Review of ultrasonic measurement methods for two-phase flow

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Abstract

Two-phase flow is commonly used in many aspects of industrial production, such as the mixed transport of oil and gas in petroleum exploitation and the feeding of coal powder or coal water slurry to coal-fired boilers. In these situations, it is necessary to measure the two-phase flow in real time and then adjust various parameters in order to achieve high efficiency, energy-saving, and safe production. The ultrasonic method is widely used to measure two-phase flow because of its various measurement approaches, wide range of measurable parameters, insignificant effect on the flow field, and its capacity for continuous online measurement. In this review, the principles, characteristics, application scope, and research examples of different ultrasonic methods used in two-phase flow measurement are summarized, their advantages and disadvantages are compared, and the future development trends are forecast, which will play a positive role in the development of two-phase flow measurement.

Keywords: Two-phase flow, ultrasonic measurement

1. Introduction

Two-phase flow occurs widely across the petroleum, manufacturing, and chemical industries, and in the medical field. In production processes, changes in flow parameters (velocity, temperature, particle size, concentration, flow pattern discrimination, etc.) play an important role in efficiency, safety, and other aspects of these processes. Therefore, it is necessary to measure the flow parameters and adjust them in real time to achieve efficient, clean, and stable production. For example, for gas–solid two-phase flow, a common industrial process is the combustion of pulverized coal in power station boilers, for which real-time measurement of the particle size and concentration of the solid phase is important for improving combustion efficiency, preventing choking and other safety problems, and for reducing pollutant emissions and energy consumption.[1]

The origins of ultrasonic two-phase flow detection technology can be traced back to 1928, when the French Rotten[2] successfully developed the world's first ultrasonic flowmeter. In 1953, Epstein and Carhart[3] established a unified acoustic model of acoustic wave theory in a particle mixture medium. Later, Allegra and Hawley,[4] McClements,[5] and Urick and Ament,[6] as well as other scholars, developed acoustic models from different perspectives, which laid the foundation for the development of ultrasonic attenuation methods for particle measurement. In 1997, Riebel *et al.*[7] proposed the Bouguer–Lambert–Beer–Law (BLBL) model, which is at the basis of the Epstein–Carhart–Allegra–Hawley (ECAH) model, to describe the attenuation effect in dilute suspensions, which was useful for measuring suspended particles in fluids. In the same year, Xu *et al.*[8] proposed an ultrasonic computed tomography (CT) system for monitoring the transmission mode of bubbly gas–liquid two-phase flow with an image speed of 41.7 frames per second. In 2003, Kupnik *et al.*[9] simulated and analyzed the performance of the ultrasonic transit time method for measuring velocity information under conditions of high-temperature airflow. In 2008, Su *et al.*[10] characterized particle size using ultrasonic attenuation spectra. Wang *et al.*[11] at the University of Leeds, UK used the ultrasonic attenuation spectrum method to measure suspensions with particle sizes of approximately 40 nm, and installed a set of nanoparticle suspension-measuring devices in 2009. Reflection from the two-phase interface is usually used to reflect the properties of the two phases, and the reflection method is widely used to identify flow patterns and determine phase interfaces. Murai *et al.*[12] used this method in 2010 to monitor the interface between gas–liquid phases. Xue *et al.*[13] characterized the particle size and concentration of a highly concentrated slurry in the same year. The ultrasonic backscattering method has been widely used in medicine before, Weser *et al.*[14, 15] applied it to the measurement of concentration and particle size in liquid–solid two-phase flow and achieved good results in 2013. Poelma *et al.*[16] used ultrasonic imaging velocimetry to measure the instantaneous velocity field in a fully developed (single-phase) turbulent flow with a Reynolds number of 5300 and demonstrated the accuracy of the method. With the development of artificial intelligence, some researchers have combined machine learning with measurement methods to improve the efficiency and accuracy of measurements.[17] For example, in 2020, Zhang *et al.*[17] realized flow pattern identification of two-phase flow in a horizontal pipe with an accuracy of 93.1% based on liquid velocity information and a machine learning method.

To realize the measurement of two-phase flow, the most commonly used methods are the optical,[18-20] electrical,[21, 22] and differential pressure methods.[23] Each measurement method has its advantages, but most of them have problems of one kind or another, such as limited application scope and inconvenient operation. Ultrasound has the advantages of strong penetration, long wavelength, insensitivity to concentration, harmless to the human body, and capacity for online contact-free continuous measurement. For these and other reasons, it has been attracting ever greater attention, and is playing an increasingly significant role in the measurement of two-phase flow.[20]

At present, numerous methods are used to measure two-phase flow, which can be classified according to the different parameters to be measured (particle concentration, flow velocity or rate, gas holdup, bubble behavior, etc.). For example, the Doppler method[24] is often used to measure flow velocity and flow rate; the acoustic attenuation spectrum,[25, 26] sound velocity spectrum,[27] and backscattering methods[14] are all generally chosen for measuring particle concentration and radius; the echo reflection method,[28] however, has important applications in characterizing gas holdup and bubble behavior; and the non-contact ultrasonic imaging tomography process method[29] appears to be used more in the imaging process. In most cases, however, the acoustic method is either the passive method (acoustic emission method) or the active method, according to the nature of the signal source.

With the passive method, since there is no emission source, using only the ultrasound generated by experimental materials or the environment as the information to be analyzed, the method is easily affected by noise, and therefore its application scope is limited. The active method uses ultrasound sources and the changes in ultrasonic parameters (attenuation, velocity, frequency, and phase) of the signals between the sound source and receiver to characterize two-phase flow. When the ultrasonic signal travels forward in one phase and encounters another phase, due to the differences in density and acoustic properties between the two phases, reflection, transmission, and refraction occur at the phase interface. Different interaction mechanisms affect the choice of measurement method. For example, if the ultrasonic scattering and reflection between the dispersed phases are weak, the transmission method is a better choice. The mechanisms and schematic diagrams of the different phenomena are given below.

1. Reflection and refraction

The preconditions for reflection and refraction are: (a) the acoustic impedance of the medium differs at the interface; and (b) the linear degree of the interface is much larger than the wavelength of the sound wave and the diameter of the sound beam.

When sound waves travel from one medium to another, if the two media have different acoustic impedances, reflection and transmission phenomena occur on their interface. Part of the energy returns to the first medium (reflection), while another part of the energy passes through the interface, goes into the second medium, and continues to travel forward (refraction).[30, 31]

2. Scattering and diffraction

When propagating in a medium, if the linearity of the obstacle is close to the ultrasonic wave, the ultrasound can bypass the edge of the obstacle, and the reflected echo is very small; this phenomenon is called diffraction. When the diameter of the obstacle is much smaller than the wavelength of the ultrasonic wave, most of the wave continues to travel through the particle, and a small part of the ultrasonic energy is radiated in all directions by the particle, which is called scattering.[32, 33] Therefore, when the scales of the measured object and the ultrasonic wavelength are different quantitatively, the ultrasound and the measured object have different types of interactions, which play an important role in the selection of the optimum measurement method. A schematic diagram of the four phenomena described above is shown in Fig. 1:

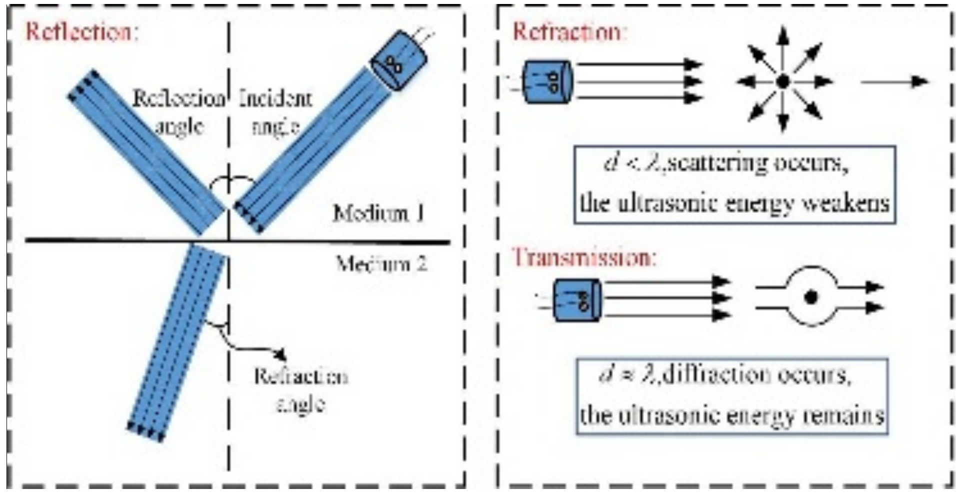

FIG. 1. Schematic diagrams of ultrasonic reflection, refraction, transmission, and diffraction.

The active method can be subdivided into the attenuation spectrum method, sound velocity spectroscopy, the process tomography method, the echo reflection method, the backscattering method, and the ultrasonic Doppler method. Except for the last two methods, the core of the former methods is that they reflect the properties of the continuous and dispersed phases by exploring the variation in the acoustic parameters (sound velocity, attenuation coefficient, etc.) of the received signal relative to the transmitted signal, which is similar to the extinction method and conforms to the Beer–Lambert law. The changes in acoustic parameters occur after the ultrasonic wave passes through the measured two-phase medium, and the degree of variation is related to the physical parameters of the two phases.[30] By establishing a theoretical model of the interaction between the acoustic parameters and the two phases, the analytical equations can be solved and information about the two phases, such as particle size and concentration, can be obtained by inversion. The difference between these methods is reflected in the different arrangement of the sensors. For the echo reflection method, the ultrasonic receiver and transmitter are aligned in the same direction or chosen to be a self-retractable transducer instead of a receiver and a transmitter, the basis for which is the reflection of ultrasound. In the attenuation spectrum method, the process tomography method, and the sound velocity spectrum, however, the receiver and transmitter are placed in a face-to-face arrangement, the basis for which is the transmission of ultrasound.

Unlike the above active methods, which are based on variations in the acoustic parameters, the backscattering method is based on the combined analysis of backscattering intensity and attenuation coefficient, in which the ultrasonic signal backscattered (scattering angle 180°) by the dispersed phase (such as coal particles, silt, etc.) is regarded as the received signal. The ultrasonic Doppler method, however, is based on the Doppler effect. Generally, it is used to measure the flow velocity and flow rate of a fluid. For the backscattering method and the ultrasonic Doppler method, the transmitting and receiving transducers are also arranged face to face. The difference is that the two transducers in the ultrasonic Doppler method are not placed strictly horizontally, but at particular angles. The transducer layout of the above measurement methods is shown in Fig. 2:

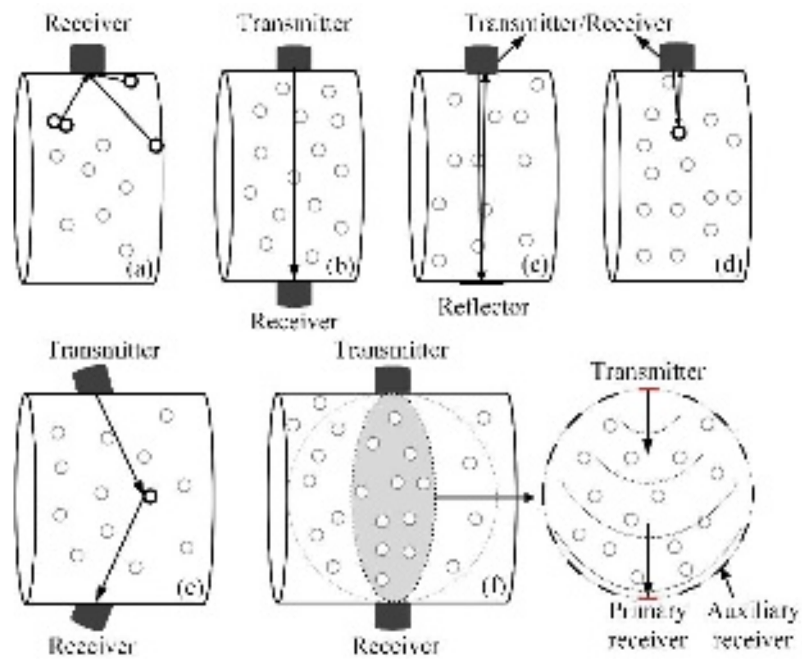

FIG. 2. Layout of ultrasonic transducers used in the different methods: (a) passive; (b) ultrasonic attenuation spectrum and velocity spectrum; (c) echo reflection; (d) backscattering; (e) ultrasonic Doppler; (f) ultrasonic process tomography.

In the measurement of two-phase flow, different methods are widely used in different industrial situations. The findings of recent studies on two-phase flow measurement using ultrasonic methods in industry are summarized in the Table I.

TABLE I. Recent studies of two-phase flow measurement in industry using ultrasonic methods.

	Measured parameters	**Two-phase**	**Technique**	**Features**
Lenz *et al.* [34]	Sound velocity in fluids (alcohol, water, and GaInSn)	Liquid–solid	Backscattering	Particles generate the strongest echo when located at the maximum point of the sound field

Wang *et al.* [26]	Irregularity and aggregation of particles in suspensions of alumina particles and olivine sand in air	Gas–solid	Ultrasonic attenuation spectrum	New fractal modification of scattering theory
Su *et al.* [10]	Sand sediment particle size characterization	Gas–solid	Ultrasonic attenuation spectrum	Broadband ultrasonic attenuation spectrum
Zou *et al.* [35]	Suspended sediment concentration underwater	Liquid–solid	Echo reflection	B-mode ultrasound imaging signals
Su *et al.* [27]	Particle sizing in oil/water emulsions	Liquid–liquid	Ultrasonic attenuation and velocity spectra	Information simultaneously from broadband ultrasonic attenuation and velocity spectra
Tsuji *et al.* [36]	Acoustical properties of methyl methacrylate and cross-linked dimethyl siloxane sheets having different cross-linker concentrations	Liquid–solid	Echo reflection	MERUS4 for solid plate
Dong *et al.* [37]	Particle size distribution of oil-in-water emulsions	Liquid–liquid	Backscattering	Dynamic ultrasound scattering
Elvira *et al.* [38]	Concentration measurement of yeast suspensions	Liquid–solid	Backscattering	Pulse-echo arrangement working at 50 MHz
Liang *et al.* [28]	Two-phase flow pattern identification in a pipe	Gas–liquid	Echo reflection	Trace of echoes reflected from the pipe's internal wall rather than the gas–liquid interface
Furlan *et al.* [39]	Local particle concentration in slurry flows	Liquid–solid	Backscattering	Concentration profiles in homogeneous and non-homogeneous slurry flows

Shen *et al.* [40]	Gas–water two-phase flow pattern recognition	Gas–liquid	Ultrasound Doppler	Electrical resistance tomography sensor measures phase fraction and continuous wave ultrasound Doppler sensor measures velocity of two-phase flow
Mathieu *et al.* [41]	Liquid density	Liquid–solid	Backscattering	Classic resonant scattering theory is used

In general, the selection of measurement methods is based first on the final objective requirements and then considers:

1. The quantitative relationship between ultrasonic wavelength and the size of the measured object.
2. The interaction between ultrasound and the measured particles.
3. The nature of the measured flow and the factors affecting it.
4. Environmental constraints.
5. Installation factors.

Previous reviews of ultrasonic measurement are mostly limited to medical aspects, such as the utility of ultrasound for measuring the degree of lesion in atherosclerosis,[42] the development of high-intensity focused ultrasound surgery,[43] the measurement of bone density,[44] the applications of the ultrasound Doppler effect to study blood flow information,[45] and three-dimensional information about arterial geometry and tissue movement.[46] There are fewer reviews of the application of ultrasonic measurement in industry, and they cover mainly the development and changeover of high-power ultrasound from cleaning to sonochemical cutting and water treatment,[47] the applications of ultrasound for measuring the quality and fat content of animal muscle,[48] and the elasticity of biological tissues.[49] Reviews of ultrasonic two-phase flow measurements are still rare; thus, the purpose of this article is to review the principles, methods, devices, and the various ultrasonic methods used in the measurement of two-phase flow and to discuss the advantages and disadvantages of the various methods. Finally, the limitations and challenges of ultrasonic methods in measuring two-phase flow are discussed, and future development trends are predicted.

2. Ultrasonic transducer

In order to measure two-phase flow using ultrasonic methods, ultrasonic transducers are essential devices because the transducer is the instrument that produces ultrasonic waves and transducers of various types and frequencies are needed for different experimental conditions of two-phase flow. For example, for two-phase flow with air as the continuous phase, an air-coupled transducer with a low frequency must be selected; for particle suspensions of micron particle size, however, underwater acoustic transducers operating at megahertz frequencies are needed; thus, it is necessary to discuss here the various transducers available. According to the different classification standards, ultrasonic transducers can be classified as follows:

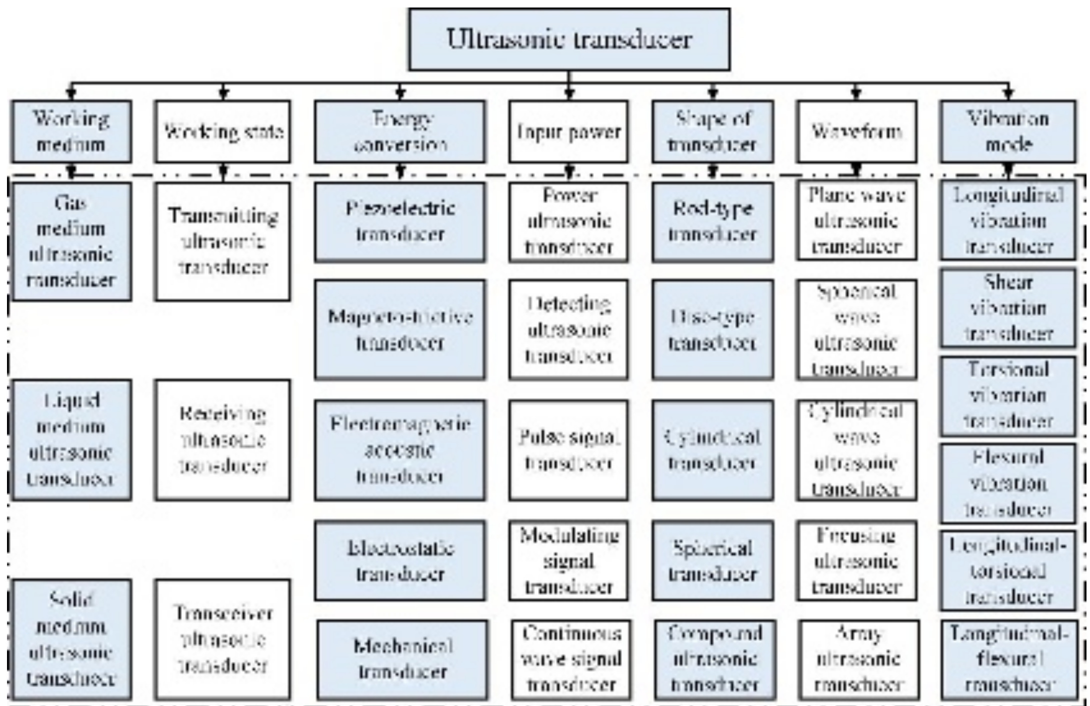

FIG. 3. Classification of ultrasonic transducers.

Among all of the above types of transducers, piezoelectric transducers are the most widely used in two-phase flow. The principle on which they operate is the piezoelectric effect, which can be divided into positive and negative piezoelectric effects. Piezoelectric transducers are manufactured based mostly on the positive piezoelectric effect, which means that when a dielectric is deformed by external forces in a certain direction, an internal polarization phenomenon occurs and positive and negative charges appear on its two relative surfaces. When the external force is removed, the dielectric returns to its uncharged state and, as the direction of the force changes, so does the polarity of the charge.

The piezoelectric transducer is composed mainly of a shell, a matching layer, piezoelectric materials, and a backing material. Different structures affect the different use characteristics of transducers. In practical applications, the type of transducers should be selected according to the specific experimental conditions.

3. Measurement methods

The principles, schemes, and typical applications of different measurement methods are introduced in this section, and the applicable scope, advantages, and disadvantages of each method are analyzed objectively.

3.1 Passive method

For the passive method of ultrasonic measurement, there is no ultrasound source. The basic principle of the passive method is that, in the experimental environment, the object to be measured can generate ultrasonic signals spontaneously or passively, and then the ultrasonic signal is used to analyze the related properties of the object. For example, for compressed gas transport, because of the large pressure difference between the inside and outside of the pressurized system, the gas inside the system rushes out from the gap. As shown in Fig. 4, the airflow rushing out quickly forms a turbulent eddy near the small hole, which produces sound waves whose frequency is related to the size of the hole. Since ultrasonic waves are mechanical waves, they can continue to travel forward in the air and then be received by the receiving transducer.

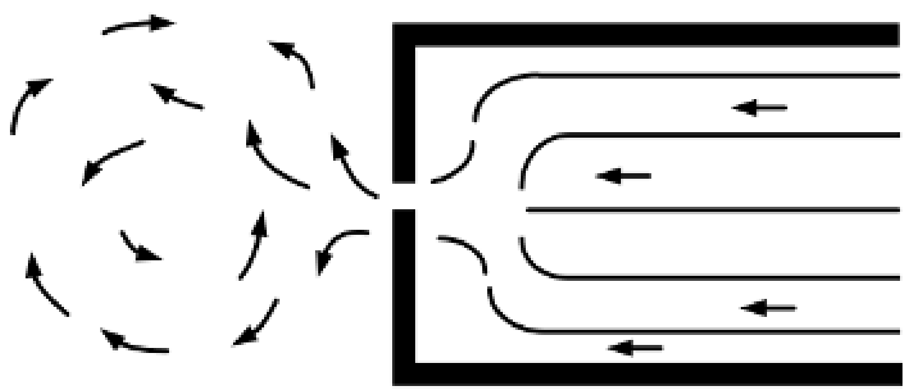

FIG. 4. Ultrasonic signals generated by gas leakage.

