Study on Flow Regimes of High-pressure and Dense-phase Pneumatic Conveying

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Abstract. High-pressure and dense-phase pneumatic conveying of pulverized coal is a key technology in the field of large-scale entrained bed coal gasification. Flow regime plays an important role in two-phase flow because it affects not only flow behavior and safety operation, but also the reliability of practical processes. Few references and experiences in high-pressure and dense-phase conveying are available, especially for the flow regimes. And because of the high stickiness and electrostatic attraction of pulverized coal to the pipe wall, it is very difficult to make out the flow regimes in the conveying pipe by visualization method. Thus quartz powder was chosen as the conveyed material to study the flow regime. High-speed digital video camera was employed to photograph the flow patterns. Experiments were conducted on a pilot scale experimental setup at the pressure up to 3.6MPa. With the decrease in superficial gas velocity, three distinguishable flow regimes were observed: stratified flow, dune flow and plug flow. The characteristics of pressure traces acquired by high frequency response pressure transmitter and their EMD (Empirical Mode Decomposition) characteristics were correlated strongly with the flow regimes. Combining high-speed photography and pressure signal analysis together can make the recognition of flow patterns in the high-pressure and dense-phase pneumatic conveying system more accurate. The present work will lead to better understanding of the flow regime transition under high-pressure.

1. INTRODUCTION
High-pressure and dense-phase pneumatic conveying of pulverized coal is a vital technology in the field of large-scale entrained bed coal gasification. The pneumatic conveying has been successfully used in the chemical engineering, energy, metallurgy and other industrial processes with advantages, such as reliability, flexibility of layout, ease of automation, low maintenance,
hygienic and environmental friendly. In recent years, numerous studies, for instance, experiment, signal analysis and numerical simulation, have been conducted on different pneumatic conveying systems. Many valuable achievements on pneumatic conveying have been obtained. Gong et al [1] investigated the flow characteristic of high solid loading pneumatic conveying under low pressure and obtained some fitted empirical equations. Wypych [2] explored the mechanism for the formation of the unstable zone experimentally and theoretically. Li [3] adopted photographic technology to measure the particle velocity and concentration profiles in the horizontal dilute-phase pneumatic conveying. Masona [4] developed a two-layer model to simulate dense phase pneumatic transport of fine powders and the model showed good quantitative agreement with experimentally determined pressure profiles for fully developed flows in straight horizontal pipes. Laouar [5,6]’s aims were to characterize the differential pressure in dense-phase pneumatic conveying line at a very low velocity and a general differential pressure law was obtained which proves to be independent of both flow regimes and pipe diameter.

However, the above achievements are mainly about the low pressure pneumatic conveying [1-10]. At present the large-scale coal gasification technology is gaining attention and developed, and dense-phase pneumatic conveying of pulverized coal under high pressure is one of its key technologies [11-12]. Few references and experiences in high-pressure and dense-phase conveying are available, especially for the flow regimes.

EMD is capable of extracting all the oscillatory modes present in signal. Each extracted mode is referred to as an Intrinsic Mode Function (IMF), which has a unique local characteristic. EMD has been widely applied in recent years in the fields of meteorology, ocean engineering, earthquake studies, etc. H.Ding et al. has used the method for characterization of gas-liquid two-phase flow and achieved satisfactory results [13]. This paper is devoted to flow regime visualization and pressure signal analysis of solid-gas flow in high-pressure and dense-phase pneumatic conveying.

2. EXPERIMENTAL APPARATUS

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 introduced at the outlet of the feeding hopper to enhance the conveying ability. Pressurizing gas is used to keep pressure constant in the feeding hopper. The pressure of the receiving hopper is controlled by the motor-drive control valve. Both the feeding hopper and the receiving hopper have capacity of 0.648m3. The conveying pipeline is stainless steel tube with an inside diameter of 10mm and a length of 53m. The gas volume rates are measured by the metal tube rotary flow meters, and solid mass in hopper is measured by the weight cells. Pressure and differential pressure are measured by the semiconductor pressure transducers with frequency response of 200Hz and precision of 0.3%. Signals of differential pressure, pressure, weight and gas volume flow rate are acquired by a multi-channel sampling system and sent to a computer through an A/D converter. Physical properties of conveyed materials are listed in Tab.1.
Fig.1 Schematic diagram of dense-phase pneumatic conveying of pulverized coal under high pressure
1-Motor-driven control valve 2-Weigh cell 3-Hopper 4-Pressurizing gas 5-Fluidizing gas 6-Supplemental gas 7-Buffer tank 8-Nitrogen cylinder 9-Visualization section 10-Computer 11-Sensors and A/D converter

| Tab.1 Physical properties of pulverized coal |
|---------------------------------------------|
| Material                        | Density/(kg.m⁻³) | Mean dₜ/μm | Moisture/% |
| Quartz powder                   | 2650             | 400        | 0          |
| Inner Mongolia pulverized coal | 1400             | 52         | 3.74       |

