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Heat and mass transfer studies in a batch fluidized bed dryer using Geldart group D particles

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Abstract The drying behavior at low temperatures has been studied with four different uniformly sized particles and three different binary mixtures at different dilutions ranging from 10 to 40 % with an interval of 10 % varying parameters such as air velocity, initial moisture content, initial bed height and temperature. Falling rate period one and two were observed and correlations were developed to predict the drying rate in falling rate periods one and two. Correlations were also developed to predict the average moisture content by considering the effect of various parameters for uniformly sized particles and binary mixture of solids. The heat and mass transfer coefficients have been found for different conditions and compared. Comparison of experimental and predicted average moisture contents for uniformly sized particles and for various binary mixtures has been made and the predicted average moisture content has been found to be in good agreement with experimental average moisture content.

List of symbols

C_{in}, C_0	Initial moisture content of solids (kg water/kg dry sand)
C_t	Moisture content with respect to time (kg water/kg dry sand)
C^*	Moisture content at the end of falling rate period one (kg water/kg dry sand)
C_{eq}	Equilibrium moisture content (kg water/kg dry sand)
$\overline{C}$	Average moisture content (kg water/kg dry sand)
$\overline{C}_U$	Average moisture content of uniform particle sizes (kg water/kg dry sand)
$\overline{C}_{BM}$	Average moisture content of binary mixtures (kg water/kg dry sand)
d_p	Diameter of the particle (m)
$\overline{d_p}$	Average diameter of particles (m)
D_v	Diffusivity (m^2/s)
H	Initial static bed height (cm)
h	Heat transfer coefficient (W/m^2 K)
$k_{g,bed}$	Mass transfer coefficient (1/s)
K	Thermal conductivity (W/m K)
M	Molecular weight
Nu_p	Nusselt number of particles, $Nu = \frac{hd_p}{K_g}$
$\Pr_g$	Prandtl number of gas, $\Pr = \frac{C_p \mu}{K_g}$
R	Drying rate (kg water/kg dry sand s)
R_1	Drying rate in falling rate period one (kg water/kg dry sand s)
R_2	Drying rate in falling rate period two (kg water/kg dry sand s)
Re_p	Reynolds number of particles, $\mathrm{Re}_p = \frac{\rho_g u_0 d_p}{\mu_g}$
Sh_{bed}	Sherwood number of bed, $Sh = \frac{k_g d_p}{D_v}$
Sc	Schmidt number, $Sc = \frac{\mu_g}{\rho_g D_v}$
t	Time (s)
T	Temperature (°C)
u, u_0	Air velocity (m/s)
V	Critical molar volume (m^3/g mol)
W	Weight of solids (kg)
X	Weight fraction
y	Mole fraction

Greek symbols

δ	Bubble fraction in bed
ρ	Density (kg/m^3)
μ	Viscosity of gas (kg/m s)

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ε Voidage
ϕ Sphericity

Subscripts
g Air
p Particles
s Solids
mf Minimum fluidization
f Fluidization
A Air
W Water
CA Critical air
CW Critical water

1 Introduction

The fluidized bed dryers are mainly designed to introduce hot gas stream at the bottom of the bed. The main advantages of fluidized bed dryers are high heat and mass transfer rates, uniform temperature in the bed, good mixing due to particle–particle and particle–wall collisions, applicability over a wide range of particles and higher relative velocities of individual phases.

Prachayawarakorn et al. [1] studied the soya bean drying using super heated steam in the temperature range of 135–150 °C and initial moisture content of 19.5 %. Srinivasa Kannan et al. [2] studied the drying behavior for Ragi, Mustard and poppy seeds at different temperatures ranging from 39 to 80 °C with initial moisture content of 18–46 %. Hashemi et al. [3] studied drying behavior of the broad beans in a fluidized bed dryer between 35 and 65 °C temperatures with initial moisture content of 75 %. Many authors have conducted the experiments at higher temperatures in the constant and falling rate periods. The present study aims to capture the drying behavior at low temperatures with low initial moisture content.

In the present study the experiments have been carried at low temperatures ranging from 40 to 60 °C, with air velocity range of 2.13–2.98 m/s, with initial moisture content ranging from 4 to 10 % and with different initial bed heights ranging 25–50 cm, for four different uniformly sized particles that belong to Geldart group D [4] and three different binary mixtures at four different dilutions ranging from 10 to 40 % with an interval of 10 %. The binary mixture has been prepared by diluting the fine particles with coarse particles. In the present study the locally available sand with density 2,500 kg/m^3 has been used.

The temperature sensors (PT 100) with Data logging and acquisition system has been used to predict the temperature at inlet, outlet and in the bed. The Relative humidity has been measured at the inlet and the outlet of the fluidized bed dryer using humidity meter (HTC HD 304) during the experimentation.

