Fundamental Study on Particle Transportation by Pressure Waves in Pipes†
— The Characteristics of Particle Transportation —

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Abstract
This study investigates the development of new technology for particle transportation in pipes with cyclic pressure waves. The flow is not steady because progressive and reflective pressure waves do exist in pipes and as a result, the flow in pipes is a pulsating one. The particles are continuously supplied into a horizontal pipe and are transported by the cyclic pressure waves. In this experiment, the loading ratio corresponds to a general high-pressure force feed system, and as a result the main flow pattern is plug flow. The properties of the plug are clarified by measuring the characteristic length and velocity of the plug, and the mean number of pressure waves between successive plug passages. Then, the properties of particle transportation are explained using the calculated apparent loading ratio.

Key words: Pneumatic Transport, Compressible Flow, Unsteady Flow, Multi-phase Flow, Pressure Wave, Plug Flow

Introduction
In recent years, pneumatic transportation methods using the force of pressure, such as plug transportation, which is called a high-pressure transportation system, are often used. However, choking is caused by a variety of transportation conditions, i.e., particle shape and material, piping arrangement, etc. in the pipeline. Therefore, methods of preventing choking1-4) and the breaking-up of particles accumulated in pipes5-7), have been studied for better transportation efficiency. It is essential to obtain the best transportation conditions, because the behavior of particles is remarkably different depending on the condition of the particles. In general, the pipe flow is steady in pneumatic transport of particles8). The particles are supplied to the pipe periodically to make the particles form plugs.

The unsteady flow in pipes has been researched with focus on oscillating flow9, 10) and pulsating flow11-13), where oscillating flow is superimposed on a mean flow. In pneumatic transportation, experimental research on the behavior with pulsating flow14) was clarified, but it seems that there has been no research on pulsating flow or oscillation flow using pressure waves.

This investigation is basic, new research on solid particle transportation using pressure waves. It is assumed that this method is suitable for plug transportation and is effective against the choking problem. In the previous report15), the unsteady drag coefficient of single spherical particles slipping or tumbling on the pipe wall was estimated by the correlation of experimental particle behavior and the loci calculated from the equation of motion. However, in practical pneumatic transportation, the theoretical elucidation of the behavior of the particles is very dif-
difficult because of friction, collision, rebound, and pressure loss. Therefore, in this report, the behavior of a lump of particles (plug) was experimentally investigated.

In this investigation, a cyclic pressure wave was generated in the horizontal pipe, and the downstream end of the pipe was allowed to remain open. Therefore, the flow in the pipe was unsteady where progressive, reflective waves existed simultaneously. The feeder continuously supplied the particles into a pipe, and the behavior of the lump of particles was analyzed. As a result, it appears that the loading ratio ranged from the low-pressure transportation system to the high-pressure one in this experiment, and the state of flow differed according to the air and particle mass flow rate. Moreover, by measuring plug behavior in pipes, the characteristics of plug transportation were clarified by the experimental and the apparent loading ratios.

Experimental equipment and method

**Fig. 1** shows an outline of the experimental equipment. A cyclic pressure wave generated by the pulsating pressure generator ① was discharged into a horizontal pipe ④, and particles were supplied into a pipe by a feeder ⑤. The pressure at the reference position was measured by a pressure probe ⑥, and the velocity at any cross-section of a pipe was measured by using I-probe hot wire anemometry ⑦. Since the downstream side of a pipe was open, progressive, reflective waves existed in pipes.

**Fig. 2** shows the detailed structure of the pulsating pressure generator. The compressed air supplied from the compressor ⑧ was adjusted with the regulator ⑨. Thereafter, an electromagnetic valve ⑩-A was opened, and the compressed air was stored in a tank ⑪ with a capacity of 400 cm³. An electromagnetic valve ⑩-B was opened just after the valve ⑩-A was shut, then the compressed air was discharged into a pipe. This operation was periodically repeated by a sequencer at 0.7s intervals. The pressure in the tank was measured with a Bourdon tube.

