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Application of Pulsed Ultrasonic Doppler Velocimetry to the Simultaneous Measurement of Velocity and Concentration Profiles in Two Phase Flow

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1. Introduction

The improvement of knowledge which governs the transport of the solid-liquid suspensions is the subject of many works having generally led to empirical or semi-empirical models which are valid only for specific conditions. Research carried out on solid-liquid suspensions has investigated the continuous phase and particularly the influence of turbulence modulation. In the works by Elghobashi and Truesdell (1993), Michaelides and Stock (1989), Owen (1969), and Parthasarathy and Faeth (1990a, 1990b), dissipation or production of turbulent kinetic energy in the continuous phase were reported. The effect of particles on the carrier flow turbulence was investigated numerically by Varaksin and Zaichik (2000) and, Lei (2000). Recently PUDV (pulsed ultrasonic Doppler velocimetry) was applied to study fluid flow alone or with solid particles by Takeda (1995), Aritomi et al. (1996), Nakamura (1996), Rolland and Lemmin (1996, 1997), Cellino and Graf (2000), Brito et al (2001), Eckert and Gerbeth (2002), Kikura et al. (1999), Kikura et al. (2004), Xu (2003), Alfonsi et al. (2003). Note that the measurement techniques cited in the above references are limited by the nature of the suspensions.

The aim of this experimental chapter is the simultaneous measurement of the local parameters which are the velocity and the concentration fields of the solid particles in flows in a horizontal pipe. The difference between our application of PUDV and those cited in the above references resides in the use of a new measurement approach of the local concentration of the solid particles. This approach consists of the representation of the local concentration profile by the ratio of the number of solid particles crossing the measurement volume, to the number of solid particles crossing the control volume. PUDV technique was selected rather than hot wire or film, or Laser, or the PIV technique, because the first would be destroyed by the particles, and with the second the ultrasonic signal is more attenuated when the volumetric concentration C_V of particles increases. The third technique as reported by Jensen (2004) requires many conditions for its application.

2. Experiment

The working principle of pulsed ultrasound Doppler velocimetry is to detect and process many ultrasonic echoes issued from pulses reflected by micro particles contained in a

flowing liquid. A single transducer emits the ultrasonic pulses and receives the echoes. By sampling the incoming echoes at the same time relative to the emission of the pulses, the variation of the positions of scatterers are measured and therefore their velocities. The measurement of the time lapse between the emission of ultrasonic bursts and the reception of the pulse (echo generated by particles flowing in the liquid) gives the position of the particles. By measuring the Doppler frequency in the echo as a function of time shifts of these particles, a velocity profile after few ultrasonic emissions is obtained.

In this study, PUDV technique originally applied in the medical field is used only for the emission and the reception of the ultrasonic signal. This technique was combined with a data processor for the flow measurement of solid-liquid suspension. This combination allows the determination of a local velocity and a local concentration of the solid particles larger than the wavelength of the ultrasonic wave.

2.1 Flow circuit

The flow circuit (Fig. 1a.) consists of a closed loop made of glass pipes with an internal diameter D of 20 mm. The flow is driven by a variable speed centrifugal pump (1). The suspension is kept at a constant temperature by the heat exchanger (2) during measurement. The test section (4) (for detail see Fig 1b), realized in a Plexiglas box which is 150 mm long, 100 mm wide, and 50 mm high, was located at $75D$ downstream of the pump where the flow was fully-developed. Plexiglas was chosen in order to reduce the reflection of the ultrasonic beam when it crosses the wall. The pressure differential along the test pipe given by two differential pressure transducer (3) allows the determination of the wall shear stress.

