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A SIMPLIFIED APPROACH TO THE DRYING OF SOLIDS IN A BATCH FLUIDISED BED

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Abstract: A simplified model for drying solids in the constant rate period in a batch fluidised bed was developed. It assumes the bed to be divided into dense and bubble phases with heat and mass transfer between the phases. The model predicts the constant-rate drying period, provided the fluid bed shape and material characteristics are known. The model is compared with experimental data reported in the literature covering a wide range of materials, gas flow rates, column diameters, material hold-ups, air temperatures and humidities. Model predictions compare satisfactorily with the experimental data.

Keywords: fluidisation, drying.

INTRODUCTION

Fluidised beds are widely used for the drying of granular solids such as grains, fertilisers, chemicals, pharmaceuticals and minerals. This technique offers advantages such as the high heat capacity of the bed, improved rates of heat and mass transfer between the phases and ease in handling and transport of fluidised solids. The drying rate in the fluidised bed is strongly influenced by the characteristics of the material and the conditions of fluidisation. Materials with no internal porosity dry at an essentially constant rate, while those with an internal porous structure have both constant and decreasing drying rates.

Knowledge of drying kinetics is essential for estimation of the drying time needed to reduce the moisture content to the desired level and for choosing the optimal drying conditions. For this it is essential to know the constant and decreasing drying rates. The drying rate in the falling-rate period is generally modelled using the mechanism of moisture movement by intraparticle diffusion according to Fick's diffusion equation. The current study focuses on developing a simplified model for predicting the drying rate in the constant-rate period.

Earlier researchers modelled the drying process in the constant-rate period using the following approaches (i) heat and mass balance equations involving transfer coefficients, (ii) empirical correlations involving the influencing parameters and (iii) theoretical models which assumed the bed to be made of emulsion, cloud and bubble phases with heat and mass transfer between the phases.

The models using heat and mass transfer coefficients and the empirical approach do not pay attention to fluidisation characteristics such as bubble formation, bubble growth, rise velocity and heat and mass transfer inside the bed. The models based on transfer coefficients are generally or related with the Reynolds number, while the empirical approach relates the drying rate with

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*To whom correspondence should be addressed system variables such as solids hold-up, gas velocity, gas temperature, humidity, etc., using a wide range of experimental data (Kettenring et al., 1950; Syromyatnikov et al., 1967; Kunni and Levenspiel, 1969; Anantharaman and Ibrahim, 1982; Chandran et al., 1990; Srinivasakannan et al., 1995 and others). On the other hand, theoretical models involving heat and mass transfer between the bubble, cloud and dense phases are too complicated, which results in differential equations for prediction of the drying rate (Hoebink and Rietema, 1980a,b; Albregtse, 1986; Palancz, 1983; Srinivasakannan et al., 1994 and others).

A simplified model for the drying of solids in the constant-rate period in a batch fluidised bed is developed in this study. It assumes the bed to be divided into dense phase and bubble phase with heat and mass transfer between the phases. Further, the model assumes that all the particles are homogeneous in character, spherical in shape and uniform in size during drying; all particles within the bed are at the same temperature and have the same moisture content at any time; and the drying medium leaving the fluidised bed is in thermal equilibrium with the particle.

Current knowledge of the drying kinetics in the constant-rate period suggests that resistance to drying is only from the gas phase surrounding the solids and that resistance of solids is negligible (Parti, 1991; Kafarov and Dorokhov, 1992. The model assumes that gas in the dense phase is in equilibrium with the solids, attaining the wet-bulb temperature corresponding to the inlet gas temperature and humidity. The transfer rate between the bubble and dense phases determines the drying rate in the constant-rate period.

It is assumed that the minimum gas flow required to fluidise the bed (minimum fluidisation velocity) to flows in the dense phase and the rest flows in the bubble phase. The amount of gas flow in the dense phase is $G_d = u_{mf} A$, while in the bubble phase it is $G_b = (u_i - u_{mf}) A$.

The enthalpy balance for interstitial gas in the dense phase is given by

$$\begin{aligned} Q &= \rho_g m_d \left(\alpha_g + y_i \alpha_v\right)\left(T_i - T_d\right) + \\ &+ \frac{6 h_{bd} \varepsilon_b}{d_b}\left(T_b - T_d\right) \end{aligned} \tag{1}$$

The enthalpy balance for solids in the dense phase is given by

$$\begin{aligned} Q &= \lambda x + \rho_s \left(1 - \varepsilon_{mf}\right) \\ &\left(1 - \varepsilon_b\right)\left(\alpha_s + \alpha_v c\right)\frac{dT_s}{dt} \end{aligned} \tag{2}$$

Substituting equation (1) into (2), the amount of moisture removed from the bed is

$$x = \frac{\rho_g m_d \left(\alpha_g + y_i \alpha_v\right)\left(T_i - T_d\right) + \frac{6 h_{bd} \varepsilon_b}{d_b}\left(T_b - T_d\right) - \rho_s \left(1 - \varepsilon_{mf}\right)\left(1 - \varepsilon_b\right)\left(\alpha_s + \alpha_v c\right)\left(\frac{dT_s}{dt}\right)}{\lambda} \tag{3}$$