The particle feeder is shown in **Fig. 3**. The feeder was mounted at right angles to a pipe axis on a horizontal plane. The particles were put in a bucket ⑫ with a capacity of approximately 3,900 cm³, and pushed into the pipe by the screw ⑬. The screw whose pitch is 28 mm was connected with a shaft of a DC motor, and its rotational speed was set within the range of 50-300 rpm. By using a bearing ⑭ and a spring ⑮, the particles were smoothly supplied into a pipe. The properties of the feeder are described in the following chapter.

**Fig. 4** shows the details of the pipe. Inside diame-
The flow in a pipe

In this investigation, the downstream edge of the pipe was open, thereby the flow in a pipe was composed of progressive and reflective waves. We first considered the flow field where there were only progressive waves. The flow in pipes was assumed to be compressible, and the solution of the velocity \( v(z,t) \) and pressure \( p(z,t) \) with only progressive waves was derived in the previous research\(^\text{15} \). The solutions are obtained from the following formulas:

\[
  v(z,t) = \sum_n \left[ A_n \cos \left( \frac{2\pi n}{T} \left( t - \frac{z}{a} \right) \right) + B_n \sin \left( \frac{2\pi n}{T} \left( t - \frac{z}{a} \right) \right) \right]
\]

\[
  p(z,t) = \rho a v(z,t)
\]

where \( T \) is the period of the pressure wave, \( t \) is time, \( A_n \) and \( B_n \) are arbitrary constants, \( \rho \) is the density of air, and \( a \) is the propagation velocity of the pressure. When there are only progressive waves in a pipe, the phase of pressure and velocity becomes the same, and the pressure is equal to the product of the velocity, the density, and the propagation velocity.

**Fig. 5** shows the pressure waves over one period at \( z/d = 1.7 \) when there are only progressive waves. \( P \) is the pressure value, and the value of the first pressure peak is defined as \( P_1 \). \( t^* \) is non-dimensional time as

\[
  t^* = \frac{t}{T}
\]

where the period of pressure wave \( T \) is 0.7 s. This time is sufficient for the response time of the electromagnetic valve and for accumulating the compressed air into a tank and discharging it. In measuring the pressure with the progressive waves, the pressure absorber was set on the downstream end of the pipe. In this case, the measured pressure has only a positive value, and the values of \( P_1 \) range between 3.5 kPa and 7.7 kPa.

**Fig. 6** shows velocity \( v \) on pipe axis \( r/R = 0.0 \) at
waves of the pressure and the velocity shifted by 180° that reached the downstream end produced reflective waves. Moreover, the phase of the reflective waves overlapped in a complex manner in a pipe. As a result, the pressure waves oscillated between positive and negative values, in spite of having the same pressure conditions in Fig. 5. The first peak values $P_1$ ranged between 3.5 kPa and 5.8 kPa, and were smaller than this when there were only progressive waves. Vibration of the particles due to pressure fluctuation seems to be effective in the case of particle transportation, because the pressure fluctuation and pressure gradient are larger than when there are only progressive waves.

**Fig. 8** shows the velocity with the progressive and reflective waves on a pipe axis at $z/d = 71.7$. The reflective pressure wave with a negative value accompanies the reflective velocity wave with a positive value, and as a result, the peak value of the velocity is larger than that in **Fig. 6**, and there are no negative values.

As mentioned above, when progressive waves and reflective waves co-exist in a pipe, there is a better effect for particle transportation. When there are a lot of particles in a pipe, it is difficult to specify the pressure wave because of the mutual interference between the flow and the particles. Therefore, the pressure with no particles shown in **Fig. 7** is treated as proxy for the pressure with particles in a pipe.

