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A comparative study of phase Doppler and laser diffraction techniques to investigate drop sizes in annular two-phase flow

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Abstract

Drop size information is a common requirement in many parts of industry. Phase Doppler anemometry and laser diffraction techniques are usually employed for this purpose. Both measuring techniques give the drop size whereas the phase Doppler anemometry also provides additional information on the drop velocities. In the present work an inclinable two-phase flow facility has been constructed and the impact of inclination on the drop sizes has been investigated. This paper describes the drop size results obtained from two laser techniques and identifies the difference in drop sizes obtained from two laser systems when measurements were made under similar flow conditions. Possible reasons for this discrepancy have been discussed and a technique has been suggested to modify the new data obtained from the phase Doppler anemometry. The modified data have then been compared with those obtained from the laser diffraction technique. Results from both laser systems reveal similar trends in the measurements made under identical flow conditions. It has been found that the drop sizes are affected by the flow orientation and the effect is more pronounced at angles greater than 50° from the vertical. The effect of liquid mass flux has also been recorded. General problems and common sources of error while employing these two laser techniques have also been identified and necessary steps required to obtain laser results have been discussed in detail.

Keywords: Phase doppler; Laser diffraction; Drop sizes

1. Introduction

Laser based optical diagnostic techniques are widely appreciated due to their non-intrusive nature. There are various laser systems available in the market capable of investigating flows in different situations ranging from simple flows in pipes to the complicated cases encountered in high speed turbomachines [1–3]. The choice of the system, however, depends upon the type of application. For instance, in case of two phase gas/liquid annular flow, one particular interest is to observe the drop sizes and their velocities in the central gas core. Phase Doppler and laser diffraction techniques are usually employed for this kind of study. The phase Doppler anemometry can provide both drop size distributions and their velocities in the flow whereas the laser diffraction technique can only measure the drop sizes. Both instruments have been frequently employed by various researchers for this purpose [4–6] but very few [7] have tried to use both systems to investigate flow under identical flow conditions so that a direct comparison of techniques could be possible.

In this work both laser diffraction and phase Doppler systems have been used to measure the drop sizes in a gas/liquid two-phase annular flow. Annular gas-liquid two-phase flow is a familiar flow regime encountered in many pieces of industrial equipment. The main feature of this flow regime is the split of the liquid between the film which travels along the channel walls and the drops which are carried by the gas flowing in the centre of the pipe. Interchange occurs between the film and the drops. The two relevant processes of entrainment and deposition have been realised and discussed in detail by many researchers [8–12]. Large droplets entrained by the gas leave the liquid film and travel at about their initial velocities until they redeposit on the film. The process of drop entrainment and of drop deposition back onto the film is important to understand the complex flow phenomenon occurring in most of the practical cases. For

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instance, in evaporating channels, heat transfer between the flow and the heated channel are substantially influenced by the liquid film and the drop entrainment. The disappearance of the liquid film between the vapour and the channel walls results in overheating of the wall and burnout occurs. Burnout conditions can be monitored by investigating the local parameters which include rate of drop entrainment and deposition, drop atomisation and velocity in the flow core. Measurement of drop sizes and their velocities in the flow channel will provide a sound physical basis to understand the complex burnout phenomenon. Similarly the measurements of drop sizes and their velocities are also required in annular gas/liquid two-phase flow in vertical and horizontal pipes. The mechanisms of entrainment in this case have been found to be very similar to those of drop break-up [10]. The information on the drop sizes and the way they are created in the flow channel is important for any calculation of redeposition and also for the modelling of pressure drop. Drop sizes are also important for erosion/corrosion where the damage done will depend on the size and velocity of the drops. The modern practice of deviated drilling of oil and gas wells makes annular flow in inclined tubes of significant interest. Here, there is a need to determine the distribution of liquid about the tube cross section so as to identify if any of the wall is unwetted and thus require protection from corrosion. Currently, most of the available data on drop sizes is in horizontal and vertical pipes [13–16]. For inclined flows, initially measurements were made for the pressure drop and void fraction and some detailed measurements were obtained for the circumferential variation of film thickness [17]. But recently some attention has been paid to investigating the effects of inclination on drop sizes [18,19]. Table 1 gives a brief summary of the work carried out by various researchers to measure drop size distributions under different flow conditions. The techniques employed for this purpose have also been mentioned in Table 1. In this paper we are presenting a comparative study of laser diffraction and phase Doppler anemometry when employed to investigate the impact of inclination on drop sizes in a two phase gas/liquid annular flow. An inclinable rig was constructed for this purpose. The experimental facilities and the flow conditions have been explained in Section 2. This paper is an attempt to examine the basic principles behind both laser techniques and some suggestions have been made to analyse the data obtained from the phase Doppler system so that a direct comparison can be made between the two techniques.

