TRANSPORT VELOCITY OF COARSE PARTICLES IN MULTI-SOLID FLUIDIZED BED*

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Key Words: Fluidization, Multi-Solid Fluidized Bed, Transport Velosity, Collisions, Acoustic Technique

The transport velocity of a coarse particle in a Multi-Solid Fluidized Bed (MSFB) consisting of particles different in size and density was measured using an acoustic technique. Effects of the solid circulating rate of fine particles on the diameter of coarse particles were studied. The equation for calculating the transport velocity was established considering the collision characteristics between the fine and coarse particles. The transport velocity of coarse particles obtained by solving the related equation demonstrated a good agreement with those obtained from the experimental data. The calculated results for air-fine 50 mm and 100 mm particles coincided with the experimental results within 20% and 34% errors, respectively. Experimental results obtained in a lab-scale MSFB with a diameter of 0.05 m showed that the transport velocity of coarse particles decreased with increasing the solid circulation rate.

Introduction

Although many studies have been performed on the transport velocity of various monosized particles in fluidized beds, there are only a few papers dealing with the transport velocity in a binary mixture containing particles different in size and density[1, 5, 6]. This subject has received some attention because of the development of a MSFB technique for the combustion process of fuels. MSFB boilers are applicable to burn a wide range of fuels including unreactive petroleum coke and anthracite, many grades of coal with low and high ash contents, peats, wood wastes and even more volatile fuels.

The behavior of a MSFB system is essentially different from circulating fluidized bed systems. A MSFB consists of a circulating bed of fine particles and a more stable dense bed of coarse particles. The size of fine particles is usually less than 300 μm and that of coares particles about 10 mm. Fine particles circulate in the reactor while coarse particles form a dense bed at the bottom part of the reactor stabilizing the combustion process and increasing the residence time of fine particles. Experiments show, however, that a dense bed of coarse particles is not stable under all circumstances[3]. Especially when the solid circulating rate of fine particles is high, coarse particles are often carried up the column. Thus, in order to keep coarse particles at the bottom, a proper estimation of their transport velocity is necessary. In this study, the transport velocity of coarse particles is defined as the gas velocity when the coarse particles start to circulate with the fine particles in the unit. A number of different experimental techniques have been developed for measurement of the transport velocity in circulating fluidized bed systems. Yerushalmi and Cankurt[8] used the flooding point in a plot of gas velocity against volumetric flow rate per column area and pressure drop measurements. Satija and Fan[5] measured the transport velocity by extrapolating the two-log plot of gas velocity versus bed voidage. Adanez *et al.*[1], determined the transport velocity by applying different methods and concluded that the method based on the measurements of the time required for all the solids to leave the bed without feeding fresh solids was especially interesting because of its rapidity and simplicity of determination.

Experiments previously reported by the authors[4] showed that the acoustic technique was suitable for studies of gas-solids behavior in a MSFB. However, application of the acoustic technique to transport velocity measurements in a MSFB has not been reported previously. The object of this paper therefore, is to measure the transport velocity of coarse particles with the acoustic measuring technique and to provide the theoretical basis for formulating the transport velocity equation in a MSFB system.

1. Experimental Equipment and Procedure

Figure 1 illustrates a schematic diagram of the experimental unit. The MSFB column had a diameter of 0.05 m id. and a length of 1.5 m. It was made of acrylic resin to permit visual observation of the flow. Air at room temperature was used as the fluidizing gas. A solid circulating rate

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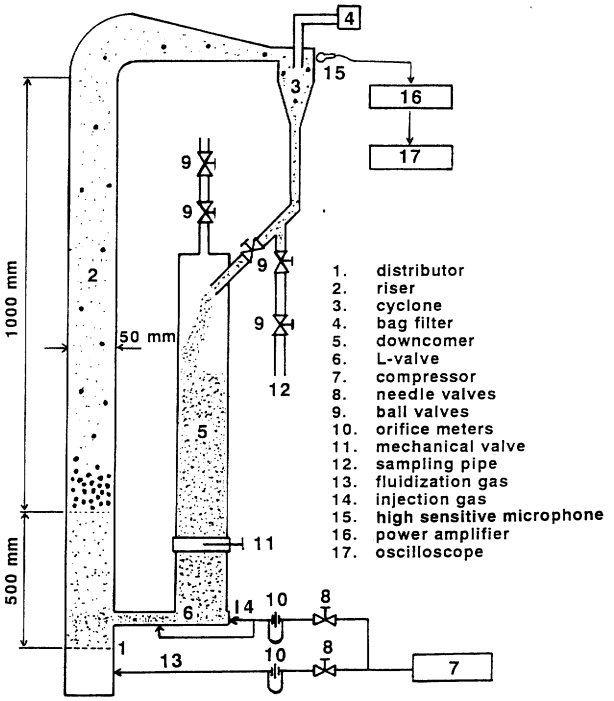