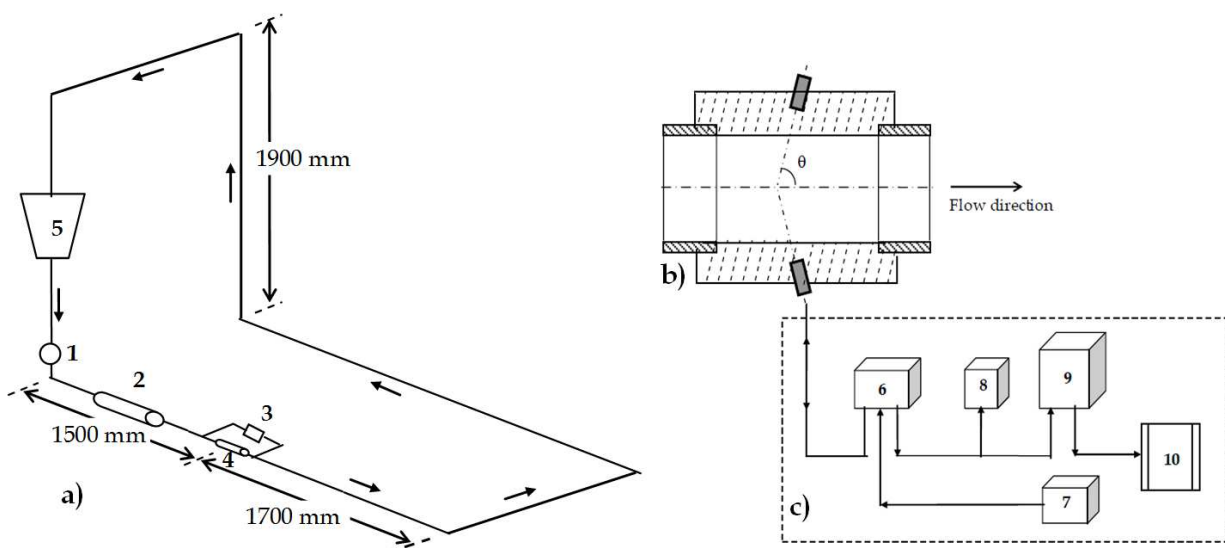


Fig. 1. a) Flow circuit: 1 pump, 2 heat exchanger, 3 differential pressure transducer, 4 test section, 5 tank of suspension; b) Detail of the test section 4: (▨) glass pipe, (▤) Plexiglas box, (▧) Ultrasonic transducer; c) Ultrasonic measurement with acquisition and treatment system: 6 displacement system of the measurement volume, 7 ultrasonic Doppler velocimeter (ECHOVAR CF8, ALVAR), 8 digital storage oscilloscope, 9 data processor (plurimat S), 10 computer

This study was performed using water as the continuous phase and glass beads for solid particles. The particles are spherical with a 5% sphericity defect and density of 2640 kg/m³. Four samples of different particle size distributions were tested. The volume-averaged mean particle diameters d_p corresponding to these samples are 0.27, 0.3, 0.4, and 0.7 mm. These particles were chosen to be larger than the Kolmogorov length scale η , estimated to 206.6 μm near the wall. The particle diameter is ranging between 1.30η and 3.38η . The volumetric concentrations (C_v) of the glass beads used in the suspension are 0.5%, 1%, 1.5% and 2%, and were determined from the volume of the flow circuit. Performed measurements within this work consider a two way coupling, i.e., taking into account the effects of the particles on the carrier fluid and vice versa. The classification of the suspension flow used is made according to Sato (1996), Elghobashi (1994) and Crowe, et al. (1996) who proposed the particle volume fractions as the criterion of classification. The particle volume fractions are ranging between 1.25×10^{-3} and 5×10^{-3} . Fine starch particles with 6 μm of diameter and density of 1530 kg/m³ were used as a tracer. The maximum concentration of the starch was fixed at 3% in order to reduce the attenuation of the Doppler signal. The flow mean velocity U_{moy} is ranging from 1 m/s to 2.5 m/s.

2.2 Ultrasonic measurement system of the velocity profiles

The method used for measurement local velocity of the large particles (larger than the wavelength of the ultrasonic wave) is based on a combination of the measurement technique PUDV (7) (type ECHOVAR CF8) used in medical physics, and a data processor (9). The technical specifications of the velocimeter are: emission frequency 8 MHz, pulse durations 0.5 μs , 1 μs , 2 μs , and pulse repetition frequency 64 μs and 32 μs . The maximum measurable distance of these two pulse repetition frequency are respectively 48 mm and 24 mm.

The position adjustment of the measurement volume is done by time step of 0.5 μs between the emission and reception of the ultrasonic wave. This time step corresponds to the penetration depth of the measurement volume of 0.37 mm for an angle θ of 67° (θ angle between the internal pipe wall and the direction of the propagation of the ultrasonic waves). The value of θ is nearly equal to that determined by the calibration of the ultrasonic transducer (67.4°). The dimensions of the cylindrical measurement volume are the same as those of the ultrasonic transducer, diameter of 2 mm and length of 0.8 mm.

In this experimental study, the signal is emitting and receiving by the same ultrasonic transducer, in this case the velocity U (axial velocity component) of the solid particles determined from the Doppler frequency is:

$$U = \frac{cf_D}{2f_e \cos\theta} \quad (1)$$

with f_D the Doppler shift frequency, f_e the emitted frequency by the transducer, c speed of the sound in the water, and θ the angle between the ultrasonic beam and the pipe axis.

The use of the PUDV technique for the solid-liquid suspensions remains however, limited by the concentration of the solid particles. Indeed, the preliminary study results show that the concentration of the solid particles and depth of the measurement volume affect the ultrasonic signal. Figure 2 shows that for a concentration higher than 2.5%, the attenuation

of the signal is about 80% (or 20% of coherent signal), and thus the maximum volumetric concentration of solid particles used in this study was $C_v = 2\%$. Because of the non-uniform distribution of the concentration in the test section, the flow is divided in two regions having the horizontal line passing through the position of the maximum concentration as a boundary. To obtain this boundary line, which corresponds to the great number of the Doppler signal visualised by a digital storage oscilloscope (Fig. 1c), we have scanned the test section by the displacement of the ultrasonic transducer along the vertical diameter. Before each measurement, the boundary line is located to be taken as the first measurement point. The first measurements with a two same ultrasonic transducers (one fixed on the pipe top wall and the other on the pipe bottom wall) shown that at the same position of the measurement volume, the velocity measured presents a difference about 3 - 4 %. For the high concentration, this difference is more significant.

