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# Hydrodynamics of a Spouted Bed with an Impermeable Draft Tube for Binary Particle Systems

**Hiroshi Nagashima†, Toshifumi Ishikura and Mitsuharu Ide**

Department of Chemical Engineering, Fukuoka University, Fukuoka 814-0180, Japan
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**Abstract**–A spouted bed with an impermeable draft tube was employed to obtain fundamental data of binary mixtures of glass beads for both the operating conditions and the design factors. These data were compared with those for the coarser particle system only. From this view point, minimum spouting velocity, pressure drop, hold-up of solid particles within a draft tube, upward gas flow rate within the annulus and solids circulation rate were determined by changing the total gas flow rate and mass fraction of finer particles as operating parameters and by changing distance of entrainment zone and draft tube diameter as geometric parameters.

Key words : Spouted Bed, Draft Tube, Binary Particle System, Minimum Spouting Velocity, Annulus Gas Flow Rate, Solids Circulation Rate

## INTRODUCTION

Conventional spouted bed (C.S.B.) technology in solid-gas system [Mathur and Epstein, 1974] has proven to be an effective means of contacting for gas and coarse solid particles such as Geldart type D materials. In addition, spouted bed in solid-liquid system has been studied [Kim, 1984, 1985; Kim and Ha, 1986]. Moreover, the insertion of an axially positioned draft tube into the conventional spouted bed has shown potential advantages due to the stability and the flexibility.

In 1997, Hatate et al. made a review on flow characteristics of draft tube spouted bed and its application; that is, many papers have been written on particle circulation [Yoshida et al., 1997; Song et al., 1998] and spouting of fine particles [Ijichi et al., 1996], and furthermore on unique flow characteristics with modified fluid inlet [Hattori and Nagai, 1996] or modified fluid outlet [Kim, 1990]. A recent trend in the development of its technology has been the application of spouting with a draft tube to a wide variety of chemical processes including coal gasification [Hatate et al., 1996], pneumatic conveying [Milne et al., 1992; Ijichi et al., 1998], particle design of pharmaceuticals [Fukumori and Ichikawa, 1997; Littman et al., 1997], drying [Khoe and Brakel, 1983], blending and so on.

On the other hand, for these applications, particle segregation in the bed is of practical importance. For the conventional spouted bed of binary mixtures of particles, Ishikura et al. [1982], Uemaki et al. [1983] and Anabtawi [1998] determined the effect of the mass fraction of finer particles on the minimum spouting velocity, and on particle segregation [Grace et al., 1983]. However, little research has been done [Ishikura et al., 1998] on a spouted bed with a draft tube for binary particle systems.

Therefore, in this study, a spouted bed with an impermeable draft tube was employed to obtain fundamental data consisting of finer and coarser glass beads for both the operating conditions and the design factors, and these data were compared with those for single particle system consisting of the coarser glass beads.

## EXPERIMENTAL APPARATUS AND PROCEDURE

Fig. 1 shows the experimental apparatus for a batch system under a steady state condition, and Table 1 gives the experimental conditions and particle properties.

Experiments in this study were conducted by using a cylindrical acrylic bench scale model. The bed consisted of a 0.1 m ID acrylic column with a conical base having an included angle of 60° and the inlet nozzle had a diameter of 12 mm. The

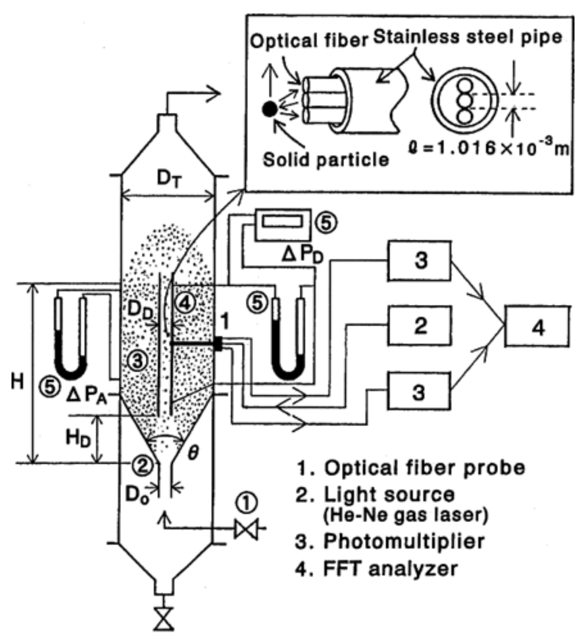


**Fig. 1. Schematic diagram of experimental apparatus.**

†To whom correspondence should be addressed.
E-mail : h-ngsm@fukuoka-u.ac.jp

**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 | $\rho_P$ [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 $\Delta P_S$, the pressure drop within the draft tube $\Delta P_D$ and the pressure drop of the annulus $\Delta P_A$, respectively. $\Delta P_S$, $\Delta P_D$ and $\Delta P_A$ were measured with digital manometers. Here $\Delta P_A$ 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:

