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Original Research Paper

Flow characteristics and flow rate prediction of pulverized coal through a regulation valve

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ABSTRACT

In this paper, experiments of dense-phase pneumatic conveying of pulverized coal were carried out in an industrial-scale system to study the control characteristics of the regulation valve and to predict the solid mass flow rate. Firstly, effects of valve sweeping gas on conveying stability and solid mass flow rate were investigated and the optimum valve sweeping gas was determined. Second, effects of valve opening on pressure distribution and solid mass flow rate were investigated by conducting experiments at different conveying pressure drops and different valve openings. A good linear relationship between the valve pressure drop ratio and the valve opening was found, and as the valve opening increased from 13 % to 70 % the solid mass flow rate increased gradually. Limit operating conditions of the regulation valve including flow blockage and control failure were consequently determined and analyzed. Finally, a robust model was established to predict the solid mass flow rate by introducing the valve sensitivity coefficient into the traditional pressure drop ratio model. The model can predict the solid mass flow rate well by providing errors mostly within ± 10 %. This study will provide certain reference for solid mass flow rate regulation in the dry coal gasification process.

1. Introduction

In recent years, the double carbon emission reduction policy has posed a greater challenge to the clean and efficient use of traditional fossil energy [1]. As a new type of gasification technology, pulverized coal pressurization gasification process [2] can significantly improve energy conversion efficiency, carbon utilization rate and combustion efficiency, and has the advantages of low operation and maintenance costs and less environmental pollution, which meets the needs of clean energy development in China. In the pulverized coal gasification process, stable supply and controlled regulation of the pulverized coal flow play an important role in process index and gasification efficiency. In order to meet the demand of gasifier operating under different loads, it is necessary to adjust the amount of coal and oxygen into the gasifier accordingly. The control of pulverized coal flow rate can be achieved by adjusting the system gas volume or conveying pressure, but both methods are inflexible and have limited adjustment range. In domestic and international pulverized coal gasification processes, a regulation valve is always installed between the pulverized coal feeding tank and the gasifier, to regulate the flow rate of pulverized coal so as to precisely control the oxygen-coal ratio in the gasifier [3]. It not only shows a better operation sensitivity for real-time controlling the pulverized coal flow, but also reduce the energy consumption, compared to the way of conveying pressure adjustment.

Researchers commonly use theoretical and experimental methods to obtain the flow-pressure characteristics in regulation valve. Nawada et al. [4] demonstrated, a proof-of-principle of a freeze–thaw valve (FTV) created in a 3D-printed fluidic device, that the additional structural complexity of the devices would not result in additional operational complexity in controlling fluid flows. Cherntongchai et al. [5] found that pressure signal could be used as a means to analyze the characteristics of fluid flow in the valve, through investigating the mathematical description of the pressure drop profile for 1-valve and 2-valve bed collapse experiments. Chattopadhyay et al. [6] conducted a similar study on the flow structure of pressure regulating valves using computational fluid dynamics methods and proposed a K-ε turbulence modelling,

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Nomenclature

d_p	particle surface area mean diameter (μm)	P_5	receiving tank pressure (kPa)
d_{10}	particle sizes for cumulative volume fractions of 10 % (μm)	ΔP	valve two-phase pressure (kPa)
d_{50}	particle sizes for cumulative volume fractions of 50 % (μm)	ΔP_g	valve gas-phase pressure (kPa)
d_{90}	particle sizes for cumulative volume fractions of 90 % (μm)	ΔP_m	miscible pressure drop (kPa)
h	valve opening (%)	ΔP_T	conveying pressure drop (kPa)
K	sensitivity factor (-)	$\Delta P/\Delta P_T$	valve pressure drop ratio (%)
K_{vg}	gas flow coefficient of valve (-)	Q_1	pressurized gas ($Nm^3 \cdot h^{-1}$)
K_{vm}	miscible flow coefficient of valve (-)	Q_2	fluidized gas ($Nm^3 \cdot h^{-1}$)
M_g	gas mass flow rate ($kg \cdot h^{-1}$)	Q_3	regulated gas ($Nm^3 \cdot h^{-1}$)
M_s	solid mass flow rate ($kg \cdot h^{-1}$)	Q_4	sweeping gas ($Nm^3 \cdot h^{-1}$)
P_0	feeding tank pressure (kPa)	Q_5	returning gas ($Nm^3 \cdot h^{-1}$)
P_1	pre-valve pressure (kPa)	Z	solid–gas ratio ($kg \cdot kg^{-1}$)
P_2	post-valve pressure (kPa)	ρ_b	bulk density ($kg \cdot m^{-3}$)
P_3	vertical pipe pressure (kPa)	ρ_g	gas density ($kg \cdot m^{-3}$)
P_4	horizontal pipe pressure (kPa)	ρ_m	miscible density ($kg \cdot m^{-3}$)
		ρ_P	particle density ($kg \cdot m^{-3}$)
		ρ_t	tap density ($kg \cdot m^{-3}$)

which was applied to regulating valves. Xiong et al. [7] tested the performance of pulverized coal regulating valves with three different spools, and compared the flow regulating performance. Amirante et al. [8] pointed out that the geometry of the spool can influence the flow characteristics of the fluid through the regulation valve, and that creating correspondingly shaped recesses in the spool can significantly reduce the flow forces and improve the flow characteristics of small valve opening. Filo et al. [9] found that, based on the results of the CFD analysis, the jet angle of working liquid depends mainly on the spool position in the regulation valve and does not depend on the pressure. Simic et al. [10] through the simple geometric modification of the spool, found that the modified spool structure can reduce the axial flow force in the control valve and eliminate the nonlinear deviation from the flow force characteristics. Thus the overall performance of the control valve is improved. Taghinia et al. [11] utilized two zero-equation sub grid-scale models, named the RAST and the DSM model, to predict the turbulent-flow structures at the gap exit of the valve. Wang et al. [12] pointed that in the actual flow process, the collision and friction between the particles, fluid and pipe wall are easily violent, which makes the pressure and flow rate in the pulverized coal regulation valve change violently and thus lead to the failure of the regulation valve.

The existing reports on regulation valves are mainly focused on incompressible fluids, compressible fluids, non-turbulent flows, gas–liquid two-phase flow, slurry-type non-Newtonian fluids, etc [13], while there are few reports on dense gas–solid two-phase flow which is commonly used in industry [14]. Dense-phase pneumatic conveying technology is usually adopted in the pulverized coal gasification process, which has the advantages of large conveying capacity, long conveying distance, high solid–gas ratio and low energy consumption. However, the dense-phase gas–solid two-phase flow through the regulation valve is very complicated as the valve has complex flow paths and encounters high concentrated and high speed movement of coal particles, which brings big challenge for researchers. Obviously, the research on the regulation valve performance and its role in the powder flow is far from enough, especially the control characteristics and limit operating conditions of the regulation valve have rarely been reported. Basic research on gas–solid flow through regulation valves under dense-phase conditions still seems to be very limited and imperfect compared to the ever increasing number of industrial applications. Therefore, it is a great need to study the regulation performance of complex regulation valves in order to provide theoretical support for industrial applications. Till now, the vast majority of regulation valves used in Chinese gasification industry are imported. And, due to the complex structure of the regulation valve, domestic and foreign scholars have conducted relatively little research on this filed. There is an urgent need to study on the mechanism of the regulation valve's role in the conveying system and to predict the solid mass flow rate with the aid of the regulation valve.

