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Investigation of Some Effective Parameters on the Fluidized Bed Grain Dryers

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Abstract: Having accurate values of the parameters which mainly govern the industrial processes in hand is the key aspect to handle the process and optimize it. To deal with this challenge, some mathematical models have been developed and modified to be epidemic. This Study aims to present the simulation of gas-solid flow in fluidized bed dryer. Numerical solution of two-dimensional, axis-symmetrical cylindrical model for both phases is the very base on which this study is conducted. Some of the versatile parameters like inlet gas velocity and temperature, diameter and density of particles during drying process went under magnification and also challenges of heat transfer along the bed are investigated and discussed in detail. Solid temperatures in the center and on the surface which are greatly affected by time as well as results of the study are shown. At the end, model outputs are compared with experimental data which shows reasonable agreement and good match.

Key words: Gas-solid flow · Fluidized bed · Grain dryer · Heat transfer · Properties of wheat

INTRODUCTION

Drying is the key process in majority of industries which deals with separation and chemical processes as well as those industries with solid products. Actually, the aim of drying process is to eliminate a liquid using a dry gas. The most troublemaker liquid is often water while the gas is dry air. Also air drying is the most common applicable commercial technique to do drying of food and chemical products. Main parameters which govern drying efficiency are reported as drying air temperature, its relative velocity and product initial moisture content [1].

Fluidized beds are currently used commercially to dry granular materials, cereals, polymers, chemicals, pharmaceuticals, fertilizers, crystalline products and minerals. Drying process of solids usually includes two separate stages; namely, constant and falling rate periods. Most food materials have short constant rate periods and they may be dried entirely in the falling rate period. In the gas-solid fluidization, the solid phase is assumed to be in the "fluid like" state. Because of the latent heat of water evaporation and relatively low energy efficiency of industrial dryers, drying is a process which requires high input energy. Input energy plays a significant role in reducing the cost of process [2-4].

Mathematical modeling of fluidized bed drying is crucial for optimizing the performance of existing systems and designing new dryers. It is highly recommended that modeling be done in 2 different models parallel to each other. The first model (CFD) is based on a continuum assumption of phases and the second one is an engineering model such as two-phase or three-phase models. The second model relies on a bubble phase without solid and a dense phase consisting of gas and solid particles [5, 6].

Palancz [7] has presented a model to describe the continuous drying process of particles based on the two-phase model, which is followed and modified by Lai and Chen [8]. Hajidavalloo and Hamdullahpur [9, 10] also have proposed a mathematical model of simultaneous heat and mass transfer in fluidized bed drying of large particles. Afterward, Urgschweiger and Tsotsas [11] performed some experiments in order to model continuous fluidized bed drying under steady state and dynamic conditions.

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Additionally, Assari *et al*. [12] have presented a model to simulate the drying process for two-dimensional cylindrical column based on mass, energy and momentum conservations. This study reveals the simulation results of a fluidized bed dryer. This dryer was used to dry the spherical grains along the column.

MATERIALS AND METHODS

Material: In this study, wheat is introduced as a solid with diameter of 3 mm and inlet temperature of 25°C to the fluidized bed and the drying operation are carried out under the various conditions. Air, the common dry gas, is used here with temperatures of 70 and 100°C and viscosity is 2.173×10^{-5} at 100°C in blown to the fluidized bed. Wheat density is 1200 kg/m^3 and its heat capacity is assumed to be $1260 kJ/kg$ °C.

Analysis and Modeling of Fluidized Drying Process: Fundamental theory of formulation of two-phase flow is discussed in detail in general [6-7] and specified references [8-12]. Two sets of conservation equations are used for gas-solid models. By means of previous attempts [8, 11, 12], background theorem for the work is considering two different fluids (wet solid particles and gas) for each phase. Equations of mass, momentum, thermal energy and continuity for each phase are the main issues which are presented here in detail.

