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Panayotopoulos, Nikolaos, Lucas, Gary and Pradhan, Suman

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Original Citation

Panayotopoulos, Nikolaos, Lucas, Gary and Pradhan, Suman (2006) Simulation of a four sensor probe using a rotating dual sensor probe. In: Proceedings of Computing and Engineering Annual Researchers' Conference 2006: CEARC'06. University of Huddersfield, Huddersfield, pp. 1-6.

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Simulation of a four sensor probe using a rotating dual sensor probe.

N. Panagiotopoulos, G. P. Lucas, P. Suman

ABSTRACT

In the current project a rotating dual sensor probe has been designed and fabricated. A set of measurements were performed using the rotating dual sensor. Analysis on the results occurred, and it showed that the rotating dual sensor with the supporting algorithm has an acceptable, reliable and repeatable performance for measurements in multiphase flows.

Keywords velocity components, conductivity probes, rotating probe, multiphase flows.

1 INTRODUCTION.

In previous work of Lucas et al [1][2][3][4] the use of multi-sensor conductivity probes in bubbly multiphase flows is presented. It shows a method of fabricating two and four sensor probes, their electronic circuits and the resulting voltage waveform at their output. Also, it shows the signal processing scheme for extracting the bubble signature from the acquired signal, and the model for calculating flow properties of the dispersed phase in the pipe. Lucas et al compared the results from his measurements in different flow conditions with reference data and data from [5] and [6].

The multi-sensors that have been used by Lucas et al, were two sensor probe and four sensor probe. In literature [1][2][3][4], the description of their fabrication and the supporting electronic circuit can be found in detail. In the same literature, the signal processing and the calculation of the flow properties are described in detail too. As it can be seen, the two sensor probe is able to measure two flow properties of the disperse phase, which are the volume fraction and the axial velocity of the bubble. The four sensor probe is able to extract more information from the signals (due to the extra sensors), which is the vector velocity of the bubble.

Several measurements have been acquired using the two types of probes. The outcome of the analysis for the dual sensor probe showed that the whole system (probe, electronics, model, implementation of the algorithm in the computer, and visual presentation) performed very well with a small error. Detailed presentation of the performance of the dual sensor can be found in [3] and [4].

The four sensor probe showed results that exhibit some ambiguities and as a result from the previous description, a further investigation on the four sensor probe system was undertaken. So, a new test rig has been made, a new type of probe has been fabricated, and more data sets have been collected. Next, a detailed description of the rotating dual sensor probe is given.

2 LABORATORY APPARATUS.

A bubble column was used in order to do the experiments. The bubble column has a bubble injector at the bottom, which is connected to a controllable air pump. The pump controls the amount of air that is inserted into the bubble column. A metal sheet over the air injector was positioned into the column. The metal sheet was drilled in many places having holes of a specific and identical diameter (6mm diameter). The pumped air from the injector was hitting the mesh and through the holes bubbles of almost 6mm diameter were created. Then the buoyancy force drives the bubbles straight to the top of the bubble column¹.

At the top of the column a probe holder or a hinge was placed. The probe holder was holding the probe (as the word also implies), and it is also able to move the probe in five distinct positions. These five distinct positions define the bubble velocity vector with respect to the probe's coordinate system, when the origin is at the tip of the front sensor. The first position is vertical, which means that the bubbles hit the probe with 0° degrees polar angle and 0° degrees azimuthal angle (using cylindrical coordinates). The second position places the probe in a predefined polar angle and 0° degrees azimuthal. The third position makes the probe to be in a predefined polar angle and 180° degrees azimuthal. It is obvious now that the other two positions are going to be some polar angle and 90° degrees azimuthal, and finally some polar angle and 270° degrees azimuthal.

¹ In reality the bubbles do not move straight, but they oscillate in the x-y plane (assuming the z axis is the axis of their motion and the x-y is the cross section plane of the column).

Since it is desirable to measure bubble vector velocities, three parameters must be acquired. These are the polar angle or gamma (γ), the azimuthal angle or beta (β), and the velocity magnitude (v). It is important to mention that in the current work the azimuthal angle is defined as the angle between the y-axis and the projection of the vector on the x-y plane; also, the polar angle is defined as the angle between the z-axis and the vector. Positive azimuthal angles correspond to clockwise direction, and positive polar angles correspond to angles smaller than 90° . This type of format is the same with the one that was used in Mishra et al [2]. So, in order to be sure that the calculations of the model are correct, it is obligatory to acquire some reference data, in order to do the comparison and measure the error.

