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Sudden Expansion of Gas-solid Two Phase flow*

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Momentum transfer from particles to gas in a decelerated flow of suspensions is confirmed experimentally in a sudden expansion of pipes of different expansion ratios by using different particles, when the flux Richardson number exceeds 0.0015.

Mean axial velocity profiles of air in a suspension are measured by a thermistor anemometer in a larger pipe in case of the expansion ratio 0.523, and it is shown that an approximately uniform profile near the maximum pressure point disappears when the flux Richardson number is 2.07×10^{-3} .

1. Introduction

In the pneumatic transport of solid particles in a horizontal pipe over a long distance, sudden expansions are used in many cases to avoid a velocity increase caused by the expansion loss for a one phase flow is wellknown as Borda-Carnot loss. However, the loss for a gas-solid two phase flow has practically never been examined. We examined the effect of addition of particles in the sudden expansion section whose diameter ratio is 0.523, and made it clear that an increase in pressure recovery (or pressure rise) above that for gas alone occurs only when the solid loading ratio exceeds a certain fixed value⁽¹⁾. Moreover, we found that the solid loading ratio at the beginning of increase is different according to the kind of particles. In the pneumatic transport of solid particles in a constant diameter pipe, the particles are generally mainly transported by the momentum from the air flow, but in a decelerated flow such as in a sudden expansion section, it is expected that a reverse transfer of momentum from particles to air occurs due to the difference of inertia between them.

In this work, we examine the onset point of a reverse transfer of momentum for a small volume concentration of particles. And, in particular, we relate the effect of

addition of particles on the flow to the flux Richardson number. By using particles with different free falling velocities, we experimentally examined the relation between the flux Richardson number and the pressure recovery, loss coefficient and pressure recovery length. We also examined the effect of expansion ratio by using lines of three different diameter ratios. And further we measured air velocity profiles by using a thermistor anemometer when P.V.C.(polyvinyl chloride) powder was added, and studied the effect of solid loadings in terms of the velocity profile.

2. Nomenclature

A; pipe cross sectional area
 C; volume concentration
 D; pipe diameter
 d; particle size
 $\bar{d}$; mean particle size
 l_E ; length for the pressure recovery= $Z_{\max}$
 M; mass flow rate
 m ; solid loading ratio= M_p/M_a
 P_1 ; pressure at the expansion interface
 $P_{\max}$; maximum pressure in the downstream pipe
 ΔP_E ; pressure recovery= $P_{\max}-P_1$
 ΔP_{BC} ; Borda-Carnot's pressure recovery
 $=\beta^2(1-\beta^2)\rho U_1^2$
 Re; Reynolds number= UD/ν
 Rf; flux Richardson number
 r; radial coordinates
 t*; relaxation time of particle
 U; superficial air velocity
 u; air velocity
 $u_{\max}$; average air velocity at the pipe axis
 v; particle velocity
 w; characteristic fluctuation velocity of air
 X; force on air per unit volume by particles
 Z; axial coordinate from the expansion interface
 $Z_{\max}$; axial coordinate for $P_{\max}$
 β ; diameter ratio= D_1/D_2
 ζ ; expansion loss coefficient, addition-

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al expansion loss coefficient
 ζ_{BC} ; Borda-Carnot's expansion loss coefficient $= (1-\beta^2)^2$
 ρ ; air density
 σ ; particle material density
 ν ; kinematic viscosity of air
 $(\bar{})$; time average of ()
 $()'$; fluctuation of ()

Subscripts

a; air
 p; particles
 1; upstream pipe
 2; downstream pipe
 r; radial component
 θ ; azimuthal component
 z; axial component

3. Experimental setup and procedure

Figure 1 shows a schematic diagram of experimental setup. The pipeline consisted of straight pipes of transparent acrylate placed horizontally. The length and inside diameter of smaller pipe were set at 4m and 42.0mm. The length of larger pipes was 6m and their inside diameter was varied from 70.0mm, to 80.3mm and 100.0mm. Air flow from a blower was used, and the particles were added to the air flow by an electromagnetic feeder at the upstream end of the smaller pipe. The particles were separated from air flow by the cyclone separator, and the air was released in to the atmosphere through a bag filter.

