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BRIEF COMMUNICATION

STATISTICAL ANALYSIS OF THE TRANSITION OF THE FLOW PATTERN IN VERTICAL PNEUMATIC CONVEYING

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1. INTRODUCTION

One of the most fundamental problems in designing a pneumatic conveying system is how low an air velocity can be allowed to maintain a certain desired solid flow rate. For vertical transport of solids, this critical air velocity is usually called the choking velocity.

In a previous paper (Matsumoto *et al.* 1982), we defined the choking velocity as the minimum permissible air velocity for stable operation of a conveying system. We showed that it corresponds to the stability limit of the whole system, including the characteristics of the blower and pipelines as well as those of the suspension itself. The prediction method for choking velocity was presented through a stability analysis on the basis of a lumped-parameter approximation.

From the above result, it is suggested that there is the possibility of stable operation at even lower air velocities than those in the previous experimental system, using the same blower, if the arrangement of pipelines is changed. This point will be confirmed through experiments presented in this paper. The main purpose of this paper is to examine the possibility of quantitative description and on-line detection of the transition of flow regimes from suspension to slug flow through the statistical analysis of static pressure and solid concentration fluctuations in the tube.

2. EXPERIMENTAL

The apparatus used is the same as the previous work (Matsumoto *et al.* 1982); i.e. a pressure-type vertical conveying system consisting of a 20 mm i.d. Pyrex glass tube of 5.6 m length. Two points are different from the previous apparatus: one is the application of an electromotive valve so as to achieve more precise control of the air flow rate; the other is a change in the arrangement of the pipelines from the blower so that the resistance coefficient of the by-pass line is increased as much as possible. The minimum permissible air velocity was remarkably reduced, and thus much higher solid concentrations than in the previous work were achieved. The volume concentration of solid ranges up to about 7%.

The fluctuations of static pressure in the tube are detected by use of a semiconductor pressure transducer connected to pressure taps on the tube wall at locations 2.82 and 3.34 m from the solid feed point. A photosensor, which consists of a pair of LEDs (light-emission diode) and a phototransistor, is used to observe the solid concentration fluctations in the tube. This photosensor is the same as that used to measure the solid velocity in a previous work (Matsumoto *et al.* 1986), where two pairs of sensors were used in a cross-correlation technique. The photosensor works as a counter of particles, as shown in the previous paper, though its signals are not proportional to the particle concentrations in the strict sense. However, we did not calibrate the relation between them, seeing that the signals are used only for the statistical analysis of the flow behavior, not for the measurement of concentrations themselves. The output signals from the pressure transducer and the photosensor were read and analyzed by an intelligent signal analyzer (Iwatsu Model SM2100A). In the analysis of fluctuations, parameters such as the sampling interval and data length were selected as follows: the number of sampled data of each signal was 4096 (limited by the signal analyzer) and the sampling interval was selected to be 12.2 ms for pressure and 2.44 ms for solid concentration, by taking account of the frequency characteristics of each variable (examined in preliminary experiments). The averaging of the signals was performed on the basis of the arithmetic average.

Operation of the experimental system and measurements were automatically performed using a personal computer. Most experiments were carried out by reducing the air flow rate, while maintaining a constant solid flow rate. Details of the control algorithm of the solid flow rate and the data-acquisition system are presented elsewhere (Matsumoto *et al.* 1985, 1986). Solid concentration fluctuations were observed in a fully developed region of the suspension, i.e. at a location 4.00 m downstream from the solid feed point. The solid particles were fed by use of a vibrating feeder.

3. RESULTS AND DISCUSSION

In dense phase flow, i.e. at lower air flow rates and higher solid concentrations, slug flow and the recirculation flow of solids in the tube appear as described by Capes & Nakumara (1973). In cases of applications to a riser cracking and other transport-type reactors, slugging and/or recirculation flow are not desirable in these operations and should be avoided. Then, the problem is how to detect, *in situ* if possible, such phenomena occurring in the line. In order to examine the possibility of a quantitative description of the flow regime, a statistical analysis was performed for fluctuations in the static pressure and solid concentration. For the horizontal gas–solid two-phase flow, Tsuji & Morikawa (1982) recently presented a detailed analysis on pressure fluctuations for the purpose of relating them to the flow patterns.

