x}\Big|_{x=0} = 0 \quad (15)$$

And at x=b, ρ_e balance can be written as

$$-D_{eff}\frac{\partial \rho\ e}{\partial x}\Big|_{x=b} + u\rho_e|_{x=b} = h_\rho\ (\rho - \rho_{e})_{x=b} \quad (16)$$

And at x = b, ρ_s balance can be written as

$$-D_{eff}\frac{\partial \rho\ s}{\partial x}\Big|_{x=b} + u\rho_s|_{x=b} = h_\rho\ (\rho - \rho_{s})_{x=b} \quad (17)$$

Mass transfer coefficient, h_p can be determined from the following relationships (Mills, 1995; Karim et al., 2005) for laminar flow and turbulent flow, respectively

$$Sh = \frac{h_p L}{D} = 0.332 Re^{0.5} Sc^{0.33} \quad \text{and} \quad (18)$$

$$Sh = \frac{h_p L}{D} = 0.0296 Re^{4/5} Sc^{0.33} \quad (19)$$

2.1.3 Heat Transfer Equation

The equation for conservation of heat can be written as:

(Heat gained in CV - Heat out of CV) + Generation = Heat storage

It is possible to derive the equation for differential heat balance in a similar fashion as that of mass balance. Considering the hypothesis that temperature in the material at any time during drying may be considered uniform. Thus, the final form of the equation is as follows:

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} = \propto \frac{\partial^2 T}{\partial x^2} \quad (20)$$

The boundary conditions are:

$T|_{t=0} = T_o$ and $\frac{\partial T}{\partial x}\Big|_{x=0} = 0$

So the heat balance at the boundary, x=b can be expressed as:

$$\left(k\frac{\partial T}{\partial x} \quad \rho c_m u T\right)\Big|_{x=b} = h(T_a - T)|_{x=b} - h_m \rho (M - M_e) h_{fg}\Big|_{x=b} \quad (21)$$

The heat transfer coefficient can be calculated from the following relationships for laminar (Eq. (22)) and turbulent (Eq. (23)) flow, respectively:

$$Nu = \frac{hL}{k} = 0.332\,Re^{0.5}\ Pr^{0.33} \quad (22)$$

$$Nu = \frac{hL}{k} = 0.0296\,Re^{0.5}\ Pr^{0.33} \quad (23)$$

2.2 Simulating the Model and Method of Solution

The model employed was simulated using MATLAB 7.0 software package. This ensures the determination of bulk densities of the solid and liquids constituent of the material. The finite differential formula applied is:

$$\rho_{i,j+1} = \rho_{i,j} + r(\rho_{i+1,j} - 2\rho_{i,j} + \rho_{i-1,j}) - U(\rho_{i,j} + \rho_{i,j+1}) \quad (24)$$

Numerical method was used to solve the governing differential equations describing the drying characteristics. Physical properties of the fruit considered in this study, being banana, were obtained from the literature (Mohaimen, 1980; Rao and Rizvi, 1986). The values of diffusion coefficient, initial moisture content, equivalent moisture content and shrinkage of the sample were determined experimentally. A computer program in FORTRAN was developed to solve the set of finite difference equations.

3.0 MATERIALS AND METHODS

Fresh, unripe bananas of approximately the same size were used in the drying experiment. Banana slices were prepared first by peeling the skin and then slicing into 5 mm thickness of approximately the same diameter. Approximately 50 g of the sliced banana sample were uniformly spread on a metal tray and then placed in an oven air dryer (Uniscope SM 9053 A Laboratory oven, Surgifriend Medicals, England). Drying was carried out at different three dry bulb temperatures of 50, 60 and 70 ^{o}C). Samples were dried for 6 h, and at one-hour interval samples were withdrawn from the dryer and weighed. The thickness of the material was measured at one-hour intervals to monitor the shrinkage of the material. After each drying test, the samples were dried at 100 ^{o}C for at least 24 h to obtain the bone-dry mass of the material and to determine the moisture content of the original material. The moisture content of both the fresh and dried samples was determined according to AOAC (1980). The average bone-dry mass was 20% of the original mass, which means that fresh banana contains about 80% water. The drying rate of the samples was calculated based on weight of water removed per unit time and per gram of dry matter (solid) and expressed in units of $gg^{-1}\ h^{-1}$ (Dandamrongrak et al., 2003; Agarry et al., 2005).

