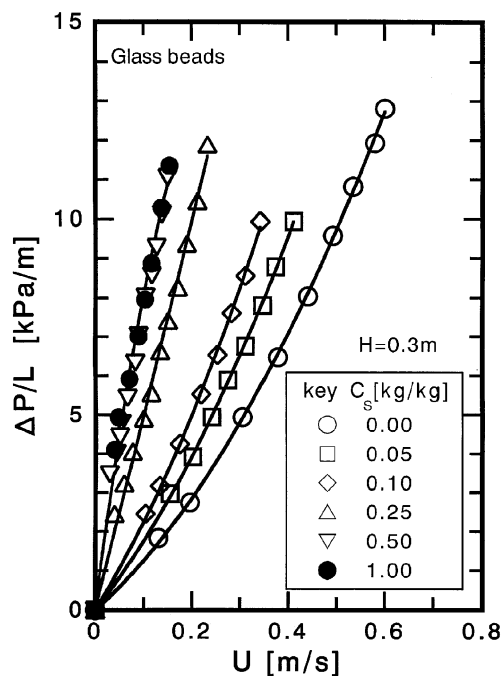


Table 1. Experimental conditions

Column			
Inside diameter	D_T [m]	:	0.10
Nozzle diameter	D_o [m]	:	0.012
Cone angle	θ [deg.]	:	60
Draft tube (material : brass)			
Inside diameter	D_D [m]	:	0.012, 0.014, 0.018
Tube length	L_D [m]	:	0.3
Distance of entrainment zone	H_D [m]	:	0.02, 0.03, 0.04
Particle (Glass beads)			
Diameter	D_p [μm]	:	1351, 477
Density	ρ_p [kg/m^3]	:	2480
Mass fraction of finer particles	C_s [kg/kg]	:	0.00, 0.01, 0.03, 0.05, 0.10, 0.15, 0.25, 0.50, 0.75, 1.00

draft tubes of 12, 14 and 18 mm ID were employed, and the distance of the entrainment zone H_D was changed from 20 to 40 mm. Two different sizes of glass beads were used. The coarser particle had a mean particle diameter of 1,351 μm and the finer particle was 477 μm in size, therefore the ratio of the both particle diameters was 2.83. About 3 kg of binary particle mixtures, of which the average mass fraction of finer particles C_s were eight kinds as shown in Table 1, were spouted at a given gas velocity.

As shown in Fig. 1, pressure taps were attached for measuring the total bed pressure drop ΔP_s , the pressure drop within the draft tube ΔP_D and the pressure drop of the annulus ΔP_A , respectively. ΔP_s , ΔP_D and ΔP_A were measured with digital ma-

**Fig. 2. Relationship between $\Delta P/L$ and U as a parameter of C_s for loose packed bed.**

nometers. Here ΔP_A was used to calculate the gas velocity through the annulus U_A . A relation between the pressure drop and the gas velocity for the annulus was found from the measurements under the state of the loose packed bed for each C_s , as shown in Fig. 2. The experimental data can be approximated by these quadratic equations, so the equations on ΔP and U were determined by the second nominal approximation for the each average mass fraction of finer particles. For example, in the case of $C_s=0.05$, the following equation was used:

$$\Delta P_A/L = 16.2U_A + 18.8U_A^2 \quad (1)$$

Moreover, the mass balance of gas for a spouted bed with a draft tube is introduced as follows:

$$Q_T = U \cdot A_T = U_A \cdot A_A + U_D \cdot A_D \quad (2)$$

where Q_T is total gas flow rate, U is superficial gas velocity in column and U_D is superficial gas velocity in draft tube.

On the other hand, before a spouted bed with a draft tube can be used as a stable efficient solid-gas contacting reactor, the solids circulation rate W_s and the hold-up of solid particles within the draft tube ($1-\epsilon_D$) must be known since these two parameters are directly concerned in the state of spouting. W_s is calculated from the mass balance of particles in the annulus as shown in Eq. (3) by using the experimental value of particle velocity within the annulus V_{PA} , and V_{PA} could easily be measured by visually following the particles at the transparent wall of the annulus and by determining the average time required for a tracer particle to descend a fixed distance ($=0.05$ m) by using a stopwatch.

