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Application of Doppler ultrasound velocimetry in multiphase flow

Tiefeng Wang, Jinfu Wang*, Fei Ren, Yong Jin

Department of Chemical Engineering, Tsinghua University, Beijing 100084, PR China

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Abstract

This work aims to extend the application of a commercial Doppler ultrasound velocimetry DOP2000 (Model 2030, signal processing S.A.) to multiphase systems. We firstly make a correction to the determination of Doppler angle and measuring location taking into account the ultrasound refraction and the ultrasound velocity difference in different medias, and then investigate the measurement of the solid concentration in a liquid–solid system and the bubble behavior in a gas–liquid system with low gas holdup. The experimental results show that the attenuation coefficient increases monotonously. A model based on the ultrasound reflection and refraction law is proposed to predict the received echo energy in homogeneous liquid–solid system. Furthermore, the signal response of bubbles is also discussed. By placing the probe in the direction of the flow, the difficulty of determining Doppler angle is avoided and the liquid and bubble rise velocities are simultaneously obtained.

Keywords: Doppler ultrasound velocimetry; Doppler angle; Particle and liquid velocity; Bubble; Solid concentration

1. Introduction

Multiphase flow reactors have been widely used in environmental, chemical and biochemical processes in last decades [6–8]. Although multiphase reactors are successfully and widely used in commercial industrial operations, much remains to be done due to the complexity of the multiphase flow. In order to gain fundamental knowledge about the complex multiphase flow behavior, research is still needed, and experimental work is obviously necessary. Measurement technique is very important in the study and design of multiphase systems and much work has been carried out in this field, but it is still a challenging research field [5,21].

Quantities needed to be measured in fluidized beds include local solid concentration, particle velocities, gas holdup, bubble behavior, liquid velocity, and their radial and axial profiles inside the system [21]. The solid distribution within the reactor greatly affects its performance [13]. Therefore the degree of dispersion of the solid (catalyst) in the reactor must be understood and controlled for the optimum design and operation of gas–liquid–solid three-phase reactors. The bubble behavior, one of the most important parameters for the reactor simulation and design, is related to the phase holdup, interphase drag and mass transfer behavior [19]. For better understanding of the multiphase flow, the local solid concentration and bubble parameters rather than spatial averaged values are needed. Computational fluid dynamics (CFDs) has been extensively investigated in multiphase flow simulation in the last two decades, while most of the models available for closure of the governing equations need the relative velocity between phases to model drag and non-drag forces [18]. This relative velocity is limited in literature due to the difficulty of velocity measurements in multiphase flow. Typically, the gas phase is measured and the relative velocity is determined through a drift flux correlation. Therefore, development of measuring the phase velocity simultaneously is a valuable work.

Extensive investigations have been carried out in developing measurement technique for multiphase flows [5,10], but there is still a great gap between the development and the requirement. Most measuring techniques reported in the literature are limited to single parameter measurement, for example, reference [11] used a electrical conductivity probe to measure the solid concentration in the liquid–solid system. Yang et al. (1999) [24] used electrolyte tracer method to measure the local liquid velocity in a three-phase circulating fluidized bed (TPCFBs) [17], used a hot wire probe to measure the local liquid velocity in the riser of an external loop airlift reactor [19,20], used a optic probe to measure the local gas holdup and bubble behavior in TPCFBs, Vassallo et al. (1999) used laser Doppler velocity (LDV) to measure the liquid and gas velocity, and Mudde et al. [12] reported on

* Corresponding author. Tel.: +86-10-62785464;
fax: +86-10-62772051.
E-mail address: wangjf@flotu.org (J. Wang).

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Nomenclature

c ultrasound velocity
d_c distance from the sensor surface to the wall
d_l distance from the measuring volume to the wall by Eq. (13)
d_l' distance from the measuring volume to the wall by Eq. (12)
dt time span for receiving a emission
d_w thickness of the wall
f_d Doppler frequency
f_e frequency of the emitted ultrasound
f_p frequency of the ultrasound perceived by a moving particle
f_r frequency of the received ultrasound
i unit vector in the axial direction
j unit vector in the radial direction
k unit vector in the tangent direction
k_{bs} backscatter coefficient
k_i model parameters, $i = 1, 2, 3, 4$
s path length
Δt_i time increment between the emission and receiving
$\mathbf{u}_p$ velocity vector of the particle
u_{pd} projection of the particle velocity in the direction of the ultrasound beam
$\bar{u}$ mean velocity in **i** direction
u' fluctuating velocity in **i** direction
v' fluctuating velocity in **j** direction
w' fluctuating velocity in **k** direction
Z acoustic impedance

Greek letters
α sensor placing angle (in Fig. 2) or attenuation coefficient
β angle of ultrasound beam in the wall (in Fig. 2)
ε_s particle concentration
θ Doppler angle
ψ angle between the particle velocity and the axis

Subscripts
c coupling media
e emission
l liquid
p particle
r receiving
w wall

laser Doppler anemometer (LDA) experiments of measuring the liquid velocity field in a bubble column. Among these methods, electrolyte tracer method needs hundreds of tracer pulses and vast data acquisition, optic probe and hot wire are very fragile and need careful calibration, and LDV is expensive and only feasible in case of low solid and gas holdup. In recent years, ultrasound technique has drawn much attention as a non-intrusive and non-invasive measurement method due to its attractive advantages over the conventional techniques: (a) an efficient flow mapping process, (b) applicability to opaque systems and (c) a record of the spatiotemporal velocity [15]. Takeda [15] discussed the ultrasonic Doppler method for velocity profile measurement in fluid dynamics and fluid engineering. Soong et al. [13] measured the solid concentration in a slurry column; they developed an ultrasonic transmission technique to measure the solid concentration in a gas–liquid–solid bubble column reactor. Their results showed that the transit time could be correlated to the solid concentration, however their method could only measured the average solid concentration between the transmitter and the receiver. Carlson and Grenberg [4] proposed a method to measure the solid concentration in a multiphase flow with pulsed ultrasound based on the changes of the received energy slope. They used two small receivers and correlated the solid concentration to the average energy ratio received by the two receivers, and found a linear relationship within the solid mass fraction range 3–15%. But for the concentrations below 3%, their method could not give accurate results. Bröring et al. [2] and Camarasa et al. [3] used the ultrasound Doppler technique to measure the bubble rise velocity, whereas the determination of the Doppler angle was questionable. Stolojanu and Prakash [14] investigated the feasibility of measuring concentrations of solids and bubbles in two- and three-phase systems. Their results show that in liquid–solid system both transmission time and amplitude ratio varies systemically with solid concentration. In presence of gas bubbles the variation of transmission time is not very regular while the relationship between attenuation of sound and phase holdups remain systematic.

