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To cite this article: Zhenghua Zhang and Peihong Wang 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **252** 052153

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# Correction of Gas-Phase Velocity Effects on Ultrasonic Measurement of Pulverized-Coal Concentration

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**Abstract.** The ultrasonic method generally calculates the acoustic attenuation coefficient of gas-solid two-phase flow based on gas single-phase flow at a certain velocity to get the concentration of solid phase. The changes of gas phase velocity have effects on acoustic attenuation coefficient and the measurement results of solid phase concentration. The paper analysed the principle of this effects, built experimental platform, and a modified formula of gas phase velocity based on the experimental samples was given. The experiment test results indicated that the measurement absolute error of the pulverized-coal concentration was reduced to about 0.7%.

## 1. Introduction

The measurement of pulverized-coal concentration in power plants belongs to the field of gas-solid two-phase flow detection, accurate monitoring of the pulverized-coal concentration plays an important role in the stability of boiler combustion in power plant and the economic and social benefits of power plant [1]. The existing gas-solid two-phase flow concentration detection methods mainly include electrostatic method, optical method, differential pressure method, ultrasonic method, etc [2-9]. The ultrasonic method mainly measures the acoustic attenuation of the two-phase flow and brings it into the simplified ECAH model to calculate the solid phase concentration. Generally, the ultrasonic signal at a certain gas phase velocity without pulverized coal passing is used as a reference, the signal when the pulverized coal passes is used as the ultrasonic attenuation signal, and the amplitude of both is divided by the logarithm to obtain the ultrasonic attenuation coefficient [10]. However, due to the limitation of the conditions, when the power plant is running, the reference signal of the ultrasound cannot be measured in real time, and the attenuation coefficient can only be calculated based on the ultrasonic signal of the previously measured in still air.

However, the velocity of the gas phase velocity is constantly changing due to operational requirements. When there is no solid phase, the amplitude of the ultrasonic signal at different gas velocity is variable. If the attenuation coefficient of the pulverized-coal is still calculated based on the ultrasonic signal of the previously measured in still air, large errors will occur, and the result of pulverized-coal concentration will not be accurate. Therefore, it is necessary to correct the change in the gas phase velocity to improve the measurement accuracy.

## 2. Ultrasound attenuation theory

The attenuation of ultrasound in gas-solid two-phase flow is mainly caused by viscous loss, heat loss, scattering loss and internal absorption loss of medium [11]. Based on the conservation of mass,



momentum and energy in the micro-volume element, the ECAH model <sup>[12-14]</sup> accurately describes the acoustic wave behavior of spherical particles in two-phase media, and obtains the theoretical relationship between the acoustic attenuation coefficient and the volume concentration of solid particles as follow:

$$\alpha = -\frac{3\varphi}{2K_c^2 R^3} \sum_{n=0}^{\infty} (2n+1) \operatorname{Re}(A_n) \quad (1)$$

Where  $\alpha$  is the acoustic attenuation coefficient,  $\varphi$  is the volume concentration of the solid phase,  $R$  is the diameters of solid phase,  $K_c$  is compressional wave number,  $A_n$  is scattering coefficient. When the wavelength is longer ( $\lambda > 20R$ ), the scattering coefficient  $A_n$  can take only  $A_0$  and  $A_1$ .

$$A_0 = \frac{i(k_c R)^3 \left( \frac{\rho_c k_s^2}{\rho_s k_c^2} - 1 \right)}{3} - k_c^2 R c T \rho_c \lambda_c H \left( \frac{\beta_c}{\rho_c C_{pc}} - \frac{\beta_s}{\rho_s C_{ps}} \right)^2 \quad (2)$$

$$A_1 = \frac{-i(kR)^3}{3} * \frac{\rho_c - \rho_s}{3\rho_c + \frac{2(\rho_s - \rho_c)}{1 + \frac{3(1+i)\delta_p}{2R} + \frac{3i\delta_p^2}{2R^2}}} \quad (3)$$

$$H = \left[ \frac{1}{1-iz} - \frac{(\lambda_c/\lambda_{cs}) \tan z_c}{\tan z_s - z_s} \right]^{-1} \quad (4)$$

Where  $i$  is imaginary,  $z = (1+i)R/\delta_t$ , subscript  $c$  denotes continuous phase, subscript  $s$  denotes solid phase,  $T$  is temperature,  $\lambda$  is thermal conductivity,  $\beta$  is thermal diffusion coefficient;  $C_p$  is constant pressure specific heat capacity;  $c$  is sound velocity.

As shown in formula (1), when the particle size distribution of the pulverized coal particles and the frequency of the ultrasonic wave are known, the volume concentration of the pulverized coal can be obtained as long as the acoustic attenuation coefficient of the gas-solid two-phase flow is measured.

