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PLUG CONVEYING OF COARSE PARTICLES IN A HORIZONTAL PIPE WITH SECONDARY AIR INJECTION

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Abstract—An experiment was made of pneumatic plug conveying of solid particles in a horizontal pipe. The secondary air was injected from a sub-pipe set up in the main pipe to produce a number of plugs along the pipe. First, an automatic data processing system was developed to obtain the length, velocity and pressure drop of individual plugs. Second, the effects of particle size and the number of the injection holes were investigated. As a result, it was found that the effects of particle size are remarkable, while the hole number has little influence on the transportation properties. The efficiency is high in the case of small particles.

1. INTRODUCTION

Plug conveying, which is now in the stage of practical use, is expected to be a prospective means of solid particle transport in view of power consumption and erosion which are primary demerits of suspension transport systems. Several workers have investigated the pneumatic plug conveying of solid particles (Lippert 1966, Muschelknautz & Krambrock 1969, Flatt & Allenspach 1969, Tomita *et al.* 1981). A key point of the technique as industrial facilities is how to make many plugs flow steadily at proper intervals. For that purpose, secondary air injections or others are usually necessary. The authors have been conducting plug conveying experiments, using a double pipe system, that is, the secondary air is injected from a pipe set up inside a main pipe. In the previous paper (Tsuji & Morikawa 1982), attention was paid on the effects of the main and sub-pipe air flow rates with other experimental conditions being the same. However a number of parameters are concerned with the phenomena and it is absolutely important for practical aspects to know the effects of those parameters. Among such parameters, particle size and the number of the secondary air injection holes are chosen in this paper. In the earlier work (Tsuji & Morikawa 1982), the authors presented a method to investigate the basic mechanism of plug flow by setting many sensors along the pipe and recording the output of these sensors simultaneously. Automatic data acquisition and processing was not easy in the experiment. That is because some plugs collapsed on the way and in order to identify each plug, delicate comparison had to be made between the data coming from different measuring stations. Therefore instantaneous values of pressure and others at several points were taken directly from the recorded paper by eyes. As is expected, this procedure needed a long time and a laborious task. Speed-up of data processing is requisite for developing this kind of research which includes many parameters. Hence an automatic data processing was attempted in this work by using a computer together with a multichannel analogue data recorder and A/D converter. First, the method of this data processing is described in the present paper, and then the results are shown of the effects of particle size and the number of the air injection holes.

2. EXPERIMENTAL ARRANGEMENT

2.1 *Conveying equipments*

Since the conveying equipment was almost the same as that of the previous paper, only main points are explained in this paper. Figure 1 shows the transport pipe line. The main pipe was a horizontal acrilic pipe with 50 mm inner diameter and about 6.2 m long from the particle feeding point to the receiver. The sub-pipe was made of soft vinyl, of which outer and inner

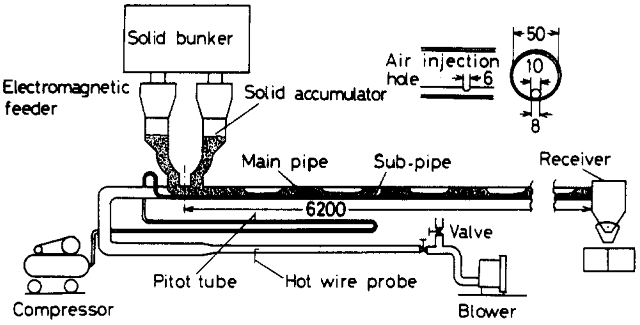

Figure 1. Experimental equipment.

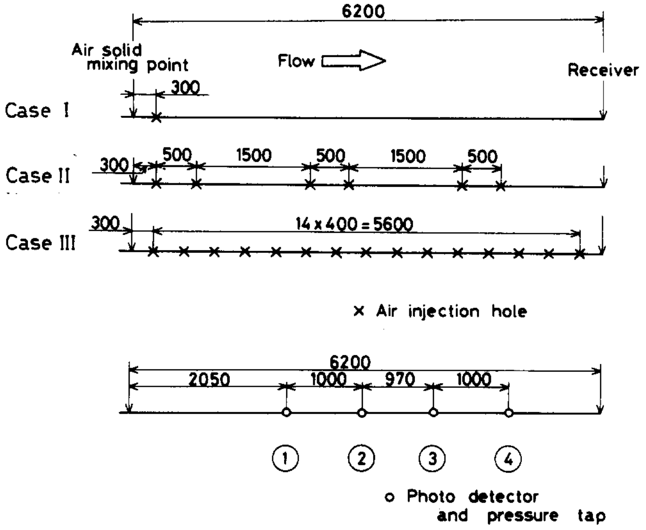

Figure 2. Longitudinal location of the air injection holes, photodetectors and pressure taps.