In this paper, flow characteristics of the regulation valve were studied on an industrial-scale diameter (50 mm) pneumatic conveying experimental system. Firstly, under different pressures of the feeding tank (200, 400 and 600 kPa), the effect of valve opening on the pressure distribution along the pipeline was studied. Further, the coupling effect of the valve opening and the conveying pressure drop on solid mass flow rate regulation was analyzed. On this basis, the blockage and failure diagnoses of the regulation valve were conducted and two critical valve openings under limit operating conditions were defined. Finally, a robust model to predict the solid mass flow rate was established by introducing the valve sensitivity coefficient into the pressure drop ratio model.

2. Experimental setup

2.1. Material

The experiments were carried out with pulverized coal as the transport medium, whose basic physical parameters are shown in Table 1. The particle size was measured by means of a laser particle size analyzer Mastersizer 2000. The entrained-flow pulverized coal gasification often operates with coal pulverized to a size in the order of 10 % < 5 μm and 10 % greater than 90 μm diameter to ensure both the reliable conveying in the pipeline and the high carbon conversion in the gasifier. Fig. 1 reports both the cumulative distribution and the distribution density of the sample, where d_p is the surface area mean diameter of particles, characterized as a sphere diameter with the same surface area as the powder particles, d_{10}, d_{50}, and d_{90} are the particle sizes for cumulative volume fractions of 10 %, 50 %, and 90 %, respectively. The powder tester PT-X was used to measure the powder bulk density (ρ_b) and tap density (ρ_t), that is, using the injection method, through a specific

Table 1
Physical properties of the pulverized coal.

d_p μm	d_{10} μm	d_{50} μm	d_{90} μm	ρ_b kg·m^{-3}	ρ_t kg·m^{-3}	ρ_p kg·m^{-3}	*MC* %
4.83	2.07	17.42	115.30	580.7	969.8	1627.5	1.27

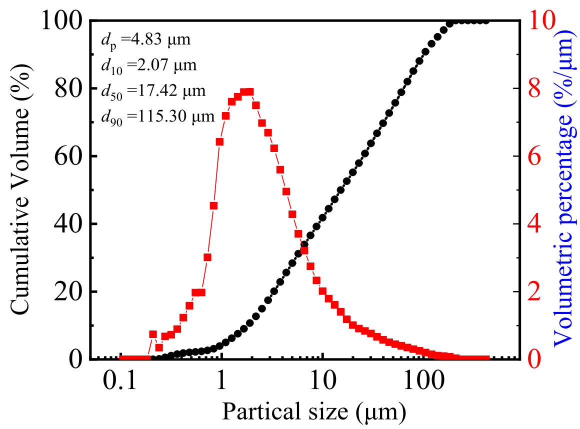


Fig. 1. Particle size distribution of the pulverized coal.

vibration method to make the air entrained powder natural fall into the special container, the natural accumulation of powder mass and the ratio of the volume it occupies is called bulk density; to the container injected powder to a certain up and down vibration, so that the powder in a tightly filled state of tap density. A 3H-2000TD true density meter, based on Archimedes' principle - gas expansion replacement method, was used to determine the particle density (ρ_p). The moisture content (*MC*) of the pulverized coal was determined at 105 °C with the aid of an infrared moisture analyzer. The detected moisture content was only 1.27 % suggesting a limited influence on flow characteristics that can be ignored.

2.2. Experimental process

The experimental platform is an industrial-scale pneumatic conveying system with diameter of 50 mm and the total length of 23 m. As shown in Fig. 2, the platform is mainly composed of gas source system (air compressor, refrigerated dryer, buffer tank, etc.), conveying system (feeding tank, receiving tank, ball valve, etc.) and instruments (data acquisition system, weighing sensor, etc.). The diagram for the process reported is a loyal similar to that of the real system. Generally, the bends adopted in industry have large radius bends *R/D* greater than 8 (where *R* is the radius of bend curvature and *D* is the pipe diameter), to decrease the wear of particles and pipes. In this work, bends with $R = 10D$ were adopted.

During the test, the air was compressed to 0.8 MPa by an air compressor (1). Then the compressed air was cooled by a refrigerated dryer (2) to remove moisture, oil and impurities. The dry and clean compressed air entered the buffer tank (3) and entered the test system in three ways: pressurized gas Q_1, fluidized gas Q_2 and regulating gas Q_3. At the specified feeding tank pressure and with the appropriate three-way gas combination, the pulverized coal was discharged from the feeding tank (5) and flowed along the pipeline to the receiving tank (7). The gas flow rate was measured and controlled by the metal tube float flow meter (H250/RRI/M9/ESK2A, Krohne) with a range of 0–250 NL·min^{-1} and an accuracy of 2.5 % fs. Pressure sensors (6) (PA-35X, Keller, accuracy 0.1 % fs) were installed on the tanks and along the pipeline to measure the pressure. The regulation valve (40CPC-PN16, produced by Hefei General Machinery Research Institute Co., ltd) installed at the outlet of the feeding tank was used to regulate the solid flow rate. In the process of valve regulation, the spool moves up and down to change the flow area with total stroke 48 mm. The valve opening (*h*) is defined as the ratio of moving distance to the total stroke. The solid mass flow rate (M_s) was obtained from a semi-floating static load weighing sensor (FW-1 t, METTLER TOLEDO) on the receiving tank with an accuracy of 0.05 % fs. All signals were collected by the PCS-4000 + data acquisition system with an acquisition frequency of 1 Hz for further processing.

In practice, it is often necessary to maintain a constant pressure in the feeding tank in order to ensure the stable operation of the entire conveying process [15–16]. In this paper, the pressure of the feeding tank is maintained at 200 kPa, 400 kPa and 600 kPa by synchronizing the valve opening and the system air volume. The receiving tank is always connected to the atmosphere and maintains atmospheric pressure. Operation parameters were provided in Table 2, where P_0 is the feeding tank pressure, kPa; Q_1 and Q_2 are pressurized gas and fluidized gas respectively, Nm^3·h^{-1}; M_s is the solid mass flow rate, kg·h^{-1}; *Z* is the solid–gas ratio, $Z = M_s/M_g$; ΔP is valve pressure drop, $\Delta P = P_1$-P_2, kPa; *h* is valve opening, %. The solid–gas ratio is an important technical index to classify the dilute and dense phase flow. It is generally accepted that dense-phase conveying process has the solid–gas ratio exceed 50 kg kg^{-1} [17]. The solid–gas ratio listed in Table 2 meets the requirements of dense-phase pneumatic conveying process, which makes the work meaningful.