3.1. Pressure fluctuations

Figure 1 shows a typical example of a time-averaged pressure drop along the test tube, and the coefficients of variation (standard deviation normalized by time average) of bottom pressure and of the pressure difference in the fully developed region. As can be seen in figure 1, the bottom pressure fluctuations exhibit no appreciable change in terms of the coefficient of variation with decreasing air flow rate, and the same holds in terms of their power spectrum. This is because a large part of the fluctuation component is affected by the whole system rather than the flow behavior itself. It thus appears that the fluctuations in bottom pressure are not appropriate for detecting directly the dynamic behavior of solids. Therefore, the pressure difference fluctuations are examined below.

It can be seen from figure 1 that the magnitude of the fluctuations in the pressure difference rapidly increased just after the pressure drop reached a minimum. Namely, the coefficient of variation of the pressure difference is $<20\%$ at air velocities from ① to ③, and a small reduction in the air flow rate after ③ brings about a great increase in the coefficient of variation, reaching 100% at ⑥. In such a state, the slugging phenomenon becomes visible. The probability density function of the pressure difference is shown in figure 2, where the numbers correspond to those in figure 1. In figure 2, the probability density function shifts, at ⑤ or ⑥, to a bimodal from a unimodal distribution.† This implies that the flow state of solids changes from homogeneous suspension flow to a heterogeneous flow patterns such as slugging, with a decreasing air flow rate. In such situations, pressure difference fluctuations are composed of a lot of weak fluctuations, they have strong components also, though not very many. Hence they have a large coefficient of variation. The few strong components of the fluctuations are considered to result from the intermittent passage of slug between the pressure taps. The frequency characteristics of these fluctuations are indicated in figure 3 in terms of the power spectral function. At sufficiently high air velocities, the power distribution of the pressure difference fluctuations is almost uniform below 5 Hz. However, some dominant frequencies appear in a lower frequency range at lower air velocities than that at the minimum point in the pressure-drop curve, and then at ⑦ an extremely strong peak is seen around 1 Hz; this indicates the occurrence of slug flow and the increase in power

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†In such cases, the zero on the $\Delta p^{\prime}$ axis in figure 2 does not coincide with the center of gravity of the distribution, because the fluctuations are calculated based on the arithmetic average.

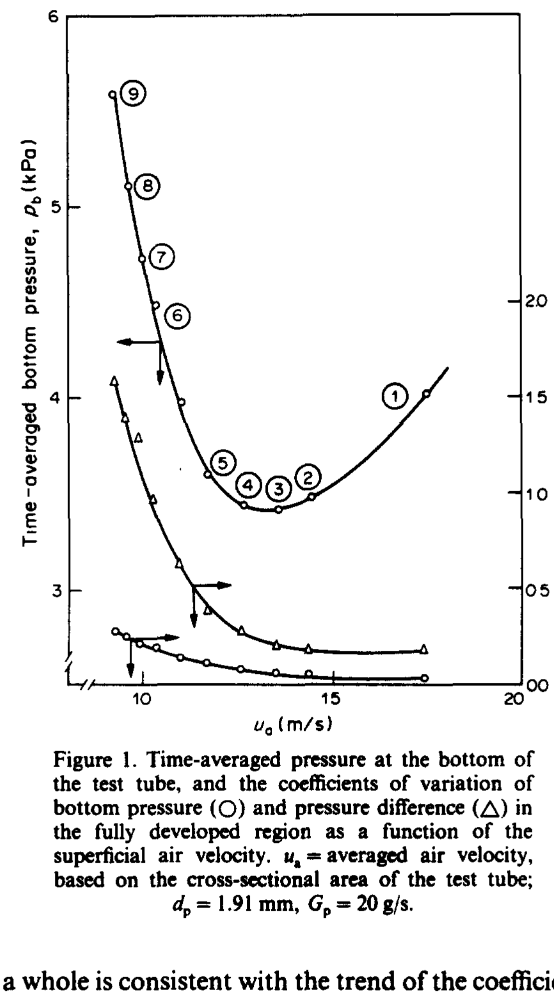

Figure 1. Time-averaged pressure at the bottom of the test tube, and the coefficients of variation of bottom pressure (○) and pressure difference (△) in the fully developed region as a function of the superficial air velocity. u_a = averaged air velocity, based on the cross-sectional area of the test tube; $d_p = 1.91$ mm, $G_p = 20$ g/s.

