Finite Element Simulation of Moisture Content Changes of Peeled Banana (*Musa x paradisiaca* L.) during Drying

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Abstract

This paper presents finite element simulation of drying of peeled banana. A two-dimensional finite element model was developed for simulation of moisture content changes during drying of peeled banana. The finite element simulation model was programmed in Compaq Visual FORTRAN version 6.5. Classical models for moisture diffusivity, sorption isotherm and volumetric shrinkage of peeled banana were experimentally determined and used in the finite element simulation. The finite element model prediction was compared with the experimental data. The agreement between the simulated moisture content changes and the experimental data was in reasonable agreement with a discrepancy in root mean square error being in the range of 2.2-14.6%. Moisture content change profiles inside peeled banana during drying were predicted and these profiles give a good picture of the moisture movement inside peeled banana during drying.

Keywords: Drying; Peeled banana; Finite element; Moisture diffusion

Introduction

Plenty of several varieties of banana (*Musa x paradisiaca* L.) are grown in Thailand. One of the most popular varieties of banana in Thailand is "Namwa" available throughout year and due to its good taste and nutrition. Variety of fresh and ripe banana of variety "Namwa" is shown (Figure 1a).

The "Namwa" are not only consumed as fresh but also as dried fruits which are not only for preservation but also for modification of its taste, flavour and texture to meet Thai consumer preferences as well as for value addition. To produce dry bananas, the fresh and ripe "Namwa" are peeled and whole fruits are dried called "peeled banana" (Figure 1b). The annual production of dried Namwa banana in Thailand is estimated to be 6,000 tons for domestic consumption and international export.

To enhance the production of high quality dried banana, information on moisture distribution inside the banana during drying is essential. Nowsaday, the finite element method is capable of predicting moisture distribution inside fruits during drying (Irudayaraj, Haghighi, & Stroshine, 1992; Janjai et al., 2008; Janjai et al., 2010; Montanuci, Perussello, de Matos Jorge, & Jorge, 2014; Nilnont et al., 2012; Pankaew, Janjai, Nilnont, Phusampao, & Bala, 2016; Prasad, Joy, Venkatachalam, Narayanan, & Rajakumar, 2014; Ranjan, Irudayaraj, Reddy, & Mujumdar, 2004; Vagenas & Marinos-Kouris, 1991).

Several studies have been reported on the banana drying methods and processes (Alagbe, Daniel, & Oyeniyi, 2020; Baini & Langrish, 2007; Baini & Langrish, 2008; da Silva, e Silva, & Gomes, 2013, 2014 & 2015; Janjai, Chaichoet, & Intawee, 2005; Janjai et al,. 2009; Jannot, Talla, Nganhou, & Puiggali, 2004; Kadam & Dhingra, 2011; Kiburi, Kanali, Kituu, Ajwang, & Ronoh, 2020; Prachayawarakorn, Tia, Plyto, & Soponronnarit, 2008; Saha, Bucknall, Arcot, & Driscoll, 2018; Schirmer, Janjai, Esper, Smitabhindu, & Mühlbauer, 1996; Smitabhindu, Janjai, & Chankong, 2008; Takougnadi, Boroze, & Azouma, 2020; Tunckal & Doymaz, 2020). Most of these studies dealed with dryers and drying kinetics of banana. None of these studies provided the accurate moisture distribution and moisture content change profiles inside the banana during drying.

Although, the finite element modeling has been advanced and used in many scientific and engineering applications (Babbar, Underhill, Stott, & Krause, 2014; Chowdhury, Wang, Chiu, & Chang, 2016; Gu, Kasavajhala, & Zhao, 2011; Kapidžić, Nilsson, & Ansell, 2014; Karaağaçlı, Yıldız, & Nevzat Özgüven, 2012; Kaye & Heller, 2006; Rodríguez-Sánchez, Ledesma-Orozco, & Ledesma, 2020; Zhao et al., 2019), its applications in drying of fruits is still relatively limited. In 2004, Ranjan and coworkers reported the finite element simulation of heat and mass transfer of banana slices considering a rectangular boundary. However, the data did not provide accurate moisture distribution profiles inside the peeled banana relating to the transport process as well as the changes of moisture content profile during drying.