3. Results and discussion

3.1. Effect of valve sweeping gas

The regulation valve is a key device to regulate the flow rate of pulverized coal during experiments [18]. Compared to conventional pneumatic conveying, the regulation valve comes with its own sweeping gas. The main function of the valve sweeping gas is to purge the inside of the spool to prevent coal dust from entering the stem through the gap between the valve body and spool, thus causing damage to the bellows. As shown in Fig. 3 (a), the direction of up and down movement of the cup is adjusted by turning the threaded handle below clockwise and counterclockwise, thereby controlling the change in outflow cross-sectional area, where the angle of inlet and outlet of these flow channels is 120°. As shown in Fig. 3(b), the solid mass flow rate is adjusted by adjusting the valve opening (i.e. spool stroke) and thus changing the throttling area of the open slot. The valve is externally piped with a 10 mm internal diameter valve purge gas line to prevent coal dust from being deposited in the valve cavity during valve adjustment, which could impede spool movement. In particular, in powders through a valve, coarse particles can be more important than fine particles, because jams are mainly caused by the coarse particles although the fines play an important role.

Generally, with the increase of valve opening, the area of the flow channel increases, resulting in the increase of the solid mass flow rate. More particles trend to deposit in the valve core, which may increase the risk of blockage. In response to this situation, the flow rate of the sweeping gas needs to be increased accordingly. The effect of valve sweeping gas on the powder conveying was examined, with respect to the flow rate and stability. Fig. 4 shows

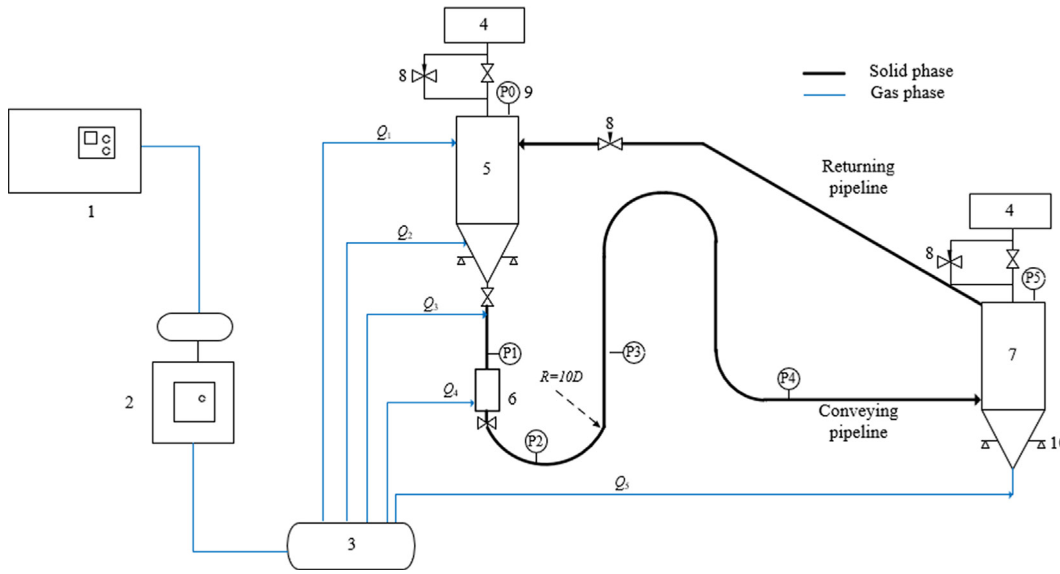


Fig. 2. Schematic diagram for pneumatic conveying of pulverized coal. 1-Air compressor; 2-Refrigerated dryer; 3-Buffer tank; 4-Dust remover; 5-Feeding tank; 6-Regulation valve; 7-Receiving tank; 8-Ball valve; 9-Pressure sensor; 10-Weighing sensor.

Table 2
Experimental range of operation parameters in this work.

P_0 kPa	Q_1 $Nm^3 \cdot h^{-1}$	Q_2 $Nm^3 \cdot h^{-1}$	M_s $kg \cdot h^{-1}$	Z kg kg^{-1}	ΔP kPa	h %
200	0 ~ 27.52	11.90 ~ 20.77	1867 ~ 6251	150.01 ~ 197.31	1.23 ~ 154.56	27 ~ 100
400	0 ~ 52.82	13.77 ~ 18.01	1403 ~ 8256	93.12 ~ 146.97	5.52 ~ 318.92	13 ~ 100
600	10.98 ~ 34.91	14.20 ~ 31.67	1547 ~ 4969	65.25 ~ 90.21	348.07 ~ 486.02	13 ~ 40

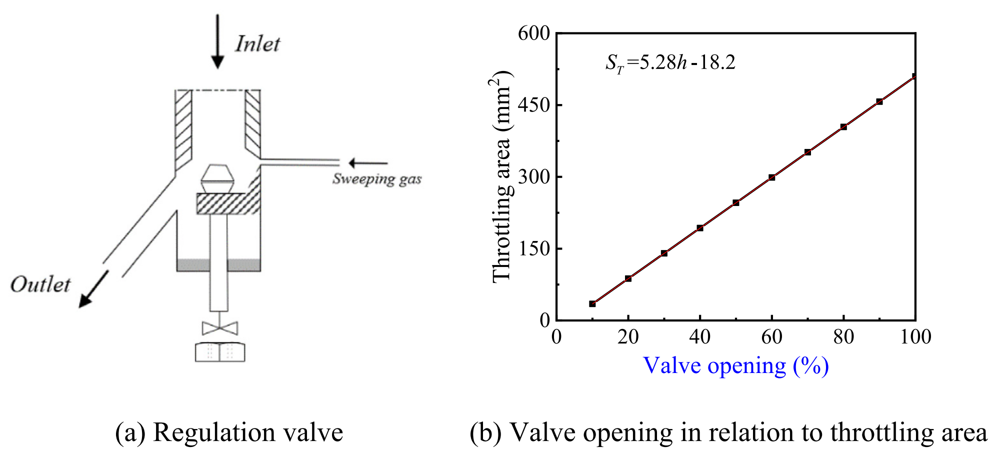


Fig. 3. Details of the regulation valve.

the *RSD* of the post-valve pressure signal as a function of the sweeping gas fraction, which is a dimensionless number. Relative standard deviation (*RSD*) refers to the ratio of the standard deviation to the arithmetic mean of the measurement result, which represent the variation of the relative standard deviation of the solid mass flow rate under different sweeping gas fraction. Q_4/Q_T defined as the ratio of the sweeping gas volume to the total gas volume. Q_4 is the sweeping gas volume and Q_T is the total gas volume entering the system, being the sum of pressurized gas Q_1, fluidized gas Q_2, regulating gas Q_3 and sweeping gas Q_4. As the sweeping gas fraction starts at 4.37 %, the *RSD* value gradually increases, which may be due to the excessive airflow strength and the formation of a more turbulent turbulence field inside the valve.

Fig. 5 shows the relationship between the sweeping gas fraction and the solid mass flow rate. It is found that with the increase of the valve sweeping gas, the solid mass flow rate shows the little changes (within 3 %), indicating that the valve sweeping gas has a relatively small impact on the solid mass flow rate.

