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Effect of Distributed Superficial-Velocity in Deep-Bed Grain Drying

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Abstract

This paper deals with influence of velocity field distribution to heat and mass transfer process in deep bed grain dryers. Two-dimensional (2D) models of deep-bed grain dryers were built by considering simultaneously momentum, heat, and mass transfer in the drying air phase. The Navier-Stokes momentum equations are applied to simulate pressure drop and velocity field of the drying airflow. Effect of velocity distribution to the heat and mass transfer coefficient distribution were simulated along the height of grains bed. The dynamic equations are solved numerically by using finite difference method by utilization of alternating direction implicit method, while the momentum equations are solved numerically by utilization of SIMPLE algorithm. The simulation results showed that velocity distribution along the grains bed - 5 cm of bed height - did not so influenced to the heat and mass transfer coefficient. Further, the vector plot of drying air superficial velocity field and contour of pressure distribution along deep bed of grain was simulated.

1. Introduction

Deep bed dryers, also known as fixed bed dryers, are one of the most common types of industrial dryers. Mathematical modelling and computer simulation of grain drying are now widely used in research in the field of drying process. However, up to recently, mathematical and numerical models which are considering combination of momentum, heat and mass transfer for some features of dryers have been rarely developed. Several models have been proposed to describe heat and mass transfer processes in the types of convective grain dryer, such as Thompson (1968), Palancz *et al.* (1985), Abid *et al.* (1990), Courtois (1991), Franca *et al.* (1994), Lopez *et al.* (1998), Sitompul *et al.*(2001), Sitompul *et al.* (2000a), and Wongwises *et al.* (2000). However, they did not consider effect of momentum transfer in the drying process. It is suggested that the more comprehensive model for the drying process is needed in which considers heat, mass and momentum transfer.

Transport phenomena of grain drying is a complex case due to coupling of heat, mass and momentum transfers phenomena. The pressure of the drying air decreases due to friction between gases and walls as well as to momentum losses caused by the collision with the particles. The temperature of drying air and grain are affected by heat transfer between drying air and the particles and heat transfer at the wall, while the moisture content of grain and drying air is affected by mass transfer between them. The slip velocity between the particles and the gas is controlled by the interfacial drag and friction forces between particles and the walls.

The aims of this paper are to simulate superficial-velocity field and pressure distribution along grain bed and to find effect of distributed superficial velocity field on heat and mass transfer coefficient.

2. Modelling Development and Numerical Solution

2.1. Modelling of Momentum Transfer in Deep-Bed Grain Dryer

In this research, two-phase mathematical model for deep-bed drying by taking into account the conservation of momentum, mass and energy within the bed and the conservation of heat and mass in the spherical grains were proposed (Istadi, 2000). Actually, the coupled of heat, mass and momentum transfer in drying air and within grains are complex case that occur during drying. The water vapor is assumed to migrate by diffusion and convection both in drying air phase and within grains to be dried. The migration of water vapor within grains was expressed by Darcy's law due to convection and Fick's law due to diffusion. The diffusion and cappillary flow occurs during drying within grains are physically in water vapor or liquid water. However, in the reason, the transfer processes within grains are due to liquid diffusion only expressed by Fick's law.

Average mass and heat transfer coefficient between the bulk gas stream and the grain surface can be correlated in terms of dimensionless groups that characterize the flow conditions. Hence, both heat and mass transfer coefficients are influenced by thermal and flow properties of the air, and the geometry of the system.

Actually, heat and mass transfer coefficient will be distributed along the bed that is depends on the superficial velocity field distribution. The assumptions were made in order to simplify the mathematical models and numerical computation (Istadi, 2000).

The governing equations of continuity, and Navier-Stokes momentum equations applied to flow in porous media were developed by volume averaging approach as developed by Liu *et al.* (1999). The two-dimensional momentum equations can be written for steady state case and general form as follows (Liu *et al.*, 1999):

$$\frac{1}{\varepsilon_b}\frac{\partial}{\partial z}\left(\rho_a u\right)+\frac{1}{\varepsilon_b}\frac{1}{r}\frac{\partial}{\partial r}\left(r\,\rho_a v\right)=0 \quad (1)$$

