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# Flow characteristics and Shannon entropy analysis of dense-phase pneumatic conveying under high pressure

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**Abstract:** Experiments of dense-phase pneumatic conveying of pulverized coal using nitrogen are carried out in an experimental test facility with the conveying pressure up to 4.0 MPa and the gas-solid ratio up to 450 kg/m$^3$. The influences of different conveying differential pressures, coal moisture contents, gas volume flow rates and superficial velocities on the solid-gas ratios are investigated. Shannon entropy analysis of pressure fluctuation time series is developed to reveal the flow characteristics. Through investigation of the distribution of the Shannon entropy under different conditions, the flow stability and the evolutional tendency of the Shannon entropy in different regimes and regime transition processes are discovered, and the relationship between the Shannon entropy and the flow regimes is also established. The results indicate that the solid-gas ratio and the Shannon entropy rise with the increase in conveying differential pressure. The solid-gas ratio and the Shannon entropy reveal preferable regularity with gas volume flow rates. The Shannon entropy is different for different flow regimes, and can be used to identify the flow regimes. Both mass flow rate and the Shannon entropy decrease with the increase in moisture contents. The Shannon entropy analysis is a feasible approach for researching the characteristics of flow regimes, flow stability and flow regime transitions in dense-phase pneumatic conveying under high pressure.

**Key words:** pneumatic conveying; high pressure; dense-phase; solid-gas ratio; Shannon entropy

Pneumatic conveying has been successfully used in chemical engineering, energy, metallurgy and other industrial processes with advantages such as reliability, flexibility of layout, ease of automation, low maintenance, hygienics and it is environmentally friendly. In recent years, numerous studies, both experiments and numerical simulations, have been conducted on different pneumatic conveying systems to characterize the flow profiles of the solids in pipes of different sizes and different pipe bends. Many valuable achievements regarding the characteristics of pneumatic conveying have been obtained. Generally, many of these systems mainly work under low pressure. At the present time, large-scale coal gasification technology is attracting more attention and development, and dense-phase pneumatic conveying of pulverized coal under high pressure is one of the key technologies involved in it[1-2]. Because of low velocity and high solid concentration under the high pressure in transportation, the gas-solid two-phase flow becomes very unsteady and complicated[3-4], and the unsteadiness of the flows often causes blockage and pipe vibration. Pulverized coal moisture content easily results in fluctuations of mass flow rate and blockage of conveying pipelines. Unfortunately, very few references and experiences in this field are available. Theories and empirical formulae of dense-phase pneumatic conveying under high pressure still do not ideate and the flow characteristics of the high pressure conveying process in gas-solid system are not fully understood. Both experimentation and theory in this field still need further research.

The pressure signals contain sufficient information on peculiar features of gas-solid two-phase flow such as flow characteristics, regimes, particle properties and energy exchange[5-6]. Many signal processing methods have been proposed to analyze two-phase flow, for example power spectrum analysis[7-8], chaotic analysis[9], process tomography[10] and wavelet analysis[11-12]. In recent years, Shannon entropy analysis has begun to be applied to the gas-solid two-phase flow. Cho et al. [13] employed Shannon entropy to study heat transfer and temperature difference fluctuations between an immersed heater and the bed proper in the riser of a three-phase circulating fluidized bed. Zhong and Zhang[14] applied Shannon entropy to analyze pressure fluctuations and identify the flow regimes in the spout-

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fluid bed. Wang et al. [15] also applied Shannon entropy to two-phase flow characteristics. Shi et al. [16] used the Shannon entropy to characterize two-phase flow and two-phase flow density wave instability in vertical pipes. Most of the investigations focus on revealing the unsteady features of dilute phase gas-solid flow at low pressure using Shannon entropy analysis. However, the studies that have used the Shannon entropy to investigate flow characteristics of dense-phase gas-solid flow under high pressure in pneumatic transportation are very few. In this research, Shannon entropy is applied to analyze flow characteristics of dense-phase pulverized coal pneumatic conveying under high pressure. Shannon entropy is a measurement of the information content or the complexity of a measurement series. This 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. A pressure fluctuation time series under different operating conditions carry the information regarding dynamic behavior. Thus, it is promising to grasp the characteristics of complex gas-solid two-phase flow in dense-phase pneumatic conveying under high pressure by Shannon entropy analysis of pressure fluctuation time series.

