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LOCAL MEASUREMENTS IN TURBULENT BUBBLY FLOWS

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Abstract : *Local measurements methods in bubbly flows are discussed. Concerning liquid velocity measurement, problems linked to HFA and LDA are first analysed. Then simultaneously recorded velocity signals obtained by both anemometers are compared. New signal processing are developed for the two techniques. Bubble sizes and velocities measurements methods using intrusive double optical sensor probe are presented. Plane bubbly mixing layer has been investigated. Local measurements using the described methods are presented as examples.*

1 - INTRODUCTION

The bubbly flow regime is encountered in many industrial processes. Accurate prediction of bubbly flow requires fine understanding of the local instantaneous interactions between dispersed and continuous phases. Usually the mean bubble diameter is higher than the Kolmogorov length scale, it is thus expected that the relative motion of the bubbles strongly modifies the turbulent field of the continuous phase when the drift velocity is comparable to the liquid velocity. On another side the reverse action of the liquid phase on the bubble instantaneous motion can also vary from purely turbulent dispersion to self-induced bubbles dispersion according to the various length and velocity scales present in the flow. Due to the complexity of these interactions, experimental approach remains fundamental in their analysis. At the present time, the available experimental studies in bubbly flows are scarce. Few flow configurations were explored, and local measurements were in most works restricted to void fraction and mean and RMS velocity of both phases. Previous works have essentially been obtained for flows in pipes (Serizawa et al., 1975; Theofanous & Sullivan 1982; Wang et al., 1985). This configuration, as well as the turbulent bubbly boundary layer along a vertical flat plate (Moursali et al.,1995), remain complex because the main features of turbulence and void-fraction are confined close to the wall. Analysis of these flows is thus complicated because of interactions between bubbles and wall turbulence structures. Consequently, other local investigations in more simple reference situations are needed. The experimental analysis of uniform grid generated turbulence or of homogeneous shear flow has already provided some instructive results for low void fraction (Lance and Bataille, 1991; Lance et al. 1991). More precise analysis of bubbly flows not only requires the definition of reference flows, but also more sophisticated measuring methods and signal processing.

In this paper, we present the experimental tools developed in our laboratory for local measurements in bubbly flows and some experimental illustrative results obtained in a reference flow : the co-current bubbly plane turbulent shear layer (Roig et al., 1993). This paper focuses on the measurement techniques which were applied to various air-water bubbly flows with liquid velocity from 0.2 to 2 m/s, bubble mean diameters at least of 3 mm, and void fraction up to 15%. The experimental facility where we studied turbulent air-water bubbly flows in a plane vertical mixing layer is described in detail in (Roig, 1993). Besides the fact that this configuration has been thoroughly studied in single-phase flow, it allows, in bubbly flows, to put into light basic interactions between the two phases : the effect of the bubbles on the liquid phase velocity (modification of mean flow and of turbulence), the reverse action of the liquid motion on the bubbles (distribution of gas phase, turbulent dispersion, entrapment of bubbles by large scale coherent structures). In the turbulent shear layer, the void fraction is low (< 5%), the ratio between the relative velocity U_R and the bulk velocity in the liquid phase is always nearly equal to 1. The inlet liquid velocities of each flows are respectively 0.54 m/s and 0.22 m/s. The bubble diameters d_B are about 2.5 mm, such that they are greater than the Kolmogorov scale, and smaller than the integral length scale. The bubble Reynolds number based on the relative velocity U_R between the gas and the liquid phases is high : $U_R d_B/\nu_L \approx 700$. In the mixing layers the hot film anemometer was used to measure the velocity of the liquid phase and the local void fraction was obtained using optical fiber probes. The results obtained in mixing layers thus illustrate the applications of the signal processing methods that we use.

2 - LOCAL MEASUREMENT METHODS FOR THE LIQUID VELOCITY

We have tested, in bubbly flows, the two classical local methods for velocity measurement used in single-phase flow: the Laser Doppler Anemometer and the Hot Film Anemometer.

The performances of the different anemometry methods are not the same. The feasibility and the accuracy of local velocity measurements in bubbly flows are closely related to the configuration considered. They depend especially on three parameters: the importance of the velocity fluctuations in comparison with the mean velocity, the void fraction, and the bubble size distribution. The two methods are not able to perform measurements in absence of a minimum mean motion. For the HFA, the limitation is the same as in single phase flow. For the LDA, the bubble crossings through the Laser beams cause an unavoidable noise near the zero-velocity (Marié, 1983; Tjiptahardja et al., 1996). With a sufficient mean motion, and for moderate void fractions (less than 2%), the two methods can be used. At higher void fractions (more than 2%), the LDA signal is no longer suitable because of the increase of the beam interruption rate by the bubble crossing. In this case, use of the HFA is recommended.

Whatever the method of measurement to be used, in order to obtain the velocity in the continuous phase, two problems must be solved: the signal noise must be suppressed and only the information related to the continuous phase should be retained. In the following paragraph we discuss about the different signal processing applied to HFA or LDA signals.