Fig. 1 Schematic diagram of experimental unit

Tabel 1 Properties of particles

kind of particle	dp	rp
coarse		
porous alumina	3.0 mm	1250 kg.m-3
	4.5 mm	1250 kg.m-3
	6.0 mm	1250 kg.m-3
fine		
glass beads	39-74 mm	2500 kg.m-3
	74-125 mm	2500 kg.m-3

of fine particles at a constant gas velocity was controlled by a mechanical valve located in the downcomer line. The experiments were carried out with an operating solid circulating rate from 5 to 27 $kg \cdot m^{-2} \cdot s^{-1}$. The solids were separated from the gas in a cyclone and returned to the column through a hopper and an L-valve. The column was provided with a perforated-plate distributor and a wire-grid (2 mm mesh) attached to the wall 50 cm above the distributor. The physical properties of both fine and coarse particles used in this study are listed in Table 1.

Figure 2 shows a block diagram of the acoustic system. In this system, a high sensitivity microphone was mounted on the cyclone wall. Then, if a coarse particle impacted on the cyclone wall, the sound level would increase instantaneously. The signal from the microphone was amplified by a differential amplifier and then sent to a digital oscilloscope. The acoustic cyclone allowed, in principle, for the determination of the presence of coarse particles in the cyclone i.e. the gas velocity that was slightly higher than the transport velocity of a coarse particle calculated from the equation of motion. The acoustic signal received from the cyclone contained both the impact signals of fine and coarse particles. However,

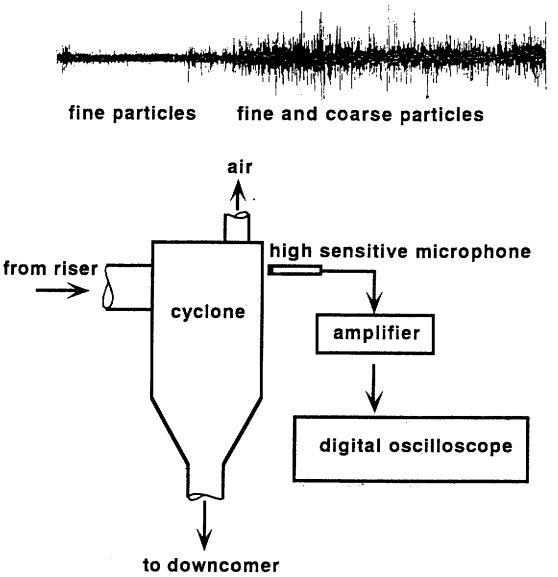


Fig. 2 Acoustic signals from cyclone

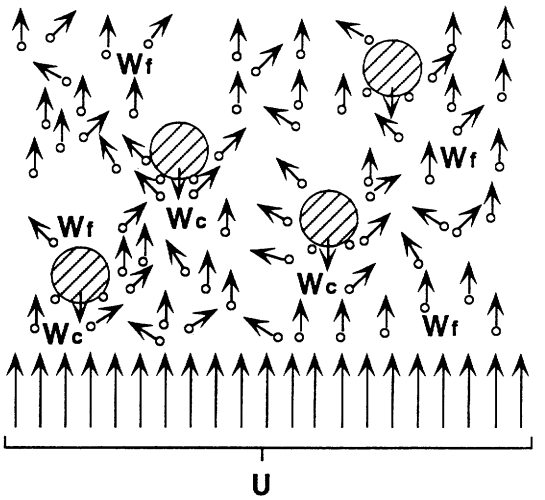


Fig. 3 Schematic diagram of fine and coarse particle motion

both signals had different amplitudes, as can be seen in Fig. 2. A detected signal of lower amplitude was attributed to fine particles. When the coarse particles started to circulate through the cyclone, signal fluctuations immediately appeared. The dominating components in the signal fluctuations came from the coarse particles. The gas velocity when the signal fluctuations appeared is the transport velocity of coarse particles and was measured by using a manometer.