2. Experimental facility and flow conditions

Fig. 1 shows the schematic diagram of the experimental facility used in this study. Filtered air from a constant pressure supply was fed into the entrance of the test section which was a stainless steel pipe of 0.038 m diameter. Air flow was measured by means of an orifice plate and the tube

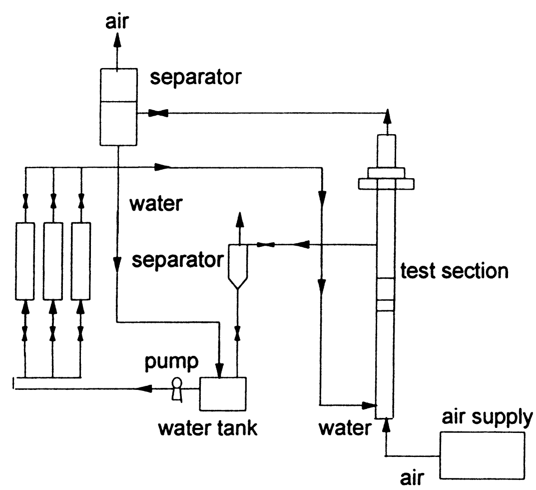

Fig. 1. Inclinable Flow Facility.

Table 1
Summary of literature survey

Author	Fluids	Tube diameter (m)	Flow direction	Gas flow (kg/m^2 s^{-1})	Liquid flow (kg/m^2 s^{-1})	Technique
Ueda (1979) [34]	Air–water	0.010	Vertical	55.8–115.2	8.32–65.13	Impaction
	Air–alcohol/water	0.030		30.6–72		
Azzopardi (1978) [22]	Air–water	0.032	Vertical	43.7–79.4	15–96	Laser diffraction
Azzopardi et al. (1980) [35]	Air–water	0.032	Vertical	43.7–115	15.9–158.8	Laser diffraction
Gibbons (1985) [12]	Air–water	0.032	Vertical	35.9–51.3	7.0–26	Laser diffraction
	Air–glycerol/water	0.0125				
Teixeira (1988) [7]	Air–water	0.032	Vertical	43.7–91.2	15.9–125.3	Laser diffraction PDA
Lopes-Dukler (1985) [36]	Air–water	0.051	Vertical	18.12–33.79		PDA
Jepson (1992) [37]	Air–water	0.010	Vertical	20–120	20–140	Laser diffraction
	Air–genklene	0.020		53–105	41–137	
	Helium–water					
	CF_4–water					
Ribeiro (1993) [38]	Air–water	0.032	Horizontal	40–75	20–70	Laser diffraction
Azzopardi and Zaidi (1996) [18]	Air–water	0.038	Vertical, horizontal and inclined	27–54	20–100	Laser diffraction

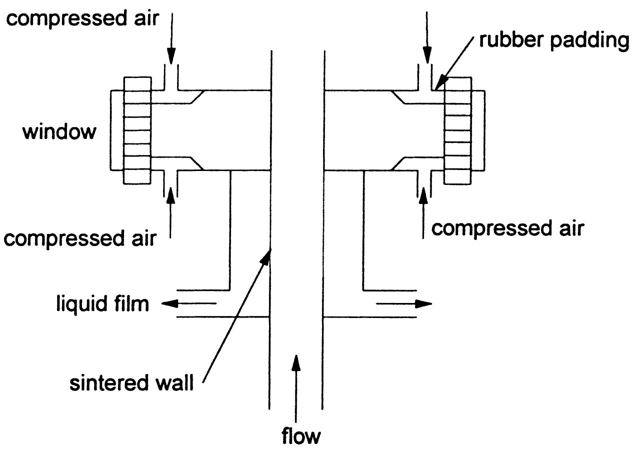

Fig. 2. Test section to incorporate optical windows.

pressure was kept constant at 0.5 bar (gauge pressure). Water from a supply tank was introduced into the test section through a porous wall section situated 0.5 m from the bottom end of the 0.038 m pipe. Variable flow meters were used to adjust the required flow conditions. The measuring section was a further 4.5 m beyond the porous wall section after which a 0.45 m long section completed the test section. The mixed air and water emerging from the test section was separated in a large vessel, the water being returned to the supply tank, the air released to atmosphere. The test section was mounted on an inclinable beam which could be positioned at any angle between the vertical and horizontal in steps of 5°.

In order to carry out laser measurements in the required test section, it was necessary to create an optical access and this was achieved by constructing a special measuring section as shown in Fig. 2. In case of annular gas-liquid flow, liquid travels as a film along the walls of the tube and removal of this film was necessary to perform laser measurements in the measuring section. A sintered tube was used for this purpose. The liquid and gas extracted from the sinter tube was fed into a cyclone to measure the flow rates so that entrained gas and liquid fractions could be calculated.