$$W_s = (1-\epsilon_A)\rho_p \cdot A_A \cdot V_{PA} \quad (3)$$

At the same time, the local velocity of particles within the draft tube V_{PS} was measured by an optical fiber probe method as shown in Fig. 1. The probe consisted of three optical fibers of 1,000 μm diameter. The central fiber guided illuminating light to moving particles and the others guided the reflected light from particles to each photomultiplier. V_{PS} was calculated by using the following equation:

$$V_{PS} = l/\tau_m \quad (4)$$

where l is effective distance between light detecting fibers and τ_m is average lag time calculated by FFT analyzer. l in Eq. (4) was calibrated as $l=1.016$ mm. The hold-up of solid particles within the draft tube ($1-\epsilon_D$) was determined from Eq. (5) based on mass balance of particles within a draft tube by using the measured value of V_{PS} and W_s calculated from Eq. (3).

$$(1-\epsilon_D) = W_s / (\rho_p \cdot A_D \cdot V_{PS}) \quad (5)$$

EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 3 shows the typical pressure drop-flow rate curves for fluidization (F. B.), and spouting without a draft tube (C. S. B.) and with a draft tube (D. S. B.). This figure shows that ΔP_s of D. S. B. is lower than those of the others, and also minimum spouting velocity U_{ms} of D. S. B. is much lower than those of the others. Therefore, D. S. B. has a considerable advantage

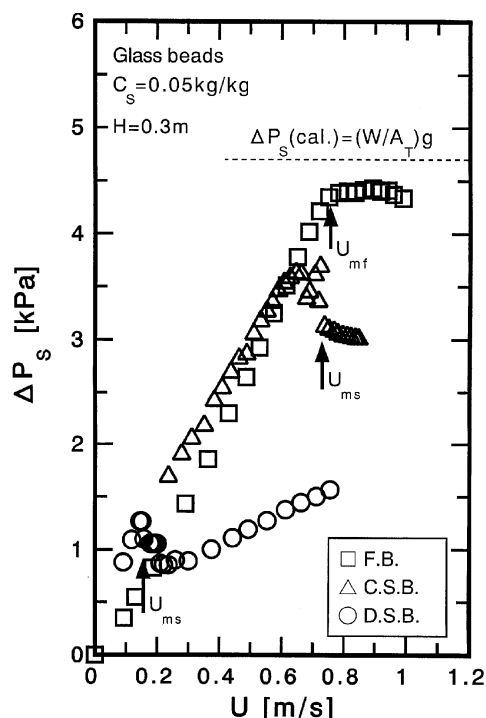


Fig. 3. Typical pressure drop-flow rate curves for fluidization, and spouting without and with a draft tube.

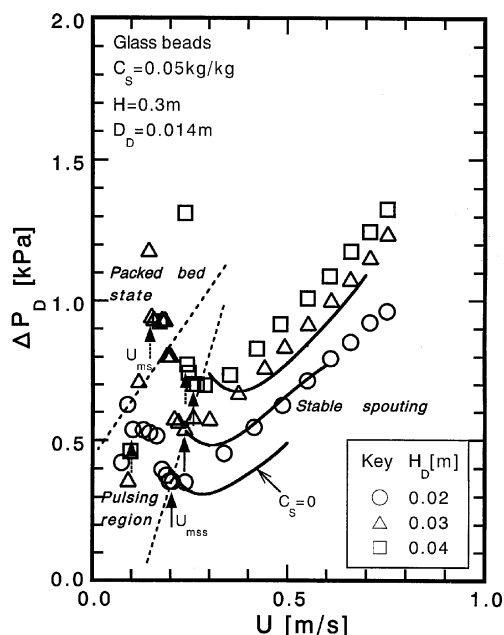


Fig. 4. Relationship between ΔP_D and U as a parameter of H_D .

from the view point of utilities such as the running costs.

Fig. 4 shows a representative ΔP_D versus superficial gas velocity in column U for the case of the mass fraction of finer particles $C_s = 0.05$, with the distance of the entrainment zone H_D as a parameter. The ΔP_D indicates the pressure drop due to solid particles within a draft tube. This figure shows that ΔP_D decreases with decrease in U for the stable spouting region. When the spouting state changes from the stable spouting region into the pulsing region, ΔP_D has a minimum value at the transitional