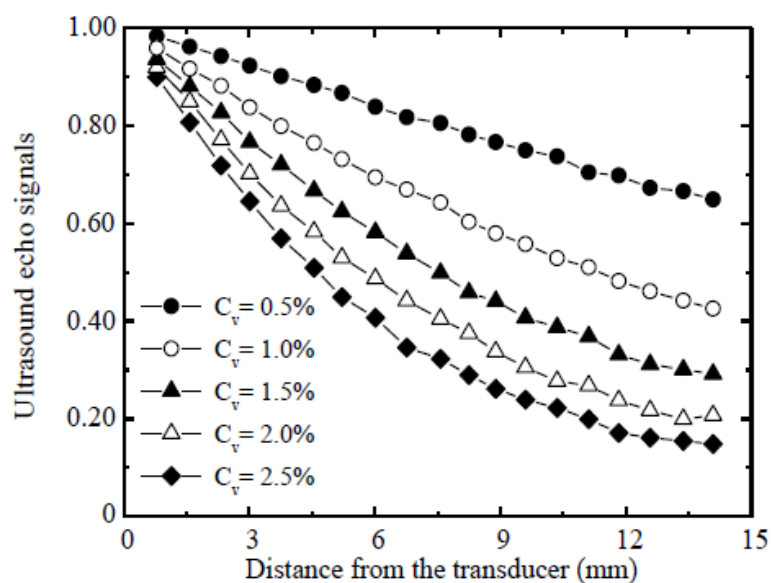


Fig. 2. Signal attenuation function of the distance from the ultrasonic transducer and the volumetric concentration of particle, $d_p = 0.7$ mm

2.2.1 Signal processing

The treatment of the Doppler signal is done using a data processor associated with the ultrasonic velocimeter. The successive Doppler signals received by the ultrasonic transducer are result from either the same particle reached by successive impulses, or various particles crossing the measurement volume. These signals depend on the particles size, the dimensions of the measurement volume, and the velocity of the particles. To avoid the spectrum overlap phenomenon and thus the loss of information, the output signal of the velocimeter is sampled with a sampling frequency about 5 to 10 times the greatest frequency of the signal spectrum. The numerical data of the sampling process are stored in the memory of the data processor to be treated. The signal processing is made by an elaborate software where frequency domain and Fourier transform were used. Figure 3 shows that the power spectral density obtained from different wall distance have the same trend as that of Gauss with a value correlation coefficient close to 0.97. To satisfy the symmetry condition of the power spectrum, a threshold was fixed, only the values greater than $2/3$ of the

maximum power spectrum were taken into account. The peak amplitude of the power spectra increases with increasing particle diameter; this confirms the difference in energy between the signals coming from the bead glass and those from the starch particles. The separation between the Doppler signals of the continuous phase and large particle is made using two fixed thresholds on the integral of the power spectral density. The higher threshold S_{sup} and the lower threshold S_{inf} are respectively given by the following relations:

$$\begin{cases} S_{sup} = E_{max} - \frac{E_{max} - E_{min}}{3} \\ S_{inf} = E_{min} + \frac{E_{max} - E_{min}}{3} \end{cases} \quad (2)$$

where E_{max} and E_{min} are respectively, the maximal and the minimal value of the integral of the power spectral density.

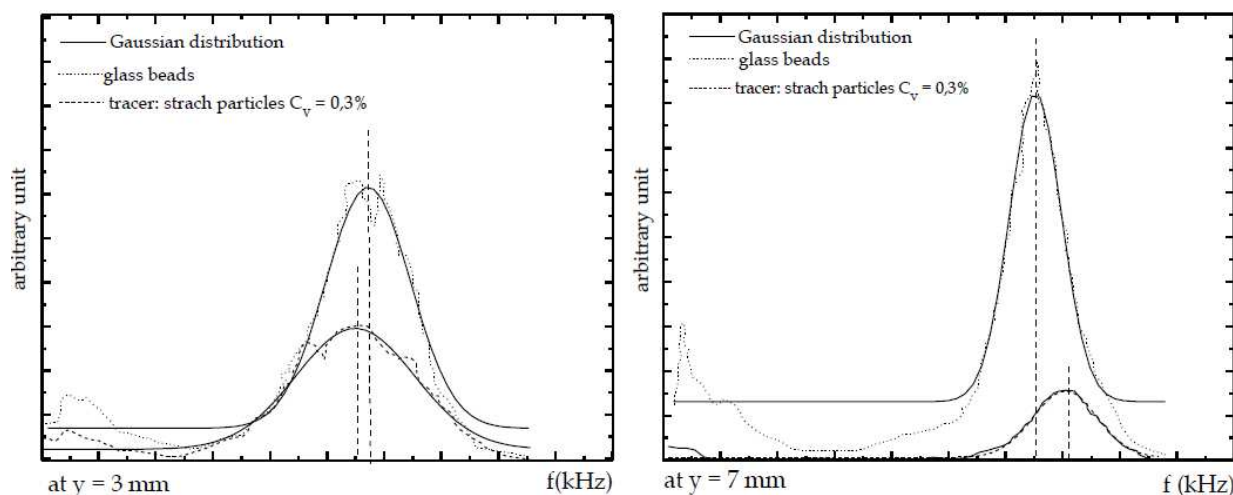


Fig. 3. Doppler power spectrum in the case of glass beads ($d_p=0.7$ mm, $C_v=1\%$) and tracer versus the wall distance