Equation of motion for solid, momentum equation in r-direction:

$$\frac{\partial}{\partial t}(\rho_s\varepsilon_s\upsilon_s)+\frac{1}{r}\frac{\partial}{\partial r}(\mathrm{r}\rho_s\varepsilon_s u_s^2)+\frac{\partial}{\partial z}(\rho_s\varepsilon_s u_s v_s)=-\varepsilon_s\frac{\partial\rho}{\partial r}+\beta_r(u_s-u_g)-\frac{\partial\tau_{rr}}{\partial r}-\mathrm{a}\dot{m}u_s \tag{1}$$

Solid momentum equation in z-direction:

$$\frac{\partial}{\partial t}(\rho_s\varepsilon_s v_s)+\frac{1}{r}\frac{\partial}{\partial r}(\mathrm{r}\rho_s\varepsilon_s u_s v_s)+\frac{\partial}{\partial z}(\rho_s\varepsilon_s v_s^2)=-\varepsilon_s\frac{\partial\rho}{\partial z}+\beta_z(v_s-v_g)-\frac{\partial\tau_{rr}}{\partial z}-\rho_s\varepsilon_s\mathrm{g}-\mathrm{a}\dot{m}u_s \tag{2}$$

In the above equations, right-hand terms are pressure gradient, drag, normal solid stresses and the source momentum due to the solid evaporation, respectively. In the equations of motion, β_r and β_z are drag coefficients between the gas and solid particles (drag coefficients are used from the literature [13]).

$$\beta_z=150\frac{s_g^2 u_g}{s_g(d_p\varnothing_s)}+1.75\frac{\rho_g\,|\,v_s-v_g\,|\,\varepsilon_g}{d_p\varnothing_s}\ \text{ for }\varepsilon<0.8 \tag{3}$$

$$\beta_z=\frac{3}{4}C_{Dz}\frac{\rho_g\,|\,v_s-v_g\,|\,s_g s_s}{d_p\varnothing_s}\varepsilon_g^{-2.65}\ \text{ for }\varepsilon\geq0.8 \tag{4}$$

$$\varepsilon_s+\varepsilon_g=1.0 \tag{5}$$

C_{Dz} is the drag coefficient in z-direction [6]:

$$\begin{aligned} C_{Dz}&=\frac{24}{Re_{sz}}(1+0.15Re_{sz}^{0.687}) && Re_{sz}<1000\\ C_{Dz}&=0.44 && Re_{sz}\geq1000 \end{aligned} \tag{6}$$

and

$$Re_{sz}=\frac{\rho_s\varepsilon_s(v_g-v_s)d_p}{\mu_g} \tag{7}$$

The expression for the friction coefficient in the radial direction is the same as that of the axial direction. Equation of motion for gas in r-direction:

$$\frac{\partial}{\partial t}(\rho_g\varepsilon_g u_g)+\frac{1}{r}\frac{\partial}{\partial r}(\mathrm{r}\rho_g\varepsilon_g u_g^2)+\frac{\partial}{\partial z}(\rho_g\varepsilon_g u_g v_g)=-\varepsilon_g\frac{\partial\rho}{\partial r}+\beta_r(u_g-u_s)+\mathrm{a}\dot{m}u_g \tag{8}$$

Gas momentum equation in z-direction:

$$\frac{\partial}{\partial t}(\rho_g\varepsilon_g v_g)+\frac{1}{r}\frac{\partial}{\partial r}(\mathrm{r}\rho_g\varepsilon_g u_g v_g)+\frac{\partial}{\partial z}(\rho_g\varepsilon_g v_g^2)=-\varepsilon_g\frac{\partial\rho}{\partial z}+\beta_z(v_g-v_s)-\rho_g\varepsilon_g\mathrm{g}-\mathrm{a}\dot{m}u_g \tag{9}$$