3. EMPIRICAL MODE DECOMPOSITION (EMD)
EMD is an adaptive technique that decomposes the original signal into a family of IMF components. Each component emphasizes the local embedded characteristics of the signal. An IMF must satisfy two constraints: (i) the number of extrema and the number of zero crossings must either equal each other or differ at most by one; and (ii) at any time, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero.
The first constraint is similar to the traditional narrow-band requirements for a stationary Gaussian process. The second constraint modifies the global requirement to a local one and is necessary so that the instantaneous frequency will not include unwanted fluctuations.
The decomposition of data series x(t) follows a number of logical steps[14,15]. These are described below.
1. Identify all of the local maxima and local minima of the signal x(t). Then use cubic spline interpolation to define the upper envelope xmax(t) and the lower envelope xmin(t) of the original data series. The mean m₁(t) of the upper and lower envelopes is calculated as follows:
   \[ m₁(t) = \frac{x_{\text{max}}(t) + x_{\text{min}}(t)}{2}. \]
2. Subtracting m₁(t) from the data series x(t) gives:
   \[ h₁(t) = x(t) - m₁(t). \]
3. In general, \( h₁(t) \) is just an IMF candidate that is unlikely to satisfy all the requirements of IMF. Iterate the above procedure k times until the mean envelope is close to zero, so the first IMF component \( I₁(t) \) that contains the highest frequency component of the signal can be designated as
   \[ h_{(k-1)}(t) - m_{1k}(t) = h₁(t), \quad I₁(t) = h₁(t). \]
The above procedure is a sifting process that has two effects: (i) to eliminate riding waves; and
(ii) to smooth uneven amplitude. In order to avoid obliterating the physically meaningful amplitude fluctuations, a stop criterion for the sifting process is defined [16].

\[
SD = \sum_{t=1}^{T} \frac{\left| \left( h_{i(k-1)}(t) - h_{ik}(t) \right)^2 \right|}{h_{i(k-1)}(t)}
\]

4. Separate \( I_1(t) \) from the rest of the data series. The residue, \( r_1(t) \), is treated as the new data series.

\( r_1(t) = x(t) - I_1(t) \)

Since the residue \( r_1(t) \) still contains much information from lower frequency components, it is subjected to the same sifting process. Repeat the above procedure on the subsequent residual \( r_2(t) \) until the range of the residue is below a predetermined value or the residue contains the lowest frequency component, and the result is

\( r_1(t) - I_2(t) = r_2(t), \ldots, r_{n-1}(t) - I_n(t) = r_n(t) \)

where \( r_n(t) \) denotes the trend of the signal from which no more IMF can be extracted and \( I_n \) is the nth IMF. Each IMF contains lower frequency components than the one extracted just before. At the end of the EMD procedure, the signal \( x(t) \) can be exactly reconstructed using a linear combination:

\( x(t) = \sum_{i=1}^{n} I_i(t) + r_n(t) \).

4. RESULTS AND DISCUSSION

4.1 Photos and pressure traces

Because of the high stickiness and electrostatic attraction of pulverized coal to the pipe wall, it is very difficult to make out the flow regimes in the conveying pipe through visualization method. So quartz powder with average diameter of 400μm and density of 2650kg/m3 was adopted as the substitute conveyed material to study the flow regime. High-speed digital video camera (125fps, 4096pics/run) was employed to photograph the flow patterns. Length of visualization section is 0.16m and interior diameter is 10mm.

Fig.2 depicts that flow regime transits from stratified flow to plug flow as superficial gas velocity diminishes under the basic condition (P=3.6MPa, ΔPT=0.8MPa). When superficial gas velocity is relatively high, a suspended phase and a settled layer of material are generally observed. With decrease in superficial gas velocity, dunes or clusters can be seen riding on a settled layer of material. At further lower gas velocity the material may flow as discreet or as a packed bed. The characteristics of pressure traces acquired by high frequency response pressure sensor were correlated closely with the flow regimes. When superficial gas velocity was relatively high, flow pattern was stratified flow and pressure signal fluctuated more quickly than that of the other flow regimes. As superficial gas velocity diminished, flow pattern transited to slug flow and pressure signal fluctuated like sine wave. Further decrease in superficial gas velocity yielded plug flow, meanwhile sine-like pressure signal fluctuated with further lower frequency and higher amplitude.

