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Flow Characteristics of Air-Solids Mixture in a Horizontal Pipeline*

(1st Report, Relations between Loss Coefficients and Behavior of Particles)

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Some experiments on two-dimensional distributions and mean free paths of particles in a horizontal pipeline for pneumatic conveyance are shown, and relations between additional pressure loss coefficients and behavior of particles are discussed. Distributions of particles for high air velocity are almost uniform in a cross-section of the pipeline. With a decrease in air velocity particles gradually concentrate in a bottom region but a perfect suspension flow is maintained and rolling or slipping of particles on the pipe wall is not investigated at all. Corresponding to the change in particle distributions, mean free paths of particles decrease with a decrease in air velocity. Loss coefficients under various combinations of air velocity and solid loading ratios are the same so long as the particle distributions are similar. Loss coefficients calculated from results of simple tests of particle velocity defects due to collisions with a wall agree relatively well with results of transportation tests.

1. Introduction

Many studies on pressure loss coefficients of an air-solids mixture in a horizontal pipeline and a loss occurring mechanism have been reported. Muschelknautz(1) and Welschhof(2) have attempted to evaluate loss coefficients considering only friction and collisions between particles and a pipe wall. Jyotaki(3) has proposed to take into account energy to suspend particles in a pipeline, and Uematsu and Morikawa(4) have shown a method on the analogy of a single phase turbulent flow.

It is well known from experiences that pressure loss coefficients vary in a wide range according to a flow condition of particles in a pipeline, therefore a detailed understanding of behavior of particles may be of importance to evaluation of pressure loss coefficients of an air-solids mixture. Some studies on one-dimensional distributions(2)(5) or some attempts to estimate mean free paths(2)(6) of particles have been reported, but they seem to be somewhat insufficient to explain the complicated behavior of particles in a pipeline.

In the present paper, two-dimensional distributions of particles in a cross-section of a pipeline are investigated and relations between the particle distributions and loss coefficients are discussed. In addition, mean free paths of particles are directly measured and defects in particle velocity due to collisions with a pipe wall are evaluated. Loss coefficients calculated from these results are compared with those obtained from transportation tests.

Main symbols used in the paper are as follows;

- c: velocity of particles
- d: inner diameter of pipeline
- Frc: Froude number $= \frac{c}{\sqrt{gd}}$
- Fru: Froude number $= \frac{u}{\sqrt{gd}}$
- Gk: mass flow rate of particles
- g: acceleration of gravity
- l: distance from mixing branch
- lg: gap of pipeline, see Fig.1(c)
- lk: mean free path of particles
- n: number of particles
- p: relative concentration of particles, defined by Eq.(6)
- Δp_k : additional pressure loss
- u: mean air velocity in pipeline
- wf: terminal velocity of particles
- Xg: centroid of particle distribution in x-direction, Eq.(7)
- Yg: centroid of particle distribution in y-direction, Eq.(7)
- λ_k : additional pressure loss coefficients, defined by Eq.(1)
- μ : solid loading ratio
- ξ : dimensionless distance $= l/d$
- ρ_{KF} : mean density of particles in pipeline

2. Experimental apparatus and procedure

A scheme of an experimental setup for transportation tests is illustrated in Fig. 1(a). An air flow from a turbo-blower (4) was led to a test section (9) through valves (8) and honeycomb (5), and its flow rate being obtained with Pitot tube (6). Particles in a hopper (1) were supplied from an electromagnetic feeder (2) into a pipeline, they were transported in the test section and collected into a tank (13). A mass flow rate of particles was determined with a load cell (12) connected to the tank. The test

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section consists of a clear acrylic pipe 12 m long. Static pressure taps ⑩ are located at 36 stations along the flow direction and the pressures being obtained with inclined multitube manometers. Inner diameters of the pipelines used in the tests are 0.027, 0.042 and 0.052 m. Transportation tests were made for $u=(6\sim 40)$ m/sec and $\mu=(0\sim 10)$.

