Dispersion of Aggregate Particles by Acceleration in Air Stream

Yasuo Kousaka, Yoshiyuki Endo, Takahiro Horiuchi, and Tohru Niida
Dept. of Chern. Eng., Univ. of Osaka Pref.

Abstract

To clarify the dispersion mechanisms of aggregate particles in air, the dispersion of aggregate particles by acceleration in an air stream, which is a typical dispersion mechanism, was examined.

In the experiment, aggregate PSL (polystyrene latex) particles (primary spherical particle diameters are: 5.2 and 2 μm) were fed into an ejector, where aggregates were dispersed into smaller sizes by acceleration in a high-speed and high pressure (critical pressure higher than atmospheric pressure) air stream. Dispersed PSL particles were introduced into a sampling chamber and sampled on several slide glasses set on the bottom of the chamber by gravitational deposition. PSL particles thus sampled were observed with a microscope. This method allowed exact evaluation of the numbers of primary particles consisting of aggregates. It was suggested from the experiment that aggregate particles consisting of about 5 μm primary particles were almost entirely dispersed into primary particles by acceleration of the particles in the ejector.

The dispersion force acting on aggregate particles in an air stream at high Reynolds number was theoretically analyzed for a model aggregate particle and compared with the existing van der Waals adhesive force. It was found that the experimental results could be well explained by the theoretical comparison between the dispersion and adhesion forces.

Introduction

The phenomenon of aggregate particle dispersion in an air stream is of importance in improving the performance of dry pulverization and classification processes of particles and also in analyzing the adhesion force between particles. Many studies using various types of dispersion apparatuses have been carried out in the past but since those were made using polydisperse and non-spherical particles such as calcium carbonate or carbon black, accurate evaluation of the experimental results was difficult.

In the present study, attention has been focused on dispersion by acceleration in an air stream which is a typical dispersion mechanism of aggregate particles. For the purpose of accurately grasping the dispersion mechanism and of searching for possibilities of obtaining high concentration PSL aerosol particles, an experiment was conducted to disperse relatively large (primary particle diameter of 2 – 5 μm) dry PSL aggregate particles in a high-speed air stream and based on the obtained results, a theoretical study on dispersion by acceleration in an air stream was made.

In industrial processes, the demand for a stable generation of high concentration mono-disperse PSL particles is increasing for the evaluation of the collecting performance of dust collectors and for forming distance pieces for liquid crystal displays.

1. Theoretical study

1.1 Dispersion force acting on aggregate particles by an acceleration in air stream

Fig. 1 shows a model of an aggregate particle consisting of a large and a small particle. Particles A and B may each be an aggregate particle. $F_d$, which is the dispersion force when this aggregate particle is placed momentarily in a uniform fluid flow, is obtained. The equation of motion for the dispersion model of the authors reported previously is as shown below. Yu et al carried out studies on this
model using the resistance which took into account the effect of adjacent spheres but for the sake of simplification, the model of the authors is used.

\[
\frac{\pi}{6} d_{vA}^3 \rho_{pA} \frac{d\rho_{pA}}{dt} = R_{IA} - F_d
\]  

(1)

\[
\frac{\pi}{6} d_{vB}^3 \rho_{pB} \frac{d\rho_{pB}}{dt} = R_{IB} + F_d
\]  

(2)

Where subscripts A and B relate to the two particles composing the particle aggregate shown in Fig. 1.

d_v is the volume equivalent diameter, \( \rho_p \) is the density of the particle, \( v_p \) is the velocity of the particle, \( R_t \) is the fluid drag force, and \( F_d \) is the dispersion force acting on the particle. Since the two particles are adhered to each other, \( v_{pA} = v_{pB} = v_p \), and \( \rho_{pA} = \rho_{pB} = \rho_p \) are assumed and from these expressions, the dispersion force \( F_d \) is expressed by the following equations.

