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FLOW PATTERN AND PRESSURE FLUCTUATION IN AIR–SOLID TWO-PHASE FLOW IN A PIPE AT LOW AIR VELOCITIES

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Abstract—An experiment was made on an air–solid two-phase flow in a horizontal pipe. The main concern was the relation between flow patterns and pressure fluctuation at low air velocities. First, the flow patterns were classified into five different types depending on the air and particle flow rates. Next, it was shown how the properties of pressure fluctuation change as the air velocity decreases. Further, fluctuation signals were analyzed in detail and differences due to the flow patterns and particle size were discussed.

1. INTRODUCTION

A flow blockage in the pipe line caused by the decrease in air velocity is the most undesirable accident in the pneumatic conveying. Hence, there have been many reports about the air velocity which has been called "minimum transport velocity" or "critical velocity" (e.g. Barth 1954, Matsumoto *et al.* 1975, 1977, 1979, Zenz & Othmer 1960). In the case of a horizontal pipe, the minimum transport velocity is usually defined as the velocity required to prevent sliding particles on the bottom of the pipe. Most of earlier workers have made an effort to deduce an empirical relation between the minimum transport velocity and various conditions like the properties of particles and pipe diameter. Their works are very important for designing pneumatic conveying facilities. However, investigation of the flow itself near the flow blockage has not been made sufficiently enough. Generally, the effects of the air velocity on the flow pattern of the two-phase flow are small when the velocity is high. On the other hand, as the air velocity decreases, even a small change in the air velocity brings about remarkable changes in the flow pattern. Such a rather unstable flow condition, which is typical of the low velocity region, makes difficult a universal and systematic analyses of data and thus detailed investigations of the flow are very scarce. Nevertheless, it is important to know the flow near the critical situation in view of damage due to the flow blockage. Although characteristics of the air-solids flow at low velocities are pulsating or fluctuating motions, properties of such fluctuations have been scarcely studied. Therefore, in this work, the pressure fluctuation which is easy to detect were considered, and the relation between the pressure fluctuation and flow patterns was investigated.

2. EXPERIMENTAL EQUIPMENT

Figure 1 shows the experimental equipment and measuring system. The air was supplied by a blower having a capacity of 4.8 m^3 air delivery and 2.7×10^4 Pa gauge pressure. A part of the air was bypassed through the valve ②. Solid particles supplied by an electro-magnetic feeder ④ were conveyed through a horizontal pipe and received by cyclone separators ⑤. A transparent acrylic pipe of 40 mm in internal diameter D was used for the whole transportation line through which the flow pattern was observed. The distance between the feeder and separator was about 14 m. Pressure transducers as well as photo-detectors were set at the measuring sections, A and B, about 1.4 m apart from each other. The measuring sections were placed at the points more than 270 D from the feeder, so that the particle mean motion was considered to be steady after acceleration by the air stream. The air flow rate was measured by a hot-wire probe ⑩ set up upstream of the feeder. The particle flow rate was measured by a load-cell under the receiver ⑥. The signals from the pressure transducers, photo-cells and hot-wire anemometer were recorded in an electromagnetic recorder and data recorder. The data

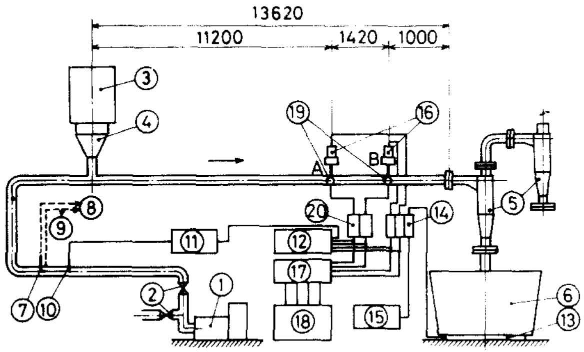

Figure 1. Experimental equipment: 1, blower; 2, flow adjusting valve; 3, hopper; 4, electromagnetic feeder; 5, cyclone separators; 6, receiver; 7, Pitot tube; 8, Göttingen manometer; 9, U-tube manometer; 10, hot-wire probe; 11, hot-wire anemometer; 12, electromagnetic recorder; 13, load-cell; 14, strain meter; 15, pen recorder; 16, pressure transducer; 17, DC amplifier; 18, data recorder; 19, photo-detector; 20, DC amplifier.

