Effect of properties of pulverized coal on dense phase pneumatic conveying at high pressure

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Abstract. Experiments of dense-phase pneumatic conveying of pulverized coal using nitrogen were carried out in an experimental test facility with the conveying pressure up to 4 MPa. The relationship between mass flow rate of pulverized coal with different mean particle size and gas injecting velocity were investigated. Also, the characteristics of pressure drop in the horizontal pipe, vertical pipe and bend with different mean particle size of pulverized coal were analyzed. Test results indicate that, with the increase in total gas flow rate enters into the feeding hopper, the mass flow rate of fine coals reach the peak value earlier than that of coarse coals, but the optimum injecting velocity is lower than that of coarse coals. In addition, it is showed that the pressure drop for coarse coals is higher than that of fine coals with the same mass flow rate, and when the coal concentration in the pipe is higher enough, the conveying pressure drop for fine coal is close to that of coarse coal. The pressure drop in vertical pipe is higher than that in horizontal pipe, and the pressure drop in horizontal pipe is lower than that in horizontal bend with the same mass flow rate.

1. INTRODUCTION
High-pressure dense-phase pneumatic conveying of pulverized coal has the advantages of high solid/gas ratio, low gas consumption, less pipe wear and stability. So, it is generally used as coal supply system in large-scale pressured coal gasification units(Shen et al., 2005). In recent years, extensive valuable achievements on dense-phase pneumatic conveying technology have been obtained(Konrad et al., 1986; Pan, 1999; Molerus, 1996; Hong et al., 1995; Herbreteau et al., 2000; Geldart et al., 1992). However, these researches mainly focused on low-pressure dense-phase pneumatic conveying; only few references on high-pressure dense-phase pneumatic conveying are available, especially for pneumatic conveying of pulverized coal with different mean particle size. An experimental setup of dense-phase pneumatic conveying of pulverized coal was developed by Southeast University with the conveying pressure up to 4 MPa and the solid/gas mass flow ratio up to 600kg/m³. Up to now, researches on conveying characteristics and pipeline resistance properties have been done with this test facility, and some important results were obtained(Xiong et al., 2004; LIANG et al., 2007; LIANG et al., 2007). The gas–solid two-phase flow becomes very unsteady and complicated in high-pressure dense-phase pneumatic conveying due to its low conveying velocity and high solid concentration. And the theory of dense-phase pneumatic conveying under high pressure is still not mature. Further experimental research and theoretical research on this field is still needed.

In this paper, some new researches reported here were carried out at Southeast University.
Pulverized coal with different mean particle size was used. The conveying characteristics and pressure drop along the pipe for pulverized coal with different mean particle size are presented. Besides, an important different between this work and that of earlier researches is that the pressure drop across bend have been evaluated by us. The results that we obtained are very important for the designing and operation of large-scale high-pressure dense-phase pneumatic conveying system.

2. Experimental apparatus and properties of coal used
The high-pressure dense-phase pneumatic conveying experimental facility is shown schematically in Fig 1. High pressure nitrogen from buffer tank is divided into fluidizing gas, pressurizing gas and supplement gas. Pulverized coal in bottom area of the feeding hopper is fluidized by fluidizing gas, and then enters the conveying pipeline driven by conveying differential pressure. During conveying process, pressurizing gas is mainly used to maintain the feeding hopper pressure, while supplement gas can effectively regulate the solid/gas mass flow ratio and maintain stable conveying. Nitrogen in receiving hopper is discharged through back pressure regulation valve while the contained pulverized coal is separated by a bag filter. The detailed description of the experimental facility is reported in Ref. (Shen et al., 2005).

![Schematic diagram of high-pressure dense-phase pneumatic conveying test facility](image)

1- nitrogen cylinder 2- buffer tank 3- pressurizing gas 4- fluidizing gas 5- supplement gas 6- hopper 7- weigh cell 8- inspection window 9-water pump

Fig.1 Schematic diagram of high-pressure dense-phase pneumatic conveying test facility

Pulverized coal with the density of 1400 kg/m³ and the mean particle size of $0.52 \times 10^{-4}$ m, $1.15 \times 10^{-4}$ m and $3.0 \times 10^{-4}$ m are used as testing material.