(a) Test rig for transportation tests

(b) Apparatus for measurement of particle distributions

(c) Apparatus for measurement of mean free paths

Fig.1 Experimental setup

An apparatus to measure particle distributions is composed of a channel of clear acrylate with a nozzle for an air jet injection, Fig.1(b). Particles entering from an upward pipeline ① shift transversely by the air jet and reenter a downward pipeline ②. A test section ③ located just upstream of the air jet is closed by three mirrors ⑤ and an electric flash ④, the other part being perfectly shielded except for a slit 3mm in width. Particles passing through the test section were illuminated with the flash and were photographed with a camera ⑦ using a telephoto lens. A screen ⑧ is a guide for particles to reenter smoothly the downward pipe.

A test rig for determination of mean free paths of particles is illustrated in Fig.1(c). It is composed of a sealed tank ① and a pipeline with a gap of l_g in length. Some of particles entering from an upward pipeline ② fly out from the gap into the tank and the others reenter a downward pipe ③. A detailed procedure will be described later.

The particles used in the tests are spherical pellets of polyethylene with diameter 1.1mm, specific weight 923kg/m³ and terminal velocity 4.1m/sec.

3. Additional pressure loss Coefficients

Additional pressure loss coefficients are evaluated from results of the transportation tests by various methods proposed in the previous papers(1)~(4), and an examination about whether the law of similarity holds or not is made. Some methods(3)(4) are inadequate to represent loss coefficients for a wide range of d , u and μ because the law of similarity does not hold well. The most favorable representation is one proposed by Welschof(2) using λ_k and F_{rc} defined by Eqs.(1) and (2).

$$\Delta p_k = \lambda_k \frac{\rho K F}{2} c^2 \frac{dl}{d} \quad (1)$$

$$F_{rc} = \frac{c}{\sqrt{gd}} \quad (2)$$

Fig.2 indicates that the law of similarity holds relatively well under various combinations of d , u and μ but the values are too widely scattered to represent by a single curve.

Fig.2 Additional pressure loss coefficients

In general, λ_k can be written in terms of w_f , u , F_{rc} and F_{ru} as follows.

$$\lambda_k = \frac{2u^2}{w_f^2} \left(\frac{1}{F_{rc}^2} - \frac{2}{F_{rc}F_{ru}} + \frac{1}{F_{ru}^2} \right) \dots\dots\dots(3)$$

From Eq.(3), λ_k for the same d , u and w_f can be represented by the same curve as indicated by a solid line in Fig.3. In the range of $F_{rc} > (15 \sim 20)$ λ_k becomes large with a decrease in μ , while an opposite tendency can be seen for $F_{rc} < (15 \sim 20)$, which suggests the necessity of an introduction of μ into an evaluation of λ_k . In the study λ_k is represented in the form.

$$\lambda_k = \frac{A_1}{(F_{rc} - A_3)^2} + A_2 \dots\dots\dots(4)$$

First of all, data for all pipe diameters are classified by μ into four groups, $\mu < 2.5$, $2.5 \leq \mu < 4.5$, $4.5 \leq \mu < 6.5$ and $\mu \geq 6.5$. Then, coefficients $A_1 \sim A_3$ are determined by the method of least squares, which leads the conclusion that $A_1 \sim A_3$ can be represented by linear relations with μ as follows.

$$\left. \begin{aligned} A_1 &= 0.106\mu - 0.0725 \\ A_2 &= -0.000365\mu + 0.00286 \\ A_3 &= -0.55\mu + 4.86 \end{aligned} \right\} \dots\dots\dots(5)$$

It must be mentioned that Eqs.(4) and (5) are derived from data for relatively small loading ratios, $\mu = (1.0 \sim 7.5)$, therefore an application of these formulae should be restricted to the same range. But it is verified that the formulae are also applicable for ranges of $\mu < 1$ and $\mu > 7.5$ by putting $\mu = 1$ and $\mu = 7.5$, respectively.

