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Drying of Suspensions in a Fluidized Bed of Inert Particles under Reduced Pressure

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Abstract

A drying method in which a heat-sensitive material is immersed in a fluidized bed under reduced pressure was used to continuously obtain dispersed, dry, fine powders of that material from a dilute suspension or solution at a low temperature with a high drying rate. The mass velocity of the drying gas, sample flow rate, and chamber pressure were varied, and the effects of these variations on the corresponding drying characteristics were examined.

The fluidization state of a fluidized bed of inert particles strongly affects the drying rate in the bed and has a greater effect than the chamber pressure on the corresponding drying characteristics. In other words, it is important to maintain a vigorous fluidization state to achieve a high drying rate. Although the maximum drying rate is independent of the chamber pressure, it can be achieved at a low mass velocity of the drying gas under reduced pressure. That is, at a low chamber pressure, a high drying rate can be achieved even at a relatively low mass velocity of the drying gas. The bed temperature at the time of drying is strongly influenced by the drying rate and decreases linearly with an increase in the maximum drying rate when the sample flow rate is equal to the drying rate.

Keywords: Fluidized bed drying; Vacuum drying; Inert particle; Dilute suspension

INTRODUCTION

Drying processes affect the quality of a dried product. In particular, heat-sensitive materials such as food and pharmaceutical products require to be maintained at a low temperature during the drying process. In order to dry a material at low temperature, drying is performed under reduced pressure. The material's temperature reduces with pressure at the time of drying. However, under extremely low pressure, the convective heat transfer rate from the drying gas to the material decreases and drying time increases; this is a problem in the drying processes used in industrial applications. Therefore, thermal conduction, microwaves, and thermal radiation are often used as heat sources.^[1-3] In this study, a fluidized bed was used to increase the heat transfer rate to the drying material. A high drying rate can be achieved by using a fluidized bed dryer.^[4-6] Kozanoglu et al. previously examined fluidized bed drying performed under reduced pressure.^[7] Unlike the case in our present study, the fluidizing particles in their study were dried. To dry a suspension of fine powders or a relatively large material, the material is immersed in a fluidized bed of inert particles.^[8-12] In our previous studies, the drying characteristics of porous materials immersed in a fluidized bed under reduced pressure were examined.^[13-17] From the results, it was found that low-temperature drying with a high drying rate was possible when performed in a fluidized bed of inert particles under reduced pressure.

In the present study, a dilute suspension of fine powders or a solution is considered as the drying material. The drying of this material can be performed using a spray dryer or a fluidized bed of inert particles. In general, the objective of drying is to obtain dispersed, fine powders from the drying material. The material can be dispersed during drying using both a spray dryer and a fluidized bed of inert particles; this is an important feature of the use of both. When the dispersion is insufficient, the fine powders form agglomerates during drying. A spouted bed of inert particles is also used to obtain dispersed, dry, fine powders from the dilute suspension or solution. In the spouted bed, a circulation of inert particles occurs, i.e., the inert particles move upward at the center and they move downward near the wall. Relatively large

particles can be used as the inert particles even with low gas velocity, though the drying rate is a little lower than the fluidized bed. In general, the scale up is easier for spray dryer than for the fluidized bed or spouted bed of inert particles, though the larger amount of liquid can be evaporated by the smaller equipment for the fluidized bed or spouted bed of inert particles. In the present study, a fluidized bed of inert particles was used for drying. By using this method, a high drying rate can be achieved and a large amount of material can be dried in a short time. This method can also be used for the coating and granulation of fluidizing particles in the bed.^[18-20] It is performed under atmospheric pressure, and a high drying temperature is usually maintained during drying. Generally, the diameter of an inert particle is relatively large, and a large amount of gas is used to fluidize a bed. In the present study, fluidized bed drying is performed under reduced pressure to treat a suspension of heat-sensitive material. To achieve a low pressure, the amount of the drying gas used should be small. Therefore, relatively small particles are suitable for use as inert particles because the fluidization state can be achieved in this case by using a small amount of gas. However, when the diameter of inert particles is too small (less than 0.03 mm), the particles make agglomerates themselves because of the interaction force between particles.^[21] In addition, the liquid bridge force acts between particles, which prevents fine fluidization.^[22, 23] The inert particles elutriate with suspension particles when the size difference between inert particle and suspension particle is small. From these, it is considered that there is the optimum diameter of inert particles for this drying method. In this study, the diameter of inert particle was 0.12 mm and the value was considered to be suitable because there was no agglomerate at steady drying state and the chamber pressure was kept 30 kPa with fluidization state.