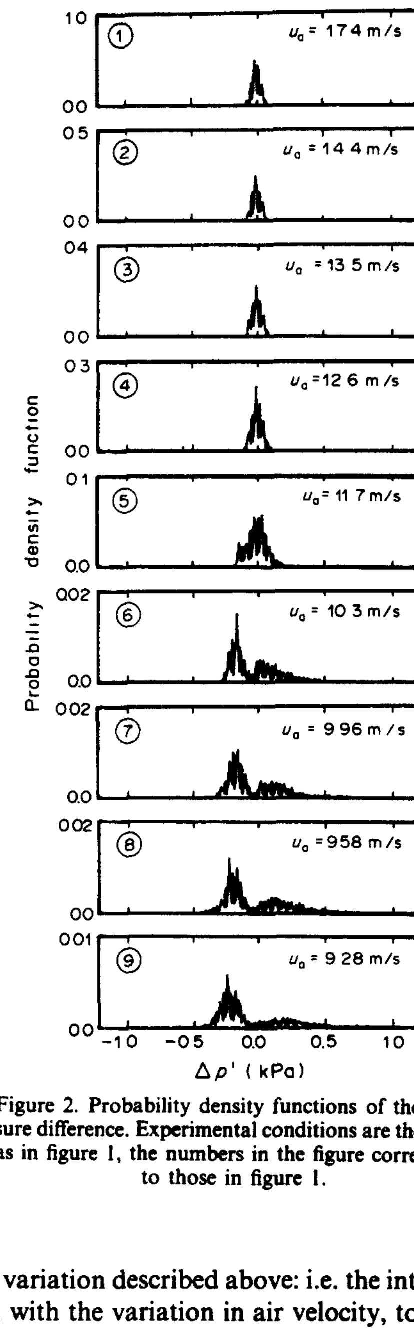

Figure 2. Probability density functions of the pressure difference. Experimental conditions are the same as in figure 1, the numbers in the figure correspond to those in figure 1.

as a whole is consistent with the trend of the coefficient of variation described above: i.e. the integral of the power spectral function shows a similar tendency, with the variation in air velocity, to that in figure 1.

It can be concluded that the pressure difference in a fully developed region, at higher air velocities and hence lower concentrations of solids, exhibits fluctuations closely resembling a white noise with small variance, and as the air velocity decreases and hence solid concentration increases, these change to periodical fluctuations with large variance. Since the probability function exhibits a bimodal distribution in such cases, these periodical components are probably due to slug flow. This point will be made clearer in the following examination of solid concentration fluctuations.

3.2. *Solid concentration fluctuations*

Figure 4 shows the power spectral function of solid concentration fluctuations under the same conditions as in figure 1. As can be seen from the figure, at a high air velocity (①), the fluctuations have almost uniform power in the frequency range up to 50 Hz, just like a white noise, and as the air velocity is decreased, they gain a great deal of power in the lower frequency range around the minimum point of the pressure-drop curve, the extent of which becomes remarkable with further