The above analysis indicates that the effect of valve sweeping gas on the solid mass flow rate is small, but as the valve sweeping gas fraction increases, the conveying stability s firstly enhances and then weakens. When the sweeping gas fraction is set as 4.37 %, the conveying system shows the best performance. Therefore, the subsequent work is carried out at this valve sweeping gas fraction.

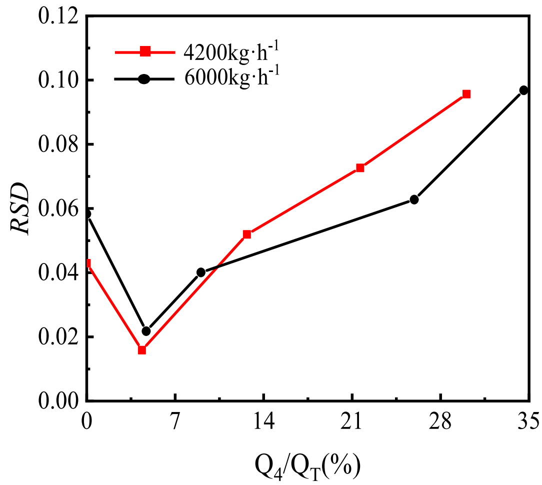


Fig. 4. *RSD* of the pressure signal as a function of the sweeping gas fraction.

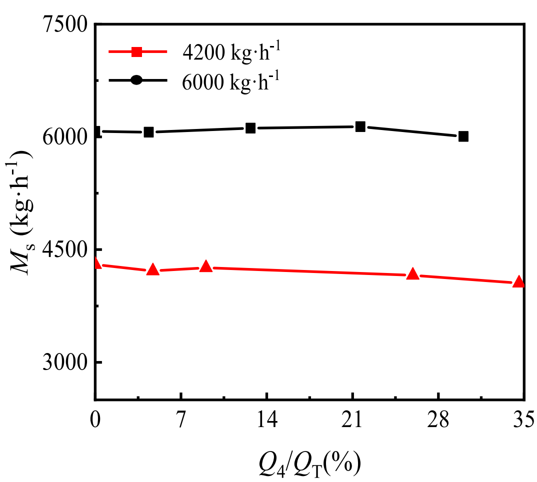


Fig. 5. Relationship between valve sweeping gas and pulverized coal mass flow rate.

3.2. Control characteristics in pressure distribution

By maintaining a certain conveying pressure drop, the effect of the valve opening on the system pressure distribution was analyzed for conveying pressure drops of 200 kPa, 400 kPa and 600 kPa. As shown in Fig. 6, as the valve opening decreases, the throttling area of the valve decreases and the resistance of the gas–solid phase flow through the valve increases rapidly, resulting in a corresponding increase in the pressure P_0 and the pressure P_1, while the pressure after the valve remains basically unchanged. As can be seen from the graph, the pressure difference between the front and rear of the valve (P_1-P_2) is large, and the conveying pressure drop is taken by the regulation valve; the smaller the valve opening, the greater the valve resistance, and the greater the pressure drop generated by the fluid through the regulation valve.

Fig. 7 shows the relationship between valve pressure drop and its opening when conveying pressure drop is 200 kPa, 400 kPa and 600 kPa. Generally speaking, there is a linear relationship between valve pressure drop and valve opening, and with the increase of valve opening, the valve pressure drop decreases accordingly.

The relationship between the above valve pressure drop and its opening is fitted respectively, and the corresponding formulas at different conveying pressure drop are shown in Table 3. From the correlation coefficient R^2, it can be seen that the fitting degree of pressure drop and opening is rather great. Furthermore, it can be seen that the greater the conveying pressure drop of the system, the greater the influence of opening on the pressure drop of the valve.

The pressure distribution in the conveying system depends on the arrangement of piping and the structure of the resistance components, etc. In order to highlight the characteristics of the regulation valve in the conveying system, the method of dimensionless valve pressure drop ratio ($\Delta P/\Delta P_T$) is used for analysis and discussion. It can be seen from Fig. 8 that valve pressure drop ratio is not depended on the conveying pressure drop, but only related to the valve opening. The valve pressure drop ratio is linearly fitted with the valve opening, as shown in the figure. On the whole, when the valve opening increases by 1 %, the valve pressure drop ratio decreases by about 1 %. The fitting formula is.

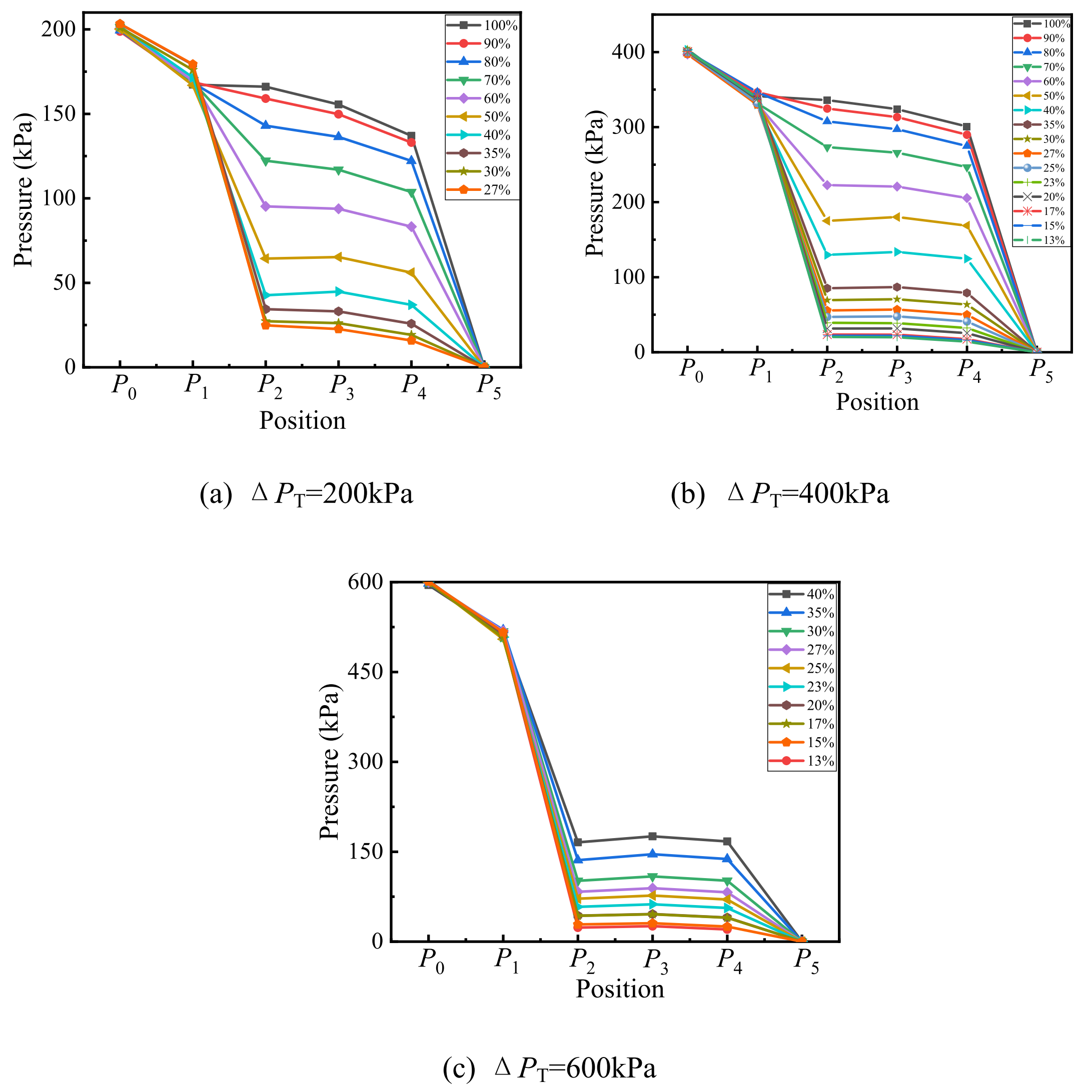
$$\frac{\Delta P}{\Delta P_T} = -h + 0.98, R^2 = 0.9711 \quad (1)$$