**Fig. 9** shows the velocity profile on a cross-section at $z/d = 71.7$, when $P_1$ is 4.4 kPa. The maximum velocity in a pipe axis is expressed by $v_{\text{max}}$. The velocity profile is nearly uniform over the test section except near the wall, and similar results were obtained in all instants. **Table 1** shows mean velocity $v_{\text{mean}}$ and mass.

$$v(t,z) = \sum_n \left[ A_n \cos \left( \frac{2\pi n}{T} t - \frac{z}{a} \right) + B_n \sin \left( \frac{2\pi n}{T} t - \frac{z}{a} \right) \right]$$

$$+ \sum_n \left[ C_n \cos \left( \frac{2\pi n}{T} t + \frac{z}{a} \right) + D_n \sin \left( \frac{2\pi n}{T} t + \frac{z}{a} \right) \right]$$

(4)

$$P(t,z) = \rho a \sum_n \left[ A_n \cos \left( \frac{2\pi n}{T} t - \frac{z}{a} \right) + B_n \sin \left( \frac{2\pi n}{T} t - \frac{z}{a} \right) \right]$$

$$- \rho a \sum_n \left[ C_n \cos \left( \frac{2\pi n}{T} t + \frac{z}{a} \right) + D_n \sin \left( \frac{2\pi n}{T} t + \frac{z}{a} \right) \right]$$

(5)

The first terms on the right-hand side of Eq. (4) and (5) are progressive waves, and the second terms are reflective waves. Moreover, the phase of the reflective waves of the pressure and the velocity shifted by 180° deg.

**Fig. 7** shows the pressure waves with the progressive and reflective waves. They were measured without the pressure absorber so that the downstream end of the pipe was opened. In this case, the supplied air pressure in the tank was equal to that in the previous experiment. As a result, the discharged pressure waves from the pulsating pressure generator were the same as in the case of **Fig. 5**. The progressive waves that reached the downstream end produced reflective waves with a value of the reverse sign, and the latter propagated upstream. Next, the reflective waves was reflected at the device on the upstream end and then proceeded downstream as a new progressive wave, and so on. Therefore, the progressive waves and the reflective waves overlapped in a complex manner in a pipe. As a result, the pressure waves oscillated between positive and negative values, in spite of having the same pressure conditions in **Fig. 5**. The first peak values $P_1$ ranged between 3.5 kPa and 5.8 kPa, and were smaller than this when there were only progressive waves. Vibration of the particles due to pressure fluctuation seems to be effective in the case of particle transportation, because the pressure fluctuation and pressure gradient are larger than when there are only progressive waves.

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![Fig. 7 Pulsating pressure waves with reflection](image7.png)

![Fig. 8 Pulsating velocity on a pipe axis with reflection](image8.png)
flow rate \( W_a \) in a pipe, calculated by measuring the amount of air in the tank.

A general pulsating flow is composed of the oscillation and mean flows, and consequently so its velocity is not zero. In this investigation, there is a time average velocity and the flow looks like the pulsating flow because of the cyclic pressure waves. Since there is no steady flow, this flow has the feature of the velocity becoming zero over the latter half of the period.

**Properties of the feeder**

Two kinds of particle shown in Table 2 were used in this investigation. The diameter and the density of the particles are designated \( d_s \) and \( \rho_s \) in this table, respectively, and ‘PS’ stands for polystyrene. Since the amount of mixing of the stone powder is different, the densities of these two kinds of particle differ. As the surface of the particles was round, the roughness of the particle surface was almost the same value.

The feeder was mounted at right angles to the pipe axis on a horizontal plane. The performance of the feeder filled with particles was tested by changing the screw rotational speed \( N \) from 50 to 300 rpm, and supplying the particles into the pipe. The particles were transported downstream by the pressure waves generated by the pulsed pressure generator, and the volume flow rate of particle \( Q_s \) was measured at the end of the pipe. Measurements were made four times for the same conditions. The measurement time ranged from about 30 seconds to 2.5 minutes according to the screw rotation speed, and was sufficient compared with one time period (0.7 s) of the pressure wave. With flow pattern Type A described later, the error of \( Q_s \) was about 1% or less. When \( Q_s \) was less and the plug formation was irregular, or when \( Q_s \) was large and the flow pattern was just before choking, the error of \( Q_s \) was about 25% or less. When the plug was almost regularly formed, the error of \( Q_s \) was about 8% or less.