The sampled function $\hat{x}(t)$ of the Doppler signal $x(t)$ is given by:

$$\hat{x}(t) = x(t) \sum \delta(t - \frac{K}{f_e}) \quad (3)$$

where K is a constant and δ the Dirac's impulse. According to the formula of Poisson, we have:

$$\hat{x}(v) \approx X(v) \sum \delta(v - nf_e) \quad (4)$$

where $X(v)$ is the Fourier transform of the Doppler signal $x(t)$. The values treated using the Fourier transform allow to the calculation of the power spectral density $P(f)$ of the Doppler signal from the product of the frequency spectrum and its conjugate. The average frequency Doppler $\overline{f_D}$ is given by the normalized moment of order 1 of the ensemble average spectrum.

$$\bar{f}_D = \frac{\sum_{n=1}^N f_n G(f_n)}{\sum_{n=1}^N G(f_n)} \quad (5)$$

where $G(f_k) = \sum_{n=1}^N P_n(f_k)$ and $k = 1, 2, 3, \dots, N$. Considering that the enlargement of the spectrum is due only to the turbulent velocity fluctuations, we can calculate the normalized moment of second order of the energy spectrum integral associated with the Doppler signals. This moment with a Gaussian trend represents the turbulent intensity given by the relation:

$$\sqrt{f_D^2} = \left[\frac{\sum_{n=1}^N (f_n - \bar{f}_D)^2 G(f_n)}{\sum_{n=1}^N G(f_n)} \right]^{1/2} \quad (6)$$

2.2.2 Measurement method of the local concentration profile

This method consists of determining the ratio of the number of particles N_p crossing the measurement volume to the total number of particles N_{pt} crossing the control volume. This control volume is obtained by the displacement of the measurement volume along the vertical diameter of the test section (Fig. 4).

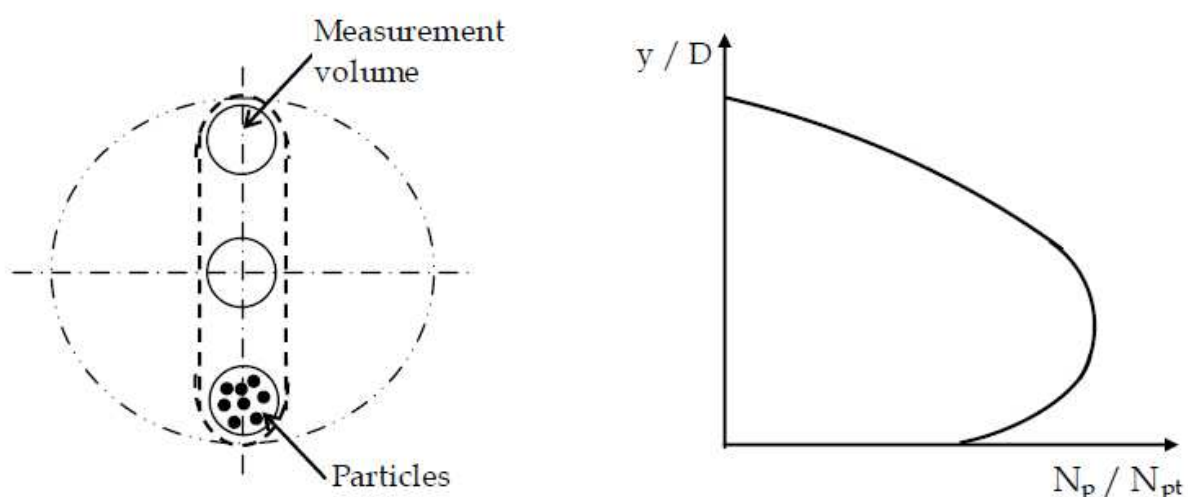


Fig. 4. Determination of the concentration profile: (-) measurement volume N_p , (---) control volume N_{pt} , (---) test section.

The numbers of particles N_p and N_{pt} are obtained by counting the number of the Doppler signal respectively in the volume measurement and in the control volume. For this counting made for each measurement point of the particle velocity, two thresholds are fixed, one on the amplitude of the Doppler signal and the other on the integral of the power spectral density. The total number of particles N_{pt} is given by:

$$N_{pt} = \sum_{i=1}^n (N_p)_i \quad (7)$$

with n the number of the measurement point. The local concentration profile is obtained by the plot of the variation of the ratio N_p / N_{pt} versus the depth of the measurement volume along the vertical diameter of the test section (Fig. 4).

