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# Flow characteristics and dynamic behavior of dense-phase pneumatic conveying of pulverized coal with variable moisture content at high pressure

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**Abstract**−Experiments of dense-phase pneumatic conveying of pulverized coal using nitrogen were performed in an experimental test facility with the conveying pressure up to 4 MPa and the solid-gas ratio up to 500 kg/m$^3$. The influences of the total conveying differential pressure, the moisture content, the superficial velocity and the pressure on the mass flow rate and the solid-gas ratio were investigated. Shannon entropy analysis of pressure fluctuation time series was developed to reveal the flow characteristics. Based on the distribution of the Shannon entropy in the different conditions, the flow stability and the evolutional tendency of Shannon entropy in different regimes and the regime transition processes were obtained. The results indicate that the solid gas ratio and Shannon entropy rise with increase in the total conveying differential pressure. A phase diagram and Shannon entropy reveal preferable regularity with superficial velocity. Shannon entropy is different for the different flow regimes, and it can be used to identify the flow regimes. As the moisture content increases, the mass flow rate, the pressure drop and Shannon entropy decrease. Shannon entropy rises with increase in pressure drop.

Key words: Pneumatic Conveying, High Pressure, Solid-gas Ratio, Shannon Entropy

## INTRODUCTION

Gas-solid two-phase flow systems have been successfully used in the chemical and industrial processes. One typical example is the pneumatic conveying of materials. Pneumatic conveying is an important operation in a number of industrial processes: transportation of materials from storage areas, catalytic cracking in the petroleum industry, and the production of synthetic fuels from coal in energy conversion systems. However, the gas-solid two-phase flow is an unsteady and complicated nonlinear dynamical system. In recent years, numerous studies, both experimental and numerical simulation, have been conducted on different pneumatic conveying systems to characterize the flow profiles of the solids in the pipes of different sizes and for different pipe bends. Many valuable achievements on characteristics of pneumatic conveying have been obtained. Generally, many of these systems mainly work at low pressure. Pneumatic conveying at high pressure and with variable moisture content in particles is infrequently reported. At present, large-scale coal gasification technology is given attention and developed, and dense-phase pneumatic conveying of pulverized coal at high pressure is one of the key technologies in it [1,2]. Because of low velocity and high solid concentration at high pressure in transportation, the gas-solid two-phase flow becomes very unsteady and complicated [3-7], and unsteadiness of flows often causes blockage and pipe vibration. Moisture content in pulverized coal would result in forming a water bridge among pulverized coal particles. Friction, surface tensility and viscosity increase, and pelleted phenomenon appears. All of those factors lead to decrement of flowability and stability. References and experiences in this field are very few. Theories of dense-phase pneumatic conveying at high pressure still do not ideate and the flow characteristic of the high pressure conveying process in gas-solid system is not fully understood. Both further experimental and theoretical research in this field is highly needed.

It is well known that the pressure drop signal contains sufficient information on peculiar features of a gas-solid two-phase flow such as the flow characteristic, the regime, the particle property and the energy exchange [8,9]. Many signal processing methods have been proposed to analyze two-phase flow: power spectrum analysis [10, 11], chaotic analysis [12,13], process tomography [14] and wavelet analysis [15,16]. In recent years, Shannon entropy analysis has begun to be applied to the gas-solid two-phase flow. Cho et al. [17] employed Shannon entropy to study heat transfer and temperature difference fluctuations between an immersed heater and the bed in the riser of a three-phase circulating fluidized bed. Zhong and Zhang [18] applied Shannon entropy to analyze pressure fluctuation and identify the flow regimes in a spout-fluid bed. Wang et al. [19] also applied Shannon entropy to two-phase flow characteristics. Shi et al. [20] used Shannon entropy to characterize two-phase flow and two-phase flow density wave instability in vertical pipes. Most of the investigations focused on revealing the unsteady features of dilute phase gas-solid flow at low pressure using Shannon entropy analysis. However, the studies that used Shannon entropy for investigating flow characteristic of dense-phase gas-solid flow at high pressure in pneumatic transportation are very few. In this research Shannon entropy was applied to analyze flow characteristics of dense-phase pulverized coal pneumatic conveying at high pressure. Shannon entropy is a measurement of the information content or complexity of measurement series, which has been used widely in natural science research fields since the twentieth century. In pneumatic conveying, different flow characteristics should contain different amounts of information. Pressure fluctuation time series at different opera-

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tion conditions carries information of dynamic behavior. Thus, it is promising to grasp the characteristics of complex gas-solid two-phase flow in dense-phase pneumatic conveying at high pressure with Shannon entropy analysis of pressure fluctuation time series.