Due to the presence of solid particle, the acoustic attenuation coefficient be calculated like this [15]:

$$\alpha = \frac{\ln\left(\frac{A'}{A}\right)}{d} \quad (5)$$

Where  $d$  is the distance between the transducers, and  $A'$  and  $A$  are the amplitude of the ultrasonic signal in the gas-solid two-phase flow and in pure gas media, respectively.

When measuring, calculating the corresponding ultrasonic signal amplitude, and bring into the formula (5) to get the acoustic attenuation coefficient of the two-phase flow. Then the concentration will be obtained by formula (1)-(4).

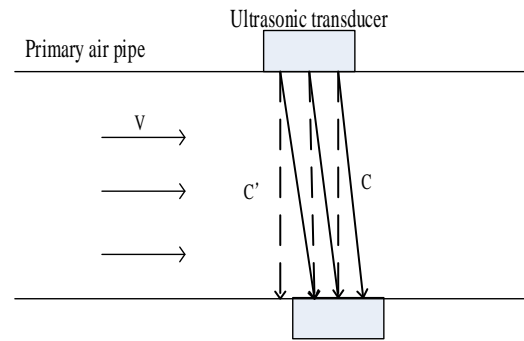
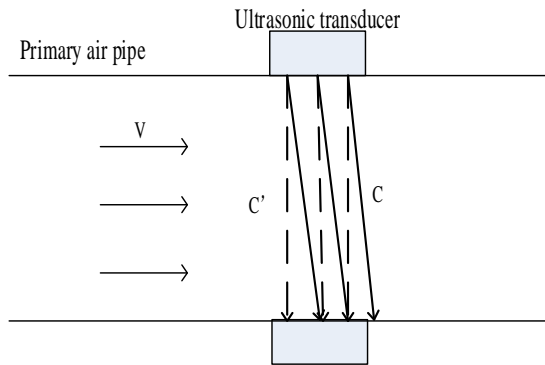
### 3. Effects of the gas phase velocity

According to the measurement principle of ultrasonic method, in order to measure the concentration of solid phase, it+ is necessary to calculate the ultrasonic attenuation coefficient by measuring the amplitude of ultrasonic signal before and after the pulverized coal passing through. Therefore, the amplitude of the received signal directly affects the pulverized coal concentration. It is found that, under the same physical parameters and environmental conditions, besides the solid concentration, the variation of gas phase velocity also affects the amplitude of the received ultrasonic signal, changes the acoustic attenuation coefficient, and thus affecting the calculation of the concentration.

#### 3.1. Theoretical analysis

Ultrasound belongs to sound wave. It is known from the superposition principle that the actual propagation velocity of sound waves in the primary air is related to the local velocity. Due to the

centrosymmetric arrangement of the ultrasonic transducer, when the velocity of the gas phase medium exists, the actual propagation path of the ultrasound is shown in Fig. 1.



**Fig.1** Effect of gas phase velocity on ultrasonic **Fig.2** Moving the ultrasonic transducer downwind

In the Fig.1,  $c'$  is the propagation velocity vector of the ultrasound when the gas phase is still,  $v$  is the velocity vector of the gas phase, and  $c$  is the actual propagation velocity vector of the ultrasound in the gas phase.

It can be seen that when the gas phase velocity exists, the received signal of the centrosymmetrically arranged ultrasonic transducer will be offset, the signal amplitude will be reduced and the attenuation will be increased. The offset increases with the increase of velocity.

### 3.2. Experimental exploration

In order to verify the principle of the attenuation of ultrasonic signal caused by gas phase velocity, the following experiments are designed. Under the condition of constant excitation voltage, transducer distance and other environmental factors, changing the velocity of gas single phase flow, measuring the amplitude of the received signal of the ultrasonic when the ultrasonic receiving transducer moves along the direction of gas flow velocity at different distances, and analyzing the relationship between amplitude, velocity of gas and moving distance.

According to the theoretical analysis, the signal offset distance caused by the gas phase flow velocity can be calculated by the formula (6).

$$l = \frac{d}{c} \cdot v \quad (6)$$

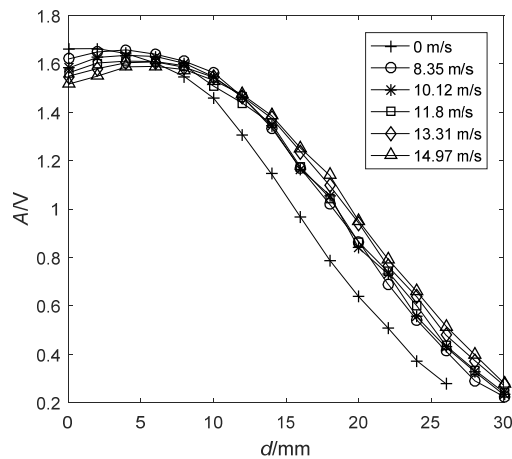
Where:  $l$  is the offset distance,  $c$  is the speed of sound,  $d$  is distance between the transducers, and  $v$  is the gas phase velocity.