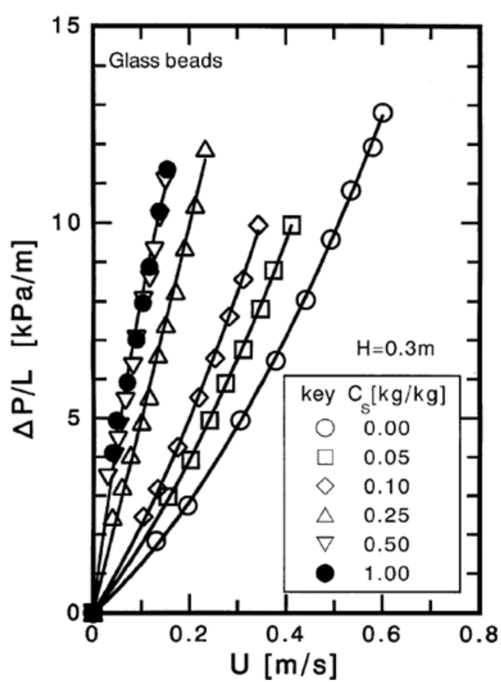


**Fig. 2. Relationship between ΔP/L and U as a parameter of $C_S$ for loose packed bed.**

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

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-$\varepsilon_D$) 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.

$$W_S=(1-\varepsilon_A)\rho_P\cdot A_A\cdot V_{PA} \quad (3)$$

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 $\tau_m$ 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-$\varepsilon_D$) 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).

$$(1-\varepsilon_D)=W_S/(\rho_P\cdot A_D\cdot V_{PS}) \quad (5)$$

## 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 $\Delta P_S$ 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