This paper is devoted to experimental investigation of the characteristics of dynamic behavior in a dense-phase pneumatic conveying line at high pressure based on Shannon entropy analysis of differential pressure drop fluctuation time series. It focuses on examining the effects of different operating parameters, in terms of the conveying differential pressure, the moisture content, the gas volume flow rate and the superficial velocity, on Shannon entropy, aiming at obtaining valuable information on the flow characteristic, flow regime and their transition.

## THEORETICAL ANALYSIS

In 1948, Shannon first defined the concept of Shannon entropy and used a mathematical formula to measure information content. In the developing process, it is associated with entropy in physics. As a state function, Shannon entropy can be utilized to predict the degree of uncertainty involved in predicting the output of a probabilistic event [21]. That is, if one predicts the outcome exactly before it happens, the probability will be a maximum value and, as a result, Shannon entropy will be a minimum value. If one is absolutely able to predict the outcome of an event, Shannon entropy will be zero. Shannon entropy eliminates the influence of information carrier and data value so as to be used in wide range of fields. It provides a scientific method to understand the essential state of things.

From the pressure drop time series of pressure fluctuations, a discrete data set of X(t) can be written as $X=\{x_1, x_2, \cdots, x_n\}$. Values of X may be divided into bins, each with a range in X(t), and denoted by values $X_1, X_2, \cdots, X_n$. Then, the probability of any value of X is $P(X_i)=X_i/n$. Hence, a set of probability $P(X_1), P(X_2), \cdots, P(X_n)$, can be created from the original data set. The Shannon entropy of any pressure time series in the pneumatic conveying can be defined as

$$S(X)=-\sum_{i=1}^{n} P(x_i)\log_b P(x_i) \tag{1}$$

Where, n is the length of time series signal, $P(x_i)$ is the probability of every component in the signal, satisfying the constraint $\sum_{i=1} P(x_i)=1$. When b=2, e and 10, the unit of S is bit, nat and hart, respectively. In this paper, the value of b equals e. Shannon entropy can be seen when there is more disorder in a system and the information entropy is larger. The Shannon entropies in pneumatic conveying reflect the dynamic behavior (e.g., turbulent motion of gas or particles, intensive interaction between particles and gas, flow instability, chaos).

## EXPERIMENTS

The pressurized experimental facility is shown schematically in Fig. 1. High pressure nitrogen from the buffer tank is divided into the pressurizing gas, the fluidizing gas and the supplement gas. The feeding hopper adopts the bottom-fluidization and top-discharge arrangement. Pulverized coal in the feeding hopper is fluidized by the fluidizing gas and enters the conveying pipeline through the accelerating segment. The supplement gas is imported to enhance the conveying ability of gas at the outlet of the feeding hopper. To adjust pulverized coal moisture content, water through vacuum pump is injected into the pulverized coal in the conveying pipeline at the constant proportion. The pressurizing gas is used to keep the pressure in the feeding hopper stable in the conveying process. The pressure in the receiving hopper is controlled by the motor-drive control valve. Each of the feeding hopper and the receiving hopper has a capacity of 0.648 $m^3$. The conveying pipeline including the vertical sections, the horizontal sections and the bends is made of a smooth stainless steel tube with an inside diameter of 10 mm and a length of about 45 m. The flow rate of each gas is measured by a metal tube variable-area flow meter, and the fluctuation of solid mass flow rate is gained by the weigh cells. Pressures and differential pressures are measured by the semiconductor pressure transducers with frequency response of 200 Hz and precision of 0.3%. Signals of differ-