Drop size measurements were taken at the following flow conditions.

Gas superficial velocity U_G (m/s):	30
Liquid flow rate G_L (kg/m^2 s)	33 – 101
Inclination angle from vertical (Degrees)	0, 20, 40, 50, 70, 90

3. Phase Doppler and laser diffraction techniques

3.1. The laser diffraction technique

The basic mathematical model for the laser diffraction technique was proposed by Swithenbank in 1976 [20] and was based on the theory of Fraunhofer diffraction. Malvern Instruments employed this technique and developed an instrument (Malvern Particle Sizer 2600) which uses a small power He–Ne laser to illuminate the flow where the drop measurements are required. In line with this laser beam and beyond the drops, the receiving optics is placed which uses a Fourier transform lens to collect the light diffracted by the drops in the forward direction. This far field diffraction pattern is focused onto a multi-element photoelectric detector (composed of several concentric annular rings) which produces an analogue signal proportional to the incident light intensity. The possible sources of errors associated with this technique have been discussed in detail by Hirleman and Dodge [21] who found that the most significant source of error was varying sensitivity of each detector ring to the incident light. The Malvern system used in this study individually calibrates each ring and therefore improves the accuracy of the system as reported in the reference [21]. Once the diffraction pattern is read, a non-linear least square analysis is used to find the size distribution which gives the most closely fitted diffraction pattern. Initially the Rosin Rammler distribution was checked by Azzopardi et al. [22] who compared their data with that from Cousins and Hewitt [23]. Good agreement was found between the light energy obtained from the data and that calculated assuming a Rosin Rammler distribution to fit the data. The general performance of this instrument was tested by Azzopardi and Yeoman [24] and Negus and Azzopardi [25]. They tested the instrument against the photographic measurements of glass beads suspended in water. A good agreement was found. In this study, a size analysis called 'model independent' was employed. This analysis enabled measurement of multimode particle sizes with high resolution. It must be noted that the size range covered by this instrument depends upon the focal length of the main lens, Table 2. In this work 1000 mm focal length lens was employed.

Although since its development, this instrument has been tested by many researchers for a number of applications and has been found to be accurate [4], its use on practical rigs is

Table 2
Size range covered by the Malvern and the PDA systems

Lens focal length (mm)	Size range (microns)	Velocity range (m s^{-1})
Malvern system		
63	1.2–118.0	
100	1.9–188.0	
300	5.8–564.0	
600	11.6–1128.0	
800	15.5–1503.0	
1000	19.4–1880.0	
PDA system		
100	0.8–51.4	2.4–8.2
300	2.4–152.4	7.0–24.5
600	4.8–304.5	14.0–49.1
1000	7.9–507.4	23.4–81.8

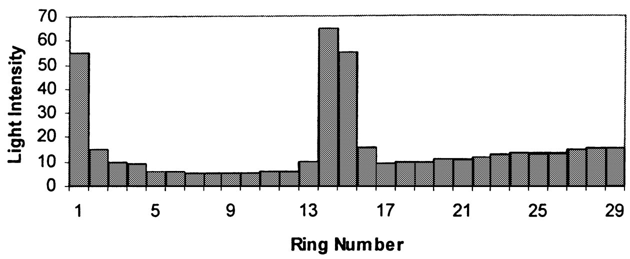

Fig. 3. Spurious signal due to glass reflections and vibration.

not free from problems and can produce erroneous results [26]. Two main sources of error affecting the size measurements in this study were vibration and glass reflections. Glass reflection came from the optical glass windows which were employed to admit laser beams into the measuring section whereas the vibrations in the system were found to be severe particularly at the higher gas and liquid flow rates. Fig. 3 shows the strong signals received due to vibration and glass reflections. These signals could easily be mistaken for the light scattered by the liquid particles during the measurements and could cause great inaccuracies in the results. The practical way to overcome the vibration problem was to use anti-vibration pads to isolate the system from the environmental perturbations. Both the transmission and the receiving sections of the laser diffraction system were individually mounted on two separate platforms. The design incorporated the provision of three-dimensional movement in both platforms, by which an alignment within micrometers could be achieved. The best way to eliminate the glass reflection signals was to tilt the optical windows [26] and this was achieved by mounting the glass windows on flexible rubber padding which could be pivoted on adjustable screws. After overcoming these problems, laser results were achieved at the flow conditions described in Section 2.

3.2. The phase Doppler anemometry

Since its early development [27], the phase Doppler technique has been extensively used in industry to measure drop sizes and their velocities simultaneously. This technique relies on the light scattered by particles crossing an interference fringe pattern which is collected over one or more apertures and then focused onto the photodetectors. Particle velocity is deduced as in laser Doppler systems whereas the particle size is deduced from measurements of signal intensity, depth of modulation or phase differences.