$$\frac{\rho_a u}{\varepsilon_b}\frac{\partial u}{\partial z}+\frac{\rho_a v}{\varepsilon_b}\frac{\partial u}{\partial r} = \frac{\mu}{\varepsilon_b}\frac{\partial^2 u}{\partial z^2}+\frac{\mu}{\varepsilon_b r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right)-\frac{\partial P}{\partial z}+\rho_a g_z - F_b \quad (2)$$

$$\frac{\rho_a u}{\varepsilon_b}\frac{\partial v}{\partial z}+\frac{\rho_a v}{\varepsilon_b}\frac{\partial v}{\partial r} = \frac{\mu}{\varepsilon_b}\frac{\partial^2 v}{\partial z^2}+\frac{\mu}{\varepsilon_b}\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(rv)\right)-\frac{\partial P}{\partial r}+\rho_a g_r - F_b \quad (3)$$

$$F_b=\frac{\partial P}{\partial n}=\left[\frac{150\,\mu}{{d_p}^2}\left(\frac{(1-\varepsilon_b)^2}{{\varepsilon_b}^3}\right)U+\frac{1{,}75\,\rho_a}{d_p}\left(\frac{(1-\varepsilon_b)}{{\varepsilon_b}^3}\right)U^2\right] \quad (4)$$

The moisture and heat balances have been developed in drying gas and grains phase were written clearly in the previous paper (Sitompul *et al.*, 2000a; Istadi, 2000). The initial and boundary conditions of the heat and mass balance equations were also developed in the previous paper (Sitompul *et al.*, 2000a; Sitompul *et al.*, 2000b; Istadi, 2000). Boundary conditions for momentum balance equation are as follows:

At the inlet flow $u=u_o$; $v=0$ At the outlet flow $\frac{\partial u}{\partial z}=\frac{\partial v}{\partial z}=P=0$

At the centerline $\frac{\partial u}{\partial r}=\frac{\partial v}{\partial r}=\frac{\partial P}{\partial r}=0$ At the vertical wall $u = v = 0$ (no slip velocity)

The interphase transport properties are expressed empirically by function of superficial-velocity and the physical properties of the drying air. The mass transfer coefficient (k_m) are expressed by mass transfer factor and related to drying air velocity by Reynold number (Re_p). The empirical correlations of mass transfer coefficient is written as follows:

$$\frac{k_m}{\rho_a\,u} = \left(\frac{C_1}{\varepsilon_b}\right)\left(Re_p\right)^{C_2}\left(Sc\right)^{C_3} \quad (5)$$

The heat transfer is chiefly controlled by heat transfer coefficient of boundary layer of flowing air covering surface of solid phase during drying. Heat transfer coefficient (h) can be expressed by the heat transfer factor and Stanton number as follows:

$$St = \left(\frac{C_1}{\varepsilon_b}\right)\left(Re_p\right)^{C_2}\left(Pr\right)^{C_3} \quad (6)$$

2.2. Numerical Solution

The governing partial differential equations are solved numerically by utilizing finite-difference method. This solution technique has been tested and proved to be highly accurate and computationally efficient for solving the above equations (Davis, 1984; Sitompul *et al.*, 2000b). Given a fixed axisymmetric geometry, the superficial velocity and pressure fields distribution and drying characteristics obtained numerically by solving the above governing equations. The pressure-velocity coupling is obtained from the combination of the continuity equation and the equations of momentum by the SIMPLE algorithm. When this method is used, good stability is found in the numerical solutions of the pressure field through segregated algorithm of pressure-velocity coupling. In the staggered grid, the components of the velocity vector are arranged and placed between two adjacent pressure points. When collocated grids are used, there is a possibility to obtain unreal pressure fields such as checkerboard and zigzag pressure with the SIMPLE type pressure-velocity coupling (Meier *et al.*, 1999; Patankar, 1980; Hoffmann *et al.*, 1993).

