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Effect of moisture content on dense-phase conveying of pulverized coal at high pressure

Xu Pan, Chen Xiaoping†, Liang Cai, Xu Guiling, Liu Daoyin, and Zhao Changsui

School of Energy and Environment, Southeast University, Nanjing 210096, China
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Abstract−In dense-phase pneumatic conveying, the solid moisture content can significantly influence the conveying process, but there are very few studies in the open literature. In this study, the conveying experiments of two pulverized coals with various moisture contents were carried out at a 4 MPa high pressure and dense-phase pneumatic conveying facility. Results show that the whole conveying system can be stably and controllably operated under the condition that moisture content below ~8%. With the increase of moisture content up to ~8%, the mass flow rate of 280 μm pulverized coal increases at first and then decreases, while that of 55 μm pulverized coal decreases continuously. The method of solid friction factor correlation is used to investigate pressure drop of the horizontal pipe, and non-dimensional parameters--Fr number, moisture content M and solid loading ratio μ--are investigated. The pressure drop predictions by this correlation are in good agreement with the experimental data. The solid friction factor correlations indicate that the fine coal is more sensitive to M, and μ plays a more important role for the coarse coal.

Key words: High Pressure, Pneumatic Conveying, Moisture Content, Pressure Drop, Solid Friction Factor

INTRODUCTION

Dense-phase pneumatic conveying technology has many advantages such as high solids/gas mass flow ratio, low gas and energy consumption and less pipe wear. And it has received great interest in many industrial applications. One typical example is that of dense-phase conveying of pulverized coal under high pressure, which is a key technology in large scale entrained flow gasification programs [1,2]. In this program moisture is beneficial to the gasification process. But pulverized coals are usually dried before feeding into gasification chambers in order to guarantee the stability of the conveying system. If the pulverized coal can be transported stably at higher moisture content, the cost of coal feeding process can be reduced to some extent.

The characteristic of dense-phase gas solid flow is very complex. Up to now, many experimental and theoretical researches on dense-phase conveying have been carried out, and some important results were obtained [3-16]. When moisture content in pulverized coal increases, the conveying process becomes more complicated. Few literatures investigated the effect of moisture content on flowability in high pressure dense-phase transport. In this case experimental research is greatly needed.

The pressure drop along a pipe is one of the most important parameters in pneumatic conveying applications. Both theoretical and experimental studies on pressure drop have been carried out by many researchers. The solid friction factor method is a classic method for analyzing pressure drop. There have been a few correlations for the solid friction factor in the literature. Molerus [17] reviewed the solid friction factor correlations for horizontal straight pipes and the physical meaning of the basic form of these correlations. Rautiainen and Sarkoma [18] compared previous correlations for solids friction factor and presented a correlation for dilute-phase ows in vertical pipes. Jones [19] performed a series of calculations to estimate the solid friction factor for four types of material conveyed in the fluidized dense-phase flow regime. Huang [20] studied the use of the solid friction factor in determining pressure drop of dense phase gas-solid flow through nozzle. These researches indicate that the pressure drop along the horizontal pipeline has a close relationship with solid concentration and the superficial gas velocity. Therefore, most of the correlations are based on two dominant non-dimensional parameters: Froude number (Fr, based on supercial gas velocity) and solid loading ratio μ. But there is a lack of investigation on the relationship between moisture content M and the solid friction factor f_S.

The main objectives of this work are: (1) to find the limiting values of moisture content for two pulverized lignite coals, (2) to investigate the effect of moisture content on flow properties of coals with different mean particle sizes, and (3) to form correlations of solid friction factor for both coals, with moisture content M greatly emphasized.

EXPERIMENTAL FACILITY AND MATERIAL PROPERTIES

The experimental facility is schematically illustrated in Fig. 1. Pulverized coal is transferred between two hoppers, and top discharge hopper is adopted. Nitrogen with pressure up to 4.0 MPa from a buffer tank is divided into fluidizing gas, pressurizing gas and supplement gas. Fluidizing gas enters the bottom area of the feeding hopper and fluidizes the pulverized coal. Pressurizing gas is used to maintain the pressure of feeding hopper and to achieve high solid mass flow rate. The introduction of supplementary gas can effectively regulate the solid/gas mass flow ratio and enhance