Table 1 Physical properties of particles and range of solid loading ratios

$\bar{d}$ (μm)	σ (kg/m^3)	t^* (s)	Range of m
P.V.C. powder	134	4.80×10^{-2}	$0 < m < 0.4$
Glass beads	240	1.77×10^{-1}	$0 < m < 0.8$
Glass beads	280	2.02×10^{-1}	$0 < m < 1.1$
Glass beads	900	6.45×10^{-1}	$0 < m < 1.9$

Fig.1 Experimental setup

The flow rate of air was measured at a calibrated orifice before the air entered the test pipeline. The mass flow rate of particles was calculated by measuring the time until a measured weight of particles was discharged. The static pressure distribution along the pipe axis was measured by static pressure taps which were placed at 12 points in the smaller pipe and 14 points in

the larger pipe. Each tap consisted of three holes bored at an interval of 120° in the pipe wall at the same cross section. The air velocity profile was measured at 7 stations in 100.0mm pipe near the expansion interface by using a thermistor anemometer.

Fig.2 Particle size distribution

Figure 2 shows the particle size distributions. The physical properties of particles and the range of solid loading ratios are given in Table 1. The range of pipe Reynolds numbers Re_1 referred to the smaller pipe is $(9.0 \sim 24.4) \times 10^4$ for $\beta=0.420$, $(2.7 \sim 23.6) \times 10^4$ for $\beta=0.523$ and $(7.3 \sim 25.1) \times 10^4$ for $\beta=0.600$.

4. Experimental results and discussion

4.1.1 Pressure recovery of one phase flow

From the measurement of pipe friction coefficient for air it was known that the pipe was hydraulically smooth. Figure 3 shows $\Delta P_E / \Delta P_{BC}$ vs. Re_1 . This figure shows that $\Delta P_E / \Delta P_{BC}$ decreases with an increasing Re_1 and that the pressure recovery ratio is the largest at $\beta=0.600$. This result agrees with the fact that the smaller the expansion ratio is, the smaller the expansion loss is.

4.1.2 Expansion loss coefficient of one phase flow

Figure 4 shows ζ_a / ζ_{BC} vs. Re_1 . It is seen that ζ_a / ζ_{BC} is also a function of Reynolds number, that is, ζ_a / ζ_{BC} increases with an increasing diameter ratio. This result agrees with Uematu's⁽²⁾

findings. It seems that the effect of wall friction becomes larger when the expansion ratio is reduced. However, ζ_a / ζ_{BC} in our work is larger than that obtained by other workers. This may be caused by the fact that the expansion section was placed in the fully developed flow region and that the value of P_1 was defined at the expan-

sion interface.

Fig.3 $\Delta P_E/\Delta P_{BC}$ vs. Re_1

Fig.4 ζ_a/ζ_{BC} vs. Re_1

Fig.5 Relation between pressure recovery and solid loading ratio when glass beads 900μm was added ($\beta=0.523$)

4.1.3 Pressure recovery length of one phase flow

The pressure recovery length being $8.5D_2$ is almost independent of Reynolds number and the diameter ratio.

4.2.1 Pressure recovery of gas-solid two phase flow

According to the previous work⁽¹⁾ the increase of $\Delta P_E/(1/2)\rho_1 U_1^2$ of a gas-solid two phase flow above that of the air alone begins after the solid loading ratio exceeds a certain value, and that the solid loading ratio at the onset point is nearly in proportion to the relaxation time of particle and it slightly depends on U_1 . Figure 5

shows the relation between the pressure recovery and the solid loading ratio when the glass beads 900μm were added for $\beta=0.523$. This figure shows that the pressure recovery begins to increase over that of the air alone after the solid loading ratio exceeds about unity. If this gas-solid suspension is regarded as a homogeneous gas whose density is $\rho_1(1+m)$, the pressure recovery must be by $(1+m)$ times larger than the value of air alone, and, in the same diagram as Figure 5, it increases linearly from $m=0$. But this does not agree with the experimental result. If the relaxation time of particles is much shorter than the characteristic time of air flow, the particles will perfectly follow the air flow and the suspension will be regarded as a homogeneous gas. This shows that the particles used in this work correspond to coarse particles whose relaxation

time is longer than the characteristic time of air flow. In this case, the turbulent fluctuation of solid phase can be neglected and turbulence of gas phase will be suppressed by the action of particles which eliminates turbulent fluctuation of gas phase, the loss due to the gas phase Reynolds stresses being decreased. Furthermore, according to the difference of inertia between the particles and the gas the mean velocity of particles in the expansion section can be larger than that of the air, the momentum transfer from particles to gas being expected thereby. Now, will consider the onset condition from the viewpoint of energy balance of gas phase turbulence. The state of fluid turbulence involving additives such as particles is characterized in terms of the flux Richardson number which is usually used to determine the stability of stratified flow or the change of the turbulent structure. According to Taylor⁽³⁾ it is 0.25 for the stability limit of stratified flow and, according to Blackader and others⁽³⁾ the turbulence no longer occurs above 0.2.