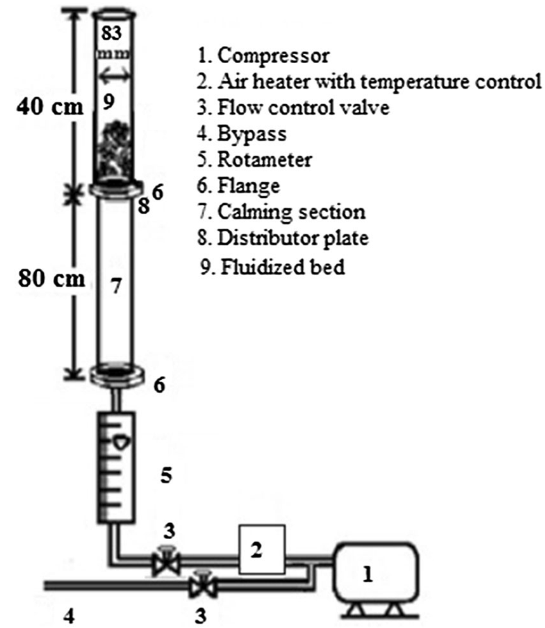

Fig. 1 Model experimental setup

2 Experimental procedure

A schematic diagram of experimental setup is shown in Fig. 1. Air at room temperature is drawn from a compressor. It is then passed through air heater to attain the required temperature. The outlet air temperature has been controlled with rheostat which is connected to the air heater. The heated air at known velocity has been passed through the fluidized bed through calming section. The perforated plate with fine mesh has been fixed above the calming section. After attaining the steady state temperature of air the moist solids were fed in the column. The sample from the top of the dense bed (middle of the column) has been drawn with respect to time to carry out the moisture analysis.

3 Results and discussion

Generally the drying rate has three different drying periods such as warm-up period, constant drying rate period and falling rate period. From the results it has been observed that only falling rate period has been exhibited and there is no constant rate period due to low initial moisture content of the solids. The solids have been introduced after the air has attained the required

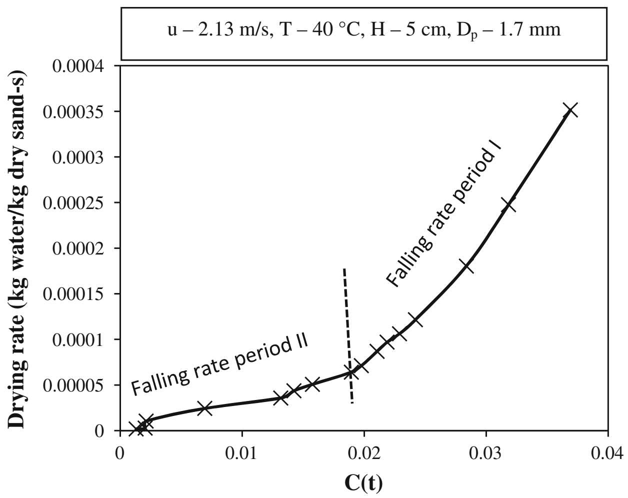

Fig. 2 Typical drying rate curve

temperature and then experiments were conducted. Hence there is no warm-up period.

The main observation from the results is that the drying rate curve exhibits two types of falling rate periods. At the initial stage of drying the falling rate period one has been observed and followed by the second falling rate period. Figure 2 presents results of uniformly sized particles of size 1.7 mm at air velocity of 2.13 m/s with initial bed height of 5 cm at air temperature of 40 °C with initial moisture content of 5 %. From the results two types of falling rate periods have been observed which are shown in Fig. 2. The moisture present initially is the moisture contained with the bed and there is no excess moisture and hence no constant rate period is observed. According to Mujumdar [5] moisture may become bound in a solid by retention in a capillary, solution in cellular structure, solution with in the solid or by chemical or physical adsorption on the surface of the solid. Since the material used is sand which is nonporous, the moisture present initially is bound by physical adsorption on the surface of the solid and also that contained in the interstices of the bed. As drying proceeds the moisture present on the surface as physically adsorbed moisture and also that present in the interstices in the upper layers of the particles in the bed first evaporates which corresponds to period one. Then the moisture present in the interstices in the bottom layers of the particles in the bed evaporates which corresponds to period two.