\[
F_d = \frac{R_{IA} - D_v^3 R_{IB}}{D_v^3 + 1} (D_v = d_{vA}/d_{vB} \leq 1)
\]  

(3)

Here, to apply up to a large Reynolds number \( (Re = d_v u_r \rho_1/\mu) \), based on the particle diameter, the following expression is used for the drag force.

\[
R_d = \frac{\pi}{8} d_{vA}^2 \rho_1 u_r^2 \left( 0.55 + \frac{4.8}{\sqrt{Re}} \right)^2 \chi
\]  

(Re \leq 10^4)

(4)

Where \( \rho_1 \) is the density of the fluid, \( u_r \) is the relative velocity between the particles and the fluid, and \( \chi \) is the dynamic shape factor mentioned in 1.3. Generally, \( \chi \) is used for the fluid drag force but as shown by Eq. (4), \( \chi \), if defined, can be applied at an high Reynolds number [2].

By substituting Eq. (4) in Eq. (3), the dispersion force \( F_d \) can be obtained using the following expression.

\[
F_d = \{0.119 \rho_1 u_r^2 d_{vB}^3 \rho_1^2 (\chi_A - D_v \chi_B) + 2.07 \mu \rho_1 u_r^3 d_{vB}^3 D_r (\chi_A - D_v^3 \chi_B) + 9.05 \mu \rho_1 u_r^2 D_v (\chi_A - D_v^2 \chi_B) / (D_v^3 + 1)
\]  

(5)

1.2 Fluid flow at the ejector

Eq. (5) consists factors relating to the fluid (relative velocity between particles and fluid \( u_r \), density of fluid \( \rho_1 \), etc.) and factors relating to the particles (volume equivalent diameter \( d_v \), dynamic shape factor \( \chi \)) and therefore the former is studied first.

The velocity of the fluid never exceeds the sound velocity (critical velocity) and therefore only the fluid velocity is considered, the dispersion force due to acceleration of the air stream cannot exceed the force equaling this. However, as can be seen from Eq. (5), for a Reynolds number which is larger than the Stokes law, if the density of fluid increases, it is possible to increase the dispersion force. For example, as in the present experiment where an ejector is used to raise the critical pressure above the atmospheric pressure by delivering high pressure gas through a very narrow clearance, the density of the fluid increases in proportion to this critical pressure and therefore even if the flow velocity has reached the critical velocity (sound velocity), an even higher dispersion force can be achieved. Furthermore, the viscosity of fluid such as air or nitrogen hardly change with pressure changes and therefore are not considered here.

The ejector used in the present experiment consists of an annular section with a very narrow
Clearance $l_1$ (variable from 0 - 3 mm) and a throat section as shown in Fig. 2, and therefore it is readily possible to make the fluid immediately after ejection from the annular section attain a flow reaching the critical pressure and critical velocity by adjusting this $l_1$ and the pressure $P_1$ of feed gas (nitrogen in this present experiment). In this case, assuming that the annular section is a convergent nozzle and considering that the energy change in this section is not a completely adiabatic change but a polytropic change with wall surface friction, then the critical pressure and critical velocity can be obtained as follows:

$$P_m/P_1 = \{2/(n + 1)\}^{n/(n-1)}$$

(6)

$$u_m = \phi_m \times RT_1$$

(7)

$$\phi_m = \sqrt{2g \chi (n-1)/(\kappa - 1) (n + 1)}$$

(8)

Where $P_1$ is the pressure at the ejector, $T_1$ is the absolute temperature of the inlet gas, $R$ is the gas constant, $g$ is the acceleration due to gravity, $n$ is the index of polytropic change, and $\chi$ is the ratio of constant pressure to constant volume heat capacity (about 1.4 in the case of nitrogen). If $n$ can be obtained, the pressure $P_m$ and flow velocity $u_m$ can be derived.