The properties of the feeder are shown in Fig. 10. It is clear that the feeder supplies the particles in proportion to the rotational speed of the screw. The particles stagnated at the outlet of the feeder in the pipe when the particle supply exceeded transportation ability by the pressure wave. For this reason, as \( P_1 \) becomes less or \( N \) becomes larger, \( Q_s \) shifts downward slightly from the line. In addition, when the particle supply increased drastically, i.e., when \( N \) is extremely large, choking occurred in the pipe near the outlet of the feeder.

**Table 1** Mean velocity and mass flow rate of air

| \( P_1 \) (kPa) | \( v_{mean} \) (m/s) | \( W_a \) (kg/s) |
|-----------------|-----------------------|-----------------|
| 3.5             | 1.23                  | 1.03x10^{-3}    |
| 4.4             | 1.80                  | 1.50x10^{-3}    |
| 5.1             | 2.60                  | 2.17x10^{-3}    |
| 5.8             | 3.14                  | 2.65x10^{-3}    |

(20°C, 101.3 kPa)

**Table 2** Condition of particles

| Particle | \( d_s \) (m) | \( \rho_s \) (kg/m³) |
|----------|--------------|---------------------|
| PS A     | 5.93x10^{-3} | 1027                |
| PS B     | 5.93x10^{-3} | 2697                |

**Fig. 9** Velocity profile over a cross-section (\( P_1 = 4.4 \) kPa, \( z/d = 71.7 \))

**Fig. 10** Properties of the particle feeder
Properties of transportation

Loading ratio

Loading ratio $\chi_s$ is defined as follows:

$$\chi_s = \frac{W_s}{W_a}$$  \hspace{1cm} (6)

where $W_s$ is the mass flow rate of the particles measured at the pipe end, and $W_a$ is the mass flow rate of air calculated according to Table 1. $\chi_s$ ranged from 2 to 23 in this investigation (Fig. 11). This value corresponds to the range of the low-pressure transportation system ($\chi_s = 1 - 10$) and the high-pressure transportation system ($\chi_s = 10 - 40$). $\chi_s$ decreases with increasing $P_1$, and increases with increasing $\rho_s$. Moreover, it is clear that when $\rho_s$ is constant, optimum pressure $P_1$ exists according to the volume flow rate of particles $Q_s$ to obtain the same loading ratio value. In this investigation, when $\rho_s$ was 2697 (kg/m$^3$) and $P_1$ is 5.1 (kPa), $\chi_s$ obtained a maximum of approximately 23.

Flow pattern

The behavior of the particles was recorded using a video camera from the reference point ($z/d = 29.3$) to the range of 1500 (mm) on the downstream side. The following flow pattern was observed in this investigation (Fig. 12).

Type A: The particle is transported without stagnating in the pipe bottom.
Type B: Unstable state of transportation in which particles alternately repeat stagnation, accumulation, and movement.
Type C: The particles accumulate in the pipe bottom. In addition, the upper part of the accumulating particles is transported irregularly by the flow of air.
Type D: The accumulating particles that are close together in a cross-section over some length of the pipe are transported by the pressure force. This type of flow is called plug transportation.
Type E: The particles choke a pipe, and cease to move. Generally, this state is called choking.

These flow patterns are demonstrated in Fig. 13 and Fig. 14. It is clear that the flow pattern differs

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**Fig. 11** Loading ratio

**Fig. 12** Flow pattern

**Fig. 13** Experimental range and flow pattern ($\rho_s = 1027$ kg/m$^3$)

**Fig. 14** Experimental range and flow pattern ($\rho_s = 2697$ kg/m$^3$)
depending on difference in $\rho_s$ and $W_8$ and $W_s$. The flow pattern in the pipe can be divided roughly into Type A, Type D, and Type E. The plug flow (Type D) is main transportation state and accompanies Type B and Type C.