In the process of transporting pulverized coal, collision and friction between the dispersed phase and the tube wall or between the phases can occur, forming the ultrasonic signal. Figure 5 is a schematic diagram of the measurement of pulverized coal concentration in a coal pipeline by Shi *et al.* using the passive method.[50] The intensity and frequency of the resulting signal are related to the concentration of the dispersed phase, which can be obtained by signal processing and inverse problem calculation utilizing spectrum analysis.

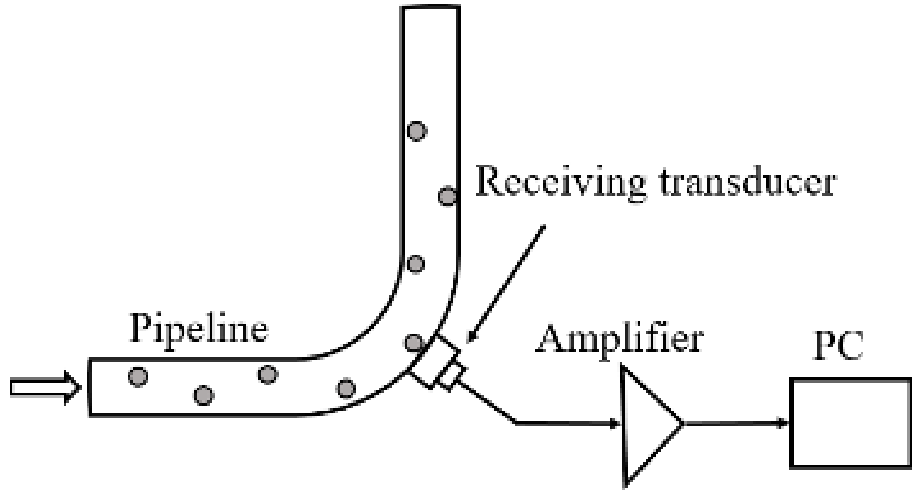

FIG. 5. Principle of an ultrasonic passive method measuring device.

Another important application of the acoustic emission method in two-phase flow is the recognition of the flow pattern in gas–liquid two-phase flow. The principle governing its operation is that gas–liquid two-phase flow in the pipeline produces noise, the intensity of which is related to the velocity of the gas–liquid phase. With an increase in the gas and liquid flow velocities, the entrainment force between the two phases of the gas and liquid flow increases, causing the flow velocity of the gas phase to increase, while that of the liquid phase decreases, thus changing the intensity of the flow noise signal. When the flow patterns are different, the acoustic emission data time-domain signals collected by the experiment are also different. By analyzing and summarizing the signals, the characteristic parameters can be extracted in order to characterize the convection patterns.[51] For example, Fang *et al.*[52] proposed extracting the wavelet energy from the acoustic emission signals in order to determine the average value of the wavelet coefficient energy, then extracting the characteristic parameters from the time-domain signals, and taking the (Euclidean) distance between the characteristic vector (Shannon entropy) composed of several characteristic parameters and the reference vectors as the parameter of flow pattern identification. Euclidean distance is a form of pattern recognition; the shortest Euclidean distance under the same flow pattern can accurately identify four typical flow patterns in vertical pipelines.

The passive method is simple in structure and can realize non-contact continuous online measurement. However, it is complex to process the signals and extract effective signals or characteristic parameters.[50] In general, the acoustic emission method still has some limitations for two-phase flow measurement, and its application is not as widespread as in the fields of material testing and metal processing and there is still much scope for its development.

3.2 Active methods

3.2.1 Attenuation spectrometry

The attenuation spectrum method is based on transmission, which means that transmitting and receiving transducers are placed in opposing directions, one for transmitting and the other for receiving. The attenuation coefficient is obtained by comparing the amplitude difference between the transmitted and received signals, and the phase information is obtained by data inversion and other operations.

3.2.1.1 Principles of ultrasonic attenuation spectrometry

An ultrasonic attenuation spectrum is used to measure particle concentration and particle size. The theory of measuring particle size and concentration can be summarized as: based on the model of the selected attenuation theory, the physical parameters of the continuous phase and the particles and the preset particle size distribution and concentration, one can obtain the acoustic attenuation spectrum theoretically. As regards data inversion, this step usually involves obtaining a relational matrix reflecting the corresponding relationships between particle parameters and the acoustic attenuation spectrum, which is the model of the matrix or the coefficient matrix.[25] Therefore, when the acoustic attenuation coefficients are obtained by experiment, the actual particle size distribution and the concentration can be obtained by data inversion combined with the model matrix. Figure 6 is a schematic diagram of the ultrasonic attenuation spectrum method.

The theory outlined above relates mainly to the following two problems:

1. How to explain the interaction between ultrasound and particles in the propagation process and its resulting effect on sound attenuation according to an appropriate theoretical model, especially how to explore the important role of particle size, concentration, and other characteristics in this process. One can call this a positive problem.

2. How to combine the actual measured acoustic attenuation with the established theoretical model matrix to obtain the most accurate particle size and concentration distribution (closest to the real situation). One can call this an inverse problem.

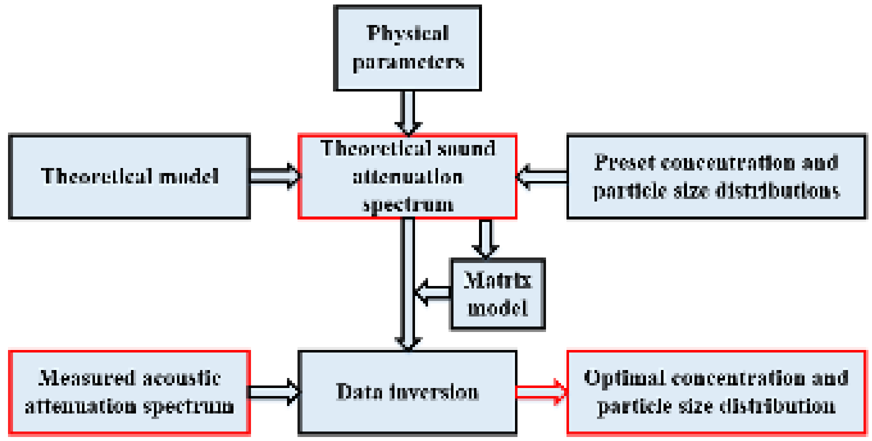

FIG. 6. Schematic diagram of the ultrasonic attenuation spectrum method.

Next, three aspects of the theoretical basis are introduced in order to solve the problem:

1. *Attenuation coefficient*

Generally, the positive problem involves mainly the selection of the attenuation model. The definition of acoustic attenuation comes from the fact that the sound wave interacts with the medium while propagating, causing the intensity of the sound wave to decrease with increasing distance. This phenomenon is called sound attenuation, which is characterized by the sound attenuation coefficient α.[53] For a plane wave propagating along a direction, the change in sound pressure P with the propagation distance x can be characterized by the sound attenuation coefficient:[4]

$$P = P_0 e^{-\alpha} . \tag{1}$$

2. *Acoustic model*

In the process of analyzing practical problems, only one or two attenuation mechanisms are dominant; other mechanisms are deemed negligible. Therefore, when the physical model is established, one can selectively ignore unimportant mechanisms according to the level of the different attenuation mechanisms, which can help to simplify the physical model and improve the computational efficiency.[3, 4, 54] Commonly used acoustic models include the ECAH model,[55] the McClements model,[56] the coupling phase models[57] (Urick and Ament model, Harker and Temple model, etc.), the expanded coupled phase model,[53] the BLBL model,[58] and the multiple scattering model.[59] Various models have different mechanisms at their core, which in general provide the basis characterizing two-phase flow with volume fractions in the range 1–50% and particle sizes from 10 nm to 1 mm. Table II describes the main attenuation mechanisms corresponding to different models and gives their applicable scope, advantages, and disadvantages.

TABLE II. Attenuation models and their features.

Model	Features
ECAH	The most basic model for two-phase flow detection, considering all attenuation mechanisms comprehensively. However, it requires a comprehensive understanding of two-phase physical parameters, so its calculation is complicated and it has a low applicable concentration range
McClements	The scattering loss is ignored; it can be seen as a simplified ECAH model in the long-wavelength region
Coupled phase	Viscous loss is the main attenuation mechanism, and discrete phase and continuous phase are used to replace particles and fluids; that is, the concept of scattering is ignored. It is suitable for systems with a large difference in concentration between the two phases
Extended coupled phase	In addition to viscous attenuation, the interaction between particles is also considered, which is suitable for polydisperse systems, while the coupled phase model is only suitable for monodisperse systems
BLBL	The scattering loss is described mainly by the Beer–Lambert law in optics
Complex scattering	In highly concentrated systems, the scattering energies of scatterers incident to other scatterers are considered

When the attenuation model is selected according to the two phases and their properties, the quantitative relationship between the attenuation coefficient and the particle size, concentration, and other characteristics (called particle properties here) can be explored, namely, the attenuation spectrum, and then the positive problem can be solved.

3. Error function

For the inverse problem, its central idea is to compare the attenuation spectra obtained from experiments with that obtained from theory; the difference between them is defined as the error function. The smaller the error function, the more consistent the actual particle properties are with those hypothesized. Therefore, the particle properties with the smallest error function can be obtained by calculation, which is the process of obtaining particle size, concentration, and other characteristics by an inversion algorithm. The error function is given in the form of the root mean square error (RMSE):

$$E_{\mathrm{RMSE}} = \sqrt{\left[\sum_{j=1}^{N}\left(\alpha_{\mathrm{sim}} - \alpha_{\mathrm{meas}}\right)^2\right] / N}\,, \tag{2}$$

where α_{meas} denotes the sound attenuation spectrum obtained in the actual measurement, and α_{sim} denotes the sound attenuation predicted (simulated) spectrum. The particle properties are uniquely determined by a process that minimizes errors. In the ultrasonic method, the most typical method used is the standard optimization algorithm based on that described by Marquardt.[60] Various mathematical software packages have provided the standard invocation of this method, which will not be repeated here.

3.2.1.2 Applications of ultrasonic attenuation spectrometry

Ultrasonic attenuation spectrometry is widely used to measure two-phase flow in industry, where it is embodied mainly in nanomaterials, food products, highly concentrated dispersed systems, marine water conservation, and other areas.[61] The results of relevant studies are listed in Table III.

TABLE III. Applications of ultrasonic attenuation methods in different industrial fields.

Field	Reference	Research
Nanomaterials	Boonkhao *et al.*[62]	The characterizations of nanoparticle suspensions using ultrasonic spectroscopy and process tomography were compared
	Liu *et al.*[63]	To characterize the particle sizes of highly concentrated nanoparticle suspensions, the effects of concentration and frequency on the results were analyzed
Food	Strybulevych *et al.*[64] and Pierre *et al.*[65]	The formation and development of bubbles in food were monitored, and the sizes of bubbles were measured in real time (>30 s)
	Awad *et al.*[66]	Applications of ultrasonic technology in food analysis, treatment, and quality control
Suspension dispersion systems	Wrobel *et al.*[67]	The ultrasonic attenuation spectrum method has been successfully applied to the online measurement of highly concentrated liquid–solid suspensions and nonuniform composite materials

	Ding *et al.*[68]	Ultrasonic attenuation measurement has been used to analyze the particle sizes of Venezuelan heavy oil in a water-dispersed system, in which the average particle size was approximately 100 mm and 80% of the particle sizes were in the range 60–178 mm
Marine water conservation	Kann *et al.*[69]	The sound characteristics and size characterization of bubbles were studied, and the theoretical value of the sound velocity was found to be qualitatively consistent with the experimental value
Industrial applications	Gielen *et al.*[70]	Monitoring the crystal precipitation process
	Phillips *et al.*[71]	Identification of various gas-phase components and proving its feasibility in nitrogen–methane–water and hydrogen–oxygen–water mixtures
	Wang *et al.*[26]	Studies of aerosols composed of non-spherical particles (e.g., glass beads, olivine, silica powder)

In addition to the above, the most important application of the ultrasonic attenuation spectrum in two-phase flow is the measurement of particle concentration and size. Hou *et al.*[72] explored the particle size distribution of nanoscale titanium dioxide suspensions (ultrasonic frequency: 25 MHz) with an attenuation superposition model composed of the McClements model and the BLBL model. The experimental results showed that this method is applicable only to a suspension with a volume fraction of less than 1% because nanoscale particles gather together very easily, leading to inaccuracies in the measured results. Gu *et al.*[73] applied the complex scattering model to explore the attenuation coefficient of air-pulverized coal in two-phase flow with superimposed ultrasonic waves with frequencies of 40 and 200 kHz. The results showed that the average deviation of the ultrasonic and microscope methods was approximately 15%. With absorption and attenuation as the main mechanisms, Su *et al.*[10] used the Harker and Temple model to explore the particle size distribution of a water suspension of glass beads. The coupled phase was also selected as an attenuation model to explore the influence of the size distribution of oil droplets on the attenuation coefficient.[27] The main experimental instruments involved in using the attenuation spectrum method, as well as their arrangement, are illustrated in Fig. 7.

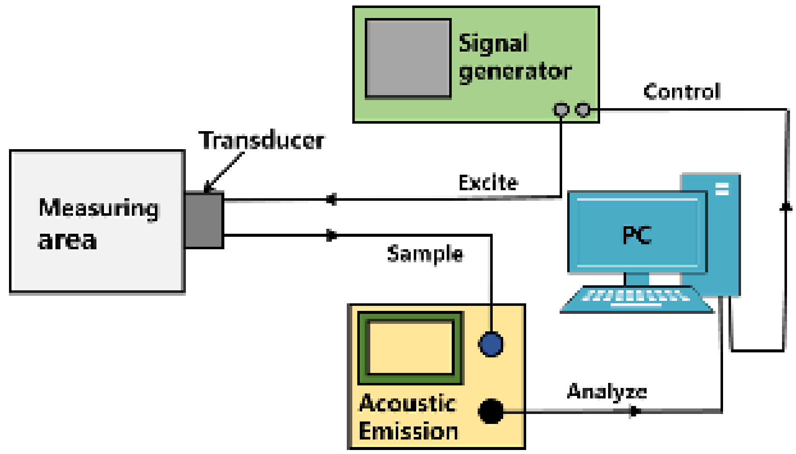

FIG. 7. Ultrasonic attenuation measurement system.

Ultrasonic attenuation spectroscopy has been well developed, and many commercial products using the technology have been produced, such as the ultrasonic inline particle sizing system named Opus manufactured by the German company Sympatec GmbH (www.sympatec.com), in which a pitch-catch arrangement of transducers is mounted within a cylindrical probe that can be fitted via a flange to a process pipe or reaction vessel. Dispersion Technology Inc. (USA) (dispersion.com) market systems that measure ultrasonic attenuation over frequency ranges which extend to 100 MHz, and the gauge length is variable in order to plot ultrasonic loss versus propagation distance.[25] Generally, this system can be used to measure samples whose particle sizes range from 10 nm to 3 mm and whose volume concentrations range from 0.01% to 70% without any dilution and other processing. Acid–alkali systems, such as corrosive slurry suspensions, emulsions, and high concentrations of particles in solution, can also be measured. The system is suitable for applications in the chemical, pharmaceutical, synthesis, food, and many other industries.

3.2.1.3 Features of ultrasonic attenuation spectrometry

The acoustic attenuation spectrum method has the advantages of a wide measurement range of particle concentration, no-contact measurement, pollution prevention, and many others, but in the process of accessing spectral information (such as the attenuation spectrum), it is necessary to have a more comprehensive understanding of the continuous and dispersed phases to be measured (density, compression wave velocity, shear granularity, shear modulus, coefficient of thermal conductivity, and other parameters). In industry, only a small number of substances, such as water, iron, and aluminum, are well understood at present, and most other substances are difficult or even impossible to measure. Therefore, the applications of the ultrasonic attenuation spectrum have many limitations, which cannot be solved at present.

3.2.2 Sound velocity spectrum method

Similar to the attenuation spectrum method, the sound velocity spectrum is often used to reflect changes in the size and concentration of the dispersed phase because the attenuation coefficient and the sound velocity both change with the physical properties of the two phases.[74] The principle of application of the method in two-phase flow measurement is consistent with the attenuation method, except that the acoustic parameter changes from the attenuation coefficient to the sound velocity. However, the attenuation coefficient changes more obviously with the physical properties, which can be seen from Fig. 8. With the change in ultrasonic frequency and particle concentration, the attenuation coefficient changes much more dramatically, while the change in sound velocity is not obvious, so the attenuation spectrum is generally chosen instead of the sound velocity spectrum. In some cases, the method of superposition of the two is also chosen. For example, Su *et al.*[27] used the superposition method of the attenuation and velocity spectra to distinguish the size information of two-phase fat emulsion droplets with a concentration below 20%.

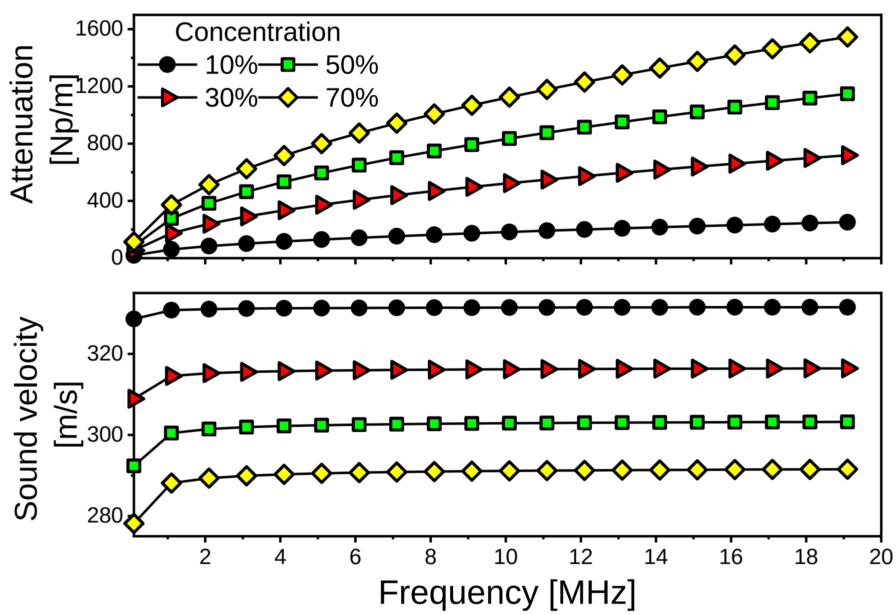

FIG. 8. Dependence of attenuation coefficient and sound velocity on frequency.

3.2.3 Echo reflection method

3.2.3.1 Principles of the echo reflection method

The echo reflection method uses ultrasonic signals reflected by the interface in the experimental environment (between the pipe and the fluid or two fluids) or the artificially placed reflector as the source of received signals. By analyzing the differences in amplitude or time domain between the received reflected signals and the initial signals, relevant information about the fluid and the dispersed phase can be obtained.

3.2.3.2 Applications of the echo reflection method

The echo reflection method is widely used in gas–liquid and liquid–solid two-phase media to identify flow patterns in gas–liquid two-phase flow, to determine liquid film thickness in gas–liquid stratified flow, and to dynamically monitor gas–liquid interfaces.[28, 34, 75-77] The gas–liquid interface or that between the phase and the container wall is usually regarded as the reflector. The artificial container wall or the plane with high reflectivity is chosen as the reflector, however, when used for determining the liquid concentration and sound velocity of the fluid in a liquid–solid two-phase medium.

1. Flow pattern recognition

Liang *et al.*[28] used the pipe wall as the reflector to determine the flow pattern of gas–liquid two-phase flow using two ultrasonic transducers with a frequency of 5 MHz installed at the top and bottom of the pipe to transmit and receive the ultrasonic signals, respectively. Due to the difference in acoustic impedance of the gas and the liquid, the ultrasonic reflection coefficient of the wall–gas interface was greater than that of the wall–liquid interface, so the echo attenuation ratio could be used to identify stratified, annular, and slug flow effectively.

Liang *et al.*'s instrumental layout is as shown in Fig. 9, in which an ultrasonic echo receiver was used to stimulate the transducer to transmit ultrasonic waves and receive echo signals, and the pulse repetition frequency was switched to 500 Hz. The received pulse-echo signals were displayed on an oscilloscope and then recorded on a computer at a sampling rate of 1 Giga samples per second. The ultrasonic reflection amplitude from the wall–gas and wall–liquid interfaces are shown in Fig. 10. It can be seen that P_1 is the original pulse in both figures, so the amplitudes are equal, and P_2 represents the first echo from the two kinds of interfaces (wall–gas and wall–liquid) in the two figures. The flow pattern can be determined by obtaining the value of the ratio P_2/P_1. In this paper, they give the range of amplitude ratios for the two amplitudes with different flow patterns (as shown in Fig. 11). Thus, the amplitude ratio between the measured echo and the original waveform in the actual industrial field can be used to determine the flow patterns in the pipeline.

With the development of artificial intelligence, some researchers have introduced the method of machine learning into two-phase flow measurement. Zhang *et al.* realized flow pattern identification with an accuracy of 93.1% based on the convolutional neural network.[17]

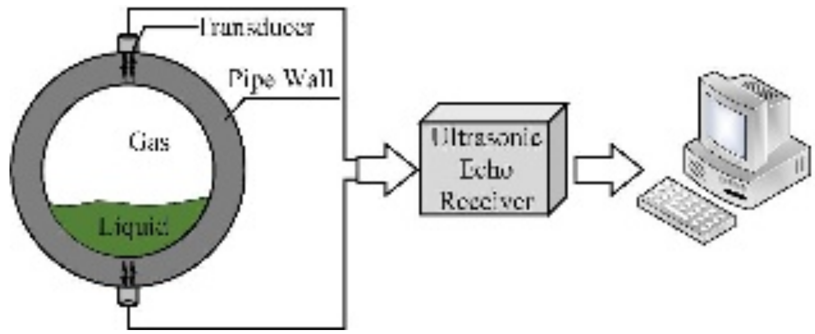

FIG. 9. Schematic diagram of the pulse-echo measurement system.

