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 Kirg, 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 $r > 0.82$R, 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 to reflections off the jet interface, as well as the presence of smaller bubbles in the laser beam paths away from the probe volume. These smaller bubbles reduced signal quality, and eventually would destroy the doppler signal by destroying the fringe pattern formed in the probe volume (Foster and King, 1985). Figs. 3.3.1 through 3.3.4 display the average bubble radial velocity versus r/R. The radial velocity bubble profiles are negative in all but the top four vertical locations. This indicates that the entrained bubbles are moving in towards the column centerline for all but the top fifth portion of the vessel and that in the top fifth region, the bubbles are moving out toward the column wall. On average, the bubbles appear to be moving inwards at roughly 5 to 7 cm/s and outwards at a velocity on the order of 10 to 20 cm/s. In all cases, the radial bubble velocities tend toward zero, or decrease significantly, at the beginning and ending radial positions. This indicates that a solid boundary is impeding the flow. For $r < 0.17R$, the initial air jet is acting as the solid boundary, while at $r > 0.82R$ the plexiglas interface is being approached.

Figs. 3.3.5 through 3.3.8 present the average bubble vertical velocity versus r/R. Vertical mean bubble velocity is largest at a fixed depth for small radius. The presence of the air jet can be directly attributed to this phenomenon. Vertical bubble velocity is zero at $r \cong .7R$ at all depths, where R is the effective radius of the hexagonal bubble column. Velocity magnitude increases with increasing vertical position for all but the last two traverses. For these two traverses (Z = 15.4, 16.1 cm) the water-air interface at the column top acts to decrease bubble velocities as the free surface is approached. The magnitude of the outwards bubble velocity near the free surface is about the same order of magnitude as the upwards bubble velocity near the air jet.

The circumferential mean bubble velocity (Figs. 3.3.9 through 3.3.12) are very nearly zero everywhere in the bubble column.

3.4 LDV RESULTS - RMS BUBBLE VELOCITIES

The RMS bubble, radial, vertical and circumferential velocities are presented in Figs. 3.4.1 through 3.4.12. The data is again plotted versus nondimensional effective column radius r/R. In all cases, the RMS velocities are smaller in the bottom half of the column, and are largest near the jet (small r) and near the free surface of the column.

In the bottom half of the column, the RMS radial and vertical velocities are essentially the same size as the corresponding mean velocity components. Radial RMS velocities are consistently larger than both RMS vertical and circumferential velocities, which are generally about the same size. In the top portion of the bubble column, both RMS velocities are more nearly equal to the magnitude of the larger of the mean vertical and radial velocities. The RMS velocities all decrease as radius is increased, similar to trends for the mean bubble velocity magnitude. Turbulence intensities are everywhere on the order of 100%, indicating very good mixing.

3.5 LDV RESULTS - AVERAGE LIQUID VELOCITIES

The average liquid radial, vertical and circumferential velocities are presented in Figs. 3.5.1 through 3.5.12. The liquid velocities follow trends which are similar to observations for the bubble velocities, except that the liquid velocities are generally smaller than corresponding bubble velocities near the top of the column and near the column centerline. This velocity difference is significant in that it clearly shows that the liquid circulation is being driven by the bubble flow.

Figs. 3.5.1 through 3.5.4 display the average liquid radial velocity versus r/R. As is the case for the average bubble radial velocities, the liquid radial velocities are negative for Z values up to about 80% of the column height. The liquid is moving radially outwards for the remaining 20% of the column height. On average, the liquid flows radially back towards the column centerline with a velocity of roughtly 2 to 5 cm/s. Liquid radial flow velocity to the column walls is roughly 8 to 10 cm/s. Zero velocity, or a significant velocity decrease at the beginning and ending radial positions, representing the air jet or wall region, is also noted.

Average liquid vertical velocity plotted versus non-dimensional effective column radius is presented in Figs. 3.5.5 through 3.5.8.. Measured vertical liquid mean velocity is a smaller positive value as compared to vertical bubble mean velocity near the central air jet, and is consistently downwards beyond $r/R \approx 0.5 - 0.7$. These results further indicate that the liquid flow lags behind the bubble flow, as expected. As is the case with the vertical bubble mean velocity, vertical liquid mean velocity decreases (Z = 14.6, 15.4, 16.1 cm) as the free surface is approached.

The circumferential mean liquid velocity, Figs. 3.5.9 through 3.5.12, are very nearly zero everywhere in the bubble column. This is consistent with the circumferential mean bubble velocity data.

3.6 LDV Results - RMS Liquid Velocities

The RMS liquid radial, vertical and circumferential velocities are presented in Figs. 3.6.1 through 3.6.12. As expected, RMS liquid velocities are generally smaller than corresponding RMS bubble velocities near the top of the column and near the column centerline. RMS radial and vertical velocities are essentially the same size as the corresponding mean velocity components in the bottom half of the column. Again this behavior is similar to that of the bubble phase data. Radial RMS velocities are consistently larger than both

RMS vertical and circumferential velocities, which are generally about the same size. Thus, it can be said that non-isotropic turbulence exists in the bubble column.

In the top portion of the bubble column, RMS velocities are more nearly equal to the magnitude of the larger of the mean vertical and radial velocities. The RMS velocities all decrease as radius is increased, similar to trends for the mean liquid velocity magnitude. Liquid turbulence intensities are everywhere on the order of 100%, again indicating very good mixing.

3.7 FLOW VISUALIZATION AND VELOCITY COMPARISONS

Figs. 3.7.1 and 3.7.2 are examples of flow visualization photography. Flow visualization was accomplished by passing a 5 watt argon-ior laser beam through a cylindrical glass rod which turned the team into a two-dimensional light sheet. The light sheet was then passed in a vertical plane through the bubble column along the minor diameter. This had the effect of illuminating the flow field in a two-dimensional plane. Photographs and video tape were used to further investigate the flow.

Fig. 3.7.1 is a view along the major diameter of the column. It should be noted that because of the plexiglas intersection, there appear to be two air jets when in fact there is only one. Fig. 3.7.2 is a view along the minor diameter of the bubble column. Both photographs provide additional information that is consistent with mean flow velocity information. Bubbles can be ovserved to rise rapidly near the central air jet, with most bubbles leaving the bubble column at the free surface. Smaller bubbles are observed to move radially outwards near the top of the column, downwards at large r, and inwards at the bottom of the column. A relatively strong toriodal recirculating vortex flow is observed in the top half of the column. The central air jet velocity was observed from video tape to be on the order of 30 to 40 cm/s.

Figs. 3.7.3 and 3.7.4 allow side by side comparisons between radial and vertical bubble/liquid mean velocities. Both figures clearly indicate that the liquid phase lags the bubble phase near the air jet and near the free surface of the bubble column.