on the records was sampled at intervals of 10 ms and recorded on magnetic tape in digital form for subsequent numerical analysis by a computer. As was stated before, fluctuating motions were main interests of the present work. Among the fluctuating motions, only the motions showing the same pattern of fluctuation during a certain period, say 2 ~ 5 min, were adopted as the data for processing. That is, cases which changed from one steady state to another during the measuring time were omitted in data processing. The criterion of such steady states was made by confirming the same pattern of wave form of the pressure fluctuation and constant increase in weight of received particles in addition to visual flow observation by eyes. Two kinds of spherical particles, small and large, were used which differ in diameter by a fraction of 10 (0.19 mm and 2.8 mm in mean diameters). Figure 2 shows the size distributions of the particles. Both particles were plastic pellets with the density of about 1000 kg/m^3.

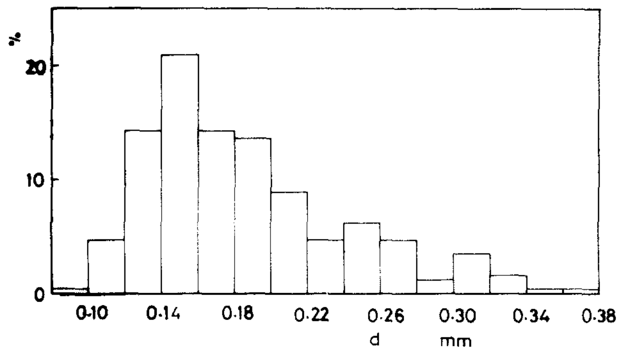

Figure 2(a). Size distribution (small particles, mean diameter = 0.19 mm).

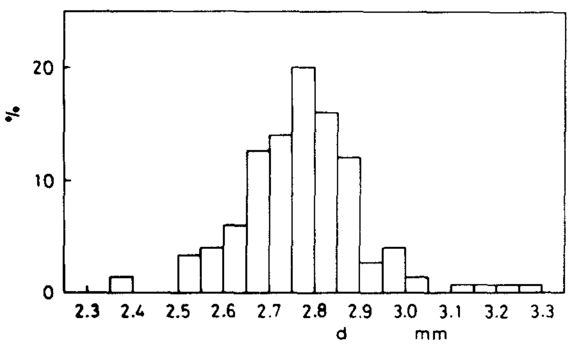

Figure 2(b). Size distribution (large particles, mean diameter = 2.8 mm).

3. RESULTS

3.1 *Classification of flow patterns*

The flow patterns in this experiment are classified into five types shown in figure 3. The pattern ① corresponds to the case of high air velocities where all particles are suspended in dispersive phase. As the air velocity decreases, the pattern changes from the type ① to ②. The particles of the pattern ② form clusters sliding on the bottom of the pipe at nearly constant intervals. The velocities of the clusters are less than half the mean air velocity. Between the clusters, particles fly at higher velocities than the cluster. The interval between the clusters depends on the air velocity. The larger the velocity, the smaller the interval. For instance in the case of small particles, the interval widely ranged from 1 to 10 m. As the air velocity decreases further, the particle cluster becomes larger and larger, and almost stops sliding. If it slides, the velocity is less than 50 cm/s. The spacing between this large cluster and pipe upper wall is so narrow that it forms a kind of throat at which particles are blown off. The blown off particles deposit one after another and are entrained into the other stationary cluster again. As a result, the size of this cluster was changeable. An additional complication is that the stationary cluster is sometimes swept out suddenly and disappears. Decreasing the air velocity further, a stationary layer of deposit particles is formed on the bottom of the pipe above which other particles fly. As the air velocity decreases further, the flow becomes very unstable. In the case of small particles, a long plug was formed and it led to the flow blockage at once. In the case of large particles, a stable plug flow was possible when the particle flow rate was not so high. The number of the stable plug was always limited to one along the entire pipe. Although figure 3 shows only five patterns. It may be possible to sub-divide each one into more detail. However the five patterns mentioned above are discussed in this paper.

