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Drying behavior of uniform and binary mixture of solids in a batch fluidized bed dryer

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ABSTRACT

The drying behavior of solids has been studied in a batch fluidized bed dryer using different uniformly sized solids and various binary mixtures of solids at different dilutions in falling rate periods one and two. To predict the drying behavior in falling rate periods one and two, correlations were developed for uniformly sized particles and for binary mixture of solids. The mixing index has been incorporated to develop the correlations for two types of falling rate periods. The average moisture content has been taken to predict the effect of various parameters on drying behavior. The correlations for average moisture content have been developed by considering the effect of various parameters such as air velocity, initial moisture content of solids, temperature, initial bed height and particle diameter for uniformly sized particles. The effect of various parameters on drying behavior has been investigated for different binary mixture of solids. To predict the drying behavior of binary solid mixtures, mixing index has been incorporated with other parameters in correlation development. The mixing index has been found to decrease with increase in the dilution of fine particles with coarse particles. The drying behavior of binary mixture of solids has been found to be similar to the uniformly sized particles. Effect of dilution on drying has been investigated, where in it is noticed that 10% diluted binary mixture gave highest drying rate and no improvement in drying behavior is found for dilution beyond 30%. The work finds importance in practice, as it involves the use of solid mixtures. The experimental results were compared with the predicted values and are found to be in good agreement.

1. Introduction

Fluidized bed dryers are most commonly used in chemical, pharmaceutical, food and process industries for drying operation. Fluidized bed dryers are mainly adopted to promote higher heat and mass transfer rates. Fluidized bed dryers provide high levels of contact between gas and solids, extremely high surface area of contact between fluid and solid per unit bed volume, high relative velocities between the fluid and the dispersed solid phase, high levels of intermixing of the particulate phase, frequent particle–particle and particle–wall collisions that lead to higher heat and mass transfer rates. In general industrial drying process, the drying behavior may not get affected much with respect to particle size in batch and continuous processes. In fluidized bed drying of solids the particle size and the particle size distribution of solids in the mixture have significant effect on drying behavior.

Particles can be classified into four groups according to Geldart group classification with respect to particle size (Geldart [1]). Fluidized bed dryers are used for drying of a wide range of Geldart group particle sizes. The present study was carried out with Geldart group D particles. Sand has been chosen for the prediction of drying behavior in fluidized bed drying for binary mixture of solids and uniformly sized solids. The locally available sand has been collected and separated using sieve analysis method. Four different uniformly sized particles of sizes ranging from 1.2 mm to 3.1 mm were used in experimental studies.

Fluidized bed dryers can be operated in batch and continuous modes with wide range of velocities, amount of solids, varying moisture content and temperature. Uniformly dried product can be obtained using fluidized bed dryer even in large scale operation, where as it is very difficult to obtain a product of uniform moisture content in tray type and other dryers. In the present study, the heat is supplied through the wall and air at room temperature is supplied from bottom. The drying behavior was studied using uniformly sized particles as well as various binary mixtures of solids. The binary mixture has been prepared by diluting the fine particles with coarse particles. Four different types of binary mixtures ranging from 10% to 40% with an interval of 10% have been prepared to study the effect of dilution on drying behavior. Three different pairs of uniformly sized particles of size ranging from 1.2 to 3.1 mm have been chosen to prepare the binary mixture and the dilution is changed from 10% to 40% for each pair.

2. Experimental setup and procedure

A schematic diagram of the experimental setup is shown in Fig. 1. Atmospheric air is compressed in the compressor which is connected to the rotameter of flow range 0–100 kg/h. Air from compressor is

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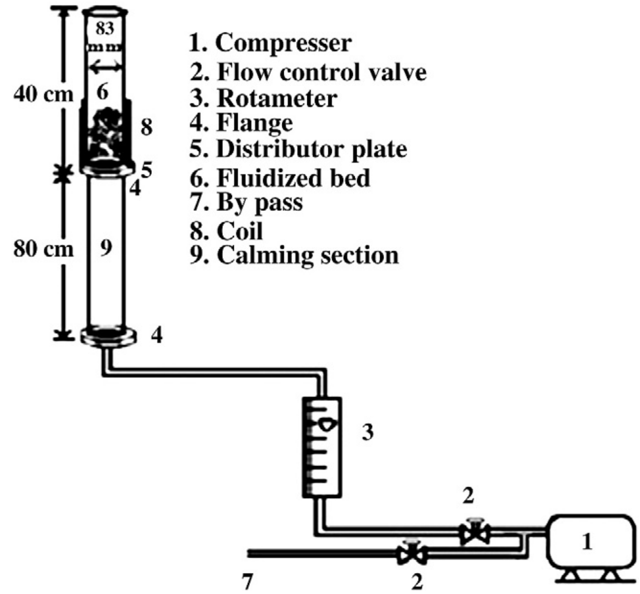

