Modeling of Agitation Fluidized Bed Granulation by Random Coalescence Model

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Modeling of agitation fluidized bed granulation was conducted using a proposed random coalescence model, in which adhesion of two colliding particles was judged by the coherent strength of a liquid bridge formed between the particles and the separation force caused mainly by agitator rotation. Properties of coherent strength and water absorbing characteristics of the starting materials, which were very important to determine granule growth, were also taken into consideration. Granule growth in various powder samples with different properties were simulated and the effects of moisture content and agitator rotational speed on this growth were numerically investigated. The simulated results were in good agreement with the actual granulation data, and granule growth in various powder samples and operating conditions could be simulated with high accuracy. The mechanism of agitation fluidized bed granulation was also elucidated by the proposed model.

Key words modeling; granulation; agitation fluidized bed; random coalescence model; coherent strength; water absorbing characteristic

An agitation fluidized bed equipped with an agitator blade at the bottom of a typical fluidized bed has been developed and its performance has gained much attention in powder handling processes. It has been widely used especially in the granulation of chemical and pharmaceutical materials because of its characteristics of reducing segregation by forced circulation and making spherical and well-compacted granules, heretofore impossible with a conventional fluidized bed granulation system.

To elucidate the mechanism of granule growth in agitation fluidized bed granulation, we earlier proposed the random coalescence model,[1] random addition model,[2] and mathematical models[3,4] using a population balance equation. These models introduced the concept of moisture content and its effect on granule growth was numerically investigated. However, although properties of powder such as its water absorbing characteristics and coherent strength are very important in determining granule growth in the granulation, there has been no theoretical study introducing these properties into the granule growth model.

The purpose of this contribution is to propose a model of agitation fluidized bed granulation using random coalescence model, in which coherent strength by a liquid bridge, separation force caused mainly by agitator rotation, and coherent strength and water absorbing properties of powder are considered. Using the proposed model, granule growth in various powder samples with different properties was simulated, and the effects of moisture content and agitator rotational speed on the granule growth were investigated numerically. The mechanism of granule growth was discussed, and validity of the model was confirmed by comparing the simulated results with the actual granulation data.

Method for Simulation Figure 1 shows a flowchart of the computer simulation employed and Fig. 2 describes particle size distributions of seed particles (lactose and cornstarch) and the spray mist used for both simulation and actual granulation.

At the start of a simulation, 500 spherical particles of two different sizes were randomly placed on a two-dimensional plane; these particles had the same size distribution as the lactose and cornstarch particles, and were mixed at a predetermined ratio. Secondly, spherical spray mist particles with particle size distribution the same as actual spray mist (Fig. 2), were stored in a different two-dimensional plane.

Two particles and the spray mist were randomly selected and the particles were allowed to collide with each other.

