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Solid particles were dried in the riser of circulating fluidized bed with internals to study the drying kinetics. Experiments were conducted in a circulating fluidized bed, having perforated plates as internals covering wide range in the operating parameters. The effects of various operating parameters, i.e., initial moisture content, temperature, and flow rate, of the heating medium and solid circulation rate on the rate of drying have been critically examined. It has been observed from the present investigation that the presence of internals enhances the solids holdup in the riser of circulating fluidized bed. The drying efficiency of a circulating fluidized bed with internals has been compared with the drying performance of a circulating fluidized bed without internals under the same operating conditions.

Keywords Circulating fluidized bed with internals; Drying kinetics

INTRODUCTION

Circulating Fluidized Bed with Internals

The versatility of circulating fluidized bed CFB technology, with its excellent heat and mass transfer characteristics, operational flexibility, and easy scale-up and maintenance, is finding increased industrial applications in recent years. One such application is extension of a circulating fluidized bed for granular materials drying. It is essentially a process of simultaneous heat and mass transfer and a very common process in many of the chemical process industries. The operation of CFB often presents a region of high solids concentration at the bottom of the riser and a region of low solids concentration near the exit of the riser. Even within these regions solids concentration varies longitudinally, presenting difficulties in scale-up and reliable estimation of its kinetic performance. Further, the variation of solids concentration with bed height results in change of heat and mass transfer rate along the riser length. Quite a number of publications have reported on improving the solids concentration profile along the length of the riser.

Zheng et al.[1] introduced different types of internals such as ring, inverse cone tube, and perforated plates in the riser and observed significant improvement of radial solids distribution. Jiang et al.[2] provided horizontal ring-type baffles with 56% open area and reported nearly linear pressure variation in the axial distance for low solids rate and a significant axial pressure variation with an increase in solids rate, with breaks in pressure profiles occurring around the baffle area. The authors compared solids holdup in the riser with baffles to that without baffles and observed that the riser with baffles gave higher solids holdup, especially at high gas rates. Van der Ham et al.[3,4] studied the variation of solids concentration with a regularly packed circulating fluidized bed. In our earlier paper,[5] perforated plates were introduced as internals along the riser length and a significant improvement in axial pressure profile and total solids holdup compared with conventional circulating fluidized bed was observed.

Drying Kinetics in a Circulating Fluidized Bed

Fluidized bed drying is advantageously used in industries for drying of granular material such as cereals, polymers, chemicals, pharmaceuticals, fertilizers, crystalline products, and minerals, as they offer a large transfer area between the phases, improved heat and mass transfer between the phases, a high degree of mixing of the materials, ease in the handling and transport of fluidized materials, fluids with negligible temperature and concentration gradient within the bed, and suitability for large-scale operation. Conventional fluidized bed dryers are increasingly used in industrial applications.[6]

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Extensive work has been reported on drying of granular materials in a conventional fluidized bed. Kage et al.[7] studied powdered coating in a vibro-fluidized bed. The authors measured coating efficiency and weight fraction of the agglomerated particles and reported their dependencies on the frequency and the direction of vibration. Tanfara et al.[8] have reported the effect of particle size distribution on local voidage in a conical fluidized bed. The authors measured the local voidage using a twin-plane electrical capacitance tomography (ECT) system. The authors reported that the local voidage is sensitive the static bed height. Adamiec[9] has studied dewatering of industrial waste sludge in a fluidized bed dryer and reported the effect of hydrodynamic parameters on sludge drying. While Abdel-Jabbar[10] developed a mathematical model for drying in fluidized bed and reported the effect of parameters on drying efficiency. The outlet solids moisture content, the outlet air humidity, and solids temperature were predicted as a function of time for the falling rate drying period. Reyes et al.[11] developed a drying kinetic model for turnip drying and reported the effect of operating parameters in fixed and pulsed fluidized bed.

