

NUMERICAL SIMULATION OF HEAT AND MASS TRANSFER INSIDE A SINGLE RICE KERNEL DURING FLUIDIZED BED DRYING

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ABSTRACT

In paddy drying process, heat and mass transfer plays a crucial role in moisture content and temperature inside paddy grain kernel. Therefore, it is essential to gain insight the process. In this study, three-dimensional transient heat and mass transfer model was developed to predict moisture content and temperature inside a single rice kernel during hot air fluidized bed drying. The model was solved using Comsol Multiphysics[®] simulation program, which uses the finite element method to solve the model equations. The simulations were performed at four drying air temperatures of 90, 110, 130 and 150 °C, initial moisture content of rice kernel of 28% dry basis, drying air velocity of 2.5 m/s and drying time of 300 s. The model results were then compared to the experimental data obtained at the same conditions. The result showed that the change with time of temperature and moisture content of paddy grain varied with the drying air temperature in trend of exponential line. In the initial period of drying course, the change of paddy grain temperature and moisture content varied rapidly. The change of temperature is faster than that of moisture content.

Keywords: Paddy drying model; Single rice kernel; Finite element method; Fluidized bed drying

INTRODUCTION

The application of drying models is important in the estimation of the drying rate and the design of a drier. Most mathematical models that describe the drying process involve coupled heat and mass transfer equations with suitable initial and boundary conditions. Several heat and mass transfer models in the literature have been developed for predicting moisture and temperature distributions in rice kernels of different shapes and sizes.

Developing mathematical models for irregularly shaped rice kernels is complex and hence, in most modelling studies, the shape of rice kernels was assumed geometrical such as spheres, spheroids or ellipsoids. The model governing equations can be solved in one, two or three dimensions by numerical methods such as the finite difference, finite volume or finite element methods [1]. It had been found that when compared to experimental or source data, the ellipsoid kernel shape in combination

with the finite element method provided a more accurate result than did other shapes and numerical methods.

Different varieties of rice such as Caloffor-nian M206 [2], Lemont [3] and Cypress [4], which are different in its properties and shape size, had been studied by various researchers. Researchers typically used tray dryers and low drying air temperature (below 60°C), yielding long drying times. Therefore, the present study utilized the fluidized bed drying technique of which advantages include high drying air temperature (above 90°C) and fast drying rates.

The purpose of this study is to develop a three-dimensional (3D) transient heat and mass transfer model for investigating the changes of moisture content and temperature inside a single rice kernel during thin layer fluidized bed drying.

MODEL DEVELOPMENT

The paddy grain kernel was modeled as ellipsoid in Cartesian coordinates and the finite element method was employed. The model was validated with the experimental results of the reference works. Main assumptions for the model developed in this study were as follows. The grain kernel was a homogeneous and isotropic material. The initial distributions of temperature and moisture content inside the grain kernel were uniform. The moisture diffused from the interior to the grain surface in liquid form. The evaporation of water occurred only at the grain surface. Only heat conduction took place within the grain kernel. Only convective heat and mass transfer took place at the paddy grain surface and the shrinkage or deformation of paddy grain kernel during drying was negligible. Based on the above assumptions, the governing equation of transient heat and mass transfer corresponding to Fourier's law of conduction and Fick's second law of diffusion can be written as follows [5, 6].

Heat transfer model

$$\rho_p c_p \frac{\partial T_p}{\partial t} = k_p \left(\frac{\partial^2 T_p}{\partial x^2} + \frac{\partial^2 T_p}{\partial y^2} + \frac{\partial^2 T_p}{\partial z^2} \right) \quad (1)$$

where T_p is the paddy grain kernel temperature ($^{\circ}\text{C}$), t is the time (s), c_p is the specific heat capacity of paddy grain ($\text{J/kg}^{\circ}\text{C}$), k_p is the thermal conductivity of paddy grain ($\text{W/m}^{\circ}\text{C}$) and ρ_p is the density of paddy grain (kg/m^3).

Mass transfer model

$$\frac{\partial M_p}{\partial t} = D_{\text{eff}} \left(\frac{\partial^2 M_p}{\partial x^2} + \frac{\partial^2 M_p}{\partial y^2} + \frac{\partial^2 M_p}{\partial z^2} \right) \quad (2)$$

where M_p is the moisture content of paddy grain kernel (d.b.), D_{eff} is the effective moisture diffusivity inside the grain kernel (m^2/s).