3. Results and discussion

3.1 The effect of injecting velocity on solids mass flow rate
Using the fluidization properties of pulverized coal could make dense-phase pneumatic conveying of pulverized coal easier. In order to maintain stable conveying, it is important to seek the optimum flow pattern of pulverized coal in the feeding hopper. As shown in Fig.2, fluidizing gas was injected into the feeding hopper through gas distributor. Pulverized coal in area A was fully fluidized, and area B is the mass-flow region where pulverized coal is moving down. Area C is defluidized zone, where there is little nitrogen to flow through this area. And pulverized coal in the bottom of area C collapses to area B. The particle concentration in area B is larger than that of area C and smaller than that of area A. Pulverized coal with different mean
particle size exhibit different fluidization behaviour. The effect of injecting gas velocity and particle size on conveying stability was researched by means of investigation on the relationship between injecting velocity and mass flow rate of pulverized coal with different mean particle size.

Tab. 1 Experimental data

| \(d_p\) (µm) | \(V_i\) (m/s) | \(M_s\) (kg/s) | \(Q_f\) (m³/h) | \(Q_p\) (m³/h) |
|-------|-------------|-------------|--------------|--------------|
| 52    | 3.0         | 0.16        | 0.4          | 0.8          |
| 300   | 2.3         | 0.21        | 0.4          | 0.8          |

Fig. 2 Schematic diagram of feeding hopper

Fig. 3 Mass flow rate of coal vs. injecting velocity

While the nitrogen entering into the feeding hopper, a part of the nitrogen is to replace the coal and maintain the feeding hopper pressure, and the other part enters into the riser. Gas velocity in the riser is called as injecting velocity. During the experiments, the pressure of receiving hopper is kept constant. Tab.1 shows that, at this experimental condition, the injecting velocity for fine coal is larger than that for coarse coal and the mass flow rate of fine coal is less than that of coarse coal. With the same volume flow rates of fluidizing gas and pressurizing gas, higher injecting velocity means that less pulverized coal is replaced, which leads to less mass flow rate of pulverized coal.

Fig.3 shows that, with the increase in injecting velocity, the mass flow rate of pulverized coal increases firstly and then declines, and the mass flow rate of fine coal reaches the peak earlier than that of coarse coal. With the increase in injecting velocity, that is to say with the increase in gas volume rate entering into the feeding hopper, the fine coal reaches the fluidized state relatively earlier than coarse coal. And the particle concentration for fine coal is higher in the incipient fluidized state. Therefore, the mass flow rate of fine coal is larger than that of coarse coal at the earlier stage, and reaches the peak earlier. After the mass flow rate reaching its peak, it declines with the increase in gas volume rate. Also the mass flow rate of fine coal decreases faster than that of coarse coal and is less than that of coarse coal lately. The reason for this phenomenon is that when the pulverized coal is fully fluidized, further increasing in gas flow rate leads to decreasing in particle concentration. Also, the interaction between particles for fine coal is larger than that of coarse coal, resulting in particle aggregation easily. If the gas volume rate is large enough, the fine coal will be in poor fluidized state and the particle concentration becomes non-uniform, so the average particle concentration above the distributor decreases more quickly than that of coarse coal, which leads to the carrying capacity of unit volume gas for the fine coals lower than that of coarse coal.
3.2 Phase diagram of dense-phase pneumatic conveying at high pressure

A phase diagram is usually a series of curves of pressure drop per unit length versus superficial gas velocity, and the solid mass flow rate $M_s$ or solid/gas mass flow ratio $\mu$ is same in each curve. The phase diagram can accurately describe the pneumatic conveying characteristics and could be used to determine the flow pattern for a given condition. It also could be used for the analysis of conveying stability and parameters optimization. The phase diagram for pneumatic conveying of pulverized coal under high pressure was given in this paper to research the conveying characteristics and conveying stability for pulverized with different mean particle size.

With high superficial gas velocity, the flow pattern is of homogeneous dilute suspension flow. The pressure drop is mainly caused by the gas phase and increases with the increase in superficial gas velocity. With the decrease in superficial gas velocity, the pressure drop for gas declines. But the particles begin to fall down to the bottom of the pipe, and the particle concentration in the bottom area increases gradually. So the pressure drop for solids increases. When the pressure drop increment for solids equals the pressure drop decrement for gas, the total pressure drop reaches minimum value. The superficial gas velocity value in this situation is defined as economic velocity (saltation velocity), and it is often used as a criterion to distinguish between steady flow and unsteady flow. If the superficial gas velocity is further decreased, a stationary or slow-moving particle layer will be formed on the bottom of the pipe, and the gas-solid two phase flow becomes unsteady and falls into dense phase flow, such as dune flow or plug flow. At this condition, the inter-particle collisions and particle-wall force are enhanced, and the pressure drop increases with the decrease in superficial gas velocity.

