SECTION 3

LASER DOPPLER VELOCIMETRY

3.1 INTRODUCTION

As part of a combined numerical (Celik and Wang, 1990), analytical (Clark, Atkinson, and Flemmer, 1987), and experimental (Gross and Kuhlman, 1990) study of bubble column hydrodynamics, measurements have been made of mean and fluctuating bubble and liquid velocities in a laboratory model bubble column. The three component laser Doppler velocimeter (LDV) described by Kuhlman and Gross (1989) has been used to obtain the bubble and liquid velocity data non-intrusively. Use of a non-intrusive flow measurement technique is essential for accurate measurements in a recirculating flow such as the circulation in a bubble column.

Many of the previous experimental studies of bubble column circulation have used intrusive probes to measure velocities, and generally only vertical velocity has been measured. For example, Hills (1974) utilized resistance and pressure probes to measure radial distributions of voidage and mean vertical velocity for turbulent flow, over a range of gas flow rates. The liquid circulation was observed to be upwards on the column centerline and downwards at large radius, near the column wall. A similar circulation pattern has been measured by photographic means for a laminar flow in a bubble column with a very small void fraction by Reitma and Ottengraf (1970).

More recently, Durst, et al., (1984) have used a non-intrusive single channel LDV to determine the mean liquid velocity distribution for an axisymmetric, laminar flow in a cylindrical column. The liquid flow was driven by a single column of discrete bubbles injected at the centerline. Again, a toroidal recirculating liquid flow pattern was measured. Flow visualization photographs clearly indicated that the presence of a probe in their bubble column could alter this liquid circulation from a single recirculation cell, to multiple cells. This points clearly to the need for non-intrusive velocity measurements in the recirculating bubble column flow.

Studies of the bubbly, two-phase flow in a vertical circular pipe have been conducted by Serizawa, et al., (1975), and by Currie and Brankovic (1987). Serizawa, et al., (1975) used a series of intrusive probes to measure both mean and turbulence quantities for both the bubble and liquid flows. There was no flow reversal in their vertical pipe, and the flow was driven by and applied pressure difference across the pipe. Radial distributions of axial bubble and liquid velocity and voidage were measured. More recently Currie and Brankovic (1987) obtained axial and radial liquid and bubble velocity measurements for an air-liquid two-phase flow in a vertical pipe with a sudden expansion, using a non-intrusive two-component LDV system. However, again the flow studied differs from the circulation in a bubble column, in that the liquid flow was driven by an applied pressure gradient.

3.2 LDV EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic of the hexagonal cross-section bubble column is shown in Fig. 3.2.1. The column is made of plexiglas and is 18 cm across the flats or 21 cm across the diagonal at the top, and can accommodate water depths up to 18 cm measured from the bubble injection manifold. For the present experiments in air bubble injection manifold made from a PVC end cap (Fig. 3.2.1) with a single, central hole of 1 mm diameter has been used. Air flow rate was 7.87 x $10^{-5} m^3/s$ (10 SCFH). Calculated jet exit air velocity was 90 m/s, so that superficial gas velocity was only 0.3 cm/s. This resulted in an initial air jet which broke into nominal 1 cm diameter or less bubbles on the centerline near the top of the column. This air jet drove a relatively strong water circulation which was observed by flow visualization to be upwards near the central column of air bubbles, and downwards near the outer walls of the column. Flow visualization video has indicated the upwards velocity of the air jet to be between 30 and 40 cm/sec. This configuration has been studied because it greatly simplifies the measurement of bubble and liquid velocity since there is very little interference with the laser beams due to bubbles crossing through the beam paths away from where the laser beams cross in the measurement volume to form interference fringes. This is because only the smaller bubbles (less than 1 mm diameter) are re-entrained by the water circulation to recirculate in the column. Note, then, that all bubble velocity data are actually for these small diameter bubbles. Also, the hexagonal cross-section has been selected because it eliminates the problems associated with optically penetrating a curved interface (Broadway and Karahan, 1981; Bicen, 1982; Durrett et al., 1985), while still remaining nearly cylindrical in shape.

The present velocity measurements have been obtained using a three-component, 5-beam laser Doppler velocimeter described by Buchave (1984). This system has previously been used by Kuhlman and Gross (1989) to measure the three-dimensional mean and turbulent velocity fields in an axisymmetric air jet. Since simultaneous, coincident data were measured by Kuhlman and Gross (1989), then it was possible to determine Reynolds stresses. These jet data were consistent with previous axisymmetric jet data. The LDV system consists of DANTEC 55X modular optics and a series 2000 5W Spectra Physics argon ion laser, which are mounted to a 3-D, computer-controlled traversing system, as shown in Fig. 3.2.2. Front lenses with a focal length of 0.6 m are used, so the angle between the two separate optical trains is equal to 60°. This large angle helps greatly to improve accuracy of the 3-D velocity measurements, as discussed by Meyers (1985).

Three separate LDV channels are formed, by use of color separation. The

488 nm and 514.5 nm wavelength beams form orthogonal fringes by means of a standard two-channel optical train, shown on the bottom of Fig. 3.2.2. The vertical velocity component is measured using the 488 nm beam, while the 514.5 nm beam measures a velocity component at a right angle to the optical axis, in a horizontal plane (i.e., inclined 30° right of the Y axis defined in Fig. 3.2.2). The third LDV channel uses the 476 nm wavelength beam from the laser, which is sent to the single-channel optical train indicated in Fig. 3.2.2. This LDV channel measures a velocity component in a horizontal plane at an angle 30° left of the Y axis in Fig. 3.2.2. Orthogonal horizontal ($r-\theta$) velocity components are computed by vector transformation from the non-orthogonal to the orthogonal coordinate system. Frequency shifting allows measurements in reversing flows, while the beam expanders increase signal-to-noise ratio. Probe volumes for all three LDV channels are 0.16 mm in diameter, by 3.3 mm long. Fringe spacing is nominally 5.84 um, yielding approximately 27 fringe in the probe volume.