To predict the drying rate in falling rate periods one and two, correlations were developed for drying rate in terms of moisture content. The developed correlations for falling rate periods one and two were presented in Eqs. 1 and 2 respectively.

$$R_1 = 1.51 \times 10^{-2}\left(\frac{C_{in} - C^*}{t}\right)^{0.57} \ln\left(\frac{C_{in} - C^*}{C_t - C_{eq}}\right) \tag{1}$$

$$R_2 = 8.02\left(\frac{C_{in} - C_{eq}}{t}\right)^{1.57} \ln\left(\frac{C_{in} - C_{eq}}{C_t - C_{eq}}\right) \tag{2}$$

The following equations have been used for predicting the average moisture content in the fluidized bed. Average moisture content has been found from Eq. 3 as reported by Satish and Pydi Setty [6] and mixing index for the binary mixture of solids has been found from Eq. 4 as reported by Sahoo and Roy [7] in the present study.

$$\frac{\overline{C}}{C_0} = \frac{\int (C/C_0)dt}{\int dt} \tag{3}$$

$$I_m = 0.3725\left(\frac{\overline{d}_p}{d_F}\right)^{0.3679}\left(\frac{h_B}{D_c}\right)^{-0.4864}\left(\frac{H_s}{D_c}\right)^{0.8258}\left(\frac{u}{u - u_f}\right) \tag{4}$$

The correlations were developed to predict the average moisture content in the bed incorporating the effect of different parameters on it and for binary mixture of solids, the mixing index has been included additionally. The developed correlations were presented in Eqs. 5 and 6. Equation 5 is for uniformly sized solids and Eq. 6 for the binary mixture of solids.

$$\overline{C}_U = 0.019\left(u^{-3.14}\right)\left(W^{0.34}\right)\left(d_p^{0.19}\right)\left(C_0^{0.91}\right)\exp\left(\frac{1{,}793}{T}\right) \tag{5}$$

$$\overline{C}_{BM} = 0.19\left(u^{-0.37}\right)\left(W^{0.06}\right)\left(d_p^{0.54}\right)\left(C_0^{015}\right)\exp\left(\frac{256}{T}\right)\left(I_m^{-1.65}\right) \tag{6}$$

The average diameter of the particles has been found from the Eq. 7 given by Kunii and Levenspiel [8].

$$\overline{d_p} = \frac{1}{\Sigma^{all\,i}\left(X/d_p\right)_i} \tag{7}$$

The average heat and mass transfer coefficients have been found from the Nusselt and Sherwood numbers [9] for all uniformly sized particles.

$$Nu_p = 1.01\mathrm{Re}_p^{0.48}\,\mathrm{Pr}_g^{0.33} \quad \text{for} \quad 50 < \mathrm{Re}_p \le 10^4 \tag{8}$$

$$Sh_{bed} = \frac{k_{g,bed}d_p y}{D_v} = 2 + 1.8\left(\mathrm{Re}_p^{0.5}\right)\left(Sc^{0.333}\right) \quad \text{for} \quad \mathrm{Re}_p > 80 \tag{9}$$

The present experimental data has been used to predict the Nusselt number and Sherwood number as given by Eqs. 8 and 9.

3.1 Emulsion phase model

For comparison, the Nusselt and Sherwood numbers have also been found using emulsion phase model [10, 11]. Minimum fluidization velocity has been found from Eq. 10

[8] and voidage at minimum fluidization for sand particles has been found from Eq. 11 [12]. In the present study locally available sand (sharp) has been chosen and value of $\phi_s = 0.67$ from Kunii and Levenspiel [8] has been used. The bubble fraction in the fluidized bed has been found from Eq. 12 [13, 14] and voidage in the fluidized bed has been found from the Eq. 13 [8]. The diffusivity has been found from Eq. 14 [15]. The Nusselt and Sherwood numbers have been found for emulsion phase from Eqs. 15 and 16 [10, 16].

$$\frac{d_p u_{mf} \rho_g}{\mu} = \left[(28.7)^2 + 0.0494 \left(\frac{d_p^3 \rho_g (\rho_s - \rho_g)}{\mu^2} \right) \right]^{1/2} - 28.7 \tag{10}$$

$$\varepsilon_{mf} = 0.586 \times (\phi_s^{-0.72}) \times \left[\frac{\mu_g^2}{\rho_g (\rho_s - \rho_g) g d_p^3} \right]^{0.029} \left(\frac{\rho_g}{\rho_s} \right)^{0.021} \tag{11}$$

$$\delta = 0.534 - 0.534 \times \exp\left(-\frac{u_0 - u_{mf}}{0.413} \right) \tag{12}$$

$$\varepsilon_f = \delta + (1 - \delta) \varepsilon_{mf} \tag{13}$$

$$D_v = \frac{0.01498 T^{1.81} (1/M_A + 1/M_W)^{0.5}}{P (T_{CA} T_{CW})^{0.1405} (V_{CA}^{0.4} + V_{CW}^{0.4})^2} \tag{14}$$

$$Nu = \left(7 - 10\varepsilon_f + 5\varepsilon_f^2\right)\left(1 + 0.7 \mathrm{Re}_p^{0.2} \mathrm{Pr}^{1/3}\right) + \left(1.33 - 2.4\varepsilon_f + 1.2\varepsilon_f^2\right) \mathrm{Re}_p^{0.7} \mathrm{Pr}^{1/3} \tag{15}$$

$$Sh = \left(7 - 10\varepsilon_f + 5\varepsilon_f^2\right)\left(1 + 0.7 \mathrm{Re}_p^{0.2} Sc^{1/3}\right) + \left(1.33 - 2.4\varepsilon_f + 1.2\varepsilon_f^2\right) \mathrm{Re}_p^{0.7} Sc^{1/3} \tag{16}$$