Comparison between LDA and HFA has been made in bubbly grid generated turbulence (Marié, 1983). It has shown differences between the moments of order higher than 2 obtained by both methods. Whatever, it is not possible to appreciate the degree of adequacy between both measuring methods in bubbly flows from literature because, to our knowledge, both anemometers have never been tested simultaneously. By performing simultaneous HFA and LDA measurements, we have tested both methods in the range of moderated void fraction.

The LDA signal processing

In two-phase flows, the crossing of the laser light by the bubbles cause an additional noise to the LDA signal. In particular, series of zero velocity peaks appear (Marié, 1983). However with a sufficient mean liquid velocity it is possible to eliminate the zero velocities by a simple velocity amplitude discrimination. Once the random time sampled data of the LDA has been resampled, the essential in the LDA treatment lies in the filtering procedure. It is therefore necessary to have a high enough laser validation rate to correctly follow the velocity fluctuations of the flow. This is the only way to allow for correct spectral analysis and noise removal. But when the void fraction is increased, the interference of bubbles with the laser light becomes more pronounced, and the LDA data rate decreases although the energy of the high frequency velocity fluctuations increases. This, of course, introduces a problem, and the method is therefore limited to moderate void fractions.

The filtering procedure consists in the use of an Optimal Wiener Filter of exponential form in the frequency domain. The filter function is estimated from power spectral density of the signal (Ellingsen et al 1997).

For LDA in bubbly flow a problem is still to be solved: LDA signal does not allow clear discrimination of the phases. Thus it will be necessary in general to associate a phase detector probe to the LDA measuring volume in order to recognise the part of the velocity signal associated to the liquid.

The HFA signal processing

The HFA that we use is composed of a Dantec 55R11 single cylindrical hot film probe (70 µm in diameter) and of a constant temperature anemometer. Contrary to the LDA, the HFA voltage signal is not proportional to the velocity, and a calibration procedure is necessary. During measurements the overheat ratio is generally kept constant in order to minimise the effects of the small temperature changes upon the calibration curve (Bourget, 1976). This overheat ratio is taken equal to 0.06 in order to avoid bubble formation at the tip of the probe.

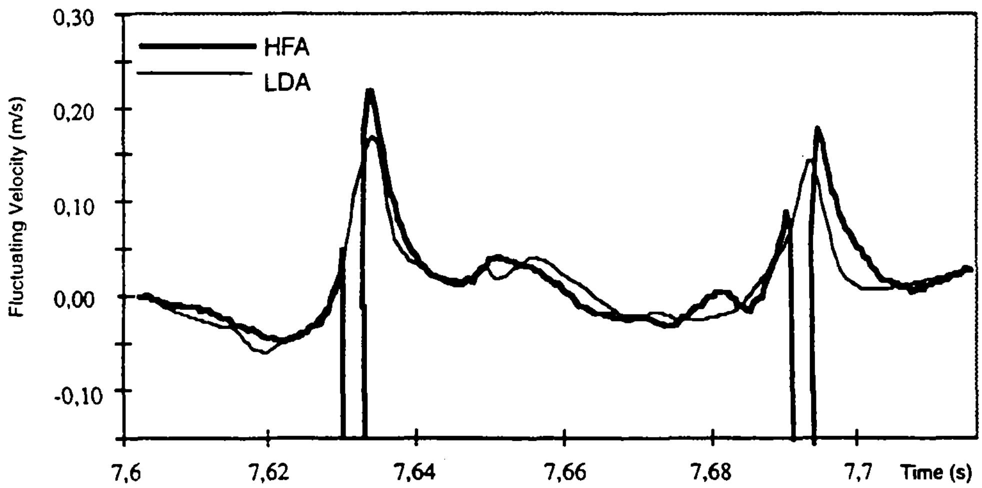

Figure 1: Untreated HFA - LDA after treatment in bubbly flow (α= 1%, d_b = 2.5 mm).

Figure 1 illustrates the peculiarity of the HFA signal observed in turbulent mixing layer bubbly flow at low void fraction ($\alpha \approx 1\%$) and for 2.5 mm bubble size. The signal is not very noisy so that filtering is not crucial in HFA measurement. When a bubble impinges the hot film, the signal suddenly drops due to the decrease of the heat transfer coefficient. When the liquid wets again the film, the signal rebuilds after a short period during which it exhibits an overshot. When the film is in the gas the signal is no longer representative of the velocity: it is thus necessary to remove this part of the signal. The phase discrimination is based on the signal processing developed at the IMFT. It consists of a thresholding technic applied to the derivative of the signal (Bel Fdhila et al, 1993). Signal processing is not only applied to the hot film voltage E(t) but also to its derivative ($\partial E/\partial t$). The maximum time derivative of the signal induced by turbulence in the continuous phase remains very low in comparison with the time derivative associated to bubble when the air-water interface impacts the hot-film sensor. Thus, this threshold method based on the derivative of the hot film signal greatly magnifies the drop due to the bubble passage and allow a better discrimination between bubbles and turbulence than a threshold method only applied to the signal

E(t). This discrimination sometimes becomes difficult, especially for high void fractions. It is also the case when a high turbulent level is associated with a non-uniform bubble size distribution because the passage of small bubbles (less than 0.5 mm) can be mistaken for turbulent fluctuations. Thus the sampling frequency must be high enough in bubbly flow (typically 2 to 5 Khz in most experiments) in order to provide a satisfactory information about whether the probe is located in liquid or in gas.

