Applied Acoustics 138 (2018) 163–170

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

# In-line measurement of pulverized coal concentration and size in pneumatic pipelines using dual-frequency ultrasound

Jianfei Gu, Mingxu Su*, Xiaoshu Cai

*Institute of Particle and Two-phase Flow Measurement (IPTFM), Shanghai Key Laboratory of Multiphase Flow and Heat Transfer in Power Engineering, University of Shanghai for Science and Technology (USST), China*

ARTICLE INFO

*Keywords:*
Ultrasonic wave
Pulverized coal
Particle size
Volume fraction
Superposed wave

ABSTRACT

The influence of pulverized coal irregularity on acoustic attenuation is investigated, the relationship among the ultrasonic attenuation, the volume fraction and size of pulverized coal is established, and the theoretical dependence of retrieved pulverized coal volume fraction and particle size is formed with experimental data. The signal excitation of superposed wave is proposed to boost integration level of the experimental setup at two different frequencies of 40 kHz and 200 kHz for in-line measurement. Then, a comprehensive method integrating Hilbert-Huang transform (HHT) and fast Fourier transform (FFT) is conducted for the effective signal identification during the signal processing. In the meantime, the influences of the designed probes on the flow field are analyzed by numerical simulation. In-line measurements are carried out at different zones/depths of the pneumatic pipelines, including one-hour continuous monitoring. The particle size comparison between imaging and ultrasonic methods shows that the latter is effective, which yields an average deviation of about 15%, and the obtained average volume fraction of pulverized coal is approximately 0.112%.

## 1. Introduction

The pulverized coal in pneumatic pipelines of a coal-fired power plant is a typical gas–solid two-phase flow. In-line monitoring the concentration and size of pulverized coal is becoming increasingly important to improve the operational safety, reduce the emission of dust and NOx, and consequently improve the coal combustion efficiency [1–3].

So far, various measurement methods of gas–solid flow parameters have been developed, such as differential-pressure method, light fluctuation method, electrostatic method, and heat balance method. Monazam et al. [4] estimated solid mass flow rate based on measurement of pressure drop in horizontal section of circulating fluid bed. Kitayama et al. [5] proposed a three-dimensional measurement method on pulverized coal by the image processing system with two microscopes. Su et al. [6] investigated the optimization parameter of the particle size inversion with light extinction spectrometry diagnostics. Cai et al. [7] conducted experiments to monitor the size and concentration variation of pulverized coal by light fluctuation method, and the results reflected an expected response under different operating modes. Zhai et al. [8] utilized the principle of heat balance to obtain the concentration of pulverized coal in the ball type pulverized system. In addition, electrostatic method relying on electrostatic fluctuation signal has been widely carried out in certain industries for the flow measurement of pneumatically conveyed solids [9–11].

The authors have noted that ultrasonic measurement has gained a remarkable development from theoretical modeling to experimental technology in particulate two-phase flow [12–14]. Although commonly used in suspensions or emulsions, it can also show sensitive changes of pulverized coal size and concentration. In addition, ultrasound possesses attractive characteristics like transmission ability, resistance to fouling when serving as an on-line measurement method. Hence, ultrasound method can be a competitive approach for in-line measurement of the pulverized coal. In principle, when ultrasound propagates in gas–solid two-phase flows, the wave will be attenuated, which is mainly characterized by the acoustic scattering, viscous loss and heat loss after experiencing the interaction with the involved particles. Currently, quite a few theoretical models can be employed to predict the acoustic attenuation coefficient in the particle system [15–17], but most of them assume that the particles are ideal smooth spheres. Therefore, ultrasonic method for in-line measurement is currently facing several challenges. The particle size of the pulverized coal is not always identical. On the contrary, the range of the measured particle size is quite broad, ranging from microns level to centimeters level [18–21]. The various shapes of particles can be spherical, ellipsoid, or arbitrary irregular geometry. In addition, a compact and stable

* Corresponding author.
*E-mail address:* sumx@usst.edu.cn (M. Su).

https://doi.org/10.1016/j.apacoust.2018.03.034
Received 31 October 2017; Received in revised form 8 March 2018; Accepted 28 March 2018
Available online 07 April 2018

experimental device is also critical in complex industrial scenes, where the mode of superposed signal, a combination of two or several different frequency components in the same time domain can show significant advantages to boost integration level of the experimental setup, especially the easy-to-operate and low-cost signal generation module.

Therefore, the influence on the acoustic attenuation caused by the irregularity of pulverized coal is firstly theoretically investigated in this paper, based on Lloyd and Berry complex scattering model with fragment correction. Numerical simulations of the acoustic behaviors are then conducted, establishing the relationship among ultrasonic attenuation, the volume fraction and Sauter mean diameter (SMD, $D_{32}$) of pulverized coal. The signal excitation mode of superposed waveform comprising two different frequencies of 40 kHz and 200 kHz is then adopted in the design of experimental system. As a core component, the probes are carefully considered from the perspective of acoustic signals capture and numerical simulations are carried out to estimate their influences on flow fields. Currently, with the help of time–frequency analysis of HHT, the effective signals can be distinguished from the noisy ones [22,23]. While, the FFT analysis of the effective signal is usually implemented to determine the expected amplitude [24,25]. Hence, Hilbert-Huang transform and fast Fourier transform are integrated to implement the effective signal identification and processing in this work. Afterwards, in-line measurements are carried out at different zones of the pneumatic pipelines. Consequently, the inversions of the particle size and the average volume fraction are performed, which are then compared with the results of image analysis to give rise to an evaluation of the proposed method.