3.2.1 Phase diagram of horizontal pipe

Fig.4 is the phase diagram of horizontal pipe for the conveying of pulverized coal with mean particle size of 52 $\mu$m. The pressure drop decreases at first and then increases slightly with the increase in superficial gas velocity. Fig.4 also shows that, at the same total conveying pressure drop (pressure difference between feeding hopper and receiving hopper), the mass flow rate of coal increase with the increase in pipe pressure. And at the same pipe pressure, the coal mass flow rate and economic velocity increase with the increase in total conveying pressure drop.

Fig. 5 is the phase diagram of horizontal pipe for the conveying of pulverized coal with mean particle size of 52 & $\mu$m and 300 $\mu$m. The pressure drop for coarse coal is higher than that of fine coal with the same mass flow rate. While the coal particles flowing with the gas, the following feature of fine coal is better than that of coarse coal. So the fine coal has the tendency to aggregate at the centre of the pipe and easy to be conveyed. On the contrary, the coarse coal tends to fall down to the bottom of the pipe due to gravity, so the wall frictional pressure drop for coarse coal is higher than that for fine coal.
Generally, when the coal concentration in the pipe is high enough, with the decrease in superficial gas velocity, the pressure drop of fine coal is close to that of coarse coal (Geldart et al., 1990). It is because that reducing the gas velocity has a greater effect on the deposition trend of fine coal than that of coarse coal. Decrease in gas velocity leads to a large number of fine coal falls down to the bottom of the pipe, so the wall frictional pressure drop increases. Meanwhile, the deposition of fine coal reduces the gas flow area. So the gas velocity is increased, which leads to the increase in the pressure drop for gas. It could be seen from Fig.5 that, to the left of the minimum point of the two curves with the coal mass flow rate of around 0.22kg/s, the pressure drop for fine coal indeed has the tendency to close to that of coarse coal when the superficial gas velocity is reduced, but further study is needed due to the limits of experimental condition.

Curve fitting analysis of the three pressure drop curves for pulverized coal with mean particle size of 52 μm, 115 μm and 300 μm in Fig.6 shows that the pressure drop for per unit length could be expressed with the following formula:

\[ \frac{\Delta P}{L} = aU^2 + bU + c \]  \hspace{1cm} (1)

Let \( \frac{d(\Delta P/L)}{dU} = 0 \), the economic velocity could be obtained. With experimental data fitting, the empirical formulas of the pressure drop for per unit length and the economic velocities for the three kinds of pulverized coal are obtained, as shown in Table 2. The economic velocity for pulverized coal with mean particle diameter of 115 μm is lower than that of other two kinds of

| \( d_p \times 10^{-4} \) m | Expression | \( U_s \) |
|----------------|-----------------|----------|
| 52 | \( \frac{\Delta P}{L} = 17.26 - 2.02U + 0.106U^2 \) | 9.53 |
| 115 | \( \frac{\Delta P}{L} = 16.48 - 1.46U + 0.08U^2 \) | 9.12 |
| 300 | \( \frac{\Delta P}{L} = 16.39 - 1.79U + 0.095U^2 \) | 9.42 |
pulverized coal. It could be assumed that the fine coal is easy to be conveyed from the view of power consumption, whereas the medium-sized coal is easy to be conveyed from the view of conveying stability. Because just three kinds of coal were tested in this paper, in order to extend the above conclusions, further study is needed.

3.2.2 Comparison of Phase diagram of horizontal pipe and that of vertical pipe

As shown in Fig. 7, the pressure drop for vertical pipe is higher than that of horizontal pipe with the same coal mass flow rate. According to Barth’s theory, the total pressure drop of the pipe could be expressed as below:

\[ \Delta P = \Delta P_g + \Delta P_s \quad (2) \]

Where \( \Delta P_g \) is the pressure drop for gas and \( \Delta P_s \) is the pressure drop for solids. For horizontal pipe, \( \Delta P_g \) and \( \Delta P_s \) are due to gas-pipe wall friction and solids-pipe wall friction respectively. While for vertical pipe, they also include pressure drop due to gas and solids gravity.

With the same superficial gas velocity, the pressure drop for gas is almost the same for the horizontal pipe and the vertical pipe. Though there was a tendency towards higher solids friction due to coal deposition in horizontal pipe, the pressure drop due to gravity in vertical pipe is relatively larger, which finally leads to the pressure drop for vertical pipe larger than that of horizontal pipe.