In the above, the flow patterns are described to depend simply on the air velocity or air flow rate G_a, but actually the pattern is largely affected by the particle size and the particle flow rate G_p. Figure 4 shows how each pattern distributes in a $G_a \sim G_p$ map. A similar map proposed by Baker (1954) and others (Weisman *et al.* 1979) is well known in the air–liquid two-phase flow. However, such data representation is rare for the air–solids flow. Ambiguous boundaries between the patterns are inevitable in the present experiment, because these kinds of flows are more or less unstable. When the particle size is small and particle flow rate is large, the transition of ① → ② → ③ → ④ takes place in the same way as shown in figure 3. However, as the particle flow rate decreases, the pattern ② is not observed clearly. The map of large particles is much different from that of small ones. First, the region where the transportation is possible is limited to the high velocity range compared with the case of small particles.† The

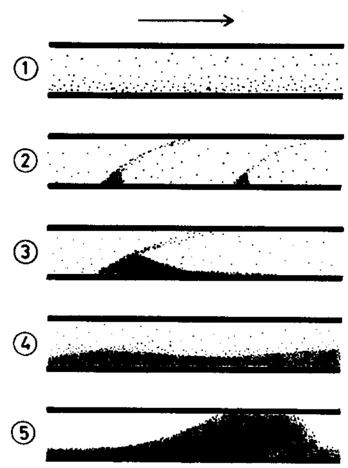

Figure 3. Flow patterns.

†One must notice that the possibility of transportation depends on the performance of a blower and pipe line system. If a blower with higher pressure performance had been used and the bypass valve had been removed, the range of transportation would have expanded to the lower velocity region.

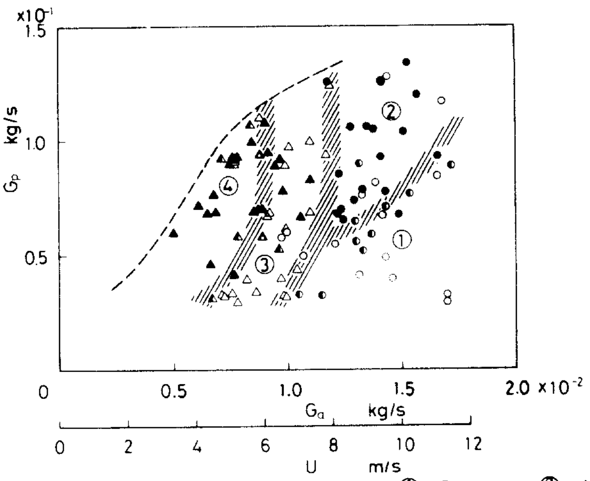

Figure 4(a). Flow pattern map for small particles (○, pattern ①; ●, pattern ②; △, pattern ③; ▲, pattern ④).

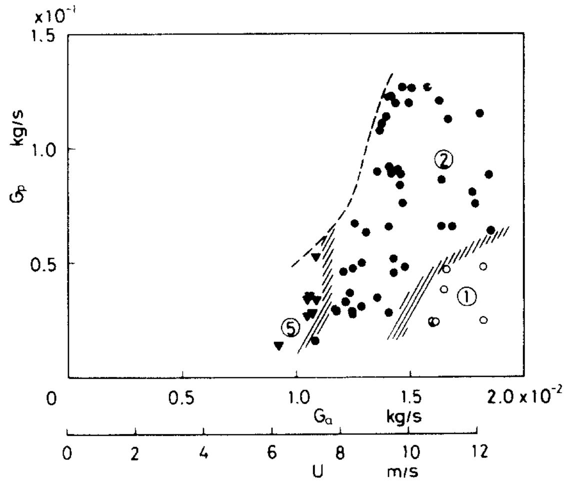

Figure 4(b). Flow pattern map for large particles (○, pattern ①; ●, pattern ②; ▼, pattern ⑤).

map of large particles shows the plug flow region ⑤ for small G_p and G_a, while it does not show regions ③ and ④. Although plug formation was observed in the case of small particles as well, it was not steady but it led immediately to the blockage. This means that higher pressure is necessary for the plug flow of small particles than large particles.