3.3. Control characteristics in solid mass flow rate

In the regulation process of dense-phase pneumatic conveying system, the concentration of pulverized coal will change accordingly with different operating conditions, and this situation is likely to cause unstable flow of pulverized coal [19], and may even cause flow blockage phenomenon [20]. At present, there are few studies on the pressure drop and flow characteristics of the pulverized coal flow regulation valve. Understanding the relationship between the pressure drop, pulverized coal mass flow rate and valve opening of the pulverized coal flow regulation valve can play a pre-regulatory role for industrial driving and provide reference for the regulation of the pulverized coal flow regulation valve.

Fig. 9(a) gives the relationship between the pulverized coal mass flow rate M_s and the valve opening h for three types of conveying pressure drop. As shown in the figure, the solid mass flow rate increases linearly with increasing valve opening, and is essentially constant when the valve opening is greater than 80 %. Under high pressure conditions, the valve opening has a more sensitive effect on the regulation of the solid mass flow rate. Fig. 9(b) shows the relationship between the conveying pressure drop (ΔP_T) and the valve opening h at different solid flow rates. When the solid mass flow rate is fixed, the conveying pressure drop decreases as the valve opening increases. On one hand, when the valve opening is high, the conveying pressure drop obviously plays a role in regulating the solid mass flow rate. On the other hand, at low valve openings, the conveying pressure drop is largely taken up by the valve, requiring a significant increase in the conveying pressure drop to meet the flow regulation.

As can be seen above, the solid flow rate can be regulated by changing the conveying pressure drop or the valve opening. In the process of pulverized coal pressurized gasification, the pulverized coal media needs to be conveyed steadily into the gasifier [21–23]. However, changing the conveying pressure drop will cause corresponding pressure fluctuations and consequently affect the stable operation of the process. Therefore, the regulation valve is more popular in practical applications. Discussion above shows that the regulation valve is able to regulate the solid mass flow rate linearly within the range of 13 %$\leq h \leq$ 70 %, providing advantages of wider adjustment range and higher sensitivity compared to the conveying pressure control. In addition, reasonable matching of valve opening and conveying pressure drop is expected. Proper valve opening and conveying pressure drop can not only meet the flow rate requirements but also save energy and improve the valve life.



(a) Δ P_T=200kPa (b) Δ P_T=400kPa

(c) Δ P_T=600kPa

Fig. 6. Pressure distribution in the conveying system.

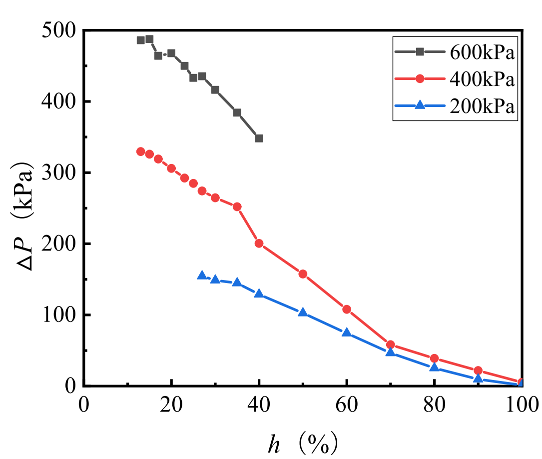


Fig. 7. Relationship between valve pressure drop and its opening.

3.4. Limit operating conditions of the regulation valve

During the experiment, the opening of the pulverized coal flow adjustment valve is either larger or smaller, which will affect the adjustment of the mass flow of pulverized coal [24–25]. When the valve is opened too small, the valve will be blocked and the pulverized coal will not pass through the valve properly [26]. When the valve is opened too wide, the adjustment performance of the pulverized coal mass flow rate is reduced or even lost.

Table 3
Fitting formula of valve pressure drop and its opening.

ΔP_T	$\Delta P \sim h$	R^2
200 kPa	ΔP = - 229.67h + 217.32	0.9843
400 kPa	ΔP = - 412.17h + 380.62	0.9757
600 kPa	ΔP = - 502.33h + 560.30	0.9637

Table 4 shows the critical operating conditions for flow blockage. As the conveying pressure drop of the conveying system increases, the energy provided by the system to the valve increases and the critical opening of the valve decreases. When the conveying pressure drop of the system is 200 kPa, the minimum opening of the valve is 27 %; when the conveying pressure drop of the system increases to 400 kPa-600 kPa, the minimum opening of the valve is 13 %, below this opening, the minimum energy required for the fluid to pass through the valve is greater than the energy provided by the system, and the valve becomes blocked.

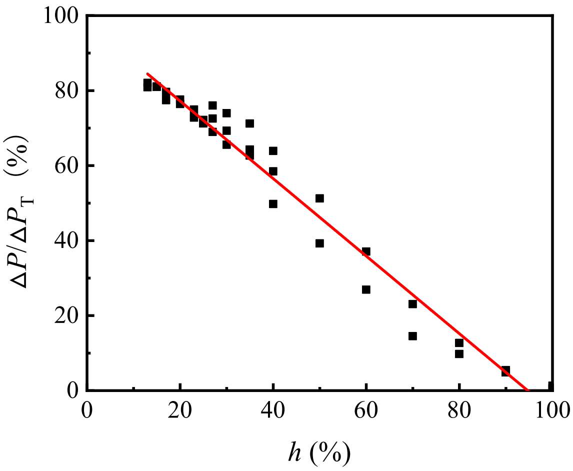


Fig. 8. Relationship between the valve pressure drop ratio and its opening.

The valve pressure drop is correlated with the conveying pressure drop to obtain a graph of the valve pressure drop versus the conveying pressure drop, as shown in Fig. 10. The valve pressure drop is fitted to the conveying pressure drop in Fig. 10 to obtain the relationship between the valve pressure drop and the conveying pressure drop during blockage, as shown in equation (2).

$$\Delta P = 0.80\Delta P_T,\ R^2 = 0.9998 \quad (2)$$

According to equation (2), under the critical valve opening, the valve pressure drop is proportional to the conveying pressure drop of the system, and the valve pressure drop accounts for about 80 %. In summary, when the valve pressure drop ratio is close to or reaches 80 %, attention should be paid to the relevant measures to prevent blockage.

