Measurements of Horizontal Air-Solid Two-Phase Flow Using
an Optical Fiber Probe^{*}
(Particle Velocity and Concentration)

by Yoshinobu MORIKAWA^{**}, Yutaka TSUJI^{***}, Toshitsugu TANAKA^{****}

An optical fiber probe was developed for measurements of velocities and concentrations of solid particles. This probe was applied to an air-solid two-phase flow in a horizontal pipe, and distributions of velocities and concentrations were obtained over the pipe cross section. It was found that the particle concentration increases exponentially in the vertically downward direction. Corresponding to the distributions of concentrations particle velocities have unsymmetrical distributions. The flow structure becomes more unsymmetrical at low air velocities and high loading ratios. Also, the gradient of concentration is well correlated to the ratio of particle to air velocity.

Key Words : Multiphase Flow, Optical Fiber, Flow Measurement, Solid Particle Velocity, Concentration

1. Introduction

Air-solid two-phase flows in pipes have long been investigated mainly on the pressure drop in relation to pneumatic conveying of solid particles. Although most treatments of the pressure drop are based on one dimensional models, real phenomena are far more complicated than the models, especially in the horizontal pipe. Therefore, a number of attempts also have been made to observe the flow structure in the pipe.

Distributions of concentrations⁽¹⁾⁻⁽⁴⁾ and the particle velocities⁽³⁾ were measured by many workers using photography or high speed cameras. As an example of innovative methods, pictures of dispersed particles were taken from the front side in a pipe which was cut immediately after the measuring section. Recently, the Laser-Doppler-Velocimeter(LDV) has been widely used, and it enables one to measure the velocities of both phases simultaneously by seeding minute tracers for the air⁽⁶⁾. Unfortunately the measurement with LDV or photography is restricted to dilute phase flows. In photography it is difficult to detect the motion of small particles at high velocities and to gain high spatial resolution.

For the last 15 years, measurement of particle velocities using optical fibers has been often reported in the field of fluidization. These measuring methods

could be classified into two kinds; one based on the correlation technique⁽⁷⁾⁻⁽⁹⁾ and the other based on the space filtering⁽¹⁰⁾ in which the frequency proportional to the particle velocity is obtained⁽¹¹⁾. Although both methods require the probe to protrude into the flow field, they are applicable to a dense phase flow.

In this paper, characteristics of an optical fiber probe which have been developed by the authors based on the principle of space filtering are described first. Next, results are shown on the distributions of particle velocities and concentrations over the entire pipe cross section which are obtained in the horizontal flow. The experiments were made under the condition of comparatively low air velocities, where distributions of particle velocities and concentrations were influenced easily by the parameters such as air velocities and loading ratios. Finally, consideration about an additional pressure loss is made based on the measured particle velocities.

2. Principle of measurement

The probe is shown in Fig.1, where optical fibers playing the roles of a projector and a receiver are aligned alternately at regular intervals. The total number of fibers is 12. The projector fibers, the other terminals of which are connected to a light source, shed light on a particle passing over the top of the probe. A part of the light reflected or scattered by the particle is caught by the receiver fibers, and the pass of the particle is detected as a burst signal of light intensity.

When a particle passes over the top of the probe with a constant velocity in the direction of optical fiber array, each of the receiver fibers detects the reflec-

^{*} Received 24th October, 1984.

^{**} Professor, Faculty of Engineering, Osaka University, Yamada-oka 2-1, Suita, Osaka.

^{***} Associate Professor, Faculty of Engineering, Osaka University.

^{****} Research Associate, Faculty of Engineering, Osaka University.

tion signal at regular time intervals. These receiver fibers are divided into three groups, A, B and C, as indicated in Fig.1. The reflection signals from each group are O_A , O_B and O_C in Fig.2. These reflection signals are converted to voltage signals by photo detectors. The differential signal V_{A-B} is yielded from O_A and O_B , as shown in Fig.2. Signal V_{A-B} has the frequency f_p which is proportional to the particle velocity v_p and inversely proportional to the interval of the fiber axis L_f . The relation between the particle velocity v_p and the frequency f_p is given by

$$v_p = 4L_f f_p \quad (1)$$

When L_f is known, v_p can be gained from f_p . In this work, f_p is obtained by analyzing the spectrum of the signal V_{A-B} .