3.2 *Particle velocity*

Velocities of particle clusters were obtained from cross correlation of the photo-cell outputs at two points, *A* and *B* which are shown in figure 1. Figure 5 presents an example of the measured cross correlation. A sharp peak in the figure corresponds to the delay time $\tau = l/U_p$, where l is the distance between *A* and *B*, and U_p is the velocity of the particle cluster. When all particles fly, fluctuating concentration of particles causes light and shade image on the photo-cell. Therefore the velocities of flying particles could be measured in the same way, although the peak value in the correlation was not so sharp as in figure 5 but rather round. The results of velocities are shown in figure 6, where the values of ②, ③ and ⑤ are the velocities of particle clusters or plugs, and the values of ① and ④ are those of flying particles. Both results of small and large particles indicate that the velocity decreases with decreasing air velocity when G_p is constant. Velocities of particle cluster in the region ② are in the same range from 2 to 6 m/s in both particles, while the velocities of flying small particles are

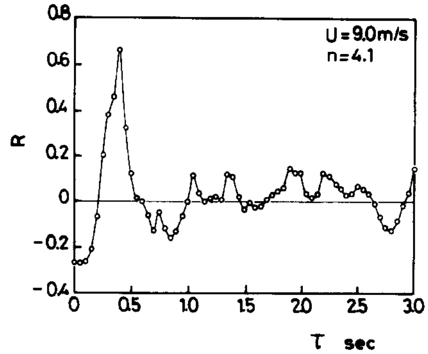

Figure 5. Cross correlation of the signals of photo-cells.

larger than large ones as the air velocity increases. Particle velocities in the region ④ are larger than the mean air velocity. That is because the stationary particle layer reduced the cross section where the air flows and increased the local air velocity substantially.

3.3 *Pressure drop and amplitude of pressure fluctuation*

The relation between the pressure drop per unit length and mean air velocity is presented in figure 7, where the region of each flow pattern is also shown. The mean value of pressure was obtained by averaging instantaneous pressure during about 40 s. The measuring region is wider in the case of small particles than large ones, because transportation of small particles was possible at lower velocities. However, data of small particles scatter more largely than large particles, which is because the flow of small particles is more unstable than large particles. Several earlier workers (for example, Zenz & Othmer 1960) related the flow pattern to the

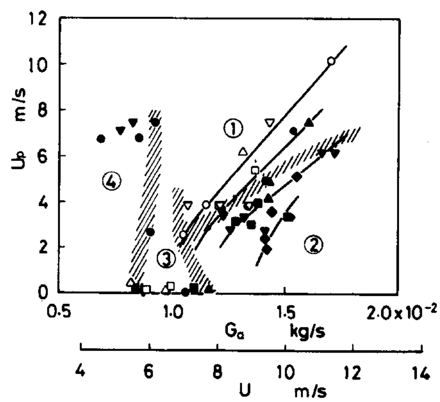

Figure 6(a). Velocities of small particles. (For legend, see Table 1).

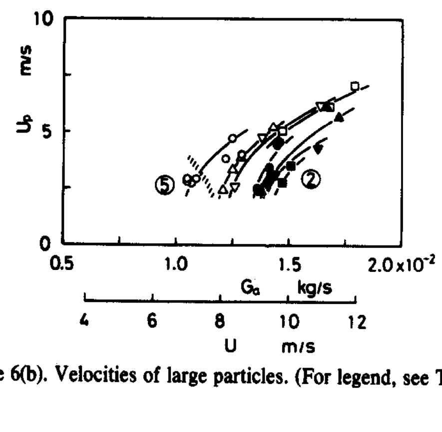

Figure 6(b). Velocities of large particles. (For legend, see Table 1).

Table 1.

G_p kg/s	
Small particle	Large particle
○ 0.03	○ 0.03
△ 0.04	△ 0.05
▽ 0.05	▽ 0.07
□ 0.06	□ 0.08
● 0.07	● 0.09
▲ 0.08	▲ 0.11
▼ 0.09	▼ 0.12
■ 0.10	■ 0.13
◆ 0.13	

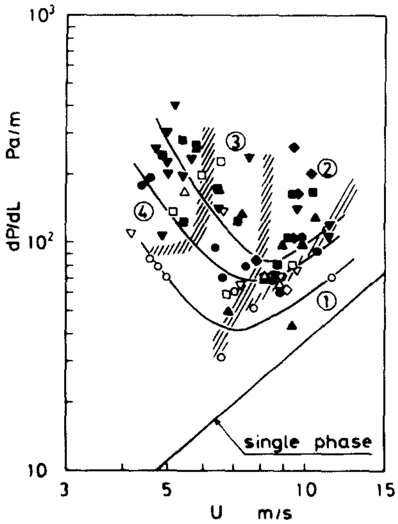

Figure 7(a). Relation between the pressure drop and air velocity for small particles. (For legend, see table 1)