During an experiment, the gas velocity was fixed and the solid circulating rate of fine particles was increased gradually until coarse particles started to circulate together with fine particles. At the moment that a coarse particle erupted to the cyclone the sound level significantly increased. The packed bed height of coarse particles was 4 cm. This rather shallow bed height allowed the bed to avoid slugging. In the current study the experiments were repeated placing coarse particles on the distributor plate and the wire-grid which was positioned 50 cm above

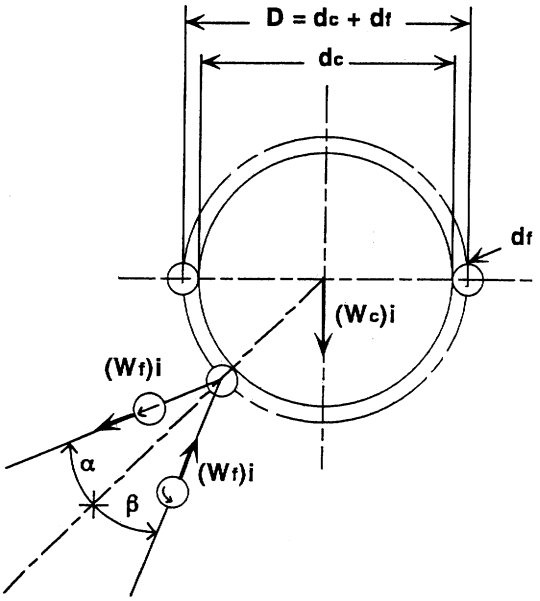


Fig. 4 Schematic diagram of collision between fine and coarse particles

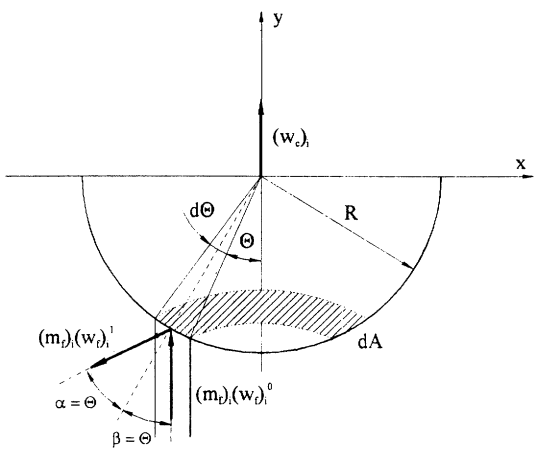


Fig. 5 Effective section of collision

the distributor plate. However, no significant differences in results were found.

2. Collisions Between Particles

In a collision process schematically illustrated in **Fig. 3**, a fine particle with velocity $(w_f)_i$ moves toward a coarse particle which then flows with velocity $(w_c)_i$. The moving direction of the fine particle is at an angle b before collision and at angle a after collision with respect to the direction of the unit vector at the collision point on the coarse particle surface (**Fig. 5**). The momentum equation for colliding particles is[7]:

$$(m_f)_i \cdot (w_f)_i^0 \cdot \cos\beta + (m_c)_i \cdot (w_c)_i^0 \cdot \cos\beta = (m_f)_i \cdot (w_f)_i^1 \cdot \cos\alpha + (m_c)_i \cdot (w_c)_i^1 \cdot \cos\theta \quad (1)$$

The reflecting velocity of a fine particle calculated from this equation becomes:

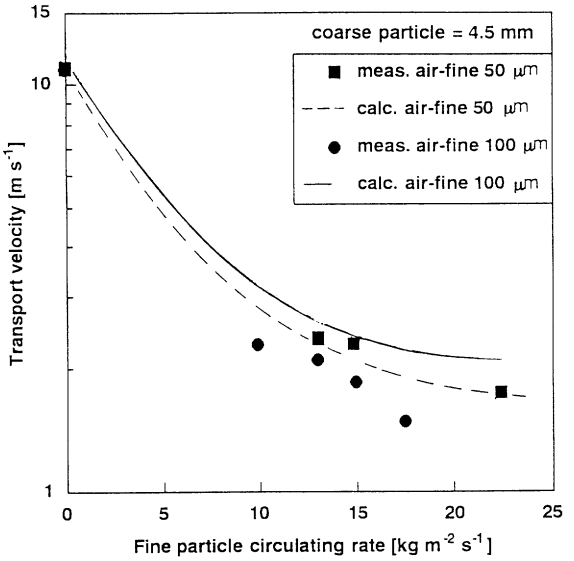


Fig. 6 Effect of fine particle solid circulating rate on transport velocity of coarse particles

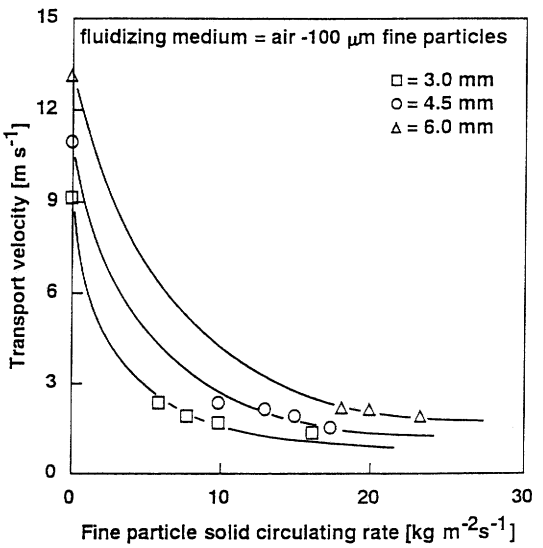


Fig. 7 Effect of fine particle solid circulating rate on transport velocity of coarse particles

$$(w_f)_i^1 = (w_f)_i^0 - (1+k)\frac{(m_c)_i}{(m_f)_i + (m_c)_i} \cdot (W_{f-c})_i^0 \quad (2)$$

$$(w_c)_i^1 = (w_c)_i^0 + (1+k)\frac{(m_f)_i}{(m_f)_i + (m_c)_i} \cdot (w_{f-c})_i^0 \quad (3)$$

where

$$(w_{f-c})_i^0 = (w_f)_i^0 - (w_c)_i^0$$

after subtraction from eq. 2 to eq. 3, we have:

$$(w_{f-c})_i^1 = -k(w_{f-c})_i^0 \quad (4)$$

If the collision is elastic, $k = 1$, the equation (4) yields:

$$(w_{f-c})_i^1 = -(w_{f-c})_i^0 \quad (5)$$

for $w_f >> w_c$ and since $m_c >> m_f$, we can assume that

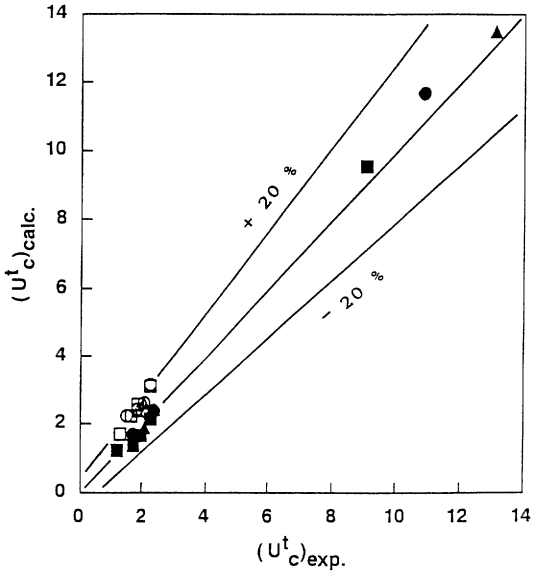


Fig. 8 Comparison of the transport velocity of coarse particles experimentally obtained and calculated results