†To whom correspondence should be addressed.
E-mail: xpchen@seu.edu.cn
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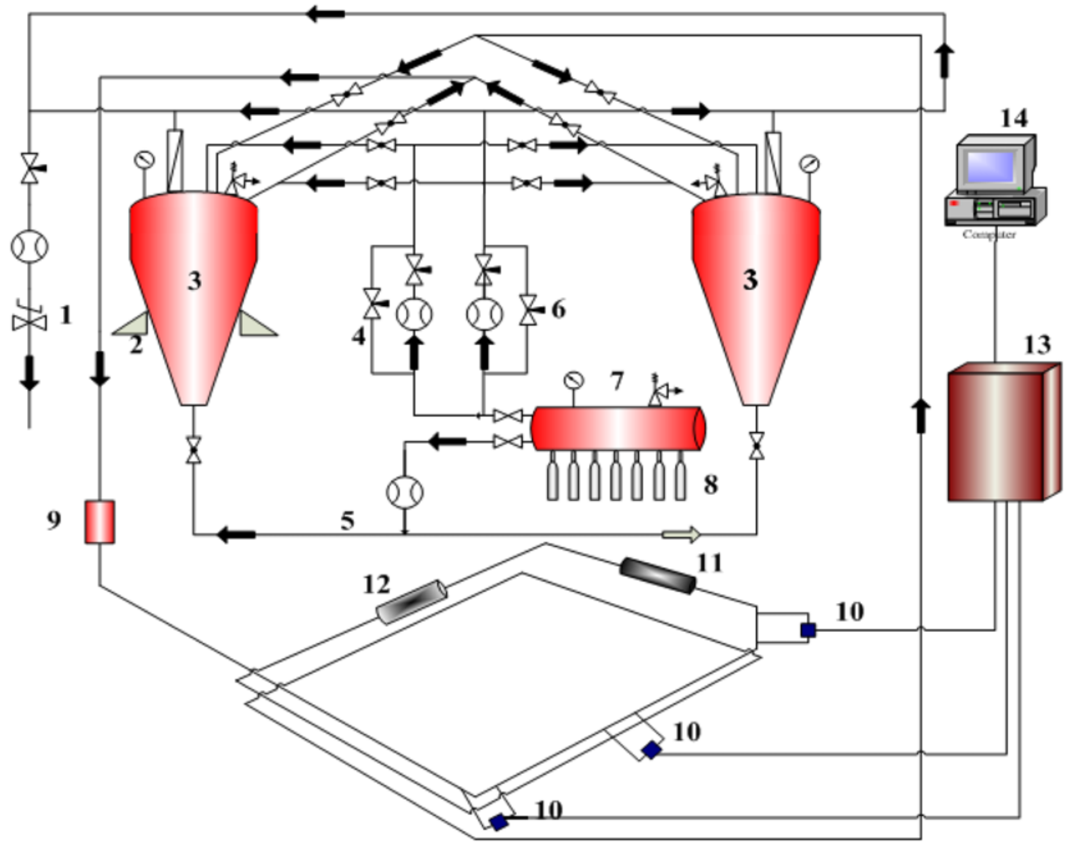

Fig. 1. Schematic diagram of high-pressure dense-phase conveying facility.

1. Motor-drive control valve
2. Weigh cell
3. Hopper
4. Pressurizing gas
5. Fluidizing gas
6. Supplement gas
7. Buffer tank
8. Nitrogen cylinder
9. Water adding device
10. Differential pressure transmitter
11. Electrostatic charge measuring device
12. Visualization test section
13. Control cabinet
14. Computer

conveying stability. The pipeline between two hoppers is about 45 m long with pipe diameter of 0.01 m. Along the pipeline four differential pressure drops are measured: pressure drop of the horizontal pipe (1 m), ΔP_h; pressure drop of the vertical pipe (1 m), ΔP_v; pressure drop of the horizontal bend (0.63 m), ΔP_{hb}; and pressure drop of the vertical bend (0.63 m), ΔP_{vb}. The detailed description of the experimental facility is reported in Ref. [21]. In the experiment process, the pressure of feeding hopper is maintained at 3.55-3.6 MPa, the pressure of the receiving hopper at 2.8 MPa and the fluidizing gas flow rate is kept at 0.4 m^3/h.

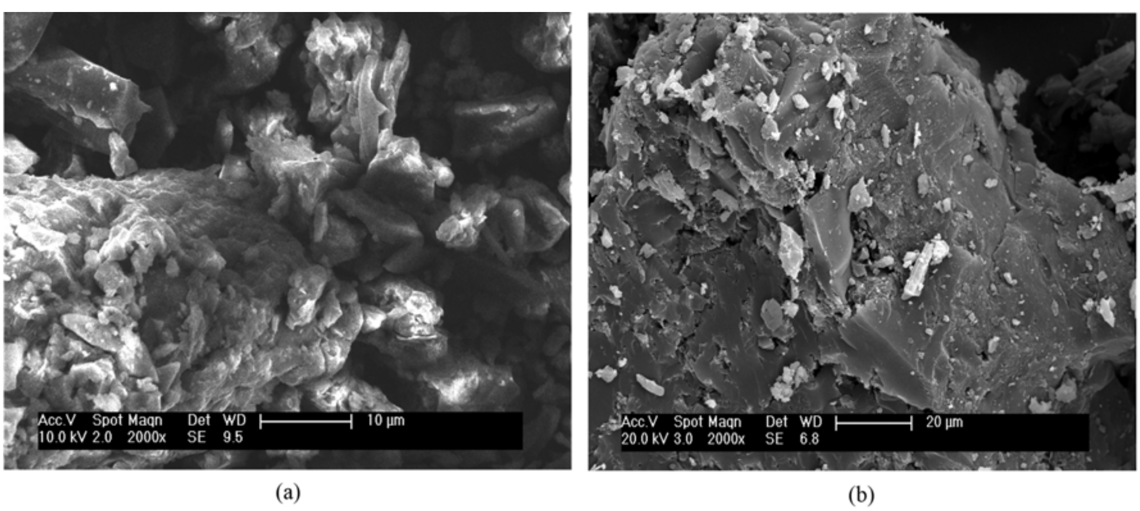

Fig. 2. SEM microphotographs of two coals: (a) 55 μm coal (b) 280 μm coal.

