# Chapter 5

# Scale-up Issues

The objective of this chapter is to study the effects of scale and operating conditions on the fluid dynamic parameters, using experimental data from the present investigation and from the literature, which will aid in the design and scale-up of bubble column reactors. The specific focus is to utilize the information on the hydrodynamics to model liquid mixing in bubble columns in the churn-turbulent flow regime. In this regard, the fluid dynamic parameters of interest are the gas holdup and holdup profile, the liquid recirculation velocity and liquid turbulence which can be quantified by the turbulent eddy diffusivities.

Gas holdup plays an important role in bubble column fluid dynamics. The global gas holdup determines the residence time of the gas phase and the pressure drop in the system. The local void fraction, which is determined by the bubble size and number density influences the rate of liquid recirculation and mass transfer across the gas-liquid interface. It is the inherent non-uniform gas holdup distribution, resulting from the various forces acting on the gas bubbles, that drives the flow in the system, inducing the generation of turbulent eddies, phase interactions and recirculation.

Gas holdup is closely dependent on bubble sizes, their distribution and frequency of formation. These in turn depend on a number of factors: 1) the operating conditions, such as the superficial velocities, pressure and temperature of the system, 2) process specific variables, such as the physical properties of the individual phases, and 3) column geometry which includes the column diameter, distributor type and type of internals, if any.

Numerous experimental studies reported in the literature discuss the effects of the various parameters, stated above, on gas holdup. These fall into two categories: global or overall gas holdup and local void fraction measurements. Global holdup measurements, owing to their ease of measurement, have been the predominant subject of research and experimental study. Investigations (e.g., Krishna and Ellenberger 1996; Wilkinson et al. 1992; Reilly el al. 1994; Hammer et al. 1984) in various systems, under different operating conditions, have aided in understanding the effects of system parameters and process variables on global gas holdup, and have resulted in several correlations, as discussed in Chapter 2.1. However, there is yet no single correlation that performs well under all process conditions. Reports on measurement of local void fractions and their spatial distribution are more recent and still relatively scarce. Nottenkamper et al. (1983), Menzel et al. (1990), De Lasa et al. (1984), Kumar (1994) and Groen et al. (1995), among others (discussed in Chapter 2), have used different techniques to measure the local void fraction and in some cases bubble sizes and phase velocities in bubble columns. Such local measurements have predominantly been used to study air-water systems under atmospheric conditions, due to simplicity of the system. Recently Adkins et al. (1996) obtained measurements of local void fraction profiles in slurry bubble columns operating under industrial conditions, using Nuclear Densitometry Gauge (NDG), to study the effects of pressure and temperature on the local gas holdup profile. They showed that, at high gas velocities (10 - 12 cm/s) the overall gas holdup increases with pressure. However, the radial gas holdup profile at high pressure is similar (parabolic) to that in an air-water system, at atmospheric pressure.

For the design and modeling of industrial bubble column reactors using phenomenological models, information on the local fluid dynamics parameters, in addition to global parameters (such as the gas holdup), is needed under industrial conditions of interest. While there exists abundant experimental information on the global gas holdup in different systems (liquid and gas properties, presence of solids, high temperature and pressure), information on the local holdups and holdup profiles, and other local fluid dynamic parameters, is still currently restricted to air-water systems. For example, measurements of the local liquid velocities have so far been made only in atmospheric air-water systems ((Hills 1974; Nottenkamper et al. 1983; Franz et al. 1984; Menzel et al. 1990; Devanathan et al. 1990; etc.). This is mainly due to the difficulties associated with applying the different experimental techniques, for local measurements, to industrially relevant systems (Kumar et al. 1997).

In light of these limitations, the objective of this chapter is to consolidate the global holdup characteristics, for which there is abundant experimental data in a variety of operating and process conditions, with the information on holdup distribution and other fluid dynamic parameters, existing only for air-water systems. The aim is to develop a basis for the approximate characterization of churn-turbulent bubble columns, which enables the estimation of certain local fluid dynamic parameters in industrial systems, based on measurements of these parameters in air-water atmospheric systems. It is well known that changes in distributor and trace impurities (in air-water systems) can affect two-phase flows considerably. Nevertheless, it is expected that such effects are more pronounced for bubbly flows and tend to diminish in the churn-turbulent flow regime. The proposed analysis is hence applied only to the churn-turbulent flow regime, in large diameter columns, greater than 10 cm in diameter. In small diameter columns, at high gas velocities slugging flow occurs, which is characteristically different from churn-turbulent flows (Shah et al. 1982).