The reference data for the azimuthal β and polar γ angles can be acquired straight from the hinged probe holder and using an inclinometer. For the magnitude of the velocity vector (which is always vertical and parallel with the bubble column) a cross correlation meter was used. This is a pipe that fits into the bubble column and has two metal strips connected at its walls. The axial separation of these strips is 5cm. These metal pieces are connected with a set of cables. A two channel electronic set up has been built to support and drive the cross correlation meter. The electronic circuit was connected with a data acquisition. A software program (written in Visual Basic) was made to use the data acquisition unit. The acquired data were processed through another program (written in MatLab) to calculate the mean velocity of the bubbles.

As a result from the above, a bubble column system has been made for acquiring reference measurements and giving the advantage of a controllable and observable environment for the experiments. The figure below (figure 1) shows the system in a diagram.

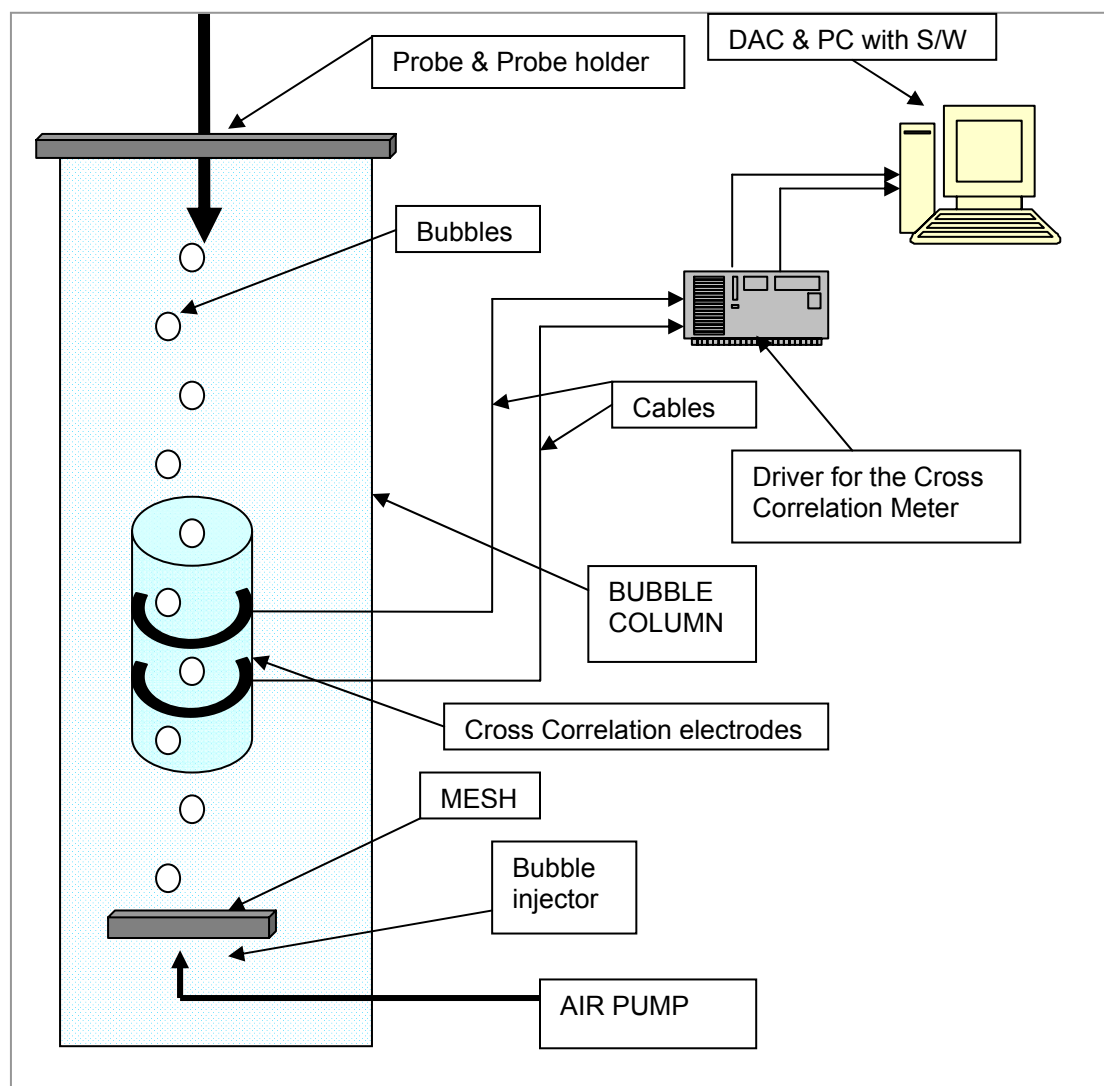


Figure 1. Schematic of the bubble column and the instruments.