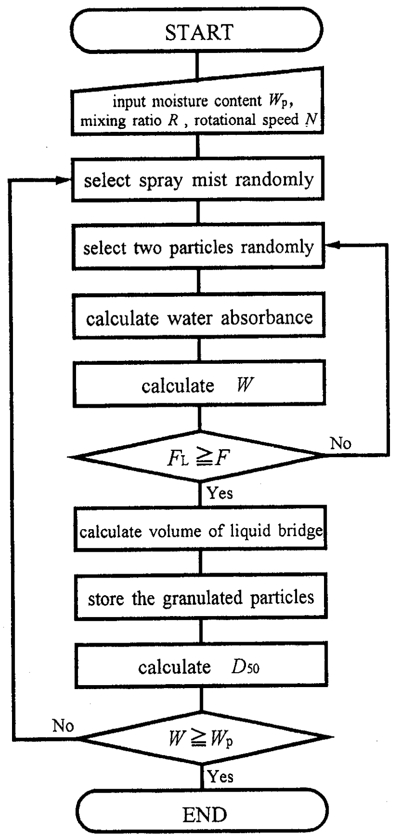

Fig. 1. Flowchart of the Computer Simulation Employed

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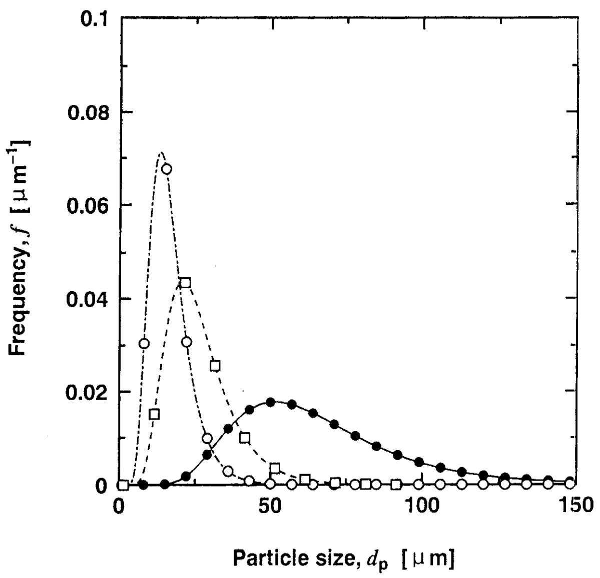

Fig. 2. Particle Size Distribution of Lactose, Cornstarch and Spray Mist

○, cornstarch ($D_{50}=15\,\mu$m, $\sigma_g=1.54$); ●, lactose ($D_{50}=60\,\mu$m, $\sigma_g=1.50$); □, spray mist ($D_{50}=35\,\mu$m, $\sigma_g=1.50$).

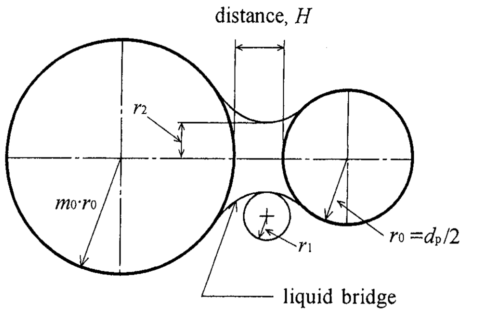

Fig. 3. Schematic Diagram of Liquid Bridge between Particles

At this time, it was assumed that part of the spray mist was absorbed by the particles and the rest of it formed a liquid bridge as illustrated in Fig. 3. In calculating the amount of water absorbed, we used data obtained by experiment (details of the method will be described later). After the particles had absorbed the water, the coherent strength of the liquid bridge, F_L, was determined using the equation proposed by Pietsch and Rumpf[5] (Eq. 1)

$$F_L=\frac{\pi}{2}\cdot d_p^2\cdot\sigma\cdot R_2\left(\frac{R_2}{R_1}+1\right) \tag{1}$$

where σ and d_p $(=2r_0)$ showed coherent strength and diameter of the smaller particles, respectively. R_1 and R_2 were the dimensionless curvature radius derived using curvature radius r_1 and radius r_2 of the narrowest liquid bridge[6] as follows:

$$R_1=r_1/r_0 \tag{2}$$
$$R_2=r_2/r_0 \tag{3}$$

The separation force was presumed to be in proportion to the periphery velocity based on the preliminary experimental results.[7] It has been reported that the separation force imposed on the granules by the agitator rotation was closely connected to the periphery velocity, but not to the centrifugal force.[7] This was supported by the fact that the particles were compacted by tumbling and rotating due to the agitator rotation, not by crushing against the vessel wall.[7] Therefore, the periphery velocity appears to determine the separation force in agitation fluidized bed granulation, and the granule growth can be controlled by the velocity if the coherent strength is the same. Thus, Eq. 4 was used to express the separation force,

$$F=k\cdot m\cdot r\cdot\omega \tag{4}$$

where m, r and ω show mass of the smaller particle, diameter of the agitator blade and the agitator angular velocity, respectively. Also, k shows a fitting parameter.

Judgement of the adhesion between the two colliding particles was made by comparing the coherent strength by the liquid bridge with the separation force; if the coherent strength was larger than the separation force ($F_L \geqq F$), the two colliding particles adhered to each other. By contrast, if the coherent strength was smaller than the separation force ($F_L < F$), the two colliding particles were assumed to separate and were returned to the original dimensional plane. New particles were then selected for the collision. When two particles adhered, volume of the liquid bridge, v, was calculated using Eq. 5 by presuming the distance between the particles to be $H=0$:

$$v\cong\frac{\pi}{16}\cdot d_p^3\cdot R_2^4 \tag{5}$$

Then, moisture content of the particles, W, was calculated using mass of water and particles:

$$W=\frac{M_w}{M_w+M_g}\times 100 \tag{6}$$

where M_w and M_g are the mass of water (amount of water absorbed and the liquid bridge) and particles, respectively. Size of a granulated particle was calculated using the volume equivalent diameter, D_a, as follows:

$$D_a=\sqrt[3]{6V/\pi\cdot(1-\varepsilon)} \tag{7}$$

where V and ε indicate real volume of particles and voidage, respectively. In calculating the granule diameter, voidage ε of granulated particles was presumed to be a constant 0.2595 (hexagonal close-packed structure), regardless of particle size distribution. The median diameter of the granulated particles was computed using number size distribution, assuming that they obeyed log-normal distribution.

After calculating the diameter of the granulated particles, the address of the larger particle in dimension was filled with the granulated particle, and the address of the smaller particle was filled with another particle selected randomly from the same dimension.

These calculations were continued until the calculated moisture content, W, exceeded the predetermined moisture content, W_p.

Experimental

Equipment An outline of the experimental apparatus is shown in Fig. 4. For wet granulation, an agitation fluidized bed[7,8] (NQ-125, Fuji Paudal Co., Ltd.) was used. The vessel's diameter was 125 mm, and an agitator blade provided tumbling and compacting effects to granules to make them spherical and well-compacted. Under the blade, three circular

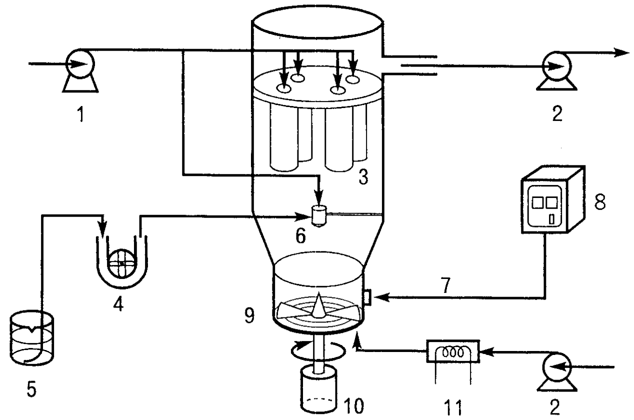

Fig. 4. Schematic Diagram of Agitation Fluidized Bed Granulator

1, compressor; 2, blower; 3, bag filter; 4, roller pump; 5, binder liquid; 6, spray nozzle; 7, optical fiber; 8, IR moisture sensor; 9, agitator blade; 10, motor; 11, heater.

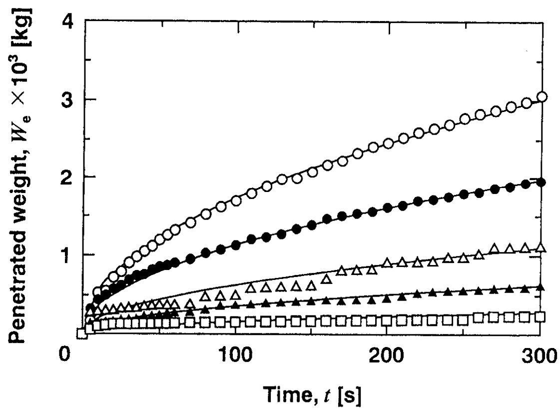

Fig. 5. Temporal Change in Water Penetrated Weight at Various Powder Samples

○, lac./corn. = 0/10; ●, lac./corn. = 3/7; △, lac./corn. = 5/5; ▲, lac./corn. = 7/3; □, lac./corn. = 10/0.

Table 1. Powder Samples Used

Sample	Number median diameter (μm)	Geometric standard deviation (—)
Lactose[a)]	60	1.502
Cornstarch[b)]	15	1.540
Hydroxypropylcellulose[c)]	21	1.507
(Total)		

a) Pharmatose 200M, DMV. *b)* Cornstarch W, Nippon Shokuhin Kakou Co., Ltd. *c)* HPC-EFP, Shin-Etsu Chemical Co., Ltd.