Besides this, the formula in the case of an adiabatic flow are as follows:

$$P_c/P_1 = \{2/(k + 1)\}^{k/(k-1)}$$

(9)

$$w_c = \phi_c \times RT_1$$

(10)

$$\phi_c = \sqrt{2gk(k + 1)}$$

(11)

Assuming an index of polytropic change $n = 1.3$, from Eqs. (8) and (11), we get,

$$\phi_m/\phi_c = 0.88$$

Since it is believed that this value of a well finished round hole nozzle may reach 0.95 - 0.975, 0.88 obtained with $n = 1.3$ is roughly a reasonable value for the present annular nozzle where the contact area between fluid and wall surface is large.

Therefore, when $n = 1.3$ is substituted in Eqs. (6) - (8), the critical pressure $P_m$ and critical velocity $u_m$ are obtained as follows:

$$P_m = 0.546P_1 \text{ [Pa, abs.]}$$

(13)

$$u_m = 16.1 \times T_1 \text{ [m/s]} \approx 280 \text{ m/s}$$

(14)

From this critical pressure $P_m$, the density of the fluid $q_f$ can be obtained. Also the initial velocity of the particles at the ejector inlet is approximated as 0, and even supposing that it is 10 m/s, the relative velocity $u_r$ between the particles and the fluid does not change much and therefore $u_r$ is taken as the critical velocity $u_m$. As can be seen from Eqs. (13) and (14), the critical velocity $u_m$ is constant. The critical pressure of the fluid, namely the density $q_f$ changes with the fluid feed pressure $P_1$ to the ejector, and by increasing $P_1$, the dispersion force in Eq. (5) can be made larger.

1.3 Structure and dispersion process of aggregate particles

The dynamic shape factor $\chi$ and volume equivalent diameter $d_v$ necessary for calculating the dispersion force are given by the following expression when aggregate particles are roughly composed of uniform spherical primary particles$^4$.

$$\chi = 0.862N^{1/3} \quad (2 \leq N \leq 10)$$

(15)

$$d_v = N^{1/3}d_{p1}$$

(16)

Where $N$ is the number of primary particles composing an aggregate, and $d_{p1}$ is the primary particle diameter. However, Eq. (15) is for chainlike aggregate particles and this point shall be studied later. The values of both expressions are dependent on the number $N$ of the primary particle and therefore, we shall next study the process by which aggregate particles actually disperse and to what extent the $N$ aggregate particles disperse.

Fig. 3 shows the dispersion process of aggregate particles by acceleration of the air stream.
When aggregate particles corresponding to particles A and B in Fig. 1 are large, as can be seen from Eq. (5), a large dispersion force $F_{ct}$ arises and it is thought that dispersion proceeds immediately. That is to say the dispersion of large aggregate particles need not be considered in such a dispersion process and it is sufficient to focus attention only on fine aggregate particles with small primary particle numbers $N$. Therefore, we shall next study dispersion force and process of aggregate particles approaching a final state.

Table 1 shows the various values necessary for calculating the dispersion force $F_d$ acting on aggregate particles composed of 2 to 4 primary particles and the adhesion force acting between the particles at the time of separation. For the dynamic shape factor $\chi_B$, Eq. (15) for calculating chainlike aggregate particles was used but due to the fact that there is no method for calculating the dynamic shape factor of small aggregate particles composed of several primary particles, and due to the fact that in this case, the fluid passes through the inside of aggregate particles, and even if their shape is cluster, it is assumed that they can be treated almost in the same manner as chainlike particles and therefore as an approximate, Eq. (15) was applied. Also the volume equivalent diameter $d_v$ was obtained using Eq. (16) except in the case where doublets disperse. If a doublet is composed of two identical spheres, the dispersion force shown in Eq. (5) becomes $F_d = 0$ and doublets do not disperse. Therefore, in this table, the value of $D_v$ of a doublet ($N = 2$) assumed to have a difference of $d_{vA}/d_{vB} = 0.9$ in the size of 2 particles is shown. The dispersion force is determined by the sort of particle resulting from the dispersion. When the value shown in this table and the fluid flow velocity and density are substituted in Eq. (5), the dispersion force $F_d$ is obtained.