On the left, the first and second terms represent rate of accumulation and net rate of outflow across the closed surface, respectively. The right-hand terms are considered the pressure gradient, drag, gravitational force and the source momentum term due to the evaporation of wet solids, respectively. Friction force due to shear stresses is neglected here. Continuity equations for solid phase:

$$\frac{\partial}{\partial t}(\rho_s\varepsilon_s x_s)+\frac{1}{r}\frac{\partial}{\partial r}(\mathrm{r}\rho_s\varepsilon_s u_s x_s)+\frac{\partial}{\partial z}(\rho_s\varepsilon_s x_s v_s)=-\mathrm{a}\dot{m} \tag{10}$$

Continuity equation for gas phase:

$$\frac{\partial}{\partial t}(\rho_g\varepsilon_g x_g)+\frac{1}{r}\frac{\partial}{\partial r}(\mathrm{r}\rho_g\varepsilon_g u_g x_g)+\frac{\partial}{\partial z}(\rho_g\varepsilon_g x_g v_g)=-\mathrm{a}\dot{m} \tag{11}$$

$\dot{m}$ stands for the moisture evaporation from the particle surface.

Thermal energy equations for the solid phase:

$$\frac{\partial}{\partial t}(\rho_s\varepsilon_s I_s)+\frac{1}{r}\frac{\partial}{\partial r}(\mathrm{r}\rho_s\varepsilon_s u_s I_s)+\frac{\partial}{\partial z}(\rho_s\varepsilon_s v_s)=\frac{1}{r}\frac{\partial}{\partial r}(rk_s\varepsilon_s\frac{\partial T_s}{\partial z})+\frac{\partial}{\partial z}+(k_s\varepsilon_s\frac{\partial T_s}{\partial z})-\mathrm{a}\dot{m}(c_{wg}T_g+\gamma\circ) \tag{12}$$

For gas phase:

$$\frac{\partial}{\partial t}(\rho_g\varepsilon_g I_g)+\frac{1}{r}\frac{\partial}{\partial r}(\mathrm{r}\rho_g\varepsilon_g u_g I_g)+\frac{\partial}{\partial z}(\rho_g\varepsilon_g I_g v_g)=\frac{1}{r}\frac{\partial}{\partial r}(rk_g\varepsilon_g\frac{\partial T_g}{\partial r})+\frac{\partial}{\partial z}(k_g\varepsilon_g\frac{\partial T_g}{\partial z})-\mathrm{a}\dot{m}(c_{wg}T_g+\gamma\circ)+ah_v(T_s-T_g) \tag{13}$$

Transfer coefficient for convective heat transfer between solid and gas is given by:

$$h_v=c_g u_g\rho_g J_h pr^{2/3} \tag{14}$$

$$\begin{aligned} In &= 1.77Re_{ic}^{-0.44} \quad \text{if Re} \geq 30 \\ In &= 5.70Re_{ic}^{-0.78} \quad \text{if Re<30} \end{aligned} \tag{15}$$

$$Re_{ic}=\frac{\rho_g u_g d_p}{s_s u_g} \tag{16}$$

The energy due to conduction is laid on two terms on the right side of equations 12 and 13 and the third one is evaporation exchange, while the last one shows energy exchange due to convention.

Numerical modeling is used to solve initial and boundary conditions because they cannot be evaluated with analytical analysis [12]. Zero is the value which is assumed for gas velocity in all direction on the wall surface. However, this is not completely true for the solid particles. The grids have been assumed on r–z axis. The domain length in the radial direction is 7 and 120 cm in the axial direction while the average voidage of gas is 0.8.