Industrial dryers are basically classified according to their mode of contact and heat transfer mechanism. The circulating fluidized bed dryer can be classified as continuous, convective dryers with dilute solids transport. The drying medium supplies the required energy and transports the solids through the riser and the dried products are separated from the drying medium at the outlet of the riser. Circulating fluidized bed dryers can be utilized for granular and free-flowing solid material as this has been extensively used for FCC, combustion, and other related process. Further, since the solids concentration (solids residence time distribution) in a circulating fluidized bed can be adjusted by both solids and gas flow rate, the circulating fluidized bed dryer can also be suitable for processing heat-sensitive material.

There is no literature available on drying kinetics in circulating fluidized bed. Baeyens et al.[12] presented a design procedure to predict moisture and temperature profiles in a pneumatic dryer based on the experimental data, which were obtained from several industrial dryers. Rocha and Paixão[13] developed a pseudo two-dimensional model for pneumatic drying and predicted axial and radial profiles for gas and solid velocity and solids moisture content. Skuratovsky et al.[14] developed a two-dimensional model was for the dilute flow of particulate materials through a pneumatic dryer and solved for a steady-state condition. In our earlier study,[15] the drying of granular material in a conventional circulating fluidized bed was examined.

It can be concluded from the critical literature survey that the axial pressure profile can be improved by providing internals along the length of the riser. Further, no experimental or theoretical work has been reported on circulating fluidized bed drying. Knowledge on drying kinetics is essential for the estimation of the drying time needed to reduce the moisture content to the desired level and for suggesting the optimal drying conditions. The present study aims at the use of internals in the riser of the CFB for improving the contact between the phases and for obtaining uniform solids concentration along the length of the riser and studying the drying kinetics in the riser of a circulating fluidized bed having internals.

EXPERIMENTAL

The schematic diagram of experimental setup is given in Fig. 1, which consists of Plexiglas column of 52 mm internal diameter and 1200 mm height. The column consists of a riser (1) with a provision for continuously feeding the solids at a controlled rate from the hopper (3). A gas–solids separator (2) and a bag filter were provided at the top of the riser for separating solids and gas. The movement of the solids cocurrent upward with air introduced at the bottom of the column. Air for fluidization was drawn from a centrifugal blower (10) through air filter (9), surge tank (7), a flow meter (6), and an air heater (5). Quick closing valves (4) were provided at the solids feed point to facilitate the measurement of solids concentration in the riser. The solids circulation rate (which can be varied by a controlling valve (4)) has been measured by collecting the solids for a noted time. The solids particles were supported on a perforated plate distributor situated at the bottom of the riser.

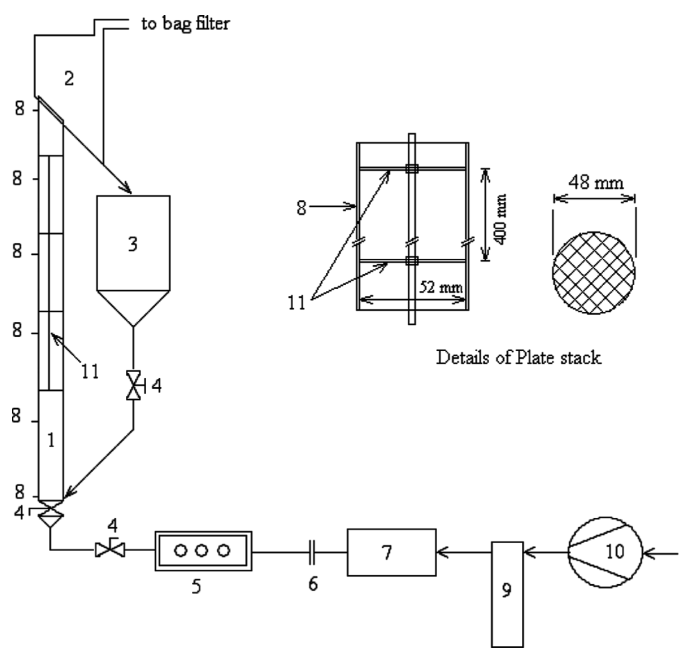

FIG. 1. Schematic diagram of the experimental setup: (1) test section, (2) gas–solids separator, (3) solids hopper, (4) control valve, (5) air heater, (6) flow meter, (7) surge tank, (8) pressure taps, (9) silica bed, (10) air blower, (11) plate stack.