In this study, only liquid (distilled water) was passed through a fluidized bed of inert particles as a sample dilute suspension or solution to determine the characteristics of the drying equipment. To evaluate just the effects of operational conditions on the ability of drying equipment, only distilled water was used as the drying sample. We confirmed that dispersed, dry, fine powders could be obtained by this drying

method on the basis of the equipment (diameter of inert particles were 0.12 mm) where we used a suspension including fly ash (with 5 μ m average diameter). The mass velocity of the drying gas, sample flow rate, and chamber pressure were varied independently. The effects of these variations on the corresponding drying characteristics were experimentally examined.

EXPERIMENTAL

An outline of the experimental apparatus is shown in Fig. 1. A drying chamber with an inner diameter of 65 mm was constructed from a glass tube. A ribbon heater was used as the heat source and fixed on the outer wall of the drying chamber; the electric power supply was set to 110 W. To control the chamber pressure, a vacuum pump and a pressure control valve were connected to the drying chamber. The inlet for the sample (distilled water) was at the top of the drying chamber. A nozzle (with an inside diameter of 4 mm) was inserted into the drying chamber, and a liquid pump was connected to the nozzle.

Dry air (293 K) was used as the fluidizing gas (drying gas). Glass beads (0.12 mm in diameter) were used as fluidizing particles (inert particles), and the static height of the particle bed was set to 100 mm. Distilled water was used as the sample dilute suspension or solution and passed through the fluidized bed via the nozzle starting from the surface of the bed.

During the initial period of drying, the bed temperature was 393 K. The drying rate and the bed temperature were measured during drying. The fluidized bed was weighed on an electric balance to determine the mass of the fluidized bed. The drying rate was calculated by using the relation between the sample flow rate and the mass of the fluidized bed. The bed temperature was measured using thermocouples (K-type), which were immersed at the center of the bed. The mass velocity of the drying gas, sample flow rate, and chamber pressure were varied as experimental parameters, and the effects of these variations on the corresponding drying characteristics were examined.

RESULTS AND DISCUSSIONS

Changes in Drying Characteristics with Time When Sample Flow Rate Is Higher than Drying Rate

Figure 2 shows the changes in the drying rate R_w , the amount of accumulated sample in the bed S_{bed} , and the bed temperature T_{bed} with time. The mass velocity of the drying gas was $0.04 \text{ kg/(s m}^2\text{)}$, and the sample flow rate was $30 \times 10^{-3} \text{ kg/(s m}^3 \text{ bed)}$. The pressure in the drying chamber was maintained at 101 kPa (atmospheric pressure) and 50 kPa. The initial temperature of the fluidized bed was 393 K. For these conditions, the drying rate was lower than the sample flow rate. Therefore, the sample (distilled water) accumulated in the bed with time.

Figure 3 shows the changes in the fluidization state with time; these were determined via visual observation. During the initial period of drying, the fluidization state was observed, and the sample was found to disperse well in the bed (A). As the amount of accumulated sample increased, the fluidization of the bed stopped and stable channels appeared in the bed (B). Finally, the void in the inert-particle bed was filled with water (sample) and fluidizing gas (air) flowed in the bed in the form of air bubbles (C). In this case, inert particles in the bed moved vigorously because the bed was gas–liquid–solid fluidized (three-phase fluidized). To continuously obtain dispersed, fine, dry powders, state (A) should be maintained in the bed while drying; i.e., the sample flow rate should be equal to the drying rate.

From Fig. 2, it can be seen that the drying rate is much higher under reduced pressure (50 kPa) than under atmospheric pressure during the initial period of drying. During this period, the heat stored in the fluidized bed is used for drying and the bed temperature decreases drastically. After this period, the drying rate is observed to be almost constant with time for both the values of chamber pressure (101 kPa and 50 kPa). Further, during this period, the drying rate is slightly higher at 50 kPa than at 101 kPa. The drying rate increases with time when the drying time is more than 180 min for both values of chamber pressure. This is because the heat transfer rate from the chamber wall to the bed as well as the contact area between the fluidized bed and the heating wall increase when the fluidized bed is filled with water (sample).

