Flow Pattern Characteristics in Vertical Dense-Phase Pneumatic Conveying of Pulverized Coal Using Electrical Capacitance Tomography

Xingliang Cong, Xiaolei Guo, Haifeng Lu, Xin Gong,* Kai Liu, Kai Xie, and Xiaolin Sun

Key Laboratory of Coal Gasification and Energy Chemical Engineering of Ministry of Education, East China University of Science and Technology, Shanghai 200237, China

ABSTRACT: Research on flow patterns can provide a better understanding of particle dynamics in dense-phase pneumatic conveying of pulverized coal. In this paper, electrical capacitance tomography (ECT) has been employed to study flow patterns in the 20 mm diameter vertical riser. Three flow patterns were identified on the basis of ECT image analysis, and their characteristics and formation mechanisms were discussed. The flow patterns at high solid concentration were more asymmetrical than those at low solid concentration. Solid concentration signals obtained from ECT were analyzed by different signal analysis methods including relative standard deviation (RSD), probability density function (PDF), and power spectral density function (PSD), which were verified to be effective enough to identify the characteristics of the different flow patterns. Additionally, the Bi model (Bi, H. T.; Grace, J. R. Int. J. Multiphase Flow 1995, 21, 1229–1239) was modified to effectively predict choking velocity in the vertical dense-phase pneumatic conveying of pulverized coal.

1. INTRODUCTION

Pneumatic conveying of pulverized coal has traditionally been divided into lean-phase and dense-phase conveying. The dense-phase pneumatic conveying has been commonly applied in the entrained flow gasification of pulverized coal and is characterized with lower rates of pipe wear and particle attrition, much smaller quantities of carrier gas consumption, and more efficient power utilization. However, unsteady dense-phase flow usually occurs at much lower gas velocity, exhibiting slug flow, which will have severely disadvantageous impacts on the gasifier performance. Flow patterns can be influenced by material properties, conveying system geometry, and operating conditions. They are considered to be very complicated and inconstant. For a long time, there is a lack of effective measurement methods for flow patterns. Generally, researchers use visual method to observe flow patterns and qualitatively describe them in words. When superficial gas velocity reduced gradually at a fixed solid mass flow rate, suspension flow, annular flow, turbulent fluidization, slug flow, bubbly transport, and packed bed flow are possible to occur in a vertical riser. However, due to adhesion of fine coal on the pipe wall, it is difficult to research flow patterns of fine coal using the visual method.

ECT is considered as an effective measurement method to identify the flow patterns of coals. Furthermore, it is capable of acquiring cross-sectional solid concentration distributions at different time. It has been applied more and more to study characteristics of flow patterns in gas–solid flow. For example, Ostrowski et al. have used ECT to measure the length, sharp, and velocity of material slugs with polyamide plastic particles conveyed in a 52 mm inner diameter (I.D.) pipe. The ECT images provided by Jaworski et al. have shown the internal structure of unsteady slug flow of polyamide particles in a 57 mm I.D. steel pipe. Zhu et al. also used ECT to study the flow patterns of granular solids in the vertical pipe. They showed us various flow patterns in the vertical riser, such as core–annular dispersed flow, slug flow with a particle-rich core, pulsing flow, and stationary and moving annular capsules with a dilute core. Later, Laurent et al. proposed a direct approach to discriminate between an annular and stratified flow pattern without the need for imaging. In the study of Azzopardi et al., a twin-plane ECT was employed to monitor the flow rate of fine coal. They found that coal particles were concentrated around the pipe wall and the solid concentration fluctuated with time. In addition, Rao et al. used power spectra of solid concentration fluctuations obtained from single-plane ECT data to identify the various flow regimes.

Based on ECT images, this paper discussed the characteristics of flow patterns in vertical dense-phase pneumatic conveying of pulverized coal. The particle concentration fluctuations obtained from ECT were analyzed using various signal processing methods to reveal the stabilities of flow patterns and the frequencies of periodic structures. The identification of flow regimes obtained from signal analysis can provide reliable guidance for operation optimization. At the last part of this paper, the Bi model was modified to predict choking velocity.