Generally, two configurations are used in the literature, namely pitch-and-catch and pulse-echo configurations [1]. In the investigations reviewed above, all the reported measurements of the phase holdup adopted the pitch-and-catch configuration and plug-in manner, while the pulse-echo which can be used in a non-intrusive manner, is mainly limited to the velocity measurement. So development of measuring methods for the phase holdup and the phase velocity simultaneously with a pulse-echo ultrasound sensor is a valuable work. Commercial Doppler ultrasound velocimetry is available, but it only provides limited function of measuring particle velocity in a liquid–solid system. If the particle size is small enough, this velocity can be considered as the liquid velocity. A commercial device Doppler ultrasound velocimetry DOP2000 is used in our investigation.

This work aims to extend its application to multiphase flows, developing ultrasound methods to measure the solid holdup in a liquid–solid system non-intrusively and to measure the liquid and bubble velocities simultaneously in gas–liquid system. Our investigation shows that the attenuation coefficient of the received echo energy monotonously increases with the increase of solid concentration, providing a method to measure the solid concentration. A model based on the ultrasound reflection and refraction law predicts the received echo energy in a good agreement with the experimental results. To measure the bubble behavior in gas–liquid or gas–liquid–solid system, it is commended to place the sensor probe in the flow direction in order to avoid the difficulty of determination of the Doppler angle. This work shows that the ultrasound Doppler velocimetry has powerful potential for mapping the flow field and phase structure in multiphase flow.

2. Algorithm and modeling

2.1. Principle of Doppler ultrasound method

DOP2000 measures the particle velocity using the Doppler effect. When the ultrasound probe emits an ultrasound beam, the moving particles scatter the ultrasound wave. Partial backscattered ultrasound is then received by the same sensor probe. The movement of the particle subjects the received ultrasound to a frequency shift proportional to the particle velocity, as shown in Fig. 1. The frequency of the ultrasound perceived by the moving particles is

$$f_p = f_e - \frac{f_e|\mathbf{u}_p|\cos\theta}{c} \quad (1)$$

and the frequency of the ultrasound received by the stationary sensor probe is

$$f_r = \frac{c}{c + |\mathbf{u}_p|\cos\theta} f_p \quad (2)$$

Combination of Eqs. (1) and (2) and considering that $|\mathbf{u}_p|$ is usually much less than c yields

$$f_d = f_e - f_r \approx \frac{2 f_e|\mathbf{u}_p|\cos\theta}{c} \quad (3)$$

From the received echo signal the Doppler frequency is estimated and then the particle velocity is calculated using Eq. (3).

2.2. Determination of Doppler angle

Accurate determination of the Doppler angle is a key problem for the Doppler ultrasound velocimetry application. It should be pointed out that the Doppler angle in Eq. (3) refers to the angle θ between the particle velocity and the ultrasound beam, not the angle α between the probe and the column wall, as shown in Fig. 2. The relationship between α and θ can be determined based on the ultrasound refraction law. Similar to the light refraction law, the following two equations hold for the refraction at the outside and the inside interface of the wall, respectively,

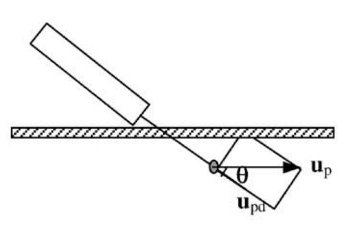

Fig. 1. Doppler effect caused by the moving particle.

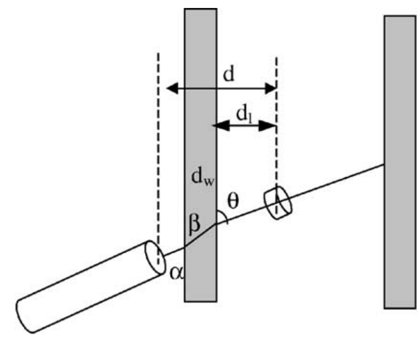

Fig. 2. Determination of the measuring location taking into account the ultrasound refraction and ultrasound velocity difference.

$$\frac{c_c}{c_w} = \frac{\cos\alpha}{\cos\beta} \quad (4)$$

$$\frac{c_w}{c_l} = \frac{\cos\beta}{\cos\theta} \quad (5)$$

Combination of Eqs. (4) and (5) yields

$$\cos\theta = \frac{c_l}{c_c}\cos\alpha \quad (6)$$

where the ultrasound velocity c and the sensor placing angle α can be measured. Therefore, the Doppler angle can be determined by Eq. (6). The coupling media we used is ultragel with ultrasound velocity about 1500 m/s, very close to that in the water, so when the liquid is water, the difference between α and θ can be ignored. However, when the liquid has an ultrasound velocity quite different from that in ultragel, take olefin as an example, it is absolutely necessary to consider the difference between the sensor placing angle and the Doppler angle.