On the other hand the value of the adhesion force between particles which maintains the aggregate shape is determined by the number of contact points shown in the table and whether dispersion will take place or not is determined by the difference between the values of this adhesion force and the above dispersion force $F_d$.

On the basis of the values shown in Table 1, calculation results of the dispersion force $F_d$ and adhesion force between particles $F_a$ under various conditions are shown in Fig. 4. Fig. 4 (a) shows the calculation results of the dispersion force $F_d$ when aggregate particles disperse into one primary particle and its remainder by nitrogen pressure ($P_1$ in Fig. 2) $1.1 \times 10^4$ kPa at the ejector inlet and the adhesion force $F_a$ between particles (van der Waals force). From the figure, it can be seen that the dispersion

<table>
<thead>
<tr>
<th>Number of primary particles $N$</th>
<th>Before dispersion</th>
<th>After dispersion</th>
<th>$d_{vA} = N^{1/3}d_{p1}$</th>
<th>$D_v = d_{vA}/d_{vB}$</th>
<th>$\chi_B$</th>
<th>Number of contact points</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>*</td>
<td>*</td>
<td>$d_{vA} = 0.9d_{vB}$ (assumed)</td>
<td>0.9</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>*</td>
<td>*</td>
<td>$d_{vA} = d_{p1}$</td>
<td>0.79</td>
<td>1.09</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>*</td>
<td>*</td>
<td>$d_{vA} = d_{p1}$</td>
<td>0.69</td>
<td>1.24</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 1 Characteristics of model aggregate particles
The primary particle diameter is $d_{P1}$ [pm], and its value is $1.1 \times 10^3$ kPa abs., $u_t = 280$ m/s, $\varepsilon = 7.0$ kg/m$^3$, $A = 1 \times 10^{-19}$ J (Hamaker constant), and $h = 4 \times 10^{-10}$ m (separation).

Equivalent volume diameter $d_{vB}$ [pm] ($a$).

Fig. 4 Calculated results of dispersion and adhesive forces.

The dispersion force $F_{d}$ becomes larger as the particle diameter $d_{vB}$ obtained from Eq. (16) becomes larger and as mentioned before, it can be understood that larger aggregate particles become more prone to disperse.

On the other hand, for the adhesion force between particles, freeze-dried standard PSL particles free of impurities (made by Nippon Synthetic Rubber Co., Ltd.), are used in the experiment and also since the fluid is nitrogen gas absolutely free of moisture, it is assumed that the liquid bridging adhesion force is extremely small. The adhesion force $F_a$ between particles is calculated using van der Waals force with the Hamaker constant of PSL particles of $1 \times 10^{-19}$ J as the average value of documented values, $6.2 - 16.8 \times 10^{-20}$ J and a separation distance between particles of 0.4 nm. As shown in Table 1, the adhesion force $F_a$ between particles changes $2F_{a1}$, $3F_{a2}$, ..., depending on the number of particle contact points. If the dispersion force exceeds this adhesion force, the aggregate particles will disperse. For example, when an aggregate particle consisting of 4 primary particles of 5 $\mu$m disperses into 1 and 3 particles, it becomes $d_{vB} = 3^{1/3} \times 5 \mu$m = 7.2 $\mu$m as shown in Table 1 and the dispersion force $F_d$ becomes $4.8 \times 10^{-7}$ N according to Fig. 4 (a). On the other hand, the adhesion force, even though it may involve a 3 point contact, becomes $3.8 \times 10^{-7}$ N and it is expected that dispersion will most likely occur. When the primary particle diameter is 2 $\mu$m whereas the dispersion force for $d_{vB} = 3^{1/3} \times 2 \mu$m = 2.9 $\mu$m becomes $F_d = 1.1 \times 10^{-7}$ N, and as the value of the adhesion force becomes $F_a = 5 \times 10^{-9}$ N, $1 \times 10^{-7}$ N, $1.6 \times 10^{-7}$ N respectively larger for 1 point, 2 point and 3 point contacts, dispersion becomes more difficult.