3.2.3 Comparison of Phase diagram of horizontal pipe and that of horizontal bend

Particles enter into the bend can be expected to aggregate at the outer lateral wall and collide with outer lateral wall due to centrifugal force. They would be rebounded backwards and collide with particles arriving later. It would cause a net loss of kinetic energy. Then, the particles would be accelerated by the gas again and leads to a loss of gas momentum. So, the pressure drop across horizontal bend is much higher than that of horizontal pipe.

![Fig. 7 Phase diagram of vertical pipe and horizontal pipe](image1)

![Fig. 8 Phase diagram of horizontal pipe and horizontal bend](image2)
As shown in Fig. 8, with the same mass flow rate of coal, the pressure drop of horizontal bend is higher than that of horizontal pipe. The higher the mass flow rate, the larger the difference between pressure drop of horizontal bend and that of horizontal pipe. The frequency of collision between solids and wall increase with the increase in the mass flow rate, which lead to the increase in the pressure drop due to kinetic energy dissipation. Furthermore, with the increase in the mass flow rate, the pressure drop due to solids friction is also increase.

With experimental data fitting, it is found that the difference value between the pressure drop of bend and that of straight pipe is $\frac{1}{2}G_s U$, which can be seen from Fig. 9.

Fig. 10 illustrates that, for horizontal bend, the pressure drop for coarse coal is larger than that for fine coal with the same mass flow rate of coal. The centrifugal force of coarse coal is larger than that of fine coal, so the coarse coal tends to move to the outer lateral wall more seriously, and the coal concentration is higher near the outer lateral wall. Therefore, the pressure drop due to collision and wall friction are higher for coarse coal.

### 3.2.4 Comparison of Phase diagram of horizontal bend and that of vertical bend

The pressure drop for vertical bend is higher than that of horizontal bend with the same conveying condition, which can be seen from Fig. 11. The pressure drop of vertical pipe is larger than that of horizontal pipe as mentioned in chapter 3.2.2. For the same reason, the pressure drop of vertical bend is larger than that of horizontal bend. Moreover, coals conveyed in the vertical bend would dissipate a part of kinetic energy due to gravity while redirecting coals from horizontal pipe to the vertical pipe. Coals would then be re-accelerating upwards, and the pressure drop due to kinetic energy of vertical bend increase as well as (Lee et al., 2004).

### 4. Conclusions

(1) With the increase in total gas flow rate enters into the feeding hopper, the mass flow rate of fine coal reaches the peak value earlier than that of coarse coal. The optimum injecting velocity for fine coal is 2.26 m/s, while this value is 2.58 m/s for coarse coal when the receiving pressure is 2.8 MPa.
(2) At the same total conveying pressure drop, the mass flow rate of coal is increased with the increase in pipe pressure. And at the same pipe pressure, the coal mass flow rate is increased with the increase in total conveying pressure drop.

(3) The pressure drop decreases at first and then increases with the increase in superficial gas velocity. The pressure drop per unit length could be expressed with the formula as eqn.(1). The superficial velocity at which the total pressure drop reaches minimum is 9.12m/s for pulverized coal with mean particle size of $1.14 \times 10^{-4}$ m. And it is lower than that of two other pulverized coal.

(4) The pressure drop in vertical pipe is higher than that in horizontal pipe, and the pressure drop in horizontal pipe is lower than that in horizontal bend at the same mass flow rate. The pressure drop for vertical bend is higher than that of horizontal bend with the same mass flow rate. With experimental data fitting, it is found that the difference value between the pressure drop of bend and that of straight pipe is $1/2G_SU$.

(5) For horizontal pipe and horizontal bend, the pressure drop for coarse coal is larger than that for fine coal with the same mass flow rate.

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NOMENCLATURE

d_p  particle size                   [\mu m]  
G_S  mass flow rate of solids       [kg/(m^2.s)]  
M_S  mass flow rate of solids       [kg/s]  
P_1  feeding hopper pressure        [MPa]  
P_2  receiving hopper pressure       [MPa]  
\Delta P_t  conveying differential pressure  [MPa]  
\Delta P/L  total pressure drop per unit length across pipe  [KPa/m]  
Q_f  volumetric flow rate of fluidizing gas  [m^3/h]  
Q_r  volumetric flow rate of pressurizing gas  [m^3/h]  
Q_s  volumetric flow rate of supplemental gas  [m^3/h]  
U  superficial velocity of gas        [m/s]  
U_s  saltation velocity               [m/s]  
V_i  injecting velocity               [m/s]  

Greek Letters

$\delta$ ($\Delta P$) the difference value between the pressure drop of bend and that of straight pipe  
$\mu$  solids to gas mass flow rate ratio

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