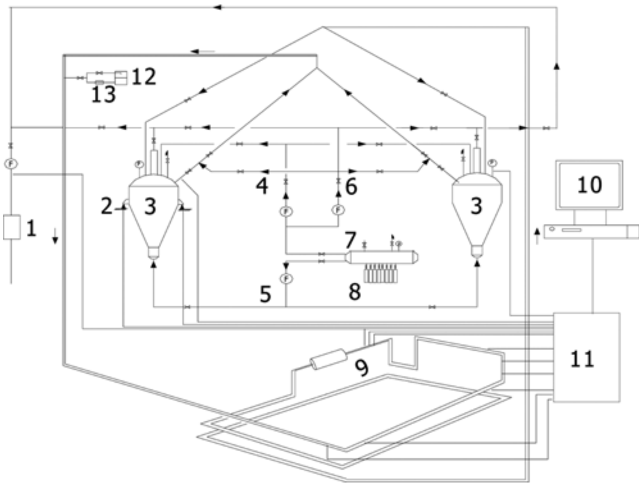


**Fig. 1. Schematic diagram of dense-phase pneumatic conveying of pulverized coal at high pressure.**

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. Visualization test section
10. Computer
11. Sensor and A/D converter
12. Water
13. Vacuum pump

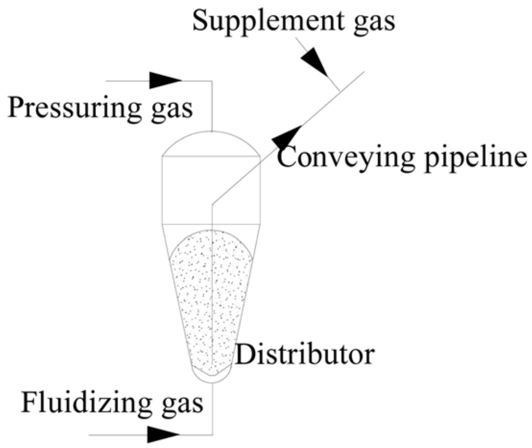


**Fig. 2. Diagram of the feeding hopper.**

ential pressure, pressure, weight and gas volume flow rate are obtained by a multi-channel sampling system and then are sent to a computer through an A/D converter. A high-speed camera is employed to photograph the flow regimes through visualization test section. Pulverized coal with the mean diameter of 36 μm and the density of 1,350 kg/m$^3$ is used as test particles. The conveying gas is $N_2$ with the maximum pressure of up to 4.8 MPa.

## RESULTS AND DISCUSSION

### 1. Shannon Entropy and Phase Diagram

Many distinct flow regimes have been reported in pneumatic conveying. They are divided into four shapes: suspended flow, stratified flow, dune flow and clusters flow. The typical Zenz phase diagram depicts several of the observed flow regimes during the conveying of coarse particles superimposed and is ratified by many researchers [3,22]. Fig. 3, which is the sample of the measured differential pressure fluctuations, shows the stability in the experimental process.