Next, Fig. 4 (b) shows the calculation results when triplets consisting of 3 primary particles disperse into 1 and 2 particles. In this case, since aggregate particles are limited to triplets, the dispersion force is determined only by the fluid resistance. As mentioned before, the figure shows that the dispersion force is determined by the density $\varepsilon$ of the fluid when the fluid velocity reaches critical velocity (280 m/s). From this figure also, it can be seen that primary 5 $\mu$m triplets can disperse and that when the primary particle diameter is 2 $\mu$m, dispersion becomes difficult.

When Stokes drag force acts on particles with diameters of 2 $\mu$m and 5 $\mu$m, the dispersion force is proportional to the particles diameter but at high
Reynolds number, the dispersion force (drag force acting on particles) becomes proportional to $1.5 - 2$ power of the particle diameter and large aggregate particles become prone to dispersion.

2. Experimental apparatus and methods

Fig. 5 shows the experimental apparatus. The ejector (made by Nisshin Flour Milling Co., Ltd.) used for dispersion by acceleration of aggregate particles and provided various gas velocities by changing the clearance $l_1$ and nitrogen pressure $P_1$ (refer to Fig. 2).

The PLS particles used in the experiments were dry particles made by Nippon Synthetic Rubber Co., Ltd. by a freeze drying process having primary particle diameters of 5.2 and 2μm. These PLS particles were fed through stainless capillary tube into the ejector and dispersed at the nozzle exit at critical pressure, critical velocity (sound velocity) nitrogen gas (maximum feed pressure $1.1 \times 10^3$ kPa, abs., gas velocity 280 m/s), then introduced into a settling chamber ($5 \times 10^{-2}$ m$^3$). When the inside of the chamber is roughly replaced by PSL aerosols, the nitrogen gas feed is stopped. A slide glass is placed at the bottom of the vessel in advance and after all particles have settled on the glass slide by gravitational sedimentation, about 1,000 particles is observed through an optical microscope. Since PLS particles with known primary particle diameters are directly viewed, the number of primary particles composing aggregates such as doublets and triplets can be clearly observed.

3. Experimental results and discussion

Fig. 6 shows photomicrographs of dispersed PLS particles. It can be seen that singlets, doublets, and triplets can be clearly observed.

Fig. 7 shows the experimental results obtained in this way and the vertical axis represents the number ratio of the aggregate particles consisting of N primary particles (including $N = 1$) against the total particle number (singlets and total aggregate particle number) after dispersion.

Fig. 7 (a) shows the experimental results using PSL particles with a primary particle diameters of 5.2μm. At $5 \times 10^5$ kPa and above, singlets ($N = 1$) representing 90% or more of the total were obtained. It was possible to generate height concentration PSL particles (about $10^{12}$ particles/m$^3$) through the PSL particles feed rate. The fact that
Fig. 7(a) Experimental results of PSL aggregate dispersion

PSL particles of 5.2μm almost all dispersed into primary particles is the same as the foreseen result in which the dispersion force exceeds the particle adhesion force and aggregate particles consisting of primary particles of 5μm disperse into 1 primary particle and a remainder before in Fig. 4. Fig. 7(b) shows the experimental results for PSL particles with a primary particle diameter of 2μm where almost never disperse. The fact that almost all PSL particles with a primary particle diameter of 5.2μm dispersed into primary particles, and the fact that PSL particles with a primary particle diameter of 2μm did not disperse so much agree with the theoretical results in Fig. 4 and it indicates that the dispersion force of aggregate particles by acceleration of an air stream can be expressed by Eq. (5). Also, the fact that doublets, except for singlets, are relatively numerous in the experimental results in Fig. 7 may be considered as verifying the fact that if doublets consist of two identical spheres, then the dispersion force shown in Eq. (5) becomes $F_d = 0$ and therefore they do not disperse.