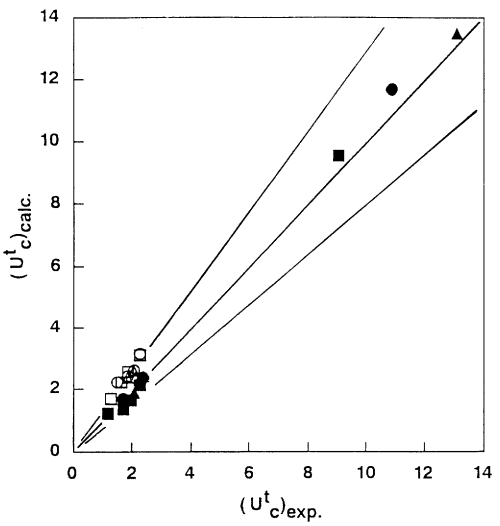


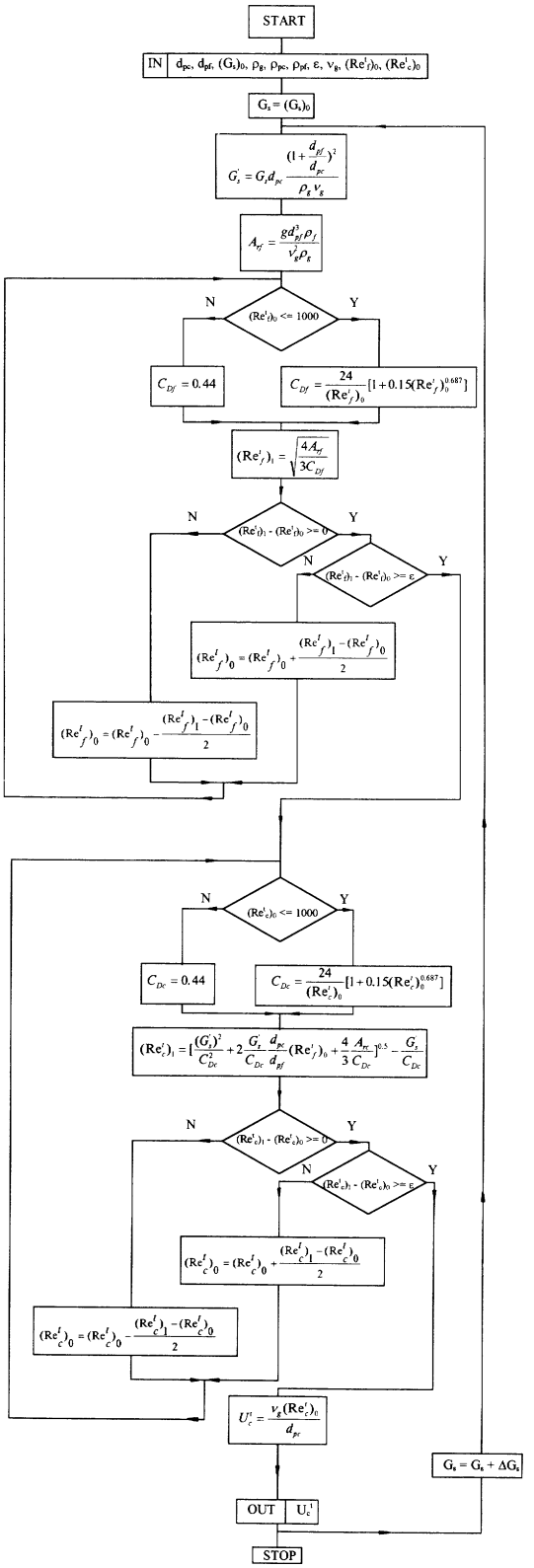
Fig. 9 Comparison of the transport velocity of coarse particles experimentally obtained and calculated result

$$|w_{f-c}|_i^1 = |wf|_i^1 = |wf|_i^0$$

and if we assume $\alpha = \beta = \theta$, thus, the momentum component perpendicular (normal) to the surface changes from $(m_f)_i (w_f)_i cos\theta$ to $(m_f)_i (w_f)_i cos\theta$. A configuration of a system of particles is similar to that employed by Benali *et al.* 2).