Fig. 1. Experimental setup.

passed through the rotameter at known velocity into the fluidized bed dryer through the calming section provided. Perforated plate was placed above the calming section with suitable mesh fixed to it. The fluidized bed column height is 40 cm with diameter of 8.3 cm and it is externally heated with a power supply. The fluidized bed is heated with a heater made up of nichrome wire fixed around the column. The power is supplied directly through the rheostat. The power supply to the column and hence the temperature of the wall and the bed are controlled by controlling the rheostat. The outside surface of the fluidized bed is insulated thoroughly using glass wool.

Binary mixtures ranging from 10% to 40% have been prepared (Table 1a and b) by diluting the finely sized particles with known amount of coarsely sized particles. The true density of solids is 2500 kg/m^3. Different binary mixture pairs have been prepared by coupling P1 & P4, P2 & P4 and P3 & P4. A measured amount of sample is collected in a beaker to which, measured quantity of water is added and thoroughly mixed to obtain solids of known initial moisture content. The sample was then placed in the fluidized bed and then air was passed through it. The samples were collected with respect to time at the top of the column and the collected samples were weighed and placed in hot air oven. The samples were heated up to observation of no change in the weight (approx 200 °C) and then collected and weighed. This gives data of variation of moisture content with time from which drying rate curve can be obtained.

Table 1
Materials used.

Uniformly sized solids		
Name		Particle size (mm)
P1		3.1
P2		2.58
P3		1.7
P4		1.2
Binary solid mixtures		
Particle size (mm)	P1 or P2 or P3	P4
Binary mixture dilution percentage		
BM1	10	90
BM2	20	80
BM3	30	70
BM4	40	60

3. Results and discussions

The minimum fluidization velocity varies with dilution by coarse particles into fine particles. The minimum fluidization velocity of binary mixtures has been calculated from different correlations suggested by various authors (Asif [2], Bilbao et al. [3]). The superficial velocity used in the work is above this minimum fluidization velocity.

3.1. Effect of air velocity

Effect of air velocity on batch fluidized drying has been studied at three different superficial velocities ranging from 2.13 to 2.98 m/s at different initial bed heights and temperatures for various particle sizes and different binary mixtures ranging from 10 to 40%. It has been found from the experimental results that increase in velocity increases the drying rate and reduces the equilibrium moisture content. Increasing air velocity increases convective mass transfer of moisture from solids to air resulting in increase in drying rate. A similar kind of effect of air velocity on drying rate has been noticed for experiments performed varying the initial bed height, temperature and initial moisture content of solids for uniformly sized particles and also for different binary mixture dilutions. Fig. 2 presents the results of ten percent binary mixture of pair one at different air velocities ranging from 2.13 to 2.98 m/s and initial bed height of 5 cm with initial moisture content of 5% at a temperature of 40 °C.

Fig. 3 presents the results of bed temperature at different velocities of uniformly sized particles of size 2.58 mm with initial bed height of 5 cm and at temperature 40 °C with initial moisture content of 5%. At the initial stage of drying the temperature has been found decreasing due to cooling effect which is caused by inlet air. From the results it can be observed that increase in velocity increases the drying rate and bed temperature. Similar kind of behavior has been observed for all uniformly sized particles and other binary mixtures.

3.2. Effect of temperature

Effect of temperature on batch fluidized bed drying has been studied at four different temperatures ranging from 40–70 °C at different velocities, initial bed heights and initial moisture contents for four different particles and various binary mixture dilutions of range 10 to 40%. It has been found from the experimental results that with increase in temperature, the drying rate has been found to be increasing and the equilibrium moisture content to be decreasing. Increase in temperature increases heat input to the system and hence increases the rate of evaporation of moisture from the moist

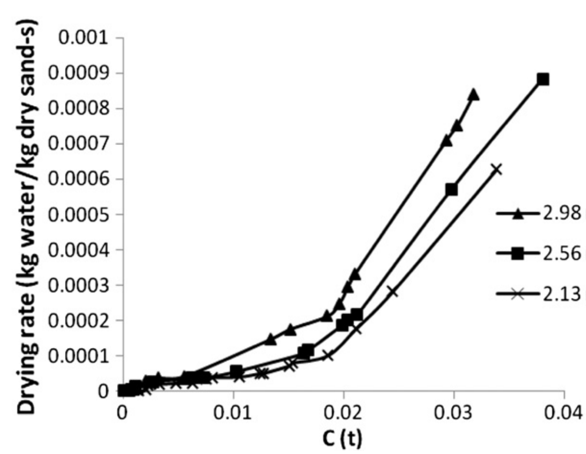

Fig. 2. Effect of air velocity on drying rate.

