Pneumatic Transport of Solids by a Blow Tank System

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Characteristics of a Fluxo-type blow tank conveying system for solid materials are examined experimentally. The discharge weight flow rate of the materials is fixed only by the air velocity blown into the tank and it is independent of the pressure drop in a pipeline, although the air velocity must be larger than the free falling velocity of the solid particle. With the weight flow rate being kept constant, the conveying air velocity can be increased by adding air into the pipe at the immediate downstream of the tank. The difference of solids flow pattern in the tank between fine particles and granular materials is visualized by the use of a small scale model tank of semi-circular crosssection.

1. Introduction

For pneumatic transport of a large amount of solids over a long distance, high pressure transport system is generally used, as the required air pressure is enormous. Since it is still difficult to feed the solids continuously into the highly pressurized region, a batch type of pneumatic transport using a blow tank is widely employed: In this type, solids are filled and sealed up in the tank and then transported in a pipeline by the air blown into the tank. The air blown into the tank discharges the solids out of the tank into the pipe and transports them to their destination. Thus, the weight flow rate of solids is dependent both on the state of air blown into the tank and on the pressure drop characteristic of pipeline. In this respect, the blow tank system differs from a low pressure system using a rotary feeder, where the solids flow rate is fixed without regard to air stream. As the operating points of a pump are decided by a characteristic curve of the pump and the pressure drop characteristic of pipeline, so the operating points of the blow tank system are determined by the blow tank characteristic as a solids pump and the pressure drop characteristic of pipeline. Therefore, it is practically important to study what characteristic the blow tank possesses as a pump and what relation it has with the structure of blow tank.

Almost no works have been done so far from this viewpoint, although there are a few studies on the blow tank transport system and the time dependent performance. As far as for this work, the results of experiments are presented.

2. Experimental apparatus and procedure

Figure 1 shows the main experimental apparatus used in this study. The primary air blown into the tank through the porous plate makes a main transport, and the secondary air which is injected into the pipe at the immediate downstream of the tank controls the flow pattern in the pipe. The pipe inlet is equipped with a conical nozzle of 65 mm diameter, whose height from the porous plate is adjustable within 125 mm. The inner diameter of the tank is 800 mm, its volume is 0.903 m³, and the inner diameter of the conveying pipe is 41.6 mm. The length of the pipeline can be changed from 15 to 92 m. The total air flow rate and the primary air flow rate are measured before the air enters the transport system, and the solids weight flow rate is measured at the end of the pipe by Fluxo type with the conveying pipe which projects from the upper part of the tank and the Ostra type with the conveying pipe which comes out directly from the bottom of the tank. The aim of this paper is mainly to study the weight flow rate characteristics of the Fluxo type blow tank.

Fig. 1 Schematic diagram of experimental apparatus

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using the weighing tank and the load cell. All the measurements are electrically executed. The transported solids are returned pneumatically to the blow tank.

In order to observe the solids behaviors in the blow tank, a semi-cylindrical model blow tank of about 0.028 m³ volume is made, and its frontal plane consists of a transparent plate. The flow pattern is photographed. In this case, the conveying pipe has a circular cross-section of 16 mm I.D.

Table 1 shows the properties of tested materials.

3. Previous works and the relation of experimental variables

As operating variables in the experiment, we use the pressure at the blow tank $P$, the total weight flow rate of air $G_w$, the ratio of the primary air flow rate $G_v$ to $G_w$, that is, the flow rate ratio $\gamma$, the initial charging fraction of solids in the tank $C$, the nozzle inlet height $N$, the length of the pipeline $L$, and kinds of solid materials. As a representative property of the solids for the transport, we use the free falling velocity of the solid particle $w$. The solid materials of which $w$ is given by Stokes' law are referred to as powdery materials and the others as granular materials.

In the case of the batch type system, the trend of the variables with time is important. It is found out that for the granular materials the transient periods at the beginning and the end of the transport are very small, compared with the steady state period, and that the fluctuations of variables are also small. On the other hand, for the powdery materials the transient periods take a much larger part of the total transport time, and the fluctuations are also larger. In the latter case, it may be controversial to define the values which represent the one batch transport performance. We use for it the values at the steady state period.