If the system is as shown in Fig. 5, then the effective section of interacting particles has a diameter of $D = d_c + d_f$. It can be assumed that in a circulating fluidized bed and pneumatic transport, all fine particles carried up by gas flowing with a velocity of $U > U_f^t$ will move from direction y (**Fig. 4**) with an average velocity and mass $(w_f)_i = w_f$ and $m_{fi} = m$, respectively. Thus, the angle $\alpha = \beta = \theta$ (Fig. 4) and the normal force due to collisions of a fine particle

Table 2 Algorithm of calculation for U_c^t



on the surface element of the sphere with diameter D according to Fig. 5 is:

$$dF_i = p_i dA \tag{6}$$

where

$$p_i = \Delta P \tag{7}$$

In equation 7, p_i is defined as the changing rate of normal component of momentum of a fine particle interacting with a coarse particle.

According to the above considerations, the momentum change of a single fine particle is:

$$\Delta P = P_1 - P_2 = 2m\overline{w_f}\cos\theta \tag{8}$$

Since in a CFB or pneumatic transport, gas and solid flows are organized in opposite directions to the gravitational force (along y in Fig. 5), therefore only the dF_y component is to be considered i.e.:

$$dF_y = p_{iy} NdA\cos\theta = p_i NdA\cos^2\theta \tag{9}$$

where:

$$dA = \sin\theta d\theta; \qquad R = D/2$$

and the fine particle flow rate representing the number of fine particles flowing through the cross-sectional area of 1 m^2 within 1 s is:

$$\dot{N} = n\overline{w_f} \tag{10}$$

Substituting Eqs. 7, 8 and 10 into 9 and integrating it over the range $0 \le \theta \le \frac{\pi}{2}$ results in:

$$\begin{aligned} dF_y = \langle F\rangle &= 4\pi R^2 \int_0^{\frac{\pi}{2}} nm\overline{w_f}^2 \cos^3\theta \sin\theta d\theta \\ &= \frac{\pi}{4}(d_c + d_f)^2 nm\overline{w_f}^2 \end{aligned} \tag{11}$$

and since

$$\int_0^{\frac{\pi}{2}} \cos^3\theta \sin\theta \, d\theta = \frac{1}{3}$$

or using known dependencies that $m = v_f r_f$ and $s = n\, v_f$ and assuming $w_f = U - U_f^t$ we obtain:

$$\langle F\rangle = \frac{\pi}{4} G_s (d_{pc} + d_{pf})^2 (U - U_f^t) \tag{12}$$

3. Transport Velocity of Coarse Particles

The transport velocity of coarse particles with assumption of no interaction between them ($n_c\, v_c < 0.01$) can be expressed from the equation of motion:

$$m_c \frac{dw_c}{dt} = F_g + F - G, \tag{13}$$

where

$$F_g = \frac{\pi d_c^2}{4} C_D \rho_g \frac{|U - w_c|(U - w_c)}{2},$$
$$F = \langle F\rangle,$$
$$G = m_c \cdot g$$

If we define d_c as the diameter of a coarse particle and assuming that $dw_c/dt = 0$, $w_c = 0$; $U = U_c^t$ we have:

$$\frac{3}{4} C_{D_f} \frac{\rho_g (U_c^t)^2}{\rho_c d_{pc}} + 2\frac{G_s}{\rho_c} \frac{\left(1 + \frac{d_{pf}}{d_{pc}}\right)^2 (U_c^t - U_f^t)}{d_{pc}} - g = 0, \tag{14}$$

which can be rearranged in the form:

$$Re_c^t = \left[\frac{(G_s')^2}{C_{D_f}^2} + 2\frac{G_s' d_{pc} Re_f^t}{C_{D_f} d_{pf}} + \frac{4}{3}\frac{Ar_c}{C_{D_f}}\right]^{0.5} - \frac{G_s'}{C_{D_f}} \tag{15}$$

where:

$$Re_f^t = \sqrt{\frac{4}{3}\frac{Ar_f}{C_{D_f}}}$$

$$G_s' = \frac{G_s \cdot d_{pc}}{\rho_g \cdot v_g}\left(1 + \frac{d_{pf}}{d_{pc}}\right)^2$$