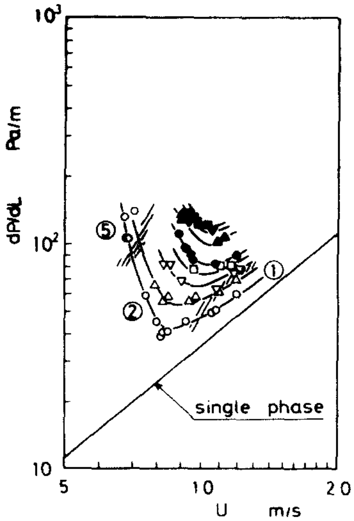

Figure 7(b). Relation between the pressure drop and air velocity for large particles. (For legend, see table 1).

pressure drop diagram as in figure 7. The present results do not always agree with them, if comparison is made precisely. Furthermore, the present results of small particles differ much from those of large particles. Therefore, one must recognize that the relation between the pressure drop diagram and flow pattern is not simple, depending on distributions of particles and other conditions.

Figure 8 shows the amplitude (RMS values) of pressure fluctuation plotted against the air flow rate or velocity with the particle flow rate as a parameter. If one pays attention to the change in the amplitude with decreasing air velocity, one notices that the amplitude generally increases as the air velocity decreases in both results of small and large particles. That is because the flow pattern changes from a dispersive type ① to fluctuating ones ② and ③ which accompany particle clusters causing the large pressure fluctuation. An unexpected result shown in figure 8 is that the amplitude of small particles decreases sharply as the air velocity is further reduced. This change is closely related to transition of flow patterns from ③ to ④. Two different amplitudes occur sometimes even though the condition of G_a and G_p is the same. That is because the flow pattern is different from each other due to delicate difference caused by other factors. As long as the pattern ③ is maintained, the amplitude keeps increasing with decreasing air velocity. Once the pattern changes to the type ④, the amplitude drastically

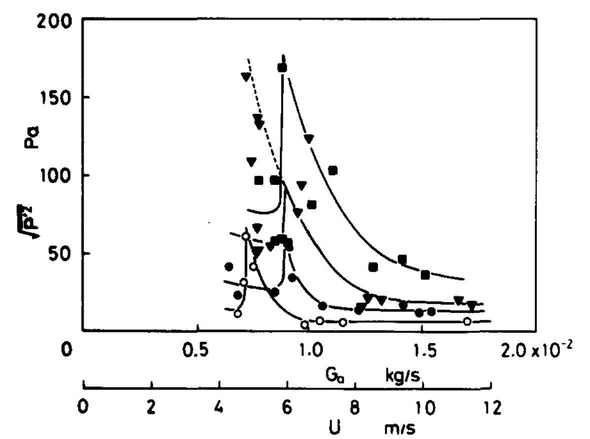

Figure 8(a). Amplitude of pressure fluctuation for small particles. (For legend, see Table 1).

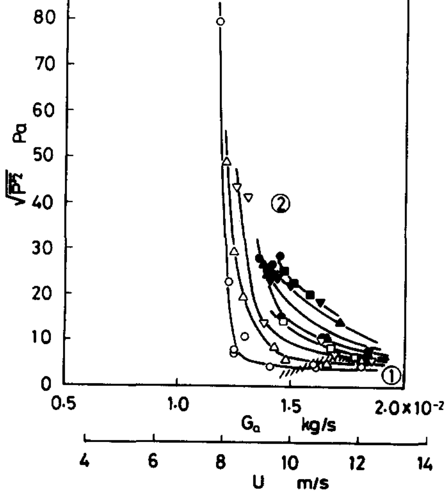

Figure 8(b). Amplitude of pressure fluctuation for large particles. (For legend, see Table 1).

decreases. Since the pattern ④ is near the state of flow blockage, the sharp decrease in pressure fluctuation can be a warning signal for blockage. The decrease in pressure fluctuation mentioned above could not be observed in the case of large particles, because large particles did not have the steady state of the pattern ④.