diameters are 10 mm and 8 mm, respectively. With respect to the effects of particle size, the results are compared for the particles of 0.4, 1.1 and 3.0 mm in average diameter. With respect to the effects of the number of the holes, cases of three kinds shown in figure 2 are compared. All the particles were spherical polystyrene pellets with 1030 kg/m^3 in true density and 640 kg/m^3 in bulk density. In this paper, these three kinds of particles are called small, middle and large particles, and the cases of three sub-pipes are called case I, II and III.

2.2 *Data processing*

Wave forms of signals in the present system are shown in figure 3 which is cited from the previous paper (Tsuji & Morikawa 1982). Signals A and B came from a hot wire anemometer and pressure transducer monitoring the air flow rates of the main and sub-pipes, respectively. Sensors of both signals were set up in the pipe upstream the feeder. The signal C came from photo-cells which indicated plug passage. Each signal D coming from pressure transducers shows the pressure difference between two sections. The numbers in figure 3 correspond to those in figure 2, showing the positions of the photo-cells and difference pressure transducers.

The above signals were recorded in an analogue data recorder. The data in the recorder was sampled at intervals of 4 ms and recorded again on magnetic tape in digital form for subsequent

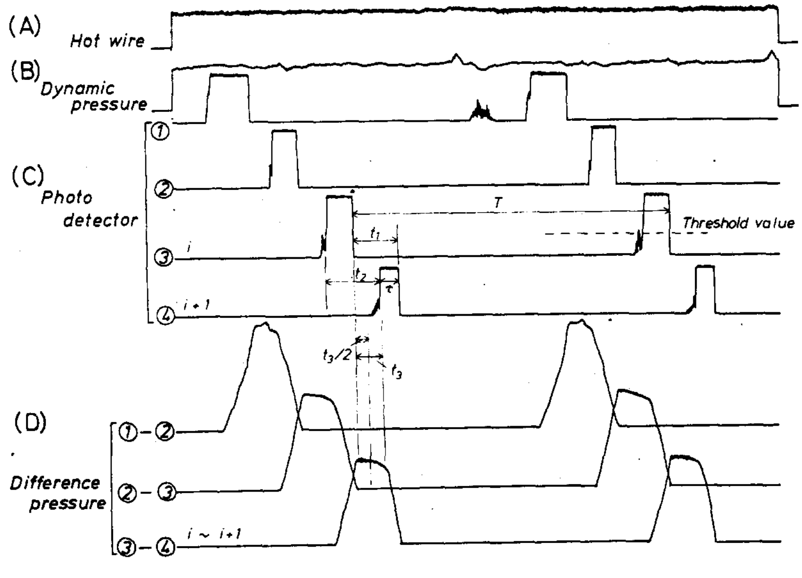

Figure 3. Recorded signals.

numerical analysis by a computer. One can obtain the passing period, velocity and length of plugs from the signal C. For instance, the passing period at the section 3 is given by T as shown in figure 3. The plug velocity V is obtained from the equation

$$V = (l/t_1 + l/t_2)/2 \qquad [1]$$

where l is the distance between the sections. Equation [1] gives the average velocity of the front and back sides of the plug. Plugs of coarse particles are not rigid but changeable in shape while moving along the pipe and thus the average value defined in the above is adopted as the plug velocity. The plug length L is calculated by the following equation

$$L = l - V(t_1 - \tau). \qquad [2]$$

The pressure drop caused by each plug is obtained as follows. In order to get the pressure drop, the pressure difference corresponding to the time when a plug exists between two pressure taps must be obtained. When the plug front passes the ith pressure tap, the photo-cell signal shows a stepwise pulse. The pressure signal increases linearly against the time until the back side of the plug passes the tap. After the back passes through the tap, the photo-cell signal returns to the original zero line, while the pressure signal remains a nearly constant value until the plug front reaches the next $(i + 1)$th tap. This constant value of the pressure corresponds to the pressure drop due to the plug. The pressure drop due to the air only is negligibly small. In reality of the data processing by the computer, the pressure drop was obtained from the pressure value at the half time between when the plug back passes the ith tap and when the plug front reaches the $(i + 1)$th tap.