To the best of our knowledge, systematic finite element simulation study on peeled banana drying has not been reported. Therefore, this study aimed to develop a finite element simulation model of peeled banana considering the irregular boundary of the peeled banana for accurate prediction of the moisture movement and moisture content change profiles inside the peeled banana during drying.

Herein, the finite element simulation of moisture transfer inside the peeled banana was investigated. Models of moisture diffusivity, sorption isotherm and volumetric shrinkage of peeled banana were experimentally determined to support the finite element simulation of moisture transfer inside the peeled banana during drying. The Visual FORTRAN version 6.4 was used for simulation of peeled banana drying. In summary, the finite element simulation of the drying of peeled banana provided useful information of the moisture transfer profiles inside the banana as well as powerful support for the design of drying processes and banana dryers. This is because the finite element model allows those who dry banana to know the moisture content inside banana during drying. In addition if they want to optimize the drying process or optimize banana dryers, they have to formulate objective function for the optimization of the drying process or objective function for banana dryers, which can be evaluated using appropriate drying model and the finite element model can be used accurately for the evaluation (Bala & Woods, 1995; Smitabhindu et al., 2008).

(a) (b)

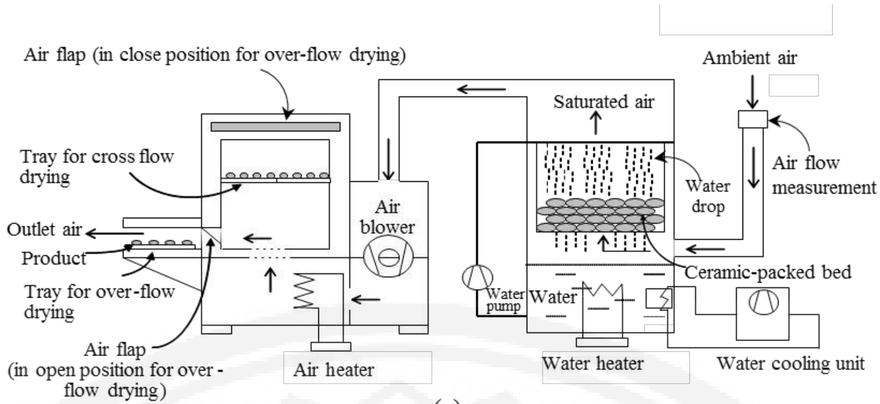
Figure 1 a) Fresh and ripe “Namwa” banana b) Peeled “Namwa” banana

Materials and Methods

The materials used in this study were Namwa banana variety, laboratory dryer and equipment for determining sorption isotherm. The methods employed in the study were described as follows.

Experimental study

The banana used in this study was collected from a local market in Nakhon Pathom, Thailand and stored at room temperature for 10 hours. This banana has ripeness degree of 7 according to the classification of Von Loesecke (1950) with the total soluble solid of 27.6 °Brix. Each banana was peeled before starting the thin layer drying experiments. Dried thin layers drying of peeled Namwa bananas were used for determination of the finite element model by comparing the finite element model predictions with the experimental data of dried thin layer of peeled bananas. The moisture diffusivity of peeled banana were also determined. The thin layer drying of peeled banana was conducted under controlled of temperature of 40, 50 and 60°C and relative humidity of 20 - 40% in a laboratory dryer (Figure 2). Peeled banana was dried as a whole fruit. The dryer consisted of a ceramic packed-bed used to saturate the air at the dew point temperature of the desired drying air temperature, an electrical heater, a blower, a drying section, measurement sensors, data recording and controlling system. Referring to dryer, the blower supplies the drying air and forces the air into the humid ceramic packed-bed where the humidity was controlled by the spray of hot or cold water at controlled temperature from the top of the packed-bed. When the air is forced through the humid ceramic packed-bed, it absorbed moisture and ultimately becames saturated. Subsequently the saturated air was heated to the desired drying air temperature by using electric heater and was passed through the peeled banana that were previously placed on a drying tray (over-flow drying). The relative humidity and temperature of drying process were controlled by adjusting the dew point temperature of the air at the exit of the humid ceramic packed-bed by using a psychometric chart as a guideline prior to heating the air to the desired drying air temperature.