Table 2. Operating Conditions

Fluidizing air velocity	0.8 m/s
Minimum fluidizing air velocity	0.071 m/s
Air temperature	313 K
Binder (water) feed rate	1.0×10^{-4} kg/s
Agitator rotational speed	5.0 rps

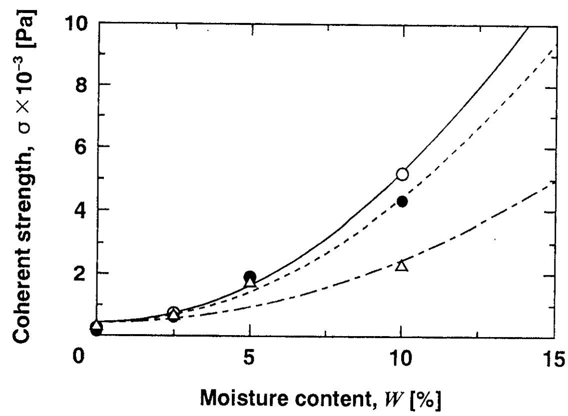

Fig. 6. Relation between Coherent Strength and Moisture Content

○, lac./corn. = 7/3; ●, lac./corn. = 5/5; △, lac./corn. = 3/7.

plates of different diameter were superimposed to function as air distributors, from which heated air was blown to fluidize the granule particles. Fine powders lifted up by the fluidization air were entrapped by bag filters and brushed down by pulsating jet of air.

Main operational variables such as inlet air temperature, air velocity, and agitator rotational speed were feedback controlled to maintain stable operation. All the operational variables were on-line monitored automatically (NQ-Touch system, Fuji Paudal Co., Ltd.), then stored on hard disk.

Coherent strength of a powder sample was measured using a powder coherency meter (EB-3300CH, Shimadzu Co.), which measured vertical tensile strength of the powder bed. The loading weight was 0.0165 kg (voidage of powder bed was 0.557) and loading pressure was 25 kgf/cm^2.

Water absorbing characteristics were determined using an instrument which measured liquid penetration rate (Penetanalyzer, Hosokawa Micron Co., Ltd.).[9] Voidage of powder bed measured was set at 0.538.

Powder Samples Table 1 lists the properties of powder samples used. A mixture of lactose and cornstarch (0.300 kg), of which the mixing mass ratio varied, was used as the powder sample. Hydroxypropylcellulose (HPC EF-P) was used as a binder, and was mixed as a dry powder into the starting materials before granulation. Purified water was sprayed through a binary nozzle located 100 mm above the powder bed.

Operating Conditions The operating conditions are listed in Table 2.

Results and Discussion

Water Absorbing Characteristics and Coherent Strength of Powder Figure 5 shows water absorbing characteristics of powder samples of various mixing ratios of lactose (lac.) and cornstarch (corn.). In this figure, the key of lac./corn. = 7/3 denotes that lactose and cornstarch were mixed at 7 : 3 by weight.

As seen from Fig. 5, water absorbing weight had a tendency to increase with an increase in cornstarch mixing ratio. Also, water absorbing weight, W_e, and processing time, t, had a correlated function as shown in Eq. 8. Since granulation was conducted while a constant damping speed was maintained ($dW/dt = 1.0\% \cdot \text{min}^{-1}$ constant), moisture content increased linearly with processing time. Thus, water absorbing weight, W_e, could be expressed as a function of moisture content, W, instead of using processing time, t. In the present computer simulation, Eq. 9 was used to express water absorbing characteristics:

$$W_e = h' \cdot \sqrt{t} \tag{8}$$

$$W_e = h \cdot \sqrt{W} \tag{9}$$

where h and h' were fitting parameters.

Figure 6 illustrates the relationship between coherent strength, σ, and moisture content, W. Here, moisture content was calculated using the drying method. As seen, coherent strength increased as lactose mixing ratio and moisture content increased, because the adhesion force between the particles increased by the surface dissolution

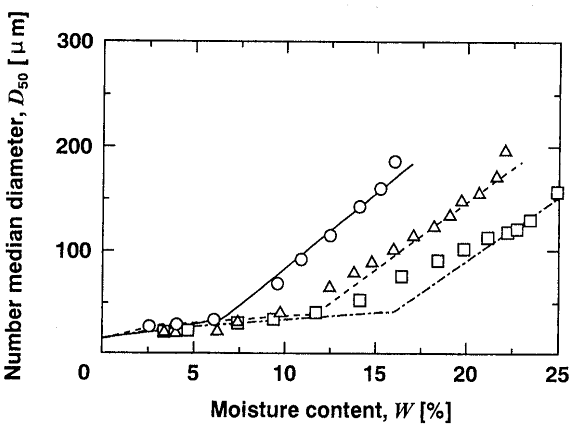

Fig. 7. Simulated Granule Growth in Various Powder Samples ($N=5.0$ rps)

—○—, lac./corn.$=7/3$; ---△---, lac./corn.$=5/5$; —·—·□—·—·, lac./corn.$=3/7$.