This technique has gone through rigorous testing by several researchers who have identified several sources of errors which can lead to incorrect size measurements. Two well known sources of errors are the Gaussian beam defect and the slit effect. The Gaussian beam defect arises from the Gaussian intensity of the laser beams. For particles large with respect to the focussed laser beam diameter, both the reflected and refracted rays reach the receiving detector and cause great error as the phase Doppler technique requires the domination of single scattering process [28]. The slit effect on the other hand arises due to the use of a slit which is used in receiving optics to have a well defined length of the measuring volume. It has been shown that this slit does not act as a perfect spatial filter and causes great error as particles passing along certain trajectories for which the corresponding length of measuring volume can be much longer than expected [29]. Techniques to minimise the Gaussian beam defect are well documented in the literature [30]. Similarly the 'slit effect' problem has also been discussed in detail by several researchers and several possible solutions have been suggested to overcome this problem including the use of modified optical arrangement, use of three or four detectors and the use of signal processing techniques which can reject bursts influenced by the slit effect [31]. Most of the existing PDA signal processors include these measures to reduce these effects to some extent but are unable to suppress them completely [32]. The phase Doppler technique is ideally suited to the measurement of spherical particles of diameters much greater than the wavelength of light used. Deviations from the spherical shape can introduce biasing which can be monitored by observing the 'shape factor' [33].

An AEA (Harwell, UK) one dimensional phase Doppler system using an argon ion laser was incorporated in this work. Table 2 shows the size and velocity range variation with the focal length of the main lens. In this study a 1000 mm focal length lens was used. The transmitting and the receiving sections of the system were mounted on two separate optical benches which were supported by a translation carriage to make the laser measurements radially across the tube. Fig. 4 shows this arrangement. It must be noted that in order to keep the fringe orientation perpendicular to the flow, the phase Doppler system was mounted on the flow pipe and was rotated along with the pipe to make measurements at various inclined positions. The attachment of the system to the rig caused several practical problems. During the operation, vibration caused optical misalignment which resulted in the loss of useful information. Special rubber mounts were used to damp the vibrations. On-line cleaning of the optical glass windows was achieved through purge air which made it possible to take laser measurements for a reasonable period before the signal deteriorated due to liquid drops appearing on the

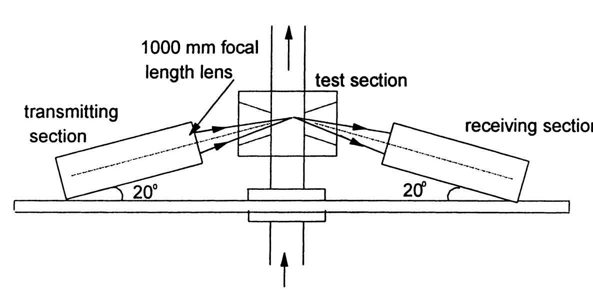

Fig. 4. Phase Doppler system mounted on the test section.

windows. Also the alignment of the laser system within the test section was difficult particularly at different inclined positions from the vertical. In fact the system had to be aligned separately at each inclined position.

4. Experimental results

4.1. Laser diffraction results

Fig. 5 shows the variation in Sauter mean diameter d_{32} against the liquid mass flux for different test section orientations. The trend shows, in general, an increase in d_{32} as the liquid mass flux increases at almost all angles except for the horizontal position where most of the data are from the stratified/atomisation flow pattern and the fluctuations in d_{32} values can be related to the film thickness from which the drops were created [19]. Fig. 6 presents the effect of inclination on drop size at 30 m/s gas superficial velocity, when the pressure in the test section was kept constant at 1.5 bar. Fig. 6 indicates that the effect of inclination over the drop size up to about 50° from vertical is small as compared to that observed at and above 50° from the vertical and is more pronounced at lower gas velocities. It can be seen from Fig. 6 that above 50° inclination, the spread of d_{32} becomes noticeably greater for the selected range of liquid mass flow rates. It must be noted that the two-phase annular flow will be affected as the test section is tilted. The uniform liquid film flowing along the walls of the tube may change as the tube deviates from the vertical position. Particularly at the horizontal position one may visualise a thick liquid film along the top surface as compared to that at the bottom of the tube. The annular flow may change into stratified flow as the tube's position is changed from the vertical to the horizontal position. This change of flow pattern is reflected by the changes in the drop size distributions in the test section. A detailed discussion and comparison of this data with the existing correlations has been presented by Azzopardi and Zaidi in reference [19].