(a)

(b)

Figure 2 The laboratory dryer: (a) Schematic diagram (b) Pictorial view

The dryer was pre-operated for approximately one hour to stabilize the drying air temperature and relative humidity before starting any experiments. All the experiments were conducted at an air speed of 1.0 m/s. Drying temperatures were monitored by using a K type thermocouple at an interval of 10 min. The weight of banana was recorded by an electronic balance (Kern, model 474-42, accuracy ± 0.01g) at an interval of 1 hr. The thin layer drying tests of peeled banana were conducted in the temperature and a relative humidity of 40-60°C and 20-40%, respectively.

Uncertainty Analysis

Herein, the uncertainty analysis was conducted for estimation of experimental error and accuracy. Uncertainty analysis refers to the uncertainty or error in experimental data that can be categorized as systematic error and random error, respectively. The systematic error can be reduced by a calibration whereas the random error is unavoidable but it can be statistically quantified.

The variable x_i that has an uncertainty Δx_i is expressed as indicated in equation (1) (Doiebelin, 1976; Holman, 1978; Schenck & Hawks, 1979):

$$x_i = x_{mean}(\text{measures}) \pm \Delta x_i \quad (1)$$

The x_i is actual value while x_{mean} is measured value (mean value of the measurements) and Δx_i is uncertainty in the measurement. There is an uncertainty in x_i which may be as large as Δx_i. The value of

Δx_i is the precision index which is usually 2 times of the standard deviation and includes approximately 95% of the population for a single sample analysis. In this study, statistical analysis was carried out to estimate root mean square error (RMSE) between the finite elements predicted moisture content and experimentally determined values, and coefficient of determination (R^2).

Development of Finite Element Model for Peeled Banana

The moisture content changes of peeled banana during drying can be expressed as shown in equation (2) (Bala, 2017):

$$\frac{\partial M}{\partial t} = \nabla \cdot (D \nabla M) \tag{2}$$

where M, D and t refer to moisture content on dry basis, moisture diffusivity and time, respectively.

In formulating the finite element model for simulation of moisture content changes, it is assumed that the drying process is isothermal, peeled banana is relatively homogeneous, initial moisture content is uniform and the moisture transport within peeled banana is two directional. Under these assumptions, the equation (2) in two dimensions can be written as shown in equation (3).

$$\frac{\partial M}{\partial t} = D\left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2}\right) \tag{3}$$

The initial and boundary conditions are shown in equation (4) and (5)

at $\quad t = 0, \quad M = M_0 \quad$ (4)

and $\quad t > 0; \quad -D\frac{\partial M}{\partial n} = h_m(M_s - M_e) \quad$ (5)

where "h_m" is the mass transfer coefficient, "M_0" is initial moisture content, "M_s" is surface moisture content on dry basis, "M_e" is the equilibrium moisture content on dry basis and "n" is the magnitude of a normal vector to the surface.

Using Galerkin's weighted residual method, equation (3) can be modified to equation (6).

$$\int_{\Omega} [N]^T \left[D\left[\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2}\right] - \frac{\partial M}{\partial t} \right] d\Omega = 0 \tag{6}$$

where $[N]$ is a matrix of interpolating function and Ω is the peeled banana domain.