The bed temperature decreases significantly during the initial period of drying for both values of chamber pressure. After this, the temperature increases slightly with time. The minimum temperature during drying is used as an index of the bed temperature, and the drying rate at this temperature is used as an index of the drying rate. The bed temperature at 50 kPa is lower than that at 101 kPa; i.e., low-temperature drying is possible at a reduced chamber pressure.

Effects of Operational Conditions on Drying Characteristics

Figure 4 shows the relationships among the drying rate, bed temperature, and sample flow rate. The mass velocity of the drying gas is $0.024 \text{ kg}/(\text{s m}^2)$, and the initial bed temperature is 393 K. The pressure in the drying chamber is maintained at 101 kPa and 50 kPa. A solid line is used to indicate the case in which the sample flow rate is equal to the drying rate. When the sample flow rate is low, the drying rate becomes equal to the sample flow rate. In this case, the fluidization state (A) shown in Fig. 3 is maintained during drying; i.e., drying is carried out continuously. When the sample flow rate is high, the drying rate becomes lower than the sample flow rate. In this case, the sample accumulates in the bed, and then, fluidization stops; this is similar to the cases involving the states (B) and (C), as shown in Fig. 3. To obtain dispersed, fine, dry powder, fluidization state (A) should be maintained during drying; i.e., the sample flow rate should be equal to the drying rate. As shown in Fig. 4, the drying rate remains almost constant with respect to the sample flow rate when it is lower than the sample flow rate. The optimum sample flow rate is maximum when it is equal to the drying rate. In this study, the optimum sample flow rate is defined as R_{wc} . It is higher at 50 kPa (reduced pressure) than at 101 kPa (atmospheric pressure).

The bed temperature decreases as the sample flow rate increases when the sample flow rate is equal to the drying rate. Further, the change in bed temperature with respect to the sample flow rate decreases when the sample flow rate is higher than the drying rate. The change in the drying rate is also found to be insignificant when the sample flow rate is higher than the drying rate. This implies that the drying rate is

strongly related to the bed temperature. The bed temperature is defined as T_{bedc} when the drying rate is R_{wc} . The bed temperature T_{bedc} is lower at 50 kPa than at 101 kPa. Therefore, it is confirmed that low-temperature drying with a high drying rate is possible under a reduced chamber pressure in a fluidized bed of inert particles.

Figure 5 shows the relationship between the drying rate R_{wc} and the non-dimensional mass velocity of the drying gas G/G_{mf} . The minimum fluidization mass velocity of the drying gas G_{mf} ($= u_{\text{mf}} \rho$) was obtained using the equation given by Kusakabe et al. (1989).^[24]

$$u_{\text{mf}} P = u_{\text{mf0}} \frac{P + P_{\text{b}}}{2} \left(1 + \frac{32K}{3} \right) \quad (1)$$

The value of G_{mf} was also determined in the experiment described in our previous paper, and the experimental data were found to be in good agreement with the results calculated by Eq. (1).^[15]

When the non-dimensional mass velocity of the drying gas is high, the drying rate remains almost constant with the non-dimensional mass velocity of the drying gas independent of the chamber pressure. The drying rate decreases with the non-dimensional mass velocity of the drying gas when the latter is below a certain value. The critical non-dimensional mass velocity of the drying gas is defined as $G_{\text{c}}/G_{\text{mf}}$ in Fig. 5, and its value decreases when the chamber pressure is reduced. In addition, the minimum fluidization mass velocity of the drying gas G_{mf} decreases when the chamber pressure is reduced.^[21] The relationship of the critical mass velocity of the drying gas G_{c} , which is defined in Fig. 5, with the chamber pressure is shown in Fig. 6. From this relationship, it is confirmed that at a low chamber pressure, a high drying rate can be achieved even at a relatively low mass velocity of the drying gas. When the mass velocity of the drying gas is sufficiently high, the sample disperses widely in the fluidized bed and the drying rate achieved is the maximum for that heat source (ribbon heater, 110 W). Therefore, the effects of the mass velocity of the drying gas and the chamber pressure on the drying rate reduce, as shown in Fig. 5. The relationship between the drying rate R_{wc} and the chamber pressure when $G_{\text{c}}/G_{\text{mf}} = 3.0$ is shown in Fig. 7. When the non-dimensional mass velocity of the drying gas G/G_{mf} is less than $G_{\text{c}}/G_{\text{mf}}$, the drying rate

increases at a reduced chamber pressure.