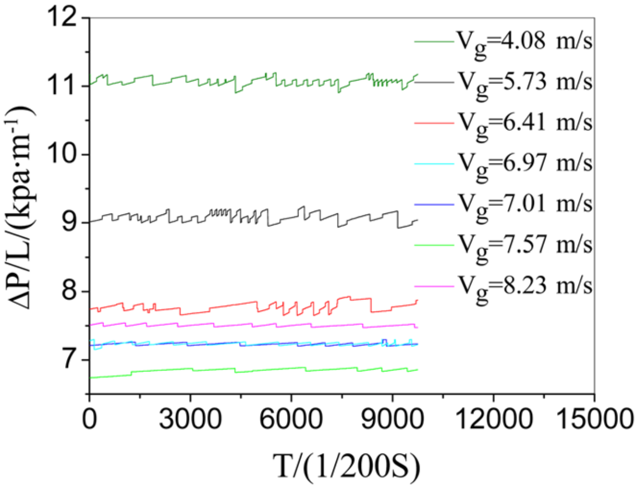


**Fig. 3. Sample of the measured differential pressure fluctuations ($P_1$=3.7 Mpa).**

The flow phase diagram of the horizontal pipe is plotted in Fig. 4. The pressure drops per unit length horizontal pipe decrease at first and then rise. The flow is quite dilute and pulverized coal is conveyed homogeneously when the superficial velocity is very high. The pressure drop is attributed mainly to gas movement. Here particles are carried in the gas while bouncing frequently against the pipe wall. As the superficial velocity decreases, the particle concentration increases. Pressure drop of the gas phase decreases and pressure drop of the solid phase rises. When the increment in the pressure drop caused by the solid phase equals the decrement in pressure drop caused by the gas phase, the pressure drop appears to be the minimum. Near the minimum of pressure drop, two phases, a suspended phase and a settled layer of pulverized coal, are frequently observed. The motion of the layer depends on the material characteristics and other parameters. To the right of the pressure drop minimum is a flow regime typically described as dilute flow. To the left of the pressure drop minimum, dunes or clusters can be seen riding on a settled layer of pulverized coal. A further reduction in the gas velocity will lead to a region typically characterized by unstable flow. At even lower gas velocities the material may flow as plugs or as a packed bed. The larger the solid flow rate, the higher the superficial velocity for the minimum pressure drop.

The Shannon entropies for various superficial velocities under the constant solid rate are depicted in Fig. 5. Shannon entropies decline at first and then rise with increase in the superficial velocity. It can be seen from Fig. 4 and Fig. 5 that Shannon entropy is different for different flow regimes, and can be used to identify the flow regimes. Shannon entropy analysis is a feasible approach to research the characteristics of flow regimes and flow regime transitions in dense-phase pneumatic conveying at high pressure. Exceeding its minimum value, Shannon entropy rises when superficial velocity increases, which implies that the degree of turbulence rises greatly in the conveying pipe. Pulverized coal is conveyed homogeneously in the pipe and the flow is suspension regime and the frequency of pressure fluctuation is very drastic. The gas-solid flow in the conveying pipe is more complex and stochastic, and thus Shannon en-

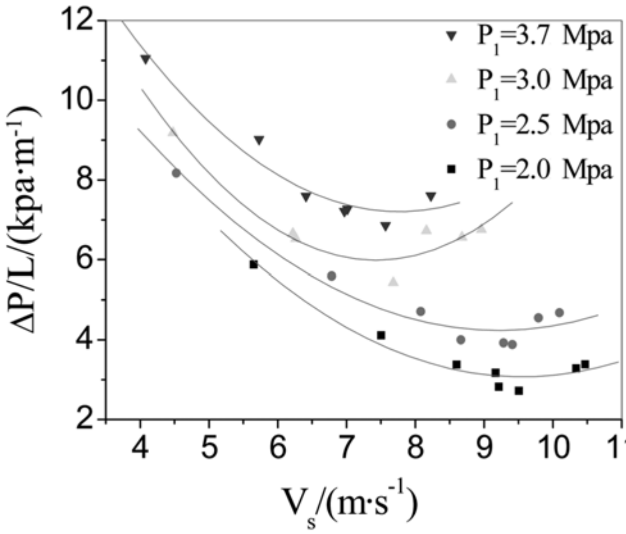


**Fig. 4. Phase diagram of horizontal pipeline.**

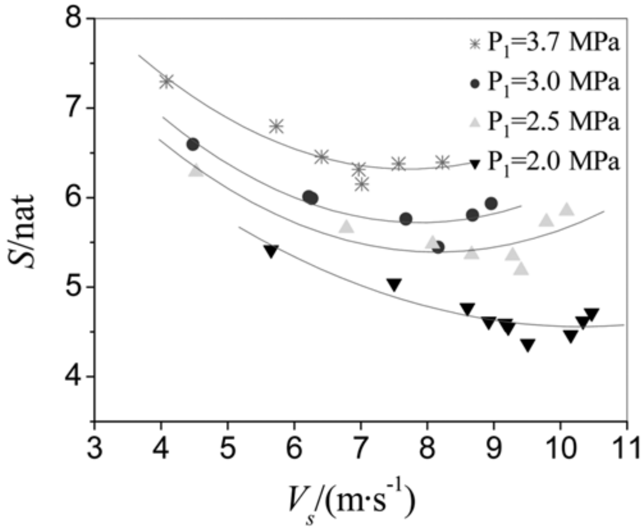


**Fig. 5. Change curve of Shannon entropy under different superficial velocity.**

tropy is larger. Pressure drop is also the minimum when Shannon entropy is the minimum, which is the most orderly and stable in the suspended flow in a constant mass flow. The minimum Shannon entropy may be attributed to the minimum frequency and amplitude of pressure fluctuation. For Shannon entropy less than its minimum, the gas-solid flow becomes sharply unstable and complex. The pressure fluctuations in the pipe are quite random due to stochastic changes in sectional area because coal particles begin to deposit on the bottom wall of pipe with reducing superficial velocity, which leads to an increase in Shannon entropy. When the superficial velocity keeps decreasing, the coarser pulverized coal particles settle in the pipe bottom and appear as dunes which hold a part of a section, coexist with collapse and move. Gas-solid two-phase flows seem to pass through many nozzles, and then appears to have greater complexity and more disorder, which results in an increase in Shannon entropy.