For gas flow alone, production of turbulence energy by the Reynolds stress and mean shear flow(gain), SP, nearly balances dissipation of turbulence energy due to the turbulent fluctuation(loss). If the particles are added, an extra production of turbulence energy by the particles, EP, appears. Rf is defined as negative ratio of extra production by the additives, EP, to shear production, SP, or $-EP/SP$. When EP is the loss, the turbulence is weakened by the additives. Our hypothesis is that the onset of an increase in the pressure recovery upon the addition of particles occurs at a certain value of Rf.

EP and SP are given as follows:

$$EP = -(\overline{u'_r X'_r} + \overline{u'_\theta X'_\theta} + \overline{u'_z X'_z})$$

$$= -\frac{1}{t^*} \{ \sigma \overline{c} [\overline{u'_r(u'_r - v'_r)} + \overline{u'_\theta(u'_\theta - v'_\theta)} + \overline{u'_z(u'_z - v'_z)}] + \sigma [\overline{c'_r(u'_r - v'_r)} + \overline{c'_z(u'_z - v'_z)}] \} \dots \dots \dots (1)$$

$$SP = \rho [\overline{u'_r}^2 \frac{\partial \overline{u}_r}{\partial r} + \overline{u'_\theta}^2 \frac{\partial \overline{u}_r}{\partial r} + \overline{u'_z}^2 \frac{\partial \overline{u}_z}{\partial z} + \overline{u'_r u'_z} (\frac{\partial \overline{u}_r}{\partial z} + \frac{\partial \overline{u}_z}{\partial r})] \dots \dots \dots (2)$$

where, we assume that X follows Stokes' law. Although Rf is originally a local parameter, we evaluate an average Rf in the sudden expansion by the following method and we refer to it as the flux Richardson number in the following.

As regards EP, if we assume that the turbulent fluctuation of particles can be neglected and the angle between the mean

turbulent mass flux $\overline{\sigma' u_1'}$ and the mean relative velocity $(\overline{u_1 - v_1})$ is nearly perpendicular at the expansion, we can put $\overline{\sigma' u_1' (\overline{u_1 - v_1})}$ equal to zero. Then EP can be put as:

$$EP \sim - \frac{\overline{\sigma' u_1'^2}}{t^*} \dots \dots \dots (3)$$

Fig.6 Relation between Rf and pressure recovery ($\beta=0.420$)

Fig.7 Relation between Rf and pressure recovery ($\beta=0.523$)

Fig.8 Relation between Rf and pressure recovery ($\beta=0.600$)

Fig.9 ζ_p vs. Rf ($\beta=0.420$)

As regards SP, it is shown⁽⁴⁾ that SP depends almost entirely on $-\overline{\rho u_r' u_z'} (\partial \overline{u_z} / \partial r)$.

Then SP can be put as:

$$\begin{aligned} SP &\sim -\overline{\rho u_r' u_z'} (\partial \overline{u_z} / \partial r) \\ &\sim -\rho w^2 (U_1 - U_2) / (D_1 - D_2) \\ &= \rho w^2 (1 + \beta) U_1 / U_2 \dots \dots \dots (4) \end{aligned}$$

Therefore, considering $\sigma c / \rho^* m$, Rf can be put as⁽⁵⁾:

$$Rf \sim \frac{m D_2}{(1 + \beta) U_1 t^*} \dots \dots \dots (5)$$

The relation between this Rf and the pressure recovery $\Delta P_E / (1/2) \rho_1 U_1^2$ is shown in Figs.6 to 8. It is seen that $m D_2 / (1 + \beta) U_1 t^*$ is a reasonable

parameter. And in any case, the pressure recovery begins to increase above that of air alone after Rf exceeds approximately 1×10^{-3} . For a suspension of glass beads 900 μm , there is a small deviation from the results with other suspensions. This may be caused by the fact that the fluid drag in this suspension does not necessarily follow Stokes' law.