Figure 8 shows the relationship between the bed temperature T_{bedc} and the drying rate R_{wc} for different values of the chamber pressure. As the drying rate increases, the bed temperature decreases, and a linear relation is observed between them independent of the chamber pressure. This implies that the bed temperature is strongly influenced by the drying rate. The heat transfer during drying depends on the evaporation of water because the latent heat of water vaporization is high.

CONCLUSIONS

A drying method in which a heat-sensitive material is immersed in a fluidized bed of inert particles under reduced pressure was used to obtain dispersed, dry, fine powders of that material from a dilute suspension or solution at a low temperature with a high drying rate. To determine the drying characteristics, only liquid (distilled water) was passed through a fluidized bed of inert particles as a sample dilute suspension or solution. The mass velocity of the drying gas, sample flow rate, and chamber pressure were varied independently. The effects of these variations on the corresponding drying characteristics were experimentally examined.

The fluidization state strongly influences the drying rate in a fluidized bed of inert particles and has a greater effect than the chamber pressure on the corresponding drying characteristics; i.e., it is important to maintain a vigorous fluidization state to achieve low-temperature drying with a high drying rate. This vigorous fluidization state can be achieved at a high mass velocity of the drying gas, and low-temperature drying can be achieved with a high drying rate even under atmospheric pressure for a sufficiently high mass velocity of the drying gas. Although the maximum drying rate is independent of the chamber pressure, it can be achieved at a relatively low mass velocity of the drying gas under reduced pressure; i.e., when the chamber pressure is low, a high drying rate can be achieved even at a relatively low mass velocity of the drying gas. The bed temperature during drying is strongly influenced by the drying rate and decreases

linearly with an increase in the maximum drying rate when the sample flow rate is equal to the drying rate. Because the latent heat of water vaporization is high, the drying rate governs the heat transfer in the fluidized bed during drying.

NOMENCLATURE

F_w	Sample flow rate (kg/(s m ³ bed))
G	Mass velocity of the drying gas (kg/(s m ²))
G_c	Critical mass velocity of the drying gas, as defined in Fig. 5 (kg/(s m ²))
G_{mf}	Minimum fluidization mass velocity of the drying gas (kg/(s m ²))
K	Knudsen number
P	Chamber pressure (Pa)
P_b	Pressure at the bottom of the bed (Pa)
R_w	Drying rate (kg/(s m ³ bed))
R_{wc}	Maximum drying rate when the sample flow rate is equal to the drying rate (kg/(s m ³ bed))
S_{bed}	Amount of accumulated sample (distilled water) in the bed (kg/(m ³ bed))
T_{bed}	Bed temperature (K)
T_{bedc}	Bed temperature when drying rate is R_{wc} (K)
u_{mf}	Minimum fluidization velocity (m/s)
u_{mf0}	Minimum fluidization velocity under atmospheric pressure (m/s)
ρ	Density of drying gas (kg/m ³)

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FIG. 1. Outline of experimental apparatus.

FIG. 2. Changes in (a)drying rate R_w , amount of accumulated sample in bed S_{bed} and (b)bed temperature T_{bed} with time t for different values of chamber pressure (Opened key: 50 kPa, Closed key: 101 kPa). (A), (B) and (C) is corresponding with those of FIG. 3.

FIG. 3. Change in fluidization state with time; (A) fluidization, (B) Non-fluidization with stable channels, (C) Bubbling of gas.

FIG. 4. Relationship among (a)drying rate R_w , (b)bed temperature T_{bed} and sample flow rate F_w when chamber pressure is 50 and 101 kPa.

FIG. 5. Relationship between drying rate R_{wc} and non-dimensional mass velocity of drying gas G/G_{mf} for different values of chamber pressure.

FIG. 6. Relationship between critical mass velocity of drying gas G_c and chamber pressure P .

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FIG. 7. Relationship between drying rate R_{wc} and chamber pressure P when $G/G_{mf} = 3.0$.

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FIG. 8. Relationship between bed temperature T_{bedc} and drying rate R_{wc} for different values of chamber pressure P .