**2. Effect of Total Conveying Differential Pressure on Solid-gas Ratio and Shannon Entropy**

The total conveying differential pressure supplies power for pneumatic conveying and determines the quantity of transferable energy in transportation. In the experiments, the fluidizing gas volume rate, the supplement gas volume rate and the pressure in the feeding hopper were kept constant. The total conveying differential pressure was adjusted by changing the pressure in the receiving hopper.

Relationships between the conveying differential pressure and the solid-gas ratio are depicted in Fig. 6. The solid-gas ratio rises with increase in the total conveying differential pressure. When the pressure in the receiving hopper decreases, the total conveying differential pressure increases and the conveying capacity per unit volume gas is enhanced. Though the conveying gas volume expands because of reducing pressure in the receiving hopper, its increasing amplitude is much less than that in growing of mass flow rate of pulverized coal. In brief, the solid-gas ratio always rises with increasing the total conveying differential pressure when other operating parameters are kept constant. It can be found from Fig. 6 that an increment in the differential pressure has a strong effect on the solid-gas ratio at lower differential pressure, and the effect becomes weaker at higher total conveying differential pressure.

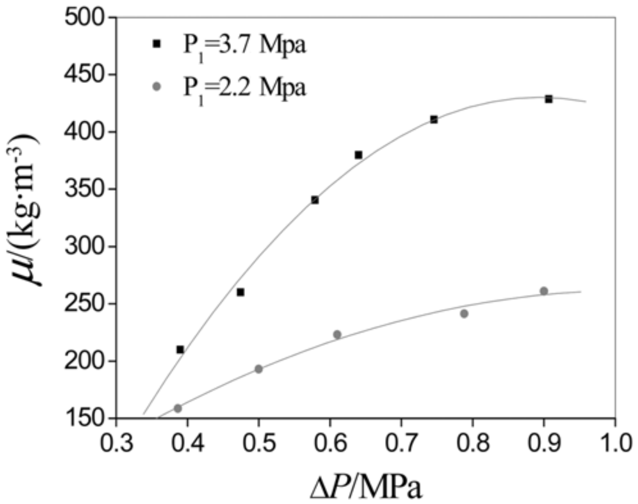


**Fig. 6. Solid-gas ratio vs. total conveying differential pressure.**

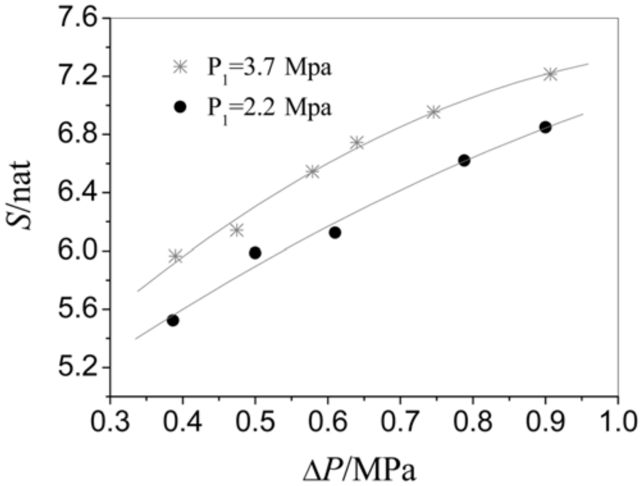


**Fig. 7. Shannon entropy curve under various total conveying differential pressure.**

Fig. 7 shows the Shannon entropies at the various conveying differential pressure for two pressures in the feeding hopper. It can be seen that Shannon entropy increases with the conveying differential pressure and its increase tendency slows down at higher conveying differential pressure. The coal mass flow rate and the solid-gas ratio rise as increasing the total conveying differential pressure. A part of the pipe section area is occupied by pulverized coal because of increase in solid concentration of gas-solid flow and conveying gas expands as the conveying differential pressure decreases at the same time. The combined result of two effects mentioned above leads to increase in conveying velocity. The frequency and amplitude of particle fluctuation become greater, the frequency and intensity of violent collision between particles, particle and pipe wall go up because of the decrease in the conveying differential pressure, which results in increasing disorder and complexity of gas-solid two-phase movement in the pipe. Thus, Shannon entropy increases. For lower conveying differential pressure, the influence of conveying differential pressure on solid is quite stronger, degree of turbulence and instability rise sharply, and Shannon entropy increases quickly. For higher conveying differential pressure, the slow increase in Shannon entropy indicates that the effect of the conveying differential pressure on gas-solid two-phase movement gets weaker.