Backscattered light generates the output of the photomultiplier tubes which is sent to three counter processors, operated in the combined mode. Output from the three counter processors goes to a DANTEC buffer interface and coincidence filter, which accept validated data from each channel, check that the velocity measurements from each channel all were measured within a user-selectable time window which defines coincidence of the data, and measure the time between each set of measurements of the velocity components. Validated, coincident data and the measured sample interval time are sent to a PDP 11/23 microcomputer for storage. Data is reduced using techniques discussed by Edwards (1987), Meyers (1988), Yanta and Smith (1973), and Gould, et al. (1989).

Air bubble velocity data have been obtained for a matrix of twenty different vertical depths, by eleven different radial locations. Liquid velocity data have been obtained at the same 20 vertical locations, but at 13 radial locations. These results have been obtained by simultaneously measuring the vertical velocity and one horizontal velocity component perpendicular to one of the column faces, using the 2-channel LDV, and then measuring the third velocity component, perpendicular to a neighboring face, at the same location at a later time. Thus, no Reynolds stress results have been obtained. Velocity data obtained from the two non-orthogonal horizontal LDV channels have been post-processed to obtain orthogonal radial and circumferential velocity results. At each location, a time history of 3754 validated LDV velocity measurements has been acquired for each of the three velocity components. Since the counter processors were operated in the "combined" mode, only one doppler signal was acquired for each bubble or seed particle that crossed through the probe volume. Also note that for this single doppler signal, the total number of fringes crossed by the bubble or seed particle was recorded. The sample interval time between each subsequent validated velocity measurement has also been measured. These data have been reduced by sorting the time series for each velocity component into a 100 bin velocity histogram (i.e., number of velocity measurements in each velocity range), and deleting the tails of the resulting histograms for each channels. Between 0.5-8% of the data have been rejected as spurious in this fashion, where for the majority of data files between 1-3% of the data have been omitted by this technique. Average and RMS bubble and liquid velocities have been computed by four different averaging methods: statistical averaging (sum of the velocities divided by number of data values), both with and without rejection of spurious data in the tails of the velocity histograms, and sample interval time weighting, again with and without rejection of spurious data.

Results presented herein have all been calculated using statistical averaging, and with the rejection of spurious "outlier" data. One exception to this is for the 2-D air bubble velocity data for the vertical traverse at the third from largest r location, where no data rejection was used, since these data files contained fewer samples (from 150-2300) due to a poor signal-to-noise ratio caused by a laser beam reflection off the column wall at this radius. Plotted mean and RMS velocity distributions changed by no more than 1% independent of which of these four data reduction methods was used, indicating that statistical bias is not a significant problem with the current data. Each data record at a point took between 30 and 800 seconds to acquire, with most files taking 200-300 seconds. These validated data rates of about 10 samples per second yielded calculated data densities (validated data rate times Taylor microscale; see Edwards, 1987) of between 0.06-0.6. Data densities tended to be higher and fewer spurious points were rejected for the 1-D data measurements. For the present results no velocity bias corrections have been applied to the calculated statistical averages (Edwards, 1987; Meyers, 1988; Yanta and Smith, 1973; Gould and Stevenson, 1989). This is not generally believed to be a significant problem, because of the low average validated data rates.

All bubble velocity measurements were obtained using distilled water in the column, with no added seed particles, and without any thresholding of the Doppler signals to reject large signals. Liquid velocity data reported herein have been obtained by adding 4μm diameter silver coated plastic sphere seed particles to the bubble column, and then by rejecting the largest Doppler signals due to the large air bubbles, through use of a 24 dB threshold setting on each of the counter processors. This level of thresholding was observed to typically reject approximately 90-95% of the Doppler signals obtained without any seed particles added to the flow. The seed particles are expected to adequately track the present flow up to frequencies of 1-2 kHz, based on the work of Hjelmfelt and Mockros (1966). It is expected that other non-intrusive methods, such as phase Doppler techniques (Bauckhage, 1985; Drain and Phil, 1985; Foster and King, 1985) or fluorescent particles (Goldman and Seasholtz, 1988) could lead to better liquid velocity data, but these methods were not available for the present work.

3.3 LDV RESULTS - AVERAGE BUBBLE VELOCITIES

The average bubble radial, vertical and circumferential velocities are presented in Figs. 3.3.1-12. The data is plotted versus non-dimensional effective column radius r/R, where R is one half the hydraulic diameter of the column. Each figure plots the data for five vertical locations (Z, in centimeters) measured relative to the location of the air injection port at the bottom of the column. Water depth, as measured from the air injection port, was held constant at 18 cm. The air flow rate through the injection port was kept constant at 7.87×10^{-5} m^3/sec (10 SCFH).

No bubble or liquid velocity measurements have been obtained for $r <$ 0.17R, because of the presence of the air jet for smaller R. When the probe volume was positioned at the edge of the jet (approximately for $r \cong 0.17$ R, or less) the photodetector signals would saturate, or appear extremely "noisy". Thus it was judged that no reliable velocity data could be obtained too close to, or inside, the jet itself. Also, no measurements have been obtained for $r >$ 0.82R, since laser light which is reflected off the column walls (water-plastic and plastic-air interfaces) saturates the photodetectors at larger r values. It was observed that the signal quality was degraded gradually as the column wall was approached (due to reflections) and as the air jet was approached. Increased signal noise near the air jet was due both