3 THE ROTATING PROBE.

The rotating probe that was made is an original design and idea suggested by Lucas. It is a dual sensor but it has the ability to be rotated having the front sensor in the axis of rotation (and at the centre of the whole probe) and the rear sensor in any position that is desired. This type of probe can be used as a multi sensor probe (two sensor probe, four sensor probe, six sensor probe, 10 sensor probe, etc). In this paper it was used as a four sensor probe. The advantage of this type is that it has a smaller area of interface than the other probes, affecting the bubble's motion less. Also, the design and fabrication of a dual sensor is simpler than a multisensor probe. The only disadvantage that this rotating dual sensor does have is that the flow condition must be in steady state during the measurements, while the other type of probes can be used in a non-steady state flow. But for the current work where the flow condition is in steady state, the specific disadvantage of the probe disappears. Figure 2 shows a drawing of the rotating dual sensor probe.

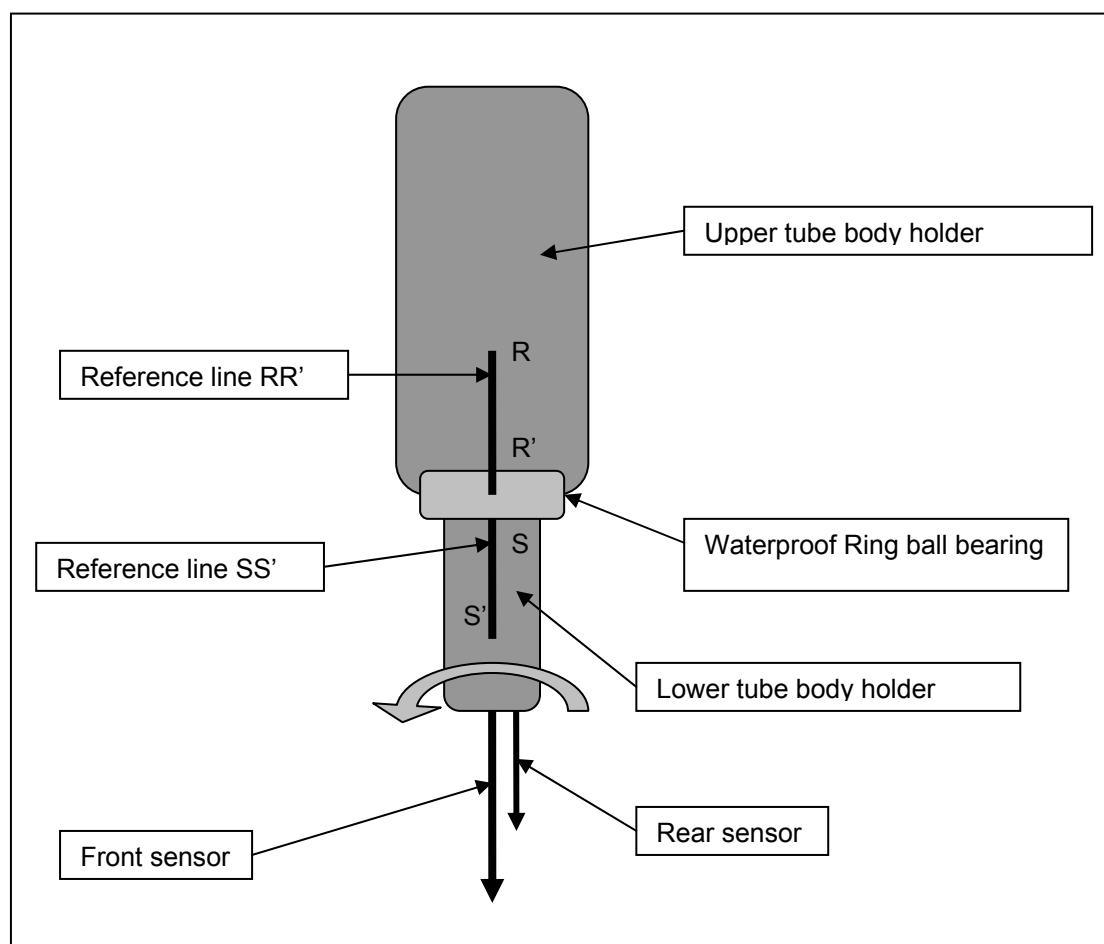


Figure 2. The rotating dual sensor probe.