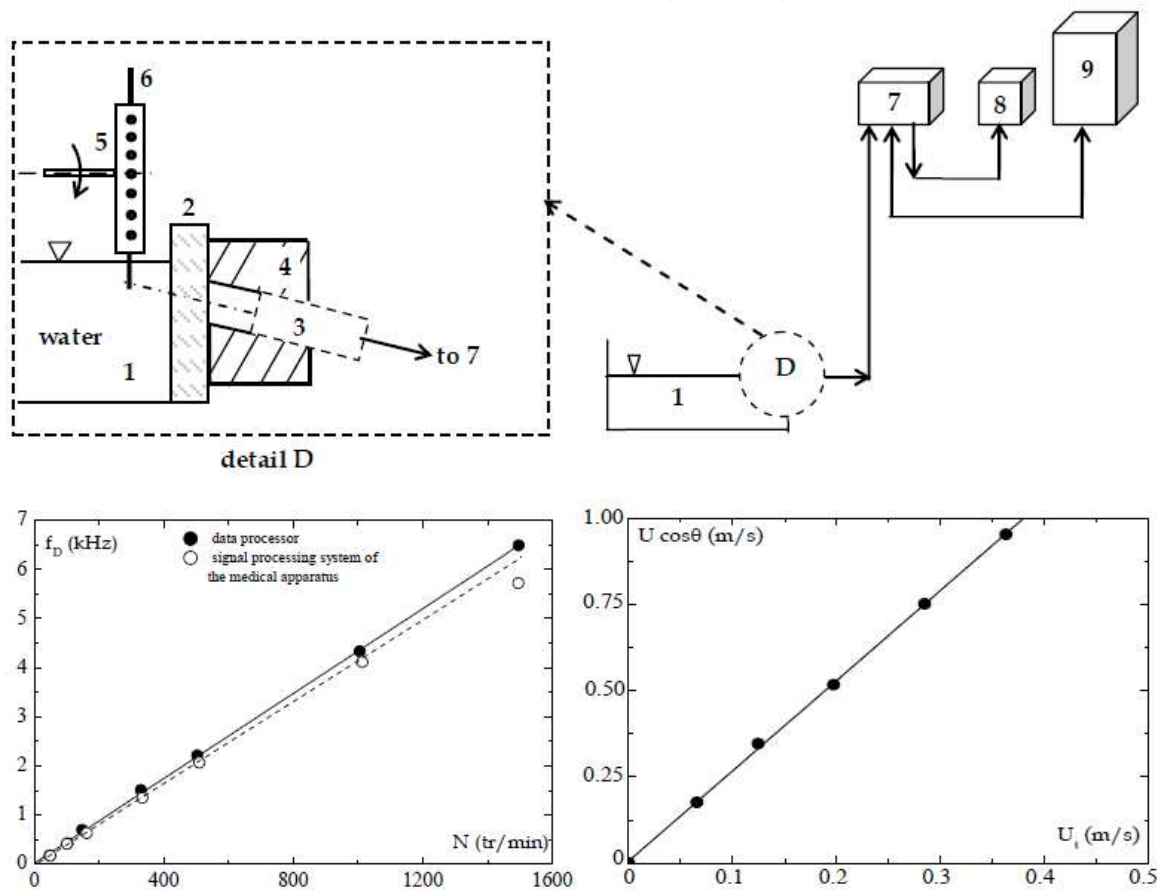


Fig. 5. a) Validation of the method and calibration of the ultrasonic transducer: 1 glass tank of calibration, 2 lateral wall of the tank, 3 ultrasonic transducer, 4 micrometric displacement system of the transducer, 5 plastic disc, 6 Abrasive cloth band or cylindrical metal rods, 7 ultrasonic Doppler velocimeter, 8 digital storage oscilloscope, 9 Data processor (Plurimat S); b) Validation curve of the signal processing method; c) Calibration curve of the ultrasonic transducer

2.2.3 Validation of the processing signal method and calibration of the ultrasonic transducer

The validation of the method applied for the signal processing consists of a comparison between the results obtained by the data processor (9) and those of the processing signal system integrated into the medical apparatus (7). For this validation we developed a device illustrated in Fig. 5a, it consists of the plastic disc (5) of 160 mm diameter turning with a variable speed motor, and on which a abrasive cloth band (6) is stuck (in Figure 5a, only the

cylindrical metal rods used for the calibration of the ultrasonic transducer are represented). The fine emery grains act as the centers of diffraction moving with a known tangential velocity in the volume measurement. This intersection between the emery grains and the volume measurement is obtained by a micrometric displacement system of the ultrasonic transducer (4) fixed on one of the lateral walls of the tank calibration (2). The Doppler frequency is determined by the acquisition and processing system (9). Figure 5b shows that, in a large tension range, the results obtained from the signal processing of the data processor have a better linearity than those from the signal processing system integrated into the medical apparatus.

For the calibration of the ultrasonic transducer (3), which consists of determining the exact value of the inclination angle of the ultrasonic transducer, the same device as that of the validation of the signal processing method was used, except for the plastic disc where the abrasive cloth band is replaced by cylindrical metal rods (6) of 1 mm diameter and 15 mm length. Figure 5c shows a better linearity between a known tangential velocity U_t of the rods crossing the measurement volume and the value of $U \cos \theta$ determined from the signal processing. The inclination angle of the ultrasonic transducer ($\theta = 67.4^\circ$) determined from the calibration curve is very close to that used in the medical apparatus ($\theta = 67^\circ$).

3. Experimental results

3.1 Velocity and concentration profiles of fine particles

The rheological study of the starch suspension in water made in a rotating viscometer of coaxial cylinders (Haake RV12), showed that the suspension have a shear thickening behaviour described by the power law rheological model.

$$\tau = k \dot{\epsilon}^n \quad (8)$$

where τ is the shear stress, k is the flow consistency index and n is the flow behaviour index. These two rheological parameters determined from the flow curves, $k = 0.33 \times 10^{-3}$ kg/ms and $n = 1.1$, are necessary to determine the velocity profile using the model of Pai (Brodkey, Lee, Chase (1961) and Brodkey (1963)) valid for the Newtonian and non-Newtonian fluids when the Reynolds number Re is lower than 10^5 . This model is given by:

$$\frac{U(r)}{U_{\max}} = 1 + a_1 \left(\frac{r}{R} \right)^{\frac{n+1}{n}} + a_2 \left(\frac{r}{R} \right)^{2m} \quad (9)$$

where U_{\max} is the maximum velocity generally taken on the pipe axis, R the pipe radius, and $r = R - y$ the variable pipe radius (y is the wall normal distance). The constants a_1 , a_2 and m depend on the nature of the fluid, the boundary conditions and the flow mean velocity. Figure 6 shows the velocity and the concentration profiles of the water-starch suspension obtained along the test section diameter. The velocity profile coincides well with the theoretical profile of Pai, and the concentration profile has a uniform distribution.