4.2.2 Additional expansion loss coefficient

To define the onset point clearly, we take up additional pressure loss coefficient ζ_p defined by

$$P_1 + \frac{\rho_1 U_1^2}{2} = P_{\max} + \frac{\rho_2 U_2^2}{2} + (\zeta_a + \zeta_p) \frac{\rho_1 U_1^2}{2} \dots \dots \dots (6)$$

where we use the value for air alone as ζ_a . Figures 9 to 11 show ζ_p vs. Rf for different diameter ratios. When ζ_p is negative, the pressure recovery is essentially larger than that of the air alone. The experimental results seem to fall on a single curve independently of the diameter ratios. The value of Rf in which ζ_p becomes negative is about 1.5×10^{-3} . If the data in Figs.9 to 11 are indicated together in a single figure, they lie on the same curve independently of β . For the suspension of glass beads 900 μm , there is also a small deviation from the results of other suspensions, the reason being probably the same as before.

4.2.3 Pressure recovery length

Figure 12 shows the dimensionless pressure recovery l_E / D_2 vs. Rf for $\beta=0.420$. Figure 13 shows the case for $\beta=0.523$.

Although there is a considerable scatter in the data in Figs.12 and 13, l_E / D_2 also comes to increase above that of air alone when Rf exceeds about 1.5×10^{-3} . This shows that the decay of jet from the

Fig. 10 ζ_p vs. Rf ($\beta=0.523$) Fig. 11 ζ_p vs. Rf ($\beta=0.600$) Fig. 12 l_E/D_2 vs. Rf ($\beta=0.420$) Fig. 13 l_E/D_2 vs. Rf ($\beta=0.523$) Fig. 14 Velocity profiles for air alone and of air in a suspension ($Rf=4.75 \times 10^{-4}$, $\beta=0.523$) Fig. 15 Velocity profiles for air alone and of air in a suspension ($Rf=2.07 \times 10^{-3}$, $\beta=0.523$)

smaller pipe is small upon the addition of particles, which is a similar result to that obtained by Laats⁽⁶⁾ who made an experiment on the turbulent jet, and attained suppression of spread of jet by addition of particles. We expect that reverse transfer of momentum occurs in this case as well. While the pressure recovery length is independent of β for one phase flow, the length for $\beta=0.420$ is larger than that for $\beta=0.523$ when the particles are added. But for $\beta=0.600$, the length is almost the same as that of air alone, that is, about $8.5D_2$. This result shows that the wall effect decreases upon the addition of particles.

4.3 Velocity profile for air flow

Figure 14 shows the velocity profiles of air in the horizontal plane with $m=0$ and 0.050 of P.V.C. powder in different stations from the expansion interface for the cases of $Re_1=14.6 \times 10^4$ ($Re_2=7.66 \times 10^4$).

In this case Rf is 4.75×10^{-4} , which is in such a range that the effect of addition of particles does not appear.

At $Z/D_2=2.62$, the profile for air alone is almost the same as that of the suspension. At $Z/D_2=4.48$, the profile of the suspension seems to be still sharp. Farther downstream, the profiles become flat and at $Z/D_2=8.22$ the profile for air alone becomes the most flat tend. This phenomenon corresponds to the behavior of $P_{\max}$. At $Z/D_2=16.00$, both profiles are much the same. From the profiles at $Z/D_2=26.84$, it is seen that the flows are developing since the velocity near the wall is decelerated.

Figure 15 shows the profiles of air with $m=0$ and 0.153 of P.V.C. powder in the case of $Re_1=18.7 \times 10^4$ ($Re_2=8.8 \times 10^4$). In this case Rf is 2.07×10^{-3} which is in such a range that the effect of addition of particles appears. At $Z/D_2=4.48$, the profile for suspension is more sharpened than that of air alone. While the profile for air alone is flat at $Z/D_2=8.22$, the profile of suspension is still sharp. At $Z/D_2=16.00$, the difference in both profiles is small. At $Z/D_2=26.84$ the flows are developing and their profiles are much the same. According to the above, the velocity profile of air for suspension for $Rf=2.07 \times 10^{-3}$ is developing without becoming flat. It is considered that, by the addition of particles, turbulent mixing is suppressed and

that mixing of momentums is weakened, accounting for the fact that the profile for suspension does become flat.

5. Conclusions

In the decelerated flow of pneumatic transport of solid such as in a sudden expansion section, a reverse transfer of momentum from particles to gas is expected. In this work we determined the onset conditions for a reverse transfer by using three different pipelines with different particles and obtained the following result.

- (1) The pressure recovery and the additional expansion loss coefficient are explained by using the flux Richardson number independent of diameter ratios and particles.
- (2) When the flux Richardson number exceeds about 1.5×10^{-3} , the effect of addition of particles occurs in the pressure recovery and the additional expansion loss coefficient.
- (3) The velocity profile of air for suspension is developed without taking a flat shape.

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