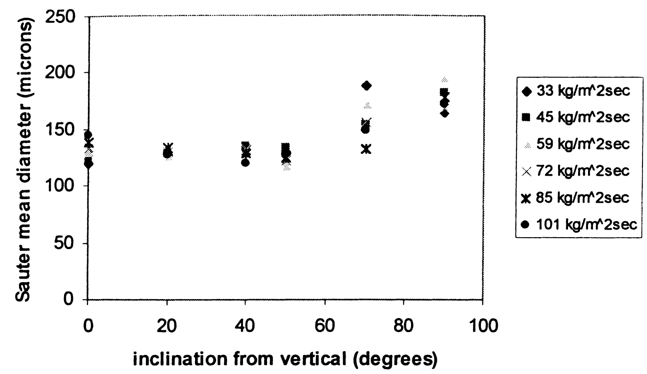

Fig. 6. Effect of inclination on drop sizes using laser diffraction technique.

4.2. Phase Doppler results

Laser measurements were carried out at the flow conditions described in Section 2. Again the main interest was to investigate the effect of liquid mass flux on the drop sizes in the flow. The effect of inclination on drop sizes has also been fully investigated. Fig. 7 shows the effect of liquid mass flow on drop size. Fig. 8 presents the effect of inclination on the drop size. PDA results show little effect of inclination on the drop size. It must be noted that all the PDA results were obtained at the centre of the pipe. The comparison of PDA results with those obtained with the Malvern diffraction system has been included in Section 5.

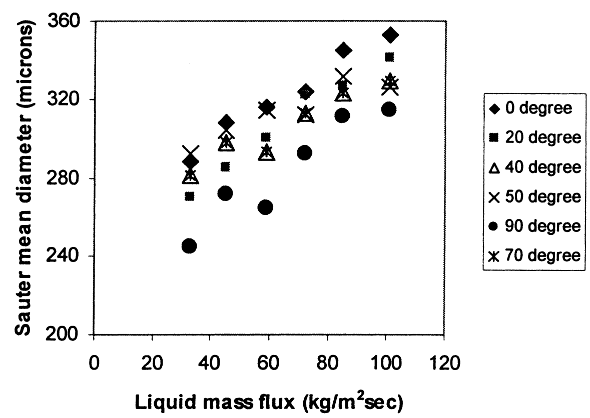

Fig. 7. Effect of liquid mass flow on drop sizes using phase Doppler anemometry.

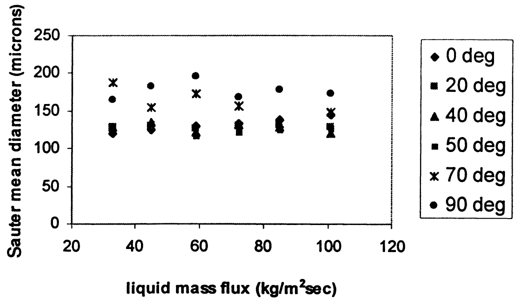

Fig. 5. Effect of liquid mass flux on drop sizes using laser diffraction technique.

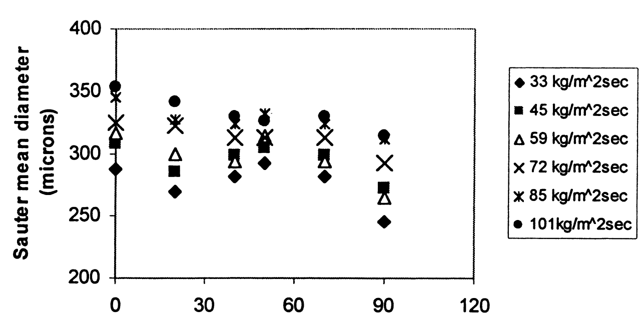

Fig. 8. Effect of inclination on drop sizes using phase Doppler technique.

5. Discussion

PDA and Malvern results have been compared for vertical, horizontal and four inclined positions of the test section when the gas superficial velocity was kept at 30 m/s. Before comparing the results from two laser systems, it would be useful to investigate how did these two systems respond as the liquid mass flux was increased. Both laser systems seem show similar trends as can be seen in Figs. 5 and 7. The results from the phase Doppler system, Fig. 7, shows that although the Sauter mean diameter increases with the increasing liquid mass flux, the data are more scattered in this case as compared to that obtained from the laser diffraction technique, Fig. 5. Fig. 7 also shows that the drop sizes in general are higher in the vertical flow orientation than those observed in the horizontal position but the effect of increasing liquid mass flux is the same in both situations. This is in contrast to what has been observed in the horizontal position in Fig. 5 where at a lower mass flux there is little effect of inclination on the drop sizes. A comparison between Figs. 6 and 8 reveals that phase Doppler results show a negligibly small effect of inclination on drop sizes.