It is noticed that the values of Nusselt number obtained from the emulsion phase model are higher compared to the values obtained from Eq. 8 and for Sherwood number the results with emulsion phase have been found to be lower than those from Eq. 9 which may due to the fact that voidage is incorporated in Eqs. 15 and 16.

The Nusselt number of particle is found to be increasing in emulsion phase incorporating the voidage in the correlation. Correlation 8 has been developed with an assumption similar to that of single particle [9] and the voidage inclusion results in increase in the available specific surface area for heat transfer from heating medium to the particles. The Sherwood number has been found to decrease for emulsion phase model which incorporates the voidage in the fluidized bed in the correlation. Correlation 9 has been developed assuming the fixed bed condition [8] and with inclusion of voidage, the volume of the solids in the bed will decrease which results in lower values of Sherwood number [9].

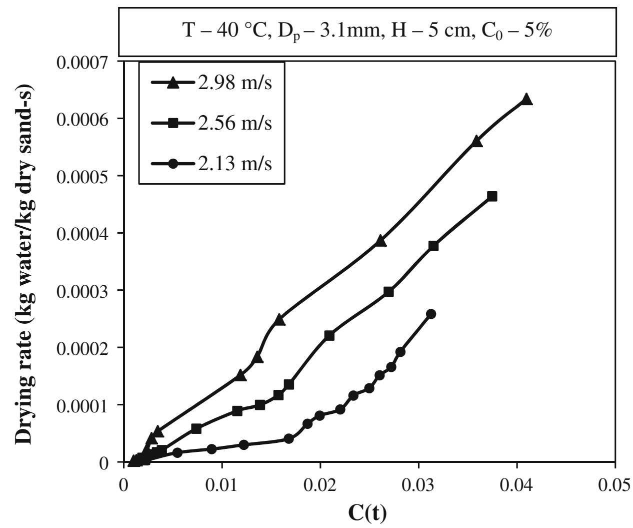

Fig. 3 Variation of drying rate with velocity

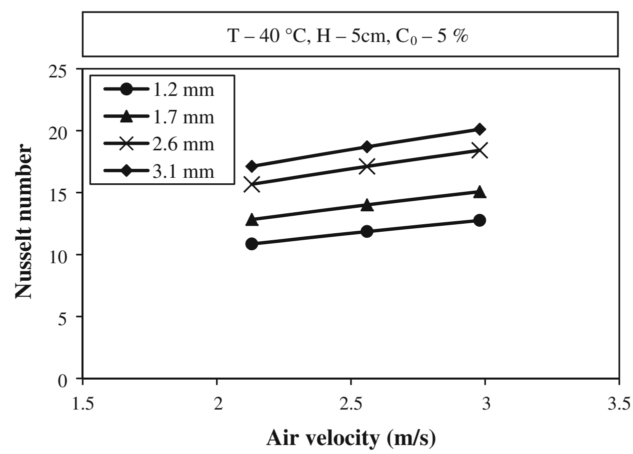

Fig. 4 Variation of Nusselt number with velocity for particles of different size

3.2 Effect of air velocity

Experiments have been carried out at three different air velocities ranging from 2.13 to 2.98 m/s for all uniformly sized particles and binary mixture of solids by varying the parameters such as initial moisture content, temperature and initial bed height. It has been observed that increasing the velocity the drying rate has been found to be increasing and the equilibrium moisture content has been found to be decreasing. Figure 3 presents the results of variation of drying rate with velocity. Figure 4 presents the results of effect of air velocity on Nusselt number found from Eq. 8 at different velocities for four different particle sizes. The heat and mass transfer coefficients have been found to be increasing with increase in the air velocity.