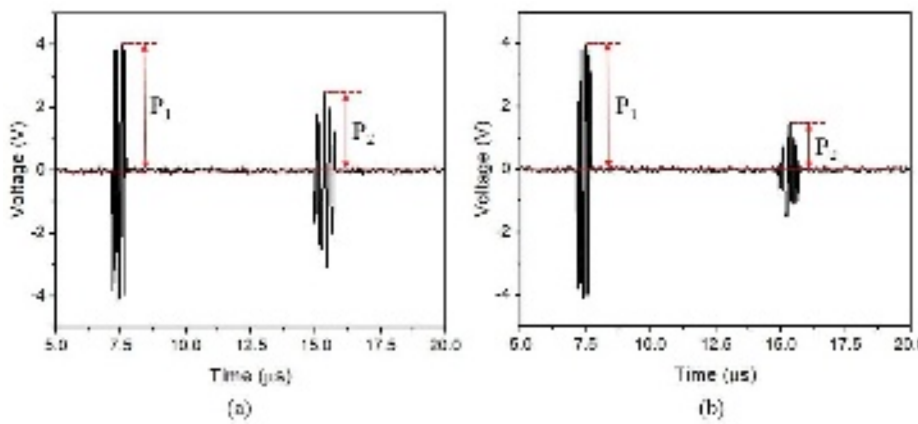

FIG. 10. Ultrasonic reflection amplitude from two different interfaces: (a) wall–gas; (b) wall–liquid.

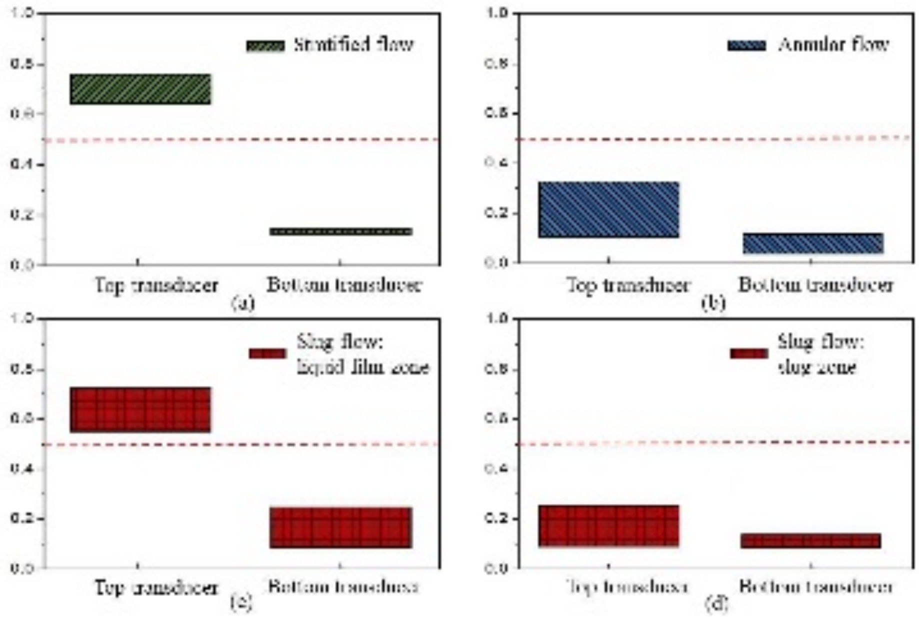

FIG. 11. Attenuation ratio of echoes in different kinds of flow: (a) stratified flow; (b) annular flow; (c) slug flow (liquid film zone); (d) slug flow (slug zone).

2. *Liquid density measurement*

Mathieu *et al.*[41] also proposed a scheme for measuring liquid density using the echo reflection method. In their experiment, approximately 25 cm lengths of nylon and copper wire (0.29 ± 0.03 mm diameter) were placed in the solution to be measured and the reference liquid, respectively, to act as reflectors (Fig. 12). For each measurement, the wires were placed at the same position in the far-field relative to the transducer. Using the preset distance of the transducer from the nylon or copper wire, divided by half the time difference between the two echoes, the propagation velocity of sound in the liquid was obtained. Previously, the reference liquid was determined in order to calculate the relationship between the sound velocity and the density as the sound velocity spectrum. In this way, the density of the liquid can be obtained by fitting the calculated sound velocity to the theoretical sound velocity spectrum.

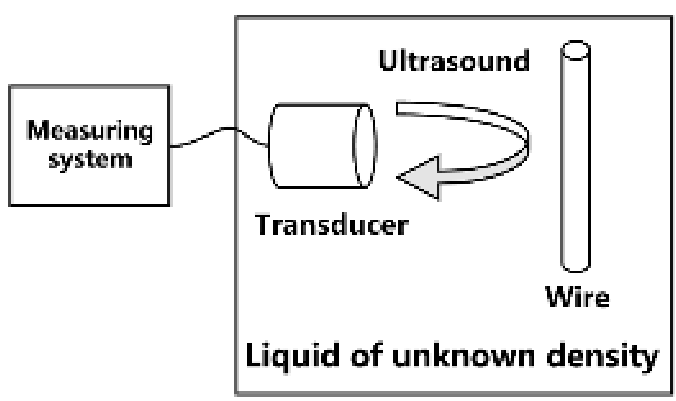

FIG. 12. Experimental diagram for measuring liquid density.

3. Simultaneous measurement of multiple parameters

Figure 13 is a schematic representation of the ultrasonic attenuation, phase velocity, thickness, and density of a polymer sheet measured simultaneously by echo reflection.[36] The general principle of the echo reflection method is that some of the sound waves are reflected when they pass through the interface of a two-phase medium with a difference in impedance, while the rest travel forward. In this experiment, the difference in acoustic resistance between the selected gas–solid phases was not very significant, so that the reflection and transmission amplitudes of the sound at the gas–solid interface were close to each other. As can be seen from Fig. 13, multiple reflections and transmission occur after the ultrasonic wave encounters the solid plate in the process of propagation, and the first two reflection and transmission signals are selected for analysis. In addition, a comparative experiment is carried out to obtain the transmitted signals when the ultrasonic wave only propagates in air. By comparing and analyzing these five signals, the relevant property of the solid plate can be obtained. For example, the sound velocity in the solid plate can be obtained by comparing the arrival time of the two reflected signals, and the attenuation coefficient of the solid plate can be calculated by comparing the first transmission signal with the transmission signal in the comparative experiment.

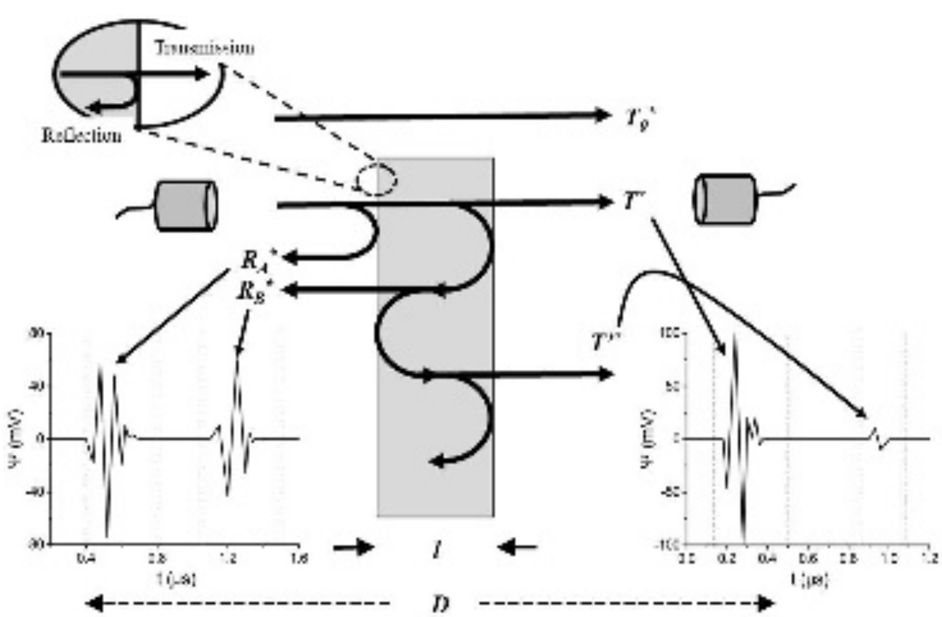

FIG. 13. Schematic diagram of the ultrasonic attenuation, phase velocity, thickness, and density of a polymer sheet measured simultaneously by echo reflection. Reproduced with permission from Ultrasonics. 99 (2019). Copyright 2019 Elsevier.

3.2.3.3 Features of the echo reflection method

Under laboratory conditions, the echo reflection method can be used for flow pattern recognition, liquid concentration measurement, and other aspects. However, under actual industrial conditions, it is difficult to determine the reflection coefficient of pipeline material after a long period of corrosion, which has a great impact on the accuracy of measurement. Also, since the transmitting and receiving transducers are aligned in the same direction, the ultrasound has to travel the sound path twice (back and forth) before it is received in the same condition. Due to the large sizes of pipelines in industrial environments, this will also affect the accuracy of measurement to some extent.

3.2.4 Backscattering method

3.2.4.1 Principles of the backscattering method

Acoustic scattering refers to the phenomenon in which part of the sound wave deviates from the original propagation path and spreads out when it encounters an obstacle. When the sound wave is incident on the obstacle, the obstacle becomes a secondary sound source and radiates part of the incident energy as scattered energy around it. The part of the sound wave that is scattered around the obstacle is called the scattered sound wave.[78] According to Mie scattering theory, when ultrasound is incident on isotropic particles, it scatters in all directions. Depending on the scattering angle, the scattered wave can be divided into forward scattered, backward scattered, and lateral scattered waves. Backward scattering (backscattering) occurs when the scattering angle is between 90° and 180°. In this situation, forward scattering is very weak, so that more accurate results can be obtained by placing the sensor in the backward direction.[79]

3.2.4.2 Applications of the backscattering method

The ultrasonic backscattering method has very important applications in medicine, such as in monitoring blood cells, blood mass, and bone density. It uses mainly ultrasonic reflections from different tissues in the body as the signal source to be analyzed.[80-83] Its main applications in industry are in liquid–solid two-phase flow for solid-phase concentration measurements.[84-86] Several studies have shown that the ultrasonic method can even be used for characterizing yeast solutions with diameters of 7 μm and concentrations in the range 10^2–10^7 cells/mL (ultrasonic frequency: 50 MHz).[38] Weser *et al.*[14, 15] used the backscattering method to measure glass beads dispersed in water and showed that there was good agreement with the theory when the dimensionless wavenumber was $0.1 < ka < 1$, even for volume concentrations as high as 30%. Furlan *et al.*[39] characterized the particle concentrations of soda-lime glass particles (195 μm diameter) in a water slurry using backscatter spectroscopy.

In this review, we have chosen to analyze Weser *et al.*'s experimental setup as a typical case, whose purpose is to determine the concentration of glass beads dispersed in water. The theoretical basis is that the signal backscattered from the particles contains the acoustic information of the dispersed phase; thus, acoustic information about the particles can be analyzed according to the ultrasound backscattered from those particles.

Weser *et al.*'s experimental arrangement is shown in Fig. 14. The pulse emitter is used to excite the transducer to transmit ultrasonic waves, whose duration is determined by the transducer's bandwidth. After the ultrasonic wave passes through the delay line and the sound window, it enters the measuring area, which is full of particles, and the ultrasonic wave is scattered by the particles and received by the transducer. The scattered ultrasonic waves thus received are amplified and registered by a digital oscilloscope, which collects the data and uploads them to the computer. In this experimental setup, the delay line and acoustic window are used to prevent particles from abrading the transducer. In addition, they also ensure that the distance between the scattering region and the transducer is large enough to avoid the near-field region of the transducer. Because of the interference of sound waves, the recorded signal appears as a series of sound pressure maxima and minima in the near-field zone, which affect the physical quantities to be detected. For example, the smaller particles at a sound pressure maximum may have the same scattering amplitude as the larger particles, which are located at a sound pressure minimum, thus affecting the measured results.

The ultrasonic frequencies selected in this experiment were 6, 10, and 14 MHz. The time-dependent attenuation extracted from the backscattering measurements of different particle fractions was compared with the sound attenuation measured by the ultrasonic attenuation spectrometer DT1200 (Dispersion Technology Inc.). The two were found to be well correlated, which means that the parameters equivalent to the attenuation coefficient can be obtained from the measurement results so that the concentration information can be obtained from the iteration of the backscattering spectrum.

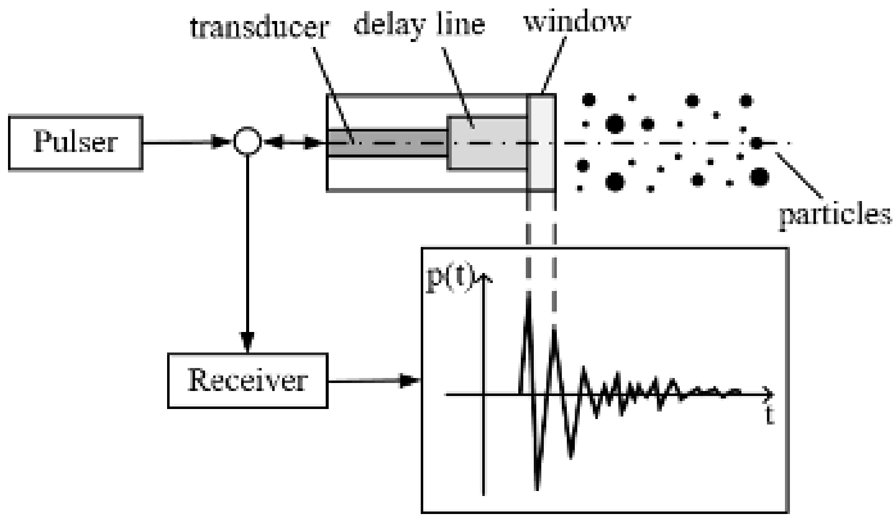

FIG. 14. Experimental setup of Weser *et al.* Reproduced with permission from Ultrasonics. 53, 3 (2013). Copyright 2013 Elsevier.

3.2.4.3 Features of the backscattering method

The application of ultrasonic backscattering operates over a certain range because, for measurements in most industrial fields, single-particle scattering satisfies the Mie scattering effect, and the scattered signals are almost all concentrated near the forward position with a scattering angle of 0°, so that the backscattered signals are weak.[87] Therefore, the detection technology that uses backscattering flow parameters requires more rigorous acquisition of the scattering data and particle concentration of the system. On the one hand, the measurement system should be designed scientifically and reasonably in order to improve the efficiency of the equipment and expand the lower detection limit of measurable concentrations. On the other hand, due to the physical limitations of the hardware, the particle concentration needs to meet certain conditions in order to generate strong backscattered signals that can be detected by the receiving transducer.

3.2.5 Ultrasonic Doppler method

3.2.5.1 Doppler effect

The Doppler effect (or Doppler shift) is a phenomenon discovered by the Austrian physicist Christian Doppler in 1842, which occurs when a wave source and an observer are in relative motion with respect to the medium. The frequency and wavelength of the wave received or detected by the observer are different from those of the source.[88] The following figure is a schematic diagram of the Doppler effect caused by the medium moving in different directions.

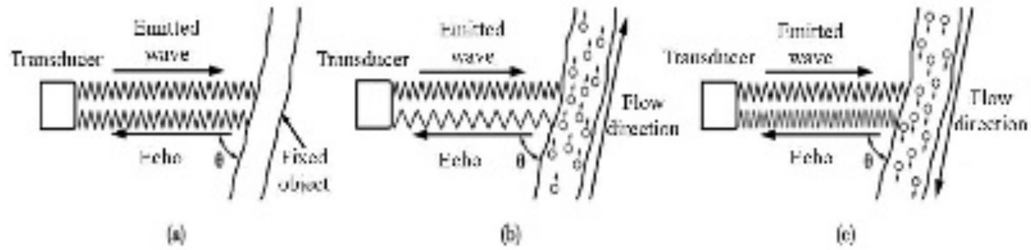

Fig. 15. Doppler effect in different situations.

3.2.5.2 Applications of the ultrasonic Doppler method

Application of the Doppler effect in two-phase flow is used mainly in the measurement of flow velocity and flow rate.[24, 89] Such measurements have been thoroughly studied by researchers globally, and commercial products have been manufactured, such as the ultrasonic velocimeter[88, 90] and the ultrasonic flowmeter.[91] However, both of these instruments have certain limitations, such that they are still in continuous development. Taking the ultrasonic velocimeter as an example, it is widely used in river channels, pipes, and urban sewage, but the presence of very large objects within range (such as large rocks, garbage, hanging tree branches, etc.) will result in inaccurate measurement results. Also, high flow velocities are difficult to measure accurately. In general, this instrument has a high requirement for an amenable site environment as well as the choice of the installation site.[92]

Recent studies have also used the ultrasonic velocimeter for flow pattern identification and other functions,[93] making it ever more widely used in the measurement of two-phase flow. Below, the applications of Doppler in two-phase flow measurement will be discussed in detail.

1. Measurement of flow velocity and flow rate

The ultrasonic flowmeter is an instrument that measures flow rate by detecting the effect of fluid flow on the ultrasonic beam (or ultrasonic pulse), the most common one of which is the ultrasonic Doppler flowmeter, whose measurement principle is shown in Fig. 16. The transducer (also known as the probe) in this system consists of an ultrasonic transmitter and an ultrasonic receiver, which are represented, respectively, by T and R in the figure. The transmitter as a fixed source constantly emits an ultrasonic signal with a fixed frequency f to the pipe, which, because of scattering objects in the pipe (such as bubbles, suspended solid particles, etc.), travels with an uneven fluid velocity v. From the receiving point of view, the signal scattered by the scattering objects can be regarded as the sound source and the receiving transducer as the observer.

When the source is moving and the observer is not, that is, $V_s \neq 0$ and $V_0 = 0$, the sound wave is compressed relative to the observer, and the wave is compressed at each period T for V_sT, then the wavelength received by the receiver is $\lambda' = \lambda - V_sT$. Since the period is inversely proportional to the frequency, the wavelength can be expressed as: $\lambda' = \lambda - V_s/f = (u - V_s)\lambda/u\lambda'$. The wave velocity relative to the observer is u, which gives $f' = u/\lambda' = uf$. Therefore, the difference in frequency between the emitted signal and the reflected signal appears as the Doppler frequency shift.[94]

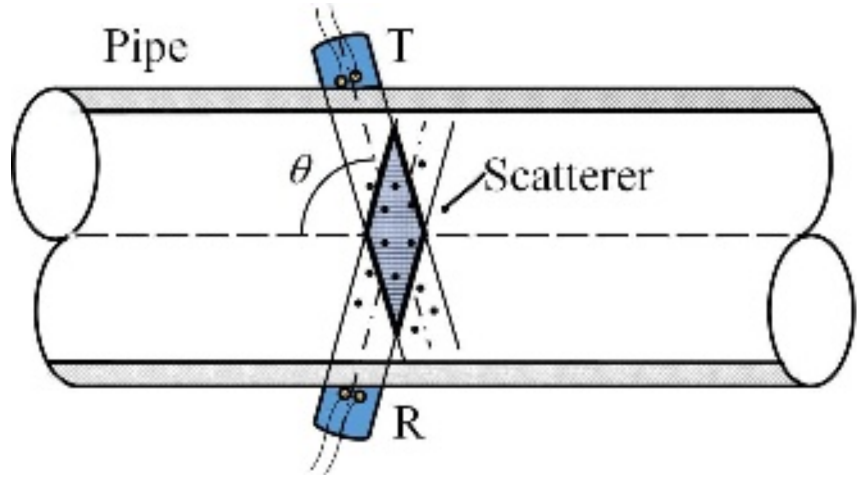

FIG. 16. Schematic diagram of the Doppler flowmeter.

The Doppler frequency shift is directly proportional to the natural frequency and motion velocity of the reflected target and inversely proportional to the velocity at which the sound waves travel in a particular medium.[95] In practical applications, the transmission and reception of ultrasound are not always in the direction of motion of the detected target; in most cases, they are at different angles. Therefore, the complete expression for the above Doppler frequency shift should be:

$$\Delta f = 2f\cos\theta \cdot v / c \tag{3}$$

The frequency shift is calculated according to the given conditions, and the velocity can be further calculated by reversing Eq. (3). However, when there are insufficient particles or bubbles in the fluid, measurement becomes unstable, which greatly limits its application because the ultrasonic Doppler flowmeter requires the presence of a source to scatter the waves in the fluid.

2. *Other applications*

In recent years, the ultrasonic Doppler method has also been applied to other aspects of two-phase flow measurement, including the identification of flow patterns. Shen *et al.*[96] thought that the traditional methods for studying flow patterns lacked a comprehensive description of the phase distribution and flow rate and that the two-phase flow model could be seen as determined by the combination of phase fraction and flow. Therefore, different detection mechanism sensors must be integrated into the experimental setup in order to study the flow pattern more comprehensively. For this reason, a resistance tomography sensor has been proposed to measure the phase fraction and a continuous wave ultrasonic Doppler sensor to measure the velocity of the two-phase flow. The results show that the combination of these two sensors can distinguish the horizontal gas–water flow very well, which lays a foundation for the identification of the three-phase oil–gas–water system.

3.2.5.3 Features of the ultrasonic Doppler method

The ultrasonic Doppler method can be used for measurements on the go (non-fixed installations), is suitable for flow condition evaluation and measurements in the pipe network, and, in principle, is not limited by the pipe diameter. However, it can only be used to measure liquids containing a certain number of suspended particles and bubbles, and its measurement accuracy is low.

3.2.6 Ultrasonic process tomography

The region for the transducer to transmit and receive sound waves is limited and, when the pipe diameter is large or the flow distribution in the pipe is uneven, it is very likely that the fluid does not pass through the region being measured. Generally speaking, increasing the number of transducers around the pipeline can solve this problem effectively. To ensure that the measurement method has a wider range of applicability, a new measurement method has been devised: ultrasonic process tomography (UPT).