point. The gas velocity at the point was defined as the minimum stable spouting velocity U_{ms} . The U_{ms} is very important for the actual stable spouting operation with a draft tube. Furthermore, when the spouting state changes from the pulsing region into the packed bed region, the transitional point is regarded as minimum spouting velocity U_{ms} . That is, the U_{ms} was defined as the velocity at a point where a slight reduction of gas velocity caused solid particles within a draft tube to clog and at the same time the pressure drop rose suddenly. It was found that both ΔP_D and U_{ms} increases with increases in H_D . The reason for this is that the gas flow rate through the annulus increases with increasing H_D . ΔP_D for $C_s = 0.05$ is higher than that for $C_s = 0$ and also U_{ms} for $C_s = 0.05$ is lower than that for $C_s = 0$ because of the decreases of the void fraction within the annulus ϵ_A . This figure shows that the behavior of both gas and solid particles within the draft tube is similar to that for vertical pneumatic conveying.

Fig. 5 shows the effects of the mass fraction of finer particles C_s on U_{ms} . It was also found that U_{ms} decreases with increasing C_s , and this trend is remarkable in the range of $C_s = 0-0.3$, because of marked decreases in the void fraction within the annulus ϵ_A at the same range of C_s . This phenomenon is similar to the one that was observed in the conventional spouted bed [Ishikura et al., 1982].

Fig. 6 indicates the effect of C_s on U_A and the gas velocity within the draft tube U_D . U_D can be calculated from Eq. (2). U_A decreases and U_D increases with increases in C_s . In this experiment, it was found that U_A is lower than U_{mf} and so the annulus region is a state of moving bed.

Fig. 7 indicates the relationship between the gas flow rate through the annulus Q_A/Q_T and the total gas flow rate Q_T with H_D as a parameter. Q_A/Q_T increases with decreases in Q_T and with increases in H_D . This is because the gas jet expands with increasing H_D . Q_A/Q_T for $C_s = 0.05$ are lower than that for $C_s = 0$ for every condition because of the decreases of the void frac-

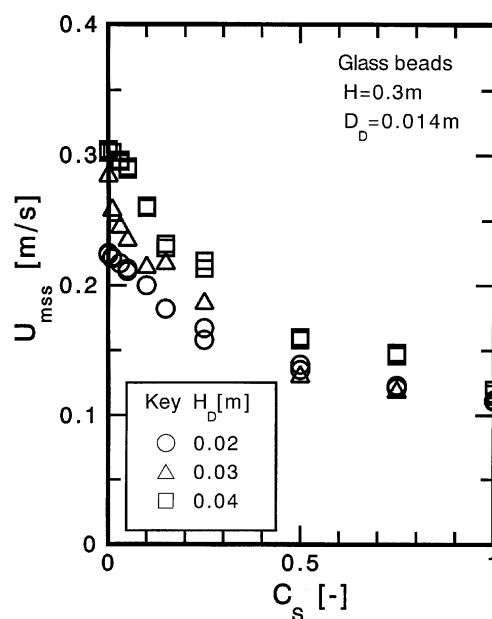
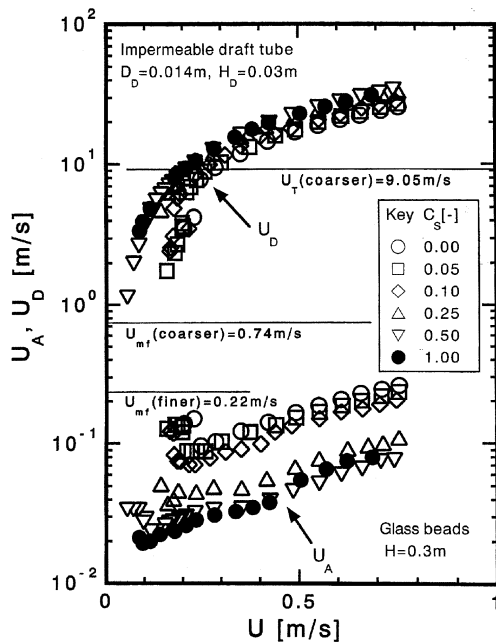
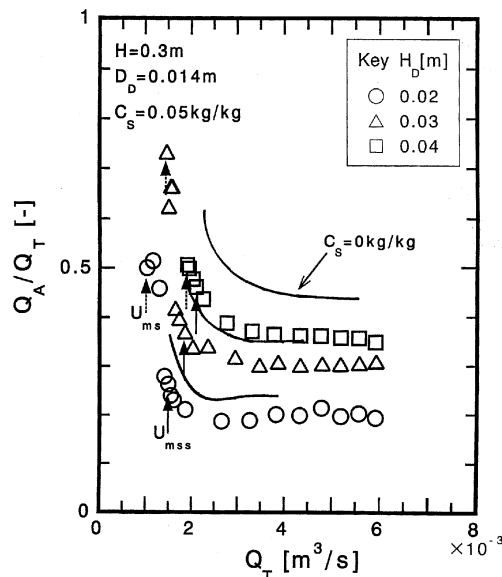


Fig. 5. Effect of C_s on U_{ms} .