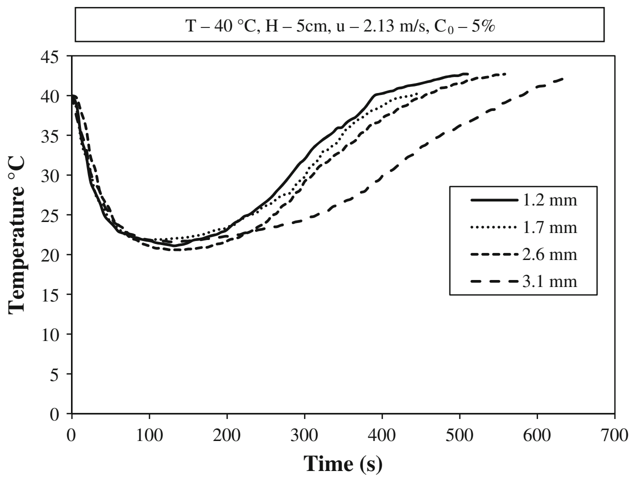

Fig. 5 Variation of bed temperature with time

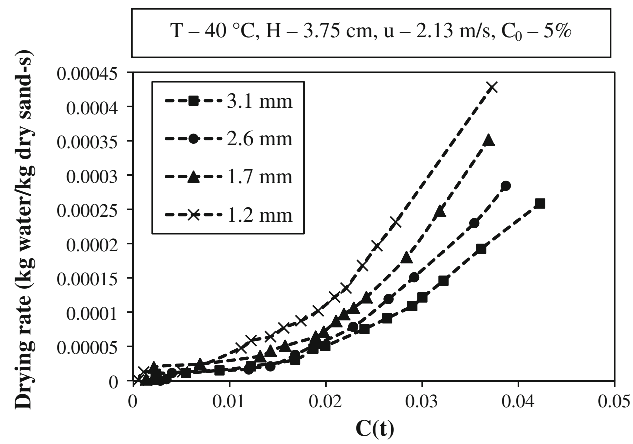

Fig. 6 Variation of drying rate with particle size

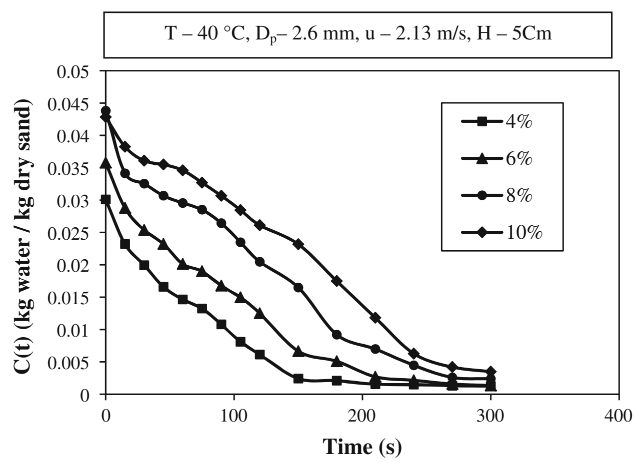

Fig. 7 Variation of transient moisture content of solids with initial moisture content

3.3 Effect of particle diameter

Experiments have been performed with four different uniformly sized particles and with three different binary mixtures at various dilutions ranging from 10 to 40 % with interval of 10 %. From the results it has been observed that with increase in diameter the drying rate has been found to be decreasing and the equilibrium moisture content has been found to be increasing. The heat and mass transfer coefficients have been found to be decreasing with increase in the particle diameter. Figure 5 represents typical variation of bed temperature with time for particles of different size. Figure 6 presents the results of variation of drying rate with particle size at initial bed height of 3.75 cm with initial moisture content of 5 % at air velocity of 2.13 m/s with an air temperature of 40 °C. From the results it has been observed that with increase in the particle diameter the drying rate has been found to be decreasing in two types of falling rate periods. The bed temperature has been found to be increasing faster for fine particles in comparison with coarse particles. The bed temperature is observed to be decreasing at the initial stage up to certain time and then the temperature is seen to be increasing. The initial drop is due to the sudden introduction of solids into the fluidized bed. The temperature was measured at the bottom of the bed.

3.4 Effect of initial moisture content

Experiments have been performed at different initial moisture content of solids ranging from 4 to 10 % with interval of 2 % for all particle sizes at different bed heights and temperatures for uniformly sized particles and binary mixture of solids. With increase in initial moisture content, the fluidized bed temperature decreases. As the temperature decreases the heat and mass transfer decrease and hence there is decrease in the drying rate. Figure 7 presents the results of variation of transient moisture content of solids with initial moisture content.

3.5 Effect of initial bed height

Experiments have been carried at three different bed heights such as 2.5, 3.75 and 5 cm for all uniformly sized particles and binary mixtures at various velocities, temperatures and initial moisture content of solids. From the results it has been observed that with increase in the initial bed height the drying rate has been found to be decreasing and the equilibrium moisture content has been found to be increasing. The heat and mass transfer coefficients have been found to be decreasing with increase in the initial bed height of solids. Figure 8 presents the effect of initial bed height on drying rate.