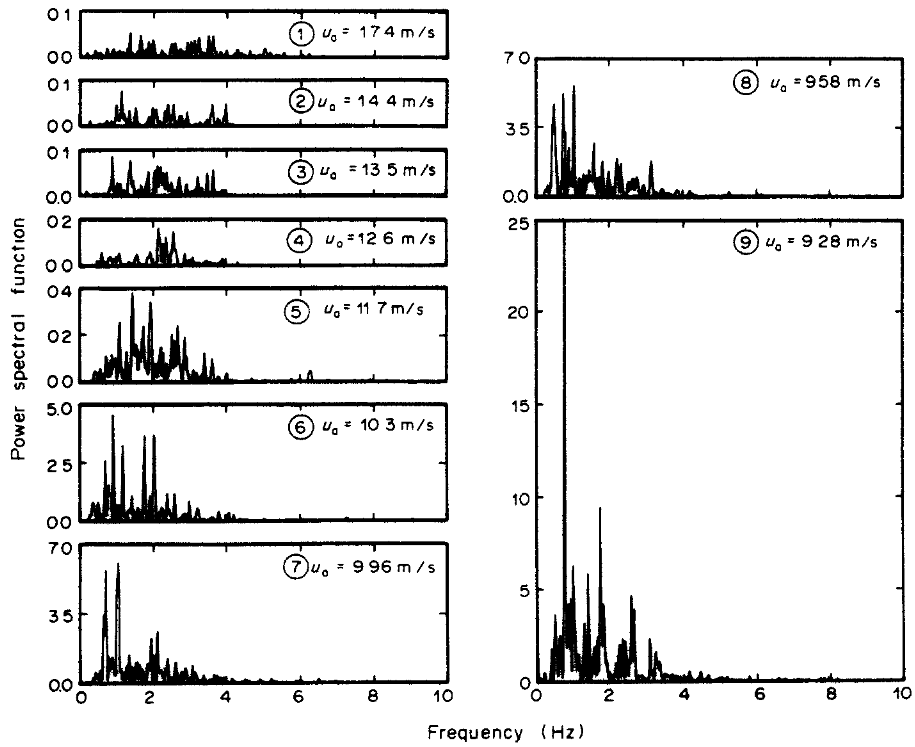

Figure 3. Power spectral functions of the pressure difference fluctuations. The numbers in the figure correspond to those in figure 1.

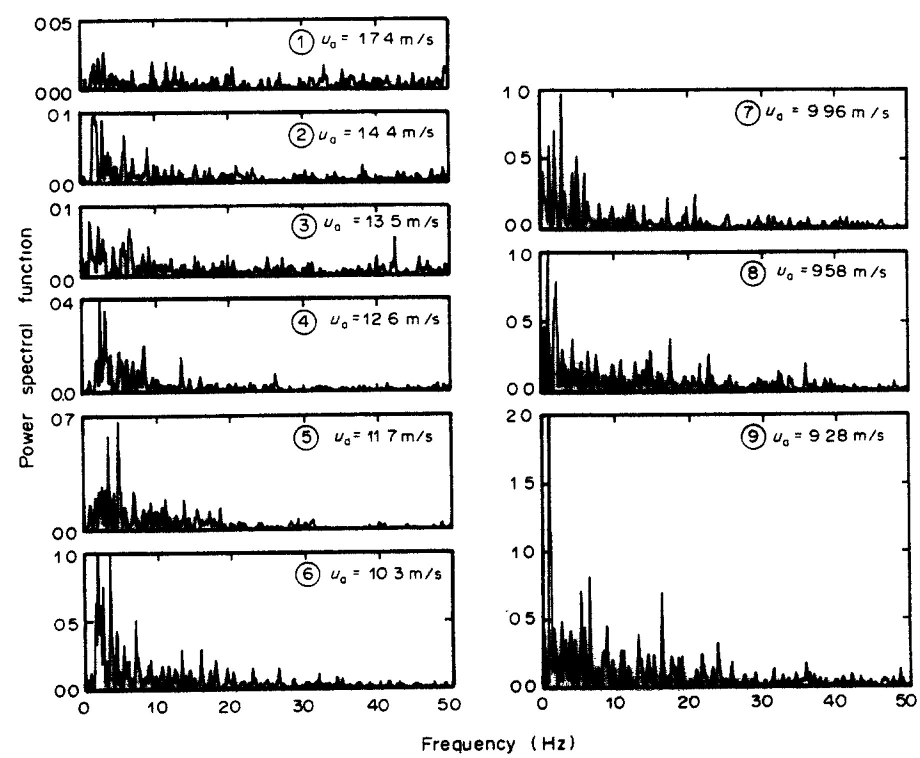

Figure 4. Power spectral functions of the solid concentration fluctuations. The numbers in the figure correspond to those in figure 1.