Fig. 11(a) shows the valve pressure drop signal as a function of time when the conveying system is blocked. As the conveying system is approaching blockage, the pressures of feeding tank (P_0) and pressure before the valve (P_1) increase gradually, and the pressure signal after the valve (P_2) fluctuates significantly. When the valve is blocked (after 200 s), the conveying system cannot convey pulverized coal normally, and a large amount of pulverized coal is blocked inside the valve and could not pass through the outlet, at this time, the pressure of the feeding tank increased rapidly and pressures before and after the valve rapidly decreased as the pressure sensor does not work due to the blockage of coal powder. Fig. 11(b) shows the pressure signal during normal conveying, from which it can be seen that the fluctuation of all above pressure signals are relatively stable.

On the other hand, when the valve opening is too large, the valve will lose its regulating effect. In this study, the mass flow rate of pulverized coal does not change beyond a certain valve opening. Table 5 gives the experimental data for the valve opening above the upper limit of failure. As the tank pressure increases, the solid mass flow rate, concentration and valve pressure drop increase accordingly, but the valve pressure drop ratio is relatively low.

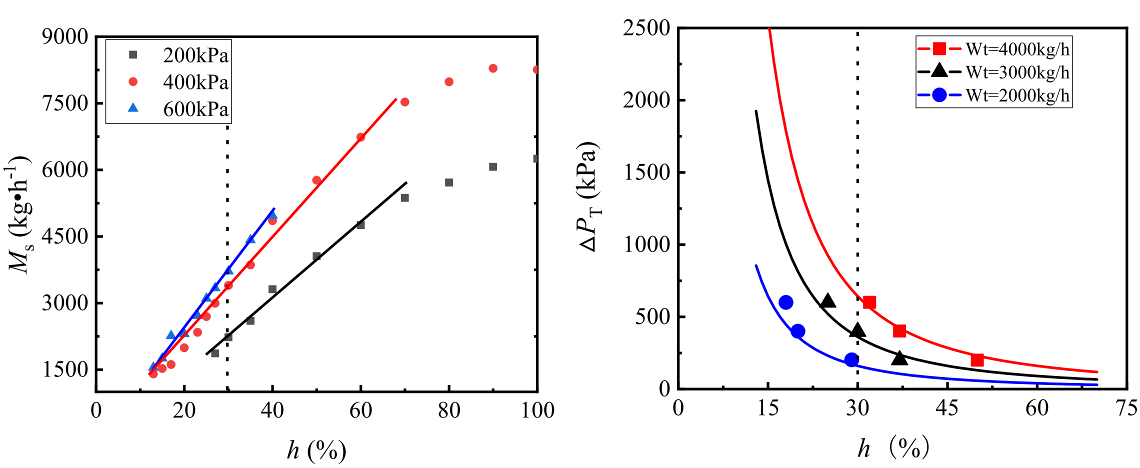
As shown in Fig. 12, at high valve openings, there is also good linear relationship between the valve pressure drop and the conveying pressure drop. However, the valve pressure drop ratio is relatively small. Fitting the above relationship yields.

$$\Delta P = 0.21\Delta P_T,\ R^2 = 0.9481 \quad (3)$$

According to control characteristics of the regulation valve in both the pressure distribution [27] and the solid mass flow rate, limit operating conditions of the regulation valve can be defined. Through the analysis and comparison of the dimensionless valve pressure drop ratio parameters, the critical valve pressure drop ratio under the condition of regulation valve control failure and flow blockage is quantitatively described, which is of great reference significance for the conveying system and the gas–solid two-phase flow in the regulation valve. The above analysis shows that when the valve opening is below 13 %, the valve pressure drop ratio is higher than 80 %, the system trends to be blocked; when the valve opening is larger than 70 %, the valve pressure drop ratio is lower than 21 %, the valve will lose the regulation effect, as shown in Fig. 13.

3.5. Solid mass flow rate prediction

Due to the complexity of valve flow path and flow conditions, few published research focus on flow characteristics and flow rate prediction [28] for gas–solid two-phase flow control valves [29–30]. Wang [31] in his analysis, simplified the dense-phase two-phase flow to the single-phase flow by giving a hypothetical equivalent density and tried to predict the solid mass flow through the regulation valve by the homogeneous flow model,



(a) M_s~h　　(b) ΔP_T~h

Fig. 9. Effect of valve opening on solid mass flow rate and conveying pressure drop.

Table 4
Limit operating conditions for flow blockage.

ΔP_T kPa	h %	M_s kg·h^{-1}	ΔP kPa	Z kg·kg^{-1}
200	27	1867	154.56	173.41
400	13	1403	318.92	101.28
600	13	1547	486.02	65.25

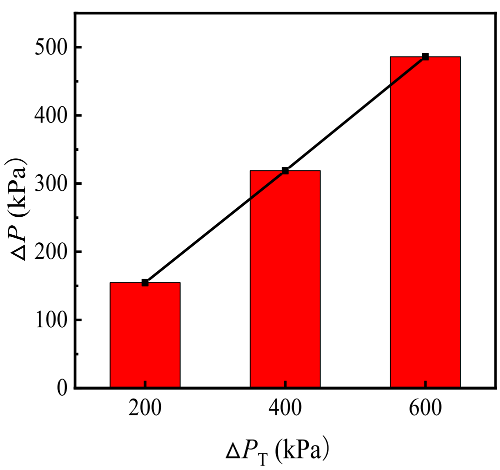


Fig. 10. Valve pressure drop versus conveying pressure drop at flow blockage.

$$M_s = 3.16 \cdot K_{vm}\sqrt{\Delta P_m \rho_m}\left(\frac{Z}{Z+1}\right) \tag{4}$$

where K_{vm} is the miscible flow coefficient; ΔP_m is the miscible pressure drop, kPa and ρ_m is the miscible density, kg·m^{-3}; Z is the solid–gas ratio, kg·kg^{-1}. As shown in Fig. 14, the homogeneous flow model provides prediction errors approaching to ± 20 %. As discuss above, the model ignores the difference between gas and solid phases, and does not take into account the complex phase interaction.

The pressure drop ratio model can be used to describe the interaction between the gas and solid phases. By considering gas-phase and gas–solid phase flowing at the same gas velocity, a linear relationship of the pressure drop ratio of mixture to gas can be established:

$$\frac{\Delta P}{\Delta P_g} = 1 + KZ \tag{5}$$

where K is the sensitivity factor, obtained by fitting experimental data; ΔP_g is the valve gas pressure drop, kPa; ΔP is the valve mixture-phase pressure drop, kPa.