Fig.3 Influence of μ on λ_k

4. Two-dimensional distributions of particles

4.1 Experimental results Fig.4 shows photographs of particles being transported in a pipeline, the direction of the acceleration of gravity being downward in every case. Particles for high air velocity are distributed almost uniformly in a cross-section and a perfect suspension flow is maintained, Figs.4(a) and (b). In such cases λ_k is relatively small, (0.002~0.0025). Figs.4(c) and (d) indicate results for low air velocity near 'critical velocity' under which particles cannot be transported any longer and particles concentrate in a bottom region. However, in spite of the low velocity most of particles are perfectly suspended. In these cases λ_k is as large as

Fig.4 Photographs of particles

(0.005~0.006). Particles for air velocity just lower than the critical velocity accumulate on a bottom wall, and rolling or slipping of particles(2) cannot be confirmed under any conditions. The results in an accelerating region ($\xi = 32$) are given in Figs.4(e) and (f), which indicate that distributions are almost similar to those in a steady velocity region as shown in Figs.4(a) and (b).

4.2 Quantitative appreciation of particle distributions Local particle concentrations are evaluated as follows. A cross-sectional area of the pipeline is divided into N elements with equal areas as shown in Fig.5, and the number of particles contained in the i -element being defined by n_i . Relative particle concentration p_i is defined as follows.

$$p_i = N \frac{n_i}{\sum_{i=1}^N n_i} \dots\dots\dots(6)$$

where $N=24$.

Equi-concentration contours are presented in Fig.6. Unlike in a vertical pipeline, it would be natural that particles in a horizontal pipeline concentrate in a bottom region due to the influence of the gravity force. In the case of high air velocity, however, concentration is nearly equal to unity in the most part of a cross-section, although a region with slightly high concentration appears in a bottom region, Figs.

Fig.5 Division of a cross-sectional area

Fig.6 Equi-concentration contour

6(a) and (b). This fact suggests that the gravity force does not play an important role in the movement of particles but a suspension flow is maintained by any other forces larger than the gravity force. In the case of low air velocity, Figs.6(c) and (d), concentration near the bottom becomes relatively large but not larger than (2.0~2.5). The concentration near the bottom for high air velocity increases with a decrease in μ , but an opposite tendency appears for low air velocity. These results correspond to the change in the influence of μ on λ_k as described above.

Fig.7 Centroid of particle distributions

4.3 Relations between particle distributions and loss coefficients Centroids of particle distributions, X_g and Y_g , are defined as follows.

$$X_g = \frac{1}{d} \frac{\sum_{i=1}^N n_i x_{gi}}{\sum_{i=1}^N n_i}, \quad Y_g = \frac{1}{d} \frac{\sum_{i=1}^N n_i y_{gi}}{\sum_{i=1}^N n_i} \dots (7)$$

where, x_{gi} and y_{gi} are coordinates of the centroid of i -element. Relations between Y_g and u are given in Fig.7. When air velocity is relatively high Y_g for large μ becomes larger than that for small μ but an opposite tendency appears for low air velocity. Such a change in the influence of μ on Y_g will be discussed later from the view point of mean free paths.

Relations between Y_g and λ_k can be represented by a single curve, Fig.8. This fact indicates that the loss coefficients are the same so long as the particle distributions are similar.

Centroids in the x -direction, X_g , are quite small in all cases, and particle distributions are almost symmetrical in the horizontal direction.

Fig.8 Relations between λ_k and Y_g

5. Mean free paths

As discussed above, particles are transported under a perfectly suspended condition, but they move in a pipeline colliding continuously with a pipe wall. In this study, the term 'mean free path' implies the mean distance which one particle can cover between collisions.

5.1 Measurement of mean free paths

In a pipeline shown in Fig.1(c), particles which collide with a pipe wall in length l_g may fly out from the gap into the tank. Mass flow rate of particles which fly out into the tank is denoted by G_{k1} and total mass flow rate by G_{k0} . Taking into consideration mean movement of particles, the ratio G_{k1}/G_{k0} may be proportional to l_g and $G_{k1}/G_{k0} = 1$ for $l_g \geq l_k$. Fig.9 indicates linear relations between G_{k1}/G_{k0} and l_g , but their slopes are different under various combinations of u and μ . The ratio G_{k1}/G_{k0} tends to saturate for large l_g , therefore l_k is determined as the value of l_g at which G_{k1}/G_{k0} reaches unity by extrapolation using data for small l_g .