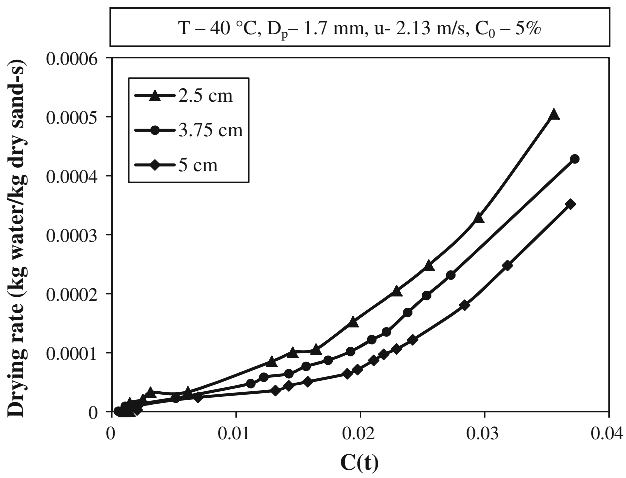

Fig. 8 Effect of initial bed height on drying rate

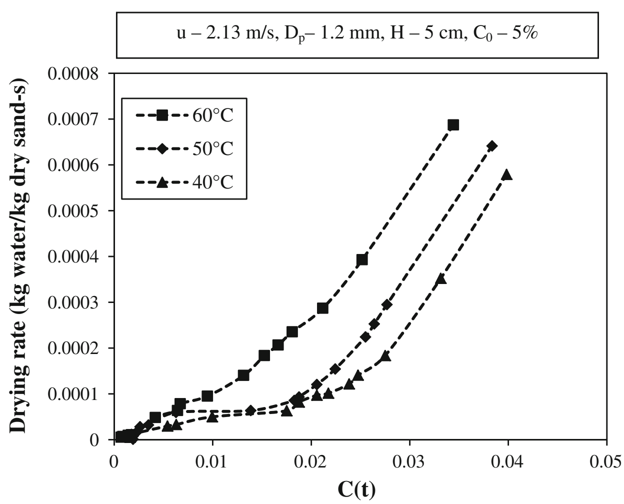

Fig. 9 Effect of temperature on drying rate

3.6 Effect of temperature

Experiments have been carried out at three different temperatures such as 40, 50 and 60 °C for all uniform particles and different binary mixtures at various dilutions ranging 10–40 % with an interval of 10 % by varying other parameters. Figure 9 presents the effect of temperature on drying rate. From the results it has been observed that increase in temperature increases the drying rate and decreases the equilibrium moisture content. The bed temperature has been found to be increasing with an increase in temperature resulting higher heat and mass transfer rates. Figure 10 presents the variation of Sherwood number with temperature and diameter of the particle. From Fig. 10 it can be seen that increase in temperature decreases the Sherwood number for all particle sizes which may be due to increase in diffusivity with increase in temperature. The Sherwood number reported in the Fig. 10 has been found from Eq. 16.

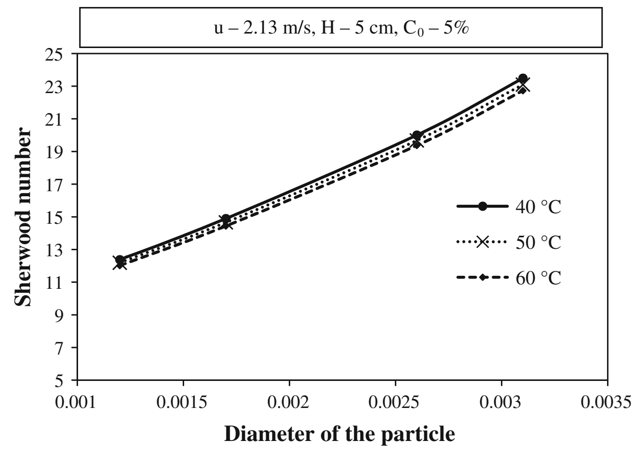

Fig. 10 Variation of Sherwood number with temperature and diameter of the particle

3.7 Effect of dilution of binary mixtures

Experiments have been carried with three different binary mixtures at various dilutions such as 10–40 % with an interval of 10 % varying parameters like air velocity, initial moisture content, initial bed height and temperature. Figure 11 presents the results of Variation of drying rate with dilution of binary mixture and also with uniformly sized particles of size 1.2 and 3.1 mm. From the results it has been observed that the 10 % binary mixture has exhibited slightly higher drying rate than the fine uniformly sized particles and also it has been observed that for binary mixture of 40 % dilution the drying rate has been decreasing slightly than the coarse particle size. The mixing index has been playing an important role in the change of the drying behavior. The mixing index has been found higher for 10 % and lower for 40 %. Average diameter of the particle has been considered for binary mixtures in correlation development. The heat and mass transfer coefficients have been predicted using the average diameter of the particle in Eqs. 8 and 9. From the results it has been noticed that for binary mixture of solids slight variation is observed for falling rate period one and almost same drying rate has been observed for falling rate period two.