Particle concentrations are obtained in the following way. As mentioned later, the intensity of reflection signal from a particle depends on the distance between the particle and the receiver fiber. Near the top of the receiver fiber, the intensity of reflection signal decreases markedly with an increasing distance. Therefore if the measuring area F_t is fixed by setting the threshold on the reflection signal, one can obtain concentrations by counting the number of the particles passing through the measuring area. The

dispersed density ρ_{KF} is given by

$$\rho_{KF} = \frac{m \cdot N}{v_p \cdot F_t} \quad (2)$$

where N is the number of the particles passing through the measuring area per unit time and m is the mean mass per unit particle. The dispersed density is the total mass contained in unit volume. In this work the dispersed density defined above is obtained as the particle concentration.

3. Characteristics of the optical fiber probe

A detailed view of the optical fiber probe is given in Fig.3. The fiber used was a quartz optical fiber of graded index type. The core diameter was $80 \mu\text{m}$, cladding diameter $125 \mu\text{m}$, and index number was 0.25. Since the optical fibers were arrayed closely, the interval of the fiber axis of this probe L_f was nearly equal to the cladding diameter of each fiber. In this work the relation between the particle velocity v_p and the frequency f_p was calibrated for accuracy, although the relation between them is given by Eq.(1).

Fig.4 shows the equipment of calibration, where a test particle is fixed on a disk driven by a motor. The relation between the frequency f_p and the particle velocity v_p is shown in Fig.5, from which

$$v_p [\text{m/s}] = 0.5146 f_p [\text{kHz}] \quad (3)$$

is obtained. An example of signal V_{A-B} is presented in Fig.6, and the spectrum

Fig. 1 Optical fiber probe

Fig. 2 Reflection signals

1.optical fiber 2,3.plate glass
4.stainless pipe

Fig. 3 Details of the probe

Fig. 4 Equipment of calibration

distribution obtained by the FFT spectrum analyzer is shown in Fig.7.

The intensity of reflected light depends on the position of a particle relative to the top end of the fiber, and thus in counting particle numbers, the relation between the intensity of light and position should be examined. This relation is important in setting up a threshold value for the reflected light, and it was obtained for the optical fiber of the group C. The results are shown in Fig.8. The abscissa Y means the distance between the particle and the top of the probe, and the ordinate V_p means the maximum intensity of the reflection signal at the distance Y . Exactly speaking, each particle has different characteristics of the light reflection. When the distance Y is small, this difference due to the particle is relatively large. The intensi-

Fig. 5 Relation between particle velocity and the corresponding frequency

Fig. 6 Differential signal

Fig. 7 Spectrum distribution

ty V_p tends to decrease sharply as the distance Y increases. The larger the distance Y , the more obscure the difference due to the particle. The threshold level was set at 0.4 V based on Fig.8.

4. Experiment

The pipeline for transport experiment is shown in Fig.9. The air flow rate was adjusted by a valve and measured with a Pitot tube. Particles in a feed tank were supplied into the horizontal pipe from an electromagnetic feeder. The horizontal pipeline was made of transparent acrylic pipes with inner diameter 52 mm. Measurement of the particle velocity and concentration was made in the measuring section 5210 mm downstream of the feeder. The solid particles used in this experiments were spherical polystyrene pellets with mean diameter 0.406mm. Details of the measuring part are shown in Fig.9(b). The test pipe of the measuring section was joined to the upstream and the downstream pipes by rotary flanges which enabled the test pipe to rotate freely about the pipe axis. In addition, the optical fiber probe was movable in the direction of the pipe radius with the traversing equipment. The head of the probe could be located at any point in the cross section by these equipments. In practice, measurement was carried out in the half cross section after confirming symmetry of the phenomena. The measuring point in the cross section are shown in Fig.10, where η is the dimensionless distance from the bottom of the pipe. The measuring points correspond to the apices of each triangle. The particles passing through the measuring section were separated from air flow with

Fig. 8 Relation between light intensity and the distance between a particle and the top of the probe

cyclone separators, and the air was discharged into the atmosphere. The flow rate of particles was measured with a load cell set under the storage bin.