4.2 EMD characteristics of pressure fluctuation signals with quartz

4.2.1 IMF components

As presented above, pressure signal traces of different flow regimes show distinguishable characteristics. In order to investigate the characteristics of pressure more deeply, EMD analysis
was employed on the pressure signals. Fig.3 shows side by side the IMF components of the pressure fluctuation signal. IMFs have different local frequencies. The EMD method picks out the highest frequency component present in the signal. Thus, each IMF component that contains a lower frequency than the preceding one extracted is presented in turn. The smaller scales...
represent the high-frequency information in the signal and the larger scales represent the low-frequency information in the signal.

![Empirical Mode Decomposition](image)

(a) IMF components (dilute stratified flow)  
(b) IMF components (dune flow)

c) IMF components (plug flow)

Fig.3 IMF components of pressure fluctuation signal of different flow pattern

4.2.2 Energy distribution of IMF

In this study, the energy distribution $H_j$ of different frequency bands is defined as

$$H_j = \frac{E_j}{E}$$

where $E_j$ (measured by Standard Deviation) stands for the local energy of the different frequency bands ($j=1$ denotes the high-frequency band, $j=2$ the middle-frequency band and $j=3$ the low-frequency band) and $E$ is the total energy (measured by Standard Deviation also). The energy distribution $H_j$ is selected as the characteristics of the pressure fluctuation signal. In this study a number of logical steps were followed:

1. Acquire the pressure fluctuation signal;
2. Apply EMD to the signal;
3. Calculate the total signal energy, each frequency band of local energy and the energy distribution;
4. Determine the energy distribution of the signal.

As per the extensive experimental work undertaken and literature published, the IMF components are divided into three frequency bands in terms of their inherent frequencies for quantitative analysis of the energy distribution: high-frequency band H1 with IMF components of IMF1, IMF 2 and IMF 3, middle-frequency band H2 with IMF components of IMF 4, IMF 5 and IMF 6, and low-frequency band H3 with IMF components of IMF 7 and IMF 8. $E_1$ represents the total energy of IMF 1, IMF 2 and IMF 3, $E_2$ is the sum of the energy of IMF 4, IMF 5 and IMF 6, and $E_3$ is the total energy of IMF7 and IMF8. Tab.2 summarizes the variations of energy characteristics $H_j$ with flow pattern.
Tab. 2 Conveying condition and energy distribution with quartz

| P (MPa) | ΔPT (MPa) | μ (kg/m³) | Vg (m/s) | Flow pattern | Energy characteristics Hj (%) |
|---------|-----------|-----------|----------|--------------|-------------------------------|
|         |           |           |          |              | H1   | H2   | H3   |
| 3.6     | 2.8       |           |          |              |      |      |      |
| 101     | 9.4       | 7         | 4        | Stratified   | 46.95| 26.11| 26.94|
| 146     | 5.6       | 4.79      | 5       | Dune        | 4.79 | 55.23| 39.98|
| 348     | 1.7       | 3.14      | 1       | Plug        | 3.14 | 54.85| 42.02|

Tab. 2 illustrates the variation of energy distribution in different frequency bands. With decreasing gas velocity, the flow pattern of solid-gas flow is continually changing and the energy characteristics Hj changes too. According to Table 2, I1, I2 and I3 carry almost half of the embedded energy for the dilute stratified flow. In the case of dune flow, the energy diverts from the high-frequency band to the lower-frequency band. Consequently, the ratio of energy embedded in the high-frequency band decreases dramatically and the ratio of energy embedded in the middle and low-frequency band increases. As for plug flow, the ratio of energy embedded in the high-frequency band decreases further and the ratio of energy embedded in the low-frequency band increases slightly.

The above results imply that the energy characteristic Hj changes with the flow pattern and can therefore be regarded as an indicator for the identification of the flow pattern of high-pressure and dense-phase solid-gas flow. The result also demonstrates that EMD is suitable for analyzing the pressure fluctuation signal. However, it has to be pointed out that Hj changes from dune flow to plug flow not as evidently as from stratified flow to dune flow.