Previous study [32] indicates that, for high pressure and dense-phase conveying system, a corrected factor α (α = 1 + $Z(\rho_g/\rho_p)$) should be considered and the solid mass flow rate can be expressed as equation (6).

$$M_s = \frac{\Delta P/\Delta P_g - 1}{K - \left(\rho_g/\rho_p\right)\left(\Delta P/\Delta P_g\right)} M_g \tag{6}$$

where ρ_g is the gas density, kg·m^{-3}; M_g is the gas mass flow rate, kg·h^{-1}.

In the experiment, by adjusting the valve opening and changing the throttling area at the spool, the pressure drop at the regulation valve is further affected, thus influencing the pressure distribution in the conveying system. Therefore the pressure drop ratio method was used to obtain the solid mass flow rate within the conveying system from the perspective of the valve pressure drop. As can be seen from equation (6), to calculate the solid mass flow rate, the valve gas pressure drop and sensitivity factor arising from the gas–solid two-phase flow are required.

The valve gas pressure drop can be calculated from the single-phase model shown in equation (7) where the gas flow coefficient K_{vg} is obtained by fitting to the valve opening h, as shown in (8),

$$\Delta P_g = \frac{M_g^2}{3160^2 \rho_g K_{vg}^2} \tag{7}$$

$$K_{vg} = 0.0422h^{2.02}, R^2 = 0.9968 \tag{8}$$

The accuracy of the gas pressure drop prediction by equation (7) is rather good, giving errors within 10 % as shown in Fig. 15.

By submitting experimental data and the calculated gas pressure drop into equation (6), it is possible to obtain the sensitivity factor K. The sensitivity factor K is further related to the pressure drop ratio ($\Delta P/\Delta P_g$). By regressing the experimental data, good linear relationships between the sensitivity coefficient and the pressure drop ratio were found at different conveying pressure drops, as shown in Table 6.

Considering effect of the conveying pressure drop gives.

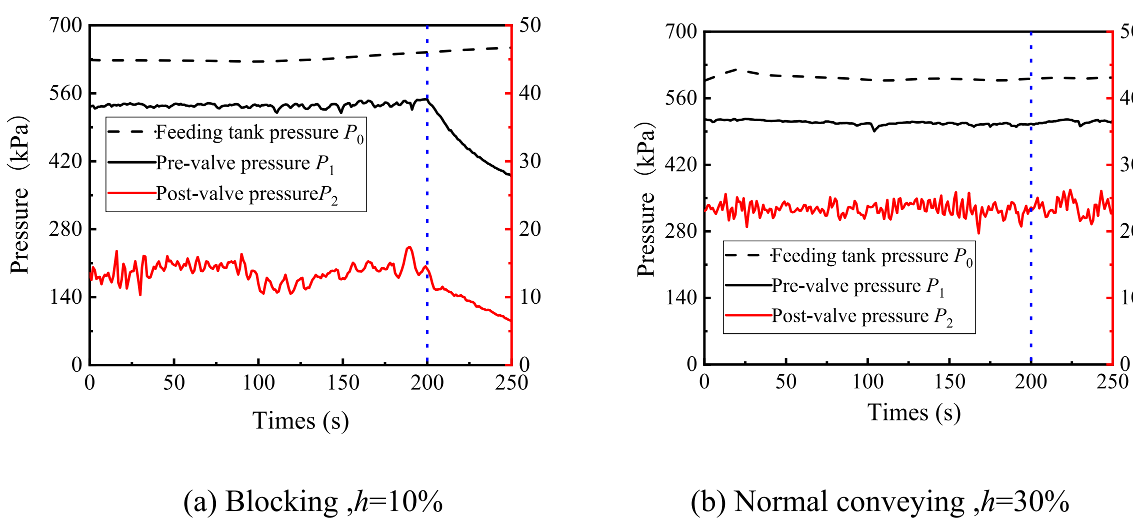


Fig. 11. Pressure signals during blockage and normal conveying.

Table 5
Limit operating conditions for control failure.

ΔP_T kPa	h %	M_s kg·h^{-1}	ΔP kPa	Z kg·kg^{-1}
82.28	80	3985	18.01	254.20
200.00	70	5714	51.34	176.43
400.00	70	8256	80.27	132.89

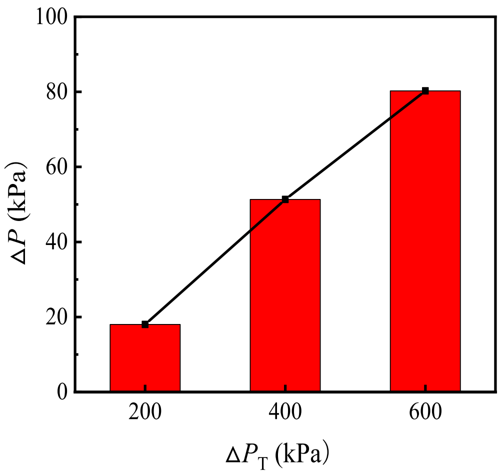


Fig. 12. Valve pressure drop versus conveying pressure drop at control failure.

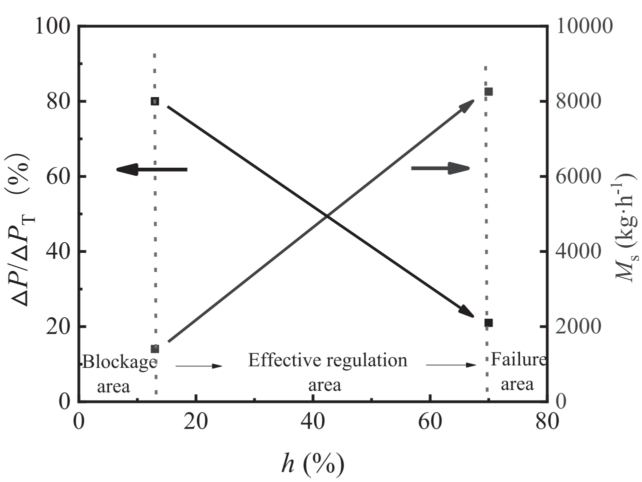


Fig. 13. Control characteristics of the regulation valve.

$$K = 2.4 \times 10^{-4} \Delta P_T^{0.6631} (\frac{\Delta P}{\Delta P_g}), R^2 = 0.9939 (13\% \le h \le 70\%) \quad (9)$$

Finally, the solid mass flow rate can be predicted by substituting equations (7) and (9) into equation (6). As shown in Fig. 16, predictions of the new developed gas–solid two-phase model agree well with experiments, giving errors mostly within ± 10 %. The model above is initially derived from Farber equation [33], which can be used for gas–solid flow through the variable cross-section, such as venture. A large number of experimental and theoretical studies have been carried out on the measurement of gas–solid two-phase flow by venture, but most were focused on low pressure and dilute-phase flow. Our previous work [32] has tried to extend the model to high pressure and dense-phase flow, but still limited in the venture. The venture with fixed structure can measure the flow rate but does not have the function of regulation. In this work, the regulation valve is adopted which can regulate the solid mass flow

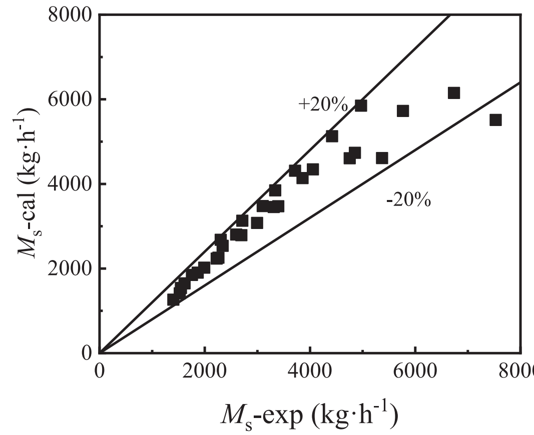


Fig. 14. Solid mass flow rate prediction of the homogeneous flow model.