As for the effect of the initial charging fraction $C$, which is a ratio of the initial charging volume of solids to the tank volume, the smaller $C$ is, the shorter the steady state period is. But transport properties during the steady state period are independent of $C$.

Particularly in the case of granular materials, there are no effect of $C$ and the steady state sets in almost instantaneously according to applied air stream, although the average solids flow rate over one cycle increases with an increasing $C$. Considering from this result the relation between the tank volume and the average solids flow rate, we can infer that the average solids flow rate increases with an increasing height of the blow tank when the tank diameter is fixed. Indeed, this is confirmed by the previous study using another blow tank.

Accordingly, if the tank dimension has some effect upon the solids flow rate, it will appear in the steady state period and, moreover, the important dimension is the tank diameter.

It is said that the secondary air reduces solids concentration in the pipe and improves the solids flow pattern. As for powdery materials, the pipeline is sometimes blocked by the solids and the transport ceases when it is not used. When the length of the pipeline increases, the pressure loss increases, and the solids/air ratio, which is defined by the weight flow rate ratio of solids to air, decreases. Further, we found that the transport condition was influenced by the tank structure.

Now, we briefly consider the relation of the variables in terms of an energy equation for steady flow without the secondary air. The application of the energy equation to solids flow has been reported. The total energy of the mixture $E$ is given by

$$E = G_v(U_v + p + T_v + n_v/kT_v/2 + g + k)$$

(1)

where

- $G_v, G_w$: Weight flow rate of solids and air in [kg/s, kg/s]
- $U_v, U_w$: Internal energy of solids and air in [kJ/kg, kJ/kg]
- $T_v, T_w$: Specific weight of solids and air in [°C, °C]
- $n_v$: Velocity of solids and air in [m/s, m/s]
- $k$: Pressure in [Pa, Pa]
- $h$: Height above reference level in [m, m]
- $g$: Gravity acceleration in [m/s², m/s²]

For a dense phase flow of solids, it is reasonable to think that air expands isothermally. Then, integrating Eq. (2) under the condition of $p = p_w$, and $n_v = n_v = 0$ in the tank, we obtain

$$G_vRT_i + G_vU_v + G_wU_w; + G_vT_v = G_vU_v; + G_wU_w; + G_vT_v - G_wT_v$$

(2)

where $R$ is the gas constant of air, $T_v$ is the absolute temperature in the tank, and $T_v$ is the gauge pressure in the tank. Solving Eq. (3) for $n_v$, we obtain

$$n_v = \sqrt{\frac{2}{a}} \left( \frac{G_vRT_i}{G_vU_v; + G_wU_w;} + \frac{G_vT_v}{G_vU_v;} \right)$$

(4)

The kinetic energy of air is neglected because it is small compared with other terms, and we put Eq. (4) as

$$n_v = a \sqrt{\frac{2}{a}} \left( \frac{G_vRT_i}{G_vU_v;} + \frac{G_vT_v}{G_vU_v;} \right)$$

(5)

where $a$ is a coefficient taking account of $\theta$ and $k$. From the relation of $G_v = AT_i$, we obtain

$$G_v = AT_i \sqrt{\frac{2}{a}} \left( a \nu_s G_s \right) \left( \frac{P_i}{P} + \frac{p_i}{p} \right)$$

(6)

where $G_s$ is $G_s$, $\epsilon$ is the solids concentration, $A$ is the cross-sectional area of pipe, $\nu_s$ is $G_s/AT_i$, and $P$ is the specific weight of air.
in the tank. \( \omega \) is a superficial air velocity at the pipe inlet, referring to the tank pressure and is called the tank outlet velocity of pipe inlet velocity. \( G \) is a constant dependent on the pipeline. From Eq.(6) it is clear that the solids flow rate \( G_s \) is determined by \( p_t \) and \( \omega_s \) for each pipeline.

In the present paper the air flow rate is measured before the air enters the tank, and it is different from that in the conveying pipe. The air flow rate in the pipe is given by a continuity equation as follows:

\[
G_a = G_t + \omega_t/T_t.
\]

The air flow rate out of the tank \( G_o \) is given by

\[
G_o = G_t + \omega_t/T_t + \omega_s/G_s/T_s.
\]

This paper describes our experimental results until now, since there is some difference in viewpoint at each experiment, the data used are a little inconsistent.