To make the above process satisfactorily by using the computer, it is required to detect the plug passage correctly and identify the plug. The passage of the plug can be detected by setting a threshold value against the photo-cell signal as shown in figure 3. However the photo-cell signal includes short pulses due to flying particles and pulses with cracks caused by local collapse of the plug. To extract only normal pulses of stable plugs from the photo-cell signal, the computer program was designed to remove pulses having too short period or too short duration. Further, plugs which were detected at an upstream station sometimes disappeared

Table 1. Symbols in the figures of particle size effects

	$G_c \times 10^3$ kg/s	
d = 0.4 mm	d = 1.1 mm	d = 3.0 mm
○ 5.46	◑ 6.12	● 5.92
△ 4.56	◮ 4.54	▲ 4.71
□ 3.11	◨ 3.52	■ 3.12
▽ 2.52	⧩ 2.33	▼ 2.46

because they collapsed on the way. This phenomena also must be caught by the computer. Fortunately all the plugs were produced before the first measuring section and not produced newly on the way. Once a plug maintained a stable form until the last measuring section, there were always pulses showing the passage of that plug at proper intervals in the 1 to 4 photo-cell signals. Therefore one can find out the pulses of the same plug, if a normal pulse is traced back from the most downstream section to the upstream. In the present experiment, data was processed mainly for the plugs which flew steadily until the last measuring section.

3. EXPERIMENTAL RESULTS

3.1 *The effects of particle size*

The comparison between different particle sizes is made for case II shown in figure 2. The meanings of symbols in the following figures are given in table 1. As was mentioned in section 2.2, some of the plugs in this experiment collapsed and disappeared on the way of transportation. Therefore, the following ratio was defined as a measure of plug maintaining

$$r = n_4/n_1 \qquad [3]$$

where n_1 and n_4 are the numbers of plugs passing the measuring points 1 and 4, respectively. The ratio r took the constant value of 0.8 when the sub-pipe air flow rate G_c was high, but r decreased with decreasing G_c. The ratio r was independent of the main pipe flow rate G_b. These tendencies were the same for all the particles. Stable plugs were not produced when G_c was less than 2×10^{-3} kg/s which means a lower limit of G_c in the present transportation system.

The effects of the main and sub-pipe air flow rates on regularity of plug passage were investigated for middle particle in the previous work (Tsuji & Morikawa 1982). As a result, it

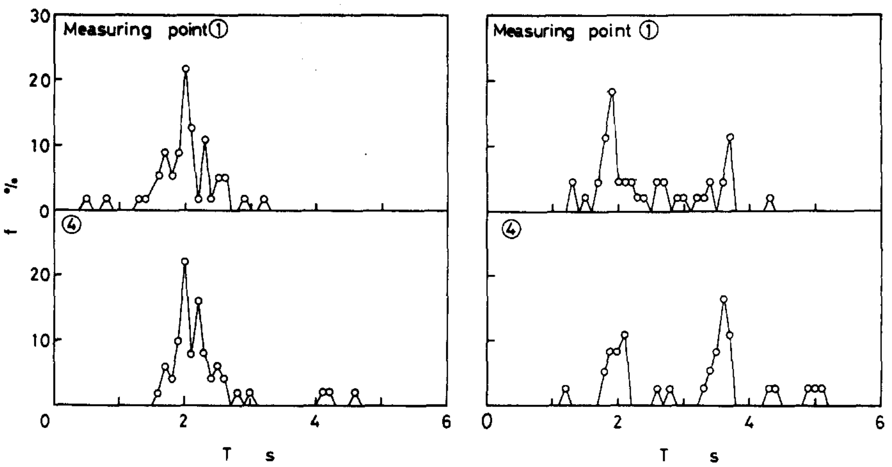

Figure 4. Frequency distribution of the plug passage period in the case of large particle (f: relative number count). (a) $G_b = 4.73 \times 10^{-3}$ kg/s, $G_c = 3.15 \times 10^{-3}$ kg/s. (b) $G_b = 4.03 \times 10^{-3}$ kg/s, $G_c = 4.85 \times 10^{-3}$ kg/s.