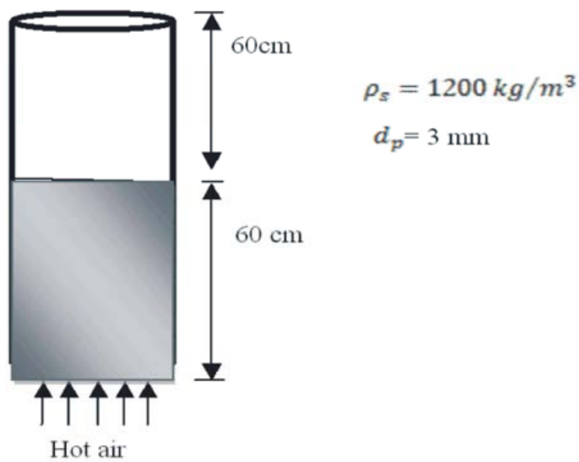

Fig. 1: Schematic of fluidized bed

Experimental Set up: An experimental apparatus has been built by Assari *et al*. [12] and BasiratTabrizi*et al*. [14]for an investigation into grain drying process in fluidized bed. Air is blown to the electrical heaters in room temperature then it is heated to be in the preset temperature. In order to have uniform flow and desired velocity, hot air afterward will be forced to go through a distributor. Then hot air with the known velocity and temperature enters the cylinder upward from the bottom. Cylinder bed is 14 cm in diameter and 120 cm in height. The grain temperature is then measured by the thermocouples installed along the bed. Figure 1 shows the schematic of system configuration.

RESULTS AND DISCUSSION

In this paper simulation of grain drying process in fluidized bed is carried out with wheat and dry air. Wheat particles were fed at initial temperature of298 K, 3 mm diameter, density of 1200 kg/m^3 and heat capacity of 1260 kJ/kg°C to the fluidized bed and filled 0.6 m height in the cylinder. In this section, the effects of parameters such as inlet gas velocity and temperature as well as size and density of grains on temperature of particles in the bed are analyzed, as it is shown in Figures 2 through 7. A comparison has been done between experimental data and simulation results for solid temperature at gas temperature of 373 and 343 K. Experimental data is obtained from literatures[12,15]. These results are shown in Figures 2 and3. The differences between the experimental and the theoretical results are due to precision of the measurement tools and the heat loss from the apparatus walls, which is more sensible in the beginning of falling rate period.

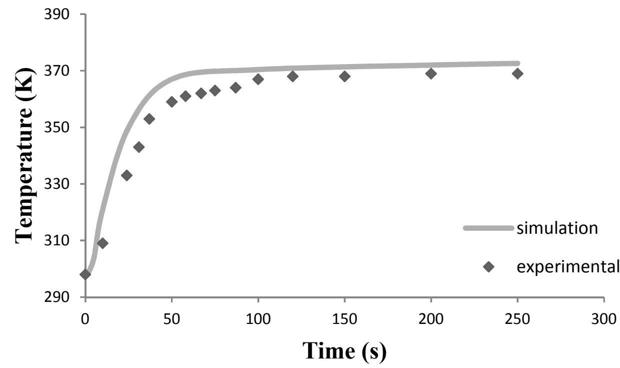

Fig. 2: Experimental vs. theoretical temperature of solid in fluidized bed at 373 K air temperature and velocity

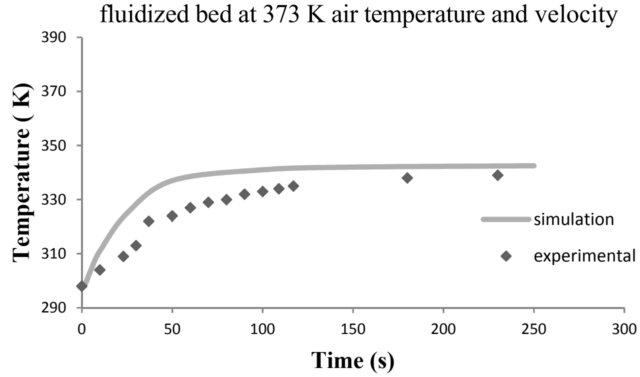

Fig. 3: Experimental vs. theoretical temperatures of solid in fluidized bed at 343 K air temperature and velocity of 4*m/s*

According to evidences, as inlet gas temperature increases, drying period for solid spheres goes down and vice versa. Although higher gas temperature at entrance leads to higher drying efficiency, it actually has detrimental effect on the integrity of drying materials. By lowering the gas temperature, the constant temperature period will begin earlier. Drying rate is very high at the initial stage of the drying process, but it decreases exponentially when all the surface moisture evaporates and the drying front diffuses inside the material. In other words, at the initial stage, temperature of solid increases until it approaches the initial temperature of air. At the second stage (constant temperature), solid temperature will remain equal to saturation temperature corresponding to the initial conditions. Also temperature of particles for 4 and 5 m/s of gas velocity obtained at 373k. These results and experimental data are shown in Figure 4.