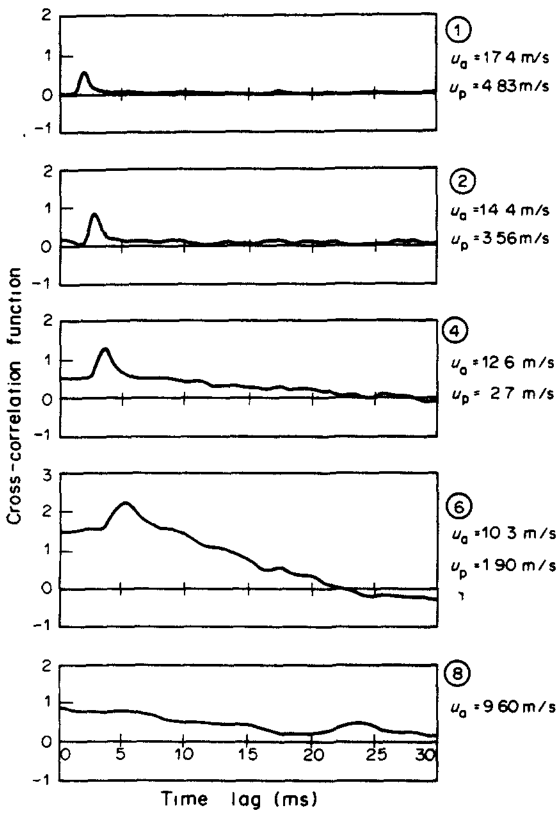

Figure 5. Cross-correlation functions of the solid concentration fluctuations. The numbers in the figure correspond to those in figure 1. u_p = average velocity of the solid particles, calculated on the basis of the peak of the cross-correlation function; d_p = 1.91 mm, G_p = 20 g/s.

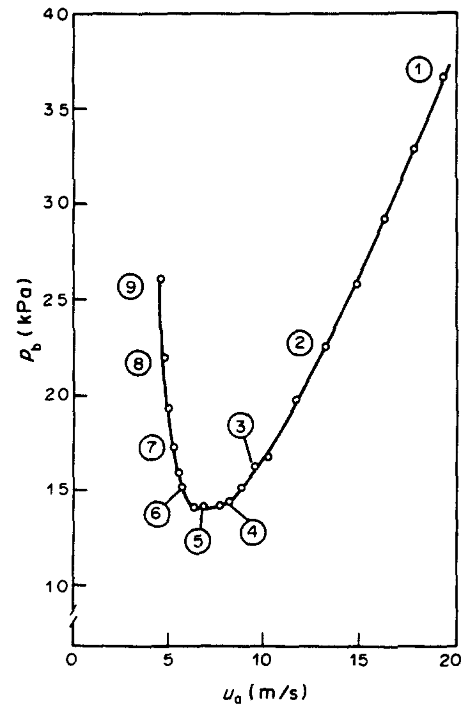

Figure 6. Time-averaged pressure at the bottom of the test tube as a function of the superficial air velocity; d_p = 0.52 mm, G_p = 10 g/s.

decreases in the air velocity. Namely, below ④ or ⑤, the dominant frequencies appear clearly to be <5 Hz. This implies that the solids are flowing in slug flow in the tube, and in such a state the cluster of solids can be observed even with the naked eye. In order to investigate this change in more detail, the cross-correlation functions of solid concentration fluctuations are examined, as shown in figure 5, by using two photosensors 9.9 mm apart. For higher air velocities, there exists an appreciable peak in the cross-correlation function and thus the average transit time of solids between the two points along the tube can be measured, leading to the calculation of the average velocity of the solids. However, as the air velocity is decreased, and heterogeneity appears in the flow behavior accompanied by the occurrence of slugging, the peak in the cross-correlation function diminishes. In figure 5, the peak disappears completely at ⑧, resulting in no correlation. This is because the flow regime is entirely in the slugging state and recirculation of solids is occurring in the tube due to quite a low air velocity for suspended solids. Since the photosensor used here works as a counter of particles, the output signals correspond to fluctuations in the local concentration of solids in the line and their power spectral function is suitable for the direct detection of the flow behavior and the transition of the flow regime. As for solid concentration fluctuations, no statistical values other than the power spectral function are examined here because they have no physical meaning. Measurements of the power spectral function of the solid concentration were attempted for other conditions (different particle size and solid flow rate). It was found that the same feature