Evaluating the weighted residual integral and using Green's theorem, the first order differential equation (7) is developed where [c], [k], and {M} are expressed in equation (8), (9) and (10).

$$[c]\frac{d\{M\}}{dt} + [k]\{M\} = \{f\} \tag{7}$$

where

$[c]$: element capacitance matrix = $\int_{\Omega}[N]^{T}[N]d\Omega$ (8)

$[k]$: element stiffness matrix = $\int_{\Omega} D\left(\frac{\partial[N]}{\partial x}\frac{\partial N}{\partial x}+\frac{\partial[N]}{\partial y}\frac{\partial N}{\partial y}\right)d\Omega$ (9)

$\{M\}$: vectors of unknown, which can be defined as $M=[N]\{M\}$ (10)

$\{f\}$: element force vector.

When the element matrices [c] are summed up with the element matrices [k] by using the direct stiffness procedure, the first order differential equations are modified as shown in equation (11) (Segerlind, 1984):

$$[C]\left\{\frac{\partial M}{\partial t}\right\}+[K]\{M\}=\{F\} \tag{11}$$

where $[C]$: global capacitance matrix

$[K]$: global stiffness matrix

$[F]$: load force vector.

Equation (11) can be rewritten in the finite difference form indicated in equation (12).

$$([C]+\Delta t[K])\{M\}_{t+\Delta t}=[C]\{M\}_{t}+\Delta t\{F\}_{t+\Delta t} \tag{12}$$

where Δt is the time step.

Then, the final system of equation (11) can be derived as shown in equation (13).

$$[A]\{M\}_{t+\Delta t}=[P]\{M\}_{t}+\{F_{*}\} \tag{13}$$

where $[A]=([C]+\Delta t[K])$

$[P]=[C]$

and $\{F_{*}\}=\Delta t\{M_{e}\}_{t+\Delta t}$ (14)

Moisture diffused from the inner side to the outer surface of banana through uniform diffusivity. To analyze the profiles of the moisture changes during drying of peeled banana, a two dimensional finite element triangular grid was constructed. The domain of the whole peeled banana in two dimensions was solely taken into account because of the irregular geometry of the peeled banana. The domain consisted of banana flesh and the finite element discretization of the peeled banana in two dimensional sections consisting of 664 nodes and 1230 triangular elements (Figure 3). Although, the mesh independence test was not carried out, the dimension of peeled banana is comparable to that of mango which worked well with 100 triangular elements (Janjai et al., 2008), therefore the use of 1,230 triangular elements should be sufficient for the finite element calculation.

The moisture content obtained from the finite element was averaged. The average moisture content of banana was calculated using the method proposed by Haghighi and Segerlind (1988).

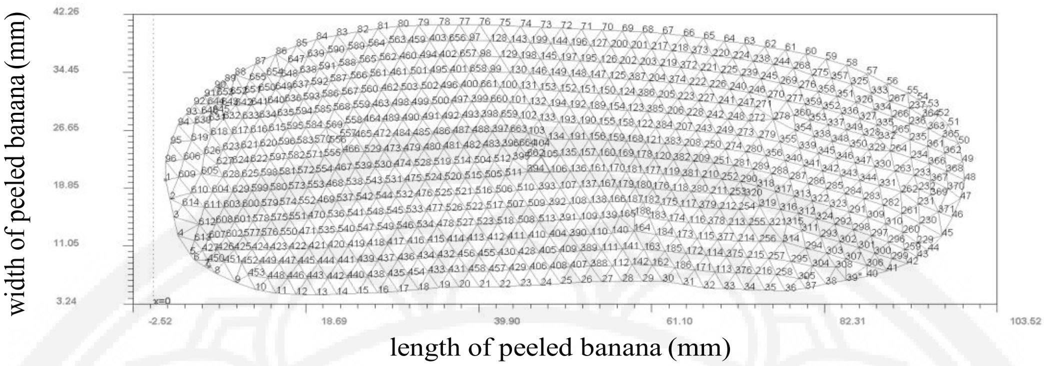


Figure 3 Mesh distribution and geometry considered in the finite element model of peeled banana