Pressure tappings were provided at different locations of the riser for the measurement of pressure drop across the riser. The air heater consisted of six heaters of 1.2 kw capacity each. The temperature of the heating medium was controlled with an accuracy of $\pm 0.1^{\circ}$C using a temperature controller attached to the heater.

For drying experiments with internals, perforated plates of 45% free area (11) were fixed in the riser at 600, 1000, 1400, and 1800 mm from the solids feed point. The experimental conditions maintained during drying in a conventional circulating fluidized bed were maintained. Drying experiments were conducted in both a conventional circulating fluidized bed (fluidized bed without internals) and a circulating fluidized bed with internals. The effect of individual parameters on drying kinetics has been critically examined. Further, the performance of drying kinetics in a circulating fluidized bed with internals has been compared with the drying kinetics in a conventional circulating fluidized bed under identical operating conditions.

RESULTS AND DISCUSSIONS

A known quantity of known moisture content of solids was taken in the solids hopper and fed into the riser at a controlled flow rate cocurrent to the hot air. Solids samples were collected at different clock times at the exit of the riser. The solids were continuously recycled from the hopper to the riser and then to the hopper. The clock time is the time elapsed from the time the solids were fed into the riser to the time of collection of sample at the exit of the riser. Recycle time, on the other hand, is the time required to recycle once the entire batch of solids and is obtained by dividing the weight of solids in the batch with the solids flow rate. Exposure time is the time the solids are exposed to the hot air and obtained by multiplying the mean holding time of solids in the riser with the number of cycles in the given clock time. It is obtained by dividing the solids holdup with the solids flow rate. The exposure time and the clock time are related as

$$t_e = t\frac{W}{W_b} \tag{1}$$

where t_e is exposure time, in seconds; t is clock time, in seconds; W is the solids holdup, in kilograms; and W_b is the quantity of material in a batch, in kilograms.

The relative moisture content C/Ci (C_i and C represent the solids initial moisture content and moisture content at time t, respectively) is plotted against exposure time, while the drying rate $-dC/dt_e$ is plotted against solids moisture content.

Experiments were carried in a circulating fluidized bed with and without internals. Figure 2 shows the variation of outlet moisture content with drying time in circulating fluidized bed with internals. It can be ascertained from

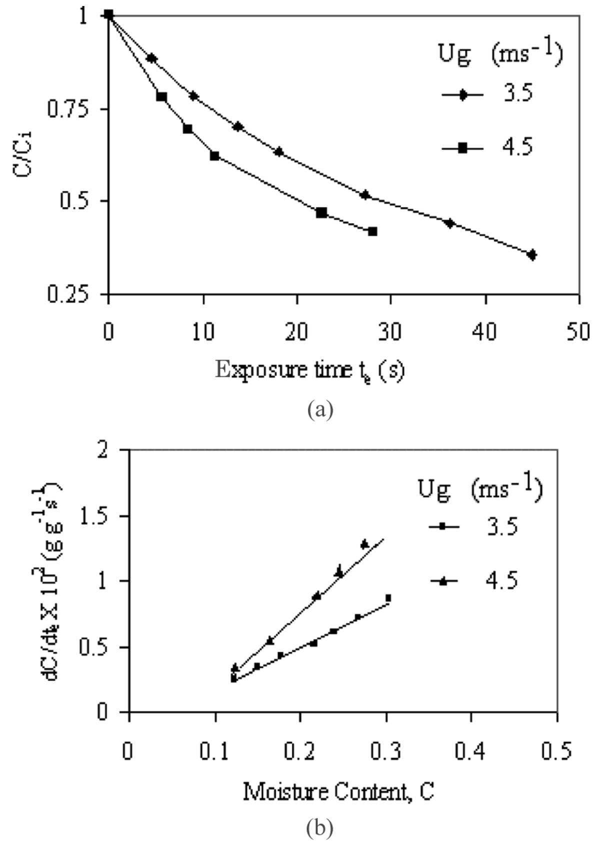

FIG. 2. Variation of (a) solids moisture content with drying time, (b) drying rate with moisture content. Material: Resin (d_p: 530 μm); initial moisture content of solids: 0.343; temperature of heating medium: 80°C; solids circulation rate: 2.51 kg m^{-2}s^{-1}.