Boundary Conditions

Corresponding to the above assumptions, the heat and mass transfer equations at the paddy grain surface are given by

$$k_p \frac{\partial T_p}{\partial n} = h_c (T_a - T_p) + \rho_p L_{\text{ev}} \frac{V_p}{A_p} \frac{\partial M_p}{\partial t} \quad (3)$$

$$D_{\text{eff}} \frac{\partial M_p}{\partial n} = h_m (M_e - M_p) \quad (4)$$

where T_a is drying air temperature ($^{\circ}\text{C}$), M_e is equilibrium moisture content of drying air on the paddy grain surface (d.b.), n is gradient normal to paddy grain kernel surface, D_{eff} is effective moisture diffusivity (m^2/s), h_c is convection heat transfer coefficient ($\text{W/m}^2^{\circ}\text{C}$), h_m is surface mass transfer coefficient (m/s), L_{ev} is latent heat of vaporization of water on the grain surface (J/kg), A_p is surface area of a paddy grain (m^2) and V_p is volume of a paddy grain (m^3)

Initial Conditions

$$\text{At } t = 0: \quad T_p = T_i \text{ and } M_p = M_i$$

where T_i and M_i is the initial temperature ($^{\circ}\text{C}$) and the initial moisture content of paddy grain (d.b.), respectively. The parameters in equation 3 and 4 were determined by the following relationships. Latent heat of vaporization of water (L_{ev}) at the grain surface calculated from Brooker et al. [7].

$$L_{\text{ev}} = (25008 - 2.3668T_p)(1 + 2.496 \cdot e^{-21.733M_p}) \times 10^3 \quad (5)$$

Determining the effective moisture diffusivity (D_{eff}) by applying in Arrhenius equation form (Markowski et al. [8]), which can be expressed as

$$D_{\text{eff}} = D_0 \exp(-E_a / RuT_p) \quad (6)$$

where D_0 is diffusivity constant (m^2/s), E_a is activation energy (J/mol), Ru is universal gas constant (8.314 J/molK). T_p is the paddy grain kernel temperature (K). The values of D_0 and E_a are $4.518 \times 10^{-7} (\text{m}^2/\text{s})$ and 22431.2 J/mol , respectively, which are estimated from a single kernel drying obtained from Chungcharoen [9].

The equilibrium moisture content of drying air on the paddy grain surface (d.b.) can be calculated from Laithong [10]

$$M_e = 0.01 \left(\frac{\ln(1 - RH)}{-3.2184 \times 10^{-6} (T_a + 198.1434)} \right)^{1/2.66} \quad (7)$$

where RH is relative humidity of drying air (decimal).

For convective heat transfer coefficient (h_c) and surface mass transfer coefficient (h_m) in equations 3 and 4, the criteria of heat and mass transfer in case of air flow across an elliptical cylinder was applied in this study. The relative

equations for calculating the value of hc and hm are written in equation 8 and 9, respectively [11].

$$h_c = \frac{Nu k_a}{D_{eq}} \quad (8)$$

$$h_m = \frac{h_c}{\rho_a c_a Le^{2/3}} \quad (9)$$

where Deq is the equivalent diameter of paddy grain kernel (m), ca is specific heat of drying air (J/kg°C), ρ_a is the density of paddy grain (kg/m³), Nu and Le are the Nusselt and Lewis dimensionless numbers, respectively.

For the case of air flow across an elliptical cylinder, equivalent diameter (Deq) in equation 8 is defined as the thickness of the body, which is equal to the thickness of paddy grain kernel (Tk) in this study.

Table 1 The relative equations for calculations of the properties of paddy grain, air and dimensionless numbers

Parameters	Relative equations	References
Specific heat of paddy grain (c_p), J/kg°C	$c_p = 1110 + 44.8M_p$ (w.b.)	[7]
Thermal conductivity of paddy grain (k_p), W/m°C	$k_p = 0.0863 + 0.00134M_p$ (w.b.)	"
Porosity of paddy grain (ϵ_p), decimal	$\epsilon_p = 0.621 - 0.25M_p$ (d.b.)	[10]
Bulk density of paddy grain (ρ_b), kg/m ³	$\rho_b = 551.6 + 311M_p$ (d.b.)	"
True density of paddy grain (ρ_p), kg/m ³	$\rho_p = \rho_b / (1 - \epsilon_p)$	"
Specific heat of air (c_a), J/kg°C	$c_a = 1003.5 + 0.0129T_a + 4.0 \times 10^{-4}T_a^2$ ($R^2 = 0.998$)	this study
Diffusion coefficient of vapor in air (D_{wa}), m ² /s	$D_{wa} = 2.0 \times 10^{-7} + 2.0 \times 10^{-5}T_a$ ($R^2 = 999$)	"
Thermal conductivity of air (k_a), W/m°C	$k_a = 0.0237 + 7.53 \times 10^{-5}T_a - 2.28 \times 10^{-8}T_a^2$ ($R^2 = 1.000$)	"
Density of air (ρ_a), kg/m ³	$\rho_a = 1.2611 - 3.7 \times 10^{-3}T_a + 6.0 \times 10^{-6}T_a^2$ ($R^2 = 1.000$)	"
Dynamic viscosity of air (μ_a), kg/m·s	$\mu_a = 1.74 \times 10^{-5} + 4.65 \times 10^{-8}T_a - 2.27 \times 10^{-11}T_a^2$ ($R^2 = 1.000$)	"
Thermal diffusivity of air (α_a), W/m°C	$\alpha_a = 2.0 \times 10^{-5} + 2.0 \times 10^{-7}T_a$ ($R^2 = 1.000$)	"
Lewis number (dimensionless)	$Le = \alpha_a / D_{wa}$	[11]
Nusselt number (dimensionless)	$Nu = 0.248Re^{0.612}Pr^{1/3}$	"
Prandtl number (dimensionless)	$Pr = c_a \mu_a / k_a$	"
Reynolds number (dimensionless)	$Re = \rho_a v_a D_{eq} / \mu_a$	"