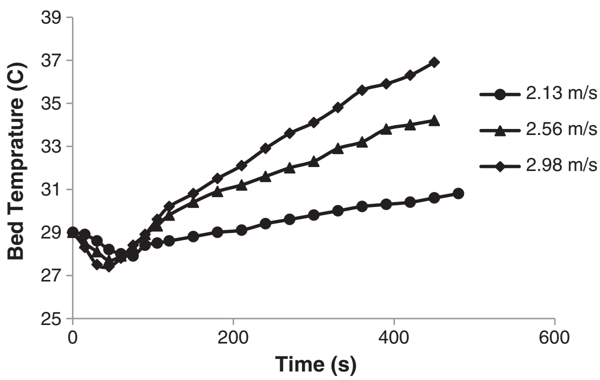

Fig. 3. Bed temperature vs time at different air velocities.

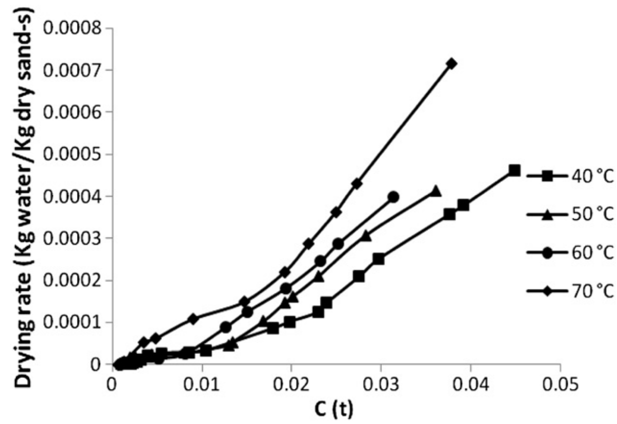

Fig. 5. Effect of temperature on drying rate.

solids. Fig. 4 presents the results of moisture content in the bed vs time for four different temperatures at initial moisture content of 4% for uniformly size particles of 1.7 mm at initial bed height of 5 cm with air velocity of 2.13 m/s and Fig. 5 presents the results at different temperatures of twenty percent binary mixture of pair one at 2.13 m/s air velocity with initial bed height of 5 cm and initial moisture content of 0.05.

3.3. Effect of initial moisture content

Effect of initial moisture content has been studied at four different moisture contents ranging from 4 to 10% at different initial bed heights, temperatures and velocities for four different particles and also different binary mixture compositions ranging from 10 to 40%. It has been observed from the experimental results that an increase in initial moisture content decreases the drying rate and increases the equilibrium moisture content. Increase in initial moisture content of solids increases the bound moisture with solids and increases the time required to obtain particular moisture content in the product. It is observed that the outlet moisture content of the solids leaving the bed increased with an increase in the initial moisture content of solids for a particular time. Fig. 6 shows the results at different initial moisture content of thirty percent binary mixture of pair one at air velocity of 2.13 m/s and initial bed height of 5 cm at 40 °C temperature.

3.4. Effect of initial bed height

Effect of initial bed height has been studied at three different initial bed heights ranging from 2.5 to 5 cm at different velocities, temperatures and initial moisture contents for four uniformly sized particles and various binary mixture compositions ranging from 10 to 40%. It has been found from the experimental results that with increase in initial bed height of solids the drying rate decreases and the equilibrium moisture content increases. Increase in the initial bed height of solids increases the amount of solids to bed dried and to dry higher amount of solids the required drying time is higher.

Fig. 7 show the results at different initial bed heights of ten percent binary mixture of pair one at air velocity of 2.13 m/s with initial moisture content of 6% at temperature of 40 °C.

3.5. Effect of particle size

Effect particle size has been studied with four different uniformly sized particles of size ranging from 1.2 to 3.1 mm at different velocities, initial bed heights and temperatures with different initial moisture content of solids. From the results it has been found that increase in particle size the drying rate has been found to be decreasing and the equilibrium moisture content to be increasing. Increase in the particle diameter decreases the available particle surface area and it results in lowering of drying rate for coarse sized particles compared with fine sizes. Fig. 8 presents the results of effect of particle size at air velocity of 2.13 m/s with initial bed height of 5 cm and initial moisture content of 0.04 at a temperature of 40 °C.