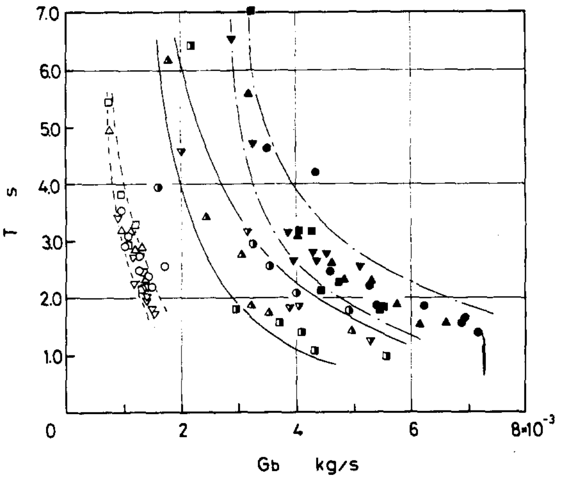

Figure 5. Relation between the average period and main pipe air flow rate at the measuring point 4. (For legend, see table 1).

was found that the greater the main pipe air flow rate G_b, the more regular the plug motion. The present work indicated that large particle has the same tendency as middle particle with respect to the regularity of the plug motion. Figure 4 shows frequencies of plug passage period of large particle. The passage period shown in figure 4(a) distributes in a narrower range than that in figure 4(b), which means that the plugs of figure 4(a) pass more regularly. Compared with middle and large particles, plugs of small particle were very irregular and showed wider distributions than figure 4.

Figure 5 shows the average plug passing period T measured at the point 4. Generally, T decreases with increasing G_b, that is, the larger G_b, the more frequently plugs are produced. G_b needed for producing plugs increases as the particle size increases, and thus plotted points of each kind of particles distribute in different regions in figure 5. However, the value T of each kind of particles is about the same order of magnitude.

Figure 6 shows the relation between the plug velocity V and G_c. The velocity V mainly depends on G_c, contrary to T which mainly depends on G_b. The flow rate G_c required for plug conveying is in the same range in each kind of particles. Generally, V increases with increasing G_c. The velocities of large and middle particles have the same values, while the velocities of small particle are larger than the others.

With respect to the plug length, large and middle particles had the same order of length

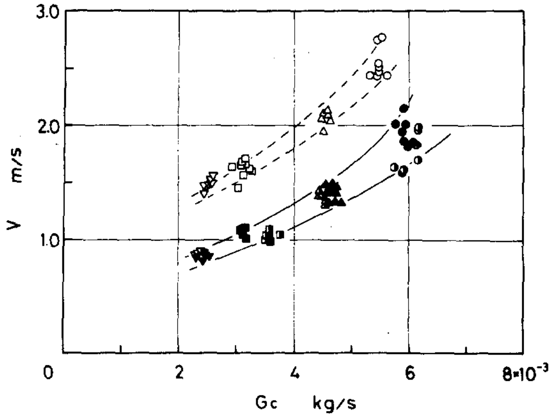

Figure 6. Relation between the plug velocity and sub-pipe air flow rate. (For legend, see table 1).

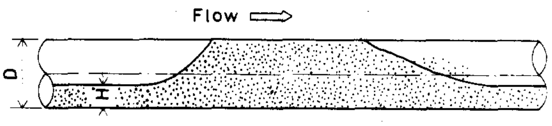

Figure 7. Shape of the plug.

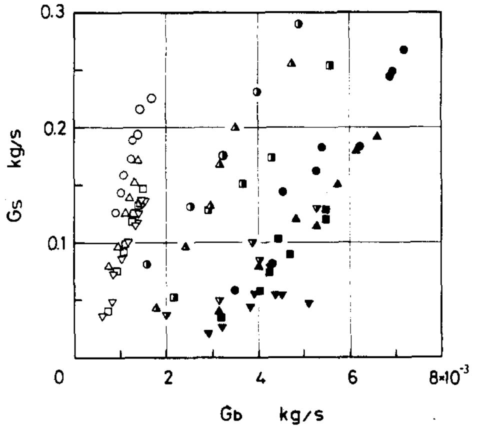

Fig. 8.