Therefore, it can be inferred that there is a point in the process of transducer moving, which makes the received ultrasonic signal maximum at this point and consistent with the amplitude of the received ultrasonic signal when the gas phase velocity is zero and the ultrasonic transducer is symmetrical in the center, as shown in Fig.2.

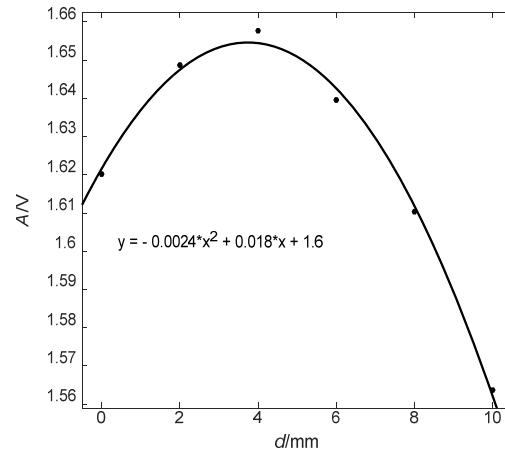
The equipment used in the experiment was a platform that could be moved by cross, with a maximum moving distance of 15 cm, and a pair of ultrasonic transducers were fixed on it. The gas phase velocity was provided by the fan, and the speed was controlled by the frequency converter. The maximum adjustable velocity is 17m/s. Before the experiment, the gas phase velocity under some specific frequency of the frequency converter had been measured by a vortex flowmeter.

During the experiment,  $d$  was set 10cm, the ultrasonic transducer was moved along the direction of gas flow velocity from 0 to 30 mm at 2 mm interval under six different gas flow velocities, and 500 signals were measured at each distance. After that, the 500 data of each group are averaged, and then

the relationship curve between the received signal amplitude and transducer moving distance under different gas flow velocities is drawn as shown in Fig.3.



**Fig.3** Ultrasonic amplitude versus transducer moving distance under different gas phase velocity



**Fig.4** Local parabola fitting of ultrasonic amplitude and transducer moving distance

As shown in Fig.3, except for 0 m/s, the amplitudes of the received signal at the others increase first and then decrease with the increase of the moving distance, that is, there is a maximum value, which is consistent with the theoretical analysis.

Local parabola fitting was made for the initial stage of each group of curves except 0m/s to find the maximum point and maximum value. Fig.4 shows the fitting result of 13.31m/s.

According to the fitted parabolic formula, the maximum point and its maximum value can be obtained. The fitting results at each velocity were shown in Table 1.

**Tab.1** The maximum value of signal amplitude fitting under different gas phase velocity

Frequency converter frequency /Hz	The gas phase velocity/(m•s <sup>-1</sup> )	The maximum point /mm	Theoretical offset/mm	Absolute error/mm	Fitting maximum amplitude /V	Theoretical maximum amplitude /V	Relative error /%
25	8.35	3.5	2.92	0.58	1.655	1.6657	0.6
30	10.12	4.09	3.54	0.55	1.639		1.6
35	11.8	4.33	4.13	0.20	1.612		3.2
40	13.31	5.16	4.66	0.50	1.610		3.3
45	14.97	5.6	5.24	0.36	1.593		4.3

From Table 1, it can be seen that the larger the gas phase velocity is, the larger the maximum point is, on the other words, the actual ultrasonic offset is larger. The absolute error between the ultrasonic actual offset and the theoretical offset is around 0.5mm. At the same time, the maximum value of the fitting amplitude is basically consistent with the theoretical value, and the relative error is within 5%.

#### 4. Correction of the gas phase velocity

From the previous analysis, it can be seen that the effects of gas phase velocity on ultrasonic measurement is changing propagation velocity vector of the ultrasound, which makes the ultrasonic signal offset and the amplitude of received signal reduce. The offset distance can be calculated. The

offset of the ultrasonic signal is equivalent to the relative movement of the ultrasonic transducer, so that the effect of gas phase velocity can be converted by formula to the relative movement of the transducer. Therefore, it may be a good way to correct the gas phase velocity that studying the relationship between the amplitude of the signal and the moving distance of the transducer.