Thermo – physical Properties of Peeled Banana

Moisture diffusivity of banana

Peeled banana was assumed to have a cylindrical shape and the analytical solution of the Fick's law of diffusion for peeled banana was fitted to the experimental data of drying of peeled banana to determine moisture diffusivity of peeled banana. The diffusivity (D in $m^2 \cdot s^{-1}$) of peeled banana was expressed as a function of the absolute temperature of banana (T_{ab} in K) using the Arrhenius type equation to develop equation. As the energy equation was not established to solve for the temperature of banana, the temperature of the banana was assumed to be equal to the temperature of drying air which was measured in the dryer. Due to the fact that the banana was dried at each temperature in the dryer for quite long time so that this assumption was justified. With the data from the experiments, the following equation was obtained.

$$D = 9.869 \times 10^{-6} \exp(-2527.53 / T_{ab}) \qquad (15)$$

This equation was used to compute the moisture diffusion within peeled banana in the finite element simulation.

Equilibrium moisture content of peeled banana

Equilibrium moisture contents of peeled banana were experimentally determined according to the method for determining the equilibrium moisture content of longan (Dimocarpus longan Lour.) (Janjai et al., 2006). The desorption isotherm curves were constructed from five models of isotherms, namely Day and Nelson (1965), modified Halsey (Champion & Halsey, 1953; Pankaew et al., 2016), modified Chung-Pfost (Chung & Pfost, 1967; Pankaew et al., 2016), modified Oswin (1946) (Pankaew et al., 2016) Kaleemullah and Kailappan (2004) using the experimental data of the experimental isotherms of peeled banana. The result revealed that the modified Oswin model was the best to fitt equilibrium moisture model for peeled banana. Then, the empirical model was specifically developed for peeled banana as shown in equation (16).

$$a_w = \frac{1}{1+\left[\frac{389.6555+(-1.0562)T}{M_e}\right]^{2.8370}} \quad (16)$$

where T is temperature (°C), a_w is water activity (decimal) and M_e is equilibrium moisture content (%, db).

Shrinkage

In general, volume shrinkage of biological materials is a function of moisture content (Souraki & Mowla, 2008). In this study, volumetric shrinkage of peeled banana during drying was experimentally determined using the laboratory dryer. Physical dimensions and the weight of peeled banana during drying were measured to determine its volume and moisture content, respectively. The volume of the peeled banana was determined from the physical dimensions and the moisture content at any time during drying. The initial values of moisture content and weight as well as the weight at that time were determined. The experimental data of volumetric shrinkage of peeled banana (V/V_i) fitted well to the experimental data of moisture content ratio (M/M_0) as indicated in equation (17):

$$\frac{V}{V_i} = 0.351 + 0.648\frac{M}{M_i} \quad (17)$$

where V_i is initial volume of peeled banana with the moisture content M_i and V is volume of peeled banana having moisture content M. This shrinkage model was used in the numerical solution of the finite element model.

Surface mass transfer coefficient

The surface mass transfer coefficient of banana (h_m) is computed according to Patil and Subbaraj (1988) as shown in equation (18).

$$h_m = \frac{D_{air}}{d}\left(2.0 + 0.522\,Re^{0.5}\,Sc^{0.33}\right) \quad (18)$$

where D_{air} is diffusivity of moisture in air ($m^2 \cdot s^{-1}$), d is equivalent diameter of peeled banana (m), Re is Reynolds number and Sc is Schmidt number. Air diffusivity values used for the simulation are 2.346×10^{-5} $m^2 \cdot s^{-1}$, 2.489×10^{-5} $m^2 \cdot s^{-1}$ and 2.632×10^{-5} $m^2 \cdot s^{-1}$ for the temperature of 40°C, 50°C and 60°C, respectively (Cengel, Turner, Cimbala, & Kanoglu, 2008).