Fig. 2a that the rate of drying decreases with increase in the exposure time. The rate of decrease is sharp at the beginning of the process and reduces gradually with drying time. This may be because the moisture is available near the surface at the beginning of the process and the moisture needs to be transported to the surface when time progresses, resulting in a higher drying rate in the beginning and a gradual decrease in the drying rate with time. It can also be ascertained that the drying rate increases with increase in the flow rate of the heating medium. This can be explained by the fact that riser solids holdup decreases with increase in the flow rate of the heating medium. Further, the increase in the flow rate of the heating medium provides a larger heat input, resulting in increased drying rate. Notice that only a falling period has been observed for the materials chosen for drying studied in the present investigation (Fig. 2b).

An increase in the inlet temperature of the heating medium reduces the outlet moisture content of the materials (Fig. 3). This is due to the fact that an increase in temperature results in higher thermal input into the system, which increases the surface temperature of the

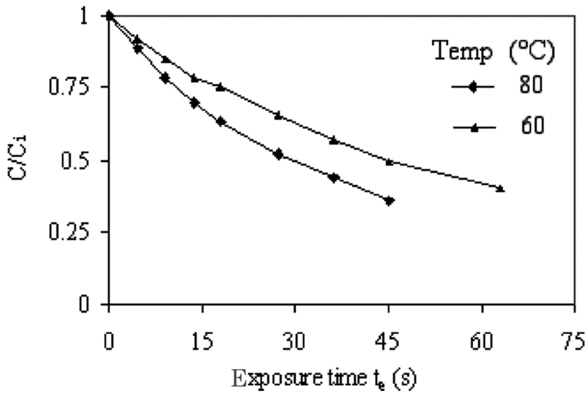

FIG. 3. Effect of temperature of heating medium on solids outlet moisture content. Material: Resin (d_p: 530 µm); solids circulation rate: 4.3 kg $m^{-2}s^{-1}$; solids initial moisture content: 0.343.

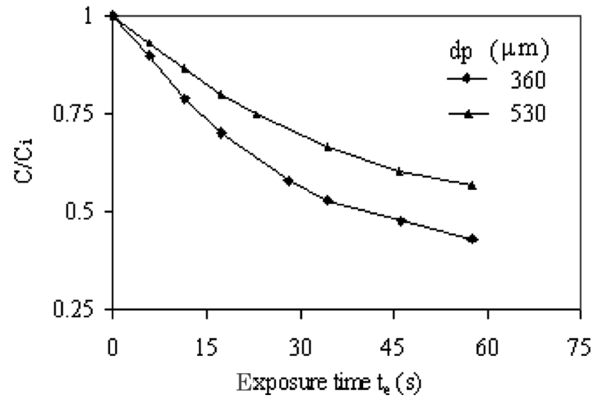

FIG. 5. Effect of particle size on solids outlet moisture content, initial solids moisture content: 0.348; temperature of the heating medium: 80°C; flow rate of the heating medium: 4.5 ms^{-1}; solids circulation rate: 3.9 kg $m^{-2}s^{-1}$.

material. This leads to lower surface humidity and increases the rate of evaporation from the material's surface. On the other hand, the outlet moisture content of the material in the product stream increases with increase in the solids circulation rate (Fig. 4). This can be explained by an increase in the solids circulation rate increasing the solids holdup inside the riser, which increases the moisture content of the solids leaving the riser.

Experiments were carried out with two particle sizes and the influence of particle size on drying rate is given in Fig. 5. It can be ascertained from the figure that the drying rate decreases with increase in the particle size. This is due to fact that the surface area of the particle per unit weight of solids is decreased with increase in particle size, resulting in a decrease in the drying rate with particle size. It has been observed that the outlet moisture content of the solids leaving the bed increased with an increase in the initial solids moisture content (Fig. 6). This may be due to fact that the ratio of moisture content per unit quantity of solids increased with increase in the initial moisture content of the solids, resulting in a decrease in the outlet moisture content. These observations are in qualitative agreement with the observations reported for the conventional fluidized bed.[16]

Figure 7 compares the performance of drying kinetics in a circulating fluidized bed with internals with the drying kinetics in a conventional circulating fluidized bed. It can be ascertained from the figure that the performance of drying kinetics in a circulating fluidized bed with internals is satisfactorily comparable with the drying kinetics in a conventional circulating fluidized bed.