2.3. Treatment of Doppler angle in turbulent flow

In a laminar flow, the tracer particle velocities remain constant both in amplitude and in direction, so the Doppler angle is invariant and easy to determine by Eq. (6). While in a turbulent flow, the turbulence makes the instantaneous Doppler angle time-dependent and almost impossible to determine. Here we make some discussions about the time-averaged Doppler angle. For a fully developed turbulent flow in a vertical tube, the instantaneous velocity can be denoted by

$$\mathbf{u}_p = (\bar{u} + u')\mathbf{i} + v'\mathbf{j} + w'\mathbf{k} \quad (7)$$

where u', v', and w' are the fluctuating velocity in the directions $\mathbf{i}$, $\mathbf{j}$, and $\mathbf{k}$, respectively. Only the projection of $\mathbf{u}_p$ in the

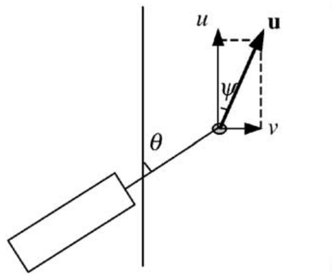

Fig. 3. Projection of the instantaneous particle velocity in the direction of the ultrasound beam.

direction of the ultrasound beam u_{pd} influences the Doppler frequency. Referring to Fig. 3, u_{pd} and can be determined by

$$u_{pd} = u\cos\theta + v\sin\theta = |\mathbf{u}_p|\cos(\theta - \psi) \quad (8)$$

and the average Doppler frequency follows:

$$\bar{f}_d = \frac{2f_e\bar{u}_{pd}}{c} = \frac{2f_e\bar{u}\cos\theta}{c} \quad (9)$$

Eq. (9) shows that the fluctuating velocities in **j** and **k** directions have no influence on the time-averaged Doppler frequency; therefore the average axial velocity can be calculated by replacing the time-dependent Doppler frequency by time-averaged Doppler frequency. This can be realized by averaging enough velocity profiles.

2.4. Determination of measuring location

DOP2000 is a non-intrusive device and the probe is fixed onto the Plexiglas tube with a coupling media. In this case an ultrasound beam passes through media with different ultrasound velocities: the coupling media from the probe to the tube wall, with c_c; the tube wall medium, with c_w; and the liquid flowing in the tube, with c_l, as shown in Fig. 2. In a pulse-echo ultrasound probe, ultrasound waves are pulsed continuously. Immediately after emitting a pulse, the system is then switched to the receiving mode. At specific time increments Δt_i the echoes backscattered from the particles are detected for a time span dt ($dt \ll \Delta t_i$), i.e. from Δt_i to $\Delta t_i + dt$ so the measuring volume is a cylindrical slab of diameter d (approximately the same as the probe diameter) and height $h = c_l\,dt$. Referring to Fig. 2, the time interval Δt_i can be expressed as

$$\frac{\Delta t_i}{2} = t_c + t_w + t_l = \frac{d_c/\sin\alpha}{c_c} + \frac{d_w/\sin\beta}{c_w} + \frac{d_l/\sin\theta}{c_l} \quad (10)$$

In the commercial software provided with the DOP2000 equipment, the ultrasound refraction at the interface and the ultrasound velocity difference in different media are not considered, as shown in Fig. 4. The following equation is used in the commercial software:

$$\frac{\Delta t_i}{2} = \frac{d_c + d_w + d_l'}{c_l\sin\alpha} \quad (11)$$

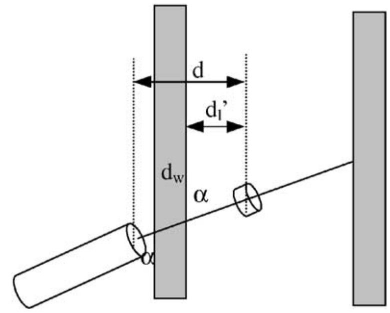

Fig. 4. Determination of the measuring location without taking into accounts the ultrasound refraction and ultrasound velocity difference.

Therefore, the commercial software calculates the location of the measuring volume d incorrectly as d':

$$d' = d_c + d_w + d_l' = \tfrac{1}{2}c_l\,\Delta t_i\sin\alpha \quad (12)$$

However, Eq. (8) provides the time information Δt_i. Substituting Δt_i into Eq. (7) yields

$$d = d_c + d_w + d_l = d_c + d_w + \left(\frac{d'}{c_l\sin\alpha} - \frac{d_c}{c_c\sin\alpha} - \frac{d_w}{c_w\sin\beta}\right)c_l\sin\theta \quad (13)$$

Thus, the correct measuring location can be obtained by modifying the DOP2000 calculated value through Eq. (13). Fig. 5 demonstrates the difference between the measuring location calculated by the DOP2000 software and by modifying Eq. (13). The difference between the two values is dependent on the ultrasound velocities in the coupling media, the wall material and the liquid. The larger is the difference among c_l, c_c and c_w, the larger is the difference between d and d_l'.

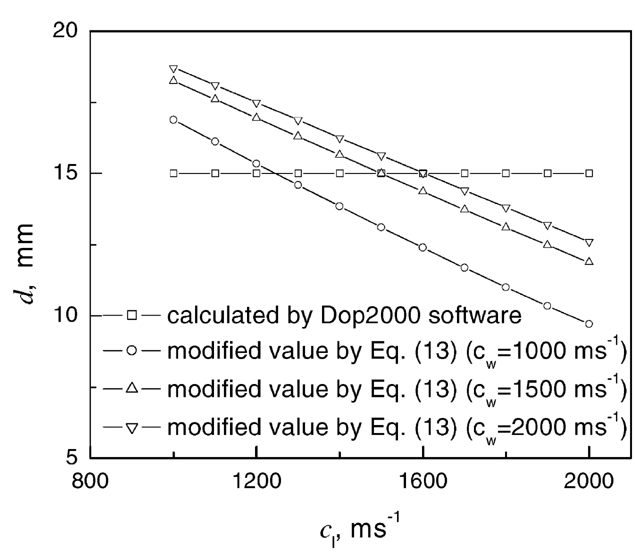

Fig. 5. Comparison between the calculated measuring location by Doppler software and by Eq. (13) under different ultrasound velocity in the wall material ($c_c = 1500$ m/s, $d_0 = 2$ mm, $d_w = 5$ mm).