Reynolds number (Re) and Schmidt number (Sc) can be defined as shown in equations (19) and (20).

$$Re = \frac{ud\rho_{air}}{\mu} \quad (19)$$

$$Sc = \frac{\mu}{\rho_{air}D_{air}} \quad (20)$$

where u is air velocity ($m \cdot s^{-1}$), d is equivalent diameter (m), ρ_{air} is air density ($kg \cdot m^{-3}$), D_{air} is diffusivity of moisture in air ($m^2 \cdot s^{-1}$) and μ is air viscosity ($N \cdot s \cdot m^{-2}$)

Method of solution

The solution was started with the computation of equilibrium moisture content (M_e) using equation (16) while surface mass transfer coefficient (h_m) of peeled banana was computed by using equation (18). These were substituted in the element equations at the surface of peeled banana. Then, the element equation (7) was assembled in form of the global equation (11) with triangularized element resolving by using the method of back substitution prior to computation of average moisture content. The process was repeated until final average moisture content was achieved.

Results and Discussion

Finite element model for peeled banana drying was simulated to predict the moisture content changes and moisture content profiles inside the peeled banana during drying by using the model program in Compaq Visual FORTRAN version 6.5. The simulated averaged moisture contents of the whole peeled banana during drying were compared with the experimental values at the temperature of 40-60°C and relative humidity of 20-40% in order to validate the model. The discrepancy in terms of root mean square error (RMSE) was in the range of 2.2-14.6% whereas the coefficient of determination (R^2) was in the range of 0.97-0.99. These results indicated that the moisture content obtained from the model and that from the experiment were correlated. The comparison of the finite element predicted moisture contents with the experimental data of peeled banana for T_a of 40-60°C and RH of 20-60% is shown in Figure 4.

