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Concentration determination in a cylinder-simulated gas–solid two phase flow using ultrasonic backscattering method

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A B S T R A C T

Determining concentration in two phase flow is challenging, especially in gas–solid two phase flow. A novel ultrasonic backscattering method is proposed to determine the fixed cylinders concentration in gas phase in this paper. An ultrasonic reflection setup with two transducers, for transmitting and receiving, respectively, is built up. The appropriate ultrasonic frequency and particle size are selected for experiments to ensure effective backscattering intensity. Statistically analyzing the backscattering signal yields the product of attenuation coefficient and sound velocity, which is sensitive to the concentration. After the linear relationship between the product and concentration is obtained by the semi-empirical method, the concentration information can be inversely deduced after the received signals are measured experimentally. This method can provide a new strategy for the measurement of gas–solid two phase flow.

1. Introduction

The measurement of flow parameters in two phase flow is very meaningful in industrial production, for example, real-time acquisition and timely adjustment of the ratio between pulverized coal and air in power plants can improve combustion efficiency, reduce pollutant emissions, and achieve the ultimate goal of safe production [1]. Among all the flow parameters, the concentration measurement has attracted tremendous attention. Currently, a wide variety of measurement techniques are utilized to determine the concentration in two phase flows, such as optical method [2,3], capacitance tomography method [4], electrostatic method [5], and light fluctuation method [6]. However, these methods all have some limitations. Specifically, the expensive instruments of optical methods and its characteristics of easily damaged in complex industrial sites impede its large-scale applications. The application of electrical methods is also limited because the materials measured by electrical methods must have specific electrical properties. Recently, owing to the features of strong penetration, low price, wide frequency range and on-line non-contact measurement, the ultrasonic methods have received an increasing attention [7,8]. The ultrasound attenuation method is applied to character the gas–solid, liquid–solid and liquid–liquid two phase flow in comprehensive aspects [9–11], e.g., Zou et al. used B-mode ultrasound imaging signals to explore the concentration of suspended sediments [12] and Tian et al. obtained the concentration of gas–solid two phase flow by utilizing the ultrasonic process tomography system [13].

Ultrasonic backscattering method has the advantages of no effect on the flow field, easy to operate and suitable for any industrial occasion [14–18], which greatly simplifies the experimental equipment and improves the operability of the experiment. For example, only one acoustic window is necessary for the ultrasonic backscattering method, while for the ultrasonic tomography system, holes are needed in all directions of the pipeline to obtain the complete flow information. Nowadays, ultrasonic backscattering method is mainly used in liquid or solid media with high frequency ultrasound in industry, Robert et al. [19] used ultrasonic backscattering method to explore the concentration and distributed particle size of dispersions. Luis et al. [17] implemented high frequency ultrasound to measure the concentration of yeasts in liquid suspensions. However, the application of ultrasonic backscattering method in gas–solid two phase flow field is rare. There are two main reasons. First, it is very difficult to collect the scattering signal from the tiny cylinders. If the particle size is too small, the backscattering signal cannot be received. Another reason can be summarized as the sound attenuation in air is much larger than that in liquid and solid (as can be seen from the comparison in Table 1). Increasing the frequency of ultrasound may be an effective technical approach [20]. In general, the higher the frequency, the better the directivity, which means the stronger sensitivity of ultrasound to the small scatterers. However, as the ultrasonic frequency increases, the attenuation in the air (proportional to the

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Table 1
The distance that the ultrasound wave goes through when it decays to 1/e of its original intensity (T = 25 ℃) [13].

Frequency/kHz	Air/km	Water/km
20	1.89×10^{-1}	3.13×10^{2}
50	3.03×10^{-2}	5.01×10^{0}
100	7.58×10^{-3}	1.25×10^{0}
1000	7.58×10^{-5}	1.25×10^{-1}

square of the frequency) enhances dramatically. As a result, it is really a challenging work to measure the flow of gas–solid phase by ultrasonic backscattering method. Therefore, finding relationship between ultrasonic frequency and particle size to reduce the restrictions of high frequency ultrasound is an urgent and yet unresolved issue. Herein, the variation of backscattering intensity with particle size and ultrasonic frequency is analyzed, and the appropriate ultrasonic frequency and particle size are selected for experiments, which ensures the feasibility of backscattering method in gas–solid two phase flow.

When existing abundant scatterers, their interaction (agglomeration and collision, etc.) will cause uneven distribution of velocity, change of particle size or shape, and even introduce noise, vibration and other interfering non-measurement factors, which brings great difficulties in characterizing concentration [21–23]. Fixed cylinders instead of flowing particles in the static experiment can effectively release the effect caused by the interaction, therefore, fixed cylinders are chosen as the dispersed phase in the experiment.

In this paper, a novel ultrasonic backscattering method for measuring concentration in gas–solid two phase flow with appropriate ultrasound frequency (50 kHz) and the fixed cylinders radius (0.5 mm) is proposed. The changes of concentration (5 %–25 %) were achieved by varying the number of cylinders, and the ultrasonic reflection arrangement was built up to gather the scattered sound waves by fixed cylinders. After statistically analyzing the backscattered signal, the product of attenuation coefficient and sound velocity can be derived, which was fitted with the concentration thereafter. Then the empirical linear relationship can be yielded to predict the concentration information directly.

