Chapter 7

Conclusions

The objectives of this research work were:

- to improve and use the CARPT technique for measurement of the fluid dynamics in bubble columns, in order to (i) generate an accurate and reliable database that can provide insight and be used to explore different closure schemes needed for the fundamental modeling of two-phase flows in bubble columns, and (ii) to study effects of scale and operating conditions on the various parameters
- to utilize the experimental information in developing a phenomenological model to study and quantify liquid mixing in bubble columns.

The first part of this chapter summarizes the principal findings of this investigation. Following this, recommendations for possible future work, in areas relevant to the present research, are outlined.

CARPT Improvements

The CARPT technique has been improved to obtain more reliable data for the liquid velocities and turbulence parameters. The principal accomplishments in this regard are summarized below.

- An algorithm has been developed which accounts for the effects of solid angle in the reconstruction algorithm for estimating the position of the particle from the calibration data. This was found to significantly reduce the error in estimation of particle position. For example, in a 14 cm diameter column, the root mean square error is reduced from 1 cm to 0.3 cm. In addition, the CARPT data processing software was modified to incorporate a new column discretization scheme that ensures uniform and better statistics in each compartment for an optimum duration of each CARPT experiment.

- A new wavelet-based filtering program has been implemented to reduce the level of white noise in the instantaneous position data. An experiment with the controlled motion of the radioactive tracer particle in air was designed and conducted to successfully validate the filtering algorithm and the estimation of the position of a continuously moving particle from CARPT experiments. Filtering of the CARPT data reduces the spurious *rms* velocities in the data by an average of 85 %, and thereby yields reliable results for the turbulence parameters. The time averaged velocities are unaffected by the filtering.

Experimental Results from CARPT

The improved CARPT technique has been used to measure the fluid dynamic parameters, such as the time averaged liquid velocities, turbulence stresses and turbulent kinetic energy, in air-water systems for various gas velocities (2 cm/s to 12 cm/s, to cover the different flow regimes) and in columns of three sizes, 14 cm, 19 cm and 44 cm. A three dimensional analysis of the data was performed, which indicated that in the long time averaged sense the flow in the middle section of the column (for L/D aspect ratios greater than 6), away from the distributor and disengagement zone, is symmetric about the axis. In addition, in this region the axial variation of the parameters is negligible and within experimental error.

Near the distributor region, however, asymmetry is observed in the time averaged flow pattern. The extent of this asymmetry varies with distributor type, being the strongest for the distributor with the smallest size holes (0.33 mm). The asymmetry was therefore attributed to the influence of the distributor, caused by non-uniformities in the distributor holes. For the distributor with the smallest hole size of 0.33 mm, **8A**, at a gas velocity of 2.0 cm/s, two stationary circulation cells were observed near the distributor that span the entire column cross-section. With increase in gas velocity the cells were found to disappear, and are replaced by sheet like structures. For the perforated plate distributor, **6B**, with the largest hole size of 1 mm, no asymmetry was noted. However, for such cases the flow is not perfectly symmetric at the distributor, and roller like patterns are observed.

The behavior of the turbulence parameters is in line with the trends of the time averaged flow pattern in the column. The turbulent stresses show symmetry about the column axis, and do not vary significantly with axial position in the middle fully developed section of the column. Hence, analysis of the results was based on the axially and azimuthally averaged results, in the middle section of the column. All the six components of the turbulent stress tensor have been measured. Measurements indicate that the axial normal stress is about two to three times larger than the azimuthal and radial normal stresses, in the middle section of the column. The τ_{rz} shear stress is always positive and lower in magnitude (by 20 to 50 %) than the radial/azimuthal normal stresses. The positive shear stress suggests that the shear in the axial direction causes an outward radial transport of axial momentum in bubble columns. The shear stresses, $\tau_{\theta z}$ and $\tau_{\theta r}$, are negligible and can be considered to be zero, indicating that there is no axial or radial transport of azimuthal momentum.

The experimental measurements from CARPT have been successfully verified against independent experimental measurements for the mean liquid velocity and turbulence stresses. The time averaged velocities in a 19 cm column, with the perforated plate distributor, **8A**, were compared with results from Heat Pulse Anemometer (HPA) experiments that were conducted as part of this investigation. The comparison between the two measurements was found to be satisfactory. CARPT data for the turbulent stresses were verified against experimental data in the literature. The Reynolds shear stress, τ_{rz}, measurements in the 14 cm diameter column, using distributor **6B**, were compared with Hot Film anemometry (HFA) data of Menzel et al.

(1990). The CARPT experiments were designed to match, to the best extent possible, the experimental conditions of Menzel et al. (1990). Reasonable comparisons were noted for both the magnitude and profiles of the turbulent shear stress. The results for the axial and azimuthal normal stresses, and $\tau_{\theta z}$ shear stress were also compared with Laser Doppler Anemometry (LDA) measurements of Mudde et al. (1997) in a 15 cm diameter column. Results showed good order of magnitude comparisons between the data. CARPT measurements for both the time averaged velocities and turbulent stresses have, therefore, been successfully verified against independent experimental measurements. This serves as an indirect way of validating the CARPT technique.