2. EXPERIMENTAL FACILITY AND MATERIAL PROPERTIES

A schematic of the vertical pneumatic conveying system is shown in Figure 1. The feeding and receiving vessels have a volumetric capacity of approximately 1 m³. The conveying pipeline of 20 mm I.D. and about 34 m long was consist of two downcomers of 3.6 and 12.2 m long, one vertical riser of 10.8 m
3. RESULTS AND DISCUSSION

3.1. Phase Diagram and ECT Images. Figure 2 shows a plot of pressure drop per unit pipe length against superficial gas velocity.

![Figure 2. Pressure drop per unit pipe length versus superficial gas velocity.](image)

According to the phase diagram (Figure 2) and the ECT images (Figure 3), three flow patterns were determined in the vertical dense-phase pneumatic conveying of pulverized coal.

1. Packed bed flow: Particles are full of the pipe cross-section at the highest solid concentration, which is close to loosely packed bed state. The flow corresponding to the highest pressure drop occurs at low superficial gas velocity.

2. Slug flow: The flow is discontinuous and alternates between gas slug and solid slug. The solid concentration of the solid slug is almost the same as that of the packed bed flow, while the solid concentration of the gas slug is close to zero.

3. Churn flow: The particle concentration near the pipe wall is higher than that at the pipe center. It seems like a circular ring near the wall and a rounded core at the pipe center. The flow appears at higher superficial gas velocities, and the corresponding pressure drop is lower.

Figure 3 shows the two-dimensional views of flow patterns obtained by stacking ECT images at different time (0–150 s). Packed bed flow and slug flow are observed under the same operation condition (case a). Packed bed flow occurs at the earlier stage of the conveying (case a1) and slug flow at the later stage (case a2). Churn flow dominates during the entire conveying process (i.e. from case b to case e). For churn flow, increasing superficial gas velocity can reduce particle concentration at different regions of pipe cross-section and their
fluctuations with time. For instance, the solid concentration in case e is lower than that in case d and changes little with time at high superficial gas velocity.

As shown in Figure 4, the increase of superficial gas velocity enforces the symmetry of solid concentration distributions. As for packed bed flow at lower superficial gas velocity, the contour exhibits an irregular shape and the cluster of fine coal adheres to the pipe wall with the highest solid concentration (Cs = 1.0). For churn flow, the cluster in the shape of crescent adheres to the pipe wall with higher solid concentration (Cs = 0.7) at the superficial gas velocities of 5.0−6.7 m/s. With further increasing of the superficial gas velocity, the solid concentration distribution becomes more symmetrical and there is not any irregular-shaped cluster adhering to the wall.

Figure 5 shows ECT contour images of the transition of solid slug and gas slug at 2 s intervals. The solid concentration of solid slug is close to packed bed density, and the distribution is not symmetrical due to some irregular-shaped fine coal clusters (t = 1 s, 3 s, 15 s). The solid concentration of gas slug is close to zero, but some fine coal clusters (Cs = 0.1−0.2) adhere to the wall (t = 7 s). Churn flow is observed during the transition between solid slug and gas slug (t = 5 s, 9 s, 11 s, and 13 s).

As for packed bed flow, the pulverized coal is of agglomeration significantly at lower superficial gas velocity (U_b = 3.4 m/s) in the riser and forms clusters with high solid concentration. As a result, the packed bed flow corresponds to a relatively high pressure drop.

When the pressure of the feeding vessel was unable to supply sufficient energy (i.e., without enough pressure head), pulverized coal began to accumulate in the bottom of the vertical pipe under the effect of gravity, resulting in a sharp increase in the static pressure. After coal cluster disappeared, the pipeline pressure decreased sharply.

The high bed height of pulverized coal in the feeding vessel can prevent the air which was introduced into the feeding vessel from flooding into pipeline. The air in the feeding vessel was mainly used to fluidize the pulverized coal and provide conveying energy. Packed bed flow dominated in the riser at high bed height. When the bed height reduced to some extent, the air in the feeding vessel started to flood into the pipeline at intervals. The air in the feeding vessel could not fluidize pulverized coal well and provide enough conveying energy. Furthermore, lower gas velocity in the pipeline could not break gas slug and solid slug. As a result, slug flow was observed in the riser at lower bed height and gas velocity.