2. Theory

2.1. Principle of acoustic attenuation

Sound waves will dissipate while traveling in the propagation medium, and the intensity of the sound waves decreases with increasing the propagation distance, which is named acoustic attenuation [24]. Acoustic attenuation is caused by the interaction between the sound waves and the medium, and it is a measure of the energy losses during wave propagation. The losses are intrinsic to the medium and are caused by many phenomena depending on the nature of the propagating medium. The most known causes are the scattering (occurs only when there is grain boundary and is sensitive to the size, shape and orientation of grains), absorption (caused by thermos-elastic effect, viscoelastic effect...), and elastic hysteresis. In the study of ultrasonic interaction with gas and solid phases, the loss due to scattering is often considered as the main reason for attenuation, and the type of the scattering attenuation depends on the scattering regimes (geometric, stochastic and Rayleigh) [24–26].

For the plane wave which propagates along a specific direction in the air, the change of its sound pressure with the propagation distance can be characterized by the sound attenuation coefficient [25]:

$$P = P_0 \exp^{-\alpha x} = P_0 \exp^{-\alpha c t} \quad (1)$$

where α is attenuation coefficient, x refers to propagation distance, c represents sound propagation speed in the air, P_0 is the incident sound pressure, and t represents propagation time. As for the backscattering method, the received echo is reflected back, and the distance traveled by ultrasound is $2x$, so the formula should be in the form of:

$$P = P_0 \exp^{-2\alpha c t} \quad (2)$$

2.2. The principle of backscattering method

Acoustic scattering refers to the phenomenon that part of the sound waves deviates from the original propagation path when it encounters scatterers in propagation process. After the sound waves incident towards the scatterers, it becomes a secondary

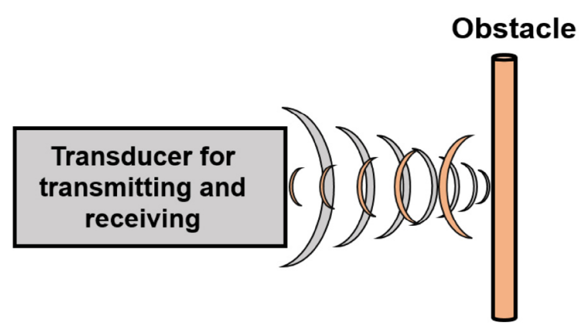

Fig. 1. Schematic of backscattering method.

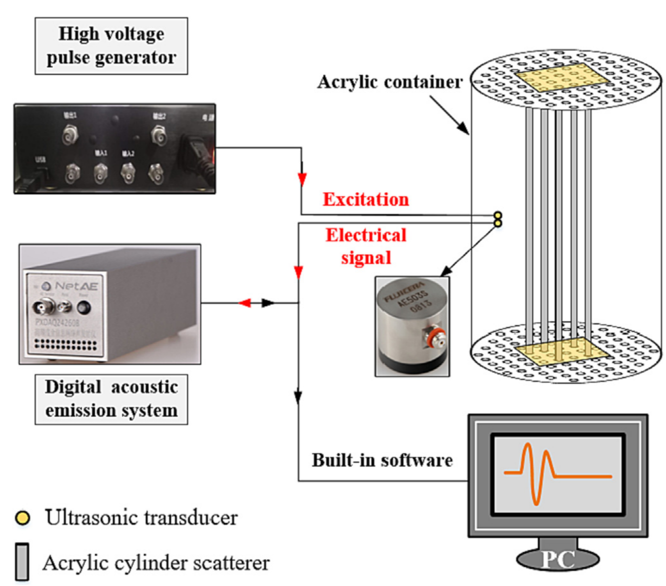

Fig. 2. Measurement setup for experiments of ultrasonic backscattering from cylinders.

Table 2
Physical parameters of air and cylinders.

	Air	Cylinders
Density (kg/m^3)	1.25	1200
Sound Velocity (m/s)	346	2165

source under the excitation of sound, and part of sound energy is converted into scattered energy. The measured backscattered sound wave in this paper refers to the sound wave with the scattering angle of 180° or reflected back from the cylinders (as shown in Fig. 1). The principle that ultrasonic backscattering method can be applied in two-phase flow is: the acoustic characteristics, such as the scattering intensity and the sound attenuation [19], are related to two phase flow information, including concentration, size, and density of cylinders, etc. [27,28].

Based on scattering theory, the dimensionless wave number is introduced to explore the scattering characteristics of the cylinders:

$$ka = \frac{2\pi fa}{c} \quad (3)$$

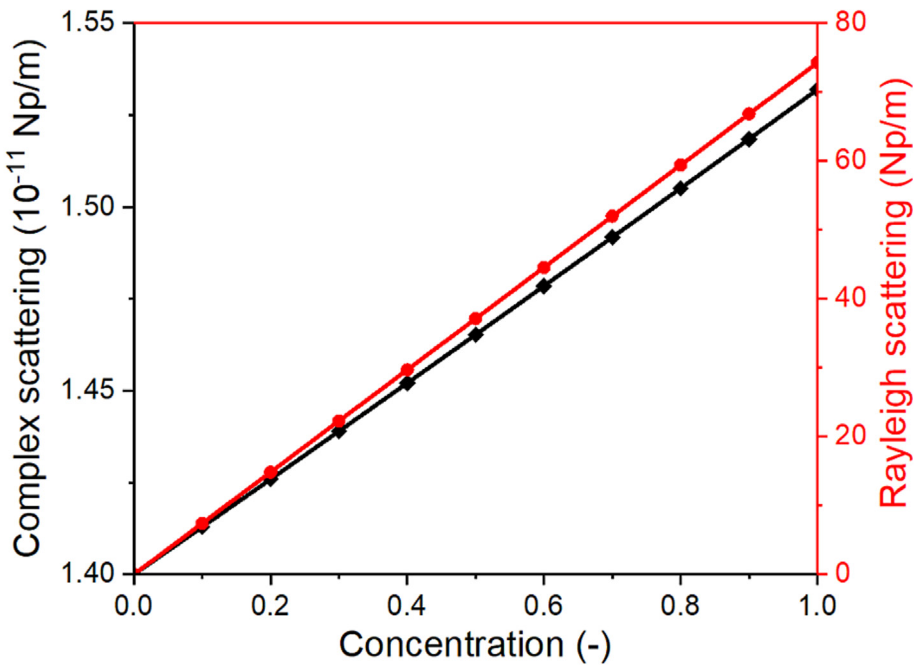

Fig. 3. Order of magnitude comparison of complex scattering and Rayleigh scattering.

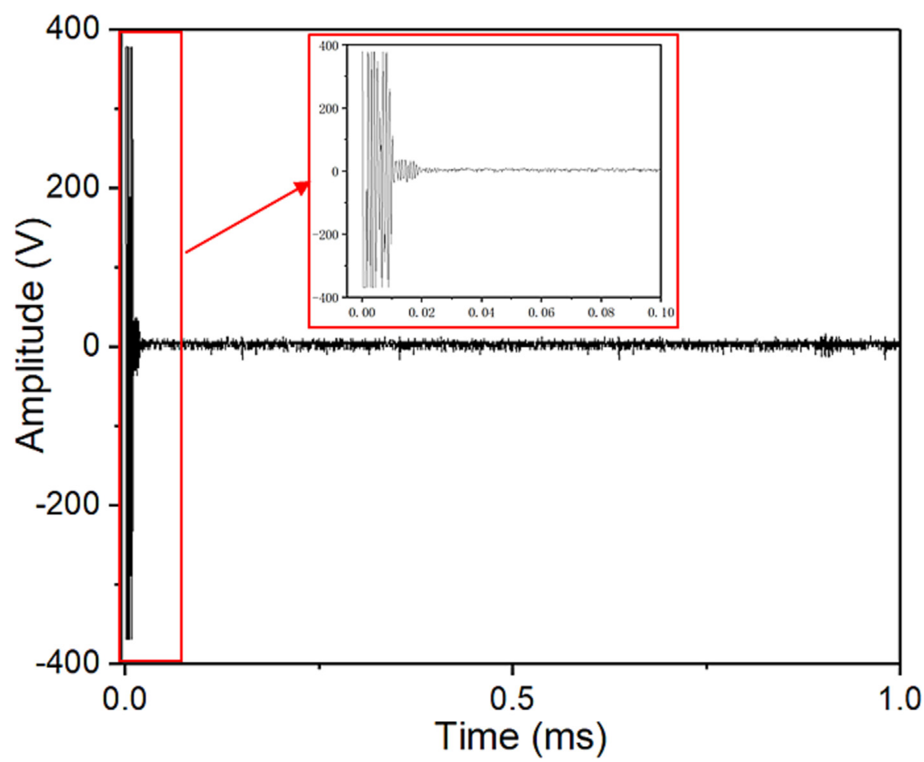

Fig. 4. Waveform of high voltage pulse from the pulse generator.

where a refers to the radius of the cylinders, f is the ultrasonic frequency, and c represents the sound velocity.

3. Experimental setup

3.1. Selection of experimental conditions

As can be seen from Table 1, when the frequency is 1 MHz, the ultrasonic wave propagates only 7.58 cm in the air until the intensity drops to 1/e of its original intensity at 25 °C. This is obviously unacceptable in the practical applications, for most gas–solid two phase flow occasions in industry, such as pulverized coal combustion, pneumatic conveying, all have large dimensions. As mentioned in Section 1, the ultrasound with higher frequency helps to improve the directivity, the propagation distance in the air, however, will decrease rapidly. In other words, directivity and measurement range cannot be guaranteed at the same time. According to our previous research [29], when the dimensionless wave number ka is equal to 0.5, backscattering amplitude reaches its maximum value. Therefore, ka should be set to be close to 0.5 while selecting ultrasonic frequency and size of cylinders, to ensure considerable measurement results.

In this work, fixed cylinders are chosen as the dispersed phase in the experiment. To keep cylinders immovable, cylinders were fixed between two orifice plates, whose orifice is the same size of cylinders (as shown in Fig. 2). After fixing the different size of cylinders between two orifice plates, it is found that the cylinder with a small radius was too soft to be fixed. After comprehensive analysis, the frequency is selected as 50 kHz, the cylindrical radius is 0.5 mm to make sure dimensionless wave number ka approaching 0.5.

In the experiment, the radius of all cylinders is consistent, thus altering the number of cylinders means changing the concentration of gas–solid two phase flow. Herein, the concentration is denoted as the number of cylinders n set in the container divided by the total number of cylinders that the container can hold N (Eq. (4)), that is, the more cylinders in the container, the higher the corresponding concentration.

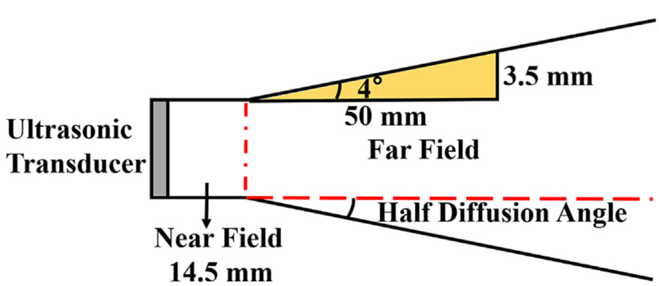

Fig. 5. Schematic diagram of probe resolution determination.