**3. The Effect of Moisture Content on Mass Flow Rate**

Moisture content in powder is an important parameter to influence powder flow characteristic in pneumatic conveying. It has a strong effect on friction property, flowability, dispersibility and briquettability of powder. As moisture content in pulverized coal is higher, free water among pulverized coal particles mainly exists as felted water, sphenoid water and rising capillary water. Surface tension of water causes traction between two particles and a so-called water bridge is formed. Pelleting phenomenon appears among the coal particles, and small particles are easily aggregated into larger particles. All of these factors result in the increment of friction coefficient and viscosity. During the experiments, atomized water was evenly injected into the pipeline with pulverized coal to adjust the moisture content in pulverized coal. All of the operating parameters except pulverized coal moisture content were kept the same; the relationship between the moisture content and the mass flow

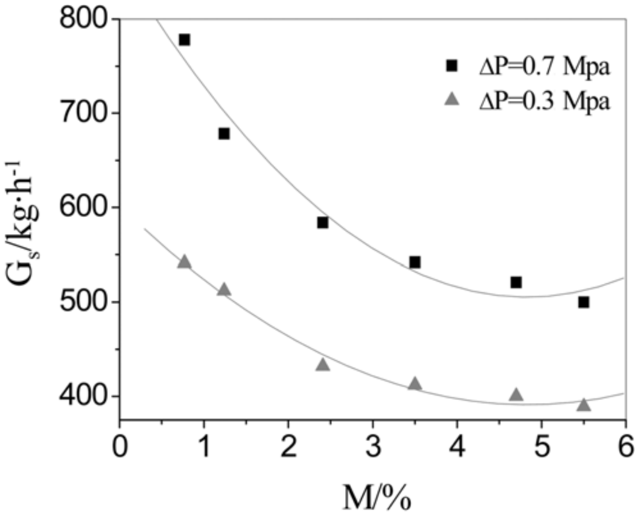


**Fig. 8. The influence of moisture content of pulverized coal on mass flow rate.**

rate is shown in Fig. 8. Along with increasing the moisture content in pulverized coal, the mass flow rate decreases. When the moisture content rises, the strength of the water bridge increases because of the increase in capillary force. The flowability of pulverized coal becomes worse and coal powder per unit mass needs to consume larger energy for pneumatic conveying. When the moisture content is greater than 6%, the flow in the pipe becomes very difficult, and blockage often occurs. The moisture content has a significant influence on the flow property of coal.

**4. The Effect of Moisture Content on Phase Diagram and Shannon Entropy**

In the experiments all of the operating parameters except pulverized coal moisture content were kept constant. Flow phase diagrams for variable moisture contents are shown in Fig. 9. For the same superficial velocity the pressure drop decreases when the moisture content rises. For lower moisture content in pulverized coal, the friction coefficient and the viscosity are less, the mass flow rate and the coal concentration are greater, which leads to an increment of pressure drop. When the moisture content rises, a water bridge forms, the friction force and the viscosity increase, and flowability of two phase flow gets worse, which results in reducing the mass flow rate. Although increment of the friction force and the viscosity has the trend of enhancing differential pressure, the effect of the pulverized coal concentration on the pressure drop is stronger because variable amplitude of the moisture content is less. So the pressure drop per unit length decreases with increase in the moisture content.