Using the experimental data generated from the present work and from the literature, the effects of column diameter and superficial gas velocity on the gas holdup, mean liquid recirculation velocity and average turbulent diffusivities are studied, first in atmospheric air-water bubble columns. Subsequently, a method for characterizing churn-turbulent bubble columns is presented. This procedure enables evaluation of the mean liquid recirculation velocity and turbulent eddy diffusivities in bubble columns under industrial conditions (example, high pressure).

## 5.1 Gas Holdup

The influence of gas velocity and column diameter on the overall gas holdup in air-water bubble columns, is considered in this section. The study is based on experimental data for the global gas holdup from the present investigation and the literature.

As a general rule, gas holdup increases with superficial gas velocity. The absolute value of gas holdup at low gas velocities, in the bubbly flow regime is affected by the type of distributor used and the presence of trace contaminants in the water. However, with increase in gas velocity, well into the heterogeneous flow regime, these differences even out. Gas holdup dependence on superficial gas velocity can be expressed in the form

$$\epsilon_g \propto U_g^n \tag{5.1}$$

where the exponent $n$ depends on the flow regime (Shah et al. 1982). Most studies from the literature suggest that the total gas holdup does not depend on the diameter of the column, for columns that are 15 cm or greater in diameter (for example, Reith et al. 1968; Akita and Yoshida 1973; Wilkinson et al. 1991). The experimental data considered in most of these investigations are for gas velocities below 20 cm/s. DeSwart (1996), shows that the effect of column diameter, while negligible at low gas velocities, becomes prominent in the churn-turbulent regime at higher velocities ($\geq$ 20 cm/s). These observations are in agreement with experimental measurements for the global gas holdup by Nottenkamper et al. (1983), as shown in Figure 5.1 along with data from the present investigation other air-water data (Reilly 1984; Guy et al. 1986; Myers 1986; Reith et al. 1968, Kumar 1994). It is seen from Figure 5.1 that at low gas velocities there is no prominent effect of column diameter on the global gas holdup. With increase in gas velocity the effect becomes apparent and at very high velocities, much greater than 20 cm/s, there is a significant influence of column diameter on the holdup. The existing correlations (other than the correlation for large bubbles by Krishna and Ellenberger (1996)) do not account for such diameter effects (Figure 5.1).

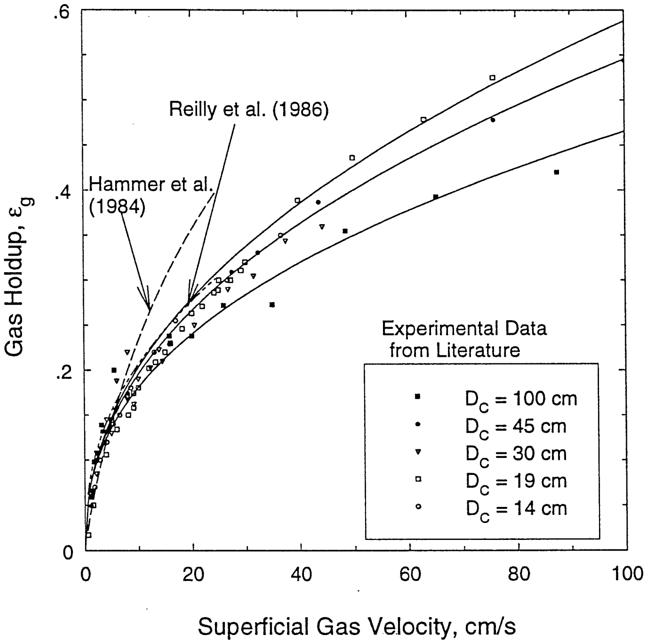

Figure 5.1: Average Gas Holdup as a Function of Column Diameter and Superficial Gas Velocity (Solid Lines Represent Equation 5.2)

The experimental data for the global gas holdup, shown in Figure 5.1, is correlated to account for effects of column diameter and gas velocity on the global gas holdup, which results in the following equation:

$$\bar{\epsilon}_g = 0.07 U_g^{0.474-0.000626 D_c} \quad \text{(in cgs units)} \tag{5.2}$$

At low gas velocities, the above equation results in global gas holdup values which are in correspondence with predictions of literature correlations (Reilly et al. 1986; Hammer et al. 1984). At higher gas velocities, it is able to capture the effects of column diameter, as observed from the data of Nottenkamper et al. (1983), which represent the only data in the open literature for gas holdup at very high gas velocities in air-water systems. Additional data under such conditions is necessary to verify Equation 5.2.