Turbulent Eddy Diffusivities

CARPT experimental data has also been used to evaluate the Lagrangian statistics in bubble columns. The Lagrangian autocorrelation coefficients calculated showed a strong dependency on radial position in the column, with a maximum near the position of flow inversion. The autocorrelation coefficient in the axial direction is much higher (2 to 3 times) than that in the radial and azimuthal directions. While the axial and azimuthal autocorrelation coefficients show a steady decay with time finally reaching zero, the radial autocorrelation coefficient exhibits negative loops. This was explained as being due to the nature of the flow in bubble column. The cross-correlation, R_{rz} is non-zero but much smaller than the auto-correlation coefficients. The other cross-correlations coefficients, $R_{\theta z}$ and $R_{\theta r}$ are zero, which is in agreement with the turbulent shear stress measurements.

The non-homogeneous nature of the flow has been properly accounted for in evaluating the turbulent eddy diffusivities. It was shown that the existence of a non-zero gradient, $\frac{du_z}{dr}$ and cross-correlation coefficient R_{rz} results in a decrease of a maximum of 25 % in the axial eddy diffusivity when compared with that obtained under ideal (isotropic and homogeneous) flow conditions. The radial and azimuthal diffusivities are unaffected. The axial eddy diffusivities are an order of magnitude larger than the radial eddy diffusivities, pointing to the highly non-isotropic nature of the flow. The diffusivity, D_{rz}, is about 5 % of the radial eddy diffusivity, which is considered to be negligible. Furthermore $D_{\theta r}$ and $D_{\theta z}$ are zero (due to zero cross-correlation coefficients). The axial and radial diffusivities vary strongly with radial position. As with the other fluid dynamic parameters, their variation with axial and azimuthal position in the middle section of the column is negligible. In the distributor region the diffusivities are higher (20 to 50 %) than those in the middle section of the column.

The Lagrangian integral time scales were found to decrease with increase in gas velocity, and are almost independent of column diameter. The integral time scales in the radial direction are an order of magnitude smaller than in the axial direction.

Scale-up

Scale-up issues have been discussed for the fluid dynamics parameters, in the churn-turbulent flow regime in large diameter columns (> 10 cm). Using experimental data in air-water systems, from the present work and from literature, scale-up equations have been developed for the mean liquid recirculating velocity and average axial and radial eddy diffusivities in air-water atmospheric systems. Based on the unified characterization of churn-turbulent bubble columns, a methodology has been proposed which enables evaluation of the liquid recirculating velocity and turbulent eddy diffusivities in systems of industrial interest (example, high pressure and temperature), using the data generated in air-water systems, at sufficiently high gas velocities. The proposed methodology requires knowledge of the global holdup and holdup distribution in the system under consideration. The equations and proposed methodology for scaling up of churn-turbulent bubble columns require substantiation with additional experimental data for the fluid dynamic parameters under suitable conditions. It is noted that the scale-up strategy proposed is applicable only to the churn-turbulent flow regime, and should not be applied to the bubbly or transition regime, where such a unified characterization cannot be made.

Liquid Mixing

A fundamentally based two dimensional convection-diffusion model has been developed and solved to describe liquid mixing in bubble columns as dictated by the fluid dynamics. The model was tested for air-water systems, for which the input model parameters were directly obtained from CARPT/CT measurements. Results indicate that the two dimensional axisymmetric convection-diffusion model provides a good representation of overall and internal liquid mixing in bubble columns. This represents the macro-scale mixing in the column, which is of importance for modeling bubble column reactors. Results also imply that CARPT measurements for the turbulent eddy diffusivities can provide suitable closure for the $\langle \vec{u}'C' \rangle^x$ terms appearing in the original balance equations.

The scale-up strategy proposed in Chapter 5 has been used to estimate the fluid dynamic parameters of interest in the AFDU slurry bubble column reactor during methanol synthesis. Presence of heat exchanger tubes in the reactor were shown to reduce the radial eddy diffusivity in the region of the tubes. The two dimensional model, along with the evaluated model parameters, resulted in fairly good predictions of the characteristic mixing times within the column as measured by the radiation detectors at various axial locations. This indirectly substantiates the proposed methodology of using the gas holdup in churn-turbulent flows, at sufficiently high gas velocities, for characterizing systems of interest, and qualifies the use of the results obtained for air-water systems to evaluate the fluid dynamic parameters of the model for an industrial reactor.