Fig. 10 reveals the relationship between the superficial velocity and Shannon entropy. For a certain superficial velocity the lower the moisture content is, the greater Shannon Entropy is. As the moisture content is lower, the mass flow rate is greater and a portion of pulverized coal settles on the bottom of the pipe wall. Reducing of the pipe sectional area leads to increment of the flow velocity. Because adhesive force and friction are less, particles leap in the conveying pipeline and frequencies of collisions among particles and particle and pipe wall are higher. Pressure fluctuation is disordered, aperiodic and indeterminate, and its amplitude goes up. So in that case Shannon Entropy is greater. With an increase in the moisture content, a water bridge forms and the interfacial force of free water is enhanced. In the feeding hopper, the adhesive force, the friction force and the viscous force rise. The fine coal particles aggregated into larger size particles and fluidization properties of coal particles become worse. More energy is needed for conveying a unit mass coal, and thus the mass flow rate decreases. In the conveying pipeline, two-phase velocity rises because of the decrease in the solid concentration, and the particles' strenuous movement weakens. Turbulivity and disorder degree of pressure fluctuation attenuate, which results in decrement of Shannon entropy.

**5. The Effect of Pressure Drop on Shannon Entropy**

Pressure drop is the macroscopic representation of two-phase flow characteristic in pneumatic conveying at high pressure. Pressure drop is correlative with particle concentration, velocity, the total conveying pressure and so on. Pressure drop per unit length reflects flow state and stability of gas-gas two phase flows. Relationship