Fig. 9(a)–(f) show the difference in results obtained from both systems for identical flow conditions. It must be noted that the phase Doppler system (PDA) consistently gave larger drop sizes as compared to those measured by the diffraction technique (Malvern) although the flow conditions were kept similar in both cases. The difference between the Malvern and the PDA results is more pronounced at the vertical position and it gradually lessens as the test section is inclined from the vertical to the horizontal position. The difference in results from the two techniques is mainly due to the different principles on which they work. The laser diffraction technique integrates the light scattered by various particles along the laser beam and thus averages the drop sizes whereas the phase Doppler system makes point measurements in the flow. It must be noted that in case of the phase Doppler system, the light intensity inside the probe volume prohibits a Gaussian profile, due to which the larger droplets are more likely to be measured in this case. Another factor which makes the PDA measurements biased

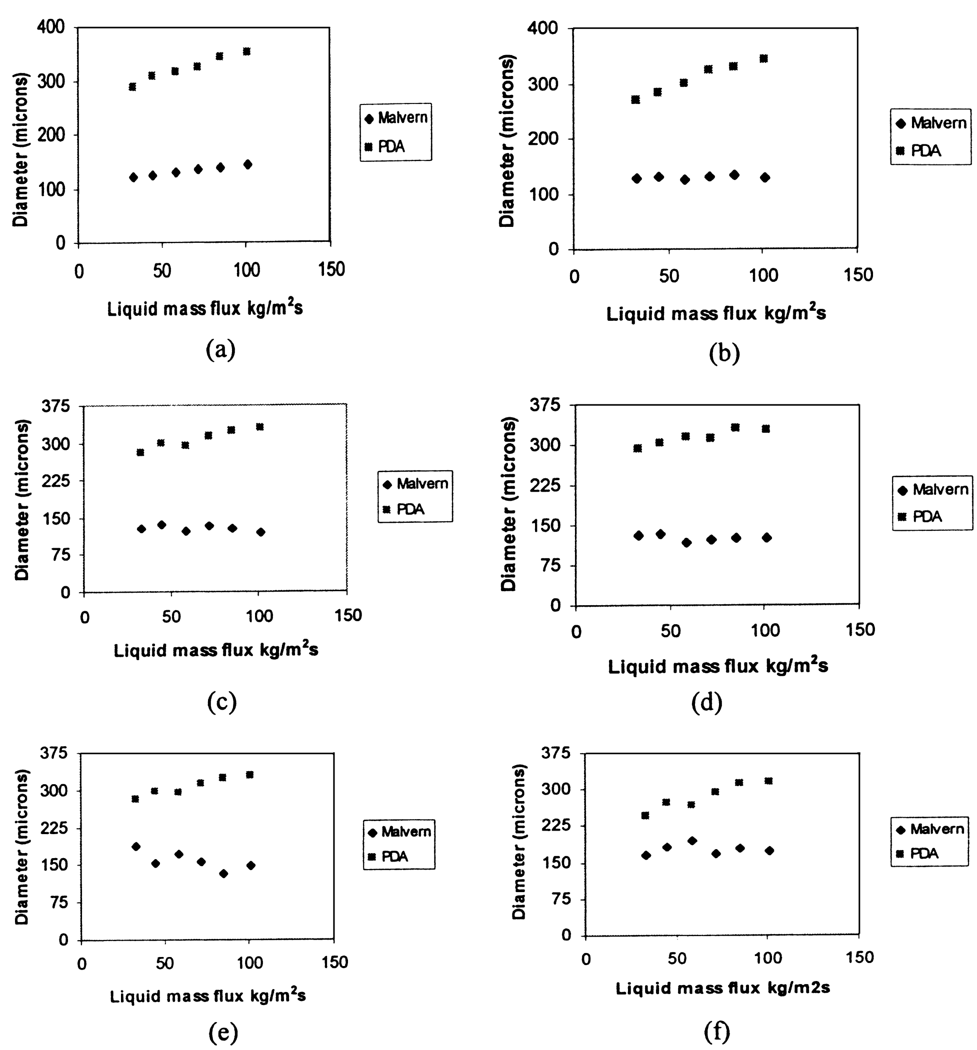

Fig. 9. (a)–(f) Comparison of laser diffraction and phase Doppler results.

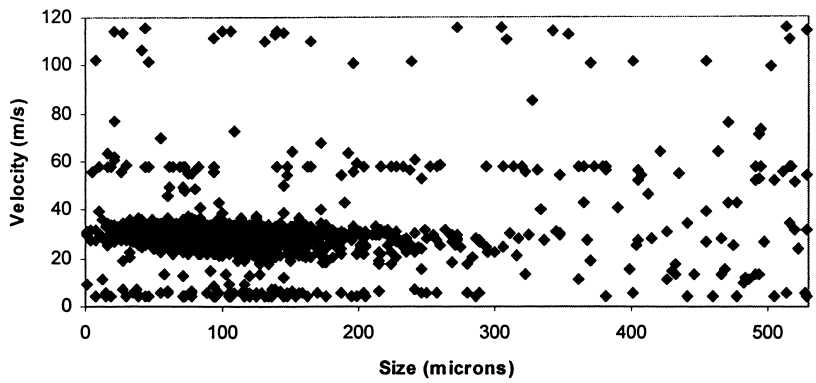

Fig. 10. Velocity and drop size distribution: a typical result from the PDA system.