Tomographic imaging technology is now considered to be one of the most valuable technologies in monitoring multiphase flow. Compared with other imaging methods, such as electrical tomography,[97] x-ray tomography,[98] and optical tomography,[99] the ultrasonic method has the following features: hard field (the physical field is not affected by changes in the physical properties and composition of the medium), safe, simple structure, no ionizing radiation, harmless to the human body, and cheap. This technology has therefore become widely used in biomedical engineering, non-destructive testing, geophysical applications, pattern recognition, and temperature and velocity field measurements.[100] Ultrasonic computer tomography (UCT) was first applied in the field of medical engineering[101] and then gradually applied to the monitoring of industrial processes from the middle 1970s onward. Different from the UCT used in medical engineering, industrial process monitoring ultrasound tomography is often simply called ultrasound process tomography.

UPT can be regarded as a combination of computer application technology and modern testing technology. It adopts two-phase flow as the main measurement object and uses non-contact or noninvasive sensors to perform non-destructive visual monitoring of internal physical changes in closed process piping, vessels, and reactors. Finally, the two- or three-dimensional distribution of process parameters is displayed using a reconstruction algorithm. Process tomography has been widely used in the field of two-phase flow parameter detection, mainly for the following:

(1) It provides direct real-time images of a certain cross-section of the measured multiphase fluid pipeline, which can be used for flow pattern identification.

(2) The local concentration distribution of each component of a multiphase fluid can be obtained by image processing and analysis, and the total concentration of each phase can be obtained by further processing.

(3) By combining flow imaging technology with relevant flow velocity measurement technology, online real-time measurement of the total mass flow rate of a multiphase fluid, the mass flow rate of phase separation, and the flow velocity distribution of a fluid on the tube section can all be realized.

3.2.6.1 Principles of ultrasonic process tomography

The essence of this technology is to carry out a Radon transform and an inverse transform for a certain characteristic distribution of the measured object field with the physically realizable system. The working process is as follows: a specially designed sensor array is used to obtain information about the measured object field in a non-contact or noninvasive way, and then qualitative or quantitative image reconstruction algorithms are used to reconstruct an image of the measured object field online in real time. By analyzing and comparing the image information at different times, the distribution state and motion change characteristics of the measured object field can be obtained (for example, the distribution state of a two-phase fluid in a certain cross-section of a pipeline or reaction vessel or the flow morphology of a two-phase fluid).[29, 102, 103]

At present, there are main two types of UPT imaging: the transmission type and the reflection type, and there are also two types of image reconstruction: ray theory (geometric acoustics theory)[104] and diffraction theory (wave acoustics theory).[105] The ultrasonic transmitter and receiver of transmission UPT are located on both sides of the measured medium, and the information about the medium is obtained from the transmitted and received ultrasonic waves. The ultrasonic transmitter and receiver of reflection UPT are located on the same side of the medium, and the image information is obtained by receiving the reflected ultrasonic echo. The ultrasonic imaging system in transmission mode is shown in Fig. 17.

The ray theory part of reconstruction theory regards the propagation path of ultrasonic rays as a straight line under the condition of no scattering; that is, the effect of medium inhomogeneity on the sound field is ignored. Diffraction theory (diffraction tomography) considers the scattering effect of sound waves, studies the influence of medium heterogeneity on the sound field under the condition of weak scattering, and establishes the relationship between the parameters of the medium and the boundary value of the scattered sound field (the received data) in order to reconstruct the distribution image of the medium parameters.

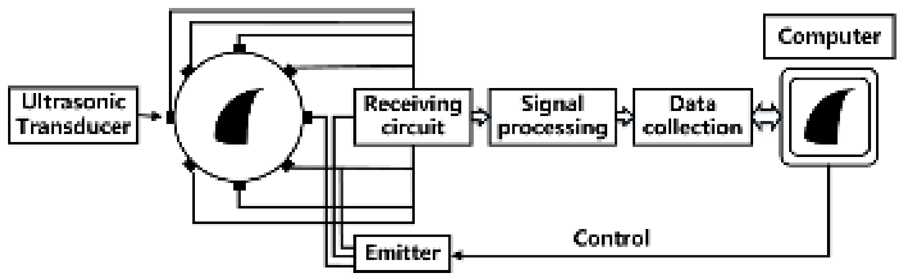

FIG. 17. Ultrasonic imaging system in transmission mode.

3.2.6.2 Applications of ultrasonic process tomography

Process tomography has developed rapidly in recent years, and a variety of process tomography systems have been applied in several areas, including fluidized beds, pneumatic conveying systems, powder concentration monitoring separators, hydraulic condition monitoring, etc.[106, 107] As a form of imaging technology, it can be used in many aspects of gas–solid, liquid–solid, gas–liquid, and liquid–liquid two-phase flow measurement, but, due to the placement of multiple transducers around the measuring devices, it places high demands on the measuring environment, resulting in limited industrial applications. The following are the main applications of ultrasonic tomography for the measurement of flow state and temperature and velocity fields.

1. Two-phase flow state measurement

Measurement of the oil–water two-phase fraction by ultrasonic tomography is chosen as an example to illustrate the tomographic technology in detail. Su *et al.*[108] chose 16 ultrasonic transducers to form a transmission mode array in order to measure oil–water two-phase fractions. Oil and water are pumped into the single-phase measuring tube from their respective tanks, which then flow through single-phase flowmeters with different flow rate ranges as inlet reference (less than 1% relative error, on average). Following calibration, the fluid enters the stainless steel tube with an inner diameter of 50 mm and an outer diameter of 80 mm. The quick-shut valves are for online phase fraction reference. The flow rate of the water is in the range of 0.3–4 m^3/h (0.04–0.57 m/s), while the flow rate of the oil is 0.5–4 m^3/h (0.07–0.57 m/s). The proportion of water varies from 7.3% to 88.3% to obtain five forms of flow, namely, stratified flow, stratified flow with mixing at the interface, dispersion of water in oil (or oil in water), oil-in-water emulsion, and water in oil emulsion.

The structure of the measurement system is as follows: the excitation signal is generated by a direct digital synthesizer and amplified by a power amplifier to excite the transducer to continuously transmit ultrasonic waves with a peak value of 20 V. The ultrasonic receiving board receives the ultrasonic attenuation signal and transmits the signals processed by demodulation and compression in a field-programmable gate array (FPGA) to a computer through a CompactPCI (CPCI) bus. Sixteen ultrasonic transducers with a diameter of 9 mm are installed at regular intervals along the pipe section. The sampling begins after 20 s, when the flow pattern is stable and continuous. The base frequency of the ultrasonic transducer is 1 MHz and the sampling frequency is 5 MHz. An average peak-to-peak distance is then calculated for each data set of 4000 points.

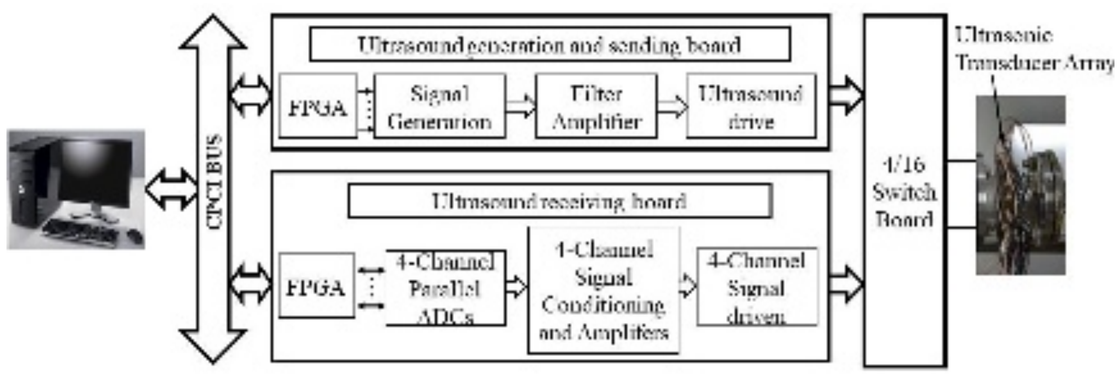

FIG. 18. Structure of the measurement system.

Analysis of the phase fraction proceeds as follows: due to scattering, absorption, and diffusion, the ultrasonic attenuation coefficient presents a nonlinear response to the dispersed phase fraction of oil–water two-phase flow. This nonlinear response requires a physics-based mathematical model to establish a linear correlation, and the phase volume fraction is estimated from the ultrasonic attenuation coefficient and the physical parameters of the oil–water two-phase flow. Based on a theoretical analysis of complex ultrasonic transmission and reflection, a unified prediction model based on the physical mechanism of ultrasonic attenuation in layered oil–water two-phase flow can be established. Finally, the proposed system and model are validated by the horizontal oil–water two-phase flow experiment. Five flow patterns were tested, and the average error of the phase fraction estimation was within 5%.

2. *Temperature field measurement*

The field distribution of furnace temperatures directly affects the ignition and burning of pulverized coal and, consequently, the safety of the boiler. The real-time online measurement of the temperature field is important for improving the efficiency of combustion in the boiler, saving energy, improving the structural design of furnaces for thermal processes, obtaining optimal control strategies, and reducing environmental pollution.[102] At present, industrial instruments for high-temperature measurement include mainly thermocouples and radiation thermometers. Thermocouples are contact-measuring instruments requiring full heat exchange with the measured medium for accurate measurement. Since the specific heats of gases are very low, there are two problems associated with the use of a thermocouple for measuring gas temperatures: the long heat transfer time and the slow system response. In addition, the temperature field near the measuring point can be affected by the heat absorption of the thermocouple, so that the temperature measured by the thermocouple is not the actual temperature of the gas at that point. Radiation thermometers are non-contact thermometers and do not affect the temperature field near the measuring point. However, disturbances in industrial environments, such as interference with the optical path, external light sources, and emissivity changes, are common and can all affect the measurements.[109, 110]

The temperature detection technology employed by the acoustic method has many advantages, such as high precision temperature measurements, a non-contact mode, wide measuring range (minus to 3000°C), simple installation of the measuring device, easy operation, and continuous real-time measurement, which are all of great practical value in the measurement of the temperature field.[111] In addition, the system is stable and reliable in actual use and can meet the requirements for accurate measurement and online control of the temperature field in both industrial production and scientific research settings, especially in high-temperature measuring environments where the method can undoubtedly have broad industrial application.

The basic principle of acoustic temperature measurement is as follows: the propagation velocity of the acoustic wave in gas is a single-value function of the medium temperature, which can be called "acoustic travel time tomography." At present, such a measuring system and its corresponding devices are used mostly in gas media: the sound wave propagates directly through the gas where the temperature is to be measured, which means that the acoustic temperature measurement is the direct measurement of the temperature field. In an ideal gas medium, the sound velocity is proportional to the square root of the absolute temperature of the medium, which satisfies Eq. (4):

$$c=\sqrt{\gamma RT/m}=Z\sqrt{T}\ , \tag{4}$$

where c represents the velocity of sound wave propagation in different gas media, with units of meters per second (m/s); m represents the molecular weight of the gas in kilograms per mole (kg/mol); γ represents the ratio of the specific heat capacity at constant pressure to the specific heat capacity at constant volume of a gas medium, which is dimensionless; R is the sound constant, which is 8.314 in joules per mole per kelvin (J/mol/K); T is the absolute temperature in kelvin; and Z can be expressed as:

$$Z=\sqrt{\gamma R/m}\ . \tag{5}$$

When the gas medium is a well-defined mixture of gases, Z is a constant. In general, the Z of air is 20.05.[112]

In this experiment, the acoustic wave propagates directly in the gas medium to be measured, and the sensor used to transmit and receive the acoustic wave is placed in an area of unknown temperature to form an acoustic path. Since the distance between the two points is a known fixed constant d, the travel time Δt of the sound wave on this path can be measured and the average speed of the sound wave along this acoustic path can then be obtained.[113] Given that the relationship between the speed of sound and the absolute temperature of the medium is known, the average temperature T of the medium over a sound path can be obtained when the average velocity over that path is obtained [Eq. (6)]. Multiple acoustic transmitting and receiving sensors are installed around the section whose temperature is to be measured to form several acoustic paths, and the temperature field is reasonably divided.

$$T=(d/Z\Delta t)^2-273.15 \tag{6}$$

The typical layout of the sensors and the division of the temperature field is shown in Fig. 19. The temperature field on the section is evenly divided into 16 small areas, and eight acoustic transmitting and receiving sensors are installed around the section, forming a total of 24 independent transmitting–receiving paths. According to a set of procedure, each acoustic transmitting or receiving sensor is switched on and off sequentially within a detection period in order to obtain a set of acoustic travel times, and then, using a reconstruction algorithm, the section temperature distribution is obtained.[114]

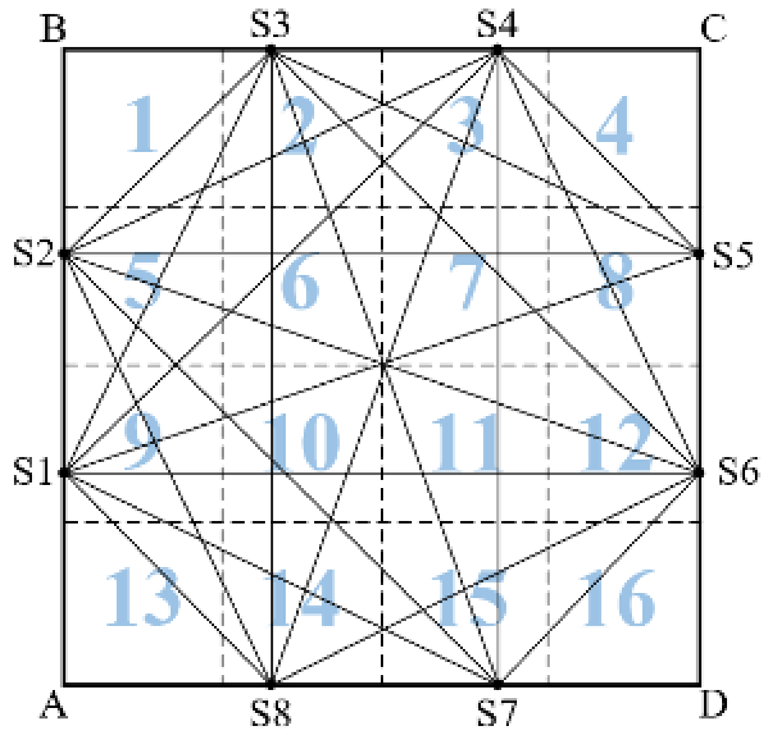

FIG. 19. Block diagram of the sensors and division of the temperature field.

3.2.6.3 Features of ultrasonic process tomography

At present, ultrasonic flow tomography is one of the main streams in the development of flow tomography, but there are still many limitations:

(1) *Real-time measurement*

Compared with electromagnetic waves, ultrasonic waves have a slower transmission speed, the data acquisition time is long, and the speed of movement in multiphase flow that can be measured by the system is limited. In addition, the ultrasonic transmitter has a long time interval between two transmissions, which extends data acquisition times and increases the difficulty of real-time measurement.

(2) *Limited scope of application*

For gas–liquid–liquid three-phase systems, such as oil–gas–water, both the droplets and bubbles of three-phase flow can form multiple phase interfaces and generate reflections, so that it is impossible to distinguish between oil and gas in the phase interfaces. In addition, with the presence of the gas phase, the projected data can only reflect the bubble contours in the imaging region, but cannot reflect the physical characteristics of the medium inside the bubble. For this reason, the extensive application of process tomography has several limitations.

(3) *Image reconstruction algorithm*

The image reconstruction algorithms used in ultrasonic flow tomography are mainly back-projection reconstruction algorithms, but the resolution and quality of the reconstructed images are not ideal.

3.2.6.4 Future development of ultrasonic process tomography

To improve the real-time performance, measurement accuracy, and image quality of tomographic imaging systems, multi-mechanism and multimode tomography will form the mainstream of future development of the technology. These can extend the system's applicable range and measurement precision by increasing the quantity of information available. For example, stemming from medical research, multimode tomographic co-reconstruction is increasingly being used in industry, and Tianjin University has carried out research into electrical capacitance/electrical resistance two-mode tomography.[115] This establishes the way forward for ultrasound process tomography, and research into multimode tomography has also recently made some progress. Steiner *et al.* combined electrical impedance tomography with ultrasound reflection tomography to form a bio-electromechanical tomography system, which improved the accuracy of detecting tumors of small size and depth.[116, 117] However, data fusion is difficult because of differences in the theoretical basis and measurement principles of the various imaging methods, and follow-up research is therefore needed.[118]

In short, with the continual development of industry, there are ever higher requirements for the real-time performance, measurement accuracy, and image quality of process tomography imaging systems. Although there are some limitations, multi-mechanism and multimode tomography will continue to be an effective method for solving these problems, which is also the development trend of process tomography.

4. Discussion

At present, ultrasonic measurement methods have been able to meet the different requirements for the measurement of velocity, concentration, temperature, flow pattern, and other parameters in two-phase flow. In general, the passive method has rarely been used in industrial settings due to its limitations, while the active method plays an important role in different industrial sectors. For example, the backscattering method is used mainly for measuring the concentration of particles in liquid–solid two-phase flow and has already been used to measure the concentration of yeast particles with sizes of approximately 10 μm. However, it is very rarely used in the measurement of gas–solid two-phase flow, the main reason for this being that high-frequency ultrasound cannot be used in air and sound decays approximately one thousand times faster in gases than in liquids.

The ultrasonic Doppler method is used in industry mainly for velocity and flow rate measurements, and there are now many commercial products available, but its limitation is that the concentration of flowing particles must be high.

In the process of ultrasonic propagation, reflections occur when ultrasound strikes the interface between two substances with different acoustic impedances. The greater the difference in acoustic impedance between the two substances, the more obvious the reflection phenomenon. From an analysis of the differences between the echo and transmitted wave, one can obtain the required information. The method is generally applied to gas–liquid two-phase flow systems, including flow pattern recognition, boundary surface monitoring, determining stratified flow liquid film thickness, etc. Because the impedance difference between the gas and liquid phases is large, one can obtain important information from the boundary surface reflection.[119] Due to its simple principle of operation, some researchers have artificially added a reflector to measure liquid density. The echo reflection method can also be used in liquid–solid two-phase systems for measuring particle concentration, but the scope of its application and effects is not as good as that of the attenuation spectrum method because the acoustic distance measured in the echo reflection method is twice that of the attenuation spectrum method for the same case, and absorption and scattering attenuation is more obvious for the echo reflection method.

The basic principle of the attenuation spectrum method is transmission, and two transducers need to be placed opposite each other in the experimental arrangement. This method can realize the measurement of concentration and particle size in gas–solid, liquid–solid, and gas–liquid two-phase flow. Studies of this method have been very comprehensive, but the attenuation spectrum method is limited to single-point measurement only.

The sound velocity spectrum method shares the same principle as the attenuation spectrum method, both of which are applied using a theoretical model inversion in order to obtain the concentration and particle size distribution that is closest to the actual parameters. However, since the correlation between sound velocity, particle size, and concentration information is not as good as that of the attenuation coefficient, application of the sound spectrum method is not widely employed. In general, the superposition of the sound velocity and attenuation spectrum methods is used to calculate single-point measurements.

To obtain more abundant two-phase flow information, single-point measurement is insufficient, the distribution of concentrations and particle sizes on the cross-section needs to be measured, and tomography is an important tool for solving this problem. By placing multiple sensors in many directions or rotating the measuring system, the measurement of each angle on the section can be realized, which is much better than all other methods at present. However, its disadvantages are also obvious. The measurement system in an industrial setting cannot be rotated due to the constraints of production conditions or production processes. In addition, to achieve a high calculation accuracy, it is often necessary to arrange multiple transducers in the 360° direction, which places high demands on the spatial requirements of the measuring environment. That is to say, there is still a lot of potential for the continued development of acoustic tomography. To solve this problem, the reflection principle should be the entry point because, for the transmission principle, two transducers are needed to realize the measurement in the one-dimensional direction, while only one transducer is needed for the reflection principle. In this way, the space problem in industrial environments can be solved, which needs to be the research focus of future studies. As for measurement accuracy, previous studies combined with our research have shown that the collaborative use of different methods can make up for the deficiencies of a single method, which will be the direction for future development.

Table IV is a summary of the different ultrasonic measurement methods, from which the advantages and disadvantages of each method can be more intuitively understood.

TABLE IV. Summary of the different ultrasonic measurement methods.

Measurement method	Features	Advantages	Disadvantages
Passive	No active sound source; sound waves are generated by experimental materials and the environment	Simple in structure; non-contact continuous online measurement	Complex extraction of effective signals; easily affected by environmental noise
Backscattering	Transducers are located in the same azimuth; signals reflected from the	Suitable for industrial environments where	Measured particle concentrations and sizes are limited;

	measured objects are analyzed	transducers cannot be placed face to face	unsuitable for gas-phase media
Attenuation spectrometry	Transmitting and receiving transducers are placed in opposing directions; based on attenuation models	Applicable to a wide range of concentrations and particle sizes	Comprehensive understanding of the physical properties is needed
Sound velocity spectrum	Principles are consistent with attenuation spectrum method	A wide range of concentrations and particle sizes	Accuracy is worse
Echo reflection	Transducers are in the same direction; reflection from the larger interface is the information source	Multiple parameters can be measured simultaneously	Acoustic distance is doubled compared to other methods
Ultrasonic Doppler	Transducers are arranged in angular opposition; the reflections of the flowing particles is received	Mainly used to measure flow rate in the pipeline; mature commercial products	Concentrations of two-phase flow are limited; not suitable for small particles
Ultrasonic process tomography	Transducers are arranged in arrays; a Radon transform and algorithm are used to reconstruct data	More probes can achieve more accurate information of the flow field	The arrangement of transducers affects flow fields; to get high accuracy is difficult

5. Conclusions and future prospects

The use of ultrasonic technology in industry has been reviewed for two-phase flow measurement applications. The measurement methods reviewed include the passive and active methods, and the measured parameters include mainly the particle size and concentration distributions of solid-phase particles, flow pattern identification, and velocity measurement. In conclusion, the applications of ultrasonic methods to two-phase flow measurement have the following characteristics.

(1) Few ultrasonic measurement methods exist for gas–solid two-phase flow. Only the ultrasonic attenuation spectrum and ultrasonic tomography methods, which are based on the transmission principle, have particular applications in gas–solid two-phase

flow. This is because ultrasonic attenuation in a gas medium is very rapid and the transmission method has a shorter sound path compared with reflection and scattering; thus, the measurement method based on the transmission principle is more effective.

