Multi-scale model for heat and mass transfer during rice drying

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Abstract. *Grain drying is a simultaneous heat and moisture transfer problem. The modeling of such a problem is of significance in understanding and controlling the drying process. The main goal of this study was to predict the heat and mass transfer processes during deep-bed rice drying. To achieve this, first, CFD simulations were carried out to analyze the external flow and temperature fields at steady-state for a control volume of a stationary rice bed. The model was used to predict the convective heat and mass transfer coefficients in the rice bed, and correlations were developed for the convective heat and mass transfer coefficients as a function of drying air flow rate.*

Then, the coupled CFD and diffusion model developed by ElGamal, Ronsse, Radwan & Pieters (2013) to investigate the heat and mass transfer for thin-layer drying of rice was extended to volumetric heat and mass transfer in a deep-bed of rice using the predicted heat and mass transfer coefficients. All models were solved numerically using the finite element method. The model was used to predict the air temperature, as well as the grain moisture content and temperature at different locations of the dryer during the drying process. The theoretical predictions of moisture and temperature profiles inside a deep-bed of rice were verified by experimental data from literature. The average mean relative deviation values for the prediction of grain moisture content varied between 1.00 to 3.13%.

Keywords: CFD, Heat and mass transfer, Thin-layer, Deep-bed, Grain drying, Mathematical modeling.

1. Introduction

Drying is a post-harvest process that not only consumes a considerable amount of energy but also affects product quality, especially in the case of rough rice. Therefore, appropriate implementation of this process in the rice industry with high capacity dryers is an important subject (Zare, Minaei, Mohamad Zadeh, & Khoshtaghaza, 2006). Rice drying is a complex process, which involves simultaneous heat, mass and momentum transfer through a porous medium. Nowadays mathematical modeling and computer simulations are widely used in bioprocess engineering research. Mathematical modeling and computer simulation of a process minimize cost and time consuming experimentations and allow understanding the physical phenomena associated with the complicated process (Naghavi, Moheb, & Ziaei-rad, 2010). The result of the numerical simulation can also lead to the design and testing of new drying processes (Izadifar, Baik, & Simonson, 2006).

Various mathematical models have been proposed to simulate grain deep-bed drying. These can be divided into three categories: non-equilibrium, equilibrium and logarithmic models. Equilibrium and logarithmic models are simplified forms of a non-equilibrium model with some assumptions in the boundary conditions to reduce the complexity and computational burden (Hemis, Singh, Jayas, & Bettahar, 2011). However, non-equilibrium models developed using partial differential equations are considered more detailed, accurate, and valid for cereal drying due to fewer assumptions being made in the simulation compared to other models (Zare et al., 2006).

Zare & Chen (2009) reported that the main error differences between the simulation variables of the deep-bed and the experimental data are due to: (1) the simplification assumption made when building the mathematical model, (2) the lack of accuracy of the thin layer grain drying equation, (3) the inadequacy of the precise equation for estimating volumetric heat transfer of paddy in a packed bed, (4) the insufficient precision of the moisture equilibrium isothermal equation at relative humidity above 90% and, (5) the error in measurement of input parameters and actual performance of the grain dryer.

To improve the deep-bed modeling, the objective of the present study was to develop a simulation model for rough rice drying in a deep-bed dryer. In this work we considered a different approach to characterize the drying of rice in a thin layer using the diffusive flux of water and developed a deep-bed model assuming no thermal equilibrium between drying air and grain in the bed. Moreover, a correlation was developed for the convective heat and mass transfer coefficients as a function of drying air flow rate.