## 2. Modeling and numerical calculation

### 2.1. Methodology

According to the Lloyd and Berry complex scattering model [26], the acoustic attenuation coefficient in the gas–solid two-phase system can be expressed as:

$$\alpha_0 = \mathrm{Im}[k_f\sqrt{(1+A_0'\phi_v)(1-3A_1'\phi_v)+6A_1'\phi_v^2}] \quad (1)$$

where

$$A_0' = -24i\sum_n\left[\Phi_n\frac{A_{0n}}{(k_fD_n)^3}\right] \quad (2)$$

$$A_1' = -24i\sum_n\left[\Phi_n\frac{A_{1n}}{(k_fD_n)^3}\right] \quad (3)$$

where $k_f$ is wavenumber of the incident wave, $A_0'$ and $A_1'$ are the scattering coefficients of the particle system, respectively. $\phi_v$ is volume fraction. $\Phi_n$ is the volume fraction of the particles with a diameter of $D_n$. $A_{0n}$ and $A_{1n}$ are the scattering coefficients of a single particle with a diameter of $D_n$, respectively. Since this theory assumes that the particles are independent and smooth spheres, it is not guaranteed that the actual pulverized coal with an ideal shape. Wang et al. proposed a fragment correction method [27], and it can be expressed as

$$\alpha = \alpha_0(\omega\tau_v)^\gamma, \omega\tau_v \geqslant 1 \quad (4)$$

$$\tau_v = \frac{D_{32}^2\rho_s}{18\mu_f} \quad (5)$$

where $\alpha$ is the corrected attenuation coefficient. $\tau_v$ is viscous relaxation time. $\omega$ is angular frequency. $\mu_f$ is viscosity of the continuous phase. $\rho_s$ is density of the particle phase. $D_{32}$ is Sauter mean diameter (Sauter mean diameter is widely used as the parameter for describing the particle size in the long wavelength region). It is noted that the correction factor $\gamma$ is independent of frequency, and it has been given and verified by experiments in Ref. [27].

**Table 1**
Physical properties of pulverized coal and air (71 °C).

| Physical parameters | Pulverized coal | Air |
|---|---|---|
| Density/(kg·m$^{-3}$) | 1400 | 1.026 |
| Acoustic velocity/(m·s$^{-1}$) | 2380 | 373.6 |
| Shear modulus/(N·m$^{-2}$) | $1.27\times10^{12}$ | – |
| Shear viscosity/(Pa·s) | – | $2.065\times10^{-5}$ |
| Thermal conductivity/(W·m$^{-1}$·K$^{-1}$) | 4.2 | 0.02969 |
| Specific heat/(kJ·kg$^{-1}$·K$^{-1}$) | 0.73 | 1.009 |
| Acoustic attenuation/(s$^2$·m$^{-1}$) | $8.8\times10^{-14}$ | $1.7\times10^{-11}$ |

### 2.2. Numerical calculation

Table 1 lists the physical parameters of the pulverized coal and air which are required for numerical calculation (The temperature is set as 71 °C which is just consistent with that of pipe flow during in-line experiments). In this calculation, the range of the pulverized coal size is 1–200 μm, and the volume fraction is from 0.01% to 1%. Therefore, ultrasonic frequencies of 40 kHz and 200 kHz are selected to ensure that the ultrasonic waves can propagate through the gas medium while the signals at different frequencies can be obviously identified, providing enough contrast of ultrasonic attenuation. As shown in Fig. 1, the relationship among the ultrasonic attenuation coefficient, the particle size, and the volume fraction of the pulverized coal is obtained by numerical calculation. The acoustic attenuation coefficient at 200 kHz is obviously higher than that at 40 kHz under the computation conditions of other factors being held constant. Fig. 2 shows the relationship of the ratio of the ultrasonic attenuation coefficients (at 40 kHz and 200 kHz), the particle size, and the volume fraction, it reveals a monotonous dependency of the attenuation ratio on the particle size. Thus, it shows that the particle size can be obtained by using experimental data only at two ultrasonic frequencies. Furthermore, when the volume fraction is within 1%, the present relationship is independent of the volume fraction of pulverized coal.

### 2.3. Influence of parameter variation on numerical calculation

The ultrasonic propagation in the gas-solid two-phase flow is complex. Therefore, the numerical calculation is affected by the physical parameters of both continuous-phase and particle. The influence of physical parameter variation on ultrasonic attenuation is thus discussed. Fig. 3 shows the influence of parameter variation ( ± 10%) on the prediction of ultrasonic attenuation. As shown in Fig. 3, the

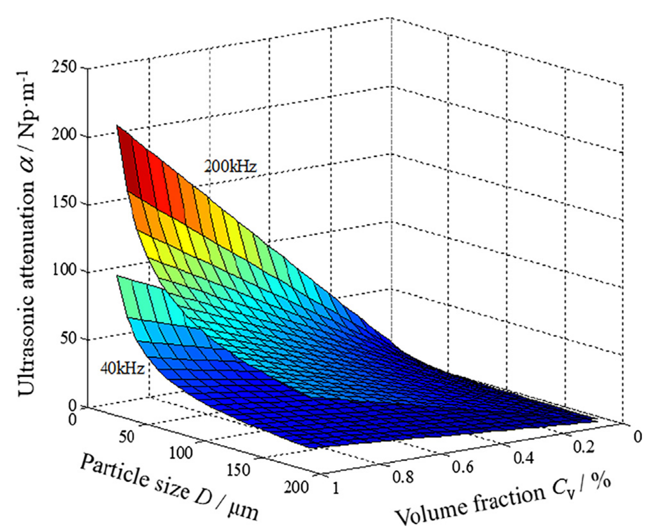


**Fig. 1.** Relationship among ultrasonic attenuation coefficient, particle size, and volume fraction of pulverized coal.