According to Furuta et al. (1977) we can thus assume that fine particle suspension which represents a tracer behaves as a homogeneous fluid and the slip velocity of the solid - liquid

suspension is negligible. In the following results the velocity profile of water alone will be represented by the model of Pai.

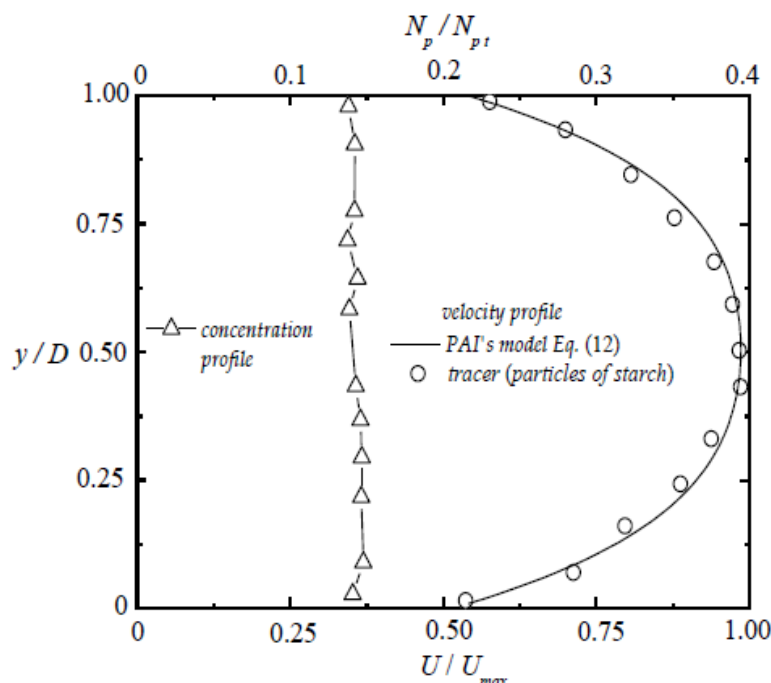


Fig. 6. Velocity and concentration profiles of water-starch suspension, $Re = 42000$, the volumetric concentration of the starch is $C_V = 0.3\%$.

3.2 Velocity and concentration profiles of large particles

Large particles of high density compared to the carrier fluid, i.e., those where the diameter exceeds the wavelength of the ultrasonic wave, do not follow the flow. In this paper, only the results corresponding to the particles of diameter 0.13 and 0.4 mm are presented.

3.2.1 Effect of the mean flow velocity

A mean flow velocity range of 1 m/s to 2.5 m/s was used. This range corresponds to the heterogeneous and saltation flow regimes. Figure 7 shows the influence of the mean flow velocity on the velocity and the concentration profiles of the solid particles of diameter 0.13 and 0.4 mm respectively. The velocity profiles are parabolas with a top around the pipe axis, very near for $d_p = 0.13$ mm and below for $d_p = 0.4$ mm. For the other particle diameter of 0.27 mm and 0.7 mm (which are not presented in this paper), the tops are below the pipe axis. The presence of the particles near the top wall was observed only for $d_p = 0.13$ mm and $U_{moy} = 2$ m/s.

The concentration profiles are in a better agreement with the observations of the flow made during the experimental tests. Indeed, for a constant volumetric concentration and a mean flow velocity ranging between 1 and 2 m/s, the flow of the particles suspension of diameter 0.27 mm, 0.4 mm and 0.7 mm is a saltation regime. It becomes heterogeneous when the flow mean velocity exceeds 2 m/s. For the particles of diameter 0.13 mm, the flow suspension is heterogeneous regime.