The enthalpy balance for the bubble phase is written as

$$\begin{aligned} &\rho_g m_b \left(\alpha_g + y_i \alpha_v\right) \\ &\left(T_i - T_b\right) = \frac{6 h_{bd} \varepsilon_b}{d_b}\left(T_b - T_d\right) \end{aligned} \tag{4}$$

On rearranging equation (4), the bubble temperature, T_b, becomes

$$T_b = \frac{\rho_g m_b \left(\alpha_g + y_i \alpha_v\right) T_i d_b + 6 h_{bd} \varepsilon_b T_d}{6 h_{bd} \varepsilon_b + \rho_g m_b \left(\alpha_g + y_i \alpha_v\right) d_b} \tag{5}$$

The heat transfer coefficient, h_{bd}, is predicted using an equation for heat transfer similar to that of Sit and Grace (1981) as follows:

$$h_{bd} = \frac{u_{mf} \rho_g \alpha_g}{3} + \frac{4 \alpha_g \rho_g k_g \varepsilon_{mf} U_b}{\pi d_b} \tag{6}$$

The bubble diameter is predicted using the equation of Mori and Wen (1975),

$$d_{bm} = 1.49\, D^2 g^{-0.2} (u_i - u_{mf})^{0.4}$$

$$d_{bo} = \frac{1.38}{g^{0.2}} \frac{A\left(u_i - u_{mf}\right)}{n}$$

$$d_b = d_{bm} - \left(d_{bm} - d_{bo}\right)\exp\left[-0.3\frac{H}{D}\right] \tag{7}$$

The rise velocity of the bubble is predicted using the equation of Kunni and Levenspiel (1969),

$$U_b = u_i - u_{mf} + 1.6\,(gd_b)^{0.5} \tag{8}$$

The height of the solids in the bed necessary for predicting bubble diameter is obtained using the equation of Aerov and Todes (1968),

$$\varepsilon_f = 1 - \frac{H_o}{H}\left(1-\varepsilon_o\right) \tag{9}$$

$$\varepsilon_f = \left(\frac{18\text{Re} + 0.36\text{Re}^2}{\text{Ar}}\right)^{0.2} \tag{10}$$

where the static bed porosity, ε_o, is 0.4.

The fraction of bubble phase in the bed is predicted using the equation

$$(1-\varepsilon_f) = (1-\varepsilon_b)\,(1-\varepsilon_d) \tag{11}$$

the dense phase may be assumed to be under the minimum fluidisation condition, $\varepsilon_d = \varepsilon_{mf}$, and hence

$$\left(1-\varepsilon_b\right) = \frac{\left(1-\varepsilon_{mf}\right)}{\left(1-\varepsilon_f\right)} \tag{12}$$

The minimum fluidisation velocity is predicted using the equation of Wen and Yu (1966),

$$u_{mf} = \left[\frac{\mu_g}{\rho_g d_p}\right]\left[33.7^2 + 0.0408\text{Ar}\right]^{0.05} - 33.7 \tag{13}$$

The drying rate in constant-rate period can be estimated solving equation (3), which requires, the dense phase temperature, T_d, the bubble phase temperature, T_b, the bubble diameter, d_b, the heat transfer coefficient between bubble phase and dense phase, h_{bd} and the volume fraction of bubbles in the bed, ε_b. The dense phase temperature, T_d, is assumed to be in wet bulb temperature corresponding to the inlet air temperature and humidity where as the bubble phase temperature, T_b, is estimated using equation (5). The heat transfer coefficient between the bubble and dense phase is estimated using equation (6) and the bubble diameter, d_b, is estimated using equation (7). The volume fraction of bubbles, ε_b, in the bed is estimated using equation (12).

The third term in the numerator of equation (3) corresponds to the rate of sensible heat rise of the material in the dense phase. Under steady state operation, in constant-rate drying period the temperature of the materials in the dense phase essentially remain constant and hence the term is insignificant.

RESULTS AND DISCUSSION

Model is simulated to assess the effects of various operating parameters on the drying kinetics and the following observations are made. An increase in gas rate or its temperature increases the drying rate while an increase in the inlet gas humidity or the bubble volume fraction decreases the drying rate. An increase in the solids hold-up decreases the drying rate due to decrease in the input enthalpy per unit mass of solids. The simulations are performed by varying one parameter at a time keeping the other parameters constant. However in practice an increase in air rate increases the bubble volume fraction as well as bed height. The simulation results qualitatively agree with earlier predictions reported in literature.