4. Experimental results and discussion

4.1 Solids weight flow rate and blowing air velocity

According to Eq.(6), the solids flow rate is determined by \( \omega_s \) and \( \omega \). The solids flow rate characteristic of the blow tank which is independent of the pressure drop characteristic of the pipeline should not include \( \omega \), since for given \( G \) and \( \omega_s \), \( \omega \) depends on the pipeline configuration. Thus, it is \( \omega_s \) which should be correlated with \( G \). When the secondary air is used, \( \omega \) is given by

\[
\omega_s = \sqrt{G_s/AT_t} - G_t/AT_t.
\]

We refer to \( \omega_s \) as a blowing air velocity which is defined by

\[
\omega_s = \sqrt{G_s/AT_t}.
\]

Figure 2 shows a relation of \( G \) and \( \omega_s \) for P.V.C. powder (which is slightly different from that of Table 1 and has a smaller particle size). The pipe crosssection for \( L = 70 \) m line is elliptic only in this case. The hydraulic radius of the elliptic pipe is approximately equal to that of a circular pipe. From this figure it is seen that \( G \) depends only on the pipe inlet air velocity \( \omega_s \), being independent of the flow rate ratio \( \varphi \) and the pressure drop characteristic of pipeline. In addition, \( \omega_s \) when \( G \) becomes zero is not zero and it is approximately equal to the free falling velocity of solid particles, which means that if the pipe inlet air velocity is below the free falling velocity, the transport is impossible. This is reasonable since the solids are transported through the air drag on each particle and the conveying pipe stands vertically in the tank.

Figure 3 shows the results for polyethylene pellets, when the pipe length is fixed and only \( \varphi \) is varied, and the same can be said of this case. From the results in Figs.2 and 3, it is seen that \( G \) increases linearly with \( \omega_s \) within the present experimental range. In using a coefficient \( \lambda \), \( G \) is put as

\[
G = \lambda \omega_f (\omega_s - \omega_f)
\]

where \( \omega_f \) is the free falling velocity of solid particle. Also, \( G \) is shown by \( \omega_f \) from Eqs.(9) and (10) as

\[
G = \frac{k\lambda(1 + \varphi)}{AT_t} (\omega_s - \omega_f)
\]

The coefficient \( k \) relates to the tank structure and to the solid materials, and by this value the performance of blow tank is described.

4.2 Tank pressure and blowing air velocity

We see from Eqs.(6) and (11) that when the secondary air is not used, \( \varphi \) is a function of \( \omega_s \) alone for each pipeline, consequently the function of \( \omega_s \), which is confirmed by Fig.4. This figure shows a relation between \( \varphi \) and \( \omega_s \), when the secondary air is not used, with the pipe length \( L \) as a parameter for P.V.C. powder. According to Eq.(12), a unique relation holds between \( G \) and \( \omega_s \). Then, the figure is thought to show a relation of \( \varphi \) and \( G \), from which the reasonable results are derived: The larger \( \varphi \) is, the larger \( \omega_s \) is needed for a given \( G \). The fact that \( \varphi \) dose not become zero when \( \omega_s \) reduces to zero is due to the impossibility of transport when \( \omega_s \) is below \( \omega_f \), as mentioned above. The total pressure drop characteristic in solids transport is usually
indicated by a diagram of $ds$ versus air velocity in the pipe, with $G$, or the solids/air ratio as a parameter. In the case of a blow tank system, when the secondary air is not used, it means that the air flow is solely fixed to obtain $G$ necessary for each $L$.

4.3 Effect of secondary air
Figure 5 shows a relation of $ds$ and the superficial air velocity in the pipe $u_s$ which is defined by

$$u_s = G/AT - G/AT$$

(13)

when polyethylene pellets are transported over a given pipeline. In the figure, curve of $\psi$ = constant and $G$ = constant are put. It is shown that by the use of secondary air, arbitrary operating points are chosen according to each $G$ = constant curves in which the corresponding velocity is larger than the velocity at the secondary air cut off. Thus, the role of the present type of secondary air is not to change the solids flow rate directly but only to change the flow pattern of solids in the pipeline.