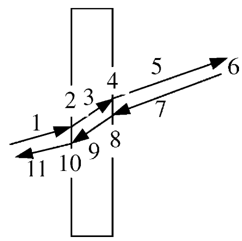

Fig. 6. Processes involved during the ultrasound emission and receiving.

Notice that the measuring volume has limited dimensions and the measuring location is associated with the center of the measuring volume, special modification should be made to the near-wall region, Wunderlich and Brunn [23] made detailed discussion on the near-wall effect and proposed a modification model.

2.5. Solid concentration measurement and modeling

In pulse-echo manner, the received echo energy is mainly influenced by the emission power, the solid concentration and the distance from the measuring volume to the probe. During the ultrasound emission and receiving, the following processes are involved, as shown in Fig. 6:

(1) Propagation in the coupling media.
(2) Refraction and reflection at the interface of the outside wall.
(3) Propagation in the wall material.
(4) Refraction and reflection at the interface of the inside wall.
(5) Propagation in the fluid.
(6) Backscattered by the particles.
(7)–(11) Receiving the backscattered ultrasound by the same sensor through processes similar to (1)–(6).

In a homogeneous liquid–solid system, the variations of the ultrasound intensity in each process are expressed in Table 1 [1], where α_c, α_w and α_l are the attenuation coefficients of the coupling media, the wall material and the fluid, respectively, Z_c, Z_w, and Z_l are acoustic impedances, and $k_{bs}(\varepsilon_s)$ is the backscatter coefficient, which is dependent on the solid concentration. In Eqs. (15), (17), (21) and (23), ζ is the modifying coefficient of oblique incidence to the normal case, which is constant when the incident angle is invariant. Among the parameters involved in Eqs. (14)–(24), only α_l and k_{bs} are dependent on the solid concentration. Therefore, combination of Eqs. (14)–(24) yields the relationship between the emitted and the received ultrasound intensity:

$$\frac{I_r}{I_e} = K(\varepsilon_s)\exp(-\alpha(\varepsilon_s)s_l) \quad (25)$$

where the correlations of $K(\varepsilon_s)$ and $\alpha(\varepsilon_s)$ should be specified. The experimental results of [9] show that the attenuation of the suspension in case of ultrasound with several MHz can be correlated as

$$\alpha(\varepsilon_s) = \frac{k_1\varepsilon_s}{k_2 + \varepsilon_s} \quad (26)$$

Eq. (26) describes a linear relationship in low ε_s range and an increase with diminishing rate in medium and high ε_s range. This is reasonable taking into account the multiple-particle effect.

When the solid concentration is very low, each particle backscatters the ultrasound independently, so the backscatter coefficient should be proportional to the solid concentration. With the increase of the solid concentration, the backscattered ultrasound may be scattered by other particles and cannot reach the receiver, thus the efficient backscatter has a gradually reduced increasing rate similar to $\alpha(\varepsilon_s)$. Therefore, a correlation with the same form as $\alpha(\varepsilon_s)$ is used to describe the dependence of $K(\varepsilon_s)$ on the solid concentration:

$$K(\varepsilon_s) = \frac{k_3\varepsilon_s}{k_4 + \varepsilon_s} \quad (27)$$

As a result, the received ultrasound intensity can be predicted by

$$\frac{I_r}{I_e} = \frac{k_3\varepsilon_s}{k_4 + \varepsilon_s}\exp\left(-\frac{k_1\varepsilon_s s_l}{k_2 + \varepsilon_s}\right) \quad (28)$$

Table 1
Variations of the ultrasound intensity in processes involved during ultrasound emission and receiving

$\frac{I_1}{I_0} = \exp(-\alpha_c s_c)$	(14)
$\frac{I_2}{I_1} = \zeta_1 \frac{4Z_c Z_w}{Z_c^2 + Z_w^2}$	(15)
$\frac{I_3}{I_2} = \exp(-\alpha_w s_w)$	(16)
$\frac{I_4}{I_3} = \zeta_3 \frac{4Z_l Z_w}{Z_w^2 + Z_l^2}$	(17)
$\frac{I_5}{I_4} = \exp(-\alpha_l(\varepsilon_s) s_l)$	(18)
$\frac{I_6}{I_5} = k_{bs}(\varepsilon_s)$	(19)
$\frac{I_7}{I_6} = \exp(-\alpha_l(\varepsilon_s) s_l)$	(20)
$\frac{I_8}{I_7} = \zeta_7 \frac{4Z_w Z_l}{Z_w^2 + Z_l^2}$	(21)
$\frac{I_9}{I_8} = \exp(-\alpha_w s_w)$	(22)
$\frac{I_{10}}{I_9} = \zeta_9 \frac{4Z_c Z_w}{Z_c^2 + Z_w^2}$	(23)
$\frac{I_{11}}{I_{10}} = \exp(-\alpha_c s_c)$	(24)

3. Experimental setup

A schematic diagram of the experimental apparatus is shown in Fig. 7. It can be operated in both gas–liquid and

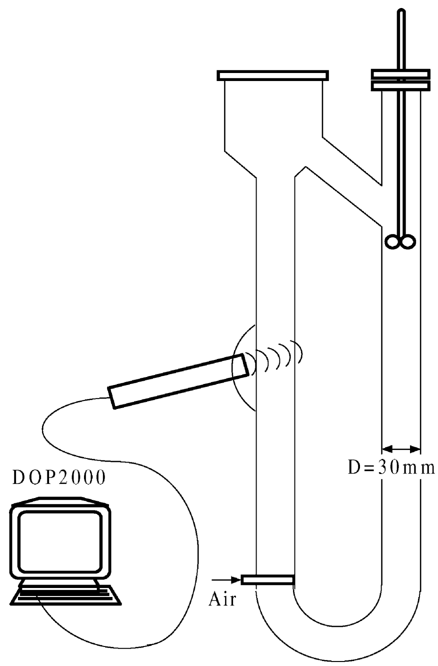

Fig. 7. Scheme of the experimental setup.

liquid–solid mode. Tap water and air are used as the liquid and gas phase, respectively. FCC of diameter 60 μm and density 2460 kg/m^3 is used as the particle phase. In the gas–liquid mode, air is pumped into the column from the bottom, distributed by a perforated-plate gas distributor. Due to the density difference between the riser and downer, liquid circulation is formed. In the liquid–solid mode, the liquid circulation is driven by the impeller. The liquid velocity can be adjusted by controlling the gas rate and the impeller rotating speed. Doppler ultrasound velocimetry DOP2000 is used to measure the liquid velocity profile, the solid concentration, and the bubble behavior under different liquid velocity and solid concentration.