Nusselt number and Sherwood numbers have been found using Eqs. 8 and 9 and also Eqs. 15 and 16. The present Nusselt number has been found to be in the region with the reported values and in the emulsion phase Nusselt number has been found slightly higher than the average Nusselt number as shown in the Fig. 12. The present Sherwood number results have been found to be in the region with the reported values and it has been observed that the Sherwood number with emulsion phase results were found to decrease than the average Sherwood number obtained from the correlation as shown in Fig. 13.

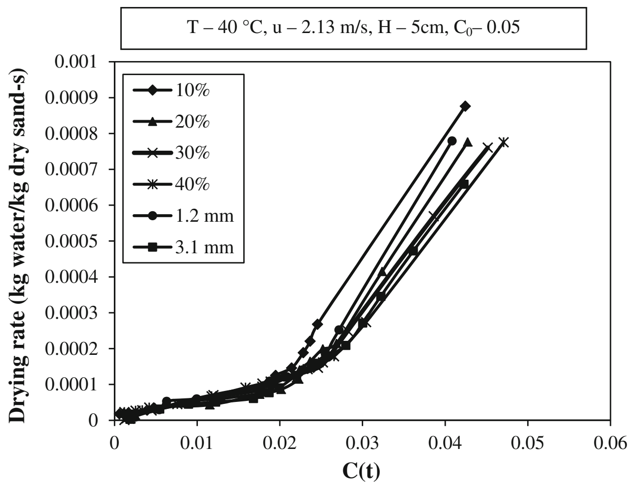

Fig. 11 Variation of drying rate with dilution of binary mixture

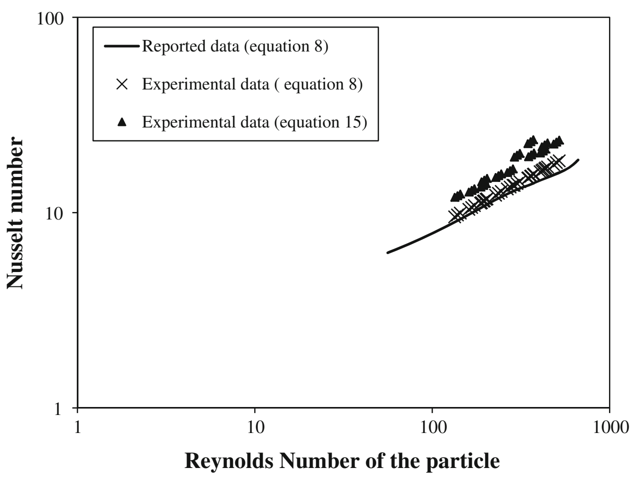

Fig. 12 Variation of Nusselt number of particle with Reynolds number of particles

The heat and mass transfer coefficients have been found for both cases and the results were presented in Figs. 14 and 15. The heat and mass transfer coefficients have been found to be increasing with increase in air velocity, temperature and found to be decreasing with increasing the particle diameter. From the drying rate results it has been also observed that the drying rate will decrease with increase in the initial bed height and initial moisture content. The heat and mass transfer coefficients were directly proportional to the drying rate. Hence decrease in the drying rate results in the decrease of heat and mass transfer coefficients.

Heat and mass transfer coefficients have been found from both methods. The heat transfer coefficients from emulsion phase model have been found to be higher and the mass transfer coefficients have been found to be lower.

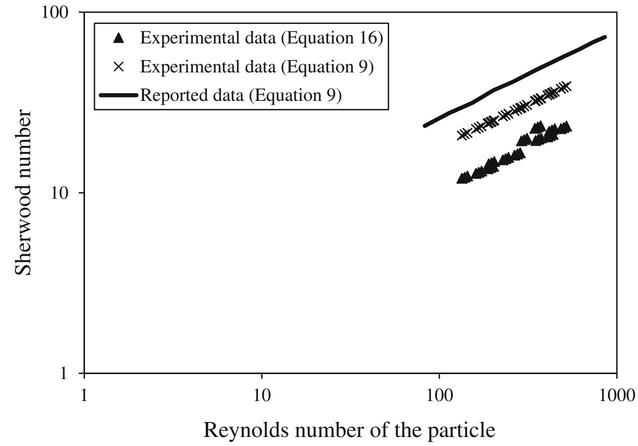

Fig. 13 Variation of Sherwood number with Reynolds number of particles

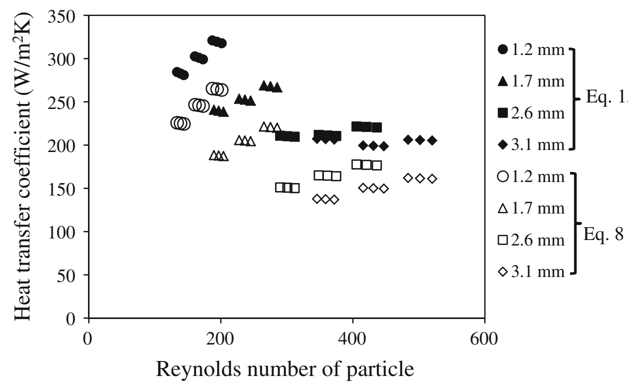

Fig. 14 Variation of heat transfer coefficient with Reynolds number of particles for four uniformly sized particles at temperature ranges of 40–60 °C at velocity range of 2.13–2.98 m/s