Figure 6 shows a relation between the solids/air ratio in pipe, $\pi$, and the tank pressure, with $\psi$ as a parameter for the same case in Fig. 5, where $\pi$ is calculated by

$$\pi = G/(G_m - G_T/T)$$

(14)

Since $\pi$ is proportional to $\pi$, $G$ is a function of $u_s$ according to Eq. (11), and $ds$, $u_s$, $H$, and $\psi$ are in a unique relationship with each other for a given pipeline, as seen from Fig. 5, $\pi$ is a function of $\psi$ and $ds$ for a given pipeline. With small $\psi$, namely, with an increasing secondary air, $\pi$ is seen to become smaller. Also, it is easily seen that for each $\psi$, $\pi = ds^{-1}$ when $u_s \geq u_s^*$. 

4.4 Solids weight flow rate and nozzle inlet height
The result in 4.1 shows that neither flow rate ratios nor the pressure characteristics of pipeline change the solids flow rate and suggests that the solids flow rate is varied by the tank structure. Figure 7 shows $G_s$ for P.V.C. powder versus $\pi$, with the nozzle inlet height $H$ as a parameter when
the secondary air is not used, that is, \( v = 100 \% \), and the length of pipeline is 15 m. In the case of \( H = 100 \text{ mm} \), the results of \( L = 26 \) and \( 48 \text{ mm} \) are also shown. From the figure it is seen that \( G \) varies with \( H \) and there exists a maximum \( G \) for a given \( u_o \); this is a value of about 75 to 100 \text{ mm} \). Since the pressure drop of pipeline increases in proportion to \( G \) for a given \( u_o \), the tank pressure increases with \( H \) which increases \( G \). This is seen from Fig. 8. Both in Figs. 7 and 8, when \( u_o \) is small, the degree of decrease in both \( G \) and \( \Delta P \) is larger. This is because in this range of \( u_o \), the flow in the pipe is unstable and flow-out of air increases, in addition to the shortness of \( L \).

4.5 Determination of transport air velocity

From the results above, we now discuss the operating characteristics of the blow tank system. When the solids weight flow rate of given materials over a fixed distance is given, we consider the required air stream to be applied to the blow tank. When solids and pipeline are given, the relation of the total pressure drop \( \Delta P \) and the air velocity in the pipe \( u \) is decided by \( G \) as a parameter, regardless of the blow tank characteristics. Accordingly, for given \( u_o \) and \( G \), \( \Delta P \) is easily found. If the relation of \( G \) and \( u_o \) is given as a blow tank characteristic of the solids weight flow rate, the relation of \( \Delta P \) and \( u_o \) is fixed for \( v = 100 \% \) by the use of the pressure drop characteristic of the pipeline. These relations are schematically illustrated in Fig. 9. The curve of DD shows the relation of \( \Delta P \) and \( u_o \) for \( v = 100 \% \). The dotted lines are a family of curves with \( v \) as a parameter. The curve of EE is the minimum \( \Delta P \) line for a given \( G \). The curve of FF is the minimum pressure consumption line for a given \( G \), where the power consumption is given by \( A \Delta P \), for an incompressible flow.

The determination of air velocity is dependent on the selection of optimum condition. Besides the line of EE and FF, for example, a lower air velocity may be chosen in order to avoid the breakage of the solids. In general, the transport becomes unstable near FF and the further reduction of velocity often causes a pipeline blockage. Since the secondary air

dose not change \( G \), it is said that the air velocity in the pipe is increased by its use from the DD curve to the left hand side along \( G \) = constant line. In order to be able to choose the objective velocity by the secondary air, the DD curve should be situated in the lower velocity region than the objective velocity. For example, by introducing the secondary air at point C on \( v = 100 \% \) line so as to pass point A or B, the transport condition is improved with respect to the power consumption or the pressure drop. Since the curve of DD or EE generally increases with \( u_o \), the role of the secondary air is important for smaller \( G \). When the DD curve is in the higher velocity region than the curve of EE or FF, \( \Delta P \) continues to increase with the secondary air. And there is no advantage with respect to power consumption. Thus, the blow tank with larger \( k \) is superior in control of solids flow by the secondary air. The required \( v \) is calculated for a given \( u_o \) by Eqs. (9) and (10) and \( N = RT \) as

\[
\nu = \frac{(NRT) / (A + G)}{(A + G)}
\]