3. Results and Discussion

The heat and mass transfer coefficient correlations are given in Eq. (7) and (8). The drying characteristics profiles along the dryer were calculated for the various bed height of 0 m, 0.025 m, 0.05 m. The simulation results of superficial velocity and pressure field distribution are depicted in Figure 1 to Figure 4. The vector plot of superficial velocity field is depicted in the Figure 1 in which plotted for dimensionless axis of both axial (z/L) and radial direction (r/R). The pressure field distribution is also depicted in Figure 2 in which plotted for dimensionless axis of both axial (z/L) and radial direction (r/R). From this figure, it is showed that the decreasing of superficial velocity and pressure fields along dryer column are happened due to friction among drying air and both the wall and grain phase. In this reason, momentum transfers from drying air phase to the wall and grains bed. The mass transfer properties are expressed empirically by function of superficial-velocity and the physical properties of the drying air as described in the following correlation:

$$\frac{k_m}{\rho_a\, u} = \left(\frac{0.9548}{\varepsilon_b}\right)\left(Re_p\right)^{-0.857}\left(Sc\right)^{-2/3} \tag{7}$$

while heat transfer properties (h) can be expressed by the following correlation:

$$St = \left(\frac{2.0048}{\varepsilon_b}\right)\left(Re_p\right)^{-0.957}\left(Pr\right)^{-2/3} \tag{8}$$

These were expected to be important if the heat and mass transfer was affected by the rate at which heat and mass were transferred between the fluid and the solid surfaces.

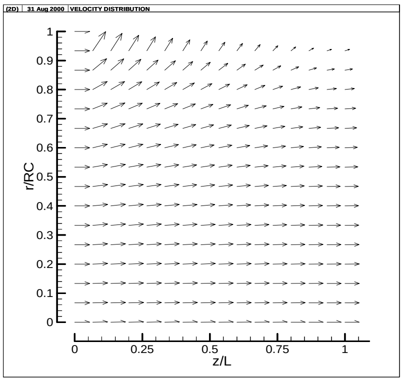

Figure 1. Vector plot of superficial velocity field of drying air accross bed for bed height of 5 cm.

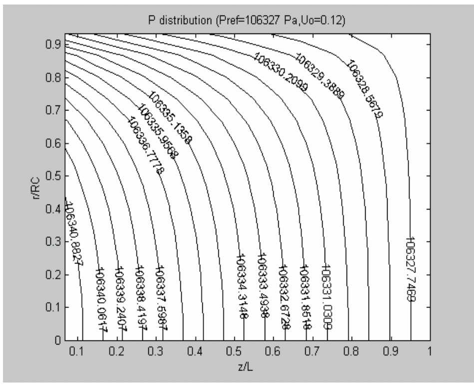

Figure 2. Contour plot of pressure field distribution of drying air accros bed for bed hieght of 5 cm

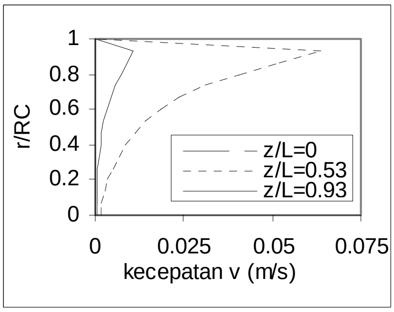

Figure 3. Radial superficial velocity (v velocity) simulated as function of dimensionless of radial column distance (r/R)

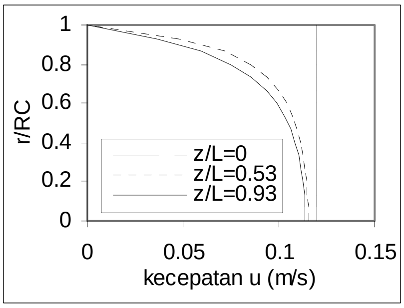

Figure 4. Axial superficial velocity (u velocity) simulated as function of dimensionless of radial column distance (r/R)

Table 1. Experimental parameters used for model validation

Parameter	Value	Parameter	Value
Y_i	0.015	$\lambda_{P\ eff}$	0.1109
X_o	0.6	$\lambda_{az\ eff}$	0.02425
T_{po}	303	$\lambda_{ar\ eff}$	0.02425
U_o	0.12	δ	0.05
a	800	ε_b	0.35
Cp_a	1017	ε_p	0.45
Cp_v	2030	ρ_a	1.025
Cp_p	1122	ρ_p	1350
ΔH_v	$2.357\text{x}10^{6}$	$D_{z\ eff}$	$1.165\text{x}10^{-5}$
L	0.05	$D_{r\ eff}$	$1.165\text{x}10^{-5}$
d_p	0.006		