Sometimes, a large rear peak just after the passage of the bubble is observed. Up to now, there was not an agreement on its validity (Wang et al, 1990; Serizawa et al, 1983; Gherson et al, 1984). The question is: Does the decreasing part of this peak actually correspond to the velocity in the liquid phase? And is this part of the peak representative of the local inhomogeneity of the flow around the corresponding bubble? This peak has been observed in LDA signal by Theofanous and Sullivan (1982) who suggested that the overshot is significant of the slip velocity. On another side the overshot observed in air-water experiments should be related to wetting phenomenon as put into light by Gherson & Lykoudis (1984) who did not observed trailing peaks using a conical film in mercury with normal gravity conditions. Wang et al (1990) suggest to suppress the rear peak signal that is said to belong to the liquid phase but to be disturbed by thermal inertia of the hot film. In a review of the state of the art of HFA in two-phase flows, Bruun (1995) clearly recalled that different signal interpretations are possible depending on the type of the probe (conical or cylindrical) and on the type of bubble-sensor interaction as explored by Bremhorst and Gilmore (1976) or Serizawa et al (1983). From visual observations these authors have classified bubble-wire interactions into 4 types : recoiled, drifting, crawling and split interactions. From their bubble-wire interaction map we can deduce that, with a 70 μm wire diameter, bubbles from 1 to 4 mm in diameter are pierced by the probe, and the interaction is either of crawling type or of splitting one.

Phase discrimination, that is retaining or not the trailing peak at the rear of bubble passage as significant of liquid velocity, has no significant effect on mean velocity measurements but it can change notably the estimation of the turbulent intensity. An estimation of this effect is given by processing a bubbly test signal such as to cut more or less the peaks at bubble passages. Removing entirely these parts of the signal can induce a 15% decrease of the turbulent intensity.

For bubbly mixing layers, mean liquid velocity profiles are plotted in the dimensionless form usually adopted in self-similar analysis of single-phase mixing layers (Figure 2) (Roig et al., 1993); the mean velocity profile is in good agreement with the analytic solution proposed by Goertler. The experimental facility consists of a vertical square channel of 2 m height and 0.4 x 0.4 m^2 cross area where the mixing layer develops from bottom to the top. In this experiment, the inlet liquid velocities $\overline{U}_1$ and $\overline{U}_2$ in the core region of each flow, the velocity difference $\Delta\overline{U}$, the mean void fraction α , the mean bubble size d_B and the slip velocity U_R are indicated in the following table :

$\overline{U}_1$	$\overline{U}_2$	$\Delta\overline{U}$	α	d_B	U_r
0,25 m/s	0,60 m/s	0.35 m/s	2 %	3 mm	0.30 m/s

Table 1 : Main characteristics of the mixing layer.

The non-dimensional longitudinal velocity fluctuations of the liquid phase are plotted (Figure 3) and compared to Wygnanski and Fiedler (1970) data obtained in single phase mixing layer : in bubbly mixing layer, the velocity fluctuations are strongly modified from their single phase values because the velocity difference $\Delta\overline{U}$ is close to the slip velocity (U_r). Liquid velocity fluctuations are produced both by shear stress ($\overline{u_{is}^2}$) and by relative movement of the bubbles ($\overline{u_{ib}^2}$). In fact, it has been shown (Roig et al., 1993) that the longitudinal fluctuating energy $\overline{u_{ib}^2}$ which is induced by the bubbles is close to the estimation proposed by Lance and Bataille (1991) : $\overline{u_{ib}^2} \approx \alpha U_r^2$

Simultaneous measurements

Recent measurements have been performed by placing the measurement volume of the LDA very close to the hot film probe (Ellingsen et al, 1997). Taylor's hypothesis was used to perform the instantaneous comparisons: a time shift was applied to the HFA signal in order to match it to that of the LDA. The filtering procedure of LDA signal was tested in this configuration in single-phase flow because the nature of the noise is the same as in two-phase flow. It proved to give the same spectrum signature as the one of the signal of the neighbouring HFA. Once the LDA noise is taken off, the two signals follow each other very well, even at the small scales in single-phase flow and in bubbly flow (Figure 1). Those measurements prove that the two signals are quite similar and a comparison with the liquid velocity measured by the LDA, for the same bubbles, eliminates any ambiguity about what part of the HFA signal that should be retained. Inspection of a large number of simultaneous measured bubble intersections reveals that only the abrupt negative voltage (velocity) fall should be removed. The large rear peak just after the bubble intersection is measured correctly , it is related to the potential flow behind the bubble and should be integrally kept,. This result confirms that the rear part of the peak may be interpreted as representative of the liquid velocity when HFA signal is obtained from cylindrical probes, as discussed in Bruun (1995) or Serizawa et al. (1983).