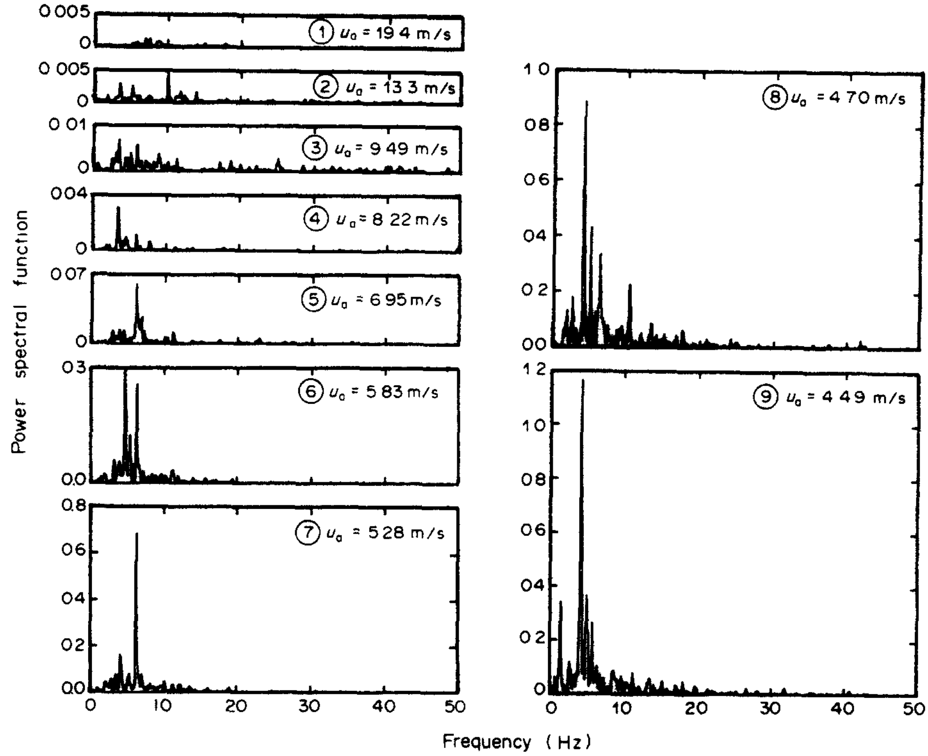

Figure 7. Power spectral functions of the solid concentration fluctuations. The numbers in the figure correspond to those in figure 6. $d_p = 0.52$ mm, $G_p = 10$ g/s.

was observed in all cases and the rapid increase in the power spectrum occurred at a slightly lower air velocity than that minimizing the pressure drop. A typical example of the measurement with smaller particles is shown in figures 6 and 7, where the pressure drop along the whole test tube (figure 6) is illustrated together with the power spectral function (figure 7). It is obvious that the points stated above hold in this case also.

Finally, it can be said that the power spectrum of the solid concentration is the most appropriate for direct detection of the transition of the flow regime to the slugging state and is capable of describing quantitatively the flow behavior of solids. The optical method presented in this work has the advantage that estimation of the flow behavior can be performed simultaneously with the measurement of solid velocity, using the same sensor. If such an optical sensing system were not available, it is also possible to estimate the flow behavior by means of a statistical analysis of the pressure difference in a fully developed region. Furthermore, when a rough prediction is needed for the transition of the flow regime to slug flow, the minimum point in the pressure-drop curve serves the purpose.

4. CONCLUSION

The transition of the flow regime to slug flow, resulting from the intrinsic instability of the suspension, can be described well in terms of the power spectral function of the solid concentration fluctuations, observed using a photosensor. This is also possible by spectral analysis of the pressure difference fluctuations in the fully developed region. The transition point at which slugging occurs can be estimated as the minimum point on the pressure-drop curve along the transport line.

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