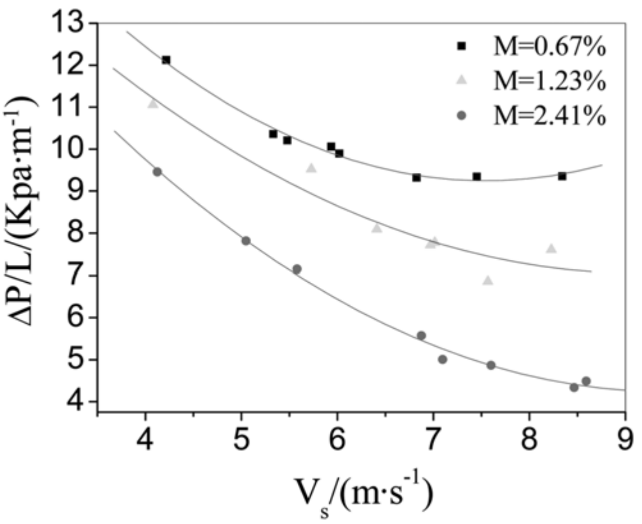


**Fig. 9. Resistance characteristics of variable moisture content in horizontal pipeline.**

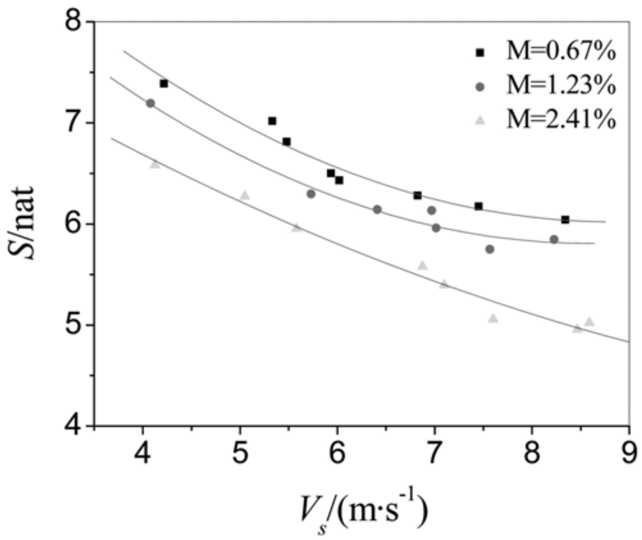


**Fig. 10. Shannon entropy curve of variable moisture content.**

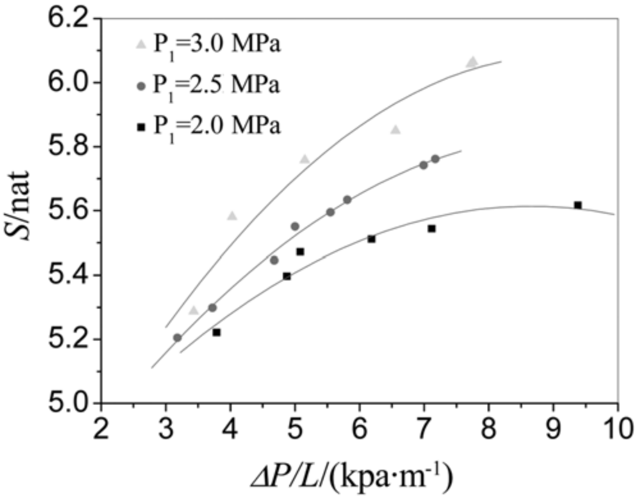


**Fig. 11. Dynamic characteristic of different pressure drop.**

between pressure drop and Shannon entropy is shown in Fig. 10. Shannon entropy rise with increase in pressure drop and increment of Shannon entropy weakens as pressure drop per unit length is bigger. When pressure drop per unit length is less, gas-solid two-phase flow is steadier. Fluctuation of pressure field is weaker and Shannon entropy is less. As pressure drop rises, gas velocity is higher than particle velocity. Gas-phase flows around pulverized coal particles and forms a boundary layer. Kinetic energy and potential energy transfer each other. With an increase in solid-phase concentration or conveying velocity, pressure drop per unit length rises and fluctuation enhances. Disorder and indetermination rise. When pulverized coal deposits on the bottom of the conveying pipeline, the coal layer moves slowly and a boundary layer is formed. As gas-solid two-phase flow passes over a great deal of dunes, two-phase flow fluctuates acutely and turbulent flow areas appear. Wake area rubs with fluid, energy consumption rises and pressure drop increases. Particles in the pipeline flow nondirectionally and even reverse with gas flow. Stability of pneumatic conveying decreases and flow field changes acutely. Because of those reasons, Shannon entropy rises. For little pressure drop, the influence increase in pressure drop on Shannon is more. As pressure drop is larger, the effect of fluctuation of pressure drop on gas-solid two-phase movement gets weaker. Increment of Shannon entropy diminishes.

## CONCLUSIONS

The influences of the conveying differential pressure, the mositure content, the gas volume flow rate and the superficial velocity on the solid-gas ratio and the mass flow rate were investigated. Shannon entropy analysis of pressure fluctuation time series was developed to reveal the flow characteristics. Through an investigation of the distribution of the Shannon entropy in the different conditions, the flow stability and the evolutional tendency of Shannon entropy in different regimes and regime transition processes were revealed and the relationship between Shannon entropy and the flow regime was also established. Shannon entropy is different for the different flow regime, and can be used to identify the flow regime. Shannon entropy analysis is a feasible approach to look into the characteristics of gas-solid two-phase flow in dense-phase pneumatic conveying under high pressure. Following main results can be summarized from experiments and theory analysis:

(1) Under a constant mass flow rate of pulverized coal, the pressure drop and Shannon entropy decrease first and then increase appreciably with increase in the superficial velocity. Shannon entropy is different for the different flow regimes, and can be used to identify the flow regime.

(2) As the conveying differential pressure rises, Shannon entropy and the solid-gas ratio increase accordingly.

(3) With increase in the moisture content in pulverized coal, the mass flow rate decreases.

(4) Along with increasing the moisture content, the differential pressure and Shannon entropy decrease.

(5) Shannon entropy rise with increase in pressure drop and increment of Shannon entropy weakens as pressure drop per unit length is bigger.

## ACKNOWLEDGMENTS

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## NOMENCLATURE

$G_s$ : mass flow rate of pulverized coal [$kg\cdot h^{-1}$]
M : pulverized coal moisture content [%]
$P_1$ : pressure in the feeding hopper [Mpa]
$P_2$ : pressure in the receiving hopper [Mpa]
$\Delta P$ : the total conveying differential pressure [Mpa]
$\Delta P/\Delta L$ : differential pressure of a unit length [$kpa\cdot m^{-1}$]
$Q_f$ : fluidizing gas volume rate [$m^3\cdot h^{-1}$]
$Q_s$ : supplement gas volume rate [$m^3\cdot h^{-1}$]
S : Shannon entropy [nat]
$V_s$ : superficial velocity [$m\cdot s^{-1}$]

### Greek Letters

$\mu$ : solid-gas ratio [$kg\cdot m^{-3}$]
$\rho_s$ : particle density [$kg\cdot m^{-3}$]

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