

Fig. 3. Correlation of aeration factor.

ζ_d = resistance coefficient due to gas
 $= k\{[1 - F_s(1 - \tau)]^2 + 0.4[1.25 - F_s(1 - \tau)]\}$ [—]
 ζ_l, ζ_σ = resistance coefficient due to liquid and surface tension [—]
 μ_g, μ_l = viscosity of gas and liquid [Pa·s]

ρ_g, ρ_l = density of gas and liquid [kg/m³]
 σ = surface tension [N/m]
 τ = ratio of hole area of dropping liquid flow per total hole area of a sieve tray [—]

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CRITICAL GAS VELOCITY REQUIRED FOR COMPLETE SUSPENSION OF MULTICOMPONENT SOLID PARTICLE MIXTURE IN SOLID-SUSPENDED BUBBLE COLUMNS WITH AND WITHOUT DRAUGHT TUBE

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Introduction

To design a solid-suspended bubble column for liquid-solid batch operation as a slurry reactor, the value of the critical gas velocity U_c required for complete suspension of solid particles should be known. A few research works on U_c for solid particles with a narrow size distribution (called here single-component particles) have been done by using a

column with a draught tube^{3,7,9)} and without it.^{1,2,4-6,10-12)} However, no research work has been done on U_c for multicomponent solid particle mixtures, e.g., solid particles with a wide size distribution or a mixture of solid particles of different materials.

The purpose of this study is to clarify experimentally the effects of column dimensions, properties of the solid particles and composition of the solid mixture on the critical gas velocity required for complete suspension of the multicomponent solid particle mixture in solid-suspended bubble columns with and without a draught tube in liquid-solid batch

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operation.

1. Experimental

Two kinds of plexiglass columns with a conical bottom having a cone angle of $\pi/3$ rad were used: one with a draught tube and the other without it. Details of the experimental setups are shown elsewhere.^{3,4)} The dimensions of the columns and the perforated plates used as gas distributors are shown in **Table 1**.

The liquid used in this work was demineralized water, and the gas used was air. The height of the static slurry above the gas distributor was 1.54 m. The operating temperature was kept at 298.2 ± 0.5 K. **Table 2** shows the physical properties of glass spheres. The methods of determining the particle diameter d_p and the terminal velocity V_t of a single particle in stagnant liquid are shown elsewhere.^{3,4)} The average concentration c of solid particles was $100 \text{ kg} \cdot \text{m}^{-3}$. Table 2 also shows binary and ternary particle mixtures used in the experiment. The weight fraction x of the solid particles having the largest value of V_t in the multicomponent particle mixture was varied in the range of 0–1.

The methods of determining U_c are the same as those reported in the previous paper³⁾: pressure drop measurement and visual observation.

2. Results and Discussion

2.1 Determination of U_c

After air was dispersed into the column at a velocity sufficient to suspend all particles, the gas velocity U_G was gradually lowered. Then, at a certain gas velocity the particles (the L-particles) having the largest value of V_t in the multicomponent particle mixture began to settle down on the periphery of the gas distributor. When U_G was decreased further, particles having smaller value of V_t began to settle down on the layer of L-particles. Pressure-drop measurement and the visual observation showed that the previous method³⁾ of determining U_c value from the total pressure drop due to the suspended solids vs. U_G curve was also applicable to the slurry of multicomponent particle mixtures.

2.2 Bubble column with draught tube

Figure 1 shows that the ratio of flow path area ($\pi D_{io}L$) under the lower end of the draught tube to the cross-sectional area ($\pi D_o^2/4$) of the column has no effect on U_c in the range of this ratio larger than about 0.4 for either the single-component particles or the binary-particle mixture.

Figure 2 shows that the degree of reducing U_c values with decreasing D_d/D_o for the binary-particle mixture is similar to that for the single-component particles.