d.b. and w.b. are moisture content of paddy grain in decimal dry basis and wet basis, respectively; T_a is air temperature (°C); All air properties equations are used for calculation for air temperature in a range of 60 - 180 °C.

MATERIAL AND SIMULATION CONDITIONS

In this study, Suphanburi 1 rice variety was used as samples. From the measurement, the mean dimensions of the paddy grain sample were 10 mm in length (Lk), 2.4 mm in width (Wk) and 2.0 mm in thickness (Tk). The simulation conditions were performed at an initial paddy grain temperature (T_i) of 30°C, initial moisture content (M_i) of 28% dry basis (d.b.), drying air temperature (T_a) of 90, 110,

The relative equations for calculating the transport and physical properties of paddy grain and air, and dimensionless numbers (Nu , Re , Pr and Le) including their sources are listed in Table 1. The air property equations setup in this study are obtained by using data from Cengel [11] with the help of regression procedure in Microsoft Excel 2003. The square of correlation coefficient (R^2) used for regression analysis can be calculated using equation below [12].

$$R^2 = \frac{\left(\sum_{i=1}^N (Y_{s,i} - \bar{Y}_s)(Y_{sim,i} - \bar{Y}_{sim}) \right)^2}{\sum_{i=1}^N (Y_{s,i} - \bar{Y}_s)^2 \cdot \sum_{i=1}^N (Y_{sim,i} - \bar{Y}_{sim})^2} \quad (10)$$

where N is the total number of data for comparison, $Y_{s,i}$ and \bar{Y}_s are the i and mean value of source data, respectively. $Y_{sim,i}$ and \bar{Y}_{sim} are the i and mean value of simulation data, respectively.

130 and 150°C, drying air velocity (v_a) of 2.5 m/s and drying time of 300 s.

SOLUTION METHODOLOGY

To solve set of equations of three-dimensional transient heat and mass transfer model of a single rice kernel drying, finite element method was used to discretize all the equations with the imposed boundary conditions. Comsol Multiphysics® simulation program was employed to solving the model. Due to the symmetry about the x, y and z axes of the

ellipsoid shape, one-eighth of the actual kernel was modeled in simulation, as illustrated in Fig. 1. The computational domain was divided into 6638 tetrahedron elements, which was generated by default by the simulation program. Grid dependency was carried out to ensure the accuracy. To obtain the result for each simulation the initial step has been done for the initial values. The set of equations with the initial solution obtained in the first step were then solved using the time dependent solver. The time step was 1 s. Fig. 1 also shows the mesh model geometry of the kernel. The flow chart of the solving steps is shown in Fig.

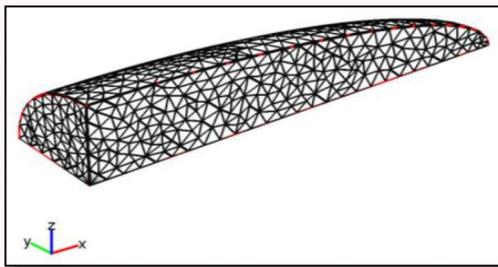


Fig. 1 Rice kernel model and mesh

VALIDATION OF THE MODELS

In this study, the experimental data for rough rice fluidized bed drying from the research of Jaibul [13] were used for a comparison between simulation results and experiment results. The square of correlation coefficient (R2) as expressed in equation 10, and root mean square error (RMSE) were used for checking the agreement of simulation data when compared to the experiment or source data. The value of RMSE was defined as [12].

$$RSME = \sqrt{\frac{1}{N} \sum_{i=1}^N (Y_{s,i} - Y_{sim,i})^2} \quad (11)$$

where N is the total number of data for comparison, $Y_{s,i}$ is the i value of source data, and $Y_{sim,i}$ is the i value of simulation data.