4.0 RESULTS AND DISCUSSION

4.1 Drying Characteristics: Moisture distribution in material during drying

In the drying operation, it is pertinent to know the temperature and moisture distribution in the sample and its change during drying; the present mathematical model developed is able to predict this. The respective experimental and predicted moisture distribution within the sample as a function of time during drying at air temperature of 50 to 70 ^{o}C is presented in Fig. 2. It can be seen that the moisture content of the banana decreases as the time of drying increases until the equilibrium moisture content will be attained. Since it is difficult to experimentally determine the moisture distribution within a sample (Balaban and Pogott, 1988), moisture distribution inside the sample was not measured in the present study. Only the overall (mean) moisture content was for the entire sample was determined and calculated. The predicted and experimental results show reasonably close agreement, which validates the model that was developed to express drying characteristics. It can be seen that the surface directly exposed to the drying air approached the equilibrium moisture content faster and the changes in the deeper layers of materials are slow.

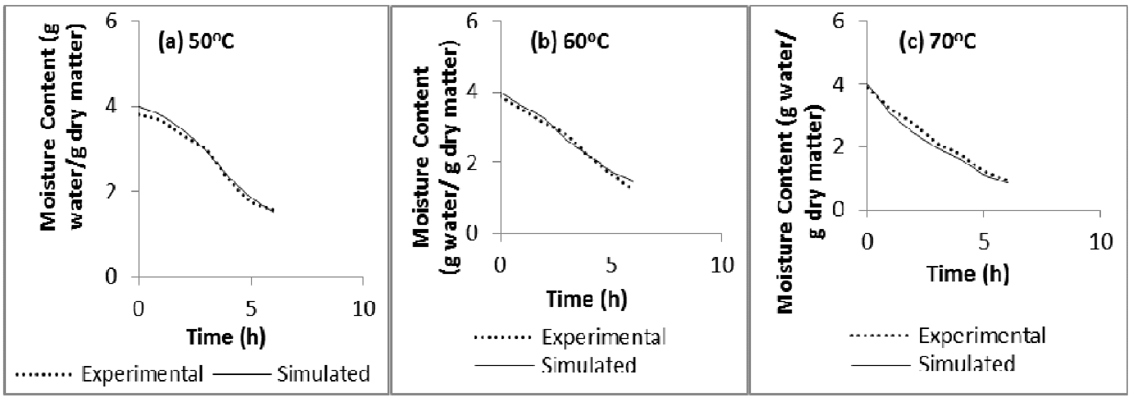

Fig. 2: Experimental and predicted variation of moisture content with time at (a) 50^{o}C, (b) 60^{o}C and (c) 70^{o}C

4.1.2 Material Temperature Distribution

The surface temperature of the sample was recorded continuously during drying. Using a computer programme, temperature was predicted at different locations from the centre of the sample. Fig. 3 shows the predicted temperature distribution inside the sample with time at temperature of 60 °C. The respective experimental surface temperature was also plotted on the same graph. The predicted surface temperatures agreed reasonably well with those obtained from experiment.