(2) In most cases, a liquid phase appears in multiphase flow measurement, such as the identification of the flow pattern in gas–liquid two-phase flow (echo reflection) and the concentration and particle size distribution of solid-phase particles in liquid–solid two-phase flow (backscattering, attenuation spectrum).

(3) Each approach has a relatively mature field of application. For example, the ultrasonic Doppler method is used mostly for the measurement of two-phase flow velocity and flow rate, the attenuation spectrum method is used mostly for the measurement of solid-phase particle sizes and concentrations, the passive method is effective in epidemic identification, and the echo reflection method is used mostly for gas–liquid two-phase flow pattern identification and gas–liquid interface monitoring.

(4) The ultrasonic method for the measurement of two-phase flow also faces some difficulties and challenges, such as the study of other measuring parameters for gas–solid two-phase flow parameters, the effects of real industrial environmental noise on measurement, simplification of the ultrasonic tomographic imaging system to adapt to complex industrial conditions, and improvements in the real-time performance and measurement accuracy of ultrasonic imaging systems.

(5) At present, the development of existing ultrasonic measurement methods are limited. To achieve more accurate and efficient measurement, it will be more promising to combine different ultrasonic measurement methods or integrate acoustic, electrical and optical methods to achieve multi-physical field measurement.

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Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

References

[1]J. Jing, Z. Li, Q. Zhu, Z. Chen, F. Ren, "Influence of primary air ratio on flow and combustion characteristics and NOx emissions of a new swirl coal burner," Energy **36**(2), 1206 (2011).

[2]J. Yoder, "Ultrasonic Meters: A Natural Choice To Measure Gas Flow," PIPELINE GAS J **227**, 19 (2000).

[3]P.S. Epstein, R.R. Carhart, "The Absorption of Sound in Suspensions and Emulsion," J. Acoust. Soc. Am. **25**(3), 553 (1953).

[4]J.R.Allegra, S.A.Hawley, "Attenuation of Sound in Suspensions and Emulsions: Theory and Experiments," J. Acoust. Soc. Am. **51**(5), 1545 (1972).

[5]D.J. Mcclements, M. Povey, "Scattering of ultrasound by emulsions," J. Phys. D: Appl. Phys. **22**(1), 38 (1989).

[6]J.R.Urick, "The Absorption of Sound in Suspensions of Irregular Particles," J. Acoust. Soc. Am. **20**(3), 283 (2005).

[7]U. Riebel, U. Kräuter, "Ultrasonic Extinction and Velocity in Dense Suspensions," (1998).

[8]L. Xu, L. Xu, "Ultrasound tomography system used for monitoring bubbly gas/liquid two-phase flow," IEEE Trans. Ultrason. Ferroelectr. Freq. Control **44**(1), 67 (1997).

[9]M. Kupnik, P. O'Leary, A. Schroder, I. Rungger, Numerical simulation of ultrasonic transit-time flowmeter performance in high temperature gas flows, in: Ultrasonics, 2003 IEEE Symposium, (2003).

[10]M. Su, M. Xue, X. Cai, Z. Shang, F. Xu, "Particle size characterization by ultrasonic attenuation spectra," Particuology **6**(4), 276 (2008).

[11]X. Wang, L. Liu, R. Li, R.J. Tweedie, K. Primrose, J. Corbett, F.K. Mcneil-Watson, "Online characterisation of nanoparticle suspensions using dynamic light scattering, ultrasound spectroscopy and process tomography," Chem. Eng. Res. Des. **87**(6), 874 (2009).

[12]Y. Murai, Y. Tasaka, Y. Nambu, Y. Takeda, S.R. Gonzalez A, "Ultrasonic detection of moving interfaces in gas–liquid two-phase flow," Flow Meas. Instrum. **21**(3), 356 (2010).

[13]M. Xue, M. Su, X. Cai, "Particle size distribution and concentration characterization in mineral slurry by ultrasonic methods," J. Eng. Thermophys. **31**(9), 1520 (2010).

[14]R. Weser, S. Wockel, B. Wessely, U. Hempel, "Particle characterisation in highly concentrated dispersions using ultrasonic backscattering method," Ultrasonics **53**(3), 706 (2013).

[15]R. Weser, S. Woeckel, B. Wessely, U. Steinmann, F. Babick, M. Stintz, "Ultrasonic backscattering method for in-situ characterisation of concentrated dispersions," Powder Technol. **268**, 177 (2014).

[16]C. Poelma, A. Gurung, Instantaneous velocity field measurement in densely-laden two-phase flows using Ultrasound Imaging Velocimetry, in: 18th International Symposium on the Application of Laser and Imaging Techniques to Fluid Mechanics, (Lisbon, 2016).

[17]Y. Zhang, A.N. Azman, K. Xu, C. Kang, H.B. Kim, "Two-phase flow regime identification based on the liquid-phase velocity information and machine learning," Exp. Fluids **61**(10), (2020).

[18]F. Gaudfrin, O. Pujol, R. Ceolato, G. Huss, N. Riviere, "A new lidar inversion method using a surface reference target applied to the backscattering coefficient and lidar ratio retrievals of a fog-oil plume at short range," Atmos. Meas. Tech. **13**(4), 1921 (2020).

[19]Y. Wang, X. Lyu, W. Li, G. Yao, J. Bai, A. Bao, "Investigation on Measurement of Size and Concentration of Solid Phase Particles in Gas-Solid Two Phase Flow," CHINESE J ELECTRON **27**(2), 381 (2018).

[20]X. Cai, J. Li, X. Ouyang, Z. Zhao, M. Su, "In-line measurement of pneumatically conveyed particles by a light transmission fluctuation method," Flow Meas. Instrum. **16**(5), 315 (2005).

[21]Z. Peng, X. Yang, W. Qi, Concentration measurement of two-phase flow by means of FastICA and LS-SVM, in: International Conference on Machine Learning & Cybernetics, (2008).

[22]C. Wang, Y. Zhang, W. Wu, Annular electrode electrostatic method of dilute phase gas-solid two-phase flow concentration measurement, in: IEEE International Conference on Electronic Measurement & Instruments, (2014).

[23]F.D. Shaffer, R.A. Bajura, "Analysis of Venturi Performance for Gas-Particle Flows," J. Fluids Eng. **112**, 121 (1990).

[24]S. Wada, H. Kikura, M. Aritomi, M. Mori, Y. Takeda, "Development of Pulse Ultrasonic Doppler Method for Flow Rate Measurement in Power Plant Multilines Flow Rate Measurement on Metal Pipe," J. Nucl. Sci. Technol. **41**(3), 339 (2004).

[25]R.E. Challis, M. Povey, M.L. Mather, A.K. Holmes, "Ultrasound techniques for characterizing colloidal dispersions," Rep. Prog. Phys. **68**(7), 1541 (2005).

[26]Q. Wang, K. Attenborough, S. Woodhead, "Particle Irregularity and Aggregation Effects in Airborne Suspensions at Audio- and Low Ultrasonic Frequencies," J. Sound Vib. **236**(5), 781 (2000).

[27]M. Su, X. Cai, M. Xue, L. Dong, F. Xu, "Particle sizing in dense two-phase droplet systems by ultrasonic attenuation and velocity spectra," Sci. China Ser. E: Technol. Sci. **52**(6), 1502 (2009).

[28]F. Liang, H. Zheng, H. Yu, Y. Sun, "Gas–liquid two-phase flow pattern identification by ultrasonic echoes reflected from the inner wall of a pipe," Meas. Sci. Technol. **27**(3), 035304 (2016).

[29]C. Tian, M. Su, X. Chen, X. Cai, "An investigation on ultrosonic process tomography system for particle two -phase flow measurement," J NANJING U(NAT SCI) **49**(1), 20 (2013).

[30]A.S. Dukhin, P.J. Goetz, T.H. Wines, P. Somasundaran, "Acoustic and electroacoustic spectroscopy," Colloids Surf.,A **173**, 127 (2000).

[31]W.G. Neubauer, "Ultrasonic reflection of a bounded beam at Rayleigh and critical angles for a plane liquid-solid interface," J. Appl. Phys. **44**(1), (1973).

[32]D.H. Rank, J.P. Mckelvey, "A Study of the Mechanism of Modified Rayleigh Scattering," J. Opt. Soc. Am. B: Opt. Phys. **39**(9), 762 (1949).

[33]R.A. Sigelman, J.M. Reid, "Analysis and measurement of ultrasound backscattering from an ensemble of scatterers excited by sine-wave bursts," J. Acoust. Soc. Am. **53**(5), 1351 (1973).
[34]M. Lenz, M. Bock, "Measurement of the sound velocity in fluids using the echo signals from scattering particles," Ultrasonics **52**, 117 (2012).
[35]X. Zou, H. Song, C. Wang, Z. Ma, "Relationships between B-mode ultrasound imaging signals and suspended sediment concentrations," Measurement **92**, 34 (2016).
[36]K. Tsuji, T. Norisuye, H. Nakanishi, Q. Tran-Cong-Miyata, "Simultaneous measurements of ultrasound attenuation, phase velocity, thickness, and density spectra of polymeric sheets," Ultrasonics **99**, (2019).
[37]T. Dong, T. Norisuye, H. Nakanishi, Q. Tran-Cong-Miyata, "Particle size distribution analysis of oil-in-water emulsions using static and dynamic ultrasound scattering techniques," Ultrasonics **108**, (2020).
[38]L. Elvira, P. Vera, F.J. Canadas, S.K. Shukla, F. Montero, "Concentration measurement of yeast suspensions using high frequency ultrasound backscattering," Ultrasonics **64**, (2016).
[39]J.M. Furlan, V. Mundla, J. Kadambi, N. Hoyt, R. Visintainer, G. Addie, "Development of A-scan ultrasound technique for measuring local particle concentration in slurry flows," Powder Technol. **215-216**, 174 (2012).
[40]Y. Shen, C. Tan, F. Dong, K. Smith, J. Escudero, "Gas-water two-phase flow pattern recognition based on ERT and ultrasound Doppler," IEEE Instrum. Meas. Mag., (2018).
[41]J. Mathieu, P. Schweitzer, "Measurement of liquid density by ultrasound backscattering analysis," Meas. Sci. Technol. **15**(5), 869 (2004).
[42]D.H. Blankenhorn, P.J. Curry, "The accuracy of arteriography and ultrasound imaging for atherosclerosis measurement. A review," ARCH PATHOL LAB MED **106**(10), (1982).
[43]A. Shaw, M. Hodnett, "Calibration and measurement issues for therapeutic ultrasound," Ultrasonics **48**(4), (2008).
[44]P.L.A.V. Daele, H. Burger, C. Laet, H. Pols, "Ultrasound measurement of bone," Clin Endocrinol **44**(4), (2010).
[45]P.R. Hoskins, "A review of the measurement of blood velocity and related quantities using Doppler ultrasound," P I MECH ENG H **213**(5), (1999).
[46]P.R. Hoskins, "Ultrasound techniques for measurement of blood flow and tissue motion," Biorheology **39**(3-4), (2002).
[47]G. Harvey, A. Gachagan, T. Mutasa, "Review of high-power ultrasound-industrial applications and measurement methods," IEEE Trans. Ultrason. Ferroelectr. Freq. Control **61**(3), (2014).
[48]A.D. Whittaker, B. Park, B.R. Thane, R.K. Miller, J.W. Savell, "Principles of ultrasound and measurement of intramuscular fat," J. Anim. Sci. **70**(3), (1992).
[49]L. Jie, "Measurement and Imaging of Biological Tissue Elasticity:A Review of the Vibration-based Ultrasound Methods," Chin Med Dev Inform **19**(3), 7 (2013).
[50]X. Shi, "Technique For Measuring Concentration of Gas- Solid Two Phase Flow Inside The Pipe Based on Ultrasonic Method," Thermal Power Generation **6**, 37 (2005).

[51]C.M. Scala, R.A. Coyle, "Pattern recognition and acoustic emission," NDT Int. **16**(6), 339 (1983).
[52]L. Fang, Y. Zhang, W. Zhang, Y. Liang, Q. He, "Flow detection technology based on acoustic emission of gas-liquid two-phase flow in vertical pipe " CIESC J. **65**(4), (2014).
[53]A.S. Dukhin, P.J. Goetz, "New developments in acoustic and electroacoustic spectroscopy for characterizing concentrated dispersions," Colloids Surf.,A **192**, 267 (2001).
[54]L.D. Hampton, "Acoustic Properties of Sediments," J. Acoust. Soc. Am. **42**(4), 882 (1967).
[55]A.S. Dukhin, P.J. Goetz, T. Wine, P. Somasundaran, "Acoustic and Electroacoustic Spectroscopy," Colloids Surf.,A **173**, 127 (2000).
[56]D.J. McClements, "Ultrasonic characterisation of emulsions and suspensions," Adv Colloid Interface Sci **37**, 33 (1991).
[57]T. Valier-Brasier, J.M. Conoir, F. Coulouvrat, J.L. Thomas, "Sound propagation in dilute suspensions of spheres: Analytical comparison between coupled phase model and multiple scattering theory," J. Acoust. Soc. Am. **138**(4), (2015).
[58]D.F. Swineharf, "The Beer-Lambert Law," J. Chem. Educ. **39**, 333 (1962).
[59]W.Mantheyt, N.Kroemerts, V.MagoriX, "Ultrasonic transducers and transducer arrays for applications in air," Meas. Sci. Technol. **3**, (1991).
[60]S.J. Rubin, J.D. Marquardt, R.H. Gottlieb, S.P. Meyers, S.M.S. Totterman, R.E. O'Mara, "Magnetic resonance imaging: a cost-effective alternative to bone scintigraphy in the evaluation of patients with suspected hip fractures," SKELETAL RADIOL **27**, 199 (1998).
[61]H. Yang, M. Su, X. Wang, J. Gu, X. Cai, "Particle sizing with improved genetic algorithm by ultrasound attenuation spectroscopy," Powder Technol. **304**, 20 (2016).
[62]B. Boonkhao, X. Wang, "Ultrasonic attenuation spectroscopy for multivariate statistical process control in nanomaterial processing," Particuology **10**(2), 196 (2012).
[63]L. Liu, "Application of ultrasound spectroscopy for nanoparticle sizing in high concentration suspensions: A factor analysis on the effects of concentration and frequency," Chem. Eng. Sci. **64**(23), 5036 (2009).
[64]A. Strybulevych, V. Leroy, A.L. Shum, H.F. Koksel, M.G. Scanlon, J.H. Page, Use of an ultrasonic reflectance technique to examine bubble size changes in dough, in: IOP Conference Series, (IOP Publishing, Madrid, Spain, 2012), pp. 012037.
[65]J. Pierre, F. Elias, V. Leroy, "A technique for measuring velocity and attenuation of ultrasound in liquid foams," Ultrasonics **53**(2), 622 (2013).
[66]T.S. Awad, H.A. Moharram, O.E. Shaltout, D. Asker, M.M. Youssef, "Applications of ultrasound in analysis, processing and quality control of food: A review," Food Res. Int. **48**(2), 410 (2012).
[67]B.M. Wrobel, R.W. Time, "Improved pulsed broadband ultrasonic spectroscopy for analysis of liquid-particle flow," APPL ACOUST **72**(6), 324 (2011).
[68]B. Ding, L. He, J. Luo, B. Peng, X. Geng, P. Wang, "Determination of particle size of heavy oil in water dispersion system by ultrasonic attenuation method," J PETROL SCI ENG **146**, 764 (2016).
[69]K.B. Kann, "Sound waves in foams," Colloids Surf.,A **263**(1-3), 315 (2005).

[70]B. Gielen, T. Claes, J. Janssens, J. Jordens, L.C.J. Thomassen, T.V. Gerven, L. Braeken, "Particle Size Control during Ultrasonic Cooling Crystallization of Paracetamol," Chem. Eng. Technol. **40**(7), 1300 (2017).
[71]S. Phillips, Y. Dain, R.M. Lueptow, "Theory for a gas composition sensor based on acoustic properties," Meas. Sci. Technol. **14**, 70 (2003).
[72]H. Hou, M. Su, X. Cai, "A study on measuring distribution of nanoparticle size based on ultrasonic attenuation spectrum," Chin. J. Acoust **30**, 261 (2011).
[73]J. Gu, M. Su, X. Cai, "In-line measurement of pulverized coal concentration and size in pneumatic pipelines using dual-frequency ultrasound," APPL ACOUST **138**, 163 (2018).
[74]J.M. Furlan, Particle Concentration Measurements in a Centrifugal Slurry Pump using A-scan Ultrasound Technique, in: Department of Mechanical and Aerospace Engineering, (CASE WESTERN RESERVE UNIVERSITY, 2011), pp. 166.
[75]R.S. Dwyer-Joyce, P. Harper, B.W. Drinkwater, "A method for the measurement of hydrodynamic oil films using ultrasonic reflection," Tribol. Lett **17**, 337 (2004).
[76]S. Wada, H. Kikura, M. Aritomi, "Pattern recognition and signal processing of ultrasonic echo signal on two-phase flow," Flow Meas. Instrum. **17**(4), 207 (2006).
[77]R.S. Dwyer-Joyce, P. Harper, B.W. Drinkwater, "A Method for the Measurement of Hydrodynamic Oil Films Using Ultrasonic Reflection," Tribol. Lett **17**(2), (2004).
[78]V.C. Anderson, "Sound Scattering from a Fluid Sphere," J. Acoust. Soc. Am. **22**(4), 426 (1950).
[79]J.N. Marsh, M.S. Hughes, C.S. Hall, S.H. Lewis, R.L. Trousil, "Frequency and concentration dependence of the backscatter coefficient of the ultrasound contrast agent Albunex," J. Acoust. Soc. Am. **104**, 1654 (1998).
[80]B.J. Angelson, "A Theoretical Study of the Scattering of Ultrasound from Blood," IEEE Trans. Biomed. Eng. **27**, 61 (1980).
[81]K.K. Shung, R.A. Sigelmann, J.M. Reid, "Scattering of Ultrasound by Blood," IEEE Trans. Biomed. Eng. **6**, 460 (1976).
[82]S. Wang, K.K. Shung, "An Approach for Measuring Ultrasonic Backscattering from Biological Tissues with Focused Transducers," IEEE Trans. Biomed. Eng. **44**(7), 549 (1997).
[83]P.M. Shankar, "A general statistical model for ultrasonic backscattering from tissues," IEEE Trans. Ultrason. Ferroelectr. Freq. Control **47**(3), (2000).
[84]M. O'Donnell, J.G. Miller, "Quantitative broadband ultrasonic backscatter: An approach to nondestructive evaluation in acoustically inhomogeneous materials," J. Appl. Phys. **52**(2), 1056 (1981).
[85]J. Li, L. Yang, S.I. Rokhlin, "Effect of texture and grain shape on ultrasonic backscattering in polycrystals," Ultrasonics **54**(7), (2014).
[86]H. Jia, X. Li, X. Meng, "Rigid and elastic acoustic scattering signal separation for underwater target," J. Acoust. Soc. Am. **142**(2), (2017).
[87]S.M. Scholz, R. Vacassy, J. Dutta, H. Hofmann, M. Akinc, "Mie scattering effects from monodispersed ZnS nanospheres," J. Appl. Phys. **83**(12), 7860 (1998).
[88]T. Wang, J. Wang, F. Ren, Y. Jin, "Application of Doppler ultrasound velocimetry in multiphase flow," CHEM ENG J **92**(1-3), 111 (2003).

[89]D. Brito, H.C. Nataf, P. Cardin, J. Aubert, J.P. Masson, "Ultrasonic Doppler velocimetry in liquid gallium," Exp. Fluids **31**(6), (2001).

[90]K. Lautscham, F. Wente, W. Schrader, U. Kaatze, "High resolution and small volume automatic ultrasonic velocimeter for liquids," Meas. Sci. Technol. **11**, 1432 (2000).

[91]W.R. Brody, J.D. Meindl, "Theoretical Analysis of the CW Doppler Ultrasonic Flowmeter," IEEE Trans. Biomed. Eng. **21**, 183 (1974).

[92]Y. Takeda, "Velocity profile measurement by ultrasonic doppler method," Exp. Therm Fluid Sci. **10**, 444 (1995).

[93]Y. Shen, C. Tan, F. Dong, K. Smith, J. Escudero, Gas-water two-phase flow pattern recognition based on ERT and ultrasound Doppler, in: IEEE International Instrumentation and Measurement Technology Conference (I2MTC), (Houston,TX, 2018), pp. 1-6.

[94]H. Kobayashi, "Ultrasonic ground speedometer utilizing Doppler effect," J. Acoust. Soc. Am. **94**(4), 2468 (1993).

[95]A. Amar, A.J. Weiss, Doppler frequency shift, in: Dictionary Geotechnical Engineering/wrterbuch Geotechnik, (Springer, Berlin, Heidelberg, 2014), pp. 401-401.

[96]X. Dong, C. Tan, Y. Yuan, F. Dong, "Measuring Oil–Water Two-Phase Flow Velocity With Continuous-Wave Ultrasound Doppler Sensor and Drift-Flux Model," IEEE Trans. Instrum. Meas. **65**(5), 1098 (2016).

[97]S.A. Hashemi, A. Sadighian, S.I.A. Shah, R.S. Sanders, "Solid velocity and concentration fluctuations in highly concentrated liquid–solid (slurry) pipe flows," Int. J. Multiphase Flow **66**, 46 (2014).

[98]S.R. Stock, "Recent advances in X-ray microtomography applied to materials," Int. Mater. Rev. **53**(3), 129 (2013).

[99]S.R. Arridge, J.C. Schotland, "Optical tomography: forward and inverse problems," Inverse Prob. **25**(12), 123010 (2009).

[100]W. Warsito, L.S. Fan, "Neural network multi-criteria optimization image reconstruction technique (NN-MOIRT) for linear and non-linear process tomography," Chem. Eng. Process. **42**(8-9), 663 (2003).