Fig.11 shows a block diagram of signal processing. The spectrum distribution of signals from the FFT spectrum analyzer was displayed on the synchroscope. The value of the frequency f_p was determined from the frequency corresponding to the peak of the spectrum distribution.

5. Experimental results and considerations

5.1 Distribution of Particle Concentrations

The mass flow rate of particles is given by

$$G_K = \int_F \rho_{KF} \cdot v_p dF \dots\dots\dots (4)$$

where the integral is made over the entire pipe cross section. From Eq.(2) and Eq.(4), we have

$$\rho_{KF} = \frac{N \cdot G_K}{v_p} \bigg/ \int_F NdF \dots\dots\dots (5)$$

The pipe cross section is divided into many triangular elements as shown in Fig.10. Assuming that the integrand has a planelike distribution which is determined

by the values at three apices, the integration in Eq.(5) was carried out numerically. The mean dispersed density ρ_{KF0} is also calculated by integrating local concentrations of the particles over the cross section, which is given by

$$\rho_{KF0} = \frac{1}{F} \int_F \rho_{KF} dF \dots\dots\dots (6)$$

Fig.12 shows examples of the distribution of ρ_{KF}/ρ_{KF0} in the cross section. In the scope of this experiment, contour lines of equal concentration form a group of horizontal lines. The distributions of the ρ_{KF}/ρ_{KF0} in the vertical plane through the pipe axis are shown in Figs.13(a) and (b), where the loading ratio μ and the mean air velocity u are presented as parameters. As is expected, particles tend to concentrate near the bottom of the pipe due to the gravity. And the degree of concentration to the bottom becomes larger at small mean air velocities and large loading ratios. It is noted that the concentration distributes exponentially in the vertical direction when the mean air velocity is comparatively large and the loading ratio is comparatively small. This relation does not hold near the bottom of the pipe as the mean air velocity decreases and the loading ratio increases.

The present results were compared with those by previous workers such as

1.Blower 2.Valve 3.Air flow rate measuring section 4.Feed tank 5,6.Electromagnetic feeder 7.Air pump 8.Ion generator for preventing electrification 9.Measuring section 10,11.Cyclone separator 12.Solid storage bin 13.Load cell
(a) Pipeline

1.Rotary flange 2.Protractor 3.Traversing Equipment 4.Optical fiber probe 5.Rotary flange
(b) Details of measuring part
Fig. 9 Pipeline for transport experiment

Fig. 10 Measuring points in the pipe cross section

Fig. 11 Block diagram of signal processing

Welschof⁽¹⁾, Ikemori et al.⁽⁴⁾ and Jotaki⁽³⁾ who used coarse particles (2~4mm) in their experiments. Though their measurements are not so detailed as this work, the exponential distributions of concentrations are observed. The particle size in the present experiment is 0.406 mm, much smaller than the sizes in the previous experiments cited above. It is found from the above comparison that the exponential distribution is common to both fine and coarse particles. The dispersed density varied from 0.01 to 200 kg/m³ in this experiment, which corresponds to the volumetric concentration ranging from 0.001 to 20 %. Measurement in such a wide range of concentrations is difficult without the optical fiber probe.

5.2 Distribution of particle Velocities

Contours of equal particle velocities represented dimensionless with mean air velocity are shown in Fig.14. Fig.15(a) and (b) show the distributions of v_p/u in the vertical plane involving the pipe axis to see the effects of the loading ratio and the mean air velocity. Figs.14 and 15 indicate that the distribution of particle velocities is rather flat at low loading ratios and high air velocities, and that

the particle velocity at the bottom of the pipe tends to decrease as the loading ratio increases and as the air velocity decreases. As a result the distribution becomes more unsymmetrical. Such a tendency is closely related to the distribution of concentrations which is shown in section 5.1. This relation mainly corresponds to the concentration of particles in the lower part of the pipe section. As shown in Figs.14 and 15 the particle velocity tends to decrease near the pipe wall. This fact is caused by the momentum loss of the particles due to collision against the pipe wall, and by the deceleration of the particles owing to the drag force due to a lower air velocity near the wall.