4. Results and discussion

4.1. Influence of tracer particle and wall effect

When DOP2000 is used to measure the liquid velocity, it is necessary to add a certain amount of tracer particles into the liquid so that the received echo energy is strong enough to estimate the Doppler frequency. Figs. 8 and 9 illustrate the influence of the tracer particles on the measured profile of the liquid velocity and the received echo energy. When no particles are added into the water, only the impurities contained in the water backscatter the ultrasound. The signal-to-noise of the received echo is not strong enough to estimate the Doppler frequency reliably and incorrect velocities are obtained. The velocity profiles for particle concentration 0.011 and 0.022 kg/l are superposed, indicating that in a certain range of low particle concentrations the measured velocity is independent on the particle concentration. The measured velocity profile of particle concentration 0.033 kg/l decreases slightly, because when the particle concentration exceeds a certain range, the suspension viscosity increases resulting a decrease in the liquid circulating velocity decreases. Above discussion shows that an appropriate amount of the tracer particle should be chosen so that the received echo energy is high enough to estimate the Doppler frequency on one hand and does not change the property of the measured system on the other hand.

Due to the wall effect, two wall regions with irregular profile exist, as shown in Figs. 8 and 9. In the wall region I,

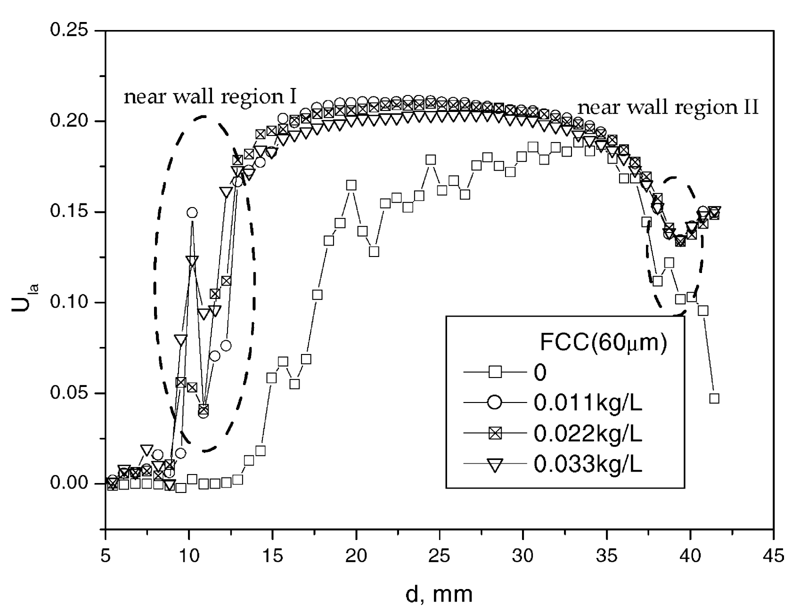

Fig. 8. Influence of the particle concentration on the velocity profile measurement.

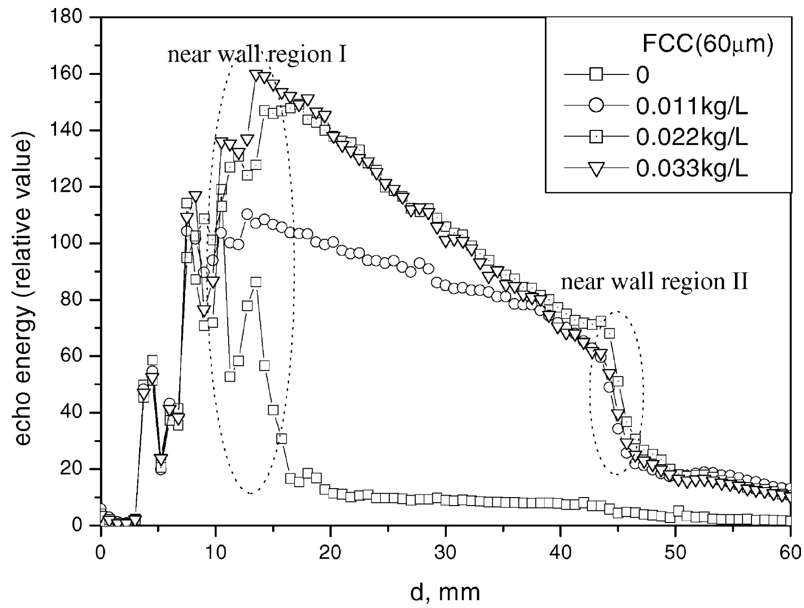

Fig. 9. Influence of the particle concentration on the received echo energy profile.

saturation generated by the sensor ring effect and multiple reflection by the wall make the results unreliable. These effects reduce when the tube is large, as shown in Fig. 10, indicating that measurement in the wall region I is improved in a larger diameter tube. In the wall region II, the reflection by the far wall will influence the velocity profile. As shown in Fig. 11, if the ultrasound beam BC forward-scattered by a particle is reflected by the far interface of the wall, the depth associated to the path ABC is located outside the flowing liquid. Imaginary velocity components are added to the real velocity profile. The velocity measurement near the far interface is affected by this phenomenon; therefore, it is common to obtain a non-zero velocity at the far wall, as shown in Fig. 11.

