1. Introduction

When developing new materials, it is important to have the capability to feed small amounts of particles (i.e. “to microfeed particles”) of a uniform composition at a constant feed rate in air or liquid continuously into a container of particulate materials. In particular, wet microfeeders, in which raw materials are charged in a vessel filled with a liquid, are necessary for feeding wet materials into the device for particulate operation in liquid, and for feeding raw materials into a small-scale wet separator [6].

In air, the microfeeding of particles of smaller sizes becomes more difficult because it is easier for them to adhere to the wall of the feeder or to cohere with each other. Matusaka et al. recently reported that capillary tubes vibrating at high frequency of less than 760Hz [1] or at an ultrasonic frequency of 20kHz [2] were effective for microfeeding fine powders in air.

On the other hand, liquid has an advantage of diminishing the particle adhesion and cohesion. It is expected that this advantage can be applied to the following wet microfeeding processes. (1) For “fine particles”, uniform-density suspension can be obtained because the settling velocity is very low. Wet microfeeders configured with a rotary pump and an elastic tube are now available to microfeed suspended fine particles. (2) For “small particles” which tend to deposit on the tube wall because the settling velocity is comparatively high, the above method (1) cannot be applied. Few reports concerning the wet microfeeding of “small particles” have been found.

In this paper, a wet microfeeder which utilizes ultrasonic force in liquid was designed and constructed on the basis that the dispersion and movement of small particles can be facilitated in the ultrasonic field in liquid. Discharge characteristics of small particles from

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Key words: Wet micro-feeder, particle discharge, ultrasonic field, nozzle aperture, particle shape
the nozzle of a thin glass tube were experimentally investigated in liquid subjected to ultrasonic force.

2. Experimental

2.1. Experimental materials

Table 1 shows the properties of experimental materials used. Three couples of spherical (s) and irregular-shaped crushed (i) mullite particles (true density $\rho_p=2920\text{kg/m}^3$) were prepared. Both the s- and i- particle groups in each couple had the same sieve opening range. The three couples had different average particle diameters ($d_p=81, 127, 180\mu\text{m}$). Each spherical particle group consisted of many spherical particles, and some irregular-shaped ones with small protuberances as shown in the particle images of representative spherical groups (Mat-Ss) from Table 1. In this paper, the irregular-shaped particles in the spherical particle group are also referred to as “spherical particles” for convenience.

The shape index $\psi$ defined by Eq. (1) presents the degree of surface roughness of the two dimensional particle image based on the circle of equivalent area:

$$\psi = \frac{4\pi A}{p^2} \quad (\leq 1.0),$$

where $A$ and $p$ respectively denote the area and perimeter length of a particle image.

The $\psi$ distributions in Table 1 were measured in the vertical direction by an image analyzer (Luzex FS, Nireco, Hachioji, Japan) for about 300 particles randomly sampled from each group. The respective $\psi_{50}$ values in Table 1 denote the medians of $\psi$ distribution concerned.

The volume shape factors $f_n$ for groups of $d_p=127, 180\mu\text{m}$ were obtained by the following equation:

$$f_n = \frac{M_n}{N_p d_p^3},$$

where $M_n$ and $N_p$ denote the mass and the number of 9,000 and 2,300 or more particles randomly sampled from 127 and 180$\mu\text{m}$ sized groups, respectively. The shape factors of the s- and i- particles in the smallest sized group ($d_p=81\mu\text{m}$) were not shown in Table 1 because reliable measurements of their $M_n$ and $N_p$ values were not obtained.

2.2. Experimental apparatus

Fig. 1 shows the schematic diagram of the wet microfeeder developed in this paper. Two ultrasonic transducers (1) (HEC-34245100, Langevin-type, Honda Electronics, Toyohashi, Japan) was fixed to the outer bottom of a rectangular vessel of stainless steel (2) (inner dimensions: 117 $\times$ 117 $\times$ 117mm). The transducers were driven by the sinusoidal power from an ultrasonic generator (W-113, including power amplifier, maximum output=100W, Honda Electronics, ibid.). The applied voltage $V_n$ (V) (peak to peak value) to each transducer was controlled through a variable transformer (SLIDAC SK105, Toshiba, Tokyo, Japan).