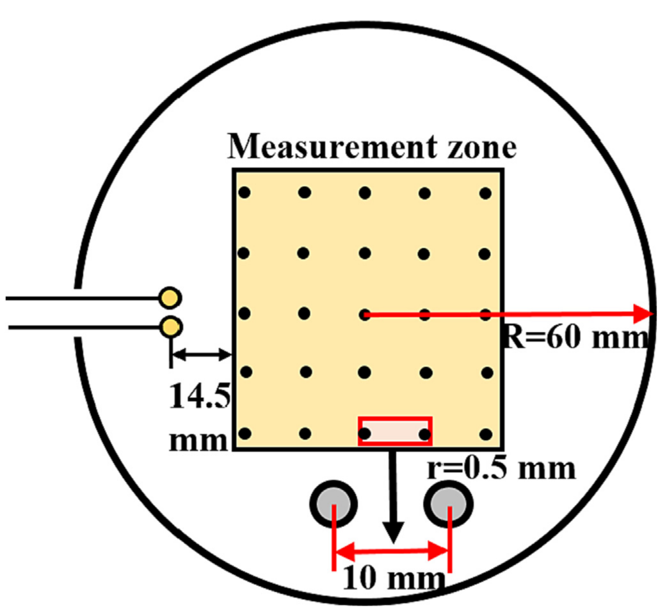

Fig. 6. Detailed diagram of the measurement area.

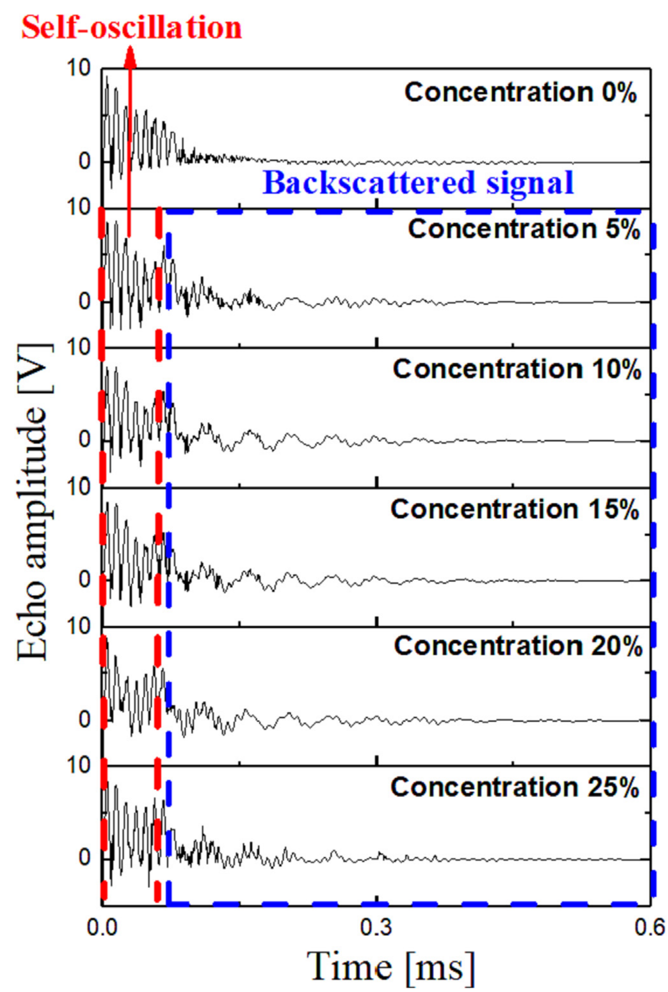

Fig. 7. Received echo amplitude versus time under different concentration.

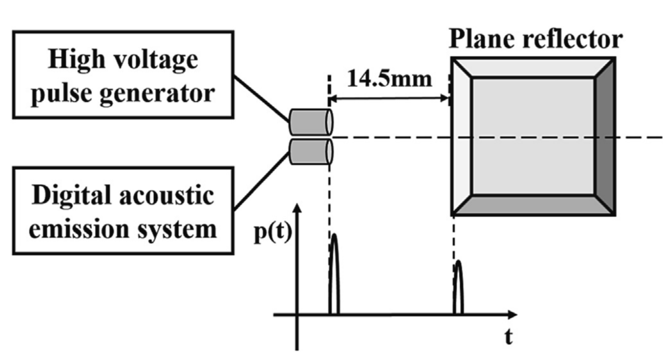

Fig. 8. Experimental setup used for substitution method.