4.2. Liquid velocity measurement

DOP2000 is used to measure the velocity radial profile of the laminar and turbulent flow in a vertical tube and the velocity is the mean value of 1000 profiles. In Fig. 12, olefin is used as the fluid. The Reynolds number is about 1600, so the flow is laminar. Good agreement is obtained between the experimental results and parabolic fit, as shown in Fig. 12. It can be seen that DOP2000 has high spatial resolution and

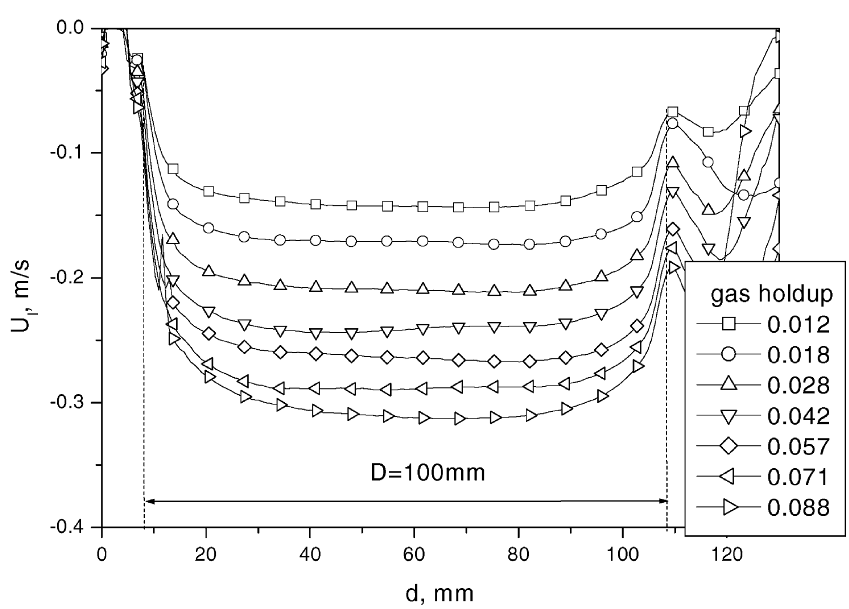

Fig. 10. Measured radial velocity profile in a vertical tube with i.d. 100 mm.

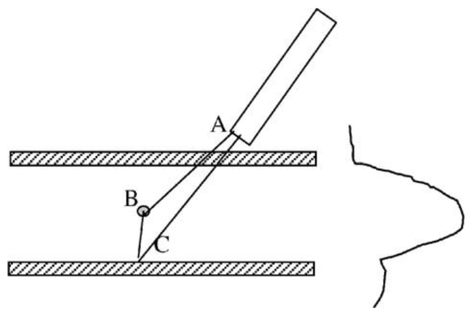

Fig. 11. Wall reflection effect to the velocity profile near the far wall.

accuracy. In Fig. 8, water is used as the fluid. The Reynolds number is about 4500 and the flow is turbulent. The experimental results indicate a typical turbulent velocity profile.

4.3. Measuring solid concentration in liquid–solid system

Experiments are carried out with solid concentration from 0 to 0.045 kg/l. Fig. 13 shows the received echo energy profiles under different solid concentration. With the increase of the solid concentration, the amplitude of the received echo energy increases and then decreases, while the attenuation coefficient increases monotonously, in accordance with the results of results of [9,25]. With the increase of the particle concentration in the suspension, both the backscatter coefficient and the attenuation coefficient increases with a gradually decreased rate. In low particle solid concentration range, the increase of the backscatter coefficient is the dominant factor, while the increase of the attenuation coefficient becomes dominant when the solid concentration exceeds a certain value, resulting in maximum amplitude of the received echo energy, in accordance with the result of [22]. The monotonous variation of the attenuation coefficient can be used to measure the solid concentration with a calibration curve. It is advantageous that the attenuation coefficient is only influenced by the solid concentration, thus a calibration curve can be used for the same liquid–solid system despite different emission power and contact status.

The received echo energy profile in homogenous liquid–solid system consists of three regions, the near sensor region (NSR), the exponential attenuation region (EAR), and outside the far wall region (OFWR). NSR includes the coupling media, the tube wall and a small part of the flow region, with irregular profile due to the wall effect. EAR reflects the attenuation characteristic of the suspension, which in turn corresponds to the solid concentration. Fig. 14 shows the logarithmic attenuation of the received echo energy under different solid concentrations. For homogenous liquid–solid system, the lines in Fig. 14 are linear with the absolute value of the slop increasing with the increase the solid concentration. For a system with non-uniform radial profile of the solid concentration, the plug-in manner may be a good choice to get accurate results in the near-wall region, as shown in Fig. 15. The ultrasound probe can detect the solid concentration with a depth up to several centimeters even in a high solid concentration. Therefore, the disturbance of the probe to the flow field is neglectable. The predictions by the developed model are compared to the experimental results, as shown in Fig. 16. Good agreement between the predictions and the experimental results is obtained.

4.4. Measuring bubble behavior in gas–liquid system

Compared to the liquid–solid system, the gas–liquid and gas–liquid–solid systems are much more complex. The

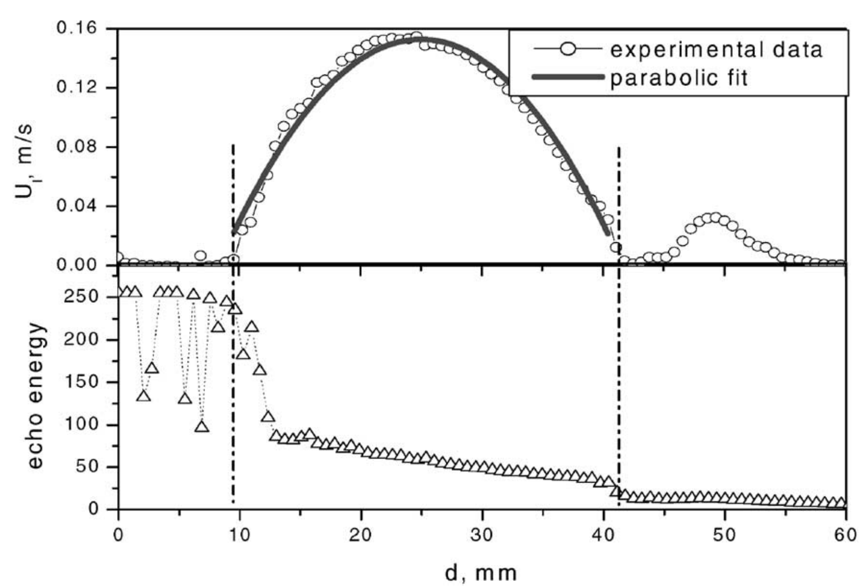

Fig. 12. Measured radial velocity profile and received echo energy of laminar flow in a vertical tube.