By performing simultaneous HFA and LDA measurements, we have moreover proved that the two methods lead to the same results provided the correct signal processing is applied. For example, at void fraction of 0.4 %, the statistical centred moments of the velocity differ less than 5% up to the sixth order. Such good agreement requires great care in the determination of the HFA calibration curve.

3 - LOCAL MEASUREMENT METHODS FOR VOID FRACTION, BUBBLE SIZE AND VELOCITY :

Void fraction measurements

Void fraction measurements at low velocity are known to be delicate. In our different experiments the liquid velocity ranges from 5 cm/s to 1 or 2 m/s. At low velocity piercing phenomenon is critical for validity of void fraction measurements. Thus resistive phase detector probes are not recommended for void fraction measurements, because their response time is large essentially due to their size. For void fraction measurements, Optical Fiber Probe (OFP) are preferred. We use a single RBI monofiber probe whose tip diameter is less than 50 μm. The detection of the presence of each phase on the OFP relies on the change of optical index between the two media. Small tip diameter and sharp geometry of the OFP ensure correct piercing of the bubbles even at low velocity and reduce the response time. For monofiber probes, Cartellier (1990) showed that the duration of the signal rise due to plane interface piercing was less than 0.3 ms for interface velocity higher than 0.3 m/s. In our bubbly flows, the residence time of a bubble on the probe is at least 5 ms (for a 2 mm diameter bubble rising in stagnant water) and the response time is always smaller than 0.3 ms. The sampling frequency is between 2.5 and 5 KHz. The phase discrimination thus induces minor errors on the local measurement of mean void fraction.

For example, in the mixing layer void fraction measurements (see table 1) were performed at several positions up to a maximum height which ensures absence of wall interactions (y=0 corresponds to the central axe of the 20 cm x 20 cm square vertical channel). Void fraction measurements (Figure 4), allowed to put into light the downstream evolution of a peak of void fraction (α) created at the entrance of the flow in the boundary layers of the splitter plate. The void fraction behaviour deviates from scalar diffusion: the peak decreases in intensity in the flow and is displaced significantly in the lateral direction due to interfacial forces .

Bubble size and velocity measurements

Few authors have measured the bubble velocity. Among them Herringe and Davis (1976) and Van der Welle (1985) have obtained the mean bubble velocity by cross-correlating the signals from two different probes. Fewer workers reported the determination of the bubble velocity fluctuations like Serizawa et al (1975) and Sun and Faeth (1986). The measuring method which was developed allows to determine the mean and fluctuating velocities as well as a characteristic bubble size. This method is based on a numerical multichannel analysis of the binary signals obtained from the double optical probe by the aforementioned method. The signal processing adopted in this work has some common features with this of Serizawa et al. Whereas they used an analogical signal processing we chose a numerical processing which allows to apply selective criteria to each event. This method is explained as follows.

When a bubble crosses the two probes, the optical signals are delayed by a time lag $\Delta\tau_i$. Once this time has been measured the velocity of the bubble is approximated by $U_{bi} = L/\Delta\tau_i$, where L is the distance between the two probes. The determination of the residence time Δt_i of the bubble on the first probe gives the chord length crossed by the probe $x_i = U_{bi}\ \Delta t_i$: this can be taken as the estimated bubble size. L the distance between the two probes (equal to 3.8 mm in our work) must be chosen greater than the mean bubble diameter in order that the downstream probe does not disturb too much the upstream probe. It is also chosen smaller than a characteristic length scale over which the bubble velocity varies. Pierced chords are not bubble sizes, thus if one is interested by exact diameter distribution, one must adopt a statistical model of bubble piercing to estimate bubble diameters from pierced chords (Herringe and Davis, 1976).

The overall method depends on the accuracy in determining $\Delta\tau_i$, so that selective criteria must be chosen in order to avoid to take into account erroneous situations when two different bubbles cross the probes (see Serizawa et al., 1975).

The time lag between two consecutive interface signatures from each probe is then compared to the most probable time lag $\Delta\tau_{mc}$ estimated at each point from the cross-correlation function. When the current time lag is far lower or far higher from $\Delta\tau_{mc}$ the two signatures are not supposed to come from the same bubble, and are thus rejected.

Moreover, when the void fraction is not small enough, it often happens that erroneous situations corresponding to consecutive bubble impacts respecting a correct time lag appearing on one of the sensor. This can lead to undetermined cases. We can observe 3 cases: 1/ more bubbles on probe A than on probe B, 2/ more bubbles on probe B than on probe A, 3/ as many different bubbles on probe A as on probe B during correct time lag. In the first cases it is not possible, according to the foregoing criterion, to associate unambiguously two signals corresponding to the passage of a single bubble on the two probes. These two cases are thus rejected. In the third case it is realistic to form events corresponding to the passage of distinct bubbles across the double sensor probe. This situation is validated according to an additional criterion based on the adequacy of the numbers of bubbles that have crossed respectively each probe in the required time lag. If the numbers of bubbles on each probe differ, the corresponding records are rejected.