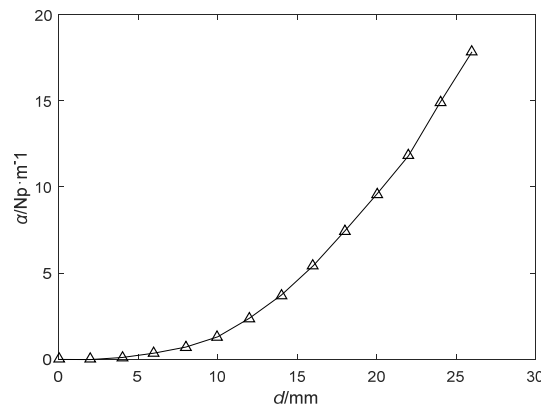
As seen from Fig. 3, in actual measurement, due to the presence of the gas phase velocity, the actual reference signal amplitude  $A''$  is smaller than the previously measured reference signal (ultrasonic signal in the still gas phase) amplitude  $A'$ . The actual acoustic attenuation coefficient is:

$$\alpha' = \frac{\ln\left(\frac{A''}{A}\right)}{d} \quad (7)$$

Therefore, the actual acoustic attenuation coefficient is smaller. From formula (5) (7), the additional acoustic attenuation coefficient caused by the change of gas phase velocity is:

$$\Delta\alpha = \frac{\ln\left(\frac{A'}{A''}\right)}{d} \quad (8)$$

For the data of the gas phase velocity at 0m/s in Fig.3, taking the ultrasonic amplitude of transducer moving distance being zero as  $A'$ , and the others as  $A''$ , according to formula (8), calculating the additional attenuation coefficient and drawing the curve, as shown in Fig. 5



**Fig.5** Additional ultrasonic attenuation versus transducer moving distance

Fitting the data points in Fig. 5:

$$\Delta\alpha = 0.02466x^2 \quad (9)$$

The accuracy is 0.98. Therefore, the additional acoustic attenuation coefficient is proportional to the quadratic moving distance of the transducer.

When the velocity of the gas phase is known, the offset distance of the signal can be calculated by formula (6). Combined with formula (6) and (9), the relationship between the additional acoustic attenuation coefficient and the gas phase velocity is:

$$\Delta\alpha = 0.00213v^2 \quad (10)$$

Due to the limitation of the conditions, when the power plant is running, the reference signal of the ultrasound cannot be measured in real time, and the attenuation coefficient can only be calculated based

on the ultrasonic signal of the previously measured in still air. Then the actual gas phase velocity was brought into the formula (10) to calculate the additional acoustic attenuation coefficient. After that, subtracting the latter from the former, to get the actual ultrasonic attenuation coefficient under the gas phase velocity. Thus, the gas phase velocity was corrected and the acoustic attenuation caused by the change of gas phase velocity was eliminated.

Several groups of pulverized-coal volume concentration in different gas phase velocity were corrected by this correction method, and the corrected results are shown in Table 2.

**Tab.2** Measurement results before and after gas phase velocity correction

Gas phase velocity/ ( $\text{m}\cdot\text{s}^{-1}$ )	Weighing method result/‰	Ultrasonic method result/‰		Absolute error/‰	
		Before correction	After correction	Before correction	After correction
13.31	0.386	0.630	0.433	0.244	0.047
11.8	0.434	0.647	0.501	0.213	0.067
10.12	0.479	0.663	0.544	0.184	0.065
8.35	0.524	0.682	0.593	0.158	0.069

Because the concentration of pulverized-coal to be measured is low, and the acoustic attenuation coefficient is small, the additional attenuation coefficient caused by the gas phase velocity accounts for a larger rate, so the error measured before the correction of the gas phase velocity is large.

Compared with results obtained by weighing method, the absolute error of ultrasonic method decreases obviously after gas phase velocity correction, which is less than 0.7%.

With the decrease of velocity, the absolute error of ultrasonic method increases. This may be due to the insufficient mixing and uneven distribution of pulverized coal particles at lower velocity.

In addition, the measured concentration values are larger than the actual values. This is because during the calculation of the concentration, the average particle size was taken. However, the particle size of pulverized-coal is not uniform with wide particle size distribution [16].

## 5. Conclusion

The variation of gas phase velocity affects the measurement of solid phase concentration in ultrasonic method. The principle of the effects was analyzed, and experiments were designed to verify it. The experimental results show that the effect of gas velocity on ultrasonic method measurement is changing propagation velocity vector of the ultrasound, which makes the ultrasonic signal offset and the amplitude of received signal reduce.

Based on it, a method of correcting the gas phase velocity was proposed, and a modified formula based on the experimental samples was given. The experiment test results indicated that the measurement absolute error of the pulverized-coal concentration was reduced to about 0.7%.

## Acknowledgements

This work was financially supported by National Natural Science Foundation of China (Nos.50376011 and 51476028) and National Key Technology Research and Development Program of the Ministry of Science and Technology of China (2015BAA03B02).

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