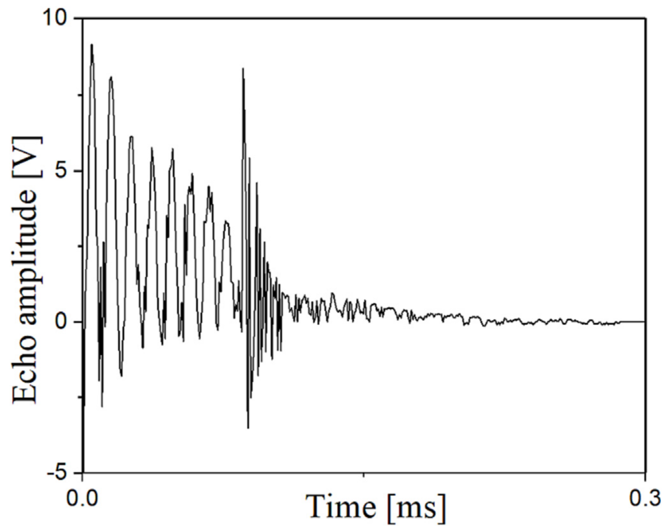

Fig. 9. Reflection signal reference achieved by arrangement in Fig. 8.

$$\phi = \frac{n}{N} \tag{4}$$

However, the interaction among them gradually becomes stronger with increasing the number of cylinders, to be specific, the probability that the sound wave scattered by single cylinder incident on another cylinder (complex scattering) shows an upward trend. The interaction among cylinders will cause uneven cylinder distribution, introduce noise and vibration, and make part of the sound waves cannot reach the ultrasonic transducer during the propagation process, which greatly affects the accuracy of experimental results.

To find out the proportion of energy loss resulted from complex scattering accounts for the total loss, numerical simulations were carried out by adopting the complex scattering attenuation model (Waterman and Truel's model) [21] and Rayleigh scattering model [22] under different concentrations with radius of 0.5 mm. The physical parameters of air and cylinders set in the simulation are shown in Table 2. Results in Fig. 3 indicated that the order of magnitude of the complex scattering is only 10^{-11} Np/m, while that of the overall attenuation is 10^{0} Np/m. Compared to total attenuation, the attenuation caused by complex scattering in this case is so small that can be ignored in this experiment. Therefore, when multiple cylinders exist, the complex scattering among them could be ignored. The concentration can then be altered by changing the number of cylinders. The total number of cylinders that the container can hold is 100, therefore, the corresponding concentration changes from 5 % to 25 % when the number of cylinders varies from 5 to 25 in this work.

3.2. Setup

Fig. 2 demonstrates the ultrasonic reflection arrangement for gathering ultrasound waves backscattered from cylinders dispersed in air. Excited by the pulse generator (380 V, as shown in Fig. 4) (PAEWG acoustic emission waveform generator, Changsha PengXiang Electronic Technology Co., Ltd), which is capable of transmitting arbitrary waveform and power amplification, the emitting transducer (Japan Fuji ultrasonic sensor, AE503S) emits pulsed ultrasonic wave. The ultrasonic wave will scatter when it

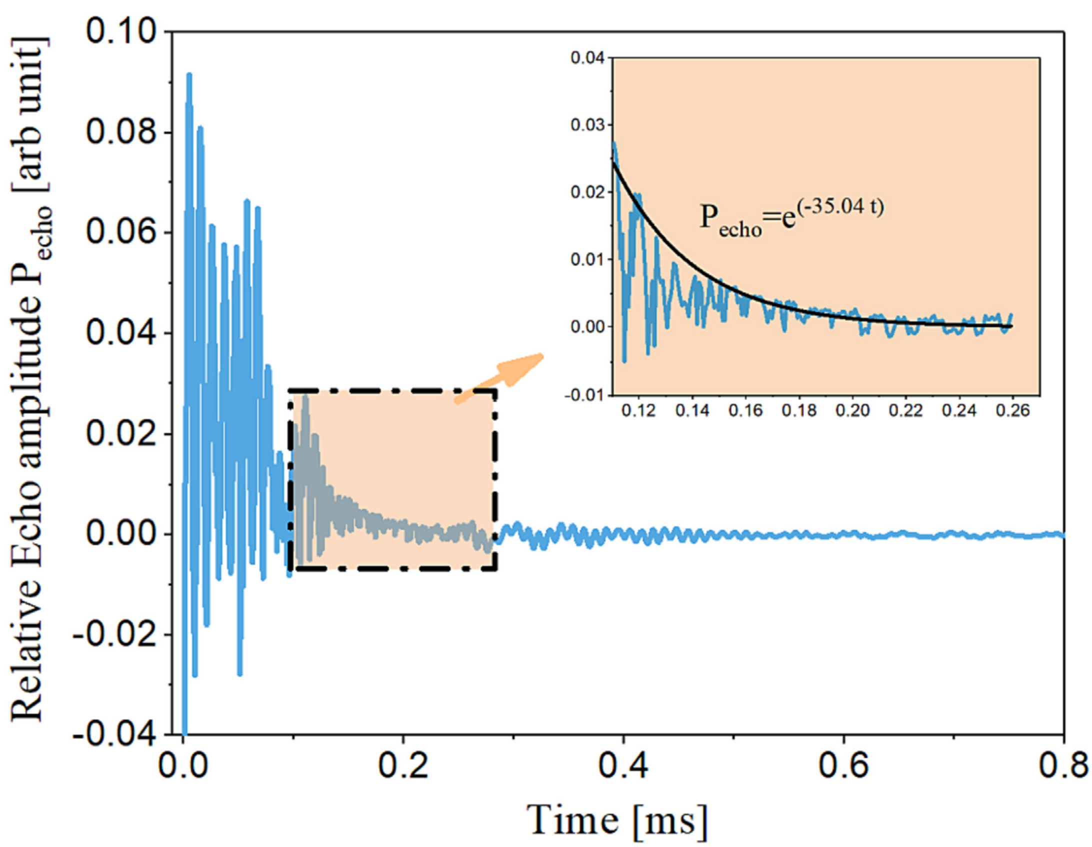

Fig. 10. Processed data in the form of backscattering amplitude in arbitrary units versus time (when the concentration is 5%).