The typical number of events which is necessary for the statistical averaging of the gas RMS velocity to converge is about 2000. The validation rate defined as the ratio between the number of retained events and the number of bubbles seen by one of the probes is about 70% in tested flows. The overall probe and measuring system performance is characterised by the smallest bubble size that can be detected in the flow: this was estimated to be about 0.1 mm.

The method of measurement was checked in a still water tank where bubbles were injected through a capillary tube. A high speed video camera allowed to validate bubble mean velocity and mean size measurements. The double peak in the histogram of bubble velocity measured from optical double probe corresponds to frequent visual observations of 2 bubbles arriving on the probe, the last one being accelerated in the wake of the first (Figure 5). The chord histogram is centred on a unique peak. The relative error on measurements of bubble mean velocity and mean size are both less than 5%.

For example, in the mixing layer, the slip velocity U_r and the RMS velocity fluctuations of bubbles were measured at several positions upstream the inlet, from section x = 6 cm to section x = 50 cm. The slip velocity U_r was found nearly constant in bubbly mixing layer. The ratio of the RMS velocity in gas phase to the RMS velocity in liquid phase (C_t) which is an important parameter for numerical computations in the two-fluid model formulation, is plotted on Figure 6 : the value of C_t is found nearly constant with a mean value $C_t = 1.5$ in all the flows, within data scatter ($1.1 < C_t < 1.8$).

4 - CONCLUSION

Measurement methods for bubbly flows have been discussed. Concerning liquid velocity measurements, HFA as well as LDA have been used. The use of the LDA implies two drawbacks: the presence of an important noise whose relative intensity increases with the frequency, and the absence of information on the bubble passages which makes it difficult to discriminate between the phases. The proposed filtering presented permits the correct suppression of the LDA noise. However, at higher void fractions (more than 2%), the LDA signal is no longer suitable because of the increase of the beam interruption rate by the bubble crossing. In this case, use of the HFA is recommended. The HFA had two major drawbacks: the difficulty to obtain a stable calibration curve, and the unknown effect of the bubble crossings on the film heat transfer. The HFA output voltage recorded in bubbly flow presents a drop of the signal that is characteristic of the presence of a bubble on the film and sometime a large rear peak just after the passage of the bubble is observed. Up to now, it was not admitted that this rear peak is representative of a real velocity in liquid phase.

This latter problem have been studied by placing the measuring volume of LDA very close upstream from the cylindrical hot film probe at low void fraction (less than 2 %). Analyses of simultaneous measurements by both methods prove that the two signals are quite similar. For example, at void fraction of 0.4 %, the statistical centred moments of the velocity differ less than 5% up to the sixth order. So, the rear peak just after the passage of the bubble is representative of the local inhomogeneity of the flow around the corresponding bubble. Thus, only the abrupt negative voltage drop which characterises a bubble presence on the film have to be removed. The results obtained in bubbly mixing layers are presented as example and to illustrate the applications of the signal processing methods that we use. Finally, local measurements of velocity moments and void fraction require careful signal processing. They were discussed. Nevertheless these measurements are not sufficient to understand the physics. In order to go on, it remains important to refine signal processing in order to be able to analyse more sophisticated information as correlations between bubble passage and velocity fluctuations.

REFERENCES

Bel Fdhila R., Suzanne C., Masbernat L., 1993, "Local measurements and Eulerian prediction of a bubbly flow downstream of a sudden pipe expansion.", *3rd World Conf. Exp. Heat Trans., Fluid Mech. and Therm.*, Honolulu, Hawaii, pp.1393-1401.

Bourget P. L.., (1976), "Méthode d'étalonnage d'un anémomètre à fil chaud", Journal of Physics E. : Scientific Instruments, 1976, vol. 9

Bremhorst K., Gilmore D. B., 1976, "Response of hot wire anemometer probes to a stream of air bubbles in a water flow", J. Phys. E.: Sci. Instr., 9, 347-352.

Bruun H. H., 1995, "Hot-Wire Anemometry, Principles and Signal Analysis", Oxford University Press.

Cartellier A., (1990), "Optical probes for local void fraction measurements : characterisation of performance", Rev. Sci. Instrum. 61 (2)

Ellingsen K., Risso F., Roig V., Suzanne C. 1996 " Improvements of velocity measurements in bubbly flows by comparison of simultaneous hot-film and Laser anemometry signals"

Gherson P., Lykoudhis P., 1984. "Local measurements in two-phase liquid-metal magneto-fluid mechanic flow.", *J. Fluid Mech.*, 222, 95-118

Herringe R. A., Davis M. R.,(1976), "Structural development of gas-liquid mixture flows", J. Fluid Mech., Vol. 73, 97-123.

Lance M., Bataille J., 1991. "Turbulence in the liquid phase of a uniform bubbly air-water flow." *J. Fluid Mech.*, 222, 95-118.