This paper is devoted to experimental investigation of the characteristics of dynamic behavior in dense-phase pneumatic conveying under high pressure based on Shannon entropy analysis of differential pressure fluctuation time series. It focuses on examining the effects of different operating parameters (conveying differential pressure $\Delta P$, moisture content $M$, gas volume flow rate and superficial velocity $V_a$) on the Shannon entropy, aiming at obtaining valuable information on the flow characteristics, flow regimes and their transitions.

## 1 Theoretical Analysis

In 1948, Shannon first defined the concept of the Shannon entropy and used a mathematical formula to measure information content. In the developing process, it is associated with the entropy of physics. As a state function, the Shannon entropy can be utilized to predict the degree of uncertainty involved in predicting the output of a probabilistic event[17]. That is to say, if one predicts the outcomes exactly before it happens, the probability will be a maximum value and, as a result, the Shannon entropy will be a minimum value. If one is absolutely able to predict the outcomes of an event, the Shannon entropy will be zero. The Shannon entropy eliminates the influence of the information carrier and the data value so it can be used in a wide range of fields. It provides a scientific method to understand the essential state of things.

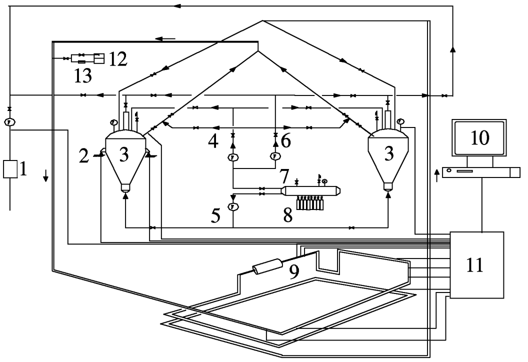
From the pressure time series of pressure fluctuations, a discrete data set of $X(t)$ can be written as $X = \{x_1, x_2, \ldots, x_n\}$. Values of $X$ may be divided into bins, each with a range in $X(t)$, and denoted by values $X_1$, $X_2, \ldots, X_n$. Then, the probability of any value of $X$ is $P(X_i)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

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

where $n$ is the length of a time series signal; $P(x_i)$ is the probability of every component in the signal, satisfying the constraint $\sum_{i=1}^{n} P(x_i) = 1$. When $b = 2$, e and 10, the unit of $S$ is bit, nat and hart, respectively. In this paper, the value of $b$ is equal to e. The Shannon entropy can be seen when there is more disorder in a system, and the information entropy is greater. 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).

## 2 Experiments

The pressurized experimental facility is shown schematically in Fig. 1. High pressure nitrogen from the buffer tank is divided into pressurizing gas, fluidizing gas and supplement gas. The feeding hopper adopts the bottom-fluidization and top-discharge arrangement. Pulverized coal in the feeding hopper is fluidized by fluidizing gas and enters the conveying pipeline through the accelerating segment. Supplement gas is imported to enhance the conveying ability of gas at the outlet of the feeding hopper. In order to adjust pulverized coal moisture content, water through vacuum pump is injected into the pulverized coal in the conveying pipeline at a constant proportion. Pressurizing gas is used to regulate pressure in the feeding hopper in the conveying process. The pressure of the receiving hopper is controlled by the motor-driven control valve. The feeding hopper and the receiving hopper both have a capacity of 0. 648 $m^3$. The conveying pipeline (vertical section and horizontal section, as well as the bend) is made of a smooth stainless steel tube with an inside diameter of 10 mm and a length of about 45 m. The gas volume rates are measured by the metal tube variable-area flow meter, and the fluctuation of solid mass flow rate is obtained by the weight cells. Pressure and differential pressure are measured by the semiconductor pressure transducers with a frequency response of 200 Hz and precision of 0. 3% . Signals of differential 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 a visualable test section. Pulverized coal with the mean diameter of 36 μm and a density $\rho_s$ of 1 350 kg/$m^3$ is used as test particles. Conveying gas is $N_2$ with a maximum pressure of up to 4. 8 MPa.