Note that the upper part of the probe is clamped in the holder. As it was mentioned before, by rotating the lower tube of the probe in three distinct positions the result is to have a four sensor probe. For the current experiments, the rotation was clockwise and the angle step was 120° . So, the first position of the rear sensor was in 90° with respect to the x-axis (in a coordinate system that has as origin the lead sensor), the second position of the rear sensor was 330° (or -30°), and the third position of the rear sensor was 210° . In other words, the first position of the rear sensor defines the y-axis of the, which passes from the lead and rear sensor. Also, based on figure 3, the first position of the rear sensor, makes the RR' to be in line with SS'. In addition, the x-axis can be defined as any 90° degrees clockwise from the y-axis when viewed from the upper to lower tube of the probe. The (x,y,z) dimensions in mm of the virtual four sensor probe for each rear sensor with respect to the front sensor are: rear sensor 1 (0,0.7326,1.1765), rear sensor 2 (0.6344,-0.3663,1.1765), rear sensor 3 (-0.6344,-0.3663,1.1765).

4 DUAL SENSOR PROBE'S ALGORITHM

After acquiring measurements from the rotating dual sensor probe, data processing has to be done. Next the algorithm that was used for processing the data is shown.

1. **Stage 1:** Calculate the numerator and denominator of $\tan(\beta)$.
2. **Stage 2:** Call N the result of numerator and D the result of denominator.

$$\text{IF } N>0 \ \& \ D>0 \ \text{THEN } \beta = \tan^{-1}\left(\frac{|N|}{|D|}\right)$$

$$\text{IF } N>0 \ \& \ D<0 \ \text{THEN } \beta = 2 \cdot \pi - \tan^{-1}\left(\frac{|N|}{|D|}\right)$$

$$\text{IF } N<0 \ \& \ D<0 \ \text{THEN } \beta = \pi + \tan^{-1}\left(\frac{|N|}{|D|}\right)$$

$$\text{IF } N<0 \ \& \ D>0 \ \text{THEN } \beta = \pi - \tan^{-1}\left(\frac{|N|}{|D|}\right)$$

$$\text{IF } N=0 \ \& \ D=0 \ \text{THEN } \beta=0$$

$$\text{IF } N=0 \ \& \ D>0 \ \text{THEN } \beta = \frac{\pi}{2}$$

$$\text{IF } N=0 \ \& \ D<0 \ \text{THEN } \beta = \frac{3 \cdot \pi}{2}$$

$$\text{IF } N>0 \ \& \ D=0 \ \text{THEN } \beta=0$$

$$\text{IF } N<0 \ \& \ D=0 \ \text{THEN } \beta = \pi$$

3. **Stage 3:** Apply stages 1 and 2 to all 6 formulae of β .
4. **Stage 4:** Find the β that gives positive γ angle. Those values are the correct ones.
5. **Stage 5:** Continue with the calculations of velocities (Azimuthial velocity, Radial Velocity, and Axial Velocity).

7) RESULTS OF THE NEW 4-SENSOR PROBE ALGORITHM.

The data that were used for testing the proposed algorithm were the same as the ones that are shown in table 1. Below, the results of data set 1 are presented when the rotating dual sensor probe and its algorithm are used. Each data set is a group of 5 flow conditions. For each flow condition the reference values of β , γ , and velocity are shown. As it was mentioned before, the reference β and γ are measured using an inclinometer and the probe holder, whilst the velocity magnitude is measured using a cross correlation instrument. Also, in the same table that presents the results of a flow condition, the β angle without considering the signs is shown for comparison reasons (this is the column that has "beta" as a label). Also the average time delays for each rear sensor are shown and they are labelled as "dt11", "dt22", and "dt33".

Next, the data results using the new algorithm are presented.