2. Model Development

2.1. Heat and mass transfer coefficients determination

The same approach reported by ElGamal et al. (2013) was used to determine the heat and mass transfer coefficients. In order to simulate a packed bed of rice, 17 rice kernels were arranged in three layers and the distances among the kernels were adapted to give a porosity of approximately 50% (Fig. 1). Based on the model simulations, polynomial correlations were developed for the heat and mass transfer coefficients as a function of the drying air flow rate as follows:

$$h_c = -2130.4G^4 + 2928.8G^3 - 1541.8G^2 + 455.7G + 3.8513 \quad (1)$$

$$h_m = -2.0687G^4 + 2.8505G^3 - 1.5034G^2 + 0.4446G + 0.0036 \quad (2)$$

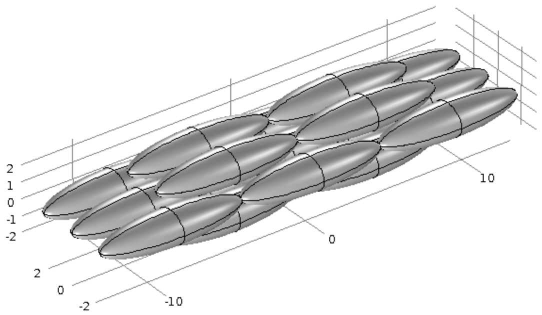

Fig. 1. Modeled rice kernels as a porous medium

2.2. Model description

The rice dryer described by Zare et al. (2006) was modeled in a two-dimensional coordinate system (Fig.2). The modeled bed was assumed to have a height of 25 cm (y- axis) with two subdomains (Air and Grain) each had the same thickness of 0.108 cm (x- axis). As such, the model allows predicting the temperature and moisture content distributions along the kernel width versus position (height) of the grain in the drying reactor. The thickness of grain and air subdomains was calculated as the average of the short axis (width and thickness) of the rice kernel.

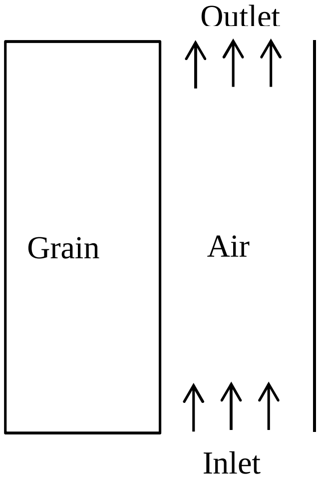

Fig.2. Modeled geometry of the rice bed

2.3. Transport equations

Based on the assumptions mentioned by Naghavi et al. (2010) the coupled CFD and diffusion model devolved by ElGamal et al. (2013) was used to describe the local heat and mass transfer in a deep-bed during rice drying with some modifications as follows:

For the rice:

Conservation of mass (water):

$$\frac{\partial M}{\partial t} = \nabla \cdot (D(T)\nabla M) \qquad (3)$$

Conservation of energy:

$$\rho_p C_p(M)\frac{\partial T}{\partial t} = \nabla \cdot \left(k_p(M)\nabla T\right) \qquad (4)$$

For the drying air:

Conservation of mass (water):

$$\frac{\partial W}{\partial t} + u \cdot \nabla W = \nabla \cdot (D_w(\theta) \nabla W) \quad (5)$$

Conservation of energy:

$$\rho_a C_a(W) \frac{\partial \theta}{\partial t} + \rho_a C_a(W) u \cdot \nabla \theta = \nabla \cdot (k_a(W) \nabla \theta) \quad (6)$$

2.4. Boundary and initial conditions:

Convective heat and mass transfer at the rice-air interface including latent heat removal:

$$-k_p \frac{\partial T}{\partial n} = h_c(\theta - T) \cdot CF - \dot{m} \cdot \lambda \quad (7)$$

$$-k_a \frac{\partial \theta}{\partial n} = h_c(T - \theta) \cdot CF \quad (8)$$

$$-D \frac{\partial M}{\partial n} = h_m(M - W) \cdot CF \quad (9)$$

$$-D_w \frac{\partial W}{\partial n} = h_m(W - M) \cdot CF \quad (10)$$

For the drying air:

$$Inlet: \; \theta(t) = \theta_\infty \quad (11)$$

$$Inflow: \; W_\infty = M_e \quad (12)$$

Initial conditions:

$$M(x, y, 0) = M_0 \quad (13)$$

$$W(x, y, 0) = W_0 \quad (14)$$

$$T(x, y, 0) = T_0 \quad (15)$$

$$\theta(x, y, 0) = \theta_0 \quad (16)$$

It should be noted that, *CF* is a correction factor to change the projected area of the kernels bulk in the experimental bed used by Zare et al. (2006) to the 2D flat surface area in the modeled bed (Fig. 2).