DiMattia *et al*. [16] have found that fluidized bed dryers reach their very high efficiency at low fluidization velocity. Figure 5 shows the temperatures of solid in the center and on surface at a given time. A little difference between the temperatures can be observed; however, temperature of particles in the center of bed is higher than

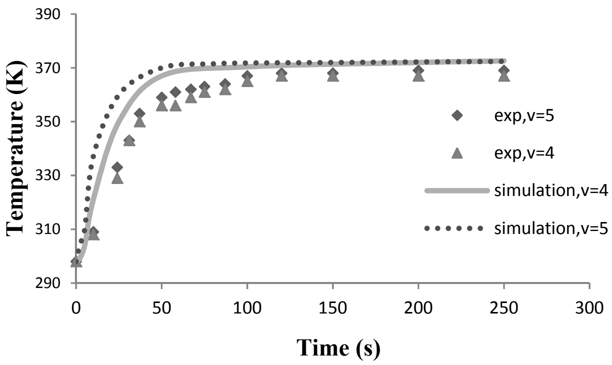

Fig. 4: Experimental vs. theoretical temperatures of solid in fluidized bed at 373 K air temperature

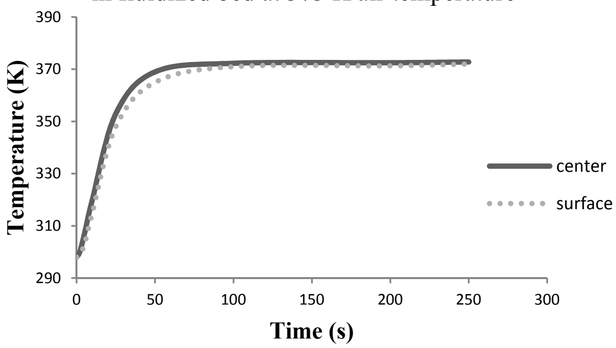

Fig. 5: Theoretical temperatures of solid in fluidized bed in the center and on the surface at 373 K air temperature and velocity of 4*m/s*

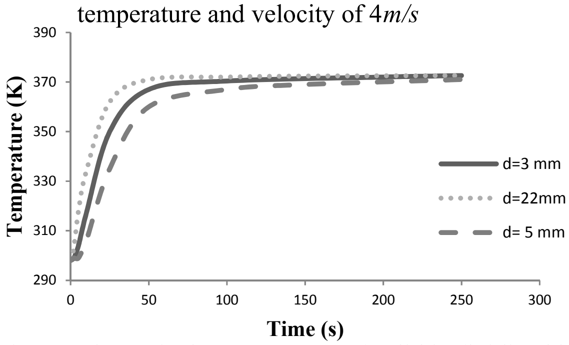

Fig. 6: Theoretical temperatures of solid in fluidized bed in different diameters of particles at 373 K air temperature and velocity of 4*m/s*

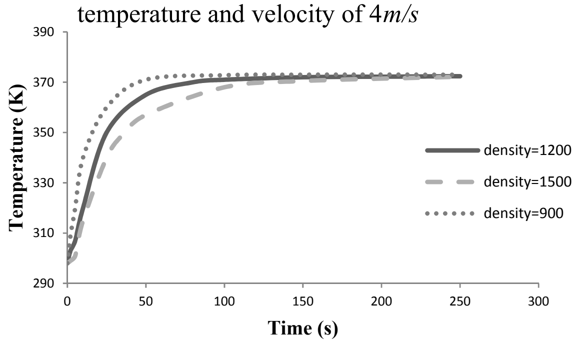

Fig. 7: Theoretical temperatures of solid in fluidized bed at different densities of particles at 373 K air temperature

the bed surface. In this simulation various parameters are investigated by changing one variable and keeping others constant. The effect of effective parameters such as size and density of particles on temperature is separately surveyed. At the initial stage, size of wheat particles is changed from 2.2, 3and 5mm in diameter. The related results are shown in Figure 6.