For cases b−e, the gas velocity at pipe center is larger than that near pipe wall. Thus, the solid concentration is lower at the center and higher near the wall. The solid concentration distribution suggests that this flow pattern seems to be similar to annular flow. Davidson et al. usually use annular flow to describe particles being carried up in the gas core and then falling down along the wall. However, our experiments indicate that the particles near the wall travel upward and there is not a

Figure 3. Two-dimensional views of flow patterns.

Figure 4. Contour of time-averaged solid concentration distributions for different cases.

Figure 5. Contour plot of cross-sectional variation of solid concentration with time for slug flow.
gas core in the pipe center for cases b−e. Churn flow in gas−liquid flow usually is observed between slug and annular flow regimes. The flow patterns for cases b−e analogous to churn flow in gas−liquid flow looks very promising, which is the same as that suggested by Azzopardi.16

At lower superficial gas velocity, the solid concentration is higher and the cohesive particles tend to agglomerate into fine coal clusters. These clusters alter the gas flow structure, forming an unevenly distributed gas flow field.2 Therefore, there is uneven particle distribution in the pipe cross-section at lower superficial gas velocity. However, increasing the superficial gas velocity reduces solid concentration and the higher gas velocity can break the clusters. Thus, the solid concentration distribution becomes relatively uniform at the higher superficial gas velocity.

3.2. Signal Analysis of Solid Concentration from ECT.

Some signal processing methods were used to analyze the solid concentration fluctuations from ECT in order to identify flow patterns objectively.

The sampling frequency is 70 Hz for particle concentration signals from ECT, but 1 Hz for pressure signals. Both the particle concentration signals and the pressure signals at the frequency of 1 Hz are shown in Figure 6 for comparison. It can be seen that the wave shape of the ECT signals is very similar with that of the pressure signals. A great many large troughs and peaks occur in both the ECT and pressure signals, which suggests that slug flow is significantly unstable flow pattern.

This paper mainly focused on discussing the ECT images and its signals. It is generally considered that the characteristics of ECT signals are similar to those of pressure signals.20 Thus, ECT signals are further analyzed below, while the characteristics of pressure signals will not be discussed again.

Schepers21 proposed relative standard deviation (RSD) to quantify complexity of changes in time series. RSD is defined as

\[
\text{RSD} = \frac{Sd}{\text{mean}}
\]
where \( S_d \) is the standard deviation of the particle concentration signals from ECT, mean is average value of the signals. RSD as a dimensionless number is used to compare complexity of changes of the signals for different flow patterns.

Figure 7 shows RSD of the signals from ECT for different flow patterns in the vertical riser. The RSD value for packed bed flow is the smallest, which indicates its excellent stability. As for churn flow, the RSD increases with the increase of the superficial gas velocity, which may be attributed to the increasing disturbance wave. Slug flow is an unsteady flow pattern. Gas slug and solid slug change alternately, causing the largest RSD.

Probability density function (PDF) is used to show probability of instantaneous particle concentration appearing in a unit range. PDF is defined as

\[
P_f = \lim_{\Delta x \to 0} \frac{\text{prob}(x < x_i < x + \Delta x)}{\Delta x}
\]  

(2)

Figure 8 shows PDF of particles concentration signals from ECT for different flow patterns in the vertical riser. The PDF of packed bed flow exhibits a narrow distribution range and a single large peak at high particle concentration. The PDF of slug flow has two peaks at high and low particle concentration. It distributes in a wide range of particle concentration \((Cs = 0-1)\). The PDF of churn flow is characterized by single peak at moderate particle concentration. It has a wider distribution range and a lower peak compared with that of packed bed flow.