2.5. Numerical solution and model validation

All mathematical models were solved using the Comsol Multiphysics® simulation program v4.3b (Comsol Inc, Palo Alto), which uses the finite element method to solve the model equations.

To validate the results of the numerical simulation, the obtained data were compared with the experimental results of Zare et al. (2006). For each test, the simulation model performance was determined by calculation of the relative error (*E*) and mean relative deviation (*MRD*) according to Zare et al. (2006).

3. Results and discussions

3.1. Grain moisture content

The predicted results for the variations of grain moisture content under different drying conditions were obtained and compared with the experimental results of Zare et al. (2006). Figs. 3 and 4 shows the results of runs 1 and 2 (see Table 1.) it can be seen that at both measured depth levels (9 and 18 cm depth), the model can gave an accurate prediction of grain moisture content at different drying conditions. In all runs the average mean relative deviation values for the prediction of grain moisture content varied between 1.00 to 3.13% as shown in Table 1.

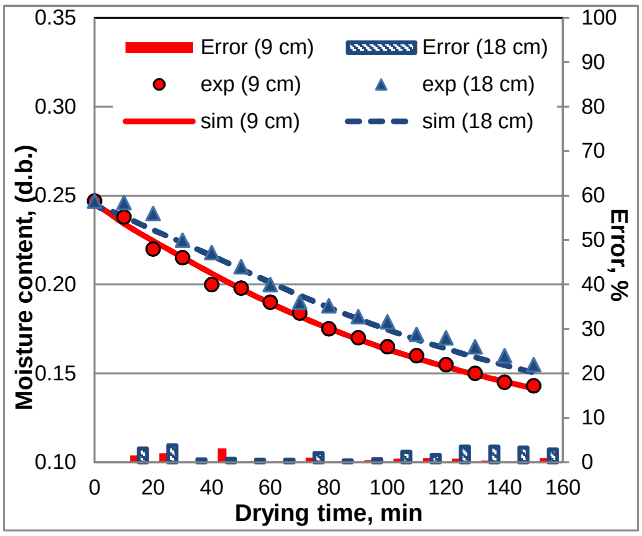

Fig. 3. Experimental (exp) and predicted (sim) grain moisture content as a function of drying time at different depths at θ = 50 (°C) and G = 0.22 (kg·m^{-2}·s^{-1}).

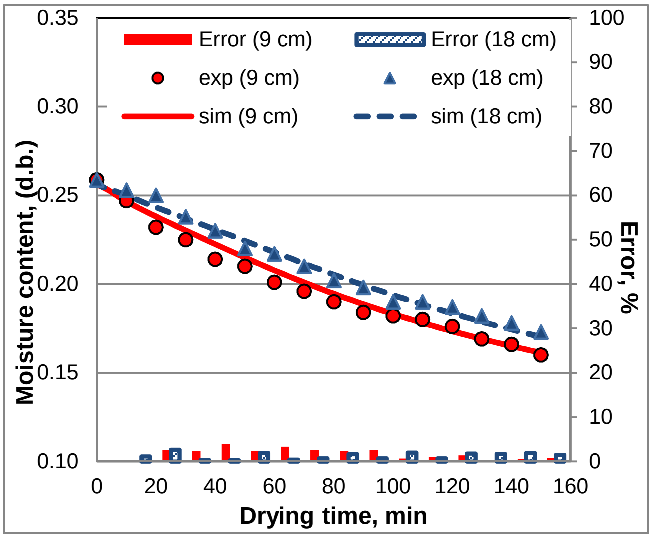

Fig. 4. Experimental (exp) and predicted (sim) grain moisture content as a function of drying time at different depths at θ = 45 (°C) and G = 0.22 (kg·m^{-2}·s^{-1}).