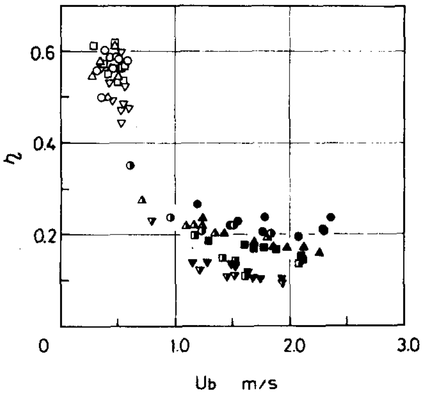

Fig. 9.

Figure 8. Relation between the particle and main pipe air flow rates. (For legend, see table 1).

Figure 9. Relation between the transport efficiency and main pipe air velocity.

(0.4 ± 0.1) m which was nearly independent of G_b and G_c. On the other hand, the length of small particles depended on G_b, increasing with G_b from 0.4 to 0.7 m.

In the present experiment there was always a stationary layer of deposited particles on the bottom of the pipe, as is shwon in figure 7. This layer is undesirable, because it reduces transportation capacity of the pipe. The height of the layer H did not depend on G_b but on G_c. Generally the height decreases with G_c. H/D of small particle changed from 0.55 to 0.25 within the present experimental conditions and H/D of large and middle particles was larger than small particle by about 0.1.

Figure 8 shows the relation betwen G_b and the particle flow rate G_s. When G_c is constant, G_s is nearly proportional to G_b in all kinds of particles. The smaller the particle size, the less the air flow rate G_b required for conveying the same amount of G_s. The reason of the above result is as follows. Permeability of air decreases as the particle size becomes smaller, and hence the force pushing the plug can be obtained by the small air flow rate G_b. Observing the figure in detail, it is found that the gradient of increase in G_s with G_b becomes smaller as G_c decreases.

As is predicted in figure 8, the loading ratios, $n = G_s/(G_b + G_c)$, reached higher values in the case of small particle than the other particles. The maximum value of the loading ratio was 34 for the small particle, while it was 20 for the large particle. However it has been reported by other workers that the loading ratio reaches a value more than 100 in the plug conveying where smaller particles than the present were used. The present value of the loading ratio was too low compared with those results even in the case of small particle. That is mainly because particles not suited for the plug conveying were used in this work.

Transportation efficiency defined by

$$\eta = gG_s/\{Q(\Delta P/\Delta L')\} \qquad [4]$$

is shown in figure 9, where Q is the air volume flow rate corresponding to the total air mass flow

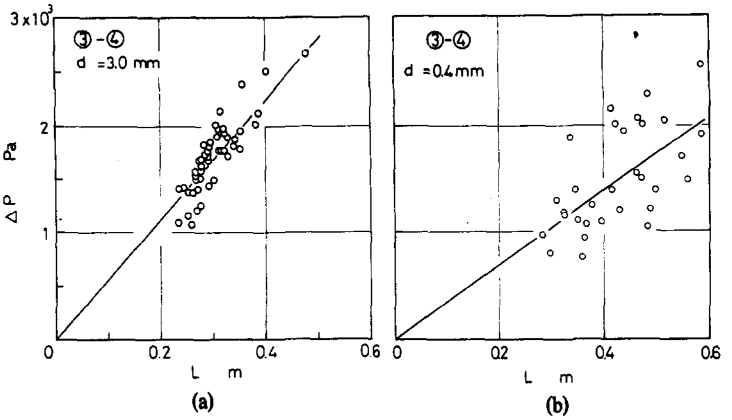

Figure 10. Pressure drop in the moving plug. (a) Large particle, $G_b = 4.73 \times 10^{-3}$ kg/s, $G_c = 3.15 \times 10^{-3}$ kg/s. (b) Small particle, $G_b = 1.73 \times 10^{-3}$ kg/s, $G_c = 3.03 \times 10^{-3}$ kg/s.

rate $G_b + G_c$, and $\Delta P/\Delta L'$ is the pressure drop per unit length of the pipe. The quantity U_b in the horizontal axis is the air velocity corresponding to G_b. Higher efficiency is obtained in small particle than large and middle particle cases. This means that the present conveying method is suitable to particles of small size.

Figure 10 shows the pressure drop plotted against the length L, which was measured for individual plugs. The result of large particle gives the similar tendency to that of middle particle reported in the previous paper (Tsuji & Morikawa 1982). The result for small particle shows large scattering in data compared with the other particles.