The power spectrum density (PSD) function is the magnitude of the fast Fourier transform (FFT) square of the signals divided by the time period. One side PSD (its unit is kpa²/Hz) used in this paper is defined as follows:

\[
PSD(f) = \frac{2\cdot \mathcal{X}(n)^2}{t_2 - t_1}
\]  

(3)

The peak value of PSD of the signals is defined as

\[
P_m = \max(PSD(f))
\]  

(4)

Average fluctuation frequency \( f_a \) of the signals is defined as

\[
f_a = \frac{\sum_{k=1}^{m} PSD(f_k)}{\sum_{k=1}^{m} PSD(f_k)}
\]  

(5)

Figures 9 and 10 show that the peak value \( P_m \) and the average fluctuation frequency \( f_a \) of the signals are related to flow patterns in the vertical pipe. The peak values are similar for different cases where flow patterns belong to the same category and so are the average fluctuation frequencies.

The solid concentration fluctuations of packed bed flow are derived from interactions between particles and particle groups, similar to Brownian movement. Thus, the ECT signals are close to random signals, resulting in the lower peak value and the larger average fluctuation frequency.

In churn flow, the ECT signal fluctuations depend on the disturbance wave, which reduces the randomness. So, the peak value increases and the average fluctuation frequency decreases, compared to that of packed bed flow.

Slug flow has long-range periodicity as solid slug and gas slug transform alternately with time. The signals from ECT are close to long-range periodic signals. Therefore, the peak value is larger, while the average fluctuation frequency is lower.

Azzopardi et al. observed two types of very periodic fluctuations, which have the higher frequency of 1.475 Hz, 1.425 Hz, 1.73 Hz, 3.425 Hz and the lower frequency of 0.0733
Hz, 0.1125 Hz. The above results are coincident with the average fluctuation frequency obtained from our experiments.

It can be seen that RSD, PDF, and PSD are certified to be effective enough to directly distinguish flow patterns. However, PSD has higher identification accuracy for different flow patterns. Thus, PSD is superior to PDF and RSD.

3.3. Prediction for Choking Velocity. Choking phenomenon in a vertical pipe brought about dramatic changes of pressure drop. Bi et al.\(^5\) proposed that flow pattern transformed into slug flow at the choking transition. Thus, the phase diagram and ECT images indicated that slug flow occurred at the superficial gas velocity of 3.4 m/s (case a), which may be corresponding to the choking velocity.

Choking velocity is calculated by Bi model. The formula is given as follows:

\[
V_{CA} = 1.53A_r \frac{0.5\mu_g}{\rho_g d_p} + \frac{G}{\rho_p (1 - e_{CA})} \frac{e_{CA}}{g} \]

\[2 < A_r < 1 \times 10^8\]  \hspace{1cm} (6)

The first term on the right side of eq 6 indicates the choking velocity is related to material properties, and the second term suggests that the operating conditions also have impact on the choking velocity.

The equation for the calculation of Ar is as follows:

\[
A_r = \frac{\rho_g (\rho_g - \rho_p) d_p^3 g}{\mu_g^2} \]

\[\text{Table 1. Archimedes number Ar calculated from eq 7 is in the range 4.64–5.75.}\]

In Bi model, the voidage at type A choking, \(e_{CA}\), ranged from 0.96 to 0.99, depending on particle properties. Bi suggested that \(e_{CA}\) was around 0.96 for group A particles and around 0.99 for group B and group D particles.\(^5\) For group C powder, \(e_{CA}\) was not reported. The pulverized coal belongs to group C powder because it has true cohesiveness. Thus, the experiments were carried out to get \(e_{CA}\) for the pulverized coal.