**Properties of plug flow**

To clarify the mechanism of plug formation, the behavior of particles in a pipe was recorded using a video camera. Photographs of the plug from generation to disintegration are shown in Fig. 15. They were taken every 0.2 seconds. The height of each photograph is equal to the inside diameter of the pipe. This example is the plug flow of Type D. The first photograph shows the particles accumulating on the pipe bottom, at the pressure of zero. In the second photograph, the pressure wave reaches the particles, the accumulated particles are pushed up and a plug is formed. The next photograph shows that the plug moves on, rolling up the accumulating particles in front of it. The last photograph shows the particles when the pressure wave vanishes again. They keep moving for a little while according to inertia force, and the upper part of the plug disintegrates gradually in front of and behind it. Finally, the plug disintegrates completely and does not move. This process from generation to disintegration is similar to the flow of Type B.

The loci of the plug are traced, and one example is shown in Fig. 16. $t^*$ is non-dimensional time and $z$ is the distance from the reference point $(z/d=29.3)$. The coordinates of the downstream and upstream points where the plug touches the upper pipe wall are $z_{p1}(t^*)$ and $z_{p2}(t^*)$, respectively. Then, the coordinate at the center of the plug is given as follows.

$$z_p(t^*) = \frac{z_{p1}(t^*) + z_{p2}(t^*)}{2} \tag{7}$$

Moreover, the length of plug $l_p(t^*)$ and the velocity of plug $u_p(t^*)$ are given by:

$$l_p(t^*) = z_{p1}(t^*) - z_{p2}(t^*) \tag{8}$$

$$u_p(t^*) = \frac{d}{dt} z_p(t^*) \tag{9}$$

A plug does not always exist in a pipe. So, a plug is generated at $t_1$ and disintegrates at $t_2$ in one period of pressure wave, and its generation and disintegration are similar with all of the plugs in this investigation.

Fig. 17 shows an example of the relation between $l_p$ and $u_p$, and each curve corresponds to one plug. The value of $u_p$ is largest at the moment the plug is formed, and decreases afterwards. On the other hand, $l_p$ shows several patterns of change. One decreases after an increase, one increases after a decrease, and one increases monotonically, decreases monotonically, or nearly preserves itself. These changes are related to the plug formation processes that depend on the state of the particles accumulating in the pipe in front of and behind the plug.
Characteristic length $L_p$ and velocity $U_p$ of the plug are defined by:

$$t_p^* = t_1^* - t_1$$  
$$L_p = L_p(t_1^* + t_2^*/2)$$  
$$U_p = U_p(t_1^* + t_2^*/2)$$

where $t_p^*$ is non-dimensional plug-existing time, and $L_p$ and $U_p$ are the length and velocity of plug at the midpoint of the existence of the plug, respectively. After calculating $L_p$ and $U_p$ for all plugs, it is clear that their tendencies vary according to the pressure wave, density of particles, and loading ratio $\chi_s$. The mean values of $L_p$ and $U_p$ are calculated as $L_p^{\text{mean}}$ and $U_p^{\text{mean}}$, and their relations to $\chi_s$ are shown in Fig. 18 and Fig. 19, respectively. In Fig. 18, the dispersion of $L_p^{\text{mean}}$ becomes large when $P_1$ is small, but it becomes small and the value of $L_p^{\text{mean}}$ decreases when $P_1$ is large. In the case of $P_1=3.5$ (kPa), $L_p^{\text{mean}}$ increases as $\chi_s$ increases, and the dispersion becomes large. However, even if $P_1$ becomes larger, this remarkable tendency cannot be seen. In Fig. 19, it is clear that the dispersion of $U_p^{\text{mean}}$ and the value of $U_p^{\text{mean}}$ increases when $P_1$ is large, and $U_p^{\text{mean}}$ remains virtually unchanged against $\chi_s$. Although the result of $\rho_s=2697$ (kg/m$^3$) is omitted in this report, the above-mentioned tendency of $L_p^{\text{mean}}$ is not found in this case. The value of $L_p^{\text{mean}}$ becomes approximately 0.18 (m) regardless of the $P_1$ and $\chi_s$ values, and its dispersion remains virtually unchanged. Moreover, the value of $U_p^{\text{mean}}$ becomes smaller than that in former case when $P_1$ is the same value, but their overall tendencies are almost the same.