3.6. Effect of dilution rate in binary mixtures

Various binary mixtures were prepared by diluting the finely sized particles with coarse particles. Four different types of binary mixtures ranging from 10 to 40% for each pair of sizes (3 pairs) are used to

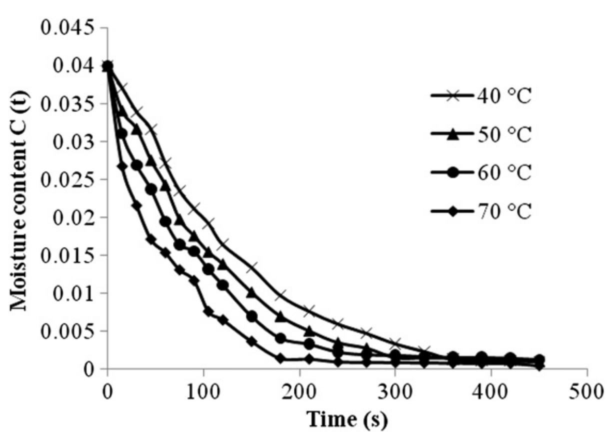

Fig. 4. Moisture content in the bed vs time for four different temperatures.

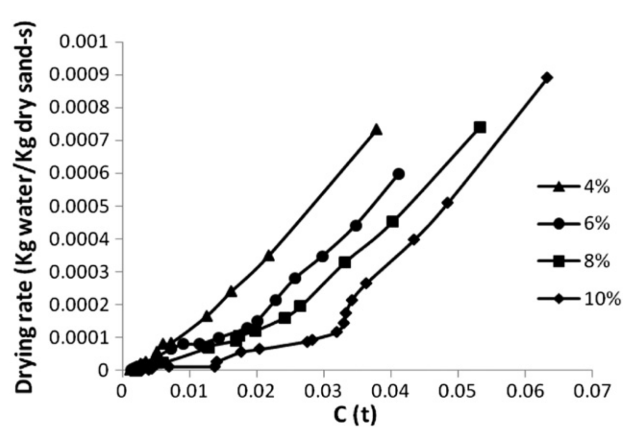

Fig. 6. Effect of initial moisture content on drying rate.

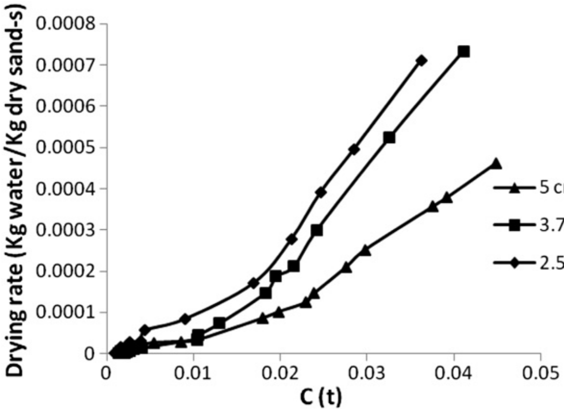

Fig. 7. Effect of initial bed height on drying rate.

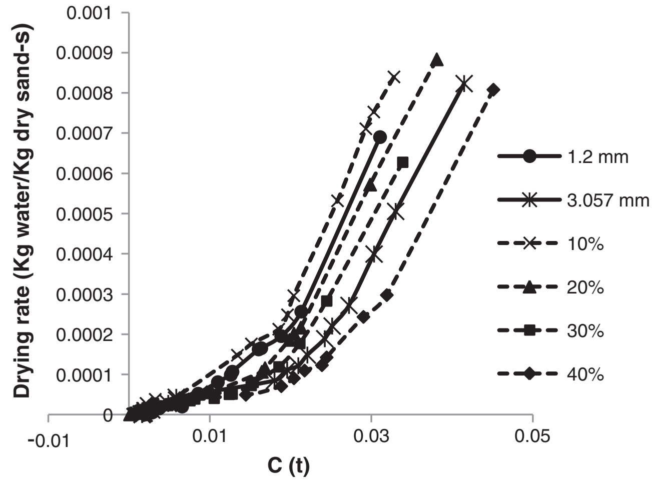

Fig. 9. Drying rate vs $C(t)$ for various binary mixture dilutions at 2.13 m/s velocity with initial bed height of 5 cm and initial moisture content 0.05 at temperature of 40 °C.