Table 1. results of validation tests for the predicted moisture content

Run	Inlet air temperature (°C)	Mass flow of air (kg·m^{-2}·s^{-1})	MRD %	
			Depth, 9 cm	Depth, 18 cm
1	50	0.22	1.15	2.31
2	45	0.22	2.07	1.47
3	50	0.16	1.00	3.13
4	45	0.16	2.04	1.27

3.2. Grain temperature

Fig. 5 illustrates the evolution of the predicted grain temperature during drying at different distances from the inlet section of the bed for run 3. At any distance as time increases grain temperature is increased. This is due to the fact that at initial stages of the drying process the heat transferred from air to the grains is mostly used for moisture evaporation. As time goes up and grains become dryer, less heat is used for moisture evaporation and the transferred heat from air to grains increases the grain temperature (Naghavi et al., 2010).

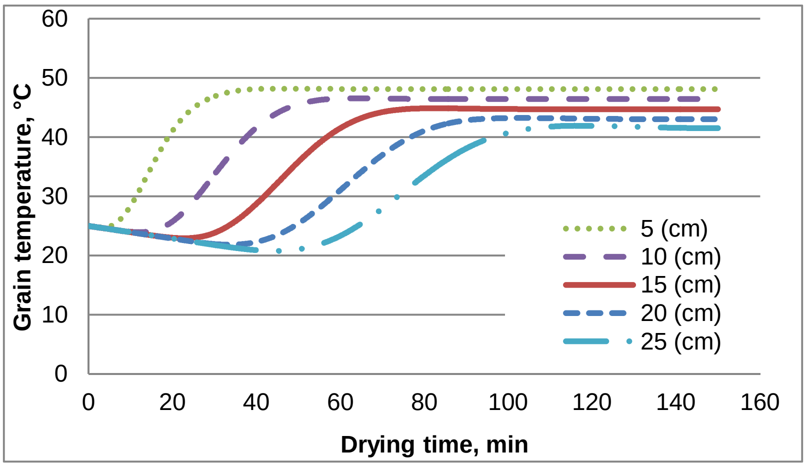

Fig. 5. Predicted grain temperature with drying time at different depths at θ = 50 (°C) and G = 0.16 (kg·m^{-2}·s^{-1}).

4. Conclusions

A coupled CFD and diffusion model developed in this study was used successfully for describing the coupled heat and mass transfer inside a deep-bed of rice during drying. The model prediction of the grain moisture content and drying air temperature at different locations in the bed was verified using experimental data from literature and was found to be satisfactory.

5. Nomenclature

C	Specific heat (J·kg^{-1}·K^{-1})
CF	Correction factor of area (m^{2}·m^{-2})
D	Moisture diffusivity (m^{2}·s^{-1})
G	Air flow rate (kg·m^{-2}·s^{-1})
h_c	Convective heat transfer coefficient (W·m^{-2}·K^{-1})
h_m	Mass transfer coefficient (m·s^{-1})
k	Thermal conductivity (W·m^{-1}·K^{-1})
M	Grain moisture content, % (d.b.)
$\dot{m}$	Mass flux (kg·m^{-2}·s^{-1})
n	Normal vector
t	Time (s)
T	Grain temperature (K)
u	Air velocity (m·s^{-1})
W	Air moisture content, % (d.b.)
∇	Divergence operator

Greek symbols

ρ	Density (kg·m^{-3})
λ	Latent heat of vaporization (J·kg^{-1})
θ	Air temperature (K)

Subscripts

0	Initial conditions
∞	Inlet air conditions
a	Air
e	Equilibrium conditions
p	Particle
w	Water vapor

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