The drag coefficients, (C_{D_f} and C_{D_c}) can be related to the Reynolds number by means of the following formulas

$$C_{D_f} = \frac{24}{Re_f}\left(1 + 0.15 Re_f^{0.687}\right) \quad for\ Re_f \le 1000$$
$$C_{D_f} = 0.44 \quad for\ Re_f \ge 1000$$
$$C_{D_f} = \frac{24}{Re_c}\left(1 + 0.15 Re_c^{0.687}\right) \quad for\ Re_c \le 1000$$
$$C_{D_f} = 0.44 \quad for\ Re_c \ge 1000$$

The measured and calculated transport velocity for coarse particle diameters 3 mm, 4.5 mm and 6 mm are shown in **Fig. 6, 7 and 8**, respectively. It can be seen that the transport velocity significantly decreased with increased solid circulating rate. Similar effects were reported from the turbulent fluidized bed voidage versus air velocity relationship by Satija and Fan[5]. Comparing the results in Fig. 6, 7 and 8, it was also found that at a constant solid circulating rate, the transport velocity decreased with increasing size of fine particles.

A comparison of the transport velocity of coarse particles experimentally obtained and calculated results are shown in **Fig 9**. The transport velocity was calculated from Eq. 15. As can be seen, there is a reasonable agreement with the calculated and measured results for 50 μm fine particles. In this case the estimations were within a 20% error. The agreement for larger fine particles was also good, but the estimation error was 34%; perhaps due to the differences in the shape of particles which were not taken into consideration in the model. The calculation procedures for transport velocity of coarse particles are shown in **Table 2**.

Conclusions

The conclusions from the present study can be summarized as follows:

1) An acoustic technique for measurements of the transport velocity of coarse particles in a Multi-Solid Fluidized Bed has been demonstrated.

2) The transport velocity of coarse particles in a binary mixture of solids has been studied based on the theory of collision between particles. The equation of transport velocity was given.

3) The predicted results of the transport velocity agree well with experimental data.
4) The transport velocity of coarse particles in a MSFB decreases with increasing solid circulating rate of fine particles.
5) The transport velocity was less affected by fine particle sizes under the same operating conditions within the experimental range of studied particles.

Acknowledgment

This paper is part of the work carried out by the International Research Team "Interfluid" supported by "the New Energy Development Organization"(NEDO, Japan at the universities of Nagoya, Chubu and Hamburg-Harburg.

Nomenclature

A	=	cross-section area	[m^2]
Ar	=	Archimedes number	[-]
C_D	=	drag coefficient	[-]
d_{pc}	=	coarse particle diameter	[m]
d_{pf}	=	fine particle diameter	[m]
d_t	=	time interval	[s]
F	=	force due to fine particles	[N]
F_g	=	drag force	[N]
g	=	gravitational acceleration	[$m \cdot s^{-2}$]
G	=	gravitational force acting on a coarse particle	[N]
G_s	=	solid rate of fine particles	[$kg \cdot m^{-2} \cdot s^{-1}$]
G_s'	=	dimensionless solid rate of fine particles	[-]
k	=	restitution coefficient	[-]
m	=	mass	[kg]
n	=	number of particles per unit volume	[$1 \cdot m^{-3}$]
N	=	solid flow rate	[$1 \cdot m^{-2} \cdot s^{-1}$]
p	=	unit force due to collisions	[$N \cdot m^{-2}$]
ΔP	=	momentum change of fine particles	[$kg \cdot m \cdot s^{-1}$]
P	=	momentum	[$kg \cdot m \cdot s^{-1}$]
Re	=	Reynolds number	[-]
U	=	superficial gas velocity	[$m \cdot s^{-1}$]
U'	=	terminal velocity	[$m \cdot s^{-1}$]
v	=	volume of a particle	[m^3]
w	=	velocity of particle	[$m \cdot s^{-1}$]
<Greek symbols>			
α,β,θ	=	angles	[-]
ν	=	gas viscosity	[$m^2 \cdot s^{-1}$]
ρ	=	density	[$kg \cdot m^{-3}$]
σ	=	volumetric concentration of particles	[-]
<Subscripts>			
c	=	coarse particle	
f	=	fine particle	
g	=	gas	
i	=	selected single particle	
0	=	incident	
1	=	reflecting	
t	=	transport	

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