investigate the effect of dilution rate in binary mixtures on drying at different velocities, initial bed heights, temperatures and initial moisture content of solids. It has been found from the experimental results that the drying rate is high for a mixture of ten percent dilution foe all the pairs and it has been found to be less for twenty to forty percent. It is also noticed that drying rate increases up to thirty percent dilution when compared with coarsely sized particles, whereas for forty percent it decreases. When the binary mixtures are used, the mixing index plays an important role in mixing of particles of different sizes. For ten percent binary mixture the drying rate has been found to be increasing than both (fine and coarse) uniformly sized particles due to good mixing of coarse particles with fine particles. Further increase in dilution in binary mixtures the mixing index has been found to be decreasing compared with ten percent dilution, due to which the drying rate has been found to be decreasing. Fig. 9 shows the results of different binary mixtures of pair one at initial bed height of 5 cm with initial moisture content of 5% with air velocity of 2.13 m/s at temperature 40 °C.

From the experimental results it has been observed that two types of falling rate periods are exhibited by the drying rate curve (Fig. 10). In the first falling rate period the bound free moisture gets dried. The falling rate period one is generally exhibited after the constant drying period as seen from the work of Chandran et al. [4] and Srinivasa kannan and Balasubramanian [5] who have used preheated air as heating medium. In the present investigation studies were carried in only falling rate period. The falling rate period two follows period one and in the falling rate period two the bound moisture attached to the particle surface dries.

Several experiments were performed to predict the drying behavior of binary mixture of solids at different dilutions and varying type of binary mixture.

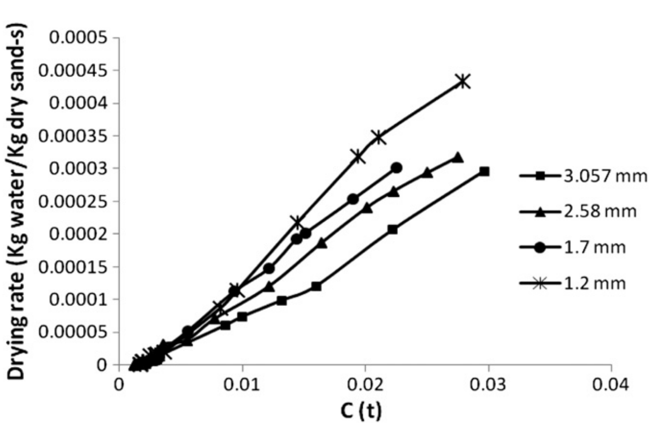

Fig. 8. Effect of different particle sizes on drying behavior.

Silva and Souza [6] studied the drying behavior of various binary mixtures in a tray dryer. He has found from the experimental results that the drying behavior of binary mixtures of solids falls in between the two individual components. The present investigation was carried out in a batch wall heated fluidized bed dryer. From the results it has been found that for ten percent binary mixture the drying rate has been observed to be higher in comparison with uniformly sized particles and other binary mixture of solids. In fluidized bed drying of solids the particle–particle collisions and particle–wall collisions play an important role in drying of solids and in drying of binary mixture of solids the mixing index influences the drying behavior. In the present studies for ten percent binary mixture the mixing index has been found higher, resulting in higher drying rate.

Fig. 11 presents the results of mixing index of different binary mixture pairs. From the results it can be observed that the mixing index is found higher for ten percent dilution with comparison of other binary mixture dilutions.

4. Correlation development

The following assumptions were made to develop the correlation.

1. The drying rate curve exhibits falling rate period.
2. Initial added moisture has been uniformly distributed in the feed.

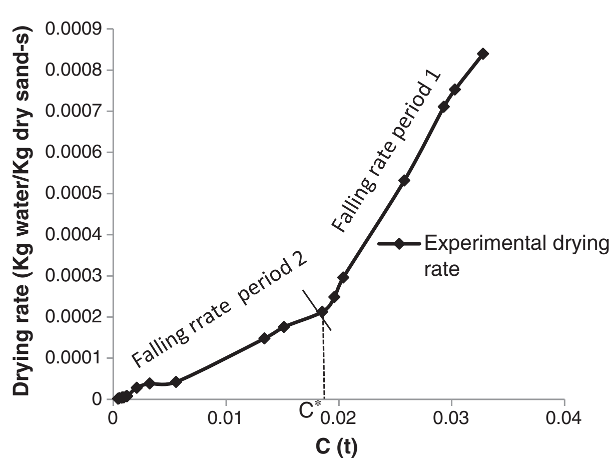

Fig. 10. Drying rate curve showing two falling rate periods.