[101]W. Chen, P. Wang, Z. Zhang, X. Deng, C. Zhang, S. Ju, "Nonlinear ultrasonic imaging in pulse-echo mode using Westervelt equation: a preliminary research," Comput Assist Surg **24**(sup2), 54 (2019).

[102]P. Beckord, G. HoÈfelmann, H.O. Luck, D. Franken, "Temperature and velocity flow fields measurements using ultrasonic computer tomography," Heat Mass Transfer **33**, 395 (1998).

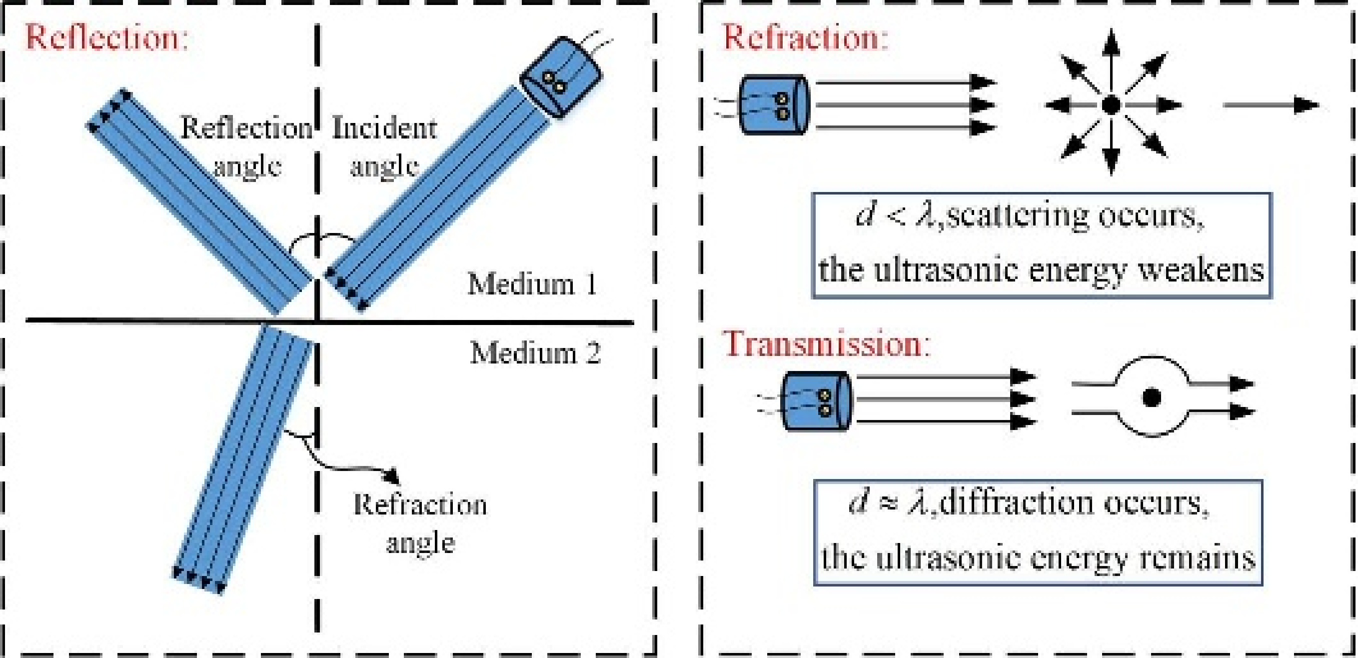
[103]B.S. Hoyle, "Process tomography using ultrasonic sensors," Meas.sci.technol **7**(3), (1996).

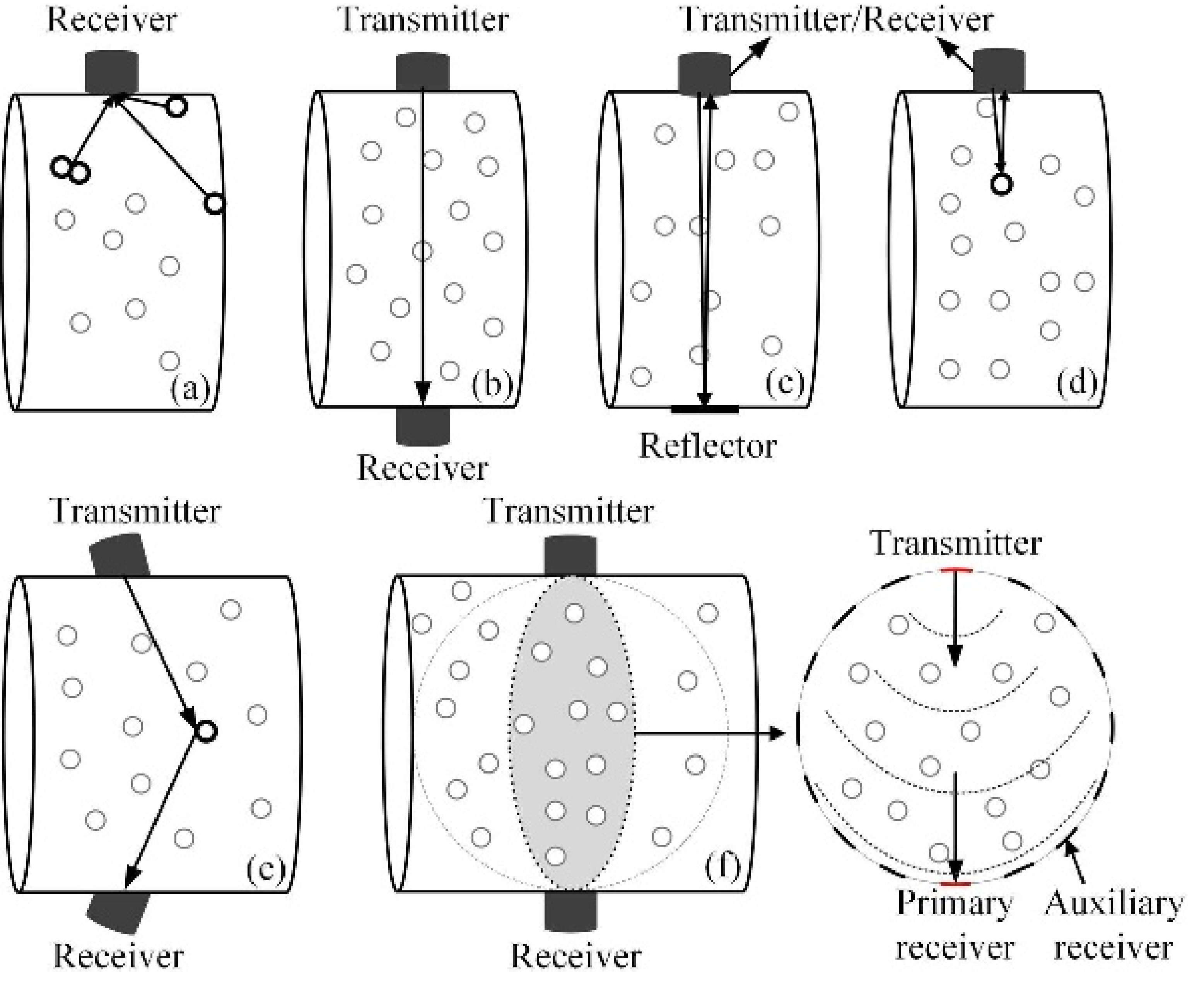
[104]M.G. Brown, "Numerical considerations in ray tracing and ray expansions of the acoustics wavefield," J. Acoust. Soc. Am. **76**(S1), S39 (1984).

[105]A.Y. Poyendinchuk, Y.A. Tuchkin, V.P. Shestopalov, "New numerical-analytical methods in diffraction theory," Math. Comput. Modell. **32**, 1029 (2000).

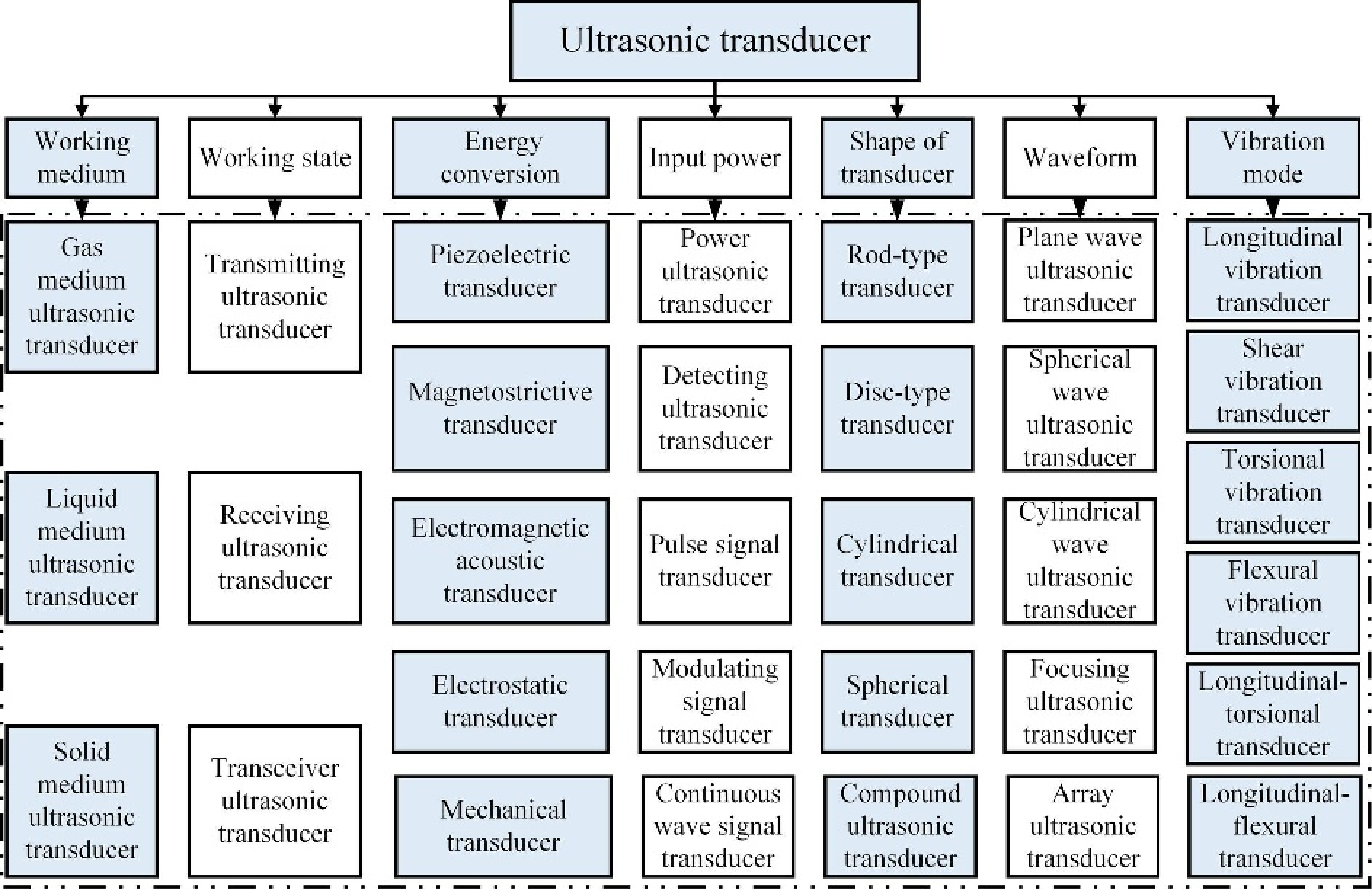
[106]H.I. Schlaberg, F.J.W. Podd, B.S. Hoyle, "Ultrasound process tomography system for hydrocyclones," Ultrasonics **38**, 813 (2000).

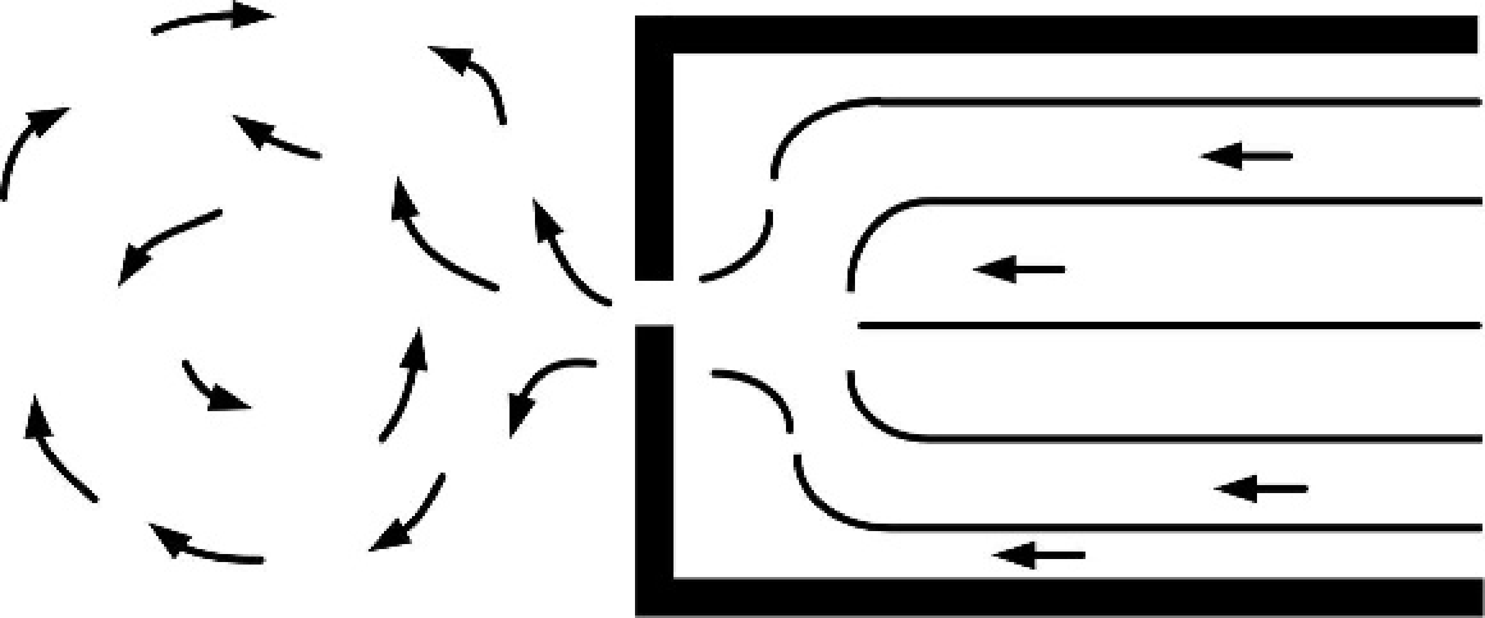
[107]B.S. Hoyle, "Process tomography using ultrasonic sensors " Meas. Sci. Technol. **7**, 272 (1996).
[108]Q. Su, C. Tan, F. Dong, "Measurement of Oil–Water Two-Phase Flow Phase Fraction With Ultrasound Attenuation," IEEE Sens. J. **18**(3), 1150 (2018).
[109]J.D. Nash, D.R. Caldwell, M.J. Zelman, J.N. Moum, "A Thermocouple Probe for High-Speed Temperature Measurement in the Ocean," J. Atmos. Oceanic Technol. **16**, 1474 (1999).
[110]U. Sarma, P.K. Boruah, "Design and development of a high precision thermocouple based smart industrial thermometer with on line linearisation and data logging feature," Measurement **43**(10), 1589 (2010).
[111]K. Mizutani, K. Nishizaki, K. Nagai, K. Harakawa, "Measurement of Temperature Distribution in Space Using Ultrasound Computerized Tomography," Jpn. J. Appl. Phys. **36**, 3176 (1997).
[112]E.V. Malyarenko, J.S. Heyman, H.H. Chen-Mayer, R.E. Tosh, "High-resolution ultrasonic thermometer for radiation dosimetry," J. Acoust. Soc. Am. **124**(6), 3481 (2008).
[113]M. Bramanti, E.A. Salerno, A. Tonazzini, S. Pasini, A. Gray, "An acoustic pyrometer system for tomographic thermal imaging in power plant boilers," IEEE Trans. Instrum. Meas. **45**, 159 (1996).
[114]Y. Liu, S. Liu, J. Lei, J. Liu, H.I. Schlaberg, Y. Yan, "A method for simultaneous reconstruction of temperature and concentration distribution in gas mixtures based on acoustic tomography," Acoust. Phys. **61**(5), 597 (2015).
[115]P. Wang, H. Wang, B. Shen, "ECT/ERT Dual-Modality Tomography Based on Inner Electrode Array," J TIANJIN U(SCI TECHNO) **48**(4), (2015).
[116]G. Steiner, M. Soleimani, D. Watzenig, "A bio-electromechanical imaging technique with combined electrical impedance and ultrasound tomography," Physiol Meas **29**(6), S63 (2008).
[117]G. Steiner, M. Soleimani, H. Dehghani, D. Watzenig, F. Podd, Tomographic image reconstruction from dual modality ultrasound and electrical impedance data, in: 13th International Conference on Electrical Bioimpedance and the 8th Conference on Electrical Impedance Tomography, (Springer, Berlin, Heidelberg, 2007), pp. 288-291.
[118]G. Liang, S. Ren, F. Dong, "An augmented Lagrangian trust region method for inclusion boundary reconstruction using ultrasound/electrical dual-modality tomography," Meas. Sci. Technol. **29**(7), 074008 (2018).
[119]A. Etminan, Y.S. Muzychka, K. Pope, "Liquid film thickness of two-phase slug flows in capillary microchannels: A review paper," Can.J.Chem.Eng., (2021).

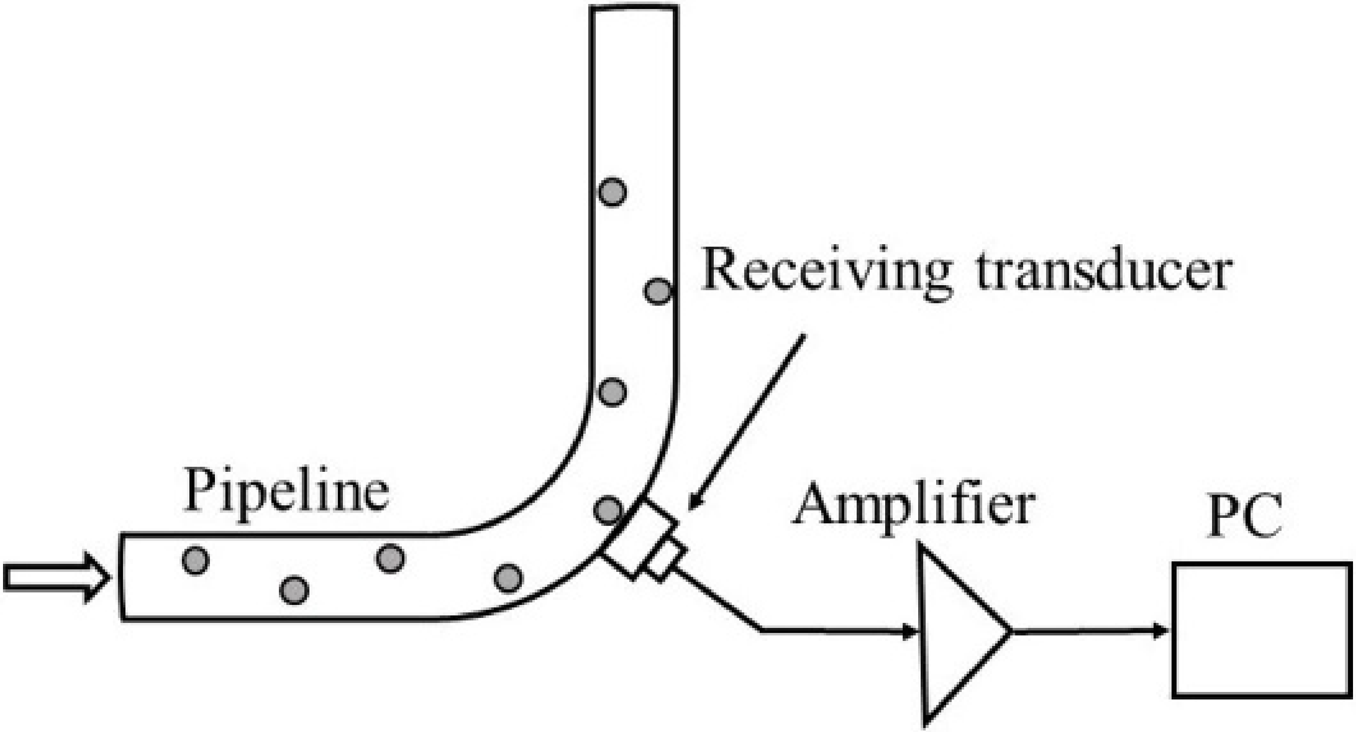

Reflection:
Reflection angle
Incident angle
Medium 1
Medium 2
Refraction angle
Refraction:
$d < \lambda$,scattering occurs,
the ultrasonic energy weakens
Transmission:
$d \approx \lambda$,diffraction occurs,
the ultrasonic energy remains