Lance M., Marié J. L., Bataille J., 1991, "Homogeneous turbulence in bubbly flows", Journal of Fluids Engineering, vol. 113, pp. 295-300

Marié J. L., 1983. "Investigation of two-phase bubbly flows using Laser anemometry". *PCH Physico Chem. Hydro.* 4,. pp. 89-95

Moursali, E., Marié, J. L., Bataille, J., 1995. " An upward turbulent bubbly boundary layer along a vertical flat plate". *Int. J. Multiphase Flow*.

Roig V., 1993, "Zone de mélange d'écoulements diphasiques à bulles", PhD Thesis of the University of Toulouse, France.

Roig V., Suzanne C., Masbernat L., 1993, *"Measurement in two-phase mixing layer"*, *3rd World Conf. Exp. Heat Trans., Fluid Mech. and Therm.*, Honolulu, Hawaii, pp. 1342-1348.

Serizawa , A, Kataoka, I., and Michiyoshi I., 1975, "Turbulence structure of air-water bubbly flows." *Int. J. Multiphase Flow* , 2, 221-259.

Serizawa , A, Tsuda K., Michiyoshi I., 1983, "Real-time measurement of two-phase flow turbulence using a dual-sensor anemometry.". *Proc., Symp. on Meas. techn. in gas-liquid Two-phase Flows.*, Nancy, France.

Sun T. Y., Faeth G. M., (1986), "Structure of turbulent bubbly jets", Int. J. Multiphase Flow. vol. 12, n°1, 99-126

Theofanous T. G., Sullivan J., 1982, "Turbulence in two-phase dispersed flows." *J. Fluid Mech.*, 116, 343.

Tjiptahardja T. , Gabillet C., Colin C., Fabre J., 1996, "LDA Investigation of a turbulent liquid flow with air blowing at a wall", *8th Int. Symp. Appl. Laser Techn. Fluid Mech.*, July, Lisbon, 2

Wang S. K. , Lee S. J., Jones O. C., Lahey R. T. , 1990, "Statistical analysis of turbulent two-phase pipe flow.", *J. Fluids Eng.*, 112, 89-95.

Wang S. K., Lahey R. T., Jones O. C., (1985), "Three-dimensional turbulence structure measurements in air-water two-phase flow", Rensselaer Polytechnic Institute Tropical Report, RPI/NSF-85-1

Welle, R. van der, (1985), "Void fraction, bubble velocity and bubble size in two-phase flow", Int. J. Multiphase Flow, Vol. 11, 317-345.

WYGNANSKI I., FIEDLER H.E., (1970), "The two-dimensional mixing region", J. Fluid Mech., Vol. 41, part 2, pp. 327-361.

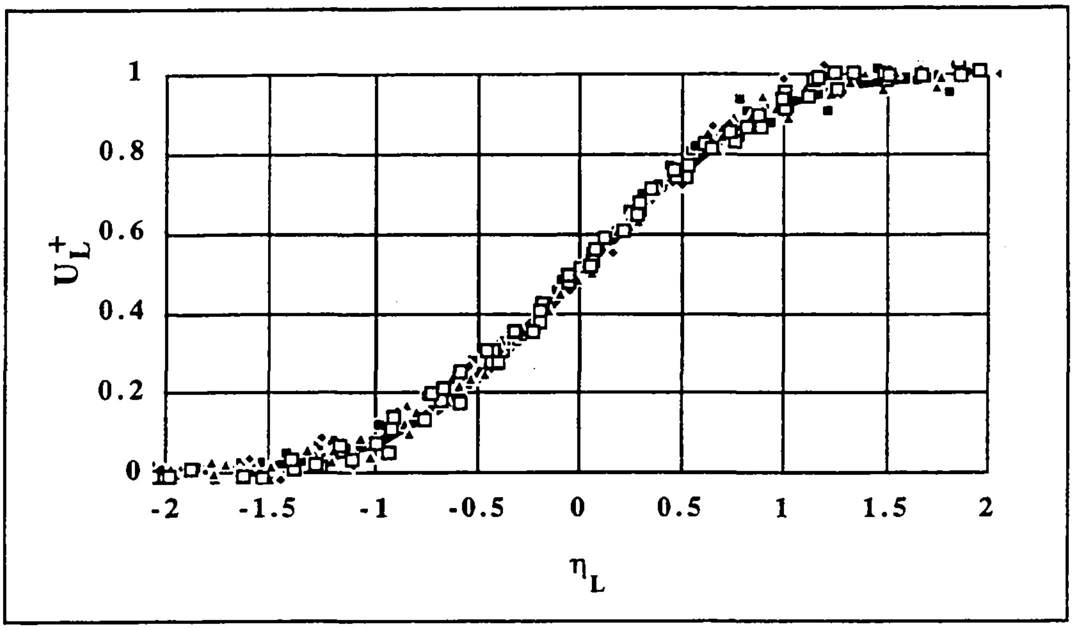

Figure 2 : Dimensionless mean velocity distributions in liquid phase in single-phase (solid symbols $\sigma \approx 24$) and in bubbly mixing layer (open symbols $\sigma \approx 11$) and Goertler law (solid line). ($U^+=(U-U_1)/\Delta U$, $\eta = \sigma y/x$)