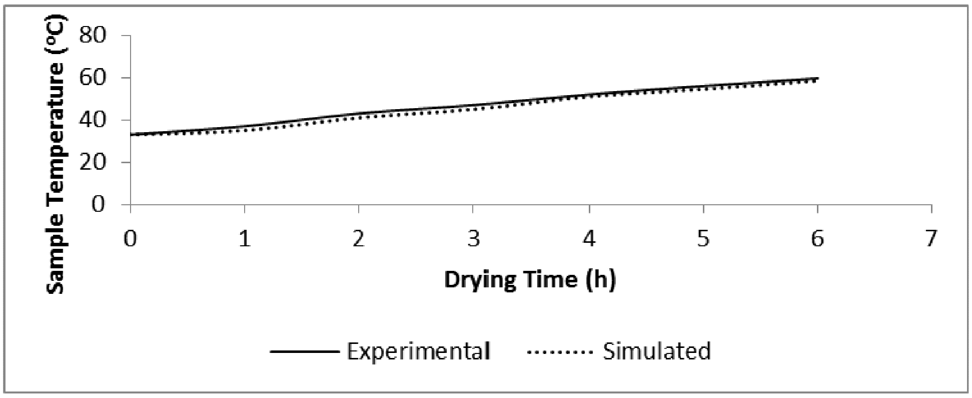

Fig. 3: Temperature distribution in sample during drying at 60°C

4.1.3 Experimental Drying Rate with Time and Moisture Content

Fig. 4 shows the experimental variation of drying rate as a function of moisture content at different drying temperature.

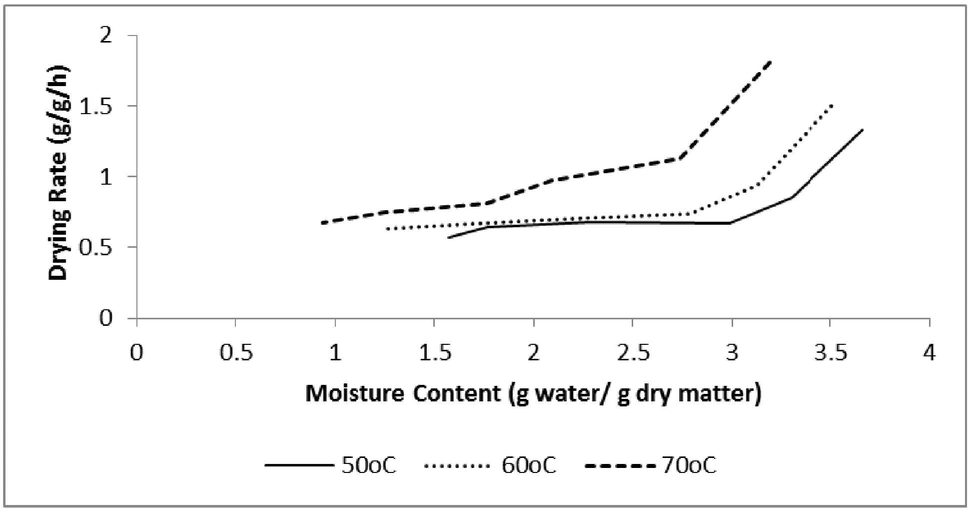

Fig. 4: Plot of drying rate as a function of moisture content at different temperature

It can be seen that the drying rate is not constant throughout the drying period. It constantly drops until the equivalent moisture content of the product will be reached. From Fig. 4, it is evident that the rate of drying increases with increase in temperature. The initial drying rate was increased from 1.333 g/(g-h) at a drying temperature of 50 °C to 1.811 g/(g-h) at a drying air temperature of 70 °C. This observation implies that drying rates of food material are majorly dependent on the temperature in which the material is exposed. No evidence of constant drying rate period can be found in the drying curves presented in this figure. This result is in agreement with previous studies (Hawlader et al., 1991; Desmorieux and Moyne, 1992; Maskan, 2002; Turhan and Demirel, 2003; Agarry and Owabor, 2012). The relationship between drying rate and moisture content at different drying temperatures is presented in Table 1. From these equations it is possible to estimate the drying rate at any condition of moisture content of the material.