The model is compared with experimental data covering a wide range of materials, gas flow rates, column diameters, material hold-ups, inlet air temperatures and humidities. Experimental data from Chandran et al. (1990), McKenzie and Bahu (1991), Thomas (1993) and Srinivasakannan et al. (1994) are compared with the model. Details of the experimental conditions used by these authors are reported in Table 1. Figure 1 shows a comparison of the experimental data with the prediction using the model. It can be observed that the experimental data compare satisfactorily with the model.

Table 1: Experimental Details of the Studies Reported in the Literature

MATERIAL	AUTHOR	D (m)	d_P X 10^3 (m)	r_S (kg/m^3)	W_S (kg)	G_g X10^2(m^3/s)	T_g °C
Millet (pennisetum typhoides)	Srinivasakannan et al. (1994)	0.148	2.2	1350	0.15-0.27	2-4	30-150
Ragi (eleusine crocane)	Srinivasakannan et al. (1994, 1995)	0.148,0.245	1.5	1207	0.13-2.6	2-6	30-105
Mustard	Thomas (1993)	0.245	1.7	1100	1.3-2.6	6-10	30-150
Poppy seeds (papaver sominiferem)	Srinivasakannan et al. (1995)	0.148	0.9	800	0.1-0.22	2-4	30-105
Ion exchange resin	Chandran et al. (1990) Mckenzie and Bahu (1991)	0.3-0.4	0.15-0.9	1480	1.1-6.1	3.9-13.7	40-90
Sand	Srinivasakannan et al. (1995)	0.245	0.17-0.41	2650	2-4.5	4-12	30-80

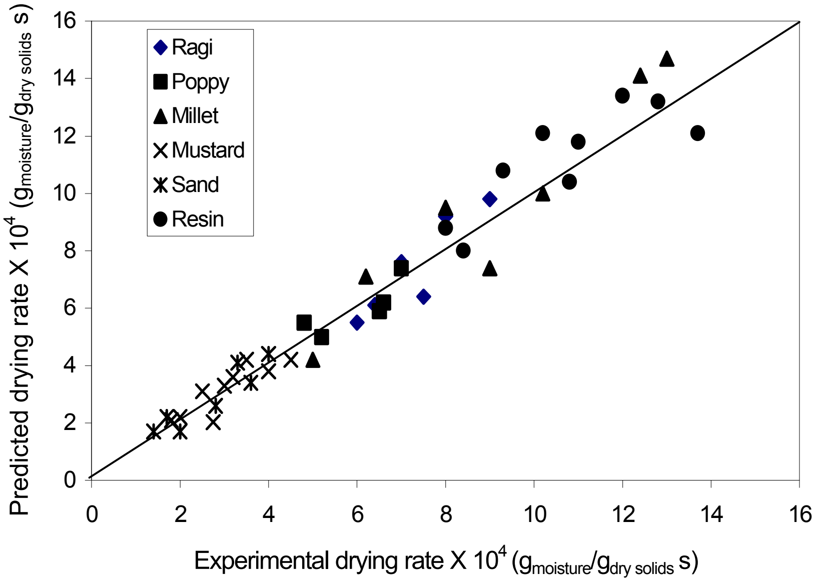

Figure 1: Comparison of experimental drying rate with the prediction using the model.

CONCLUSION

A simplified model for drying of solids in constant-rate period in a batch fluidised bed is developed, considering the bed to made of dense phase and bubble phase with heat and mass transfer between the phases. It is assumed that the solids in dense phase to be in thermal equilibrium with the interstitial gas in the dense phase. The bubble size, its rise velocity, and the bubble volume fraction are taken into account while developing the model. The model is compared with experimental data reported in literature covering wide range of operating parameters and found to match satisfactorily.

NOMENCLATURE

A	area of the bed, m^2
Ar	$d_p^3 g \rho_g(\rho_s-\rho_g)/\mu^2$
c	average moisture content of solids

D	diameter of the bed, m
d	diameter, m
g	gravitational constant, m^2/s
G	flow rate, m^3/s
H	height of the fluidised bed, m
h	heat transfer coefficient , kcal/m^2 s $^\circ$C
k	thermal conductivity, kcal/m s $^\circ$C
m	mass flow per unit volume of the bed, s^{-1}
n	number of holes in the distributor plate
Q	total heat input/unit volume of the bed, kcal/m^{3}s
Re	Reynolds number, $d_p \rho_g u_i / \mu$
T	temperature, $^\circ$C
u	gas velocity in the bed, m/s
U	rise velocity, m/s
W	hold-up, kg
x	rate of moisture removal per unit volume of bed, kg/m^3 s
y	gas humidity, kg of moisture/kg of dry air

Subscripts

b	bubble
bd	bubble to dense phase
d	dense phase
f	fluidised bed
g	gas
i	inlet
mf	minimum fluidisation
o	static
p	particle
s	solid
v	vapour

Greek letters

ρ	density, kg/m^3
α	specific heat, kcal/kg $^\circ$c
λ	latent heat of evaporation, kcal/kg
ε	void fraction
μ	viscosity of the gas, kg/m s

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