Figure 11 shows the relation between the pressure drop per unit length $\Delta P/L$ and air velocity U. The figure includes calculated results based on Ergun's formula

$$\frac{\Delta P}{L} = 150\frac{(1-\epsilon)^2}{\epsilon^3}\frac{\rho_a \nu}{d^2}U + 1.75\frac{1-\epsilon}{\epsilon^2}\frac{\rho_a}{d}U^2 \tag{5}$$

where ϵ, ρ_a, ν and d are, respectively, porosity, air density, kinematic viscosity and particle diameter. Equation [5] gives the pressure drop due to the fluid flow in a stationary particle bed. For comparison of the present results with the Ergun's formula, the velocity U in the figure is the relative velocity obtained by subtracting the plug velocity from bulk air velocity. The figure indicates that the present results show different tendencies from the Ergun's equation and that

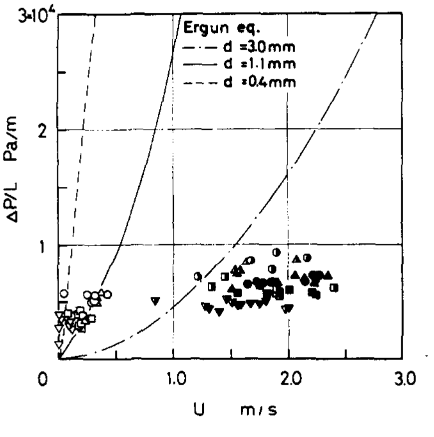

Figure 11. Relation between the pressure gradient and relative air velocity. (For legend, see table 1).

Table 2. Symbols in the figures of hole number effects

$G_c \times 10^3$ kg/s		
Pitch 1	Pitch 2	Pitch 3
◭ 3.90	○ 5.46	◒ 5.10
◧ 3.12	△ 4.56	⬓ 3.04
⧨ 2.13	□ 3.11	
	▽ 2.52	

$\Delta P/L$ of all kinds of particles have the same value of magnitude. This result means that one can not rely on existing formulae of pressure drop to arrange the data in such a complicated situation like the present. The present plug moves in a complicated flow field accompanying the secondary air injection from the sub-pipe.

3.2 *Effects of the number of air injection holes*

The foregoing section indicates that the present conveying method is suited to small particle although the plugs of small particle are not regular. This section shows the effects of the number of air injection holes with respect to small particle. The meanings of symbols in the following figures are given in table 2.

The plug maintaining ratio r which is defined by [3] took the value of about 0.8 in case I and II but the ratio remarkably decreased less than 0.6, in case III. That is because plugs collapsed more often in case III than in the other cases.

The effects of the hole number on the plug passage period are discussed as follows. First, frequency distributions of the plug passage period in case I are shown in figure 12 which were obtained at the measuring sections 1 and 4. Figure 12(a) gives an example which is typical of regular and stable plugs. These stable plugs were usually observed when the main pipe air flow rate G_b is small. As the air flow rate G_b increases, the distributions change to the patterns shown in figure 12(b) and (c), which are more dispersive than those of figure 12(a). In figures 12(b) and (c), the distributions are narrower in the downstream than in the upstream. The period in figure 12(d) shows two peak values in the distribution. Figure 13 gives the results of case III. Figure 13(a) shows that a wide distribution in the upstream section changes to a narrow one with a remarkable peak in the downstream. This means that many of the plugs produced at random in the upstream collapse and plugs of a certain period survive in the downstream. Figure 13(b) shows wide distributions in both upstream and downstream, meaning that the plug motion is highly random. It can be said from both the previous work (Tsuji & Morikawa 1982) and the present one that the relation between the behavior of plugs and various parameters is extremely complicated.

Average values of plug passage period measured at the measuring section 4 are shown in figure 14 which indicates that the period is short in case II and long in case I. There are many holes of air injection in case III but in reality most of the air was exhausted from several upstream holes. Thus the tendency in the results are not always in the order of case I, II and III. The plug maintain ratio is low in case III as mentioned at the beginning of this section but at the same time many plugs are produced. Therefore, although many plugs collapse in case III, the number of the plugs which are conveyed until the downstream is not so different from the other cases.