Figure 3 shows that U_c at a constant value of c has a minimum value at $D_i/D_o \approx 0.6$. **Figures 4** and **5** show

Table 1. Experimental apparatus

Column: $D_o = 0.014$ m and 2.30 m high
Draught tube: $D_i = 0.066, 0.082, 0.094$ and 0.104 m, $t_w = 3$ mm, $H = 1.40$ m and $L = 0.015$ – 0.05 m
Perforated plates*:
P1; $D_d = 0.035$ m, $\delta = 3$ mm and $n = 3$
P2; $D_d = 0.050$ m, $\delta = 3$ mm and $n = 7$
P3; $D_d = 0.070$ m, $\delta = 3$ mm and $n = 7$
P4; $D_d = 0.140$ m, $\delta = 1$ mm and $n = 55^{**}$

* Covered with a stainless steel wire gauze of 260–300 mesh.

** Used only for the column without draught tube.

Table 2. Properties of solid particles

Materials	Abbrev.	d_p [μm]	$V_t \times 10^2$ * [$\text{m} \cdot \text{s}^{-1}$]
Glass sphere	200 G	200	2.47
$\rho_p = 2500 \text{ kg} \cdot \text{m}^{-3}$	106 G	106	0.943
	79 G	79.0	0.555
High index glass sphere	79 HG	79.0	1.25
$\rho_p = 4680 \text{ kg} \cdot \text{m}^{-3}$			

Binary component solid particles:

200 G – 106 G, 200 G – 79 G and 200 G – 79 HG

Ternary component solid particles:

200 G – 106 G – 79 G ($c_2/(c_2 + c_3) = 0.26$)**

* V_t in water at 298.2 K.

** c_2, c_3 : solid concentrations of 106 G and 79 G, respectively.

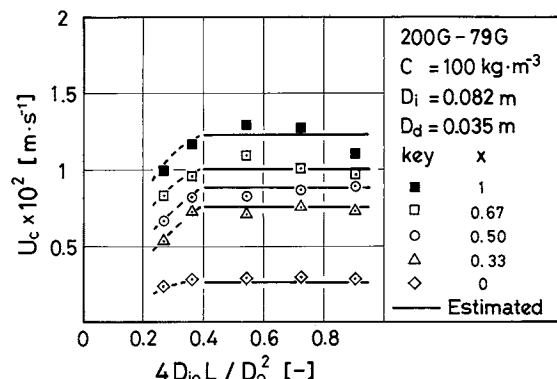


Fig. 1. Effect of flow path area under lower end of draught tube on U_c .

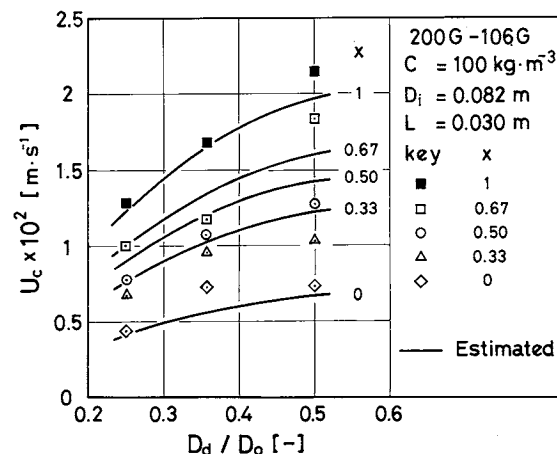


Fig. 2. Effect of shape of conical bottom on U_c .

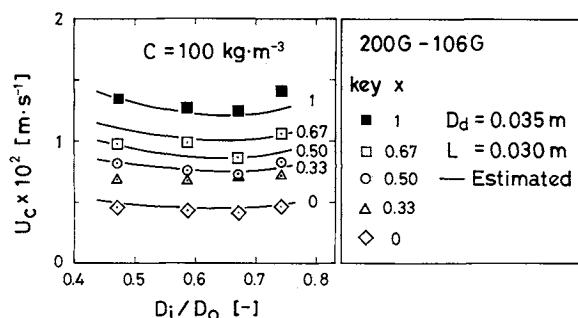


Fig. 3. Effect of inner diameter of draught tube on U_c .