A thin glass tube (3) (inside diameter=2mm, length =235mm) for charging and feeding particles was fastened with a joint (4) at the center of the rectangular-vessel top cover. The glass tube (3) had a cone-shaped nozzle of inside diameter $D_n$ at the bottom from which particles could be discharged as shown in Fig. 1. This made it possible to observe the behavior of particles discharged from the nozzle, whose bottom was placed at $-30\text{mm}$ in $h$ which denotes the distance in the vertical direction from the inner bottom of the rectangular vessel.

A dilute aqueous solution of a surfactant (Extran MA03, 0.2vol%, density=997$\text{kg/m}^3$, viscosity=0.888 mPa·s at 25°C, Merck Japan, Tokyo) was added to fill the space of the apparatus drawn with grey-hatching as shown in Fig. 1.

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Table 1  Experimental materials used (mullite particles: density $\rho_p=2,920\text{kg/m}^3$)

<table>
<thead>
<tr>
<th>Material</th>
<th>Size (µm)</th>
<th>Shape</th>
<th>Shape index $\psi$ (-)</th>
<th>Volume shape factor $f_n$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sieve opening range (Average diameter $d_p$)</td>
<td></td>
<td>Min ~ Max</td>
<td>Median value $\psi_{50}$</td>
</tr>
<tr>
<td>Mat-Ss</td>
<td>74 ~ 88 (81)</td>
<td>Spherical</td>
<td>0.780 ~ 0.988</td>
<td>0.961</td>
</tr>
<tr>
<td>Mat-Si</td>
<td>105 ~ 149 (127)</td>
<td>Spherical</td>
<td>0.333 ~ 0.900</td>
<td>0.625</td>
</tr>
<tr>
<td>Mat-Ms</td>
<td>149 ~ 210 (180)</td>
<td>Irregular</td>
<td>0.792 ~ 0.986</td>
<td>0.976</td>
</tr>
<tr>
<td>Mat-Mi</td>
<td>127 ~ 178 (180)</td>
<td>Spherical</td>
<td>0.306 ~ 0.886</td>
<td>0.680</td>
</tr>
</tbody>
</table>

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Fig. 1
2.3. Experimental procedure

Particles were charged in the glass tube (3) and rubber tube-a (8) under the condition that both pinchcock-a (10) and pinchcock-b (11) were opened, while pinchcock-c (12) was closed. Then pinchcock-b (11) was closed so that the liquid in the glass and rubber tubes could not drain.

The ultrasonic power was supplied to transducers beginning 1 minute after pinchcock-c (12) had opened. The term \( t \) was defined as the time elapsed from the start of the ultrasonic power supply. The particles were sampled for 5 seconds at a sampler (7) from \( t/30 \) seconds. The first sampling from \( t/30 \) seconds was determined by considering the time required for particles to settle from the bottom of the nozzle to the sampler. Similar samplings of 5 seconds were repeated 15 times in 30-second intervals. Sixteen samples were obtained through a series of measurements for \( t/30 \) to 560s. The number of particles in each sample was counted through a light microscope. The corresponding number of particles discharged from the nozzle per unit time, \( N_i \) (s\(^{-1}\)) \((i=1 \text{ to } n; n \) denotes the total number of samples, i.e., 16), was calculated respectively. Hereafter, the term \( N_i \) is referred to as the particle discharge rate.

The above experiments were carried out at room temperature (20–29°C) under the following conditions:

- Oscillation frequency applied to the transducer: \( f = 25, 45, \) and 100kHz
- Corresponding applied voltage: \( V_0 = 0–900, 0–400, 0–400V_{p-p} \)
- Inside diameter of nozzle tip: \( D_n = 0.16–0.67\)mm

The position of the upper surface of the particle bed charged in the glass tube (3) and rubber tube (8) changed in the range between the top and bottom of the rubber tube.

The behavior of particles near the nozzle was observed by visual observation using the naked eyes and/or a camera under the above experimental conditions. It was decided based on this observation whether or not the particles could be successfully discharged from the nozzle.

The ultrasonic power applied to the liquid in this experimental apparatus was measured under the condition of \( V_0 \) and \( f \) by means of an ultrasonic sound pressure meter (SONIC SENSOR HUS-5, straight-typed probe, Honda Electronics, ibid.) using the following method. It was difficult to directly measure the ultrasonic power using the probe under the experimental conditions shown in Fig. 1. Therefore, the top cover of the rectangular vessel together with the set of parts affixed to the top cover, e.g., the glass and rubber tubes, was removed from the apparatus. The probe was inserted from the upper surface of the liquid, and the bottom of the probe was positioned at \( h=60\)mm, which corresponded to the top position of the particle collector of the glass tube (5). The indicated value of the ultrasonic sound pressure meter, \( V_{re} \) (mV), was read under the conditions of \( V_0 \) and \( f \), and was employed as a representative of ultrasonic power applied. Though the value of \( V_{re} \) doesn’t present the sound pressure itself, the relative degree of ultrasonic power applied can be inferred.

3. Results

3.1. Qualitative particle discharge characteristics

Fig. 2 shows the qualitative discharge characteristics of particles from the nozzle obtained through a
A series of observations of the particle behavior near the nozzle at $t \equiv -60s$. When discharging and no discharging of particles could be confirmed, the corresponding values of $N_i$ were presented in Fig. 2 as $N_i>0$ and $N_i=0$, respectively. Experimental conditions of A (Ex-A) and B (Ex-B) show the results obtained when ultrasonic power was applied at $0 \leq t \leq 560s$, and when ultrasonic power was not applied, i.e. only gravitational force was applied.

The qualitative discharge characteristics for Ex-A were classified into three cases of A1, A2, and A3, and those for Ex-B into two cases, B1 and B2, by considering $N_i$ at $t=60s$ and $t=560s$ (= in a steady state). The cases in A2 were further classified into two sub-cases, A2-1 and A2-2, and those in B-1 were classified into three sub-cases, B1-1 to B1-3, based on $N_i$ at $t \equiv -60s$.

In this paper, the qualitative discharge characteristics were divided into 4 cases based on the combinations (A1-A3/B1, B2) of Ex-A at $t \equiv 0$ and Ex-B at $t > 560s$ (= in a steady state): Case-1 (A1/B1), Case-2 (A2/B1), Case-3 (A3/B1), and Case-4 (A3/B2) as stated bellow.

- [Case-1]: no particles could be discharged from the nozzle under both conditions of Ex-A and Ex-B at $t \equiv -60s$ (A1, B1-1).
- [Case-2]: under the Ex-A conditions in the range of $t < 0$, no particles could be discharged (A2-1) or particles could be discharged only at $t = -60s$ (A2-2); in both cases of A2-1 and A2-2, however, particles could be discharged when the ultrasonic power was applied in the range of $0 \leq t \leq 560s$, while they stopped discharging after it was not applied ($t > 560s$).
- On the other hand, under the Ex-B conditions, particles could not be discharged at $t \equiv -60s$ (B1-1), or particles could be discharged only at $t = -60s$ in the range of $t < 0$. (B1-2)
- [Case-3]: under the Ex-A conditions, particles could always be discharged at $t \equiv -60s$ (A3); under the Ex-B conditions, particles could be discharged to the middle of $0 \leq t \leq 560s$, and subsequently could never be discharged (B1-3).
- [Case-4]: both under Ex-A and Ex-B conditions, particles could always be discharged at $t \equiv -60s$ (A3, B2).

Figs. 3a and 3b show the qualitative discharge characteristics of spherical and irregular particles based on their corresponding cases, Case-1 to Case-4, at the oscillation frequency $f = 25kHz$ for various particle diameters $d_p$ and the nozzle inside diameters $D_n$, respectively. The discharge characteristics of particles belonging to Case-1 in the small range of $D_n$ for any values of $d_p$, and for both spherical and irregular particles were found to shift from Case-2 to Case-3 or Case-4 as $D_n$ increases.

Figs. 3c and 3d show the results obtained by converting $D_n$ in the absissa of Figs. 3a and 3b into

<table>
<thead>
<tr>
<th>Case</th>
<th>Key</th>
<th>Experimental condition A (Ex-A)</th>
<th>Experimental condition B (Ex-B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>×</td>
<td>(A1)</td>
<td>(B1-1)</td>
</tr>
<tr>
<td>2</td>
<td>○</td>
<td>(A2-1)</td>
<td>(B1-1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(A2-2)</td>
<td>(B1-2)</td>
</tr>
<tr>
<td>3</td>
<td>▲</td>
<td>(A3)</td>
<td>(B1-3)</td>
</tr>
<tr>
<td>4</td>
<td>■</td>
<td>(A3)</td>
<td>(B2)</td>
</tr>
</tbody>
</table>

**Fig. 2** Particle discharge characteristics, Case-1 to Case-4, classified on the basis of the combination of respective $N_i$ variations (A1-A3 vs. B1 and B2) obtained under the experimental conditions, Ex-A and Ex-B.
It was found that the boundary value of $D_n/d_p$ between Case-1 and Case-2, $(D_n/d_p)_c$, was about 3.0, irrespective of $d_p$ and the particle shape. The value of $(D_n/d_p)_c=3.0$ obtained for the particles in the present apparatus was less than $(D_n/d_p)_c=4.5$ for dry particles which were discharged in air from circular orifices under the gravitational field [3, 5]. This indicates that when $d_p$ is constant, particles can be discharged through smaller-$D_n$ orifices under the ultrasonic field in liquid than under the gravitational field in air.

Hereafter, the experimental results are summarized only for Case-2 (A2-1, A2-2), Case-3 (A3), and Case-4 (A3, B2). In Case-2 (A2-1, A2-2), particles could be discharged by applying ultrasonic power ($0 \leq t \leq 560$s), while they could not be discharged without applying it ($t>560$s), as described above. In Case-3 (A3) and Case-4 (A3, B2), particles could always be discharged both with and without ultrasonic power.

### 3.2. Effects of operating conditions on particle discharge rate

Figs. 4a and 4b show representative photographs taken by camera when the spherical particles, Mat-Ms, were settling through the liquid in the particle collector of the glass tube after they had been discharged from the nozzle when $V_0=60$ and $320V_{pp}$, respectively. It can be seen that the particles were discharged from the nozzle somewhat intermittently, and that they tended to settle downwards while moving in the horizontal direction, and, therefore they were discharged from a nozzle in liquid with ultrasonic wave force.

**Fig. 3** Particle discharge characteristics (Case-1 to Case-4) obtained for particle diameter $d_p$ and nozzle inside diameter $D_n$.

<table>
<thead>
<tr>
<th>Key</th>
<th>Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\times$</td>
<td>1</td>
</tr>
<tr>
<td>$\bigcirc$</td>
<td>2</td>
</tr>
<tr>
<td>$\blacktriangle$</td>
<td>3</td>
</tr>
<tr>
<td>$\blacksquare$</td>
<td>4</td>
</tr>
</tbody>
</table>

Mat-Ms ($d_p=127\mu m$, Spherical)

$D_n=0.40\text{mm}$, $f=45\text{kHz}$, Case-2 (Shutter speed=1/500s)
persed throughout a broader section of liquid. The number of particles discharged from the nozzle per unit time using the larger \( V_0 (=320V_{p-p}) \) was higher than the number discharged using the smaller one \( (=60V_{p-p}) \) under these experimental conditions.

The behavior of particles near the inside wall of the nozzle was observed under the same conditions as in Fig. 4. The particles moved actively in the nozzle and were discharged from the nozzle. Consequently, the liquid under the nozzle flowed into the nozzle to replace the space of the particles higher up in the nozzle. The liquid flow resulted in the vertical circulation of particles in the nozzle.

Fig. 5 shows the representative relationships between the particle discharge rate \( N_i (s^{-1}) \) and the elapsed time \( t (s) \) with respect to spherical and irregular particles under two kinds of applied voltage \( V_0 \). Each broken line in Fig. 5 show the average value of \( N_i \), referred to as “average discharge rate \( \bar{N} (s^{-1}) \),” which is derived using the following equation.

\[
\bar{N} = \frac{1}{n} \sum_{i=1}^{n} N_i \quad (n=16)
\]  

The coefficient of variation \( CV \) (-) and the average mass discharge rate \( \bar{M} \) (kg·s\(^{-1}\)) in Fig. 5, and the standard deviation of \( N_i \)-distribution, \( s \) (s\(^{-1}\)), in Eq. (4), were calculated using the following equations.

\[
CV = \frac{s}{\bar{N}}
\]  

\[
\bar{M} = \rho f_d d_p^3 \bar{N}
\]  

\[
s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (N_i-\bar{N})^2} \quad (n=16)
\]

These results show that present apparatus was able to achieve a stable and continuous discharge of small amounts of particles, and that the \( \bar{N} \)-values varied for different applied voltages and particle shapes.

Figs. 6a–6c show the representative relationships

![Fig. 5 Representative results of discharge rate \( N_i \) through elapsed time \( t \)](image)

![Fig. 6 Relationships between average discharge rate \( \bar{N} \) vs. applied voltage \( V_o \), and calibration curves of \( V_o \) vs. \( V_e \) for each frequency \( f \)](image)
between the average discharge rate \( \bar{N} \) and the applied voltage \( V_0 \) at frequencies of \( f = 25, 45, \) and 100kHz.

The following tendencies can be observed. In Fig. 6a \( (f = 25\text{kHz}) \), \( \bar{N} \) increased with \( V_0 \) in the range of \( 50 \leq V_0 \leq 730 \text{V}_{\text{p-p}} \) and decreased with decreasing nozzle inside diameter \( D_n \). In contrast, in Fig. 6b \( (f = 45\text{kHz}) \), \( \bar{N} \) became larger in the order of \( D_n = 0.35, 0.45, \) and 0.40mm at a given \( V_0 \) in the range of \( V_0 \geq 200 \text{V}_{\text{p-p}} \). The relation between \( D_n \) and \( \bar{N} \) at \( f = 45\text{kHz} \) differed from that at \( f = 25\text{kHz} \). In Fig. 6c \( (f = 100\text{kHz}) \), the relationship between \( \bar{N} \) and \( V_0 \) was not linear, and the \( \bar{N} \)-values could not be controlled by \( V_0 \).

Figs. 7a–7c show the relations between the coefficient of variation \( CV \) and the applied voltage \( V_0 \) with respect to the results in Figs. 6a–6c. At \( f = 25\text{kHz} \) (in Fig. 7a), the \( CV \)-values at \( D_n = 0.35 \text{mm} \) were found to be larger than those at \( D_n = 0.40 \text{ and } 0.45 \text{mm} \) on the whole. This indicates, for example, that the discharge of particles can be achieved more stably at \( D_n = 0.40 \text{mm} \) than at \( D_n = 0.35 \text{mm} \). In contrast, at \( f = 45 \text{kHz} \) (in Fig. 7b), there were no significant variation in the \( CV \) among the three \( D_n \)-values when compared with \( f = 25\text{kHz} \).

As a result, it was confirmed that the effects of \( V_0 \) and \( D_n \) on the discharge characteristic indices, \( \bar{N} \) or \( CV \), depended on the frequency \( f \). The cause of these results seems to be that the behavior of particles in the nozzle became complicated because of the simultaneous actions based on the effects of the particle dispersion by the ultrasonic force and of the liquid circulation as observed in Fig. 4.

Hereafter, the effects of various operating conditions on the particle discharge rates, \( \bar{N} \), were investigated only at \( f = 25\text{kHz} \) because it was considered that \( \bar{N} \) could be more easily controlled by \( V_0 \) and \( D_n \) at \( f = 25\text{kHz} \) than at \( f = 45 \) or 100kHz.

Each solid line in Fig. 6 represents the calibration curve between the applied voltage \( V_0 \) and the corresponding indicated value measured by the ultrasonic sound pressure meter, \( V_{\text{re}} \) (mV). It can be seen that \( V_{\text{re}} \) was proportional to \( V_0 \) at \( f = 45 \) and 100kHz, and was almost proportional to \( V_0 \) at \( f = 25\text{kHz} \) only in the range of \( 0 \leq V_0 \leq 400 \text{V}_{\text{p-p}} \). The relations between \( \bar{N} \) and \( V_{\text{re}} \) at \( f = 25\text{kHz} \) were determined based on the calibration curve in Fig. 6a and were used hereafter.

Fig. 8 shows the discharge characteristics for spherical particles of 81 and 127\( \mu \text{m} \) in particle size \( d_p \). It can be seen in the range of smaller \( D_n \) (\( \leq 0.40 \text{mm} \): Case-2) that \( \bar{N} \) increased with \( V_{\text{re}} \) for both sizes of particles. In the range of larger \( D_n \) (\( \geq 0.50 \text{mm} \): Case-4), no obvious tendencies were found in the relation between \( \bar{N} \) and \( V_{\text{re}} \). A comparison of the results of \( D_n = 0.40 \text{mm} \) with these two particle sizes shows that the \( \bar{N} \)-values for 81\( \mu \text{m} \)-sized particles were greater than those for 127-sized ones.

Fig. 9 represents the discharge characteristics for irregular particles. For the particles of \( d_p = 81\mu \text{m} \) shown in Fig. 9a, \( \bar{N} \) increased along with \( V_{\text{re}} \) for the smaller \( D_n \) particles (\( \leq 0.40 \text{mm} \): Case-2). In contrast, \( \bar{N} \) decreased as \( V_{\text{re}} \) increased when \( D_n = 0.55 \text{mm} \) (Case-4). For the 127\( \mu \text{m} \)-sized particles shown in Fig. 9b, the relationships of \( \bar{N} \) vs. \( V_{\text{re}} \) under the conditions of small \( D_n \) (\( \leq 0.45 \text{mm} \): Case-2) and large \( D_n \) (\( = 0.67 \text{mm} \): Case-3) were similar to those for 81\( \mu \text{m} \)-sized particles shown in Fig. 9a.

The results shown in Figs. 8 and 9 indicate that
the discharge characteristics of particles from the nozzle in the present apparatus is dependent on the strength of the ultrasonic wave force $V_{re}$, the particle size $d_p$, the nozzle inside diameter $D_n$, and the particle shape.

4. Analysis

The effects of various factors on the average particle discharge rate $\bar{N}$ were quantitatively investigated based on the multiple regression analysis [4] as follows. The analysis was restricted to the results of $f=25$kHz and Case-2 (see Fig. 3).

First, it was assumed that $\bar{N}$ depends on the indicated value of the ultrasonic sound pressure meter, $V_{re}$, the nozzle inside diameter, $D_n$, the particle size $d_p$, and the representative value of particle shape index, $\psi_{50}$, and that the following equation holds true.

$$\bar{N} = a_0 V_{re}^{a_1} D_n^{a_2} d_p^{a_3} \psi_{50}^{a_4}$$ (7)

Taking logarithms of both sides yields the following linear equation,

$$\ln \bar{N} = \ln a_0 + a_1 \ln V_{re} + a_2 \ln D_n + a_3 \ln d_p + a_4 \ln \psi_{50}$$ (8)

where $\ln a_0$ is the constant term, and $a_1$-$a_4$ are partial regression coefficients.

The values of $\ln a_0$ and $a_1$-$a_4$ were estimated by multiple regression analysis on the basis of Eq. (8), and the following equation was obtained.

$$\bar{N} = 2.25 \times 10^{6} V_{re}^{0.35} D_n^{2.29} d_p^{-1.74} \psi_{50}^{1.07}$$ (9)

The dimension of each variable in Eq. (9) corresponds to $\bar{N}$ (s$^{-1}$), $V_{re}$ (mV), $D_n$ (mm), $d_p$ (µm), and $\psi_{50}$ ($-$).

Table 2 shows the results of the above analysis in detail. Every partial $F$ value for the corresponding partial coefficients satisfied the general criterion, $F \geq 2.0$. Therefore, it was statistically confirmed that the respective independent variables in Eq. (9) affected $\bar{N}$.

It was found that the power exponent, 2.29, of nozzle inside diameter $D_n$ in Eq. (9) was greater than the known values of 2.5 to 3.0 [3] when dry powders were discharged from a circular orifice in air, and was
included in the range of 2.0 to 2.5 when dry powders were discharged from capillary tubes vibrating at high [1] or ultrasonic frequencies [2] in air.

Fig. 10 shows the relationship between the estimated \( \bar{N} \)-values by Eq. (9), \( \bar{N}_{\text{cal}} \), and the experimental ones, \( \bar{N}_{\text{obs}} \). The multiple correlation coefficient \( R \) \( =0.828 \) was found to be comparatively large. The solid curves in Figs. 8 and 9 present the relationships of \( \bar{N}/L_{1152} \) vs. \( V_{\text{re}} \) as estimated by Eq. (9), and they are in agreement with the tendencies of the experimental ones.

The results estimated by Eq. (9) and the relationship between \( V_0 \) and \( V_{\text{re}} \) in Fig. 6a (calibration curve) prove that the larger the applied voltage \( V_0 \) and the nozzle inside diameter \( D_n \), or the smaller the particle diameter \( d_p \), the larger the average discharge rate \( \bar{N} \). Furthermore, as the shape index \( \psi_{50} \) approaches unity, that is, as the roughness of the particle surface declines, the \( \bar{N} \)-values increase.

Therefore, the present apparatus can be used as an effective wet microfeeder because it is possible to control the discharge rate \( \bar{N} \) for given particles of shape index \( \psi_{50} \) and size \( d_p \) by appropriate selection of the nozzle inside diameter \( D_n \) and the voltage that is applied to the ultrasonic transducers \( V_0 \).

5. Conclusion

A wet microfeeder that utilizes ultrasonic wave force in liquid was developed, and the discharge characteristics of small particles from a nozzle were experimentally investigated. As a result of these experiments, the following were confirmed.

(1) The critical ratio of particle blockage in the present wet microfeeder (\( (D_n/d_p)_c \approx 3.0 \) \( ) \), was smaller both for spherical and irregular particles than that previously obtained in the gravitational field for dry powders. The index \( (D_n/d_p)_c \) denotes the ratio of the nozzle inside diameter \( D_n \) to particle diameter \( d_p \) where particles begin to block up the nozzle.

(2) It was possible to continuously and stably discharge small particles of about 80 to 180 \( \mu \)m in diameter using the present feeder.

(3) Multiple regression analysis at a frequency of \( f=25\text{kHz} \) proved the following facts. The average discharge rate, that is, the number of particles discharged from the nozzle per of unit time, \( \bar{N} \), was dependent on the applied voltage to the ultrasonic transducers \( V_0 \), the nozzle inside diameter \( D_n \), the median value of the particle shape index (surface roughness, \( \psi_{50} \)), and the particle diameter \( d_p \). The \( \bar{N} \)-value was proportional to \( D_n^{2.29} \). Therefore, it was possible to control \( \bar{N} \) by adjusting the parameters \( V_0 \) and \( D_n \).

Nomenclature

\( A_p \) : area of a particle image \( (\text{m}^2) \)
\( a_0 \) : constant in Eq. (7) \( (\text{–}) \)
\( a_1 \sim a_4 \) : partial regression coefficients defined in Eq. (8) \( (\text{–}) \)
CV coefficient of variation (Eq. (4))

$D_n$ inside diameter of nozzle tip (m)

$(D_{o/d_p})_c$ critical ratio of outlet diameter to particle diameter

$d_p$ average particle diameter (m)

$F$ partial F-value

$f$ oscillation frequency (Hz)

$h$ vertical distance from the inner bottom of rectangular vessel (see Fig. 1) (m)

$M_v$ mass of particles sampled for $f_v$-measurement (kg)

$\bar{M}$ mass of discharged particles per unit of time (Eq. (5)) (kg·s$^{-1}$)

$N_i$ discharge rate (number of discharged particles per unit of time) obtained from i-sample (s$^{-1}$)

$\bar{N}$ average discharge rate (Eq. (3)) (s$^{-1}$)

$N_v$ number of particles sampled for $f_v$-measurement

$n$ number of samples

$p$ perimeter of a particle image (m)

$R$ multiple correlation coefficient

$t$ elapsed time (s)

$V_0$ voltage applied to ultrasonic transducer (peak to peak value) (V)

$V_{re}$ indicated value of ultrasonic sound pressure meter (mV)

$\gamma$ partial correlation coefficient

$\rho_p$ true density of particles (kg·m$^{-3}$)

$s$ standard deviation of $N_i$-distribution

$y$ shape index defined as surface roughness (Eq. (1))

$y_{50}$ median value of $y$-distribution

$f_v$ volume shape factor (Eq. (2))

References


Author’s short biography

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Dr. Kenichi Yamamoto worked as an Associate Professor of the Department of Material Systems Engineering and Life Science at Toyama University from 1997 through 2002, and he has been a Professor at the same institution since 2002. He received his doctorate degree in 1994 from Osaka Prefecture University. His main fields of research are particle shape analysis, shape separation, solid mixing, and segregation. His current research activities are focused on the development of equipment such as a wet shape separator, a microfeeder, a useful resource separator, and a 3-D particle shape analyzer.

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Mitsue Shiokari received her BE and ME degrees from the Department of Materials Science and Engineering at Toyama University in 2001. After graduating, she began working at Sugino Machine Limited as a research and design engineer. Her main interest is the research and development of machines for particle micronization.
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Dr. Masunori Sugimoto was previously a Professor of the Chemical Engineering Department (1979-1990), and of the Materials Science and Engineering Department (1990-2002) at Toyama University. He received his doctorate degree in 1971 from Nagoya University. He is currently a Professor Emeritus at Toyama University. His major research interests are solid mixing and segregation, particle shape characterization and separation, and particle design with granulation. His current research activities are focused on the development of a continuous granulation process by simultaneous operation of granulation, grinding, and separation using the segregation behavior of particles passing through a rotating vessel, and the formation of small composite granules.