CONCLUSIONS

Circulating fluidized beds can be advantageously used for drying of material that has fluidization difficulties, material with large moisture content, and for drying coupled with transportation. Drying experiments were

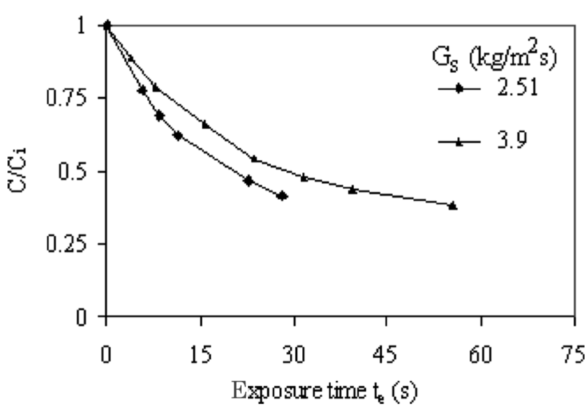

FIG. 4. Influence of solids circulation rate on solids outlet moisture content. Material: Resin (d_p: 530 µm); solids initial moisture content: 0.343; temperature of the heating medium: 80°C; flow rate of the heating medium: 4.5 ms^{-1}.

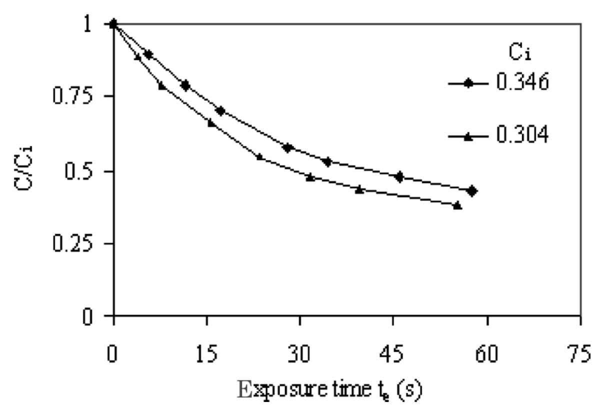

FIG. 6. Effect of initial moisture content of solids on drying rate, temperature of the heating medium: 80°C; flow rate of the heating medium: 4.5 ms^{-1}; solids circulation rate: 4.3 kg $m^{-2}s^{-1}$.

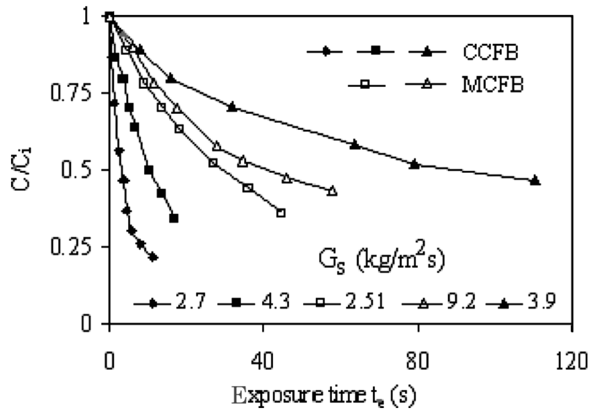

FIG. 7. Comparison of the drying kinetics in conventional circulating fluidized bed with circulating fluidized bed internals. Material: Resin (d_p: 530 μm); initial moisture content of solids: 0.343; temperature of heating medium: 80°C; flow rate of the heating medium: 4.5 ms^{-1}.

conducted in the riser of circulating fluidized bed with and without internals. It has been observed from the present experimental results that the rate of drying in the riser of a circulating fluidized bed is found to increase with increase in the initial moisture content, the flow rate, and temperature of the heating medium, while it was found to decrease with increase in the particle size.

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