1—Motor-driven control valve; 2—Weight cell; 3—Hopper; 4—Pressurizing gas; 5—Fluidizing gas; 7—Buffer tank; 8—Cylinder; 9—Visualable test section; 10—Computer; 11—Sensor and A/D converter; 12—Water; 13—Vacuum pump

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

## 3 Results and Discussion

### 3. 1 Shannon entropy and flow regimes

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 has been ratified by many researchers[3, 18]. The flow phase diagram of the horizontal pipe is plotted in Fig. 2. The flow is quite dilute and pulverized coal is conveyed homogeneously when the superficial velocity is very high. Pressure drop $\Delta P/\Delta L$ is created mainly by 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. The pressure drop of the gas phase decreases and the pressure drop of the solid phase increases. When the increment of solid pressure drop equals the decrement of gas pressure drop, the pressure drop appears to be at the minimum. Near the minimum of the 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 a diluted or suspended 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 still lower gas velocities the material may flow as plugs or as a packed bed. The greater the solid flow rate is, the higher the superficial velocity of the pressure drop minimum is.

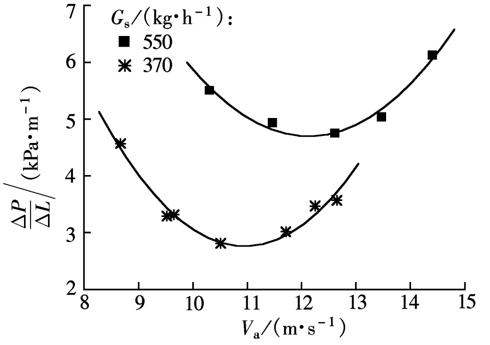



**Fig. 2** Differential pressure vs. superficial velocity

The Shannon entropies for various superficial velocities under the constant solid rate are depicted in Fig. 3. Shannon entropies decline at first and then rise with the increase in the superficial velocity. Through the information in Figs. 2 and 3, it can be seen that Shannon entropy is different for different flow regimes, and can be used to identify the flow regimes. The Shannon entropy analysis is a feasible approach to researching the characteristics of flow regimes and flow regime transitions in dense-phase pneumatic conveying under high pressure. To the right of the Shannon entropy minimums, Shannon entropies rise when the superficial velocity increases, the implied degree of turbulence rises greatly in the conveying pipe. Pulverized coal is conveyed homogeneously in the pipe and the flow is a 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 the Shannon entropy is greater. Pressure drop is also minimum when the Shannon entropy is minimum, which is the most orderly and stable in the suspended flow in a constant mass flow. The minimum Shannon entropies may be attributed to the minimum frequency and the amplitude of pressure fluctuation. To the left of the Shannon entropy, gas-solid flow becomes sharply unstable and complex. The pressure fluctuations in the pipe are quite random due to stochastic changes in the sectional area because coal particles begin to deposit on the wall of the pipe with reduced superficial velocity, which leads to an increase in Shannon entropy. When superficial velocities keep decreasing, large pulverized coal settles in the pipe bottom and appears as dunes which hold a part of the 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 the Shannon entropy.

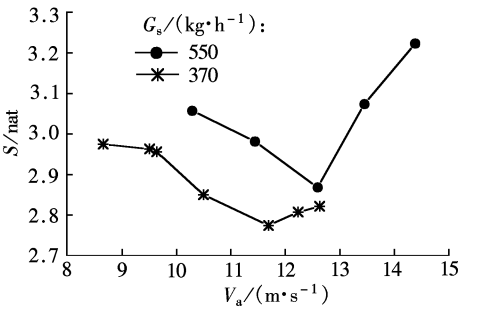



**Fig. 3** Shannon entropy vs. superficial velocity

### 3.2 Effect of fluidizing gas volume rate on solid-gas ratio and Shannon entropy

Fluidizing gas is applied to fluidize coal particles through a bowl-type gas distributor in the feeding hopper. At a certain velocity, coal particles are suspended and appear to be properties of a fluid in order to be conveyed more easily. In the experiments, pressures in both the feeding hopper and the receiving hopper remain constant and the total conveying differential pressure is 0.5 MPa. The influences of the fluidizing gas volume rate $Q_f$ on the solid-gas ratios $\mu$ and the Shannon entropies are shown in Figs. 4 and 5.