Fig. 6. Effect of C_s on both U_A and U_D .Fig. 7. Relationship between Q_A/Q_T and Q_T as a parameter of H_D .

tion within the annulus ϵ_A .

Fig. 8 indicates the effect of draft tube diameter D_D on Q_A/Q_T . Q_A/Q_T increases with decreases in D_D and also Q_A/Q_T for $C_s=0.05$ are lower than that for $C_s=0$ for every condition.

Fig. 9 shows the effects of both U and C_s on W_s . W_s was measured by observing carefully coarser particles except in the case of $C_s=1$. When C_s is low, that is, $0 \leq C_s \leq 0.1$, W_s increases monotonously with U . But when C_s reaches to 0.25, W_s has a maximum value at $U \approx 0.2$ m/s, as in the case of the patterns of the solids circulation that have been observed for fine particles [Ijichi et al., 1996], and W_s has a minimum value at $U \approx 0.4$ m/s. W_s for finer particle is lower than that for binary mixtures. It is considered that W_s is influenced significantly by the behavior of both gas and particles within the entrainment zone.

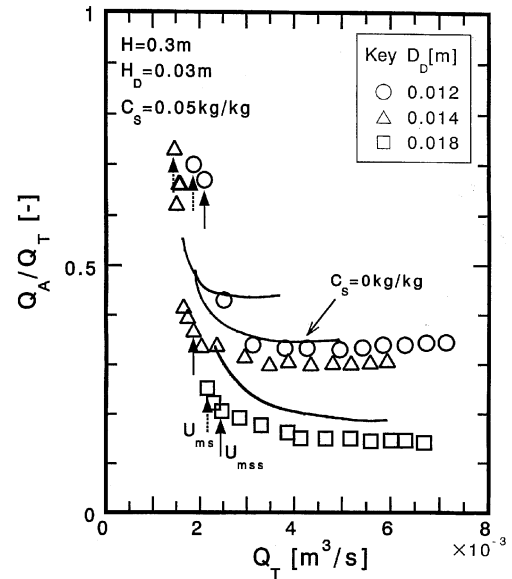
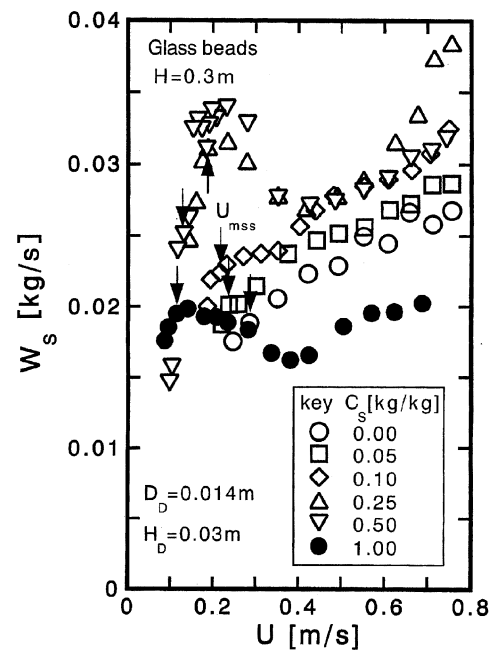
Fig. 8. Relationship between Q_A/Q_T and Q_T as a parameter of D_D .Fig. 9. Relationship between W_s and U as a parameter of C_s .