**Frequency histogram of plug passage**

A number of pressure waves between successive plug passages at a position $(z/d=58.3)$ of the pipe were measured as $N_c$. An example of the frequency histogram of the plug passage for each $\chi_s$ is shown in Fig. 20. $n_p$ is the plug passage frequency, and $N_p$ is the total plug passage frequency. When $\chi_s$ is small, $N_c$ is distributed over a wide range up to large value. With increasing $\chi_s$, $N_c$ comes to be distributed over a narrow range on the small value side. This tendency is similar to that in the other condition of $P_1$ and $\rho_s$. Moreover, it was observed that two or more plugs were formed at the same time in the pipe when $\chi_s$ was large ($N_c$ is small).

The mean number of pressure waves, $N_{c\text{ mean}}$, was defined as follows:

$$N_{c\text{ mean}} = \sum \left( \frac{N_c}{N_p} \cdot \frac{n_p}{N_p} \right)$$  

Fig. 21 shows the calculated result. In all condi-
tions and \( P_1 \), \( N_{c\,\text{mean}} \) decreases with increasing \( c_s \) and grows with increasing \( r_s \) when \( r_s \) is large. In this investigation, the minimum value of \( N_{c\,\text{mean}} \) was about 4.5. From the above-mentioned observation, it becomes clear that the frequency of plug passages in cyclic pressure waves is closely related to \( P_1 \), \( r_s \), and \( c_s \).

**Apparent loading ratio**

To elucidate the role of the plug in particle transportation, assuming that the plug transports the particles, apparent loading ratio \( \chi_{as} \) is given as follows:

\[
\chi_{as} = \frac{c_s \cdot L_{p\,\text{mean}} \cdot \frac{\pi \cdot q^2}{4}}{N_{c\,\text{mean}} \cdot T \cdot W_s}
\]

(14)

where \( c_s \) is the real bulk density of the particles in the pipe. To calculate \( c_s \), a cylindrical container \((V=3.28 \times 10^{-4} \text{m}^3)\), which has the same inside diameter \((d=30.0 \text{mm})\) as the pipe used in the experiment, was filled with particles, and the mass was measured. \( c_s \) is given by:

\[
c_s = \frac{\rho_c W}{V(\rho_s - \rho)}
\]

(15)

where \( W \) is the mass of the particle and \( \rho \) is the density of air. Real porosity \( \phi \) is given as follows:

\[
\phi = 1 - \frac{\rho_b}{\rho_s}
\]

(16)

Moreover, theoretical bulk density \( \rho_{b\,\text{th}} \) and porosity \( \phi_{b\,\text{th}} \) in a hexagonal closed-packed structure are given as follows:

\[
\rho_{b\,\text{th}} = \frac{\sqrt{2}}{6} \pi \rho_s
\]

(17)

\[
\phi_{b\,\text{th}} = 1 - \frac{\rho_{b\,\text{th}}}{\rho_s}
\]

(18)

Table 3 indicates the real and theoretical values of the bulk density and porosity of the particles. Real porosity is approximately 1.5 times greater than theoretical porosity. This is because, near the wall of the container, there are insufficient particles. As a result, the bulk density is less than the theoretical density. However, it appears that these values are almost equal to the actual density and porosity of the plug formed in the pipe.