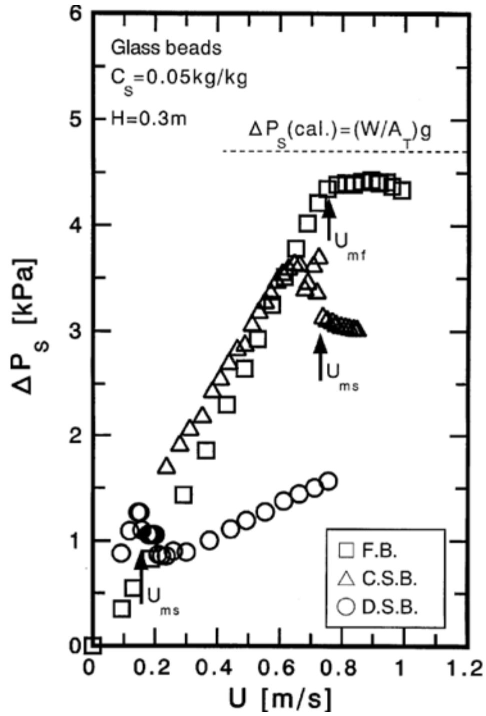


**Fig. 3. Typical pressure drop-flow rate curves for fluidization, and spouting without and with a draft tube.**

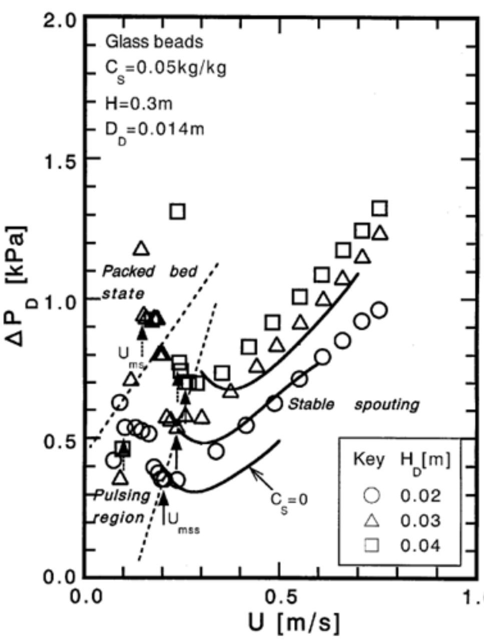


**Fig. 4. Relationship between $\Delta P_D$ and U as a parameter of $H_D$.**

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

Fig. 4 shows a representive $\Delta P_D$ 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 $\Delta P_D$ indicates the pressure drop due to solid particles within a draft tube. This figure shows that $\Delta P_D$ decreases with decrease in U for the stable spouting region. When the spouting state changes from the stable spouting region into the pulsing region, $\Delta P_D$ has a minimum value at the transitional point. The gas velocity at the point was defined as the minimum stable spouting velocity $U_{mss}$. The $U_{mss}$ 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 $\Delta P_D$ and $U_{mss}$ increases with increases in $H_D$. The reason for this is that the gas flow rate through the annulus increases with increasing $H_D$. $\Delta P_D$ for $C_S$=0.05 is higher than that for $C_S$=0 and also $U_{mss}$ for $C_S$=0.05 is lower than that for $C_S$=0 because of the decreases of the void fraction within the annulus $\varepsilon_A$. 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 $U_{mss}$. It was also found that $U_{mss}$ 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 $\varepsilon_A$ 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-

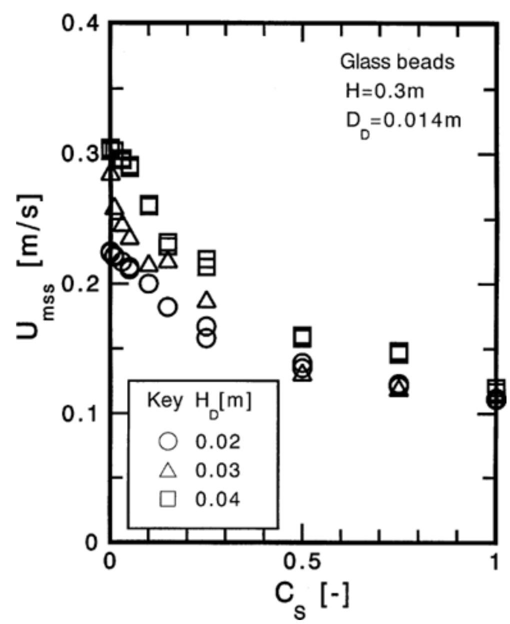


**Fig. 5. Effect of $C_S$ on $U_{mss}$.**

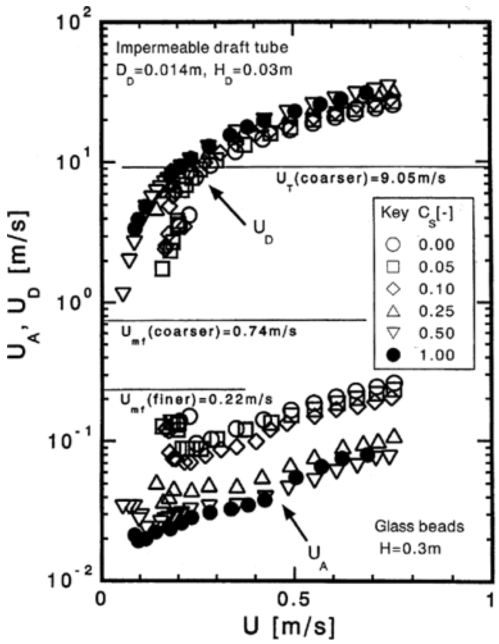


Fig. 6. Effect of $C_S$ on both $U_A$ and $U_D$.

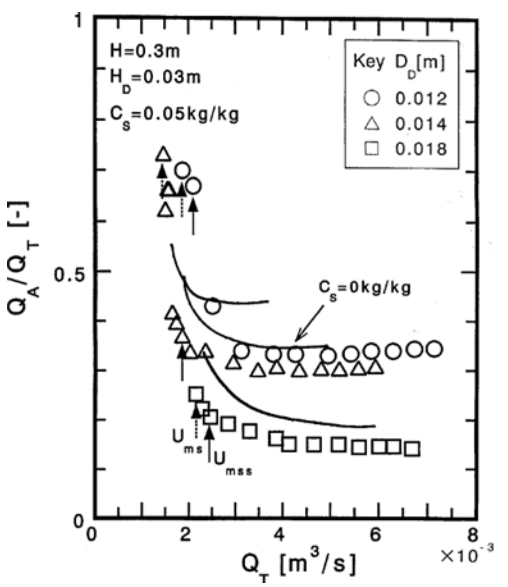


Fig. 7. Relationship between $Q_A/Q_T$ and $Q_T$ as a parameter of $H_D$.