Fig. 10 shows the effects of both superficial gas velocity in draft tube U_D and C_s on total pressure drop within the draft tube ΔP_{DT} and $(1-\epsilon_D)$. $(1-\epsilon_D)$ were calculated from the mass balance within a draft tube as shown in Eq. (5), using V_{ps} that was measured by the optical fiber probe. It is recognized that $(1-\epsilon_D)$ has little difference for the comparison of $C_s=0$ and 0.05, as in the case of ΔP_{DT} . The kinetic energy of particles decreases with decreases in U_D ; therefore, ΔP_{DT} decreases with decreases in U_D within the stable spouting region. Moreover, after ΔP_{DT} reaches a minimum value, ΔP_{DT} increases inversely with decreasing U_D . As U_D decreases further, $(1-\epsilon_D)$ increases remarkably. Furthermore, when $(1-\epsilon_D)$ reaches about 0.04, the behavior of particles within the draft tube can not maintain the stable pneumatic con-

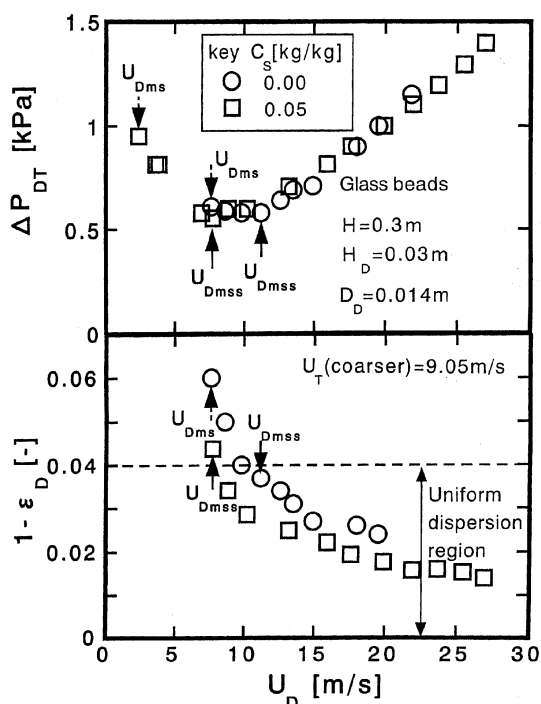


Fig. 10. Effect of U_D on both ΔP_{DT} and $(1-\epsilon_D)$.

veying state.

CONCLUSIONS

The following conclusions were drawn for binary mixtures of particles :

The minimum stable spouting velocity decreases with increases in the mass fraction of finer particles, and decreases with decreases in the distance of the entrainment zone. The gas flow rate through the annulus decreases with increases in the mass fraction of finer particles. The effect of the gas velocity on the solids circulation rate indicates complicated change with the mass fraction of finer particles.

It is important to understand clearly the behavior of gas and particles within the draft tube to maintain a stable spouting.

NOMENCLATURE

A_A	: cross-sectional area of annulus [m^2]
A_D	: cross-sectional area of draft tube [m^2]
A_T	: cross-sectional area of column [m^2]
C_s	: average mass fraction of finer particles [kg/kg]
D_D	: inside diameter of draft tube [m]
D_o	: inlet nozzle diameter [m]
D_p	: mean particle diameter [μm]
D_T	: column diameter [m]
g	: gravitational acceleration [m/s^2]
H	: depth of spouted bed [m]
H_D	: distance from gas inlet nozzle to bottom of draft tube (=distance of entrainment zone) [m]
L	: distance between pressure taps in annulus [m]
l	: effective distance between light detecting fibers [m]

Q_A	: gas flow rate through annulus ($=U_A \cdot A_A$) [m^3/s]
Q_T	: total gas flow rate ($=U \cdot A_T$) [m^3/s]
U	: superficial gas velocity in column [m/s]
U_A	: superficial gas velocity through annulus [m/s]
U_D	: superficial gas velocity in draft tube [m/s]
U_{mf}	: minimum superficial gas velocity for fluidization [m/s]
U_{ms}	: minimum superficial gas velocity for spouting [m/s]
U_{mss}	: minimum superficial gas velocity for stable spouting [m/s]
U_T	: terminal velocity for a single particle [m/s]
V_{PA}	: particle velocity within annulus [m/s]
V_{PS}	: local particle velocity within draft tube [m/s]
W	: particle bed mass [kg]
W_S	: solids circulation rate [kg/s]

Greek Letters

ΔP_A	: pressure drop within annulus [kPa]
ΔP_D	: pressure drop due to solid particles within draft tube [kPa]
ΔP_{DT}	: total pressure drop within draft tube [kPa]
ΔP_S	: total bed pressure drop [kPa]
ϵ_A	: void fraction within annulus [-]
$(1-\epsilon_D)$: hold-up of solid particles within draft tube [-]
θ	: cone angle [deg.]
ρ_p	: particle density [kg/m^3]
τ_m	: average lag time [s]

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