towards the larger particles is the inability of the system to measure the drops smaller than about 40 microns as will be seen in the data presented below. In order to overcome this problem, the data from each individual measurement was analysed. Fig. 10 shows the typical size distribution obtained from the PDA system. The data presented in Fig. 10 suggests the presence of large drops with higher velocities (60 and 120 m/s) which is untrue as the gas superficial velocity was set at 30 m/s. The presence of larger drops seen in Fig. 10 needs more attention as they influence the mean Sauter diameter to a great extent. It must be noted that according to Teixeira [7] these large particles could have come from a larger probe volume. He suggested a method for compensating for this bias. However, in this study, a simple approach was adopted to eliminate these drops from the main data. A cumulative normalised distribution C, Fig. 11, was obtained from the PDA data. In order to identify the first minimum, the derivative of the cumulative (dC/dd) was plotted against the drop size as shown in the Fig. 12. It can be seen that for the large drops the distribution does not approach zero and also a bi-model distribution can be observed from the data. The Malvern results consistently present a uni-model drop size distribution for these flow conditions. Therefore, it was decided to consider the data under the first peak in Fig. 12 and the rest of the data was rejected. The new selected data was plotted with that from the Malvern system for the identical case and

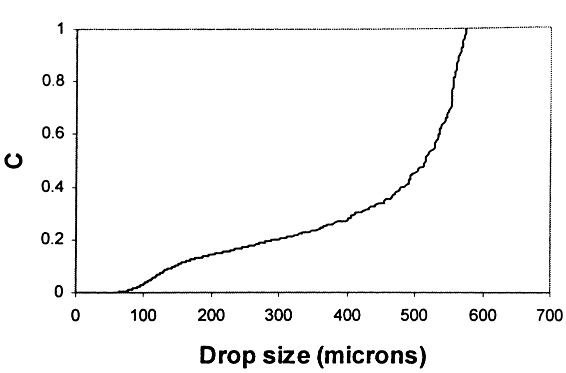

Fig. 11. Cumulative normalised distribution (C) for drop sizes.

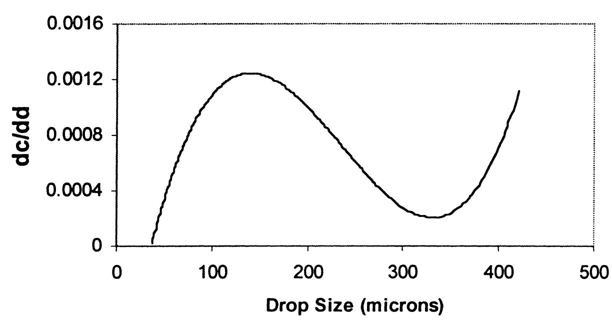

Fig. 12. dC/dd against the drop size.

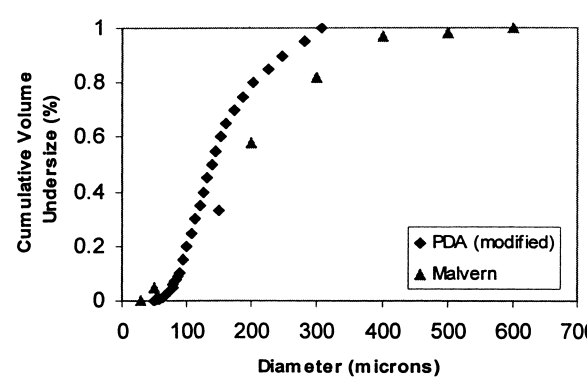

Fig. 13. Cumulative fraction of drops – Malvern and corrected PDA results.

the results have been presented in Fig. 13. Mean Sauter diameter was also calculated for this case and in this case was reduced from a value of 288.0 to 151.8 μm whereas the corresponding value from the Malvern system was 120.0 μm. This procedure was repeated for all the data sets obtained for different angles and at all flow conditions described in Section 2. Fig. 14 shows the new comparison of results and it can be argued that two sets of data from the two systems do agree if the data from the PDA system is re-analysed with the procedure described above. The modified PDA data has also been plotted to examine the effect of liquid mass flux and inclination on the drop sizes. Figs. 15 and 16 give the results which show that the effect of

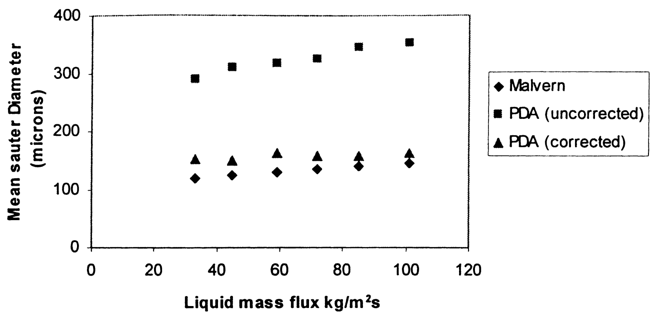

Fig. 14. Comparison of the Malvern and the phase Doppler results for identical flow conditions.