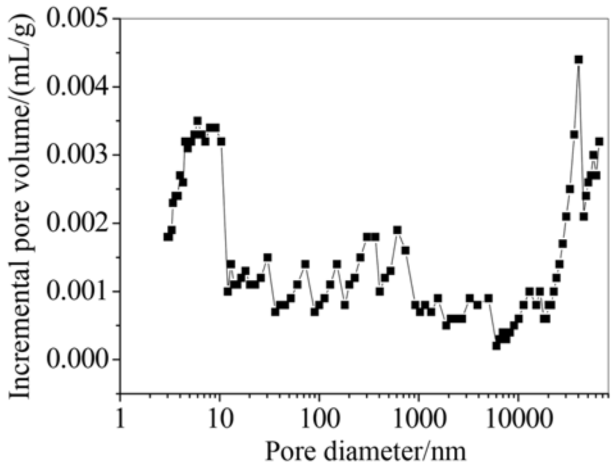

Fig. 3. The pore size distribution of coal.

Two pulverized lignite coals with density of 1,220 kg/m^3 are used, which are mean particle size (d) of 55 μm with original external moisture content of 3.24% and mean particle size of 280 μm with original external moisture content of 0.80%. Lignite coal is low rank coal with relatively low density and high specific surface area. Fig. 2 shows the surface characteristics of two coals. The surface is rough and uneven, on which there are many pores and cracks. Mercury intrusion test is adopted to analyze the pore size distribution. 280 μm coal is screened and the coal sample with diameter between 300 μm and 350 μm is tested. The result is shown in Fig. 3. There are many pores larger than 10 μm (10,000 nm) and the volume of pores larger than 1 μm reaches 0.053 mL/g.

During the transport process, water is sprayed into the gas-solid system in constant flux through the water injecting system. To ensure the water added is fully absorbed and evenly distributed in the coal, pulverized coal is transported twice between two hoppers and then is left in the hopper for at least 24 hours. Coal samples before and after a set of experiments for each moisture content are tested. Results show that the moisture contents before and after several times of transport stay constant.

RESULTS AND DISCUSSION

1. Stability of Transport Process and Limiting Value of Moisture Content

Fig. 4 shows the weight change history and pressure drop of 55 μm coal with moisture content of 4.23%. The conclusion can be drawn that the mass flow rate of coal is nearly constant and the pressure drop of each pipe section is very stable. It indicates that the distribution of moisture in pulverized coal is uniform and the whole experiment system can be stably and controllably operated.

During the process of adding water into gas-solid flow after a set of experiments for 55 μm coal with M=7.99%, blocking in the pipeline occurred. After the blocking was cleared, the conveying process could not successfully continue because the coal could not be discharged from the hopper. The same situation appeared for 280 μm coal during conveying when moisture content was increased to 10%. Fig. 5 shows horizontal pipe pressure drop fluctuations at respectively highest moisture contents of both coals under relatively

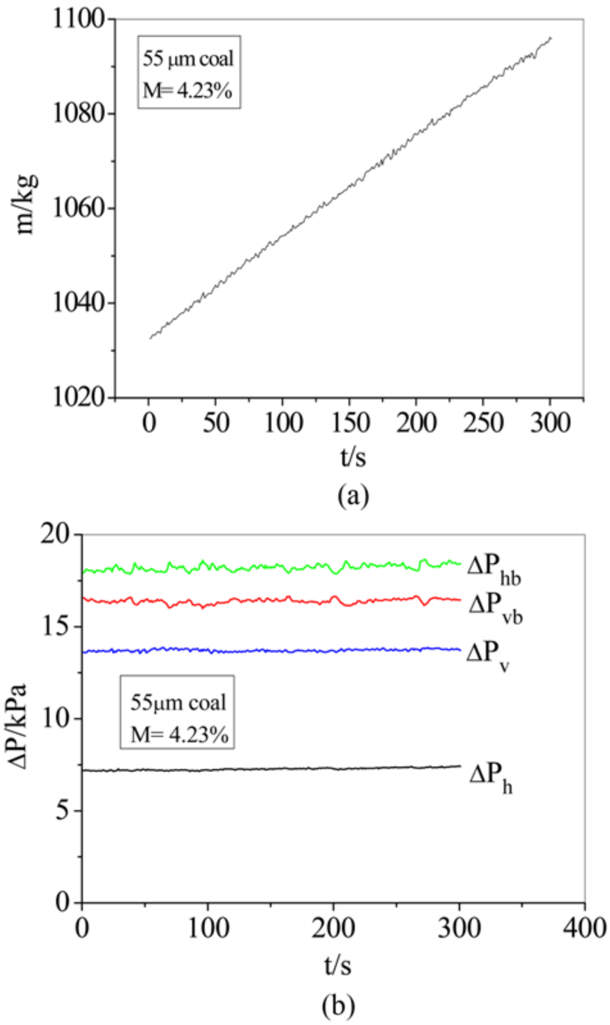

Fig. 4. The history of coal weight and pressure drop for 55 μm coal with moisture content of 4.23%: (a), (b).

stable flow. For 55 μm coal, two of the six experiments show situations demonstrated in Fig. 5(a); the pressure drop suddenly fluctuates violently. When the coal is transported at high moisture content, particles agglomerate and form clumps inside the tank, and the effect of fluidization above gas distributors deteriorates greatly. It tends to form funnel flow and arching at conical part of the hopper. Occasionally, large parts of agglomeration collapse into the fluidization area, causing instable discharging. While for 280 μm coal transported at M=8.00%, all the experiments are stable, like Fig. 5(b). Limiting value of moisture content for 55 μm coal is about 8%, and that for 280 μm coal is between 8% and 10%.