3.4 *Wave form analysis of pressure fluctuation*

Figure 9 shows the wave form of instantaneous pressure of each flow pattern, where p_0 is the atmospheric pressure. The wave form of pattern ① shows a very small fluctuation as the foregoing section indicates. The wave forms of patterns ③ and ⑤ are rather peculiar compared with others in that both include remarkably long period components. The large fluctuation in the wave form ⑤ exactly corresponds to the plug passing through the pressure measuring point. However, the long period component of flow pattern ③ does not necessarily correspond to the movement of the particle cluster. This component is mainly related to the process that the large cluster is grown up and swept out. The particle cluster in pattern ③ is so large that its change in shape affects the pressure near the cluster. In this paper the pressure fluctuation was obtained as a deviation from the average value taken for about 40 s. Thus the amplitude of pressure fluctuation shown in figure 8 includes the long period

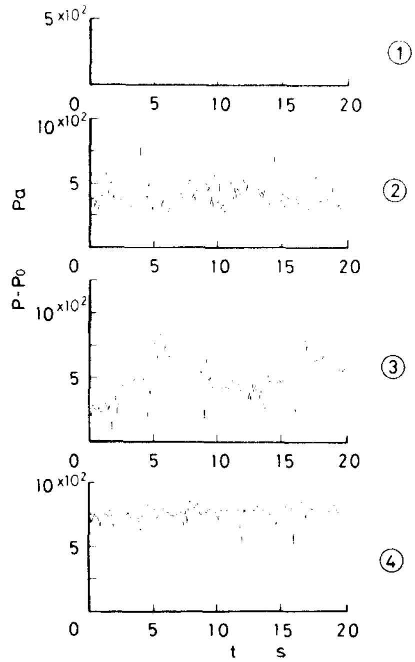

Figure 9(a). Pressure fluctuation (small particles).

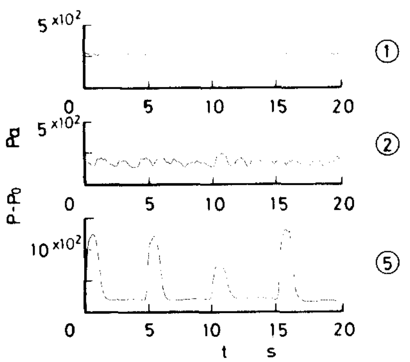

Figure 9(b). Pressure fluctuation (large particles).

component mentioned above which contributes much to the overall amplitude, especially in the cases of flow patterns ③ and ⑤. If the average has been taken for a shorter time, the fluctuation would have become much smaller. In the case of flow pattern ⑤, the fluctuation amplitude is very small except when the plug passes through the measuring section.

The frequency power spectrum of the pressure fluctuation up to 10 Hz was obtained by FFT technique. Figure 10 shows the spectrum of small particles which is normalized by the total amplitude. Characteristics in spectrum of each flow pattern are as follows. The spectrum of pattern ① shows that comparatively high frequency components are dominant, while in pattern ②, dominant components are in the range of 0.1 to 1 Hz. The pressure fluctuation of pattern ② results from the particle cluster sliding on the bottom of the pipe, because the cross correlation of the pressure at the points, A and B, has the same tendency as that of the photo-cell out put. In the case of the pattern ③, the frequency of the dominant component in the spectrum is very low, which corresponds to the long period component mentioned before. The spectrum of the flow pattern ④ is similar to that of pattern ②.

Figure 11 shows the spectra of the flow patterns ② and ⑤ of large particles. The spectrum of pattern ② is similar to that of the corresponding case of the small particles. However, the spectrum peak is generally more remarkable than the case of small particles. The spectrum of pattern ⑤ shows the sharp spectrum peak because of high regularity in the present plug flow.

To discuss the statistical properties of the pressure fluctuation further, the skewness factor S and flatness factor F defined by

$$S = \overline{p'^3}/(\overline{p'^2})^{3/2}$$
$$F = \overline{p'^4}/(\overline{p'^2})^2$$

are shown in figures 12 and 13 instead of the probability density. When the fluctuation follows the Gaussian probability distribution, the skewness and flatness factors have the values of 0 and 3, respectively. Thus figures 12 and 13 indicate how the present pressure fluctuation differs from the Gaussian. The figures show that flow patterns ① and ② follow the Gaussian approximately. The flow pattern ③ has the positive skewness, while flow pattern ④ has the negative one. As for the flatness factor, all the flow patterns except the pattern ① and ② give flatness factors larger than 3. It is found from the above result that the pressure fluctuation at low air velocities deviates from the Gaussian type fluctuation.