Figure 7 shows the effect of change in density (900, 1200 and 1500 kg/m^3) on the temperature of particles. Results implies that in the same density, the greater the particle diameter, the longer time for drying it needs. Therefore, drying process will be commonly done either with small wheat particles or with low density spheres due to the increase in temperature of particles.

CONCLUSIONS

In this study, simulation of gas-solid flow in fluidized bed was carried out in order to verify effective parameters on drying wheat particles on the bed. Essential parameters were monitored during the process and the related graphs were recorded. Results help to manage the system and show the way to choose optimized parameters in order to have highest drying efficiency. A comparison was conducted between model outputs and experimental data to find out how accurate the model is. Gas inlet temperature has the major effect on drying efficiency and actually the higher the gas inlet temperature, the higher the process' efficiencywill be. However, it may be detrimental to particles integrity and, thus, an upper limit should be considered for that. The drying temperature of solids shows a rising and flat period, which is well described by two proposed fluid models (gas-solid flow).

Nomenclature
English

a	Specific surface, 1/m
c	Specific heat kJ/kg °C
Cdz	Two phase drag coefficient
d	Particle diameter, m
D	Molecular diffusion, m^2/s
F1, F2	function, as defined in text
g	Gravity, m/s^2
G(εg)	solids stress modulus
hv	heat transfer coefficient, kJ/s m^2 °C
I	Enthalpy, kJ/kg
J_h	Heat transfer dimensionless
k	Thermal conductivity, kJ/m °C

L	Constant
n	Constant
$\dot{m}$	Moisture evaporation
Pr	Prandtl number
p	Pressure, kPa
Re	Reynolds number, as defined in text
r	Radial distance from the centerline, m
T	Temperature, °C
t	Time, s
u	Radial velocity, m/s
v	Axial velocity, m/s
x	Moisture content, kgw/kgs
z	Elevation, m

Greek symbols

β	Gas–solid drag coefficient
γ°	heat of vaporization, kJ/kg
ε	Void fraction
μ	Viscosity, kg/m s
ρ	Density, kg/m^3
σ	Evaporation coefficient, kg/m^{2}s
τ	Stress, kPa
φ_t	Spherically of a particle

Subscripts

Dz	Drag in z-direction
g	Gas
ic	Inlet-cell
p	Particle
pg	Gas on the surface of a particle
r	Radial
rr	Radial-stress
s	Solid
sc	Solid-critical
sz	Solid-axial
v	Vapor
w	Water
wg	Water-vapor
z	Axial
zz	Axial-stress

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Persian Abstract

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چکیده

داشتن مقادیر دقیق پارامترهایی که بر فرایندهای صنعتی حاکم هستند، یک جنبه کلیدی برای انجام یک فرایند و بهینه سازی آن است. برای غلبه بر این چالش، مدل های ریاضی جهانی توسعه و اصلاح شده اند. این مطالعه در نظر دارد تا شبیه سازی جریان گاز-جامد در خشک کن بستر سیال را ارائه دهد. حل عددی دوبعدی و مدل استوانه ای متقارن محوری برای دو فاز که یک مبنا در این مطالعه می باشد، انجام شده است. چند پارامتر فراگیر شبیه سرعت و دمای گاز ورودی، قطر و چگالی ذرات طی فرایند خشک کردن و همچنین چالش های انتقال حرارتی در امتداد بستر، به طور جزیی بحث و بررسی شدند. دمای ذرات جامد در مرکز و سطح که به شدت تحت تاثیر زمان هستند، در نتایج نشان داده شده اند. در انتها، خروجی های مدل با داده های آزمایشگاهی مقایسه شدند که توافق خوب و منطقی را نشان می دادند.