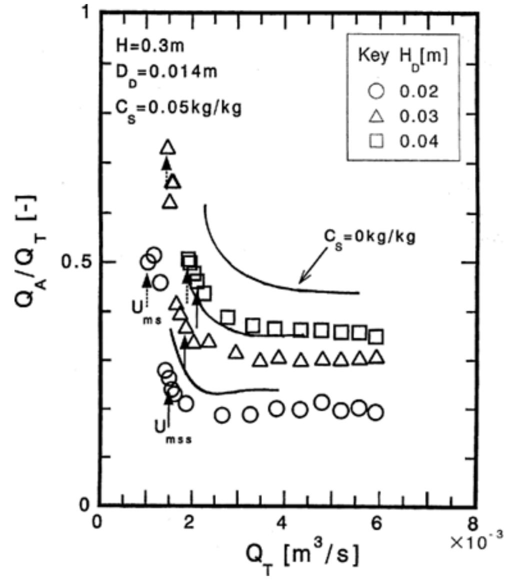


Fig. 8. Relationship between $Q_A/Q_T$ and $Q_T$ as a parameter of $D_D$.

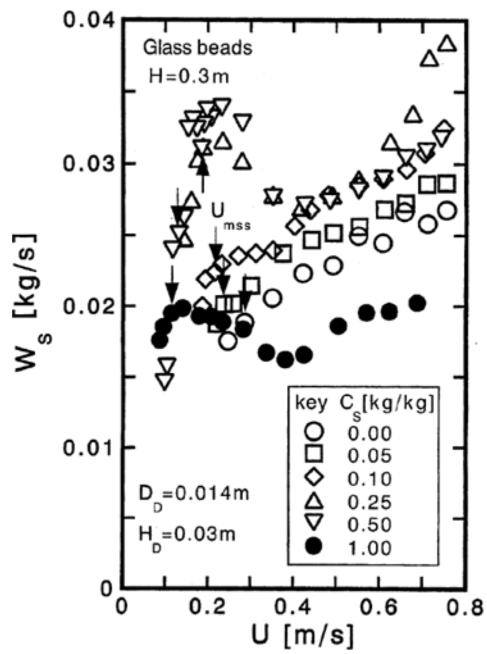


Fig. 9. Relationship between $W_S$ and U as a parameter of $C_S$.

tion within the annulus $\varepsilon_A$.

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 ≒ 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 ≒ 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. 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 $\Delta P_{DT}$ and $(1-\varepsilon_D)$. $(1-\varepsilon_D)$ 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 $(1-\varepsilon_D)$ has little difference for the comparison of $C_S$=0 and 0.05, as in the case of $\Delta P_{DT}$. The kinetic energy of particles decreases with decreases in $U_D$; therefore, $\Delta P_{DT}$ decreases with decreases in $U_D$ within the stable spouting region. Moreover, after $\Delta P_{DT}$ reaches a minimum value, $\Delta P_{DT}$ increases inversely with decreasing $U_D$. As $U_D$ decreases further, $(1-\varepsilon_D)$ increases remarkably. Furthermore, when $(1-\varepsilon_D)$ reaches about 0.04, the behavior of particles within the draft tube can not maintain the stable pneumatic con-

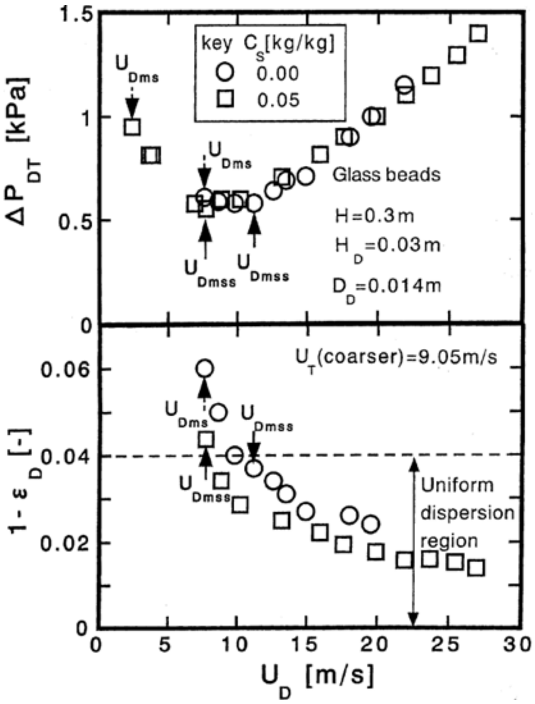


**Fig. 10. Effect of $U_D$ on both $\Delta P_{DT}$ and $(1-\varepsilon_D)$.**

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**

$\Delta P_A$ : pressure drop within annulus [kPa]
$\Delta P_D$ : pressure drop due to solid particles within draft tube [kPa]
$\Delta P_{DT}$ : total pressure drop within draft tube [kPa]
$\Delta P_S$ : total bed pressure drop [kPa]
$\varepsilon_A$ : void fraction within annulus [-]
$(1-\varepsilon_D)$ : hold-up of solid particles within draft tube [-]
$\theta$ : cone angle [deg.]
$\rho_P$ : particle density [$kg/m^3$]
$\tau_m$ : average lag time [s]

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