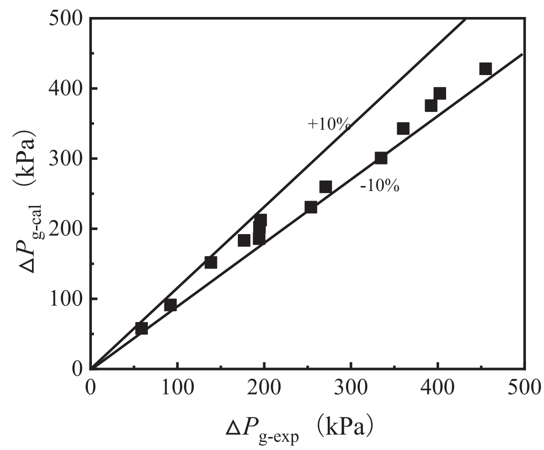


Fig. 15. Comparison of experimental and calculated gas pressure drops.

Table 6
Sensitivity factor versus pressure drop ratio.

ΔP_T (kPa)	Fitting formula	R^2
200	$K = 0.0095\left(\frac{\Delta P}{\Delta P_g}\right)^{0.9671}$	0.9367
400	$K = 0.0219\left(\frac{\Delta P}{\Delta P_g}\right)^{0.8891}$	0.9307
600	$K = 0.0235\left(\frac{\Delta P}{\Delta P_g}\right)^{0.9257}$	0.9834

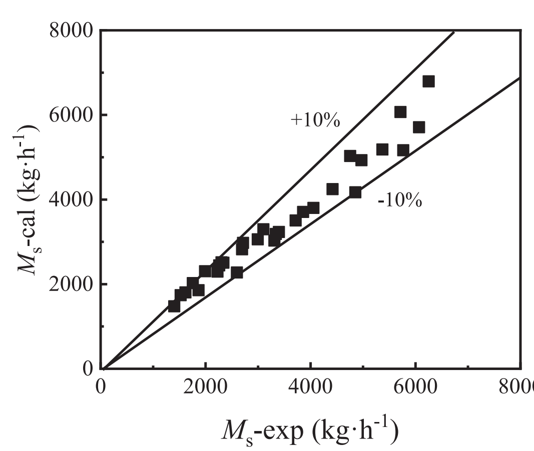


Fig. 16. Average solid mass flow rate prediction of the developed gas–solid two-phase model.

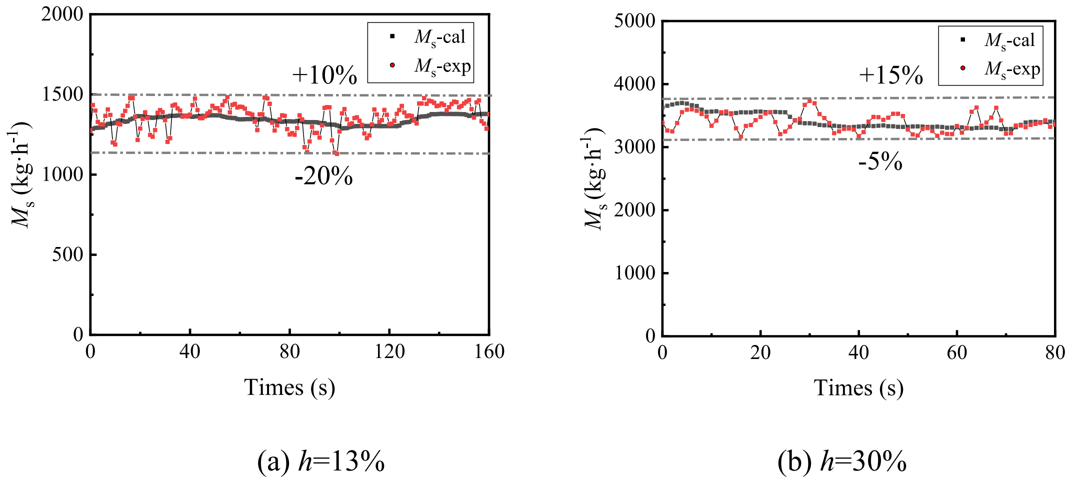


Fig. 17. Comparison of solid mass flow rate between predictions and measurements.

rate by changing its opening. We therefore, further extend the model to this valve. On the basis of above, the mode developed in this work is more advanced. It sounds for the regulation valve, and also the venture or other resistance components if degraded.

The model developed above was further subjected to real-time online prediction, as shown in Fig. 17. The graphs (a) and (b) show the variation of the solid mass flow rate for an opening of 13 % and an opening of 30 %, respectively, where the larger valve opening shows better predictions because of its stable conveying condition. It should be noted that, there is obvious fluctuation of the experimental solid mass flow rate, since it was obtained by the difference of weighting cell signal. Nevertheless, the real-time prediction shows a satisfactory effect. Considering the fact that, the weighing measurement always brings errors due to friction in the fulcrum bearings, the real-time prediction method based on model proposed in this work is meaningful. The use of the model for real-time online prediction is a strikingly important direction for future work.

4. Conclusions

(1). The sweeping gas can play a role in preventing the valve's internal cavity from blocking. It shows certain regulating effect on the conveying stability and almost little effect on the solid mass flow rate. The optimum sweeping gas fraction 4.37 % was determined for the regulation valve studied in this work.

(2). Both the valve pressure drop ratio and the solid mass flow rate increase linearly with the valve opening from 13 % to 70 %, showing good regulation and control performance. Reasonable matching of valve opening and conveying pressure drop is expected for operation optimization, which can not only meet the flow rate requirements but also save energy and improve the valve life.

(3). The limit operating conditions of the regulation valve were obtained and two critical valve openings 13 % and 70 % were defined. When the valve opening is below 13 %, the valve pressure drop ratio is larger than 80 % and the conveying system is prone to flow blockage. When the valve opening is above 70 %, the valve pressure drop ratio is smaller than 21 % and the regulation valve will lose its regulating role, named as control failure. And 13 %∼70 % is the linear regulating range of the regulation valve.

(4). Based on the pressure drop ratio method and the regulation characteristics of the regulation valve, a gas–solid two-phase model for solid mass flow rate prediction was established. The average solid mass flow rates were predicted with deviations mostly within ± 10 %, better than the traditional homogeneous model. The model, which can be further used for real-time online prediction, is very meaningful for solid mass flow rate monitor and regulation, and is a strikingly important direction for future work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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