encounters the cylinders in the process of propagation, the scattered waves are then gathered by the receiving transducer (Japan Fuji ultrasonic sensor, AE503S), which is linked to acoustic emission equipment (High precision single channel acoustic emission collector PXDAQ24260F, Changsha PengXiang Electronic Technology Co., Ltd). Acoustic emission device is equipped with functions such as data acquisition, automatic filtering, and automatic control operation of built-in software (PXAES digital all-network acoustic emission system). In the experiment, the sampling rate was set at 1.25 MS/s according to Nyquist's theory, and the repetition rate of the pulse was 1000 Hz to make sure that the reflected echo was completely received. In detail, the time required for the ultrasound to pass through the measuring container is 0.694 ms (Eq. (5)), therefore, the pulse repetition rate is set as 1000 Hz, that is, 1000 pulses are emitted per second (each pulse lasts 1 ms) can definitely meet the measurement requirements.

$$T = \frac{2d}{c} = \frac{2 \times (2 \times 60mm)}{346m/s} = 0.694ms \tag{5}$$

As shown in Fig. 5, the sound beam cannot be collimated like the light beam, but will spread at a certain angle after the near field in practice, therefore, ultrasonic transducer has the certain range resolution. That is to say, the two cylinders cannot be distinguished by the transducer when they are staying too close. The length of the near field can be obtained by dividing the square of the radius of the transducer by the wavelength:

$$N = \frac{R_s^2}{\lambda} = \frac{(1cm)^2}{\frac{346m/s}{50000Hz}} = 14.5mm \tag{6}$$

The near field is generally not selected for measurement zone because of the wave interference [20]. Hence, the transducers are placed 14.5 mm away from the measurement zone to keep the cylinders in the far field (as shown in Fig. 6). The length of the measurement zone is about 50 mm, and the half diffusion angle of the probe is 4°. The longitudinal resolution can be calculated as follows:

$$L = 50mm \times \tan 4^{\circ} = 3.5\ mm \tag{7}$$

The distance between the two adjacent cylinders was set at 10 mm in the experiment, and the details are as shown in Fig. 6.

4. Analysis and results

Fig. 7 displays the echo amplitude received by the transducer under different concentrations (the change in the number of cylinders) with time, the reflected signal at zero concentration is shown here only to contrast with the reflected signal at other concentrations. The first small segment of each line is the transmitted signal and self-oscillation due to the probe material. After the self-oscillation, it is the needed sound waves backscattered by the cylinders. As can be seen from the figure, the backscattered echoes from cylinders look very similar for 5 %, 10 %, 15 % and 20 %, because Fig. 7 shows only the backscattered signals at different concentrations received in a single experiment. For each concentration, 200 experiments were conducted to reflect the influence of concentration on backscattering more accurately. Only after analyzing the results of 200 experiments can the overall situation reflect the difference between different concentrations.

In actual measurement, how to eliminate the influence of measurement system is a problem that cannot be ignored while analyzing data. Substitution method [28,30] could be a possibility to overcome this problem, and the corresponding experimental setup is shown in Fig. 8. The reflection signal $P_{reference}$ achieved by this arrangement is used as a reference (Fig. 9). In this way, the