The decrease in particle velocity with an increase in the loading ratio is a phenomenon which should be noticed in connection with the problem of pipe blockage. Fig.16 shows the relation between the loading ratio and the non-dimensional velocity at the bottom of the pipe where the particle velocity takes the minimum value. In the case of $u=8$ m/s, the particle flow becomes unsteady at $\mu=6\sim7$ where v_p/u approaches zero. When the loading ratio increases further, the flow

Fig. 12 Contour lines of equal concentration

Fig. 13 Distributions of concentration in vertical direction

changes to the one accompanying a fixed bed.

5.3 Relation between particle velocity and Concentration

The results described above are qualitatively the same as those reported by previous workers. Hence, in order to get more information the authors investigated the correlation between the particles velocity and the distribution of concentrations.

It is clear from Fig.12-15 that there

exists a close relation between the particle velocity and the distribution of concentrations. The relation is obvious especially near the bottom of the pipe. The particle velocity at the bottom of the pipe clearly decreases with increasing in the concentration. The relation between ρ_{KF}/ρ_{KF0} and v_p/u at the bottom of the pipe is shown in Fig.17, where it is found that there exists a linear relation between ρ_{KF}/ρ_{KF0} and v_p/u within the range of the present experiment. It is expected that

Fig. 14 Contour lines of equal particle velocity

Fig. 15 Distributions of particle velocity in the vertical direction

Fig. 16 Relation between loading ratio and particle velocity at the bottom of the pipe

Fig. 17 Relation between concentration and particle velocity at the bottom of the pipe

the gradient of the concentration in the vertical direction is affected significantly by the inertia or particle velocity. Therefore, the effect of the particle velocity v_p on the concentration gradient $\Delta(\log \rho_{KF})/\Delta\eta$ which is obtained from Fig.13 is considered. As a result, the velocity ratio v_p/u is found to be well correlated to $\Delta(\log \rho_{KF})/\Delta\eta$, as indicated in Fig.18. Although the data are largely scattered in the figure, the relation is independent of the air velocity.

5.4 Coefficient of pressure drop

In this section, the coefficient of pressure drop is shown, which is obtained in the region where the particle velocity is sufficiently developed, and the particle velocity calculated by the one dimensional analysis⁽¹²⁾ is compared with the velocity obtained directly by the optical fiber probe.

The coefficient of pressure drop λ_z^* is defined by

$$dW_R = \lambda_z^* \frac{dx}{d} \frac{\rho_{KF0}}{2} c^2 F \quad (7)$$

where dW_R is the frictional force acting between the particles and the pipe wall in the region dx , c is the particle velocity, d is the pipe diameter, and ρ_{KF0} is a mean dispersed density. ρ_{KF0} is given by

$$\rho_{KF0} = \frac{G_K}{FC} \quad (8)$$

From the balance of the forces acting on particles in the region dx , we have

$$dW_R = F dp_K \quad (9)$$

where dp_K is the additional pressure drop at dx . If c is known, λ_z^* can be obtained by the above equations. From the conservation equations of momentum for the air and particles,

$$c/u = \gamma - \sqrt{\gamma^2 - 1} \quad (10)$$

is derived, where

$$\gamma = \frac{dp_K/d\xi}{2C_D\beta\mu\rho_L u^2} \quad (11)$$

$$\beta = \frac{3}{4} \frac{\rho_L d}{\rho_K d_K} \quad (12)$$

Fig. 18 Relation between particle velocity and gradient of concentration

$\xi = x/d$, ρ_L is the air density, ρ_K is the particle density, d_K is the particle diameter and C_D is the drag coefficient of a single particle.

Using the above equations, λ_z^* is obtained from the additional pressure drop. Fig.19 shows the effect of loading ratio on λ_z^* . It is found that λ_z^* increases rapidly with increasing the loading ratio in the range of low air velocities ($u \leq 7$ m/s). In the middle range ($u = 8 \sim 10$ m/s), λ_z^* tends to become larger at low loading ratios. It is considered for this reason that the particle velocities calculated by Eq.(10) take smaller values than measured values in the range of low loading ratios. At high air velocities larger than 12 m/s, λ_z^* slightly decreases with increasing loading ratio. In the case of $u = 12$ m/s λ_z^* indicates a tendency of increase at the loading ratios larger than 13.