Table 1: Relationship between drying rate and moisture content at different drying temperature

Drying Temperature (^oC)	Relationship between drying rate and moisture content
50	$d_R = 0.034M^4 + 0.025M^3 - 1.369M^2 + 4.126M - 2.838$
60	$d_R = 0.161M^4 - 1.241M^3 + 3.463M^2 - 4.073M + 2.339$
70	$d_R = 0.231M^4 - 1.646M^3 + 4.245M^2 - 4.455M + 2.309$

Fig. 5 shows the experimental variation of drying rate as a function of drying time at different drying temperature. Also, from Fig 4, it can be seen that at different drying temperature of 50 ^oC to 70 ^oC the drying rate decreases with increase in drying time.

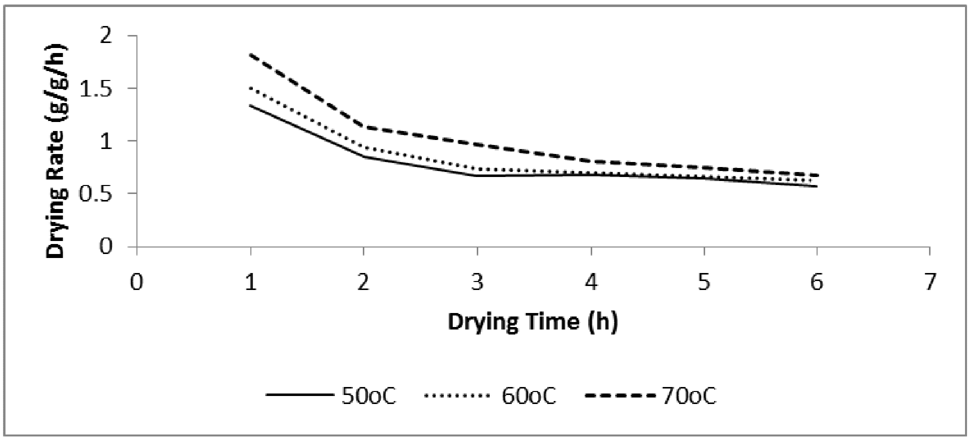

Fig. 5: The plot of drying rate as a function of drying time at different temperature

The relationship between drying rate and drying time at different temperatures is shown in Table 2. Drying time required can be estimated from these equations. In these equations d_R indicated the relationship of drying rate with moisture content (M) and drying time (t_d), respectively.

Table 2: Relationship between drying rate and drying time at different drying temperature

Drying Temperature (^oC)	Relationship between drying rate and drying time
50	$d_R = 0.002t_d^{\,4} - 0.054t_d^{\,3} + 0.435t_d^{\,2} - 1.448t_d + 2.397$
60	$d_R = 0.004t_d^{\,4} - 0.081t_d^{\,3} + 0.568t_d^{\,2} - 1.766t_d + 2.775$
70	$d_R = 0.008t_d^{\,4} - 0.141t_d^{\,3} + 0.861t_d^{\,2} - 2.379t_d + 3.459$

4.1.4 Effective Diffusion Coefficient

The moisture transfer (water transport) during drying was described by applying the Fick's diffusion model. The experimental drying curves obtained at the different drying temperature were adjusted to the Fick's diffusion equation as given in Eq. (25):

$$MR = \frac{8}{\pi^2} \exp\left[\frac{-D_{ref}}{4L^2}\pi^2 t\right] \qquad (25)$$

Where D_{ref} is reference moisture diffusivity (m^2/s), t , drying time and L , thickness (m).

When the experimental values of $\ln MR$ are plotted against t/L^2 , the slope of the curve is a measure of reference diffusivity. Fig. 6 shows such a plot for the drying of banana at 50 ^oC to 70 ^oC.