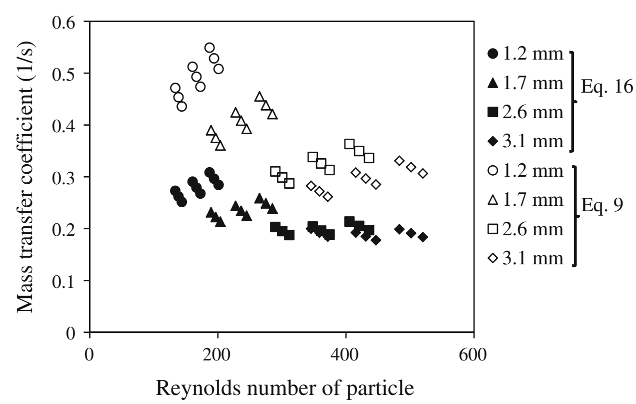

Fig. 15 Variation of mass transfer coefficient with Reynolds number of particles for four uniformly sized particles at temperature ranges of 40–60 °C at velocity range of 2.13–2.98 m/s

The experimental and predicted average moisture content have been compared for uniformly sized particles and also for binary mixture of solids as presented in Figs. 16

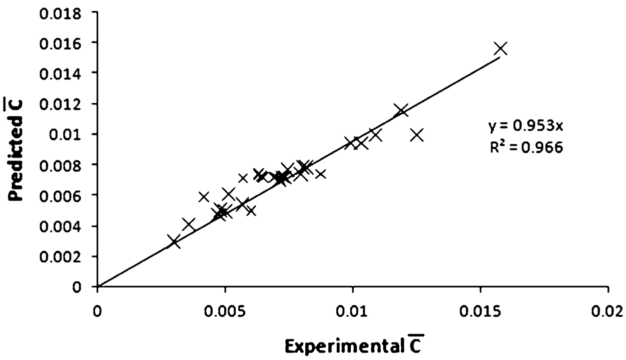

Fig. 16 Comparison of experimental and predicted average moisture content for uniformly sized particles

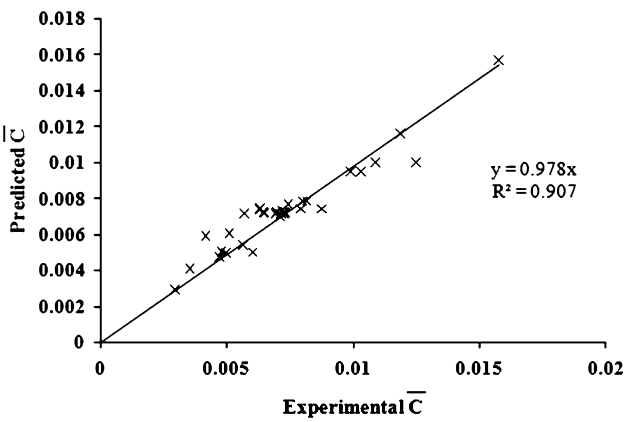

Fig. 17 Comparison of experimental with predicted average moisture content for various binary mixture of solids

and 17. From the results it can be observed that the predicted results (Eqs. 5 and 6) were matching with experimental results and hence it can be used to estimate the appropriate average moisture content.

4 Conclusions

The present study has been carried at low temperatures, at just above the ambient conditions varying parameters such as air velocity, initial moisture content, particle diameter, initial bed height and temperature in a batch fluidized bed dryer for four different uniformly sized particles and three different binary mixtures at different dilutions ranging from 10 to 40 % with an interval of 10 %. The heat and mass transfer studies has been carried for all these experiments.

Correlations have been developed to predict the drying rate for falling rate periods one and two and also to predict the average moisture content by relating it with different parameters.

With increase in air velocity and temperature, the drying rate has been found to be increasing and the equilibrium moisture content has been found to be decreasing. Increase in initial moisture content, initial bed height and particle diameter decreases the drying rate and increases the equilibrium moisture content. For 10 % binary mixture of solids it has been observed that the drying rate was slightly increasing in comparison with fine particles. The drying rate has been observed from the results that for 20 and 30 % binary mixtures slightly greater than the coarse particle size and slightly lower for 40 % binary mixture for all types of binary mixture. The Nusselt and Sherwood numbers have been found to be nearer to the literature reported values.

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