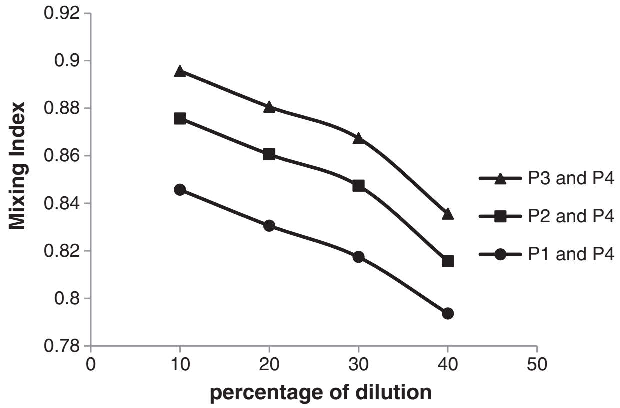

Fig. 11. Mixing index of various binary mixtures.

3. The continuous constant heat has been supplied during the drying process.
4. Constant drying conditions with reference to weather are assumed.

For constant and falling drying rate periods, a model has been developed by Chandran et al. [4]. The present model is developed for only the falling rate period with bound moisture in a batch fluidized bed.

Chandran et al. [4] developed a correlation for batch drying of uniformly sized particles. The authors [4] used hot air as a drying medium and at high initial moisture content of solids due to which, they [4] observed and reported constant drying rate period and falling rate period. In the present study experimentation was carried out with wall heating and at low initial moisture content of solids and hence only falling rate period is noticed. Hence correlations have been developed incorporating initial moisture content of solids instead of critical moisture content of solids [4]. Similar kind of correlations have been obtained for falling rate periods one and two for uniformly sized particles as shown in Eqs. (1) and (2).

$$R = 1.9738 \left(\frac{C_{in} - C^*}{t}\right)^{1.1818} \ln\left(\frac{C_{in} - C^*}{C_t - C_{eq}}\right) \quad (1)$$

$$R = 2.534394 * 10^4 \left(\frac{C_{in} - C_{eq}}{t}\right)^{1.1818} \ln\left(\frac{C_{in} - C_{eq}}{C_t - C_{eq}}\right) \quad (2)$$

The drying behavior was found different for various binary mixtures of solids. In drying of binary mixture of solids the mixing index of solids plays an important role. Sahoo and Roy [7] developed a correlation (Eq. (3)) for mixing index in a fluidized bed, which is used in the present study to determine the mixing index of various binary mixtures and the results were presented in Fig. 11. The correlations have been developed to estimate the appropriate drying