The plug velocity V is presented in figure 15 which shows that the velocity increases with increasing air flow rates and it is not affected by the hole number. Figure 16 gives the efficiency defined by [4]. The efficiency is a little high in case I but generally the results differ only slightly from each other case. Although presentation of results is omitted here, differences due to the hole number were found to be small or negligible in the plug length, height of the stationary layer, particle flow rate and pressure drop.

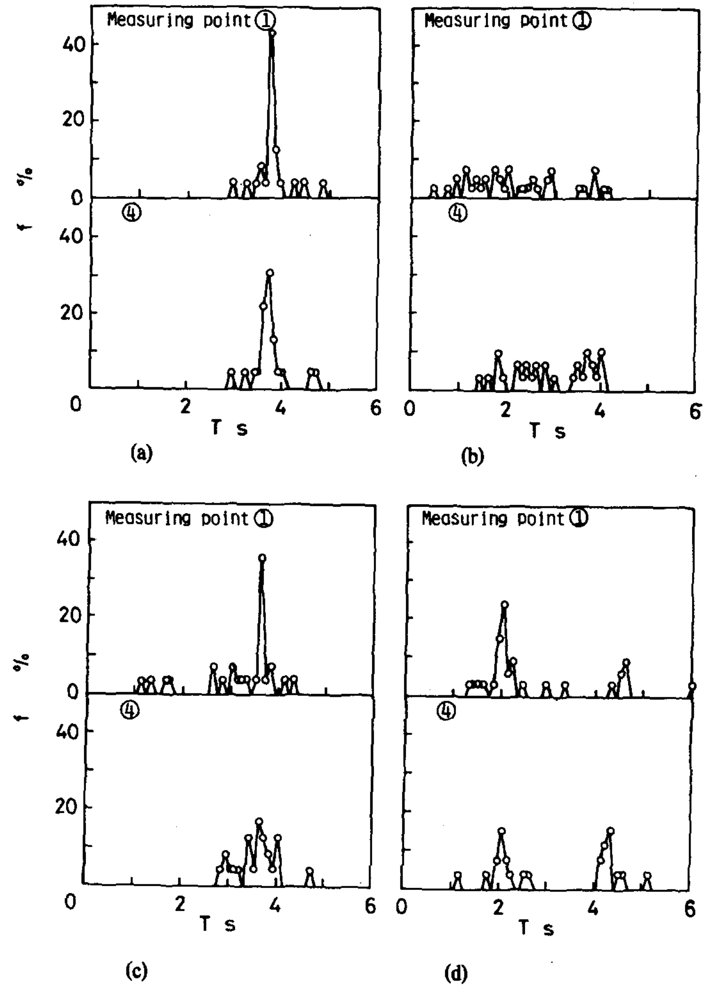

Figure 12. Frequency distribution of the plug passage period in the case of small particle and case I. (a) $G_b = 1.10 \times 10^{-3}$ kg/s, $G_c = 3.91 \times 10^{-3}$ kg/s. (b) $G_b = 1.66 \times 10^{-3}$ kg/s, $G_c = 3.87 \times 10^{-3}$ kg/s. (c) $G_b = 1.27 \times 10^{-3}$ kg/s, $G_c = 3.98 \times 10^{-3}$ kg/s. (d) $G_b = 1.78 \times 10^{-3}$ kg/s, $G_c = 3.12 \times 10^{-3}$ kg/s.

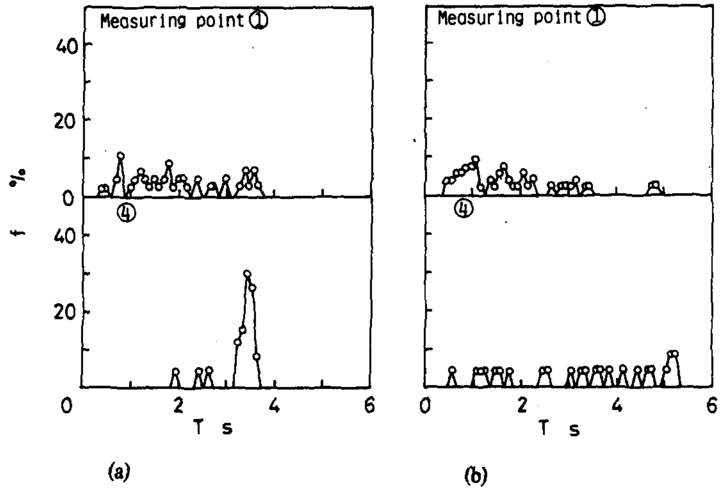

Figure 13. Frequency distribution of the plug passage period in the case of small particle and case III. (a) $G_b = 1.85 \times 10^{-3}$ kg/s, $G_c = 5.11 \times 10^{-3}$ kg/s. (b) $G_b = 1.10 \times 10^{-3}$ kg/s, $G_c = 3.08 \times 10^{-3}$ kg/s.