2. The Effect of Moisture Content on Mass Flow Rate

Moisture content in particles is one of the significant parameters which influence the flow characteristics in pneumatic transport process. According to Liang [8], as moisture content in pulverized coal goes higher, pelleting phenomenon appears between coal particles and small particles are easily aggregated into larger ones.

Fig. 6 shows that when the moisture content increases from 0.80% to 4.30%, the mass flow rate of 280 μm coal increases slightly. The initial moisture content 280 μm coal is very low, and high electrostatic effect appears during conveying process; when moisture con-

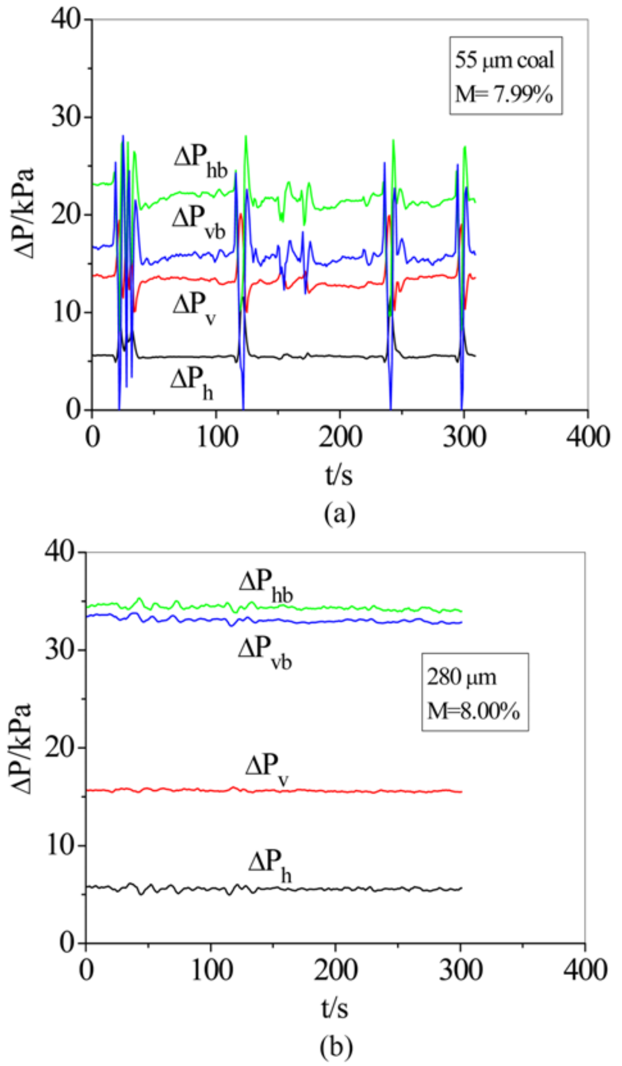

Fig. 5. Pressure drop fluctuations at high moisture content: (a) 55 μm coal with M=7.99%, (b) 280 μm coal with M=8.00%.

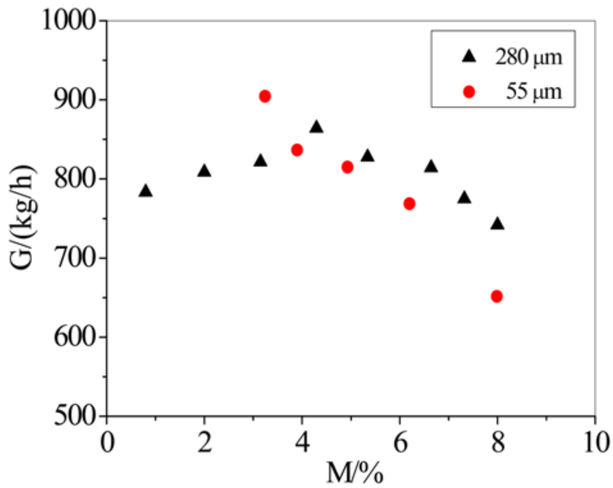

Fig. 6. Influence of moisture content on mass flow rate.