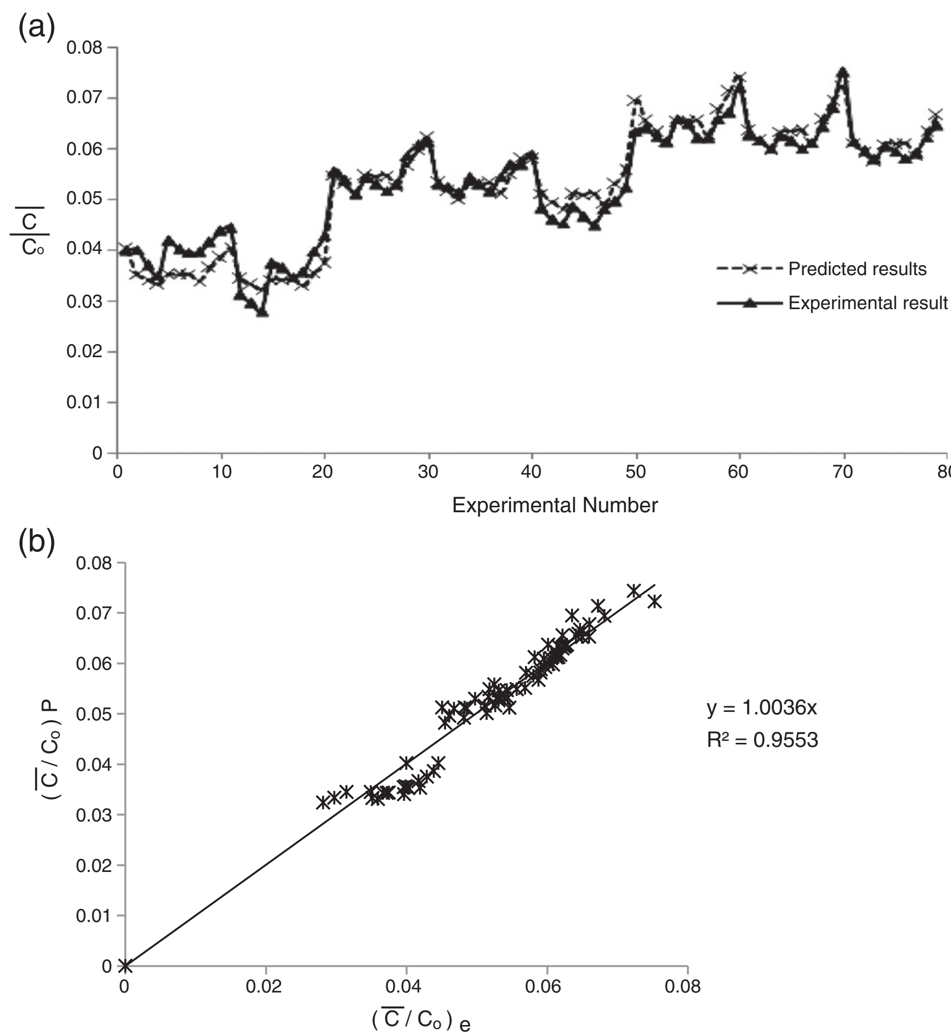

Fig. 12. a and b Experimental and predicted values of average moisture content for uniformly sized solids.

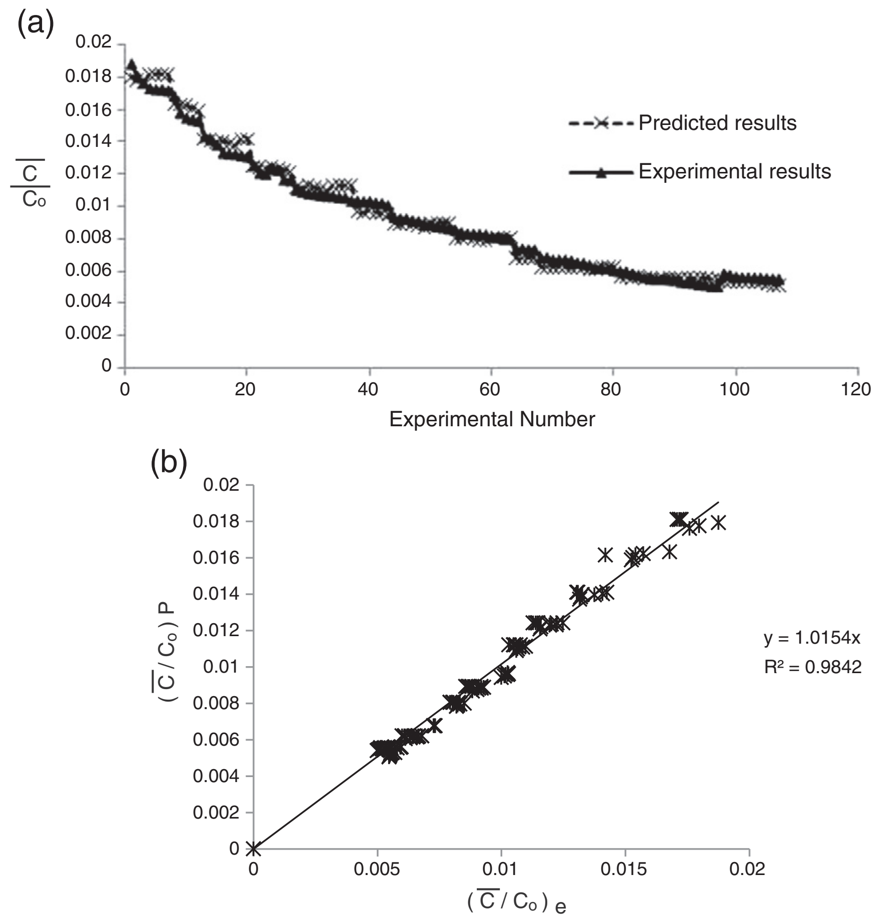

Fig. 13. a and b Experimental and predicted values of average moisture content for various binary mixtures.

behavior for various binary mixtures in falling rate periods one and two incorporating mixing index. The developed equations are given by Eq. (4) for falling rate period one and Eq. (5) for falling rate period two.