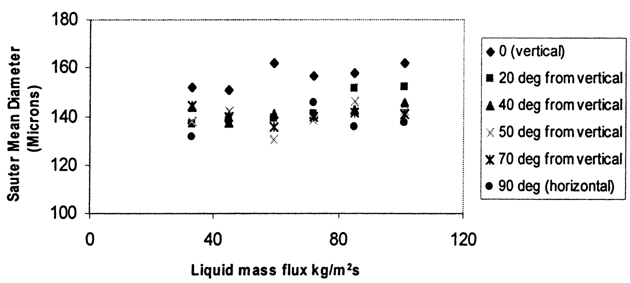

Fig. 15. The effect of liquid mass flux on drop sizes (corrected PDA data).

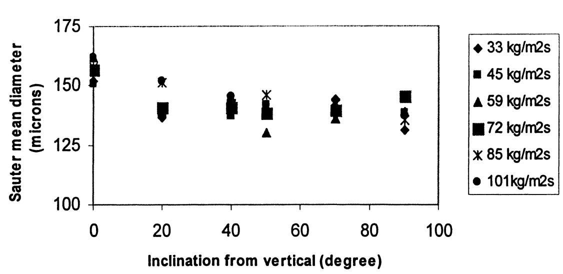

Fig. 16. The effect of inclination on drop sizes (corrected PDA data).

increasing liquid mass flux on the drop sizes is similar to that observed in Fig. 5 but, on the other hand, the PDA results do not show any significant change in the mean drop sizes as the pipe is inclined from the vertical to horizontal position. It must be noted that as the flow orientation changes from vertical to horizontal position, the drop size distribution changes across the tube. The PDA system making point measurements at the centre of the pipe was unable to detect any significant change whereas the Malvern system averaged out the mean diameters across the tube and therefore was able to detect the impact of inclination on the drop sizes.

The general problems associated with the laser diffraction technique have already been detailed in Section 3.1. One factor which could have affected the Malvern results in this study is that the mean drop size varies across the test section, Fig. 17, which implies that the drops at the central region of the pipe will contribute more to the sample mean than those near the wall and also the distance travelled inside the probe volume varies along the radial position. The bias associated due to these two effects can be combined to evaluate the

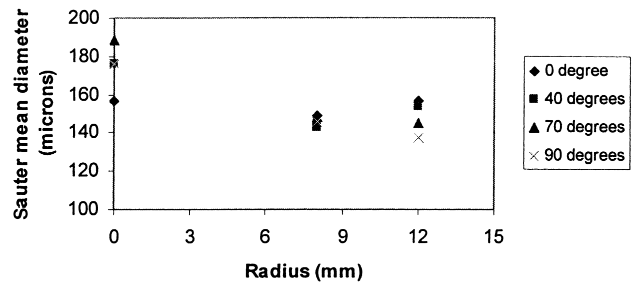

Fig. 17. Radial distribution of drop sizes (PDA results: $U_G = 30\ \mathrm{m\ s^{-1}}$).

corrected mean drop diameter. For this purpose an expression was derived by Teixeira [7] who concluded that due to these two effects the laser diffraction technique can introduce significant bias into the mean diameter (up to 10% for d_{32}). The laser results presented in this paper do not include the correction due to the bias described above but it is anticipated that doing so can bring the PDA and Malvern results closer although no change in the general trend is expected.

6. Conclusions

Laser diffraction techniques and phase Doppler anemometry have been employed to investigate the effect of inclination on drop sizes in an annular two phase gas-liquid flow. A test section of 0.038 m diameter was used for this purpose. The results from the phase Doppler anemometry have been compared with those obtained from the laser diffraction technique. Both laser techniques show a similar trend but a noticeable difference in size distribution was observed when the data from both techniques was compared. Several factors creating this discrepancy in results have been identified and some suggestions have been made to overcome this problem. Experimental results, in general, show no significant effect of inclination on drop sizes up to an angle of 50° from the vertical but beyond this angle the change in drop size distribution is quite noticeable. This effect is more visible in case of laser diffraction measurements whereas the phase Doppler shows little effect of inclination on the drop sizes. The effect of increasing liquid mass flux is found to have similar effects in results from both laser systems. The general problems in employing the two laser techniques have also been identified and discussed in greater detail.

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