Conclusion

Using an ejector operating at a critical pressure higher than atmospheric pressure as the dispersion equipment and conducting dispersion experiments on PSL aggregate particles by acceleration in an air stream, the following results were obtained.

(1) PSL aggregate particles with a primary particle diameter of 5.2μm subjected to acceleration under high pressure and a critical velocity at the nozzle outlet were almost all dispersed into primary particles but for primary particles with 2μm diameter, it was found that dispersion by acceleration in air stream was difficult. The number concentration also depends on the particles feed rate but a fairly high concentration aerosol particles were obtained.

Consequently, for aggregate particles with a primary particle diameters of about 5μm or larger, it was proved that an ejector using air stream acceleration operated under a critical pressure higher than atmospheric pressure can be used as a mono-
disperse, high concentration aerosol generator.

(2) The dispersion results obtained from the above experiment has been fairly well explained by comparing the theoretical dispersion force acting on model aggregate particles for which the dynamic shape factor was introduced with the theoretical values of the adhesion force between particles using the existing van der Waals force.

Nomenclature

\[ A = \text{Hamaker constant} \quad [J] \]
\[ D_v = \text{diameter ratio} \left( = \frac{d_A}{d_B} \right) \quad [-] \]
\[ d_v = \text{volume equivalent diameter} \quad [m] \]
\[ d_{p1} = \text{primary particle diameter} \quad [m] \]
\[ F_a = \text{adhesion force} \quad [N] \]
\[ F_d = \text{dispersion force} \quad [N] \]
\[ g = \text{acceleration due to gravity} \quad [m \cdot s^{-2}] \]
\[ h = \text{separation distance between two spherical primary particles} \quad [m] \]
\[ k = \text{ratio of constant pressure to constant volume heat capacity} \quad [-] \]
\[ l = \text{clearance shown in Fig. 2} \quad [m] \]
\[ N = \text{number of primary particles} \quad [-] \]
\[ n = \text{index of polytropic change} \quad [-] \]
\[ P_c = \text{critical pressure at adiabatic flow} \quad [Pa] \]
\[ P_m = \text{critical pressure at friction flow} \quad [Pa] \]
\[ P_l = \text{pressure at ejector inlet} \quad [Pa] \]
\[ R = \text{gas constant} \quad [J \cdot K^{-1} \cdot \text{mol}^{-1}] \]
\[ R_t = \text{drag force} \quad [N] \]
\[ T_1 = \text{temperature at ejector inlet} \quad [K] \]
\[ t = \text{time} \quad [s] \]
\[ u_c = \text{critical velocity at adiabatic flow} \quad [m \cdot s^{-1}] \]
\[ u_m = \text{critical velocity at friction flow} \quad [m \cdot s^{-1}] \]
\[ u_r = \text{relative velocity} \quad [m \cdot s^{-1}] \]
\[ v_p = \text{particle velocity} \quad [m \cdot s^{-1}] \]
\[ \chi = \text{dynamic shape factor} \quad [-] \]
\[ \mu = \text{viscosity of fluid} \quad [Pa \cdot s] \]
\[ Q_p = \text{density of particle} \quad [kg \cdot m^{-3}] \]
\[ Q_t = \text{density of fluid} \quad [kg \cdot m^{-3}] \]
\[ \phi_c = \text{value given in Eq. (11)} \quad [m^{1/2} \cdot s^{-1}] \]
\[ \phi_m = \text{value given in Eq. (8)} \quad [m^{1/2} \cdot s^{-1}] \]

Subscripts

A = particle A shown in Fig. 1
B = particle B shown in Fig. 1

Literature cited