Fig.9 Relations between G_{k1}/G_{k0} and l_g Fig.11 Relations between λ_k and l_k

5.2 Mean free paths Experimental results of l_k are illustrated in Fig.10, which shows l_k for relatively high air velocity is almost constant but becomes rapidly small with a decrease in u . For high air velocity, l_k decreases with a decrease in μ but an opposite tendency appears for small air velocity. These results correspond to changes in particle distributions as discussed above.

5.3 Relations between mean free paths and loss coefficients Relations between l_k and λ_k are given in Fig.11. Although λ_k and l_k change in a wide range under various combinations of u and μ , the relations can be represented by one curve for every d . This fact corresponds to the results indicated in Fig.8.

On the basis of the results described above, it can be concluded that an additional pressure loss of an air-solids mixture originates from energy loss due to collisions between particles and a pipe wall.

6. Calculation of loss coefficients

6.1 Defects in particle velocity

The deficiency in particle velocity due to collisions is determined by two methods, i.e., to drop particles onto a rotating disk(1) or onto an inclined plate at rest. Fig.12 illustrates particle velocity vectors just before and after a collision. A velocity defect in y -direction, $\Delta c_y = c_{y1} - c_{y2}$, is important to a mechanism of suspension, whereas that in x -direction, $\Delta c_x = c_{x1} - c_{x2}$, gives a large influence on loss coefficient.

Fig.10 Mean free paths

Fig.13 indicates the results obtained using the same particles and the same material of a plate as those used in transportation tests. Muschelknautz(1) has pointed out that $\Delta c_y/c_1$ for small θ ($\sin \theta = 0.02 \sim 0.06$) becomes negative and has suggested that this fact causes a suspension flow. Although a perfect suspension flow is attained in this study as shown in Fig. 4, negative values are not obtained at all. The inconsistency suggests that the cause of a suspension flow proposed by him is not valid but it must be studied from an other point of view.

6.2 Comparison of results Loss coefficients λ_k can be written as follows (1).

$$\lambda_k = 2 \left(\frac{\Delta c_y}{c_1} \right) \frac{d}{l_k} \quad (8)$$

It can be estimated from experimental values of l_k that particles in a pipeline collide on the wall at $\theta = (2 \sim 6)^\circ$, therefore a mean value of $\Delta c_y/c_1$ in the same range is used in a calculation of λ_k . Calculated loss coefficients, λ_{kc} , and those obtained from transportation tests, λ_{ke} , are compared in Fig.14. Because only collisions between particles and a pipe wall is considered in Eq.(8) but the other factors such as three-dimensional motion or mutual collisions of particles and an air velocity

Fig.12 Vector diagram of particle velocity

Fig. 13 Defect in particle velocity due to collision

profile are neglected, the agreement is partially unfavorable. But they seem sufficiently accurate for a practical use. In the procedure to calculate loss coefficients for a general use, not only $\Delta c_x/c_1$ but also lk must be known. In general, the latter can be evaluated by an analysis of the movement of an individual particle with consideration of factors of suspension and detailed discussions will be shown in a next report.

7. Conclusions

Distributions and mean free paths of particles being transported in a horizontal pipeline are determined experimentally and relations between additional pressure loss coefficients and behavior of particles are discussed. The results obtained can be summarized as follows.

(1) Particles being transported in a pipeline are perfectly suspended although they slightly concentrate in a bottom region for quite low air velocity, and slipping or rolling of particles does not appear.

(2) An additional pressure loss of an air-solids mixture originates from energy loss due to collisions of particles with a pipe wall. Therefore, loss coefficients under various combinations of d , u and μ are the same so long as the particle distributions are similar.

(3) Loss coefficients calculated from defects in particle velocity and mean free paths determined from simple tests agree relatively well with those obtained from transportation tests.

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Fig. 14 Comparison between calculated and experimental loss coefficients