Further, a Taylor type analysis has been applied to the convection-diffusion equation to obtain the contributions of convective recirculation and turbulent diffusion to overall liquid backmixing the bubble columns. This has resulted in a relationship for the effective axial dispersion coefficient in terms of the fluid dynamic parameters in the column. Using the scale-up equations developed, along with the characterization methodology proposed for churn-turbulent bubble columns, the above development allows the evaluation of the liquid phase axial dispersion coefficient under industrial conditions of high temperature and pressure, and the presence of heat exchanger tubes. Model predictions have been shown to compare fairly well with experimental data for the axial dispersion coefficient under various process conditions.

7.1 Recommendations for Future Work

CARPT Technique

In Chapter 3, it was shown that the presence of the flange and the plenum results in higher errors in estimation of the particle position near the distributor. The reason for this is the high attenuation of the Plexiglas medium in the path of the radioactive source particle and detector, which cannot be accounted for in the existing reconstruction algorithm. This problem can be solved by modeling the radiation measured by the scintillation detectors, using a Monte-Carlo based method. Such a model will be able to account for a change in the attenuation of the medium, and can help in reducing the errors in position estimation near the detectors. Monte Carlo simulation will also help in reducing the errors in particle location for the largest column of diameter 44 cm.

Implementation of a new wavelet filtering algorithm was performed resulting in reduction in the spurious velocities. However, the programs are computationally intensive and substantial time is required for filtering the data. With the rapid advancement in the field of wavelets, it may be possible in the near future to obtain better programs, which are computationally more efficient, thereby reducing the time for data processing.

CARPT Data Analysis

The asymmetric patterns at the distributor were shown for certain operating conditions to always be aligned along the same direction - roller like patterns. Future CARPT experimental results should be analyzed to check for the presence of such roller like structures and the repeatability in their alignment. In addition, experiments should be conducted with an 'ideal' perforated plate distributor, with small size holes (≤ 0.4 mm) that are perfectly uniform, to study the influence of distributor imperfections on the time averaged flow field.

The Gaussian pdf's of the instantaneous velocities obtained from CARPT measurements indicate that the flow is turbulent and random. CARPT data can be further analyzed using different methods, such as Hurst's analysis, wavelet decomposition, chaos theory analysis to investigate the flow behavior in bubble columns, which may provide more insight for the fundamental modeling of bubble column flows.

The effects of distributor were discussed based on visually observed bubbles sizes, in the bubbly flow regime, and qualitative bubble sizes based on the global gas holdup measurements, in the churn-turbulent flow regime. These results stress the importance of bubble sizes in dictating the fluid dynamics in the column. Measurements of bubble sizes under operating conditions similar to those considered in this investigation will help in quantifying the effects of bubble sizes (discussed in Chapter 4 on a qualitative basis) on the fluid dynamics and turbulence, such as length scales of turbulence.

It is clear from the measurement of the turbulent stresses, that the turbulence in bubble columns is highly non-isotropic. This suggests that the use of Boussinesq's hypothesis for steady state modeling, with a single eddy viscosity, for all the directions, may not be a valid assumption. Better models for turbulence closure are required that take into consideration the non-isotropic behavior. In addition, the experimental results for the azimuthal and radial normal stresses indicate that there is frequent cross-over of the eddies at the axis. Such a physical picture cannot be captured in a two dimensional transient axisymmetric model. This suggests that in order to model the transient flow of cylindrical bubble columns, a fully three dimensional model is necessary. Therefore, from the point of view of fundamental modeling, considerations for transient modeling and large eddy simulation (LES) should be attempted in a three dimensional coordinate system, rather than a two dimensional axisymmetric system.

Scale-up

The results for the present experiments have led to the development of preliminary correlations for the mean liquid recirculation velocity and turbulent eddy diffusivities. These scale-up equations proposed, especially for the turbulent eddy diffusivities, require further verification with additional CARPT experimental data in air-water systems at high gas velocities, in the churn-turbulent flow regime. In addition, the characterization methodology proposed for churn-turbulent bubble columns based on the global gas holdup also requires direct experimental verification, by conducting experiments for example, under high pressure and at high gas velocity conditions. In order to first verify the proposed scale-up methodology, a well designed set of experiments should be conducted using CARPT. The variables of greatest importance are the system pressure (or gas density) and presence of internal tubes in different arrangements. It should be kept in mind that the experiments should be conducted at sufficiently high gas velocities, preferably higher than 15 cm/s. The existing air-water database under atmospheric conditions should first be extended to include higher gas velocities, especially in larger columns. Once verified, the proposed methodology will prove useful for applying air-water data to evaluate the fluid dynamic parameters in systems of industrial interest.

Modeling

The phenomenological model (two dimensional model and one dimensional RCFDM) developed for liquid mixing in bubble columns enables the direct use of the liquid recirculation velocity and turbulent eddy diffusivities, obtained from CARPT, and the holdup profiles from CT, to evaluate the extent of liquid mixing in bubble columns. The next step in phenomenological modeling, is to incorporate the gas phase balance and include mass transfer terms to study the combined effect of phase mixing and transport on reactions in bubble columns.