$$I_m = 0.3725 * \left(\frac{d_p}{d_F}\right)^{0.3679} * \left(\frac{h_B}{D_c}\right)^{-0.4864} * \left(\frac{H_s}{D_c}\right)^{0.8258} * \left(\frac{u}{u-u_f}\right) \quad (3)$$

$$R = 1.165\left(\frac{C_{in}-C^*}{t}\right)^{1.109} \ln\left(\frac{C_{in}-C^*}{C_t-C_{eq}}\right) * (I_m)^{3.49} \quad (4)$$

$$R = 1.95 * 10^2\left(\frac{C_{in}-C_{eq}}{t}\right)^{2.07} \ln\left(\frac{C_{in}-C_{eq}}{C_t-C_{eq}}\right) * (I_m)^{-3.07} \quad (5)$$

The average moisture content in the bed is obtained from Eq. (6) given by Sathish and Pydisetty [8]. Based on the effect of different variables on drying behavior of solids the average moisture content has been related to these variables for uniformly sized particles as given by Eq. (7). Eq. (8) represents a correlation for average moisture content for binary mixture of solids which was developed by incorporating the mixing index along with other variables. The correlations were developed by using a user defined non-linear equation performing regression analysis with DATA Fit software with an input of experimental results.

$$\frac{\overline{C}}{C_0} = \frac{\int (C/C_0)\, dt}{\int dt} \quad (6)$$

$$\frac{\overline{C}}{C_0} = 57.7\,(u)^{-0.18}\,(W)^{0.098}\left(d_p\right)^{1.047}(C_0)^{0.18}\ \exp\left[\frac{16.97}{T}\right] \quad (7)$$

$$\frac{\overline{C}}{C_0} = 0.083\,(u)^{-3.207}\,(W)^{0.36}\,(C_0)^{1.1}\ \exp\left[\frac{100}{T}\right](I_m)^{-4.64} \quad (8)$$

The correlations developed in the present study as shown above are verified with experimental results and found to be in good agreement.

Figs. 12a and b and 13a and b indicate the experimental and predicted values of average moisture content of solids for uniformly sized solids and binary mixture of solids (all pairs) respectively, where it is noticed that there is good agreement between the two.

Fig. 12a represents the experimental and predicted average moisture content for uniformly sized particles. The results (Fig. 12a) shows the effect of particle diameter on drying rate and indicates that increase in particle diameter increases the average moisture content.

Several experiments have been carried by varying various parameters such as air velocity, initial moisture, temperature and amount of solids at different dilutions to predict the drying behavior in a batch fluidized bed dryer. From the experimental results it has been observed that the drying rate increases with increase in the air velocity and temperature and decreases with increase in particle size, initial moisture content and amount of solids (initial bed height). The drying rate is found to be highest for ten percent diluted binary mixture as compared with uniformly sized particles and other binary mixtures. The drying rate of twenty and thirty percent binary mixtures is noticed to be higher than the uniformly coarse sized particles. The drying rate for forty percent binary mixture is found lowest when comparison with uniformly sized particles and other binary mixtures.

5. Conclusions

The experimental work has been carried out to investigate the drying behavior of different uniformly sized particles as well as various binary mixtures of solids with different dilutions of fine size particles with coarse particles with different pairs of uniformly sized particles. It is noticed that for both uniformly sized particles and different binary mixtures, drying rate is found to increase with increase in air velocity, temperature and decrease with increase in diameter of the particles, initial moisture content of solids and initial bed height of solids. The drying rates are found to be highest for ten percent binary mixture compared with uniformly sized particles and other binary mixtures and lowest for forty percent binary mixture. This indicates that the dilution beyond thirty percent is not beneficial. In practice mixture of solids is used instead of uniformly sized particles and hence, the work finds the importance in practice as it gives important investigation on drying behavior of mixture of solids and also comparison with uniformly sized particles.

Nomenclature

BM1,2,3,4 Binary mixtures
C_{in}, C_0 Initial moisture content (kg water/kg dry sand)
C_{eq} Equilibrium moisture content (kg water/kg dry sand)
C^* Moisture content at the end of falling rate period one (kg water/kg dry sand)
$C(t)$ Moisture content with respect to time (kg water/kg dry sand)
$\overline{C}$ Average moisture content (kg water/kg dry sand)
d_p, $\overline{d}_p$ Diameter of particle (m)
d_F Diameter of float sample (m)
D_c Diameter of column (m)
h_B Height of the bed samples drawn (m)
H_s Static bed height (m)
I_m Mixing index
P1,2,3,4 Particle sizes (mm)
R Drying rate (kg water/kg dry sand-s)
T Temperature (°C)
t Time (s)
u Superficial air velocity (m/s)
u_f Minimum fluidization velocity (m/s)
W Weight of solids (kg)

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