Figure 5 shows prediction of average grain moisture content as drying proceeds through the bed at any positions along the bed. The grain moisture content decreases during the removal of the moisture. As shown on Figure 5, the removal of moisture up to about 0.14 kg moisture/kg dry grain from initial moisture content of 0.57 kg moisture/kg dry grain takes at about 3.8 hours under certain variable conditions. The relative error deviation in the reason of comparison between simulated and experimental result is about 6.11 %. Generally, the moisture transport is restricted to diffusion of liquid water or water vapor with a gradient in moisture content as driving force. However, flow driven by capillary action is possible since the capillary pressure and permeability are functions of the moisture content. The constant drying rate period is very short time in initial drying period which indicates that drying process of corn is mainly controlled by liquid diffusion mechanisms. The insignificant effect of air velocity on the drying rate of corn confirms that the controlling mechanism is the diffusion of moisture only compared to the external transfer process in boundary layer. In the reason, the moisture content and temperature of grain have a greatly effect on the effective diffusivity coefficient.

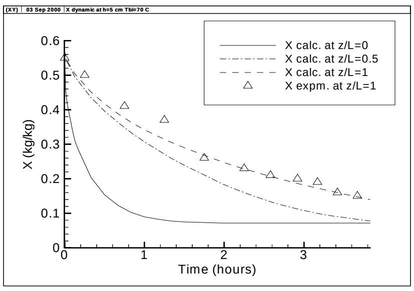

Figure 5. Comparison between simulated and experimental result of average grain moisture content at T_{bi}=70 C

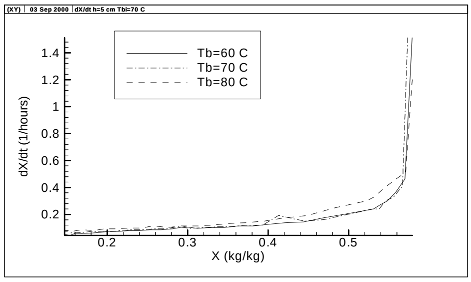

Figure 6. Drying rate curve at various inlet air temperature

The drying rate curves at various inlet air temperature (60, 70, 80 ^{o}C) are depicted in Fig. (6). The higher drying rate is achieved at 80 ^{o}C. From this figure, it is seen that the drying rate for bed layer of 5 cm was not so influenced by the various inlet air temperature in the range of 60-80 ^{o}C.

4. Conclusions

The governing equations of continuity, and Navier-Stokes momentum equations were developed by volume averaging approach to study flow in a porous media in deep bed drying process. The pressure drop force exerted in deep bed was expressed by Ergun correlation that accommodate laminar and viscous flow. The correlation was a source term of Navier-Stokes equations. A set of partial differential equations can be solved numerically by using finite difference method by utilizing alternating direction implicit algorithm. The SIMPLE algorithm with staggered grid was sucessfully conducted to solve the governing momentum equations.

Superficial velocity and pressure fields distribution have small change along the bed. In this reason, the distribution of superficial velocity of drying air did not so influence heat and mass tranfer coefficient distribution for the bed height of 5 cm.

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Notation

C_1, C_2, C_3	constants of heat and mass transfer correlations	-
d_p	particle diameter	m
F_b	body force	
g	acceleration of gravitatation	m s^{-2}
h	heat transfer coefficient	J m^{-2} s^{-1} K^{-1}
k_m	mass transfer coefficient	kg m^{-2} s^{-1}
L	height of bed (thickness)	m
P	pressure	Pa
R_C	radius of deep bed	m
R_P	radius of grain	m
Re_p	particle Reynold number ($\rho_a u\ d_p /\mu$)	dimensionless
Sc	Schmidt number (μ / ρ D)	dimensionless

St	Stanton number ($h / Cp\ \rho_a u$)	dimensionless
u	axial air velocity	$m\ s^{-1}$
v	radial air velocity	$m\ s^{-1}$
X	grain moisture content	kg moisture / kg dry grain
Y	air humidity	kg moisture / kg dry air
z	axial direction for cylindrical coordinate	m

Greek Symbols

ε_b	bed porosity	$m^3\ m^{-3}$
ε_p	grain porosity	$m^3\ m^{-3}$
ρ_a	density of air	$kg\ m^{-3}$
μ	dynamic viscosity of air	$kg\ m^{-1}\ s^{-1}$

Subscripts

a	drying air phase	s	surface
b	bed or air phase	p	grain phase
r	radial direction	n	normal direction
o	inlet	z	axial direction

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