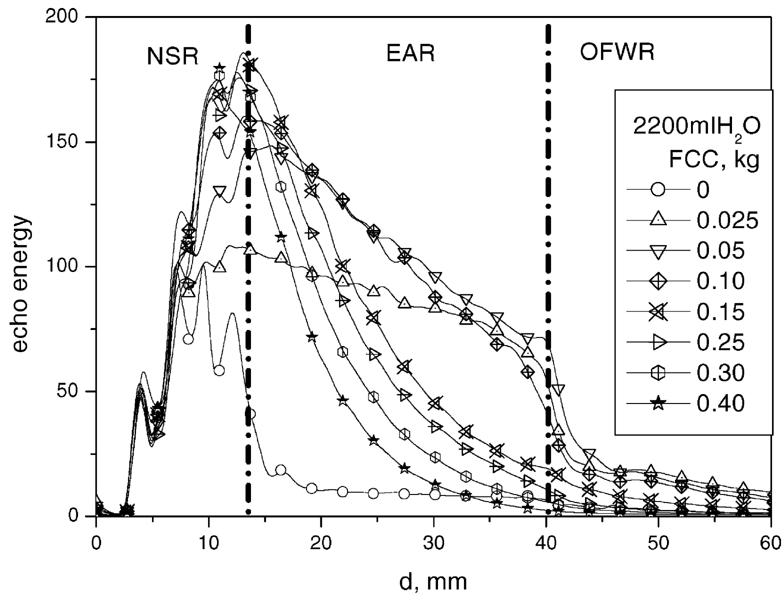

Fig. 13. Radial profiles of the received echo energy in homogenous liquid–solid system under different solid concentrations.

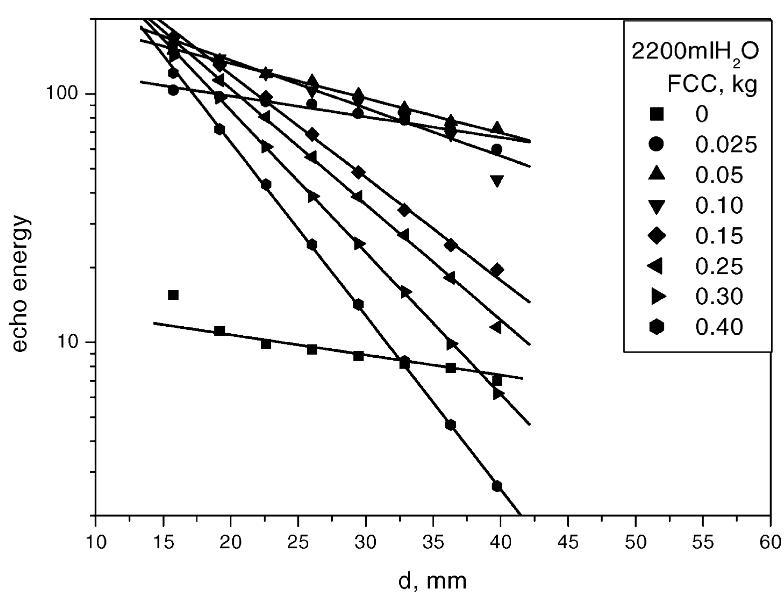

Fig. 14. Radial profiles of the logarithmic received echo energy in EAR.

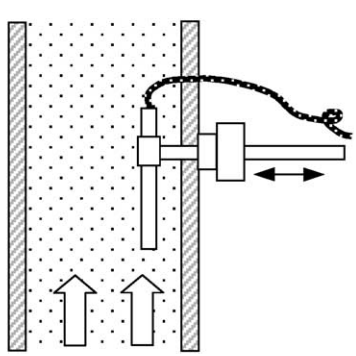

Fig. 15. Placing the ultrasound sensor to diminish the difficulties of determining the Doppler angle.

bubble movement and coalescence-breakup behavior induce turbulent fluctuation to the flow field both in amplitude and in direction. The complexity of the ultrasound reflection at the bubble interface makes the signal rather difficult to deal with. Placing the probe inside the column in the flow direction is a good choice for such systems, as shown in Fig. 15. In such a case, the measured velocity by DOP2000 is directly the velocity projection in the flow direction; therefore the difficulty of determining the Doppler angle is voided. Considering the axial profile in a scale of several centimeters can be regarded as uniform, the measured axial profiles can be used to determine the flow field of one position by signal distinguishing and statistics. The flow parameters