3.5 *Volume fraction of particles in the pipe*

The volume fraction of particles is defined by

$$f = V_p/V$$

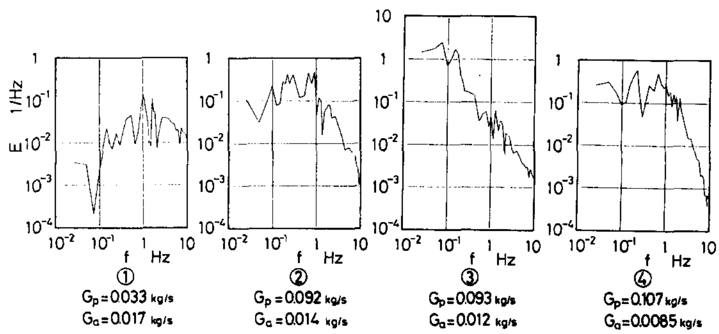

Figure 10. Spectra of pressure fluctuation (small particles).

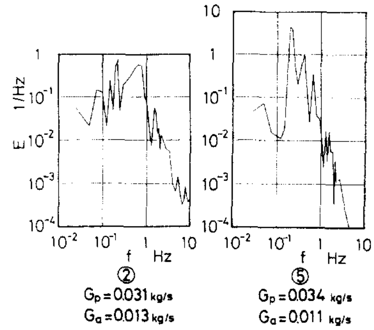

Figure 11. Spectra of pressure fluctuation (large particles).

where V_p is the volume occupied by the particles in a certain length of the pipe of which volume is V. Usually, the volume fraction of solid particles in a pneumatic conveying is negligibly small as long as the mass flow ratio n defined by $n = G_p/G_a$ remains a moderate value. However, when the particles tend to slide or deposit on the bottom of pipe as in the present experiment, the volume fraction is not necessarily small even when the mass flow ratio is not high. Particle mass within the pipe was measured by measuring the particles received from the instant when the feeder stopped particle supply. Such quantities like density of particle and volume of the inside of the pipe were known, and thus the volume fraction for the entire pipe was obtained. The volume fraction V_p/V is plotted against the mass flow ratio n in figure 14. The volume fraction of the flow pattern ① is proportional to the mass flow ratio and remains small. However in other flow patterns, it increases non-linearly. The volume fraction of flow patterns ④ and ⑤ are more than 10 times as large as that of ① for the same mass flow ratio. These high values can not be neglected in an analysis of the pneumatic conveying.

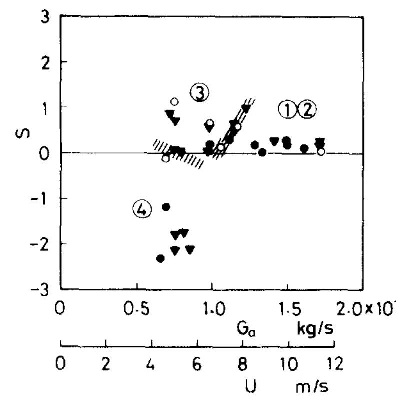

Figure 12(a). Skewness factor of pressure fluctuation for small particles. (For legend, see table 1).

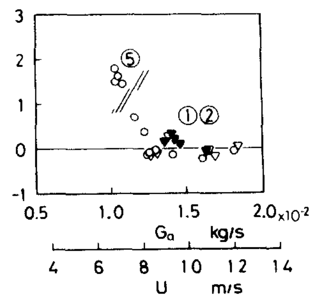

Figure 12(b). Skewness factor of pressure fluctuation for large particles. (For legend, see table 1).

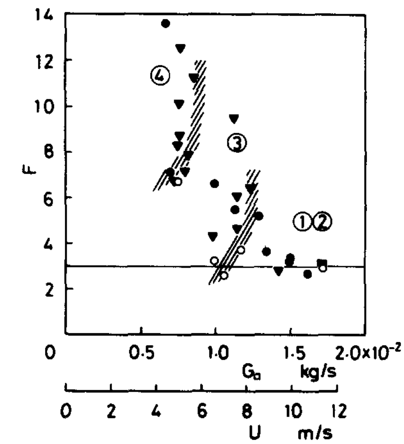

Figure 13(a). Flatness factor of pressure fluctuation for small particles. (For legend, see table 1).