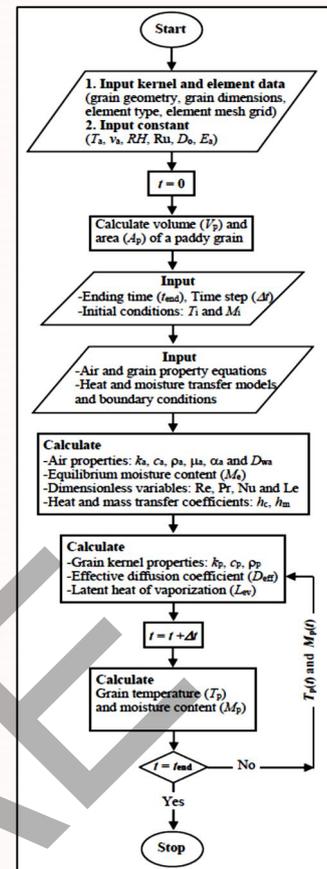


Fig. 2 Computational step flow chart

RESULTS AND DISCUSSIONS

The average temperatures and moisture contents of paddy grain kernel after fluidized bed drying obtained from the simulation (lines) and experiments (symbols) at drying air temperature of 90, 110, 130 and 150 °C are compared in Fig. 3 and 4, respectively. Table 2 shows the evaluation of the square of correlation coefficient (R2) and the root mean square error (RMSE) of the results from simulations. It was found that the simulation results of moisture content of paddy grain agree well with the experimental data. However, the grain temperature between the simulation and experimental results was slightly different, especially, during the first 60 seconds of drying period. Moreover, in case of drying temperature of 150 °C the value of RSME was higher than the other cases. Fig. 3 and 4 show that in the first 90 seconds of drying period, for all drying temperatures, moisture contents of paddy grain kernel considerably decreased whereas the temperatures increased more sharply before approaching steady values. It can be noticed that change

in the temperature seems to be higher than the moisture content.

In future studies, we will improve our heat transfer models, in particular heat transfer coefficient between drying air and paddy grain surface calculation by adding more features obtained from previous studies of Saravacos and Maroulis [14] on heat transfer in food processing for drying in a fluidized bed and Douglas and Churchill [15] on single-phase gas convective coefficient for case of horizontal tubes in fluidized bed.

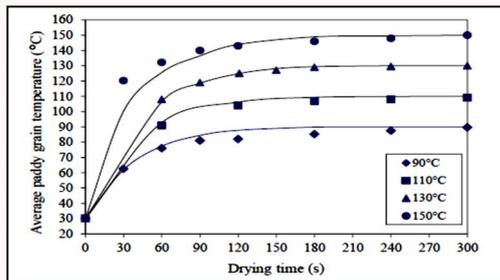


Fig. 3 Comparison of paddy grain temperatures between simulation result and experimental data [13], in case of drying air temperature of 90, 110, 130 and 150 °C.

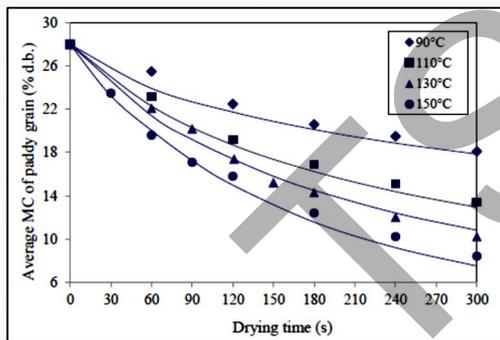


Fig. 4 Comparison of moisture contents (MC) of paddy grain between simulation result and experimental data [13], in case of drying air temperatures of 90, 110, 130 and 150 °C.

Table 2 Validation statistic results of temperature and moisture content (M_p) of paddy grain, compared with experimental data of Jiboon [13].

Drying Temperature (°C)	Temperature (T_p)		Moisture content (M_p)	
	R ²	RMSE	R ²	RMSE
90	0.9909	3.5341	0.9776	0.8923
110	0.9968	2.5941	0.9898	0.9399
130	0.9981	2.1032	0.9893	0.6815
150	0.9669	7.6809	0.9977	0.7924

CONCLUSION

The heat and mass transfer inside a single rice kernel during fluidized bed drying were investigated numerically. The simulation results agreed well with the experimental data. However, in the beginning of drying time (first 30-60 seconds), the paddy grain temperature of the simulation was slightly different from the experimental results, especially in case of drying air temperature of 150°C. The *RMSE* value was much higher than the case of other drying air temperatures. In the future studies, the heat transfer model needs to be improved to give more accurate paddy grain temperature prediction, especially, in the first period of drying.

ACKNOWLEDGEMENT

The authors would like to express their sincere appreciations to the "Research Chair Grant" National Science and Technology Development Agency (NSTDA), Thailand, for financial support for this study. Thanks to School of Energy, Materials and Environment, King Mongkut's University of Technology Thonburi (KMUTT), Thailand, for providing COMSOL Multiphysics® program.

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