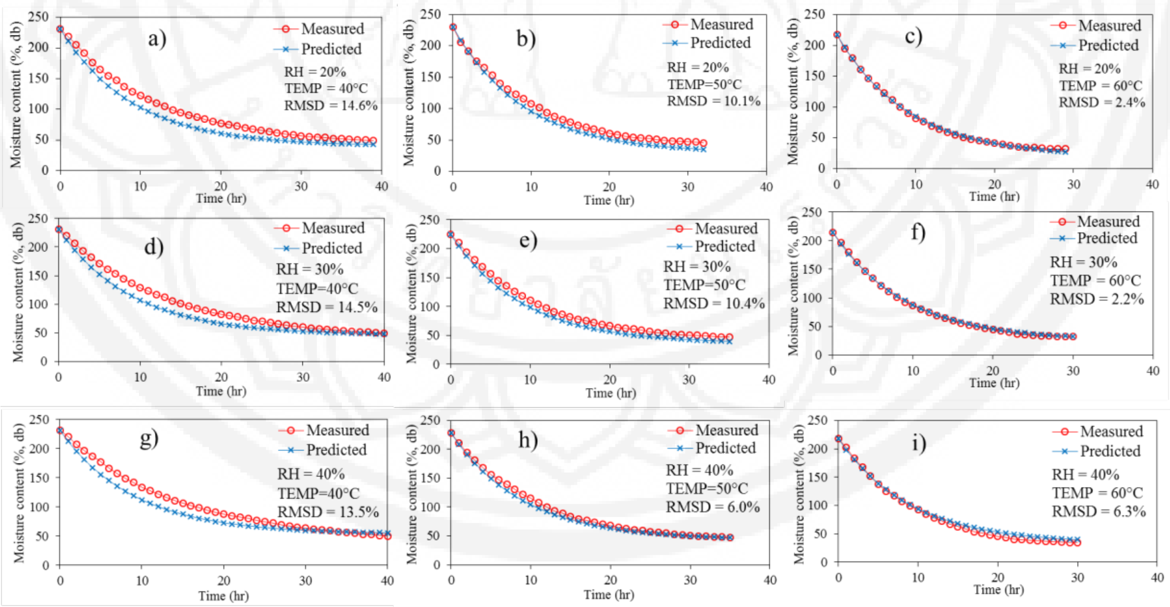
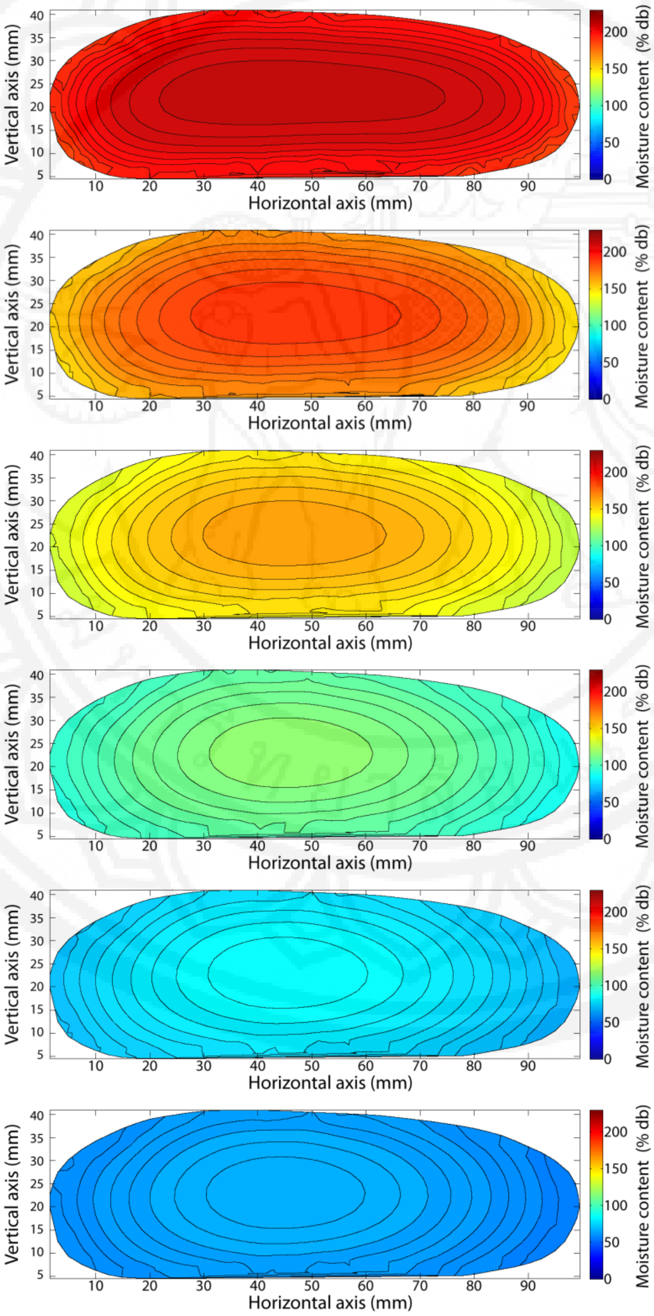


Figure 4 Comparisons between average moisture contents obtained from the finite element model with those from the experimental data for T_a of 40-60°C and RH of 20-60%.

Figure 5 shows the distribution of the predicted moisture contents inside banana at various times of drying of the peeled banana for drying air temperature of T_a = 50°C and relative humidity of RH = 20% and this figure revealed that the dried zone and drying front move further inside the peeled banana with passage of time until the peeled banana was fully dried to moisture content in equilibrium with drying air. The data was corresponded to those report by Janjai and coworkers that the patterns of moisture profiles inside mango slices for finite element simulated drying of mango slices.

The result in Figure 5 can be directly used to determine appropriate drying time for drying of banana and in this case the drying time of 30 hours is appropriate drying time as the moisture content distributed homogeneously inside banana already with the final moisture content corresponding to the final moisture content required by consumers in Thailand. If ones wants to rigorously optimize the drying operation they have to set up an objective function and this finite element model can be used to find operational parameters which minimize or maximize the objective function (Bala & Woods, 1995; Smitabhindu et al., 2008).