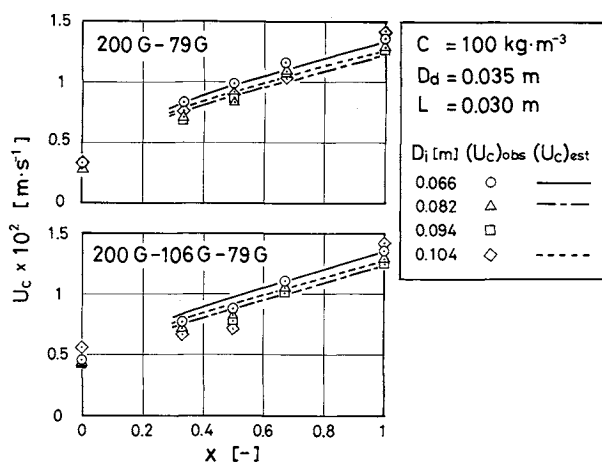


Fig. 4. Effect of x on U_c .

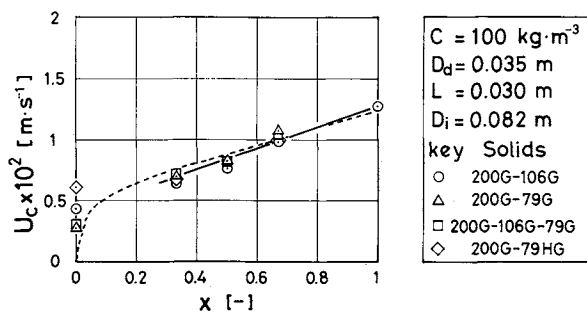


Fig. 5. Effect of x and properties of solid particles other than L-particles on U_c . Dotted line: $(U_c)_{est}$.

that U_c increases almost linearly with x . Figure 5 shows also that the properties of solid particles other than the L-particles have almost no effect on U_c in the range of $x \geq 0.33$.

1) Method of estimating U_c value Visual observation shows that at $U_G \approx U_c$ the L-particles tend to settle along the conical bottom and the other particles are suspended, and that their properties have almost no effect on U_c as shown in Fig. 5. Therefore, U_c values for the multicomponent particles were estimated by Eq. (A-1) in Appendix, the correlation for U_c of the single-component particles,³⁾ with the following assumptions.

(1) The L-particles settle in the liquid with density of ρ_{SL} and viscosity of μ_{SL} .⁸⁾

$$\rho_{SL} = \rho(1 - \varepsilon_p) + \bar{\rho}_p \varepsilon_p \quad (1)$$

$$\mu_{SL} = \mu \left[1 + \frac{3}{\frac{1}{\varepsilon_p} - \frac{1}{0.52}} \right] \quad (2)$$

(2) The solid concentration c_1 of the L-particles and their terminal velocity in the liquid with density of ρ_{SL} and viscosity μ_{SL} are used, respectively, as the solid concentration and the terminal velocity in Eq. (A-1).

The estimated values of U_c are compared with the experimental ones in Figs. 1–5. The error of estimation was within 14% for 60 data. Figure 5 shows that the properties of solid particles other than the L-particles might affect the U_c value if x approaches zero, and so the model proposed here might not be valid in such a range of x . Further work is necessary in this respect. As this model is examined only by the data taken at $c = 100 \text{ kg} \cdot \text{m}^{-3}$ for $200 \mu\text{m}$ glass spheres as the L-particles, further experimental work regarding U_c in which the solid concentration and the kind of the L-particles are changed is also necessary.

2.3 Bubble column without draught tube

Figure 6 shows that U_c increases with increasing x and D_i/D_o values. A similar method to that stated in the preceding section was used to estimate U_c values of the binary particle mixture. In this case the correlation of U_c of single-component particles in a bubble column without draught tube⁴⁾ was used instead of the correlation of U_c used in the preceding section.³⁾ Figure 6 shows that $(U_c)_{est}$ agrees relatively well with $(U_c)_{obs}$.

Conclusions

1) The effects of column dimensions on the critical gas velocity U_c required for complete suspension of multicomponent solid particles in a bubble column with draught tube are similar to those on U_c of single-component solid particles. U_c decreases with decreasing weight fraction of the solid particles (L-particles) having the largest value of V_t among the solid particles used, and the properties of particles other than the L-particles have almost no effect on U_c in the range of $x \geq 0.33$. Based on these observations is proposed a method to estimate U_c value of a multicomponent solid particle mixture by utilizing the correlation for U_c of the single-component solid particles.