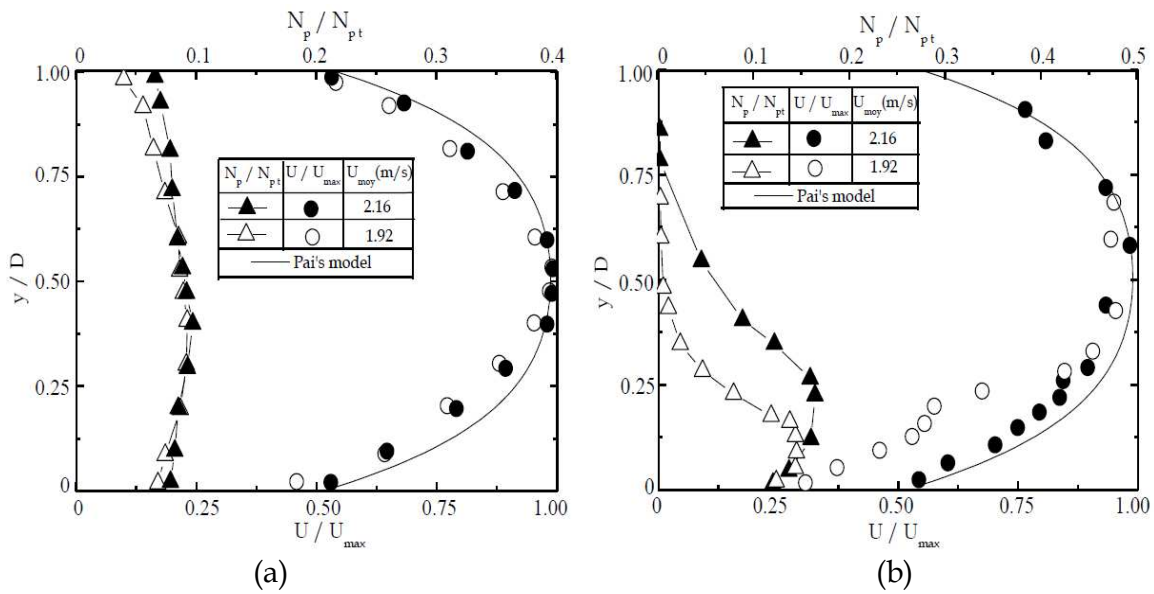


Fig. 7. Velocity and concentration profiles of glass bead for $C_v = 1\%$: a) $d_p = 0.13$ mm; b) $d_p = 0.40$ mm

3.2.2 Effect of volumetric concentration

Figure 8 shows the influence of the volumetric concentration of the solid particles on the velocity and local concentration profiles. Note that the difference between the velocity profile of the solid particles and that of the carrying fluid (Fig. 8a), which represents the solid-liquid slip velocity, increases with the increase in the volumetric concentration. The local concentration profiles (Fig. 8b) present a maximum value, whose position moves away from the internal pipe bottom wall when the volumetric concentration decreases. For the lower volumetric concentration, the local concentration profile tends to that of the carrying fluid (or the fine particles) which is almost uniform. The presence of the particles near the pipe top wall was observed for the volumetric concentration lower than 0.5 %.

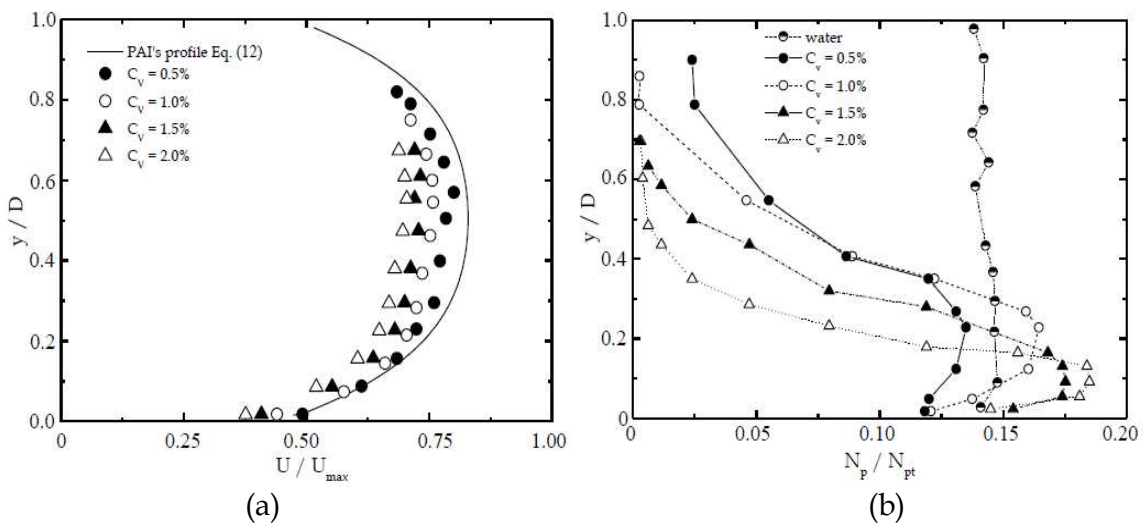


Fig. 8. Effect of the particle volumetric concentration on: a) the velocity profiles; b) the local concentration profiles for $d_p = 0.27$ mm and $Re = 44600$.

3.2.3 Effect of diameter

The figure 9a shows that for all the particle diameters used, the velocity profiles of the solid particles have the same trend as that of the carrying fluid. The difference between the velocity profile of the continuous phase and that of the solid phase confirms the existence of the solid-liquid slip velocity which, increases with increasing particle diameter. Figure. 9b shows that for the solid particles of diameter 0.13 mm and 0.27 mm, the local concentration profiles tend to that of the carrying fluid.