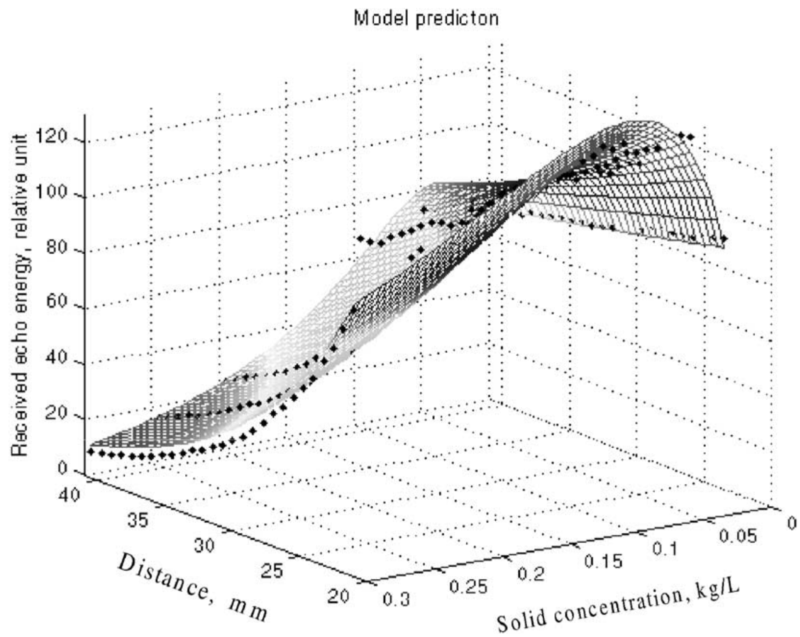

Fig. 16. Comparison of model predictions and experimental results of the received echo energy under different solid concentrations.

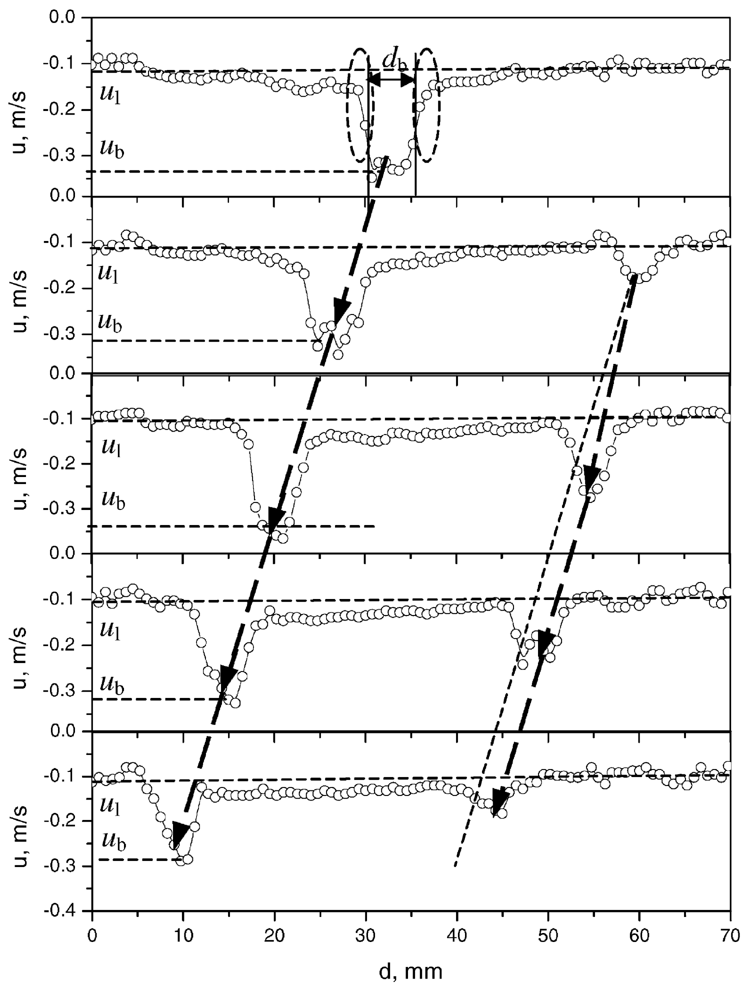

Fig. 17. Bubble measurement in gas–liquid system by placing the ultrasound sensor in the flow direction.

include gas holdup, liquid velocity, bubble size, and bubble rise velocity. Fig. 17 shows several sequent profiles displaying the bubble signal evolution. With the bubble rising up, the distance from the bubble to the sensor surface decreases linearly with time elapsing. The bubble rise velocity can be determined in two ways: one way is to average the rise velocities of the same bubble measured in different time, the other way is to divide the bubble displacement between two sequent profiles by the time interval, and then average the results. The results through the two ways are in good agreement. An attractive characteristic is that the liquid and bubble rise velocity can be measured simultaneously. The liquid velocity u_l in Fig. 17 is 0.12 m/s, and the bubble rise velocity u_b is 0.32 m/s. The bubble slip velocity $u_b - u_l$ is 0.20 m/s, in accordance with the single bubble rise velocity in water [16]. Reliable bubble swarm relative velocities are lacking because most results are only absolute bubble rise velocity (i.e. the bubble rise velocity relative to the column wall) or liquid velocity. Local information about the bubble relative velocity is especially useful to understand the multiphase flow and describes the phase interaction. In our case the gas holdup is very low, if the gas holdup and the bubble number increase, the flow will become more complex and the received signal will become more difficult to interpret. Further investigation is needed for bubble measurement in higher gas holdup case.

5. Conclusions

This work aims to extend the application of the Doppler ultrasound velocimetry DOP2000 to multiphase flow measurement. Some corrections have been made to the commercial software. The methods of measuring the solid concentration in liquid–solid system and the bubble behavior in gas–liquid system with low gas holdup have been proposed. The investigation concludes the following:

- Ultrasound refraction has influence on the determination of the measuring location and Doppler angle especially when ultrasound velocities in the coupling media and in the fluid are much different.
- The attenuation coefficient of the received echo energy in homogeneous liquid–solid system monotonously increases with the increase of the solid concentration. A calibration curve can be used for the system of the same solid and liquid in different measurement case.
- A model has been proposed to predict the relationship between the received echo energy and the solid holdup. Good agreement between the model predictions and the experimental results has been obtained.
- DOP2000 can be used to measure the bubble behavior in gas–liquid system with low gas holdup by placing the sensor in the direction of the flow and with special signal processing.
- Further investigation is needed for the liquid–solid system with non-uniform solid holdup and gas–liquid system with high bubble numbers.

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