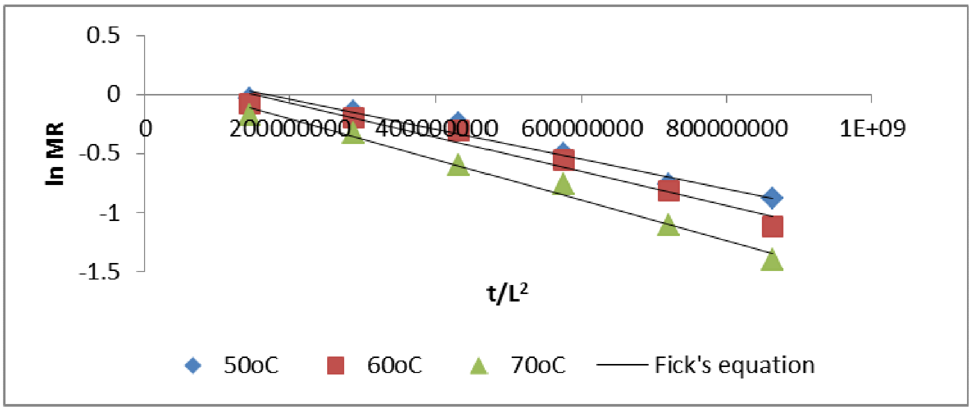

Fig. 6: Plot of ln MR against t/L^2 to determine moisture diffusivity

The good linear adjustment to this equation with determination coefficient (R^2) ranging from 96-98% at the three different drying temperature showed that drying of banana is well represented by the diffusion model proposed by Fick; and this allowed for the calculation of the moisture diffusivity (D_{ref}) at the different drying temperature, respectively. It can be seen that the slope of the curve, i.e. diffusivity decreases as the drying progresses. This is expected as the shrinkage and hardening of the material offer increasing resistance to moisture diffusion (Karim and Hawlader, 2005). This result differs from the results reported by Hawlader et al. (1991) for tomato drying. They reported an increasing slope of the curve, hence increasing diffusivity towards the end of drying. In Eq. (25), the thickness L was assumed to be constant throughout the drying process. However, experiments and literature show that the thickness of a sample is not constant, but shrinks significantly (Karim and Hawlader, 2005). For example, in one of the present experiments the final thickness of banana was 3.25 mm, which is 65% of the initial thickness. To take this shrinkage into account, Eq. (11) was used to obtain the effective moisture diffusivity throughout the drying process. The diffusivity calculated from Eq. (25) was considered as the reference moisture diffusivity. Experimentally determined reference moisture diffusion coefficients of banana at the different drying temperature considered in this study are presented in Table 3. The results show that the reference moisture diffusivity for banana slices ranged from 3.29 to 5.07 × $10^{-11} m^2/s$. These values are within the general range 10^{-11} – $10^{-9} m^2/s$ for drying of food materials (Doymaz, 2005; Kaleemullah and Kailappan, 2006; Sacilik and Elicin, 2006; Doymaz, 2007; Honoŕe et al., 2014). The results in Table 3 showed that effective moisture diffusivity increased with increase in drying temperature. A similar observation has been reported for increase in diffusivity coefficient as air drying temperature increases (Rahman and Kumar, 2007; Sobukola, 2009; Kadam et al., 2011; Khawas et al., 2014).

Table 3: Values of effective moisture diffusivity for oven air drying of banana slices

Drying Temperature (°C)	Moisture diffusivity (D_{ref})× 10^{-11}	Determination Coefficient (R^2)
50	3.29	0.97
60	3.80	0.96
70	5.07	0.98

Conclusion

A mathematical model describing simultaneous heat and mass transfer processes is proposed to describe the drying characteristics of the product being dried. The mathematical model provides a good prediction of the drying rate, temperature and moisture distribution of food material with time. Experiments were conducted using banana samples to evaluate the results predicted by the model. Since the material model agreed closely with the experimental values, the mathematical formulations and the related assumptions are considered reliable to predict the performance of dryers. Empirical drying rate equations are developed. These equations will be helpful in the estimation of the drying rate at any moisture condition of the material and in the estimation of the drying time for a particular task.

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