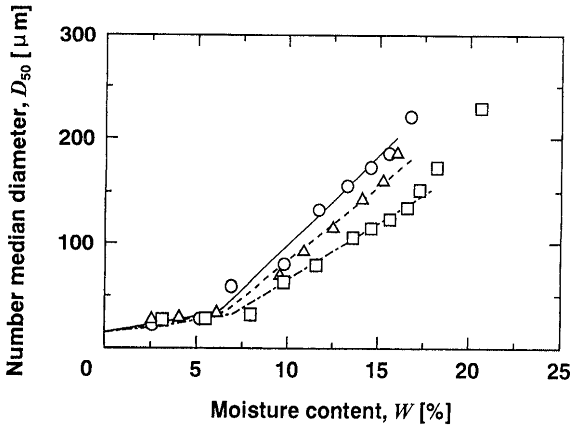

Fig. 8. Simulated Granule Growth at Various Agitator Rotational Speeds (lac./corn.$=7/3$)

—○—, $N=2.5$ rps; ---△---, $N=5.0$ rps; —·—·□—·—·, $N=10.0$ rps.

of lactose particles and by the increased volume of the liquid bridge. The coherent strength could be expressed as the following function:

$$\sigma = aW^2 + c \qquad (10)$$

where a and c were constants depending on the lactose and cornstarch mixing ratios. By substituting the coherent strength, σ, into Eq. 1, coherent strength of liquid bridge, F_L, could be calculated.

In the following, computer simulation of agitation fluidized bed granulation was conducted using water absorbing characteristics and coherent strength.

Effects of Powder Properties and Agitator Rotational Speed on Granule Growth Figure 7 shows the results of simulation using powder samples of various mixing ratios of lactose and cornstarch. Plots and lines indicate experimental data and simulated results, respectively.

As shown, the simulated results were in good agreement with the actual granulation data. The secondary agglomeration, where rapid granule growth occurred, had a tendency to begin at a higher level of moisture content if the cornstarch ratio was large. This was because the cornstarch had such a strong water absorbing potential that the liquid bridge could not be formulated in the small moisture content range. Also, since cornstarch had a small particle diameter and a weak coherent strength, the granule growth was suppressed if the cornstarch ratio was increased.

From results of the present simulation, it was concluded that the water absorbing characteristics were a very important factor in determining granule growth, and that granule growth using various powder samples could be simulated by the present model.

Figure 8 indicates the results of simulation at various agitator rotational speeds using a powder sample of lac./corn.$=7/3$.

The simulated results were in good agreement with the actual granulation data. There was a tendency for the granule growth rate to decrease, if the agitator rotational speed increased. This was because the separation force increased due to the increase in agitator rotational speed, and thus the adhesion probability decreased.

It could thus be concluded that granule growth at various mechanical agitation speeds could be simulated if the separation force related to agitator periphery speed was used in the model, and the granule growth mechanism in agitation fluidized bed could be elucidated by the results of the present model.

Conclusions

Granule growth in agitation fluidized bed granulation was simulated using a proposed random coalescence model, in which adhesion of two colliding granules was judged by the coherent strength by a liquid bridge and the separation force primarily caused by the agitator rotation. Coherent strength and water absorbing characteristics were measured and were applied to the present model to express granule growth correctly. Granule growth at various starting materials of different lactose and cornstarch mixing ratios was simulated, and the granule growth at various agitator rotational speeds was numerically analyzed. Both the simulated results were found to be in good agreement with the actual granulation data, and granule growth at various powder samples and operating conditions could be simulated correctly. The granule growth mechanism and the effects of operating variables and powder properties on the growth could thus be elucidated by the proposed model.

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