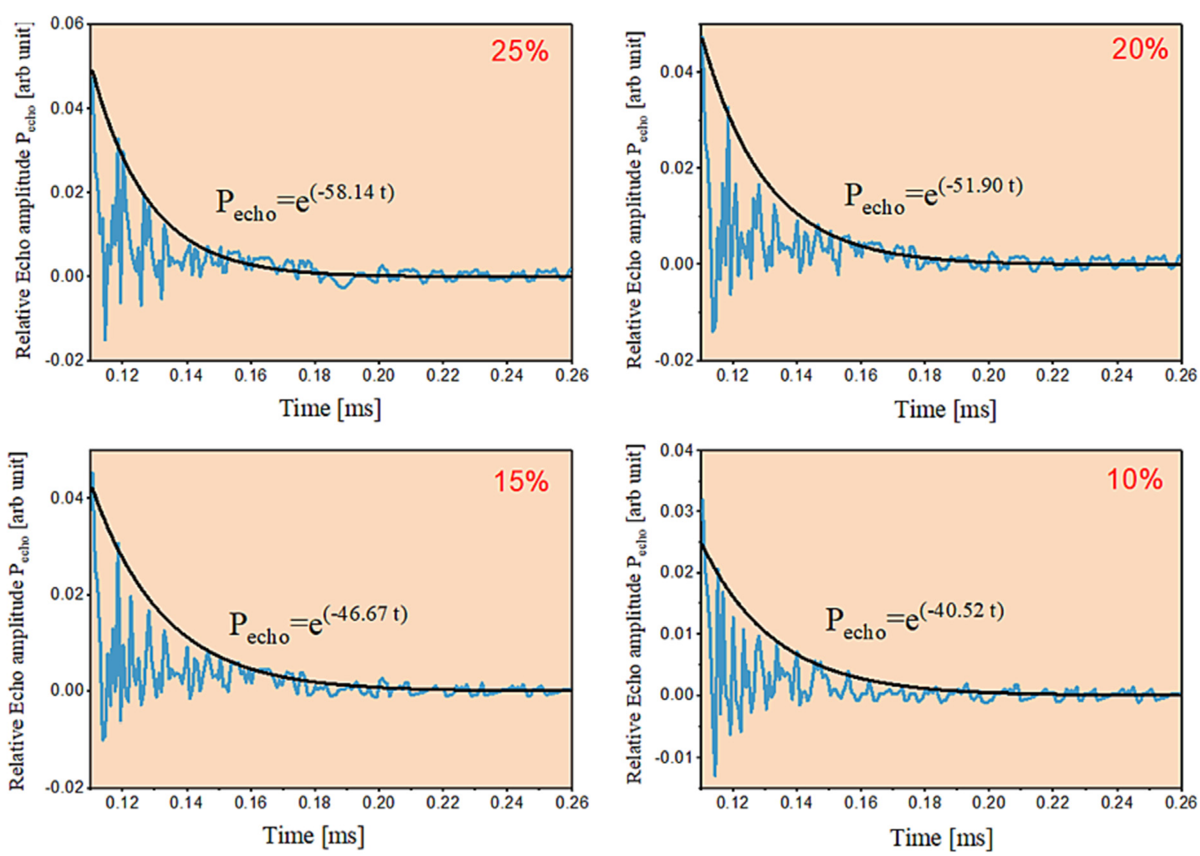

Fig. 11. Corresponding exponential interrelation at different concentration.

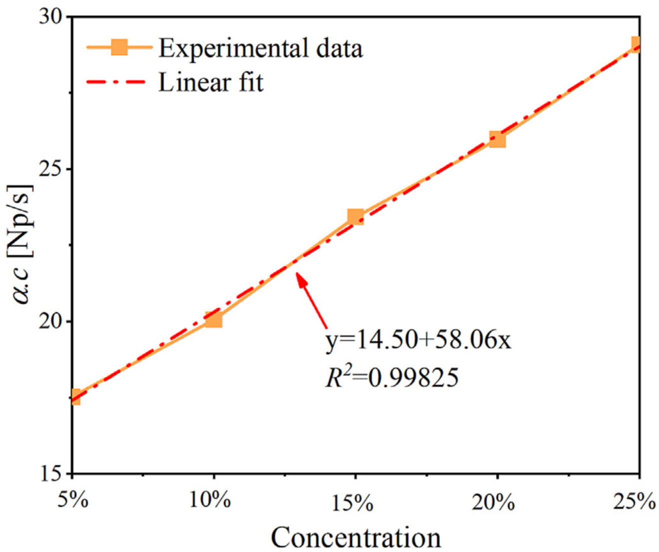

Fig. 12. Different αc changes with concentration.

dimensionless sound pressure, which eliminates the influence of field diffusion, misalignment and other factors, can be expressed as:

$$P_{echo} = \frac{P_{measure}}{P_{reference}} R \tag{8}$$

where P_{echo} is echo amplitude that eliminates the influence of field diffusion in arbitrary units, $P_{measure}$ refers to the reflection signal captured with backscattering measurement setup (Fig. 2), and R is the reflection coefficient at the front surface of the plane reflector. In this paper, the reflection coefficient of the acrylic plane reflector is 0.4, which is calculated based on the acoustic impedance (the product of density and the speed of sound) between the coupling agent and the acrylic plane reflector. Specifically, the acoustic impedance of the coupling agent oil between the probe and the acrylic plane reflector is 1.12MRay (the density is 800 kg/m^3, and the sound velocity is 1400 m/s), and the acoustic impedance of the acrylic reflector is 2.60MRay (the density and the sound velocity are as displayed in Table 2), and the reflection coefficient can be solved by the definition of reflection coefficient as 0.4 (Eq(9)).

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{2.60MRay - 1.12MRay}{2.60MRay + 1.12MRay} = 0.4 \tag{9}$$

Where Z_1 and Z_2 represent the acoustic impedance of the coupling agent oil and the acrylic plane reflector, respectively.

More than 200 tests with the position of fixed cylinders changed were performed for the same concentration, and the data were processed by self-editing procedures to ensure a representative of the whole collective. Finally, the relationship between the backscattering amplitude and time was obtained by the substitution method. Fig. 10 exhibits the processed experimental data when the concentration is 5 %. The enlarged part is the processed useful signals which reflect the flow information.

As displayed in Fig. 10, the echo amplitude and time meet an exponential interrelation, which conforms to the definition of attenuation coefficient. Similarly, the exponential interrelations at different concentration can be acquired consequently, and the results are demonstrated in Fig. 11. According to Equation (2) and (8), the following equation can be obtained:

$$P_{echo} = \exp^{-2\alpha ct} \tag{10}$$

Corresponding to the relation in Fig. 10, the product of attenuation coefficient and sound velocity is 35.04/2 = 17.52 [Np/s] when the concentration is 5 %, and the product can be worked out as 20.26 [Np/s], 23.335 [Np/s], 25.95 [Np/s], and 29.07 [Np/s] respectively, at the concentration of 10 %, 15 %, 20 % and 25 % (as exhibited in Fig. 12). The attenuation coefficient corresponding to different concentrations can then be estimated on the basis that