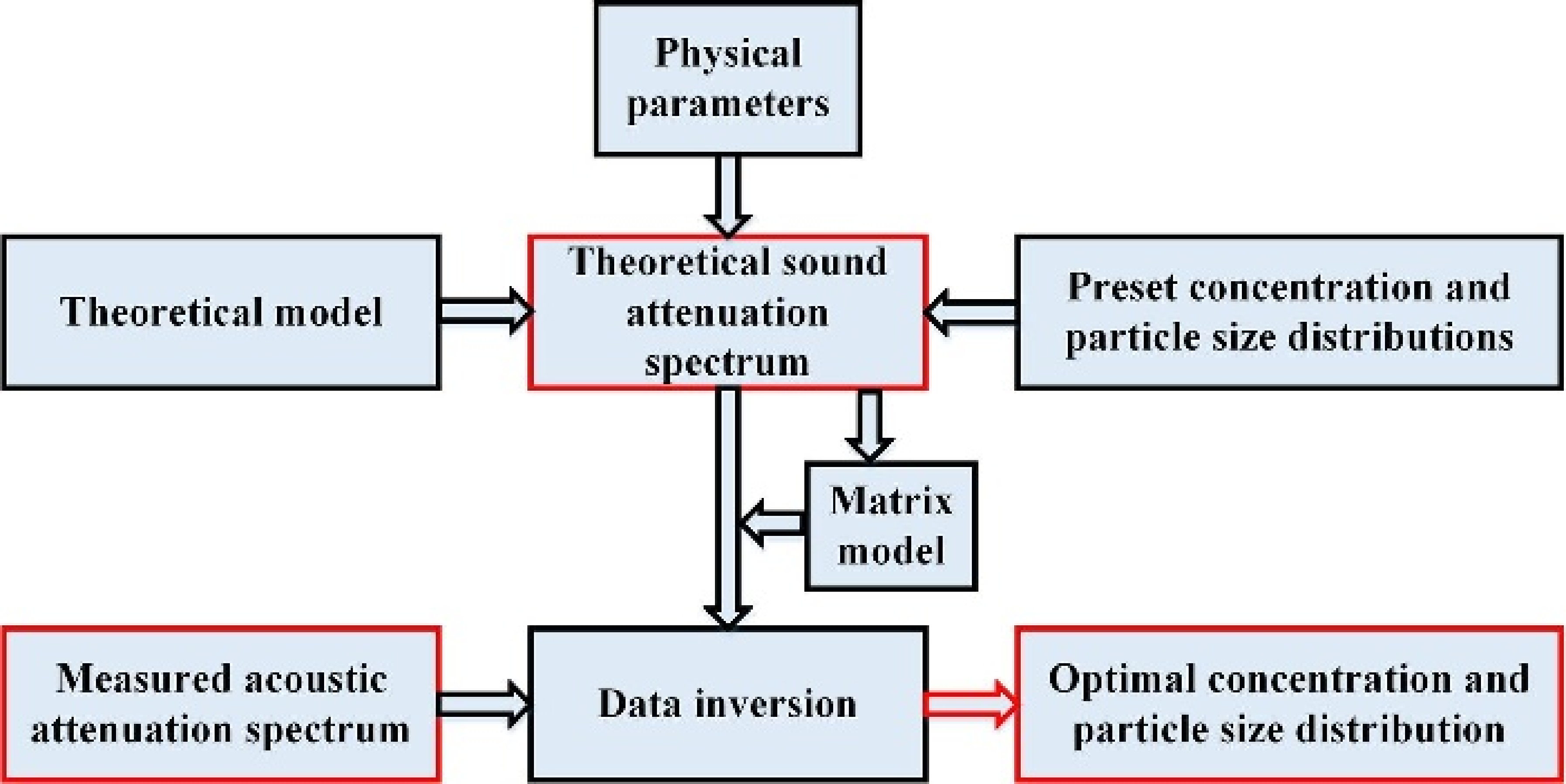


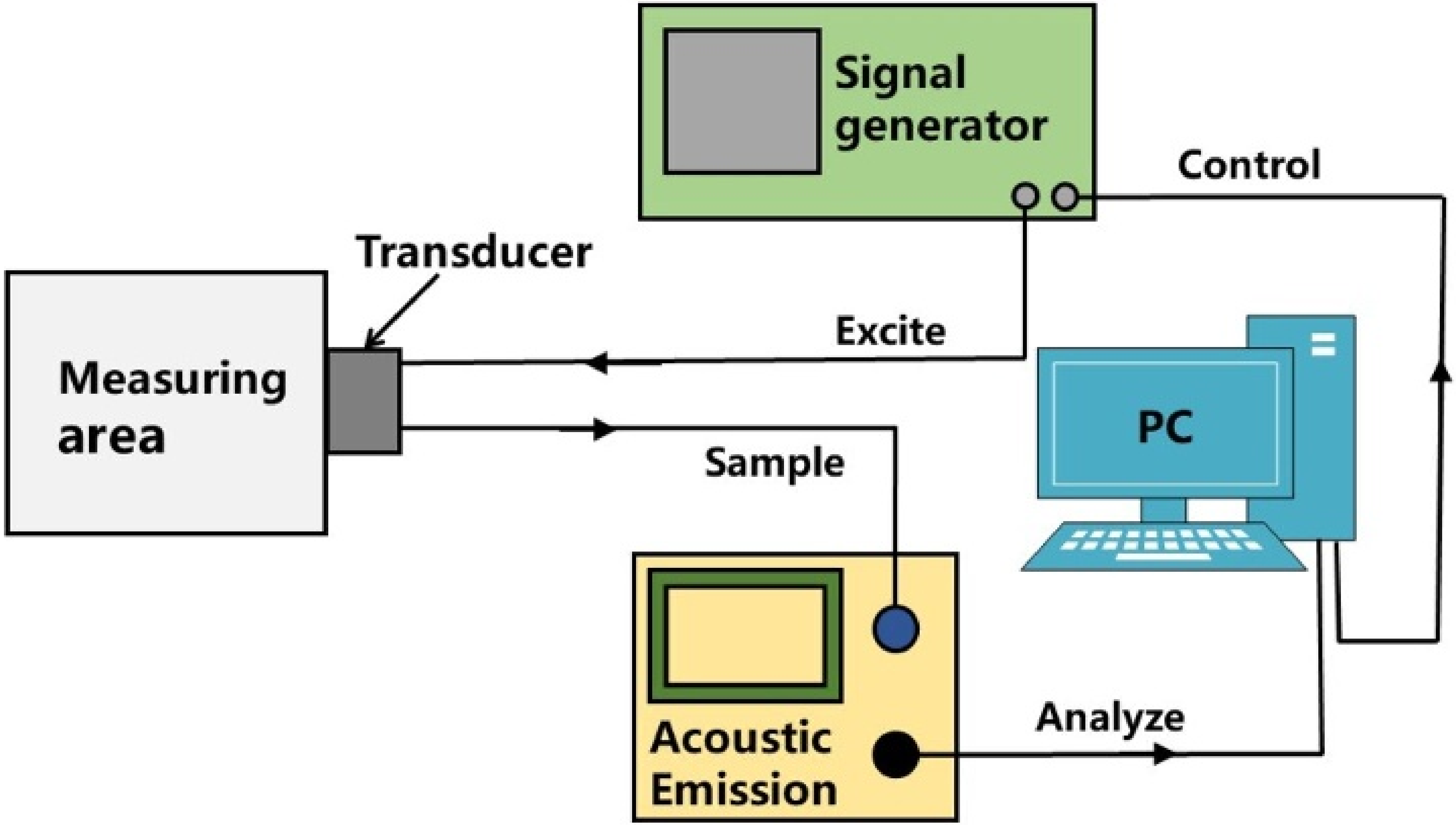
Receiver
(a)
Transmitter
(b)
Receiver
Transmitter/Receiver
(c)
Reflector
(d)
Transmitter
(e)
Receiver
Transmitter
(f)
Receiver
Transmitter
Primary
receiver
Auxiliary
receiver

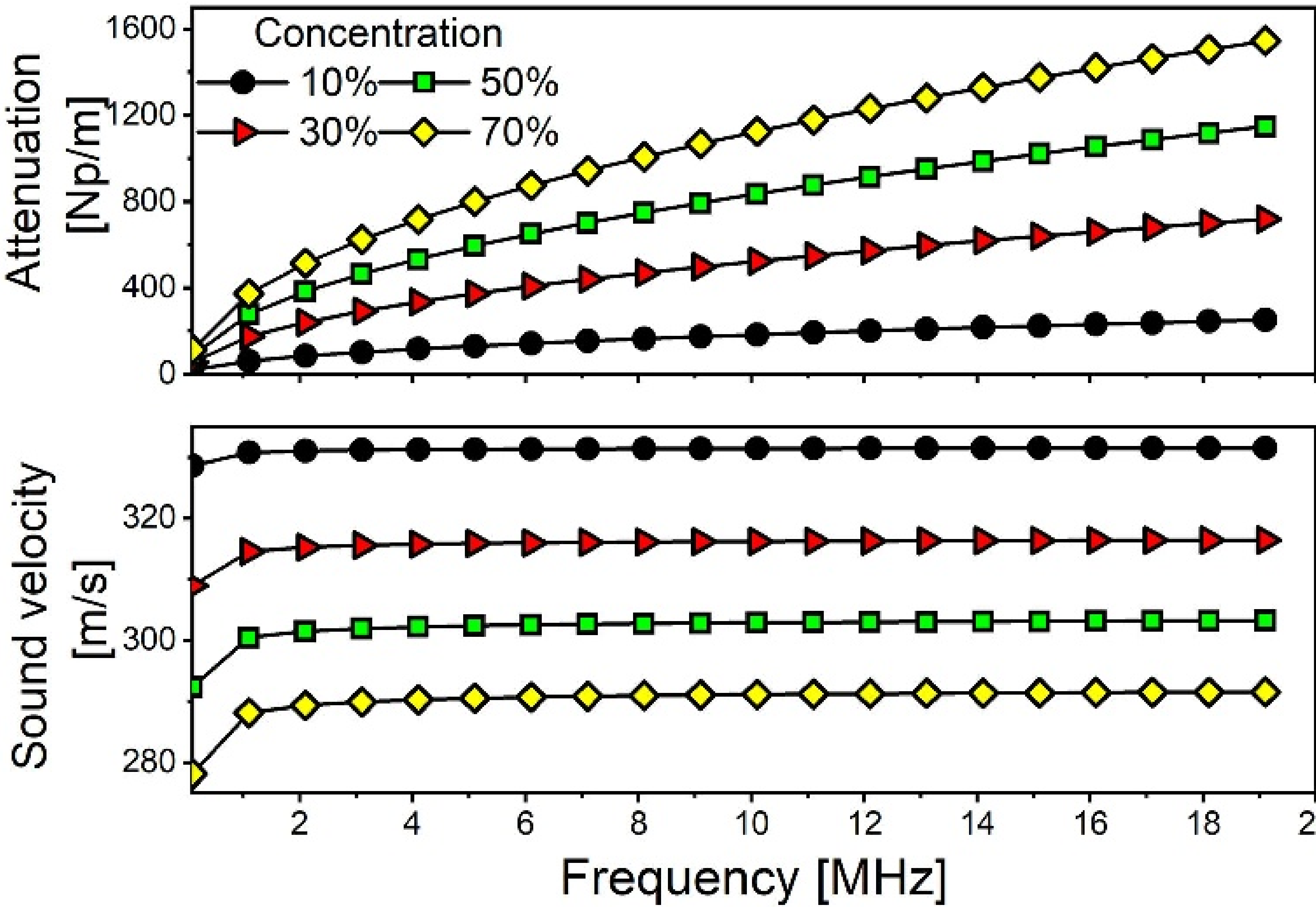

Ultrasonic transducer
Working medium
Working state
Energy conversion
Input power
Shape of transducer
Waveform
Vibration mode
Gas medium ultrasonic transducer
Liquid medium ultrasonic transducer
Solid medium ultrasonic transducer
Transmitting ultrasonic transducer
Receiving ultrasonic transducer
Transceiver ultrasonic transducer
Piezoelectric transducer
Magnetostrictive transducer
Electromagnetic acoustic transducer
Electrostatic transducer
Mechanical transducer
Power ultrasonic transducer
Detecting ultrasonic transducer
Pulse signal transducer
Modulating signal transducer
Continuous wave signal transducer
Rod-type transducer
Disc-type transducer
Cylindrical transducer
Spherical transducer
Compound ultrasonic transducer
Plane wave ultrasonic transducer
Spherical wave ultrasonic transducer
Cylindrical wave ultrasonic transducer
Focusing ultrasonic transducer
Array ultrasonic transducer
Longitudinal vibration transducer
Shear vibration transducer
Torsional vibration transducer
Flexural vibration transducer
Longitudinal-torsional transducer
Longitudinal-flexural transducer



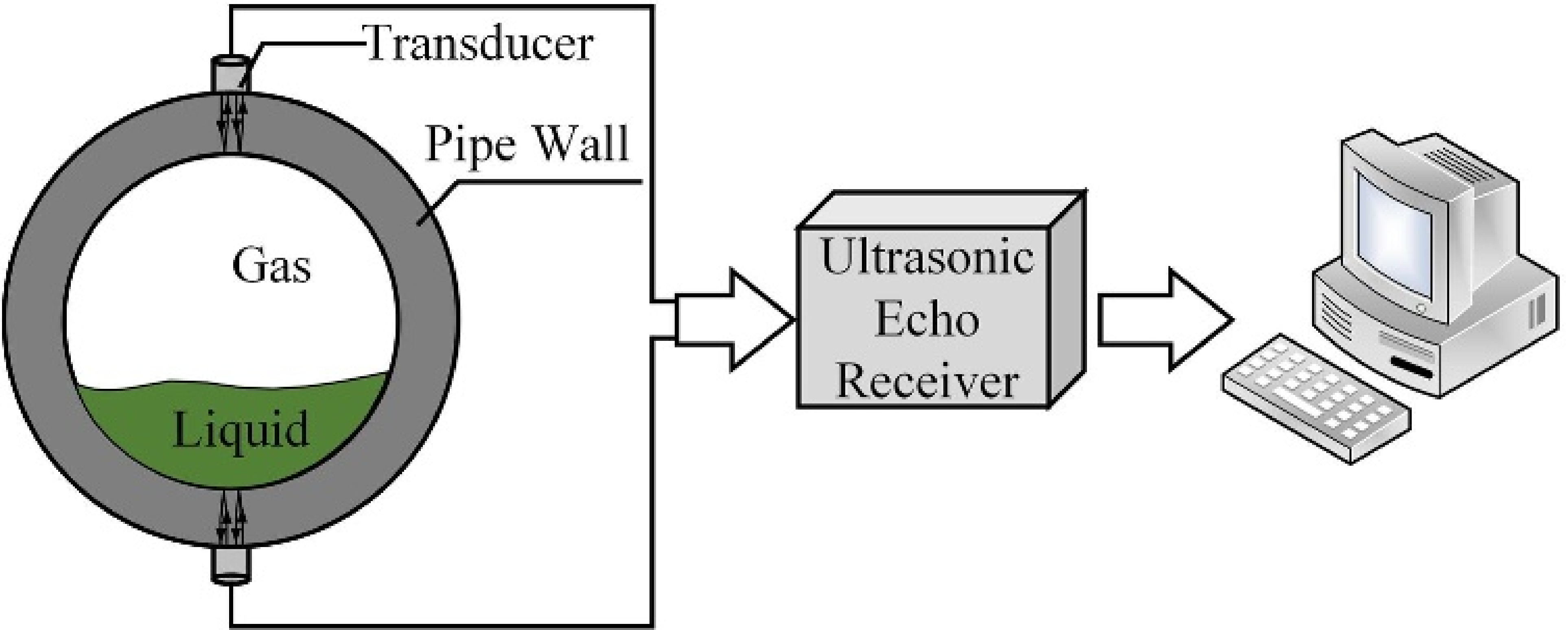

Receiving transducer
Pipeline
Amplifier
PC

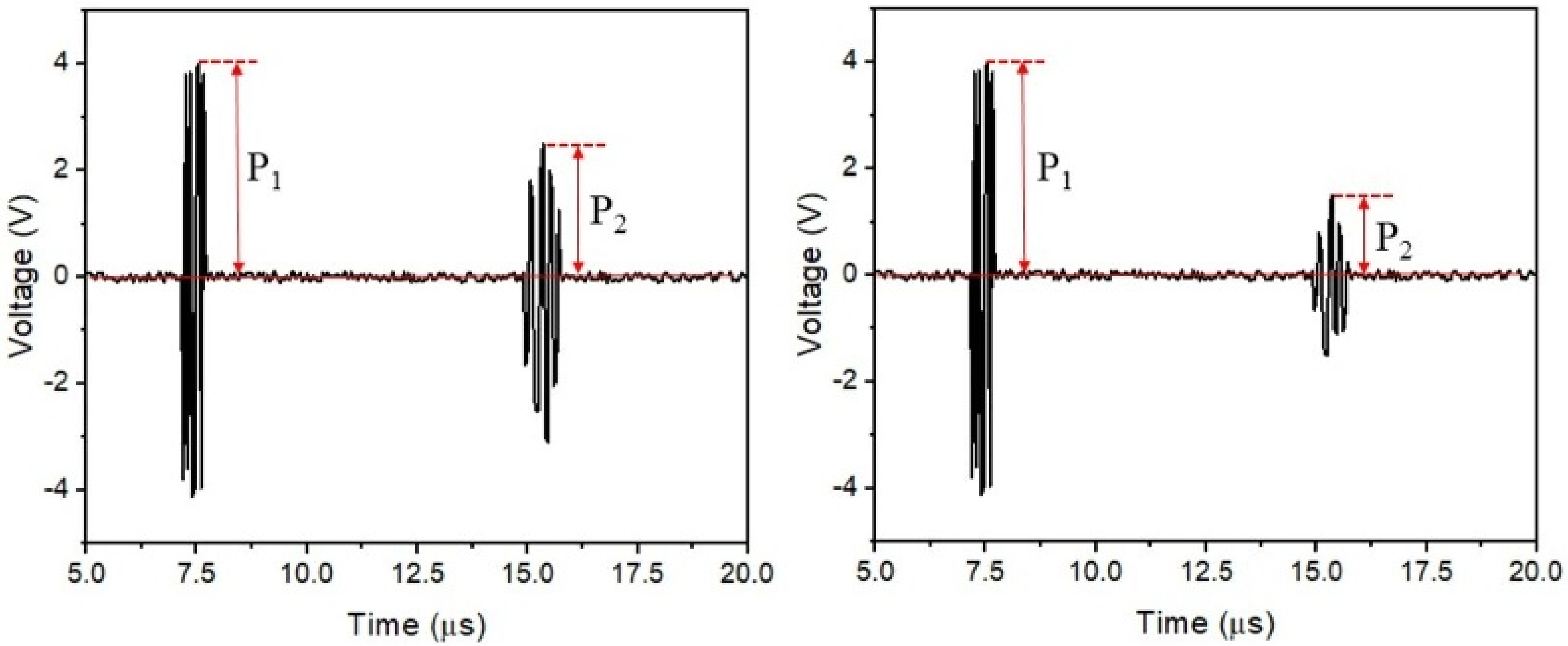

Physical parameters
Theoretical model
Theoretical sound attenuation spectrum
Preset concentration and particle size distributions
Matrix model
Measured acoustic attenuation spectrum
Data inversion
Optimal concentration and particle size distribution


Signal
generator
Control
Transducer
Excite
Measuring
area
PC
Sample
Acoustic
Emission
Analyze



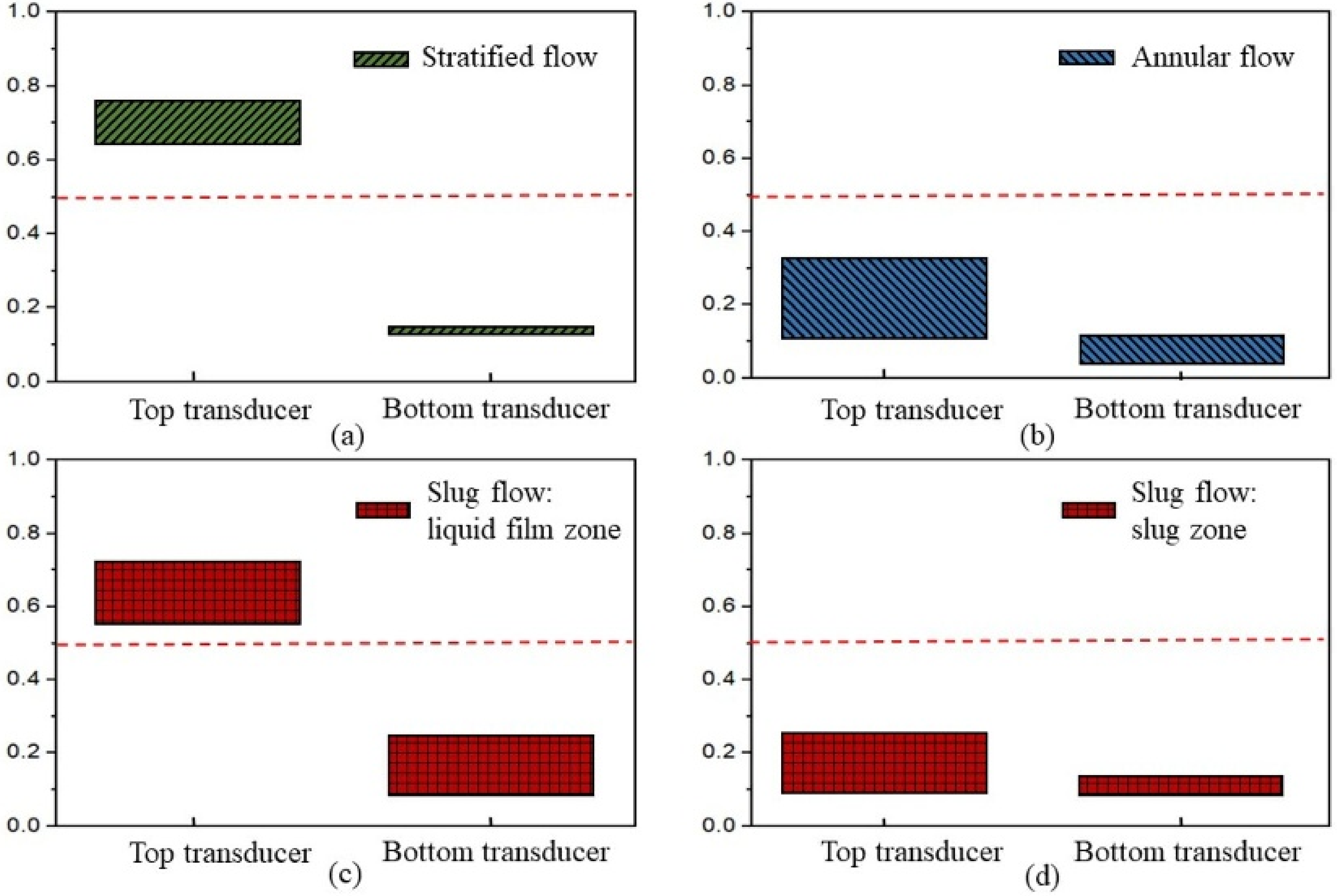
Concentration
10%
50%
30%
70%
Attenuation [Np/m]
0
400
800
1200
1600
Sound velocity [m/s]
280
300
320
2
4
6
8
10
12
14
16
18
20
Frequency [MHz]