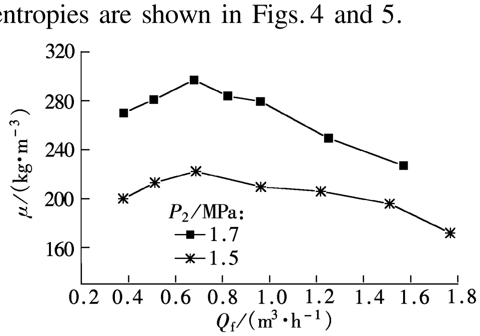



**Fig. 4** Solid gas ratio vs. fluidizing gas flow rate

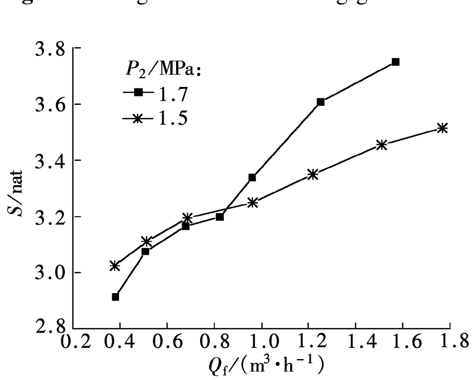



**Fig. 5** Shannon entropy vs. fluidizing gas flow rate

The solid-gas ratio is defined as the ratio of the solid flow rate $G_s$ to the gas flow rate, and classified as the mass flow ratio, the volume flow ratio and the mass/volume flow ratio. The mass/volume flow ratio is chosen to reflect the conveying capacity of unit volume gas. Solid-gas ratios increase at first and then decrease with the increase in fluidizing gas volume rates. When the fluidizing gas volume rate is very small, the fluidizing effect of pulverized coal around the discharge orifice is quite poor. Coal particles need to consume more energy in the process of movement and are more difficult to convey, and thus the conveying capacities of a unit volume gas and solid-gas ratios are very low. As the fluidizing gas volume rate increases, the fluidizing effect of solid particles is enhanced and pulverized coal around the discharge orifice shows fluidal characteristics. Increment in the solid mass flow rate is greater than increment in the gas volume rate. So, solid-gas ratios increase. When $Q_f > 0.68$ m$^3$/h, the effect of the fluidizing gas volume rate on the solid mass flow rate slows down, the increment of gas volume becomes greater. Solid-gas ratios decrease with increasing fluidizing gas volume rates.

Fig. 5 shows the Shannon entropies for various fluidizing gas volume rates. It can be seen that the Shannon entropies increase with the increase in fluidizing gas volume rates. When $Q_f < 0.68$ m$^3$/h, Shannon entropies rise with increasing fluidizing gas volume rates which implies a rapid increase in complexity and disorder of gas-solid dynamics and the conveying velocity. As $Q_f \geqslant 0.68$ m$^3$/h, the evolutional tendency of the Shannon entropy is influenced by both solid-gas ratios and conveying velocity. The increase in Shannon entropies with increasing fluidizing gas volume rates indicates that the effect of the fluidizing gas volume rate on the Shannon entropy is the main factor because the increment of conveying velocities have the tendency to cause greater complexity and more disorder in gas-solid interaction.

### 3.3 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 remain constant. Total conveying differential pressure is adjusted through changing the pressure in the receiving hopper. Evolutional tendencies of solid-gas ratios and the Shannon entropies are shown in Figs. 6 and 7.