λ_z^* tends to hold a constant value when the air velocity is large and the loading ratio is small. In a vertical pipe, it is known that λ_z^* has a constant value determined by materials of pipe and particles⁽¹³⁾. Such characteristic properties are considered to be valid also for the horizontal case if the Froude number $F_r^* = c/\sqrt{gd}$ is so high that the effect of the gravity can be neglected. In the range in which λ_z^* takes a constant value independent of the loading ratio and the velocity, the mean value of λ_z^* is 0.0057. This value is not so different from the value 0.0045⁽¹²⁾ which was obtained from the pressure drop in a vertical pipe where particles are accelerated.

Fig.20 shows a comparison between c/u calculated from Eq.(10) and $\bar{v}_p/u$, where $\bar{v}_p$ is the mean particle velocity defined by

$$\bar{v}_p = \frac{\int_F \rho_{KF} v_p^2 dF}{\int_F \rho_{KF} v_p dF} \quad (13)$$

At any velocity, both velocities c and $\bar{v}_p$ almost agree with together except at low loading ratios. At low loading ratios, c/u is smaller than $\bar{v}_p/u$. This is caused by increasing λ_z^* as the loading ratio decreases.

Fig. 19 Coefficient of additional pressure drop

Fig. 20 Comparison of particle Velocity between calculations and direct measurements

6. Conclusions

An optical fiber probe based on the space filtering technique was developed for measurement of the particle velocity and concentration. After examining the characteristics of the probe, the experiments of transport were made in a horizontal pipe on the condition of comparatively low air velocities, where spherical polystyrene pellets were used. The mean diameter of particles is 0.406 mm. Particle velocities and concentrations were obtained over the pipe cross section. In addition, the coefficient of pressure loss is considered. Also, particle velocities, calculated from additional pressure drop are compared with the velocities obtained by the optical fiber probe. The following conclusions are obtained.

(1) The present optical fiber probe is useful over a wide range of particle concentrations.

(2) Contour lines of equal concentration form a group of horizontal lines, and the concentration increases exponentially in the vertically downward direction. The gradient of concentration tends to increase with a decreasing air velocity and an increasing loading ratio.

(3) Within the range of the present experiment, the relation between v_p/u and ρ_{KF}/ρ_{KF0} at the bottom of the pipe is independent of the air velocity u . Furthermore, it is found that there exists a relation between the gradients of distribution and v_p/u (see Fig.18).

(4) The particle velocities derived from pressure drops, based on the one dimension model, well agree with direct measurements, except for the low loading ratios. Furthermore, as air velocities become large, the characteristics of coefficient of pressure drop λ_2^* for horizontal pipe approach the one for vertical pipe.

Acknowledgments

The authors wish to thank Mr. S. Nishida and Mr. T. Shiratori for their assistance in the present experimental work.

References

- (1) Welschhof, G., VDI-Forsch. -Heft 492 (1962).
- (2) Uematu, T. and Morikawa, Y., Bull. JSME, Vol. 4, No. 15 (1961), p. 525.
- (3) Jotaki, T., Pneumatic Conveying of powder and particles (in Japanese), Nikkankogyo (1974), p. 141.
- (4) Ikemori, K., et al., J. Soc. Powder Tech., Japan (in Japanese), Vol. 19, No. 12 (1982), p. 24.
- (5) Takegawa, T., et al., Bull. JSME Vol. 22, No.170 (1979), p. 1107.
- (6) for example, Tsuji, Y., et al., J. Fluid Mech., Vol. 120 (1982), p.385
- (7) Oki, K., et al., Kagaku Kogaku (in Japanese), Vol. 37, No. 9 (1973), p. 965.
- (8) Patrose, B. and Caram, H., S., AIChE J., Vol. 28, No. 4 (1982-7), p. 604.
- (9) Petrak, D. and Hoffmann, A., Proc. 2nd Conf. Pneum. Convey., B22 (1978), p. 225.
- (10) Naito, M., et al., J. Soc. Instrum. Control Eng. (in Japanese), Vol.7, No. 11 (1968-11), p. 761.
- (11) Ishida, M., et al., Kagaku Kogaku Ronbunshu (in Japanese), Vol. 5, No.5 (1979), p. 487.
- (12) Sunami, T., et al., Bull. JSME, Vol. 21, No. 153 (1978), p.447.
- (13) Morikawa, Y. and Tanaka, T., J. Soc. Powder Tech., Japan (in Japanese), Vol. 21, No. 2 (1984-2), p. 21.