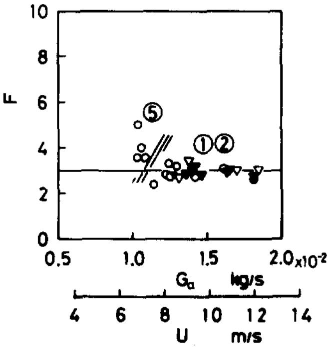

Figure 13(b). Flatness factor of pressure fluctuation for small particles. (For legend, see table 1).

4. CONCLUSIONS

An experiment was made of an air–solids two-phase flow in a horizontal pipe. To study unstable flow near the flow blockage, attention was focused on the behavior at low air velocities and the relation between the flow pattern and pressure fluctuation was investigated. Test particles were spherical plastic pellets of about 0.2 mm and 2.8 mm in diameters and the pipe was 40 mm in inner diameter. The results are summarized as follows.

(1) Classifying the flow pattern into five kinds, maps were proposed which showed the relation between the flow pattern and flow rates of air and particles. The map was found to be different with particle size.

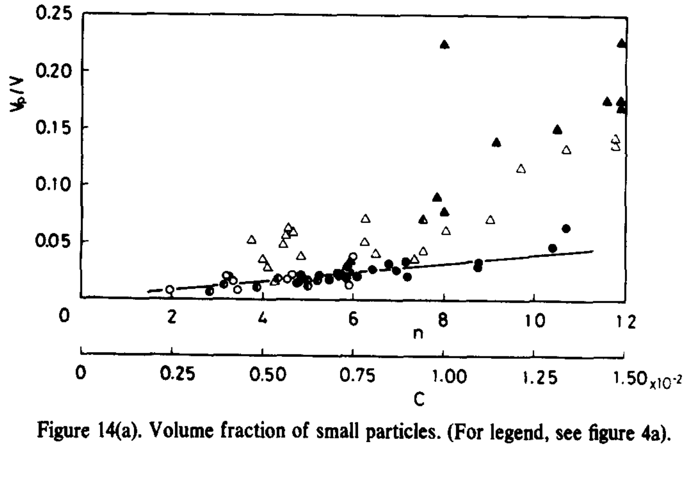

Figure 14(a). Volume fraction of small particles. (For legend, see figure 4a).

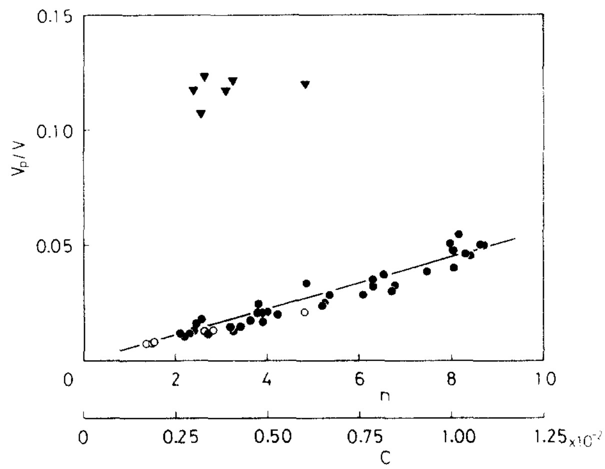

Figure 14(b). Volume fraction of large particles. (For legend, see figure 4b).

(2) Particle clusters formed at low air velocities cause large pressure fluctuation. Each flow pattern shows characteristic properties in the frequency spectrum, skewness and flatness factors of the pressure fluctuation.

(3) In the range of low air velocities, the volume fraction of particles increase non-linearly with the mass flow ratio of particle to air and becomes too high to be neglected.

Acknowledgement—The authors are very grateful to Mr. S. Sugimoto who made the experiment with great competence and enthusiasm.

NOTATION

- D pipe diameter
- d particle diameter
- E spectrum density
- F flatness factor
- f frequency
- G_a air flow rate
- G_p particle flow rate
- n particle-air mass flow ratio
- p static pressure
- p' pressure fluctuation
- R cross-correlation
- S skewness factor
- U superficial air velocity
- U_p mean particle velocity
- V inner volume of the pipe

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