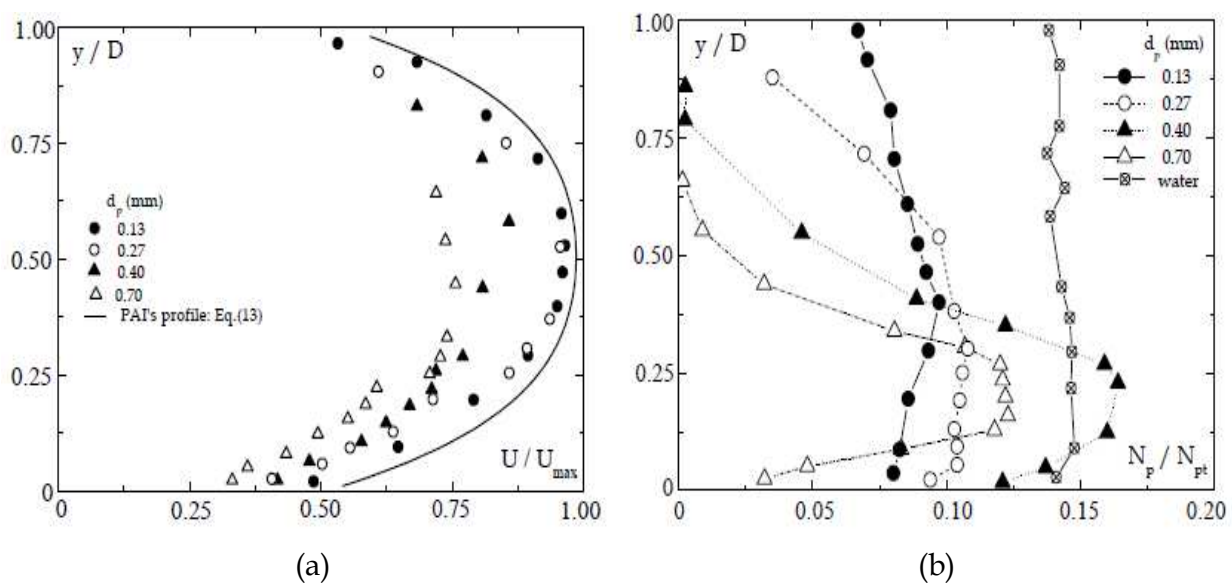


Fig. 9. Influence of the particle diameter on: a) the velocity profiles; b) the concentration profiles for $C_v = 1\%$, $Re = 44600$.

The maximum of local concentration profile appears for $d_p = 0.4$ mm and $d_p = 0.7$ mm. The solid particles are present near the pipe top wall only for the small diameter (0.13 mm).

4. Conclusion

In this experimental chapter, we have tested a new approach measurement in order to determine simultaneously the velocity profiles and the concentration profiles of the solid

particles (glass bead) and the continuous phase (water) of two phase flow in horizontal pipe. The distinction between the Doppler signals coming from the solid phase and the continuous phase was obtained by imposing a threshold on the integral of the power spectral density. The use of this approach measurement is limited to small concentrations lower than 2%. Indeed when a concentration of 2% is exceeded, the ultrasonic signal is attenuated. This approach measurement shows the effects of the particle diameter and volumetric concentration on the local mean velocity and local mean concentration profiles of the suspensions.

The results obtained show that for the fine particles, the suspension behaves like a homogeneous fluid; the velocity profile is in a better agreement with the Pai's model and the concentration profile is almost uniform. For the large particles, saltation and heterogeneous flow regimes were obtained. These two regimes depend on the diameter and volumetric concentration of the particle, and on the flow mean velocity. The slip velocity which is responsible for the fluid-particle interaction depends on the flow regime.

In our next chapter concerning the solid liquid suspension, PUDV and Particle-Tracking Velocimetry (PTV) will be applied together. The most advantage of PTV is the possibility of measurements of large particles, by which the fluid-particle interactions and the particle-response property will be able to be examined. This allows us perhaps the best understanding of the phenomenon caused by the fluid-particle interactions, and also probably by the particle-particle interactions because of high concentration near the wall. It is also necessary to investigate interactions between these phenomenon and particle motion due to two-way and four-way couplings in a wide range of particle diameter, specific density, and sediment concentration, and then to develop reasonable computer simulation models of two phase horizontal pipe flow.

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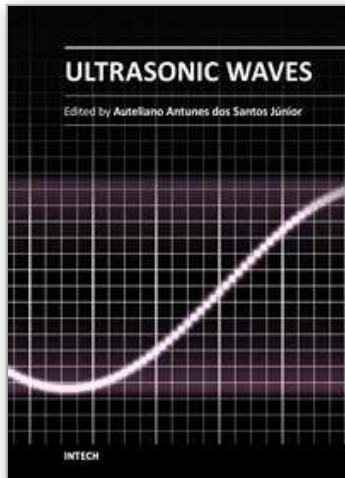
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Ultrasonic waves are well-known for their broad range of applications. They can be employed in various fields of knowledge such as medicine, engineering, physics, biology, materials etc. A characteristic presented in all applications is the simplicity of the instrumentation involved, even knowing that the methods are mostly very complex, sometimes requiring analytical and numerical developments. This book presents a number of state-of-the-art applications of ultrasonic waves, developed by the main researchers in their scientific fields from all around the world. Phased array modelling, ultrasonic thrusters, positioning systems, tomography, projection, gas hydrate bearing sediments and Doppler Velocimetry are some of the topics discussed, which, together with materials characterization, mining, corrosion, and gas removal by ultrasonic techniques, form an exciting set of updated knowledge. Theoretical advances on ultrasonic waves analysis are presented in every chapter, especially in those about modelling the generation and propagation of waves, and the influence of Goldberg's number on approximation for finite amplitude acoustic waves. Readers will find this book a valuable source of information where authors describe their works in a clear way, basing them on relevant bibliographic references and actual challenges of their field of study.

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