4.3 Energy distribution of IMF with pulverized coal

Inner Mongolia pulverized coal with mean diameter of 52μm was conveyed in the experimental facility. Conveying condition is shown in Tab. 3. Because of the high stickiness and electrostatic attraction of pulverized coal to the pipe wall, it is very difficult to recognize the flow regimes in the conveying pipe through visualization method. It’s also unclear and impossible to identify the flow pattern through the pressure signal trace alone. Through the preceding results, EMD is considered as an effective method to analyze the pressure fluctuation signal in order to identify the flow regime in the pipeline indirectly.

Similar varying tendency of the energy characteristic Hj with the deceasing gas velocity was found. With decreasing gas velocity, the energy characteristics Hj changes obviously. According to Tab. 3, H1 carry more than 70% of the embedded energy at the relatively high Vg which is 11.1m/s. When Vg changes from 6.2m/s to 10.2m/s, the energy diverts from the high-frequency band to the lower-frequency band. Consequently, the ratio of energy embedded in the high-frequency band decreases to about 60% and the ratio of energy embedded in the middle and low-frequency band increases. Further decreasing Vg to 4.1m/s or below, the ratio of energy embedded in the high-frequency band decreases and the ratio of energy embedded in the low-frequency band increases significantly.

As a result, though impossible by visualization method, three flow patterns can be classified approximately according to the energy characteristics Hj when conveying pulverized coal.

Tab. 3 Conveying condition and energy distribution with pulverized coal

| P (MPa) | ΔPT (MPa) | μ (kg/m³) | Vg (m/s) | Energy characteristics Hj (%) |
|---------|-----------|-----------|----------|-------------------------------|
|         |           |           |          | H1   | H2   | H3   |
|         |           |           |          |      |      |      |
| 3.4     | 0.4       |           |          |      |      |      |
| 102     | 11.1      | 70.17     | 15.04    | 14.79 |
| 126     | 10.2      | 56.28     | 11.52    | 32.20 |
| 166     | 9         | 58.60     | 11.71    | 29.69 |
| 213     | 7.9       | 61.85     | 13.00    | 25.15 |
| 309     | 6.2       | 61.17     | 16.01    | 22.81 |
| 531     | 4.1       | 28.60     | 14.51    | 56.89 |
5. CONCLUSIONS

(1) Three distinguishable flow regimes, dilute stratified flow, dune flow and plug flow were observed visually when conveying quartz powder under high-pressure and dense-phase pneumatic conveying. When superficial gas velocity was relatively high, flow pattern was dilute stratified flow and pressure signal fluctuated more quickly than that of the other flow regimes. As superficial gas velocity diminished, flow pattern transited to dune flow and pressure signal fluctuated like sine wave. Further decrease in superficial gas velocity yielded plug flow, meanwhile sine-like pressure signal fluctuated with lower frequency and higher amplitude.

(2) When conveying quartz powder, the characteristics of pressure traces acquired by high frequency response pressure transmitter were correlated closely with the flow regimes. When superficial gas velocity was relatively high, flow pattern was dilute stratified flow and pressure signal fluctuated more quickly than that of the other flow regimes. As superficial gas velocity diminished, flow pattern transited to dune flow and pressure signal fluctuated like sine wave. Further decrease in superficial gas velocity yielded plug flow, meanwhile sine-like pressure signal fluctuated with lower frequency and higher amplitude.

(3) In order to investigate the characteristics of pressure more deeply, EMD has been applied in the analysis of a pressure fluctuation signal. Results have demonstrated that the extracted energy characteristics reflect the energy shift with the variation of flow pattern. The energy characteristic Hj changes with the flow regimes and can therefore be regarded as an indicator for the identification of the flow regimes.

(4) It’s unclear and almost impossible to identify the flow pattern through the pressure signal trace alone. Using EMD analysis on the pressure signal, the flow regime in the pipeline can be identified indirectly.

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NOMENCLATURE

\[ V_g \]  \quad \text{superficial gas velocity} \quad [\text{m}\cdot\text{s}^{-1}]

\[ \mu \]  \quad \text{solid-gas ratio} \quad [\text{kg}\cdot\text{m}^{-3}]

\[ P_e \]  \quad \text{ending pressure (pressure in the sending hopper)} \quad [\text{MPa}]

\[ \Delta P_T \]  \quad \text{total conveying differential pressure} \quad [\text{MPa}]

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