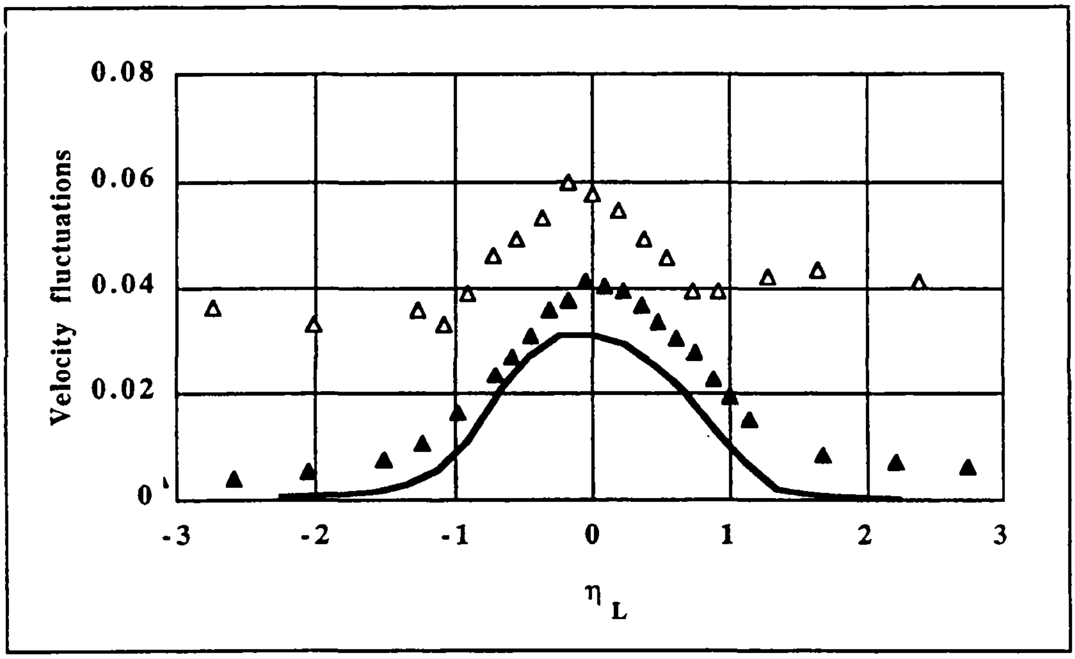

Figure 3 : Dimensionless longitudinal turbulent velocity fluctuations in liquid: $u'^2/\Delta U^2$
Single phase (▲), bubbly mixing layer (△) and Wygnanski and Fiedler single phase data (solid line).