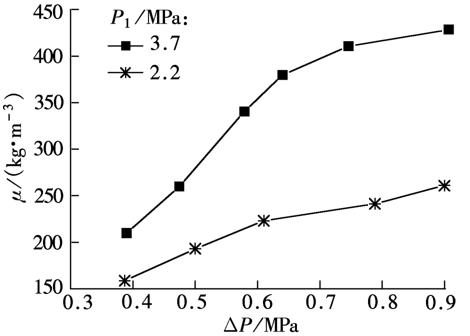



**Fig. 6** Solid gas ratio vs. total conveying differential pressure

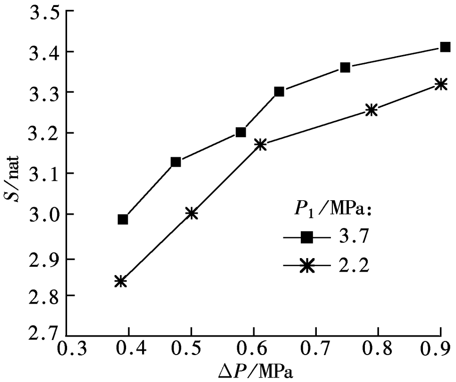



**Fig. 7** Shannon entropy vs. total conveying differential pressure

Relationships between conveying differential pressure and solid-gas ratios are depicted in Fig. 6. Solid-gas ratios rise with the 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 of unit volume gas is enhanced. Though conveying gas volume expands because of reducing the pressure in the receiving hopper, it is much less than the growing amplitude of the mass flow rate of pulverized coal. In brief, solid-gas ratios always rise with the increasing total conveying differential pressure when keeping other operating parameters constant. It can be found from Fig. 6 that an increment in differential pressure has a strong effect on the solid-gas ratio under lower differential pressure, and slows down when the total conveying differential pressures are higher.

Fig. 7 shows Shannon entropies under various conveying differential pressures. It can be seen that Shannon entropies increase with conveying differential pressure. Mass flow rates and solid-gas ratios rise in the process of the increasing total conveying differential pressure. A part of the pipe section is occupied by pulverized coal because of an increase in the concentration of gas-solid flow, and conveying gas expands as the conveying differential pressure decreases at the same time which leads to an increase in conveying velocity. The particles collision, concentration, regime transition, pulverized coal collapse and conveying velocity are enhanced because the decrease in conveying differential pressure results in increasing disorder and complexity of gas-solid two-phase movement in the pipe. The Shannon entropy then increases. When conveying differential pressure is low, the influence of conveying differential pressure on solids is quite great, degrees of turbulence and instability rise sharply, and Shannon entropies increase quickly. When conveying differential pressure is high, the slow increase in the Shannon entropies indicates that conveying differential pressures slow down the effect upon gas-solid two-phase movement.

## 4 Conclusions

The influences of different conveying differential pressures, mositure contents, gas volume flow rates and superficial velocities on the solid-gas ratios and mass flow rates are investigated. Shannon entropy analysis of pressure fluctuation time series is developed to reveal the flow characteristics. Through the investigation of the distribution of the Shannon entropy under different conditions, flow stability and the evolutional tendency of the Shannon entropy in different regimes and regime transition processes are discovered and the relationship between Shannon entropies and flow regimes is also established. The Shannon entropy is different for different flow regimes, and can be used to identify the flow regimes. The Shannon entropy analysis is a feasible approach to researching the characteristics of gas-solid two-phase flow in dense-phase pneumatic conveying under high pressure. Through experiments and theory analysis, the main results can be summarized as follows:

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

2) Solid-gas ratios increase first and then decrease, and Shannon entropies increase first, then decrease and finally increase again with the increase in fluidizing gas volume rates when pressures in the feeding hopper and the receiving hopper remain constant.

3) As conveying differential pressure rises, Shannon entropies and solid-gas ratios increase accordingly.

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# 高压浓相粉煤气力输送特性及信息熵分析

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**摘要:** 在输送压力可达 4.0 MPa,固气比高达 450 kg/m$^3$ 的高压气力输送试验台上,用氮气进行粉煤高压浓相气力输送试验研究. 分别在不同的输送差压、煤粉湿度、浓度和速度等条件下进行了输送试验,考察操作参数对煤粉固气比等气力输送特征参数的影响,用信息熵分析试验过程中采集到的压力波动时间序列,探讨流动稳定性和流型变迁过程中信息化趋势,建立信息熵和流型之间的关系. 结果表明:在输送差压增大的过程中,固气比和 Shannon 信息熵均增大;气体流量与 Shannon 信息熵和固气比之间呈现较好的规律性;不同流动形态的 Shannon 熵差异较大,不同流型之间的 Shannon 熵区分度较好. 随着煤粉湿度的增大,煤粉质量流量和 Shannon 熵均降低. Shannon 信息熵分析为研究高压浓相气力输送流型、流动稳定性及其转变特性提供了一种行之有效的方法.

**关键词:** 气力输送;高压;浓相;固气比;Shannon 信息熵

**中图分类号:** TQ051