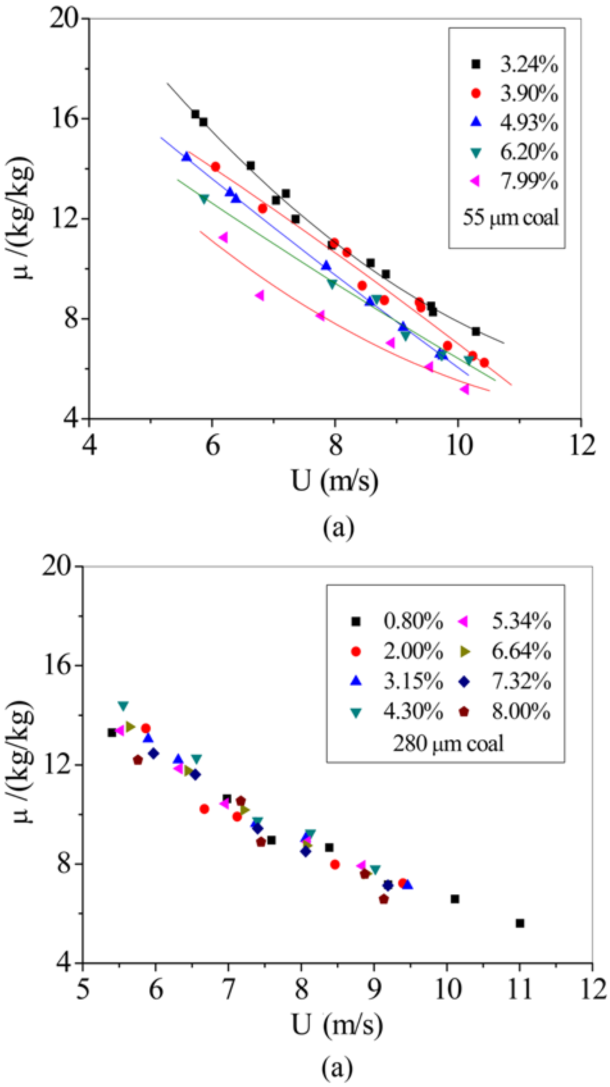

Fig. 7. Solid loading ratio vs. superficial gas velocity at different moisture content: (a) 55 μm coal, (b) 280 μm coal.

tent increases, the electrostatic interaction is suppressed. Meanwhile, when moisture content is increased, most of the added water goes into the pores and cracks on the coal surface. This kind of moisture has less impact on the flow characteristics, so the mass flow rate increases slightly. However, if moisture content continues to increase (more than 4.30%), most of the added water stays on the particle surface; viscous forces and the adhesion increase, resulting in increment of mass flow rate. For 55 μm coal, the initial moisture content is relatively high (3.24%), electrostatic interaction is weak, and most of the increased water stays on the particle surface. So the mass flow rate increases with increasing moisture content.

3. The Effect of Moisture Content on Solid Loading Ratio

In pneumatic conveying, the solid loading ratio μ is a very important parameter. It represents the solid concentration in the conveying system. The definition is that the mass flow rate of solid divided by the mass flow rate of gas $\mu=(m_s/m_g)$. Fig. 7 shows that solid loading ratio of two coals under different moisture content decrease with the increase of superficial gas velocity. For 55 μm coal, solid loading ratio also decreases with the increase of superficial gas velocity. While for 280 μm coal little difference can be detected. This reflects that fine coal is more sensitive to moisture content than coarse coal. To achieve high solid loading ratio under the condition of ensuring continuous and stable flow, the moisture content of fine coal must be limited to relatively low values.

4. Horizontal Pipe Pressure Drop Analysis

The popular approach of pressure drop determination in gas-solid two-phase flow is to assume that the total pressure drop is comprised of two hypothetical pressure drop components: pressure drop due to the gas alone and the additional pressure drop due to the particles [17]. In this experiment, the pipe length between the testing points of the horizontal bend and the horizontal straight pipe is much more than 100D, (D is pipe diameter, 0.01 m). It can safely be assumed that the gas-solid flow in the horizontal pipe is in stable state. Therefore, the acceleration pressure drop due to solids kinetic energy losing in the pipe can be ignored. The total pressure drop in horizontal straight pipe is expressed as follows:

$$\Delta P=\Delta P_g+\Delta P_s=\Delta P_g+\Delta P_F \quad (1)$$

Where ΔP is the total pressure drop of horizontal pipe, ΔP_g is the pressure drop due to gas phase, ΔP_s is the pressure drop due to solids, and ΔP_F is the pressure drop due to solids friction.

While calculating pressure drop due to gas in horizontal dilute phase flow, the use of fanning equation with blasius friction factor gives satisfactory results; f_g is gas friction factor. Geldart [14] pointed out that this method could be also suitable for dense phase flow.

$$\Delta P_g=2f_gL\rho_gU^2/D \quad (2)$$

$$f_g=0.079Re^{-0.25} \quad (3)$$

Where L is the pipe length, D is the pipe diameter, m_g is the viscosity of nitrogen kg/(m·s),

Xiong [22] proposed that when Re exceed the blasius scope (2320 $<Re<10^5$), Eq. (4) should be used instead. All our experimental data are out of blasius scope. Through calculation, it is found that the results of both formulas show high accuracy. We followed convention and used Eq. (3) to calculate ΔP_g in this study. Note that the experimental facility in this paper is the same one used in Xiong's work.

$$f_g=\frac{1}{4}(0.0032+0.2208/Re^{0.237}) \quad (4)$$

The concept of solid friction factor f_S is used in determining the pressure drop due to solids. Values of the friction factor f_S might reflect the interaction between particles or between particles and wall. In this method solid particles are analyzed in a form analogous to single phase flow. Klinzing [23] claimed that the commonly used equation to calculate the solids particle contribution to the pressure drop could be presented as follows:

$$\Delta P_F=\frac{2f_s\rho_s(1-\varepsilon)U_s^2L}{D} \quad (5)$$

Where $1-\varepsilon$ is solids volume fraction, ρ_s is the density of coal and U_S is the velocity of coal. In high pressure dense-phase flow, we simply assume that $U_S \approx U$, U is the gas velocity.