## 5.2 Liquid Recirculating Velocity

Time averaged results from various experimental techniques indicate the existence of global liquid recirculation in the time averaged sense, with liquid flowing upward in the central region of the column, and downward near the wall. In the well developed region, (middle section in large L/D columns), this is represented by a recirculating axial liquid velocity profile (Figure 4.54), with negligible radial velocities. Liquid recirculation in its simplest form is modeled using the one dimensional recirculation model (discussed in Appendix A) for predicting the time-averaged axial liquid velocity profile. This model requires as input, the holdup profile and a closure for the turbulent shear stress (typically using either eddy viscosity or mixing length). Experimental measurements are used to supply the input holdup profile to the model. The mixing length (or eddy viscosity) is the other unknown, to which the model is found to be very sensitive (Kumar 1994). Various attempts have been made at developing functional forms for the eddy viscosity (Ueyama and Miyauchi 1979) and mixing length (Clark et al. 1987; Luo and Svendsen 1992; Rice and Geary 1990) required for solving the one dimensional model. However, Kumar (1994) shows that there is truly no universal expression for the mixing length or the eddy viscosity that can be successfully used under a wide range of operating conditions, to predict the liquid recirculating velocity profile.

In the present investigation the effect of scale on liquid recirculation in air-water atmospheric systems, is studied by considering a mean liquid recirculation velocity or an average liquid upflow velocity, defined as:

$$\bar{u}_{rec} = \frac{\int_0^{r^*} u_z(r)\epsilon_l(r)rdr}{\int_0^{r^*} \epsilon_l(r)rdr} \tag{5.3}$$

where $r^*$ represents the radial position of flow inversion. The above expression holds for the case of batch liquid ($U_l$=0) and in situations of low superficial liquid velocities, such as those typically encountered in bubble column operations, where $U_l \ll \bar{u}_{rec}$.

Experimental data for the liquid velocity profile ($u_z(r)$) and the holdup profile ($\epsilon_l(r)$), from the literature and the present investigation, are used to calculate $\bar{u}_{rec}$ for various operating conditions ($U_g$ and $D_c$ ($> 10$ cm)) in air-water systems. The results are plotted in Figure 5.2. Assuming the following functional form for the dependence of $\bar{u}_{rec}$ on column diameter and gas velocity,

$$\bar{u}_{rec} \propto D_c^m U_g^n \tag{5.4}$$

and performing a regression using the data from CARPT/CT (CT data for the holdup profile is taken from Kumar (1994)), shown in Figure 5.2, and data from Nottenkamper et al. (1983) at $U_g$=82.3 cm/s, yields $m = n = 0.4$. Thereby we arrive at the following expression for $\bar{u}_{rec}$:

$$\bar{u}_{rec} \ \text{(cm/s)} = 2.2 D_c^{0.4} U_g^{0.4} \tag{5.5}$$

Predictions using the above equation compare reasonably well with data of Menzel et al. (1990) and Nottenkamper et al. (1983) at $U_g$= 32.4 cm/s, as shown in Figure 5.2. A similar dependency of $(U_g D_c)^{0.33}$ has been reported by Joshi and Sharma (1979) and Zehner (1982) for the liquid circulation velocity that was derived based on the assumption of the existence of multiple circulation cells. Koide et al. (1979) report a dependency of $D_c^{0.5}$ and $U_g^{0.28}$ for the centerline liquid velocity. The scale-up Equation 5.5, developed here, can be used to estimate the mean recirculation liquid velocity in an air-water bubble column ($D_c > 10$ cm), at atmospheric pressure operating in the churn turbulent flow regime.

With a knowledge of the mean recirculation velocity, $\bar{u}_{rec}$, and the holdup profile, it is possible to calculate the liquid recirculation velocity profile in the column by a procedure described in Figure 5.3. The one dimensional model of Kumar et al.