SET 1				SET 1			
Reference		DATA 1		Reference		DATA 2	
beta:	0	dt11:	0.005207	beta:	0	dt11:	0.006878
gamma:	0	dt22:	0.005556	gamma:	24	dt22:	0.004833
Vb_xcorr:	0.4026	dt33:	0.005675	Vb_xcorr:	0.4026	dt33:	0.004912
		beta	gamma			beta	gamma
Rotating probe		194.145	4.702547	Rotating probe		358.0497	21.19236

Table 1

Table 2

SET 1				SET 1				
Reference		DATA 3		Reference		DATA 4		
beta:	180	dt11:	0.004164	beta:	90	dt11:	0.005428	
gamma:	21	dt22:	0.005946	gamma:	5	dt22:	0.005777	
Vb_xcorr:	0.38845	dt33:	0.005887	Vb_xcorr:	0.38845	dt33:	0.005637	
		beta	gamma			beta	gamma	
Rotating probe		178.3495	19.39786	Rotating probe		156.4698	3.325042	
Table 3				Table 4				
SET 1				SET 1 (measured velocities of the data)				
Reference		DATA 5		Data	Vaz	Vrad	Vax	V
beta:	270	dt11:	0.005631	DATA 1	-0.00868	-0.03443	0.431614	0.433072
gamma:	3	dt22:	0.005427	DATA 2	-0.00454	0.133465	0.344428	0.36941
Vb_xcorr:	0.3743	dt33:	0.00576	DATA 3	0.004392	-0.15243	0.433075	0.459138
		beta	gamma	DATA 4	0.009724	-0.02233	0.419247	0.419954
Rotating probe		277.3747	3.174744	DATA 5	-0.02299	0.002976	0.418032	0.418675
Table 5				Table 6				

8) COMMENTS ON THE RESULTS.

Visual inspection of the results, show that polar and azimuthal angles are very close to the reference values. It is important to mention again that for the flow conditions where the probe is vertical to the flow of bubbles there is no obligation that the azimuthal angle must be 0° degrees. It can take any value between 0° and 359° degrees. Therefore, for this flow condition the value of β angle is not of great interest. The next two tables show the error percentage of polar, azimuthal, and velocity magnitude of the two data sets.

SET 1	Error beta	Error gamma	Error V
DATA 1	N/A	2.61%	7.57%
DATA 2	-1.08%	-1.56%	-8.24%
DATA 3	-0.92%	-0.89%	18.20%
DATA 4	36.93%	-0.93%	8.11%
DATA 5	4.10%	0.10%	11.86%

Table 7

As it can be seen from the previous tables the polar angle is very close to the reference value and it is positive. This means that the flow is upwards and the algorithm could calculate the γ angle with an acceptable accuracy.

The azimuthal angle is closer to the reference value (except the vertical flow conditions). But the error in azimuthal angle is bigger than the error of polar angle. This indicates that the accuracy of the system is better to polar angles than to azimuthal ones. The reason for this difference in accuracy might be the way the bubbles flow upwards. From [7] [8] [9] and [10] it can be seen how irregular is the behaviour that the bubbles exhibit. This behaviour introduces error to the time differences and the algorithm gives less accurate result than the polar ones. Also from [11] a dedicated analysis of an oscillating bubble plume is presented. In [11] a plume of fine bubbles has been specifically generated within a rectangular vertical tank (exactly the same as the one that was used for the current measurements) by means of capillary tubes. The plume oscillates in the transverse direction, and the mean frequency is 0.235Hz. Therefore, this kind of bubble behaviour introduces an error during the calculation of β angle due to the nature of the bubble plume. Figure 5 shows how the bubble plume oscillates [11].

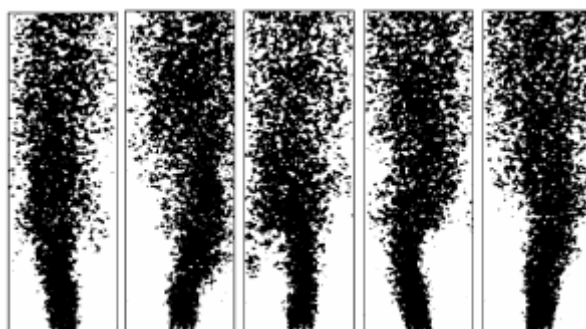


Figure 5. Oscillating plume [11].

It is also interesting how big the error of β for "DATA 4" flow condition becomes in both data sets. There is no currently any valid explanation regarding this case, therefore no comment can be said.

The polar angle is very close to the reference data. Looking at the tables, it is obvious that the error is small (less than 2%). This can be classified into the 95% confidence level in statistics.

9) Conclusions

Considering all the above, a new type of probe has been developed. Data have been acquired with the new probe and validated using the new algorithm. The results show a significant improvement for the calculation of azimuthal angle with a small errors comparing with the reference data. The comparison between the polar angles showed that a significant improvement has been achieved as well, with a small error (less than 2%). Also, a limitation has been proposed for the use of the specific algorithm. This limitation is that the knowledge of the direction of flow is essential and must be known.

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