ΔP_F is obtained by subtracting pressure drop due to gas ΔP_g from total pressure drop of horizontal pipe ΔP_h. Using Eq. (3), values of solid friction factor f_S are obtained. Fig. 8 shows that f_S of two coals under different moisture contents show similar situation to solid loading ratio except for 55 μm coal at M=7.99%. It can be inferred that moisture content has little effect on solid friction factor for 280 μm coal.

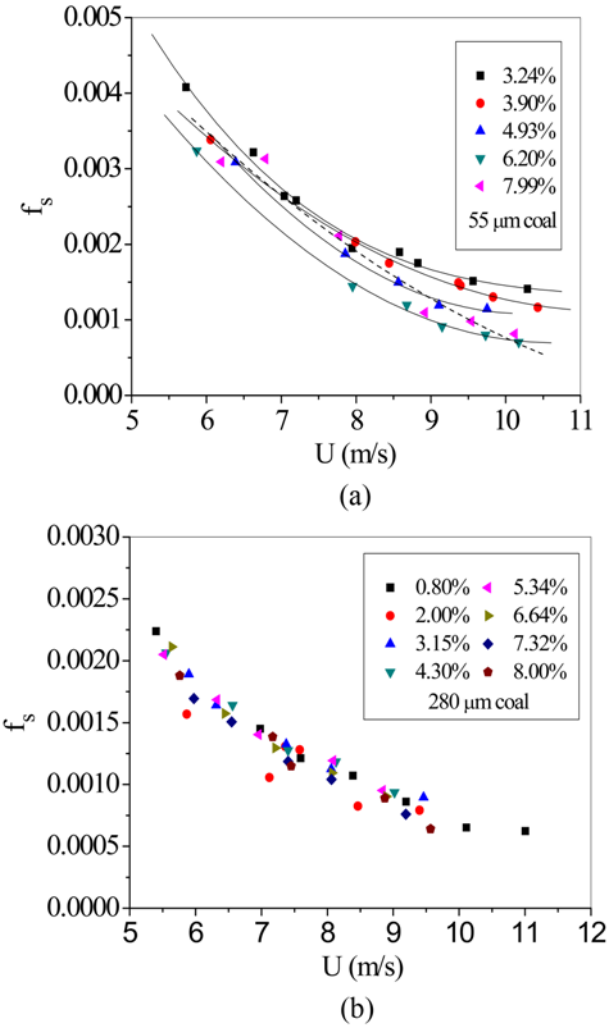

Fig. 8. Solid friction factor of horizontal pipe vs. superficial gas velocity at different moisture content: (a) 55 μm coal, (b) 280 μm coal.

A considerable amount of research indicates that the Froude number (Fr, based on supercial gas velocity) and solid loading ratio μ are the most dominant non-dimensional parameters for horizontal conveying of the solids. But little research has investigated the role of solids moisture content played in friction factor correlation. Since the moisture content has different effect on pulverized coals with different mean particle sizes in dense phase flow, it is necessary to make a quantitative comparison about solid friction factors between fine and coarse coals. In this study moisture content is taken into consideration, and the friction factor correlation is shown as Eq. (6).

$$f_S=\varphi Fr^aM^b\mu^c \quad (6)$$

As is mentioned above, some of the experiments for 55 μm coal with M=7.99% are not very stable, so we only introduce the experiment data with the range of M 3.24-6.20%. The solid friction factor correlation achieved for 55 μm coal horizontal flow is presented below:

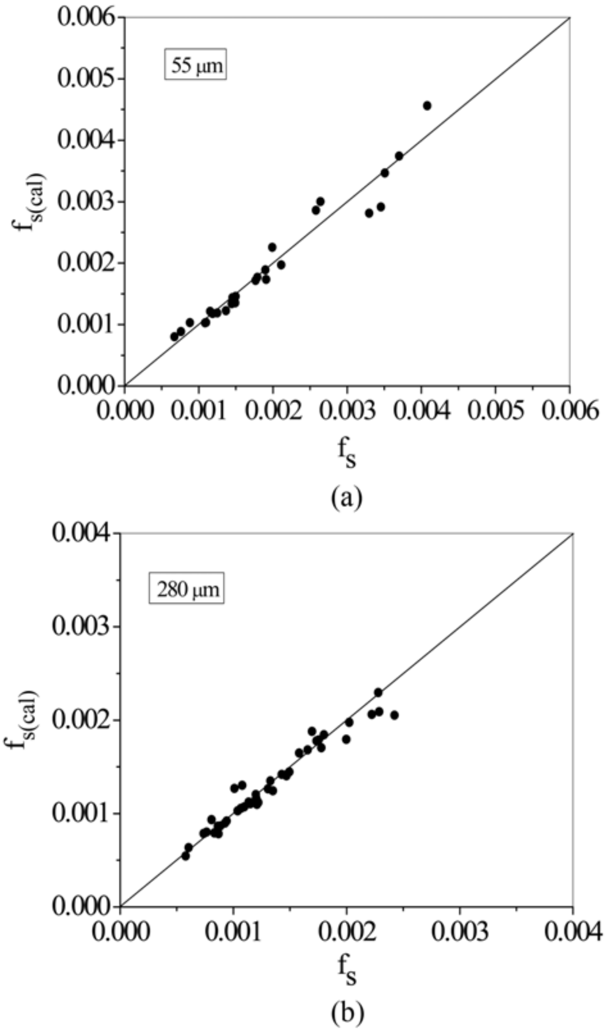

Fig. 9. Comparison of measured with calculated solid friction factors: (a) 55 μm coal, (b) 280 μm coal.