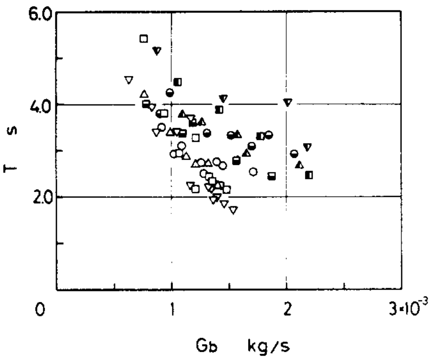

Fig. 14.

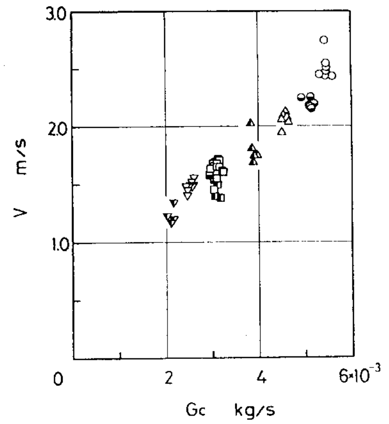

Fig. 15.

Figure 14. Relation between the average period and main pipe air flow rate. (For legend, see table 2).

Figure 15. Relation between the plug velocity and sub-pipe air flow rate. (For legend, see table 2).

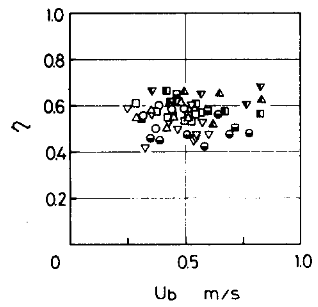

Figure 16. Relation between the transport efficiency and main pipe air velocity. (For legend, see table 2).

From the above results the effects of particle size and hole number are summarized as follows. Generally the effects of the particle size are remarkable on the behavior of plugs and transportation properties, while the hole number has little effect on such quantities. It is difficult to produce a number of plugs without the secondary air injection. However once the plug conveying is realized, the properties of particle and air flow rate are more decisive factors than the position of air injection.

Finally, the present plug conveying is compared with conventional pneumatic conveying. The velocity of particle groups and bulk air velocity were much smaller (almost one tenth) than those of conventional conveying. Thus, the present conveying obviously has an advantage for reduction of pipe erosion and particle attrition. However, the value of transport efficiency was lower than the conventional high speed and dense phase conveying. For instance, the efficiency based on the same definition to [4] reaches almost 1.0 in a case of horizontal pneumatic conveying as was reported by Welschof (1962), while the maximum value of the present efficiency was about 0.7. Reduction of power consumption has to be one of advantages of the plug conveying system. Further, the transport distance in the present experiment was too short compared with usual conveying lines. Therefore, from the viewpoint of practical use, there is much to be modified in the present conveying system.

4. CONCLUSIONS

An experiment was made of pneumatic conveying of solid particles in a horizontal pipe. The secondary air was injected from a sub-pipe set up in the main pipe to produce a number of plugs along the pipe. First, an automatic data processing system was developed to obtain the length, velocity and pressure drop of individual plugs. Second, the effects of particle size on the phenomena were investigated by using three kinds of spherical particles with diameters, 0.4, 1.1 and 3.0 mm. Further, measurements were made for three kinds of sub-pipes having different number of air injection holes, namely the cases of one (case I), six (case II) and fifteen (case III).

(1) The effects of particle size are as follows. The smaller the size, the less the required air flow rate. Large and medium sized particles have the same tendency with respect to the velocity, length and transportation efficiency defined by [4]. All the above quantities are larger in the case of small particles than large and medium sized particles.

(2) The effects of the hole number are as follows. When the hole number is large, a number of plugs are produced in the upstream but at the same time many of them collapse on the way of transportation. As a result the relation between particle and air flow rates is not so different among the cases.

Generally, the effects of the hole number are small compared with the effects of particle size.

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