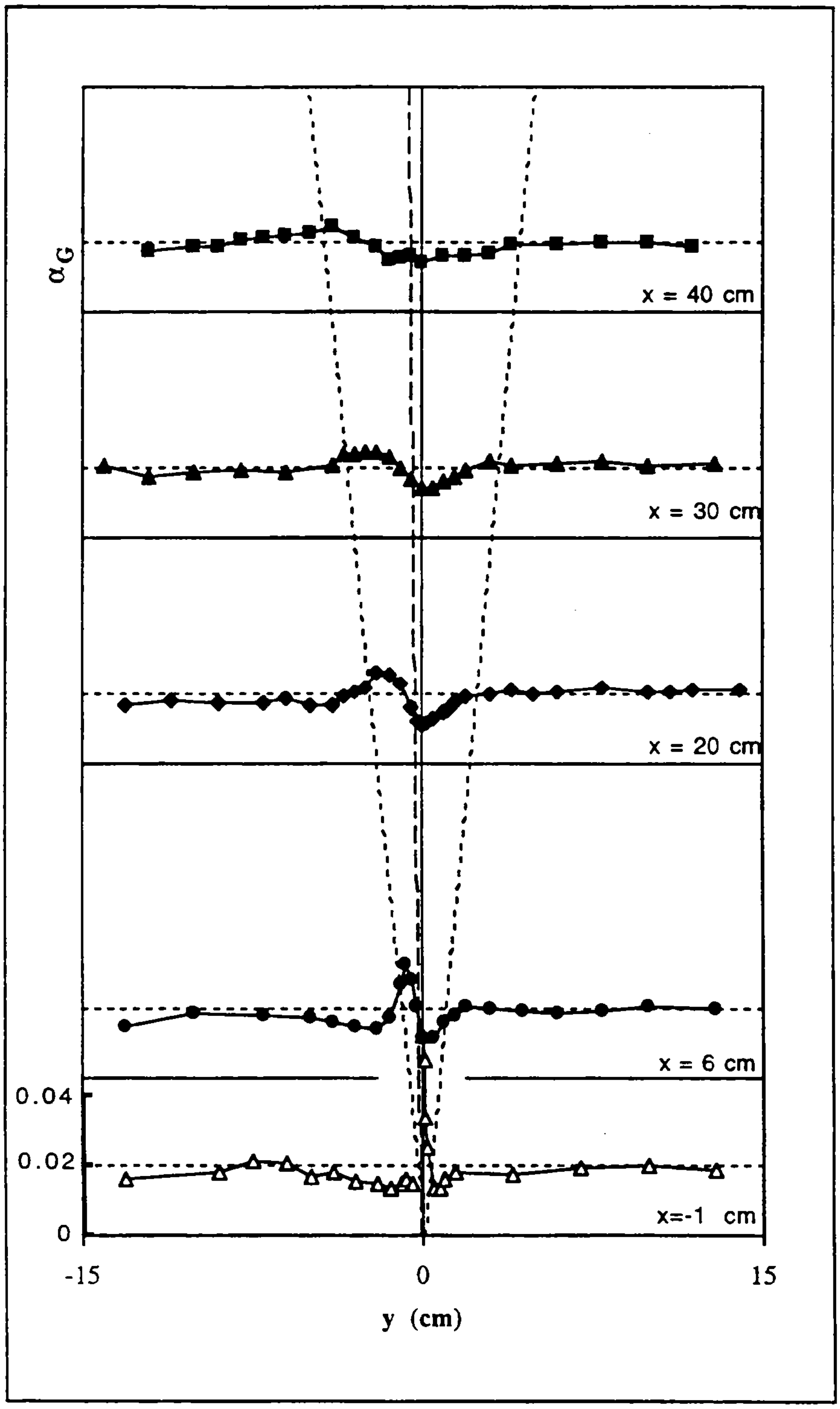

Figure 4 : Transverse Void fraction profiles at different longitudinal sections in bubbly mixing layer (y=0, axe of 20 cm x 20 cm square vertical channel)

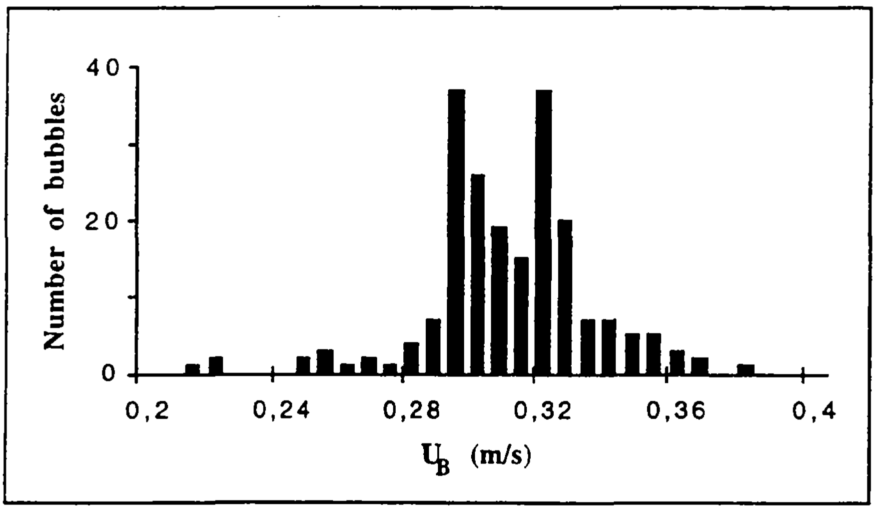

Figure 5: Bubble velocity histogram in stagnant water (Mean associated bubble chord: 1,8 mm)

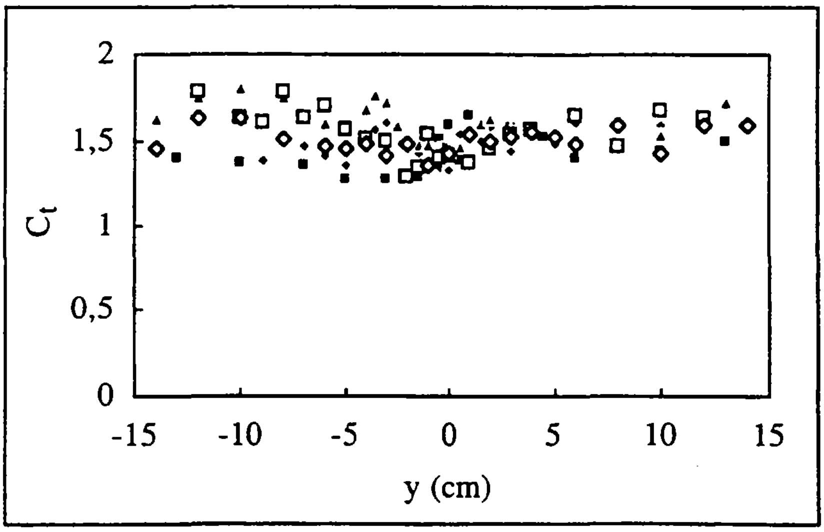

Figure 6 :Dimensionless longitudinal velocity fluctuations in gas phase: $Ct = u'_G/u'_L$. Transverse profiles at different longitudinal sections in bubbly mixing layer (from x = 6 cm to x = 50 cm).

SESSION V

OPTICAL PROBE METHODS