**Fig. 22** shows the relation between experimentally obtained loading ratio \( \chi_s \) and apparent loading ratio \( \chi_{as} \). The oblique straight line shows the case in which \( \chi_s \) and \( \chi_{as} \) are equal. A plotted point on a straight line means that the plug formed in the pipe transports the particles efficiently. Plotted points above the straight line mean that the plug transports only a portion of the particles. Therefore, it is thought that the moving particles in the plug are only in the upper part, except for the bottom part (Type C), and that the bottom part of the plug does not assist transportation. When the plotted points are below the straight line, the particles are transported not only by the plug but also by accumulating particles (state of Type B). These results correspond well with the observation of plug behavior.

| Particle | \( \rho_{b\,\text{th}} \) (kg/m\(^3\)) | \( \phi_{b\,\text{th}} \) | \( \rho_s \) (kg/m\(^3\)) | \( \phi \) |
|----------|---------------------------------|----------------|------------------------|-------|
| PS A     | 760                             | 0.26          | 601                    | 0.41  |
| PS B     | 1997                            | 0.26          | 1554                   | 0.42  |

**Fig. 21** Relation between \( N_{c\,\text{mean}} \) and \( \chi_s \)

**Fig. 22** Apparent loading ratio
Conclusion

1. When cyclic pressure waves are generated upstream the pipe, transportation using both progressive and reflective waves is more effective than using only progressive waves.

2. The loading ratio ranges from 2 to 23 in this investigation. These values range from low-pressure transportation to high-pressure one.

3. The flow pattern in the pipe is divided roughly into Type A, plug flow, and choking. Plug flow usually accompanies Type B or Type C.

4. The plug in the pipe is generated and disintegrates for one period of pressure wave. The characteristics of the plug are clarified by measuring its length and velocity in relation to the pressure waves, the density of the particles, and the loading ratio.

5. The number of pressure waves between successive plug passages decreases as the loading ratio increases, and its minimum value is 4.5 in this investigation.

6. The properties of transportation by the plug becomes clear from a comparison between the experimental and apparent loading ratios.

Principal nomenclature

- $a$: propagation velocity of pressure (m/s)
- $d, d_s$: diameter of pipe and particle (m)
- $l_p$: length of plug (m)
- $L_p$: characteristic length of plug (m)
- $L_{\text{p,mean}}$: averaged characteristic length of plug (m)
- $n_p$: plug passage frequency
- $N$: rotating speed of screw (rpm)
- $N_c$: number of pressure waves between plug passages
- $N_{\text{c,mean}}$: mean number of pressure waves
- $N_p$: total plug passage frequency
- $P$: pressure (kPa)
- $P_1$: peak value of pressure (kPa)
- $Q_s$: volume flow of particles (m$^3$/s)
- $r$: radial coordinate (m)
- $R$: radius of pipe (m)
- $t$: time (s)
- $t^*$: non-dimensional time, $t/T$
- $t_p^*$: non-dimensional plug-existing time
- $T$: period of pressure (s)
- $u_p$: velocity of plug (m/s)
- $U_p$: characteristic velocity of plug (m/s)
- $U_{\text{p,mean}}$: averaged characteristic velocity of plug (m/s)
- $v$: velocity of air (m/s)
- $v_{\text{max}}$: maximum instantaneous velocity (m/s)
- $v_{\text{mean}}$: mean velocity of air (m/s)
- $W$: mass of particles (kg)
- $W_a$: mass flow of air (kg/s)
- $W_s$: mass flow of particles (kg/s)
- $z$: axial coordinate (m)
- $\phi$: real porosity ($\rho_b - \rho_s$)/$\rho_s$
- $\phi_{\text{th}}$: theoretical porosity
- $\rho$: density of air (kg/m$^3$)
- $\rho_s$: density of particles (kg/m$^3$)
- $\rho_b$: real bulk density of particles in pipe (kg/m$^3$)
- $\rho_{b,\text{th}}$: theoretical bulk density (kg/m$^3$)
- $c$: loading ratio
- $c_a$: apparent loading ratio
- $\chi_s$: loading ratio $W_s/W_a$

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