1 hour drying time

3 hour drying time

5 hour drying time

10 hour drying time

15 hour drying time

20 hour drying time

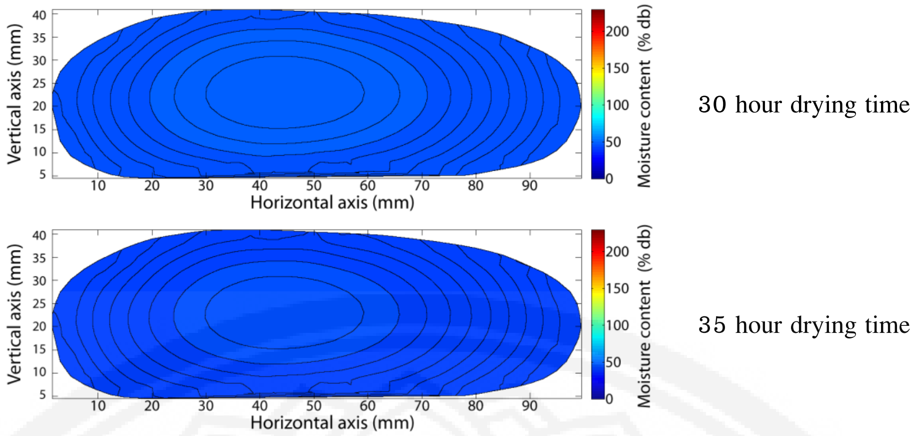


Figure 5 Distribution of moisture contents inside the peeled banana for different drying times, at drying condition of T_a = 50^{o}C and RH = 20%

Conclusions

A two-dimensional finite element simulation model has been developed for prediction of the moisture content of peeled banana during drying. The models for moisture diffusivity, sorption isotherm and volumetric shrinkage were determined from experimental data and these models were used in the finite element modeling. The finite element model can predict the moisture content distribution inside peeled banana during drying and the average moisture contents estimated from this distribution reasonably correlated to the average moisture contents of whole fruit of peeled banana obtained from the drying experiments. The model was quite capable to provide the information on the dynamics of moisture movement and progression of moisture content profiles during drying of peeled banana for its use in the operation and design of banana dryers. Finally, this model has high potential for optimal design of banana dryers.

Nomenclature

[A] intermediate parameter matrix

a_w water activity (decimal)

[C] global capacitance matrix

[c] element capacitance matrix

D moisture diffusivity ($m^2 \cdot s^{-1}$)

D_{air} diffusivity of air ($m^2 \cdot s^{-1}$)

d equivalent diameter (m)

$\{F\}$ global load force vector

$\{F_*\}$ intermediate parameter vector

$\{f\}$ element load force vector

h_m mass transfer coefficient ($m \cdot s^{-1}$)

[K] global stiffness matrix

[k] element stiffness matrix

M moisture content of product on dry basis (%, db)

M_o initial moisture content of product (%, db)

M_e equilibrium moisture contents of banana on dry basis (%, db)

M_s surface moisture content on dry basis (%, db)

$[N]$ matrix of interpolating function

n magnitude of the outward normal vector to the surface

[P] intermediate parameter matrix

R correlation coefficient

RH relative humidity (%)

Re Reynolds number

RMSE root means square error (%)

Sc Schmidt number

T_a air temperature (ºC)

T_{ab} absolute temperature of the product (K)

t time (s)

u air velocity ($m \cdot s^{-1}$)

x spatial coordinate in x direction

y spatial coordinate in y direction

Δt time step (s)

ρ_{air} density of air ($kg \cdot m^{-3}$)

μ viscosity of air ($N \cdot s \cdot m^{-2}$)

Ω banana domain

∇ operator $\frac{\partial}{\partial x}\hat{i}+\frac{\partial}{\partial y}\hat{j}+\frac{\partial}{\partial z}\hat{k}$

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