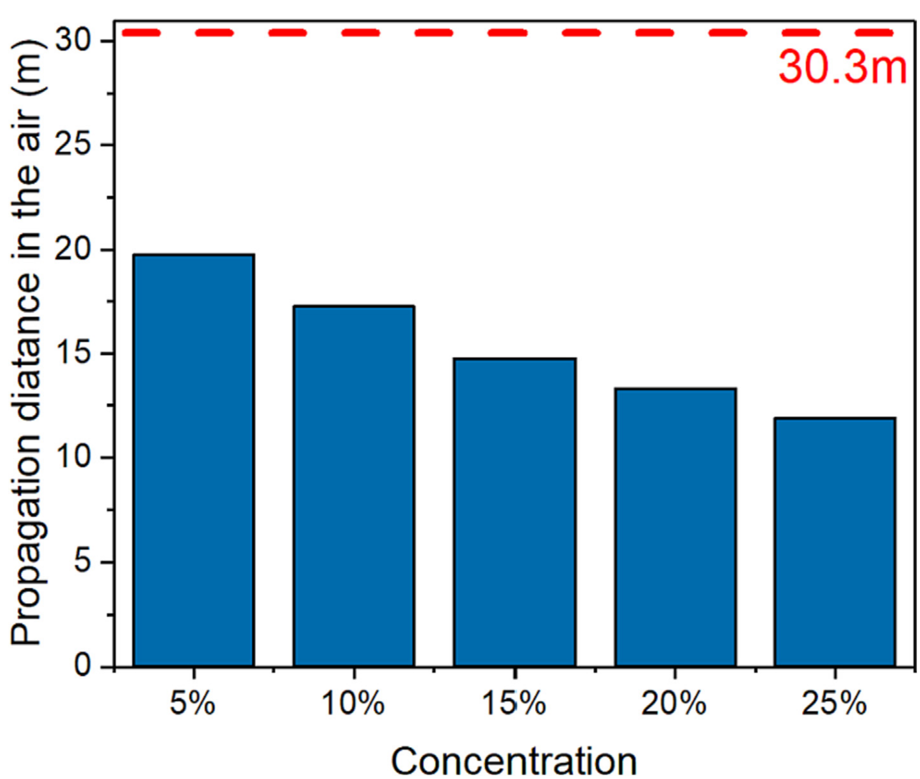

Fig. 13. Propagation distance of ultrasound in the air at different concentrations.

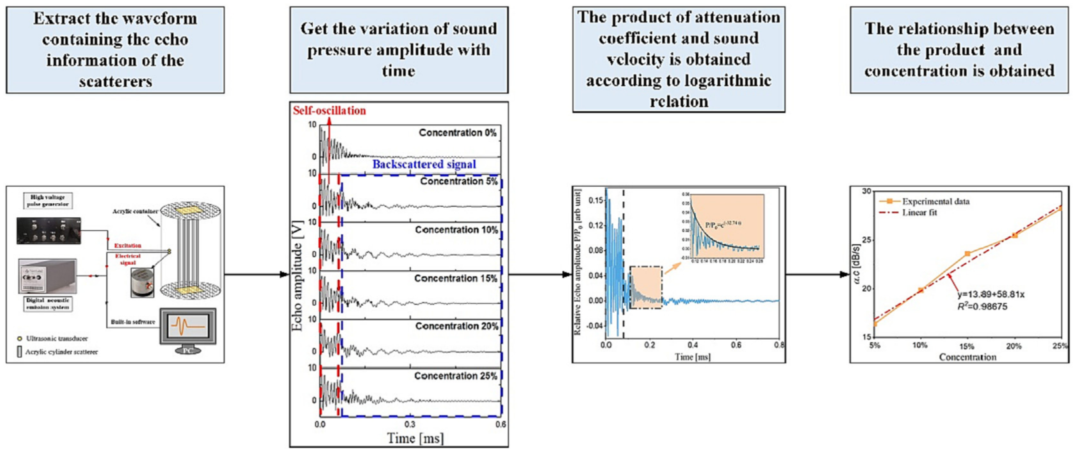

Fig. 14. The framework of this paper.

the sound speed in air is 346 m/s. Finally, the distance that the ultrasound wave goes through in the air with different cylinder concentrations when it decays to 1/e of its original intensity can be obtained, which is demonstrated in Fig. 13, and the results were compared with the soft value (30.3 m) in Table1. According to the results above, it can be found that the product of attenuation coefficient and sound velocity has a good linear relationship with concentration, thus the concentration information can be inversely deduced after the relation of P_{echo} is obtained from the echo signal in the actual experiment. The experimental results provide basis for the industrial measurement of gas–solid two phase flow.

Fig. 14 demonstrates the main ideas and experimental processes of this paper, which contributes to better understand the framework of this paper.

5. Conclusions

In this paper, fixed cylinders were selected as the solid phase instead of flowing particles to avoid uneven cylinder distribution, noise and vibration. The ultrasonic frequency and size of cylinders were selected as 50 kHz and 0.5 mm respectively to ensure effective backscattering intensity, and the changes of concentration (5 %–25 %) were simulated by the number of cylinders. Simultaneously, the simulation results indicated that the influence of complex scattering is very small under the experimental conditions. Finally, a semi-empirical formula is established by exploring the relationship between the product (attenuation coefficient and sound velocity) and the concentration of gas–solid two phase flow after the analysis of experimental data. In this way, the concentration information can be obtained quickly after obtaining the echo signal. Besides, the feasibility of ultrasonic backscattering method to measure gas–solid two phase flow is verified by experiments in this paper, which provides guidance for measuring gas–solid two phase flow in industrial occasions.

CRediT authorship contribution statement

Jinhui Fan: Conceptualization, Methodology, Writing – review & editing. **Fei Wang:** Supervision. **Haibin Cui:** Investigation. **Wenyuan Wang:** Resources.

Data availability

The data that has been used is confidential.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Fei Wang reports financial support was provided by National Natural Science Foundation of China. The remaining authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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