4.6 Solids weight flow rate and solid materials

Figure 10 shows a relation of the solids flow rate characteristic of blow tank with the kind of materials: In it the data for polyethylene pellets and P.V.C. powder are shown by dotted lines. The cement raw

Fig. 8 Tank pressure and nozzle inlet height

Fig. 9 Determination of air velocity in pipe

Fig. 10 Solids weight flow rate and materials
materials whose free falling velocity is 0.07 m/s are regarded as powdery materials. The others are regarded as granular materials. As for granular materials, \( \mu_s \) at \( G = 0 \) is approximately equal to \( \mu_s \), and the slope of \( G \) against \( \mu_s \) decreases with an increasing \( \mu_s \). On the other hand, it is shown that as for cement raw materials \( \mu_s \) at \( G = 0 \) is considerably larger than \( \mu_s \). The difference between granular materials and powdery materials is also observed in the time dependent performance as mentioned above, and the difference suggests that the solids flow from the blow tank to the conveying pipe is different between the two materials. Thus, it may be guessed that as for granular materials individual particles flow smoothly in the pipe, and that as for powdery materials particles flow in pulsatory motion in blocks.

4.7 Behavior of solid particles in blow tank

The flow pattern of particles flowing into the conveying pipe is observed without using the secondary air. The glass beads are used to represent granular solids. The colored and non-colored beads are put alternately into the tank in order to observe the flow according to the shift of time. Figure 11 shows the photographs for \( H = 50 \text{ mm} \). The flow is very stable and the flow pattern is almost similar to that of gravity flow from a hopper. In the central region near the conveying pipe the flow is slowed down under the wall effect. The solids near the porous plate at rest and the air stream percolates through the solids, provided that the solids free surface is higher than the nozzle inlet. The solids enters the pipe in turn from the upper layer. When the free surface comes below the nozzle inlet, the remaining solids in the tank are vigorously fluidized as a whole and flow into the conveying pipe. Although no such photographs are obtained for P.V.C. powder since it is difficult to color P.V.C. powder, an approximately similar pattern is observed when \( \mu_s \) is small. When \( \mu_s \) becomes large, the solids in the vicinity of the nozzle are fluidized, and with a more increase in \( \mu_s \), a bubbling phenomenon happens. The bubbles are generated intermittently between the porous plate and the nozzle inlet. Because of this, the rate of the solids flow rate by \( \mu_s \) decreases and loses the linear relation seen in the case of a larger blow tank. This is partly seen also in Figs. 2 and 7. Thus, it is inferred that there is a limit in \( \mu_s \) for the linear relation of Eq. (11).

Figure 12 shows a case of cement raw materials. As predicted, the flow pattern is completely different from that with granular solids. The solids are greatly disturbed between the porous plate and the nozzle inlet. It seems that in this region the solids cave in and are drawn into the air stream rather than fluidized by the air stream. As shown in the figure, the air passage, or the so-called channelling, where the air drag of solids layer seems to be weak, occurs and the displaced air passes rising upward. The passage remains until the last stage of the transport and the solids break down around this passage. Further, the powdery materials are transported in a blow which is a solid fragment on the occasion of their breaking down. The pulsating flow phenomenon seems to be related to this intermittent flow pattern of solids in the tank.

The effect of the blow tank structure such as a tank diameter or a pipe diameter on the solids flow rate characteristic remains an important problem to be solved.

5. Conclusions

The operating characteristics of the pneumatic transport by the blow tank system have been studied. The obtained results are that the solids weight flow rate is related only to the air velocity blown into the blow tank and is not influenced by the pressure drop characteristic of the pipeline. The tank pressure required for the transport is fixed by both the pressure drop characteristic of the pipeline and the solids weight flow rate. By the secondary
air injected into the pipe at the immediate downstream of the tank, arbitrary air velocities in pipe are chosen. The solids flow pattern in the blow tank is different between the fine particles and the granular solids. In the former, the solids intermittently flow into the pipe in a bloc. On the other hand in the latter individual particles flow into the pipe continuously. When the blowing air velocity is small, the solids weight flow rate increases in proportion to the velocity. With further increase in the velocity the solids in the vicinity of the nozzle are fluidized, and with the occurrence of the bubbling phenomenon the rate of increase of the solids weight flow rate is slowed down.

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