Void fraction of the pulverized coal in the vertical pipeline is calculated by

\[
\varepsilon = 1 - \frac{G}{U_s \rho_p} \]

\[\text{where } U_s \text{ is particle velocity measured by the solid velocity meter.}\]

A new parameter \(K\) is defined as

\[
K = \frac{\varepsilon}{1 - \varepsilon} \]

\[\text{The parameter } K \text{ represents gas–solid volume ratio. The experimental results indicate the parameter } K \text{ is related to superficial gas velocity and solid mass flux, as shown in Figure 11. The parameter } K \text{ increases with the increase of superficial gas velocity and decreases with the increase of solid mass flux. The equation for the calculation of } K \text{ is as follows}\]

\[
K = aU_g^{b}G^{c} \]

\[\text{When eq 11 is substituted into eq 6, the result is as follows}\]

\[
V_{CA} = 1.53A_r \frac{0.5\mu_g}{\rho_g d_p} + 340V_{CA}^{0.8}G^{0.2} \]

\[\text{Figure 11. Parameter } K \text{ and superficial gas velocity.}\]

where \(a, b, c\) are constants defined by eq 10.

The least-squares method is used to fit the experimental data in order to obtain the equation for the calculation of \(K\), which is as follows

\[
K = 340U_g^{0.8}G^{-0.8} \]

\[\text{Figure 12 shows that the calculated values of } K \text{ agree well with the experimental data with the error of <15% except individual points.}\]

\[\text{Figure 12. Experimental and calculated values of } K.\]

The superficial gas velocity \(V_{CA}\) calculated from eq 12 is 3.4 m/s at the choking transition. When \(V_{CA} = 3.4 \text{ m/s}\) is substituted into eq 11, the calculated value of \(e_{CA}\) is equal to 0.68, close to the voidage (\(e = 0.67\)) of the loosely packed bed state. The phase diagram and ECT images suggested that the superficial gas velocity of 3.4 m/s (case a) corresponded to the choking velocity. Thus, the predicted choking velocity from Bi model is consistent with the experimental result. Furthermore, the \(e_{CA}\) for the pulverized coal can be estimated by the voidage of the loosely packed bed state.
4. CONCLUSION

ECT images show the flow patterns of the pulverized coal in the vertical dense-phase pneumatic conveying. The flow patterns observed in our experiments were packed bed flow, slug flow, and churn flow.

Packed bed flow occurred at higher bed height of the feeding vessel, while slug flow was observed at lower bed height. Churn flow was not related to the bed height and dominated during the entire conveying process. Experiments indicated that the flow pattern was not symmetrical at high solid concentration.

The ECT signals were similar to pressure signals. The three methods (RSD, PDF, and PSD) were verified to be effective in distinguishing flow patterns, and PSD was a preferable method.

The previous model was modified to predict the choking velocity for the pulverized coal vertical pneumatic conveying. The experimental results confirmed that the model could accurately predict the choking velocity.

During the practical industrial operation, the minimum conveying velocity is considered to avoid the unstable flow regime, which may affect the feeding consistency of the pulverized coal. Bi model can be used to predict the choking velocity. The conveying velocity of the pulverized coal must be larger than the choking velocity. In the normal running, the flow pattern in the riser for dense-phase conveying is churn flow, which can be identified online by ECT signals or pressure signals. Once the signals vary obviously, the timely intervention could be provided by an operator to avoid the flow instability and the pipe blockage.

AUTHOR INFORMATION

Corresponding Author
*Tel.: +86-021-6425-2521. E-mail: gongxin@ecust.edu.cn.

Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors acknowledge financial support from the National Key Program of Basic Research in China (2010CB227002-3) and “Chen Guang” project supported by Shanghai Municipal Education Commission and Shanghai Education Development Foundation.

NOMENCLATURE

- \( P_c \): conveying pressure, kPa
- \( U_s \): superficial gas velocity, m/s
- \( \Delta P \): vertical pressure drop per unit pipe length, kPa/m
- \( G \): solid mass flow flux of the pulverized coal, kg/(m²·s)
- \( U_v \): particle velocity, m/s
- \( Cs \): mean relative solid concentration of ECT images
- \( e \): cross-sectional averaged void fraction
- \( t \): time, s
- \( p_i \): probability of instantaneous particle concentration \( x_i \) in a unit range
- \( f_k \): average fluctuation frequency, Hz
- \( P_m \): peak value of PSD of the solid concentration signals
- PSD(\( f_k \)): PSD corresponding to the frequency \( f_k \)
- \( \varepsilon \): void fraction at the choking transition

REFERENCES