$$f_s=e^{1.687}Fr^{-2.230}M^{-0.67}\mu^{0.093} \tag{7}$$

Introduction of the experiment data for 280 μm coal yields the solid friction factor correlation presented below:

$$f_s=e^{-9.611}Fr^{-0.108}M^{-0.0013}\mu^{1.444} \tag{8}$$

In Fig. 9, the comparison between experimental solid friction factor and calculated solid friction factor is demonstrated. The calculation shows good accuracy; the data value points scatter evenly along the straight line $f_{s(cal)}=f_s$.

From Fig. 10, it can be seen that the horizontal pipe pressure drop $\Delta P_{h(cal)}$ calculated using $f_{S(cal)}$ is in good agreement with the experiment data ΔP for both coals. The error is between ±12% for 55 μm coal and between −8% and +12% for 280 μm coal for most experiment data.

Fig. 11 shows calculated solid friction factor for both coals with various moisture content. Solid friction factor for 55 μm coal decreases with the increase of moisture content and superficial gas velocity. And the effect of moisture content on f_s is more significant at low gas velocity than at high velocity. But for 280 μm coal, f_s is almost constant when moisture content increases. Comparing Eq. (7) and Eq. (8), the exponents of moisture content M of two coals are −0.539 for 55 μm coal and −0.0013 for 280 μm coal. It is concluded that moisture content has a significant effect on fine

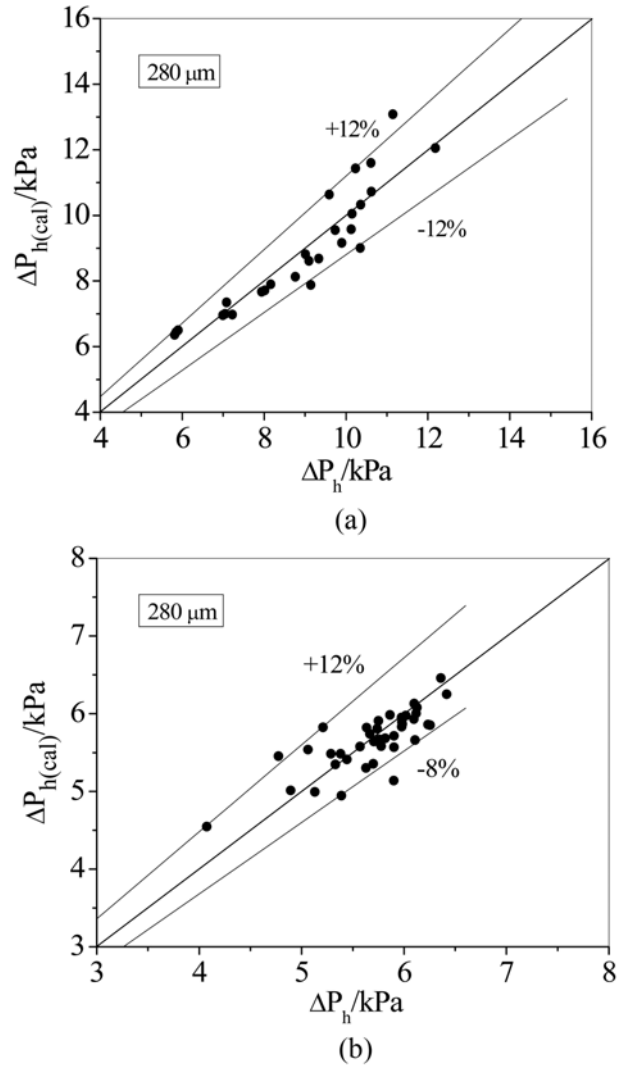

Fig. 10. Comparison of measured with calculated horizontal pressure drop: (a) 55 μm coal, (b) 280 μm coal.

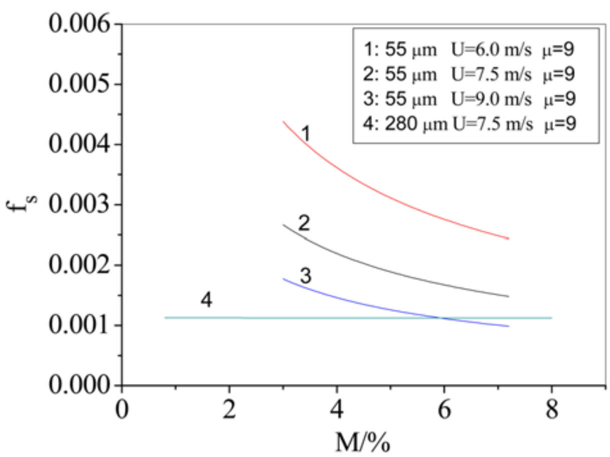

Fig. 11. Calculated solid friction factors of two coals vs. moisture content.