Transducer
Pipe Wall
Gas
Liquid
Ultrasonic
Echo
Receiver

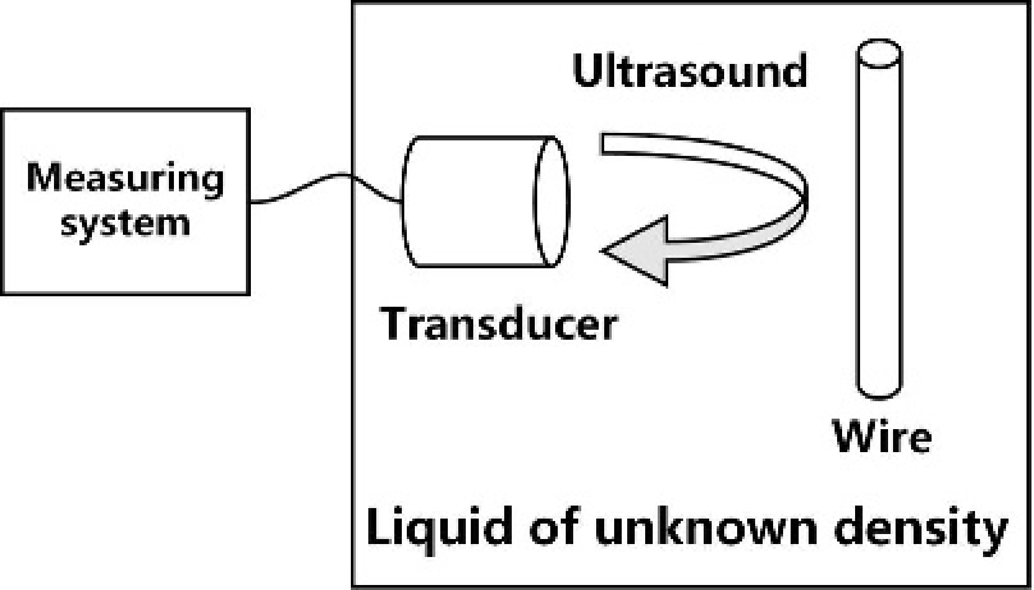


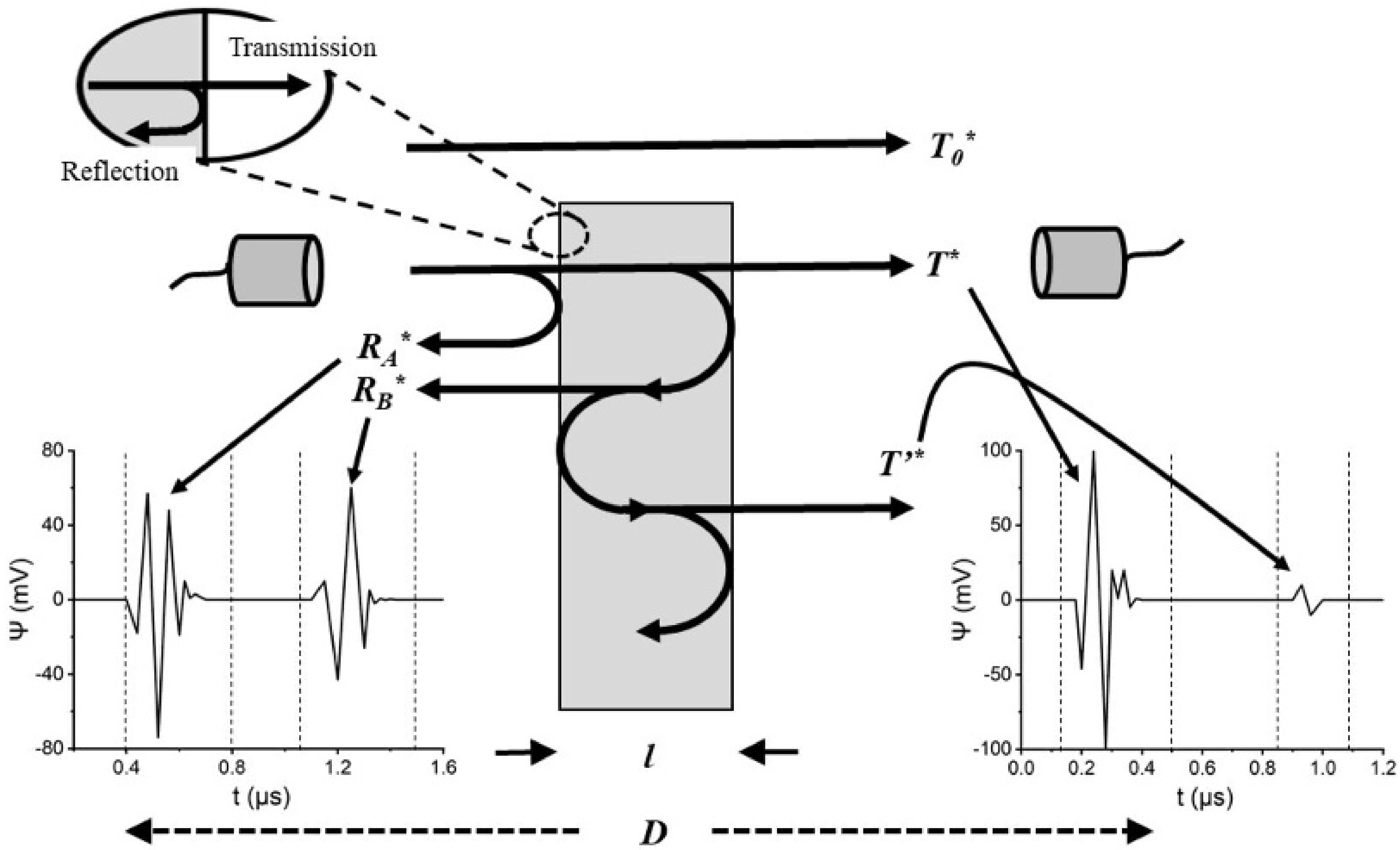
(a)

(b)

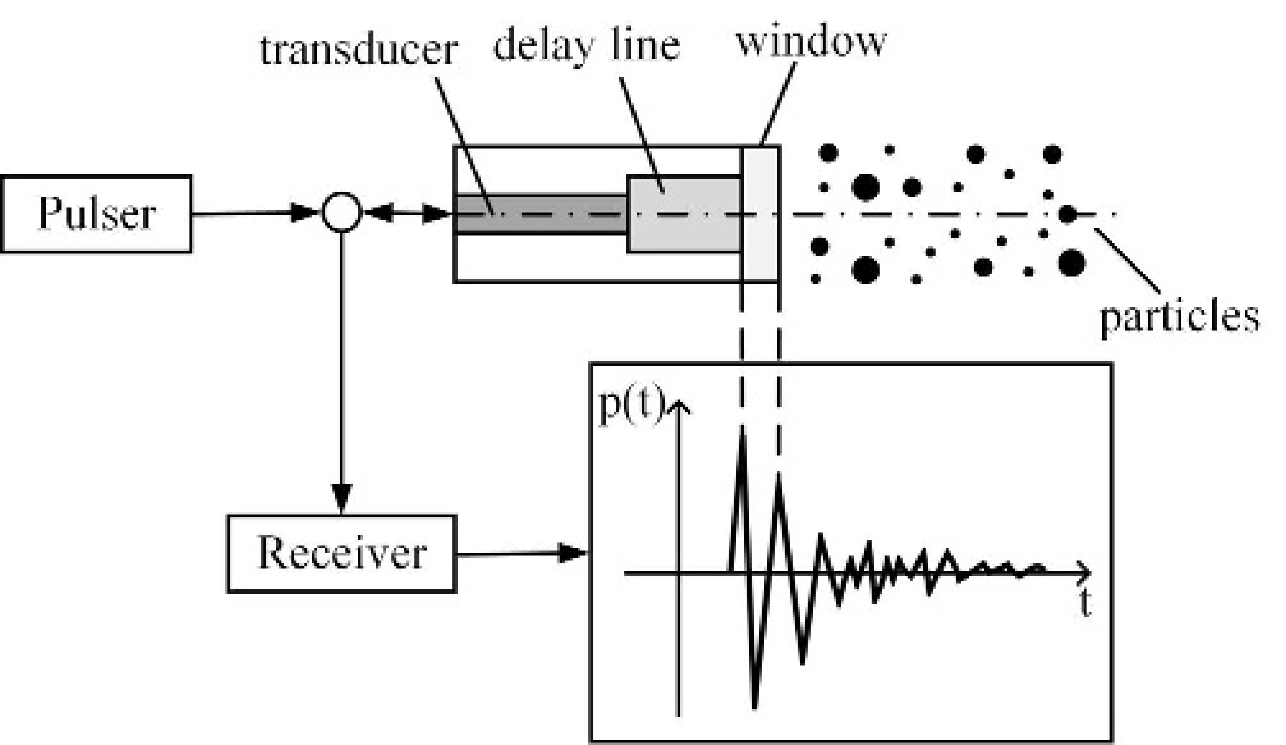


1.0
0.8
0.6
0.4
0.2
0.0
Stratified flow
Top transducer
Bottom transducer
(a)
Annular flow
Top transducer
Bottom transducer
(b)
Slug flow:
liquid film zone
Top transducer
Bottom transducer
(c)
Slug flow:
slug zone
Top transducer
Bottom transducer
(d)

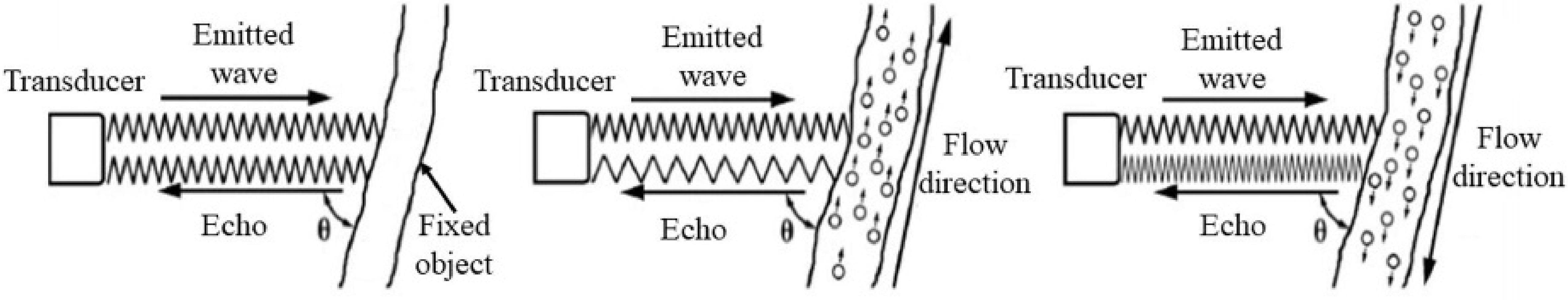

Measuring system
Ultrasound
Transducer
Wire
Liquid of unknown density



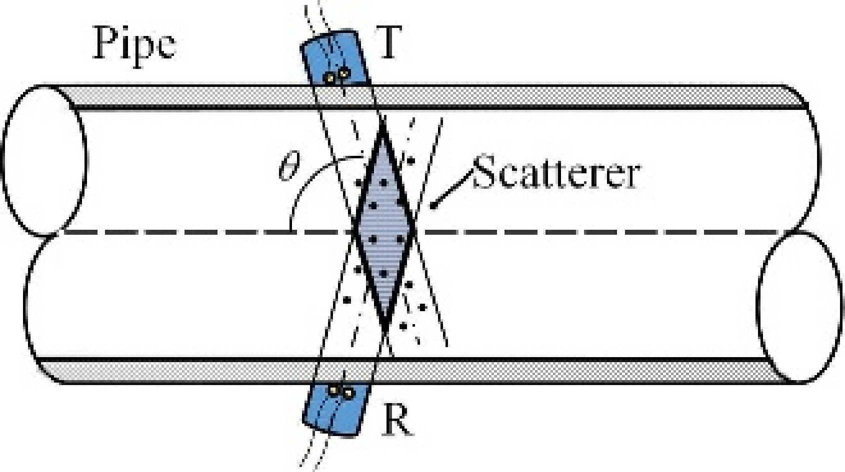
Transmission
Reflection
T_0^*
T^*
R_A^*
R_B^*
T'^*
Ψ (mV)
t (µs)
l
D

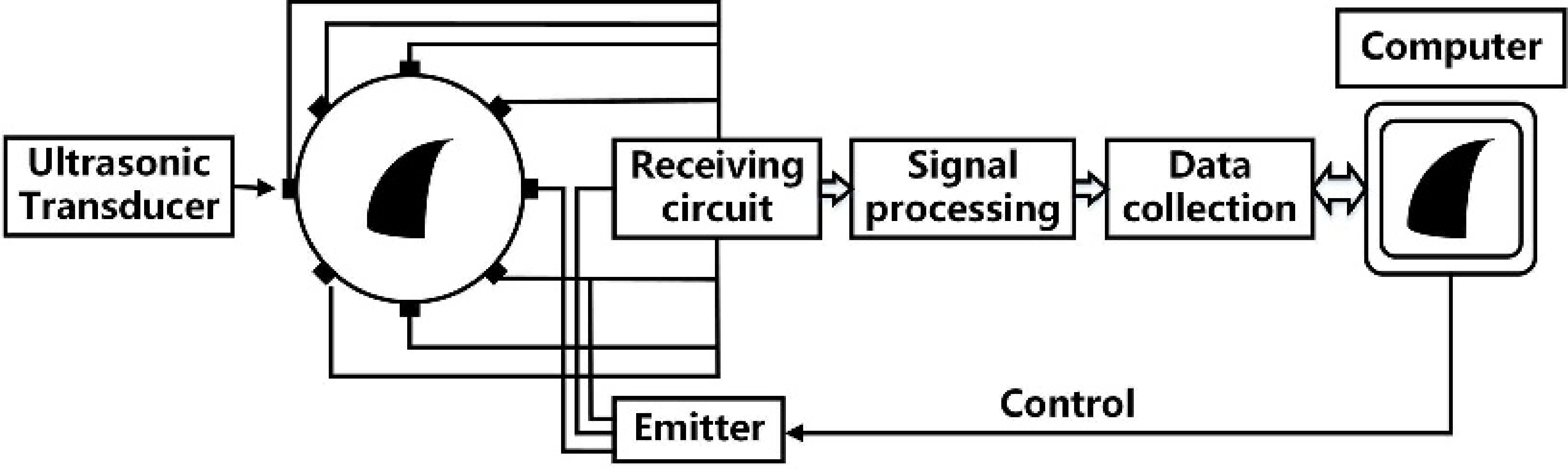


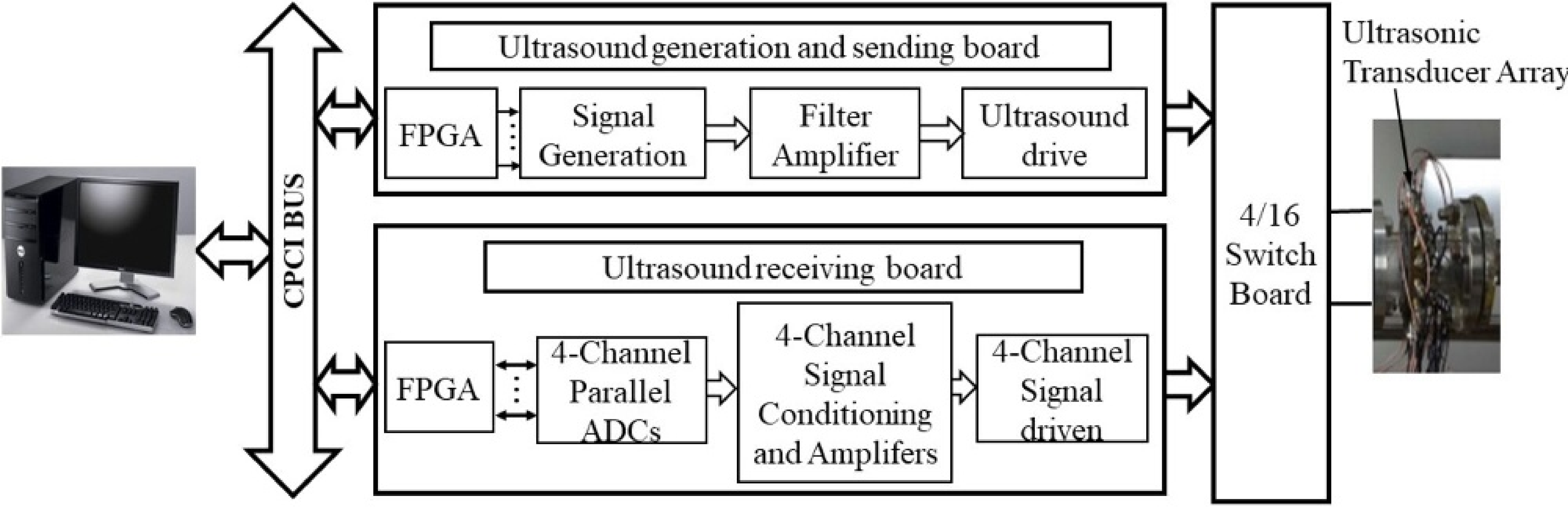
transducer
delay line
window
Pulser
particles
Receiver
p(t)
t

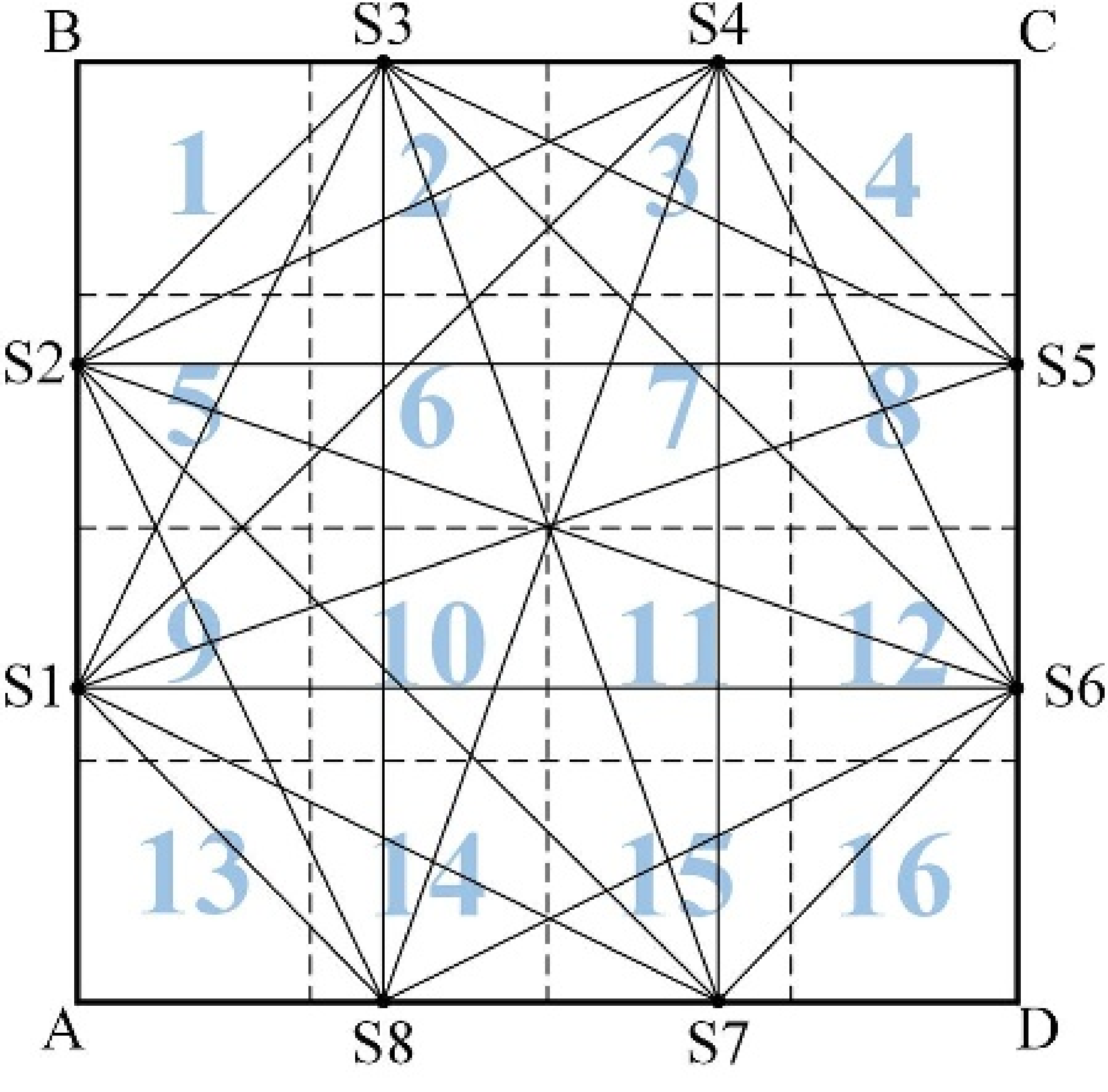

Transducer
Emitted wave
Echo
θ
Fixed object
Transducer
Emitted wave
Echo
θ
Flow direction
Transducer
Emitted wave
Echo
θ
Flow direction

(a) (b) (c)


Pipe
T
θ
Scatterer
R


Computer
Ultrasonic Transducer
Receiving circuit
Signal processing
Data collection
Emitter
Control


CPCI BUS
Ultrasound generation and sending board
FPGA
Signal Generation
Filter Amplifier
Ultrasound drive
Ultrasound receiving board
FPGA
4-Channel Parallel ADCs
4-Channel Signal Conditioning and Amplifers
4-Channel Signal driven
4/16 Switch Board
Ultrasonic Transducer Array



B
S3
S4
C
S2
S5
S1
S6
A
S8
S7
D
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16