2) A similar method as stated above is applicable to estimate U_c values of multicomponent solid particles in a bubble column without draught tube.

Appendix

The correlation for U_c of the single component particles is given by Eq. (A-1),³⁾

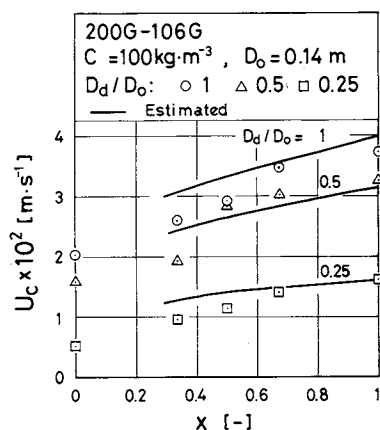


Fig. 6. Effect of x and shape of bottom on U_c in bubble column without draught tube.

$$\begin{aligned} \frac{U_c}{V_t} = & 4.60 \left(\frac{c}{\rho_p} \right)^{0.273} \left(\frac{\rho_p - \rho}{\rho} \right)^{0.750} \left(\frac{V_t \mu}{\sigma} \right)^{-0.634} \\ & \times \left(\frac{D_o^2 g \rho}{\sigma} \right)^{-0.340} \left(\frac{S_o}{S_a} \right)^{0.546} \left(\frac{S_o}{S_i} \right)^{0.454} \\ & \times \left\{ 1 + 897 \left(\frac{g \mu^4}{\rho \sigma^3} \right)^{0.290} \right\} \\ & \times \left\{ \left(\frac{V_t}{\sqrt{gH}} \right) + 1.47 \times 10^{-4} \left(\frac{H}{D_o} \right) \right\} \\ & \times \left\{ 1 - 1.32 \left(1 - \frac{D_d}{D_o} \right)^{0.997 (D_o^2 g \rho / \sigma)^{0.172}} \right\} \end{aligned} \quad (A-1)$$

where g is gravitational acceleration and σ liquid surface tension, and S_a , S_i and S_o , respectively, are the cross-sectional areas of annulus, draught tube and column.

Nomenclature

c	= average solid concentration in gas-free slurry	[kg·m ⁻³]
c_j	= concentration of j -th component of solid mixture ($j=1-N$, where 1 refers to L-particles) in gas-free slurry	[kg·m ⁻³]
D_d	= diameter of gas distributor	[m]
D_i	= inner diameter of draught tube	[m]
D_{io}	= $D_i + 2t_w$, outer diameter of draught tube	[m]
D_o	= diameter of column	[m]
d_p	= diameter of solid particle	[m]
H	= length of draught tube	[m]
L	= vertical clearance between lower end of draught tube and wall of conical bottom	[m]
N	= number of components of solid mixture	[m]
n	= number of holes in gas distributor	[m]
t_w	= wall thickness of draught tube	[m]

U_c	= critical gas velocity based on cross section of column required for complete suspension of solid particles	[m·s ⁻¹]
U_G	= gas velocity based on cross section of column and on static pressure on gas distributor	[m·s ⁻¹]
V_t	= terminal velocity of single particle in stagnant liquid	[m·s ⁻¹]
x	= c_1/c , weight fraction of L-particles	[—]
δ	= diameter of holes in gas distributor	[m]
ε_p	= volume fraction of solid particles in gas and L-particles free slurry	[—]
μ	= liquid viscosity	[Pa·s]
μ_{SL}	= viscosity of gas- and L-particles free slurry	[Pa·s]
ρ	= liquid density	[kg·m ⁻³]
ρ_p	= density of solid particle	[kg·m ⁻³]
$\bar{\rho}_p$	= average density of solid particles in gas- and L-particles free slurry	[kg·m ⁻³]
ρ_{SL}	= density of gas- and L-particles free slurry	[kg·m ⁻³]

<Subscripts>

est	= estimated value	
j	= j -th component of solid mixture ($j=1-N$); 1 refers to L-particles	[—]
obs	= observed value	

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