coal during transport but has little effect on coarse coal. It can be explained as follows. For coarse coal with original moisture content, the flow mode is dense-phase flow. Generally, there is a layer of dense-phase coal moving along the pipe with dilute-phase ow in the upper layer, so most particles aggregate at the bottom zone. Even when the moisture content increases, this mode of flow does not change much; therefore, there is little change in solid friction factor given the same solid loading ratio. Fine coal with original moisture content is almost suspension flow in the pipe. The particles fill the whole cross-section of the pipe. When the moisture content increases, the fine particles agglomerate and the mean particle size increases, more particles fall to the bottom of the pipe resulting in the change of flow mode. Therefore, the solid friction factor changes. It also can be seen from Eq. (7) and Eq. (8) that the exponent of solids loading ratio μ for 280 μm coal is much higher, so in coarse coal transport, solids loading ratio μ plays a more significant role in determination of solids friction than in fine coal transport. Fig. 12 validates it: the solid friction factor increases greatly when μ increases.

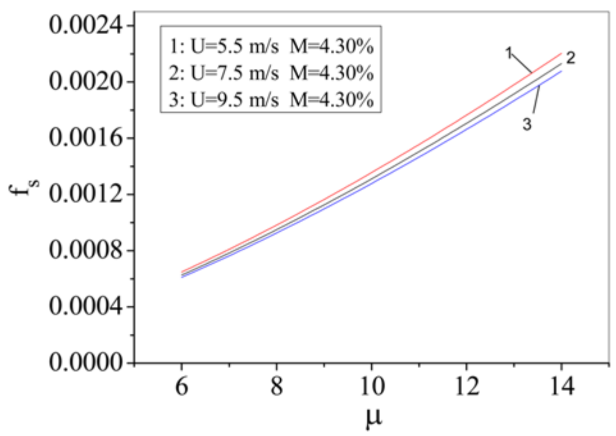

Fig. 12. Calculated solid friction factors of 280 μm coal vs. solid loading ratio.

Table 1. Typical experimental data

d/μm	M/%	U/m·s^{-1}	μ/1	$(1-\varepsilon)$/1	ΔP/kPa
55	3.24	8.5802	10.234	0.219	10.357
		6.628	14.120	0.261	12.183
	3.90	8.443	9.324	0.206	9.012
		6.055	14.079	0.259	10.619
	4.23	9.752	6.517	0.166	7.223
		8.564	8.662	0.200	7.939
	6.20	7.954	9.422	0.211	7.049
		8.677	8.816	0.202	6.995
	7.99	10.121	5.182	0.142	5.669
		6.198	11.247	0.234	8.961
280	0.80	6.980	10.631	0.231	5.978
		11.006	5.605	0.153	6.096
	2.00	7.122	9.911	0.222	4.774
		9.398	7.226	0.182	5.751
	3.15	5.899	13.048	0.258	5.984
		8.060	9.034	0.209	6.018
	4.30	6.562	12.276	0.248	6.360
		9.019	7.807	0.190	6.117
	5.34	6.326	11.849	0.244	5.902
		8.838	7.926	0.191	5.980
	6.64	6.444	11.764	0.241	5.736
		8.071	8.745	0.202	5.760
	7.32	6.546	11.613	0.238	5.636
		9.190	7.135	0.175	5.286
	8.00	9.567	6.174	0.160	4.892
		7.170	10.540	0.225	5.976

CONCLUSIONS

1. The conveying experiments of two pulverized coals with various moisture contents were carried out at a 4 MPa and dense-phase pneumatic conveying facility. Results show that the whole conveying system can be stably and controllably operated under the condition moisture content below ~8%.

2. Mass flow rate of 280 μm pulverized coal increases at first and then decreases with the increase of moisture content, while that of 55 μm pulverized coal decreases all along. The solid loading ratios of the two kinds of coal with various moisture contents decrease with the increase of superficial gas velocity.

3. The method of solid friction factor correlation is used, and non-dimensional parameters Fr number, moisture content M and solid loading ratio μ are investigated. Calculation shows good agreement. Fine coal is more sensitive to the change of moisture content and solid loading ratio μ plays more important role for coarse coal.

ACKNOWLEDGEMENT

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NOMENCLATURE

L : pipeline length [m]
d : mean particle size [m]
D : internal pipeline diameter [m]
f_s : solid friction factor of horizontal pipe
$f_{s(cal)}$: solid friction factor of horizontal pipe
G : mass flow rate of solids [kg/h]
M : moisture content of coals
P : conveying pressure [MPa]
P_2 : receiving pressure [MPa]
ΔP_g : pressure drop due to gas friction [kPa]
ΔP_F : pressure drop due to solids friction [kPa]
ΔP_h : pressure drop of horizontal pipe [kPa]
$\Delta P_{h(cal)}$: calculated pressure drop of horizontal pipe [kPa]
U : superficial velocity of gas [m/s]
U_s : velocity of solids [m/s]
ρ_g : gas density [kg/m^3]
ρ_s : particle density [kg/m^3]

Greek Letters

μ : solids loading ratio

μ_g : the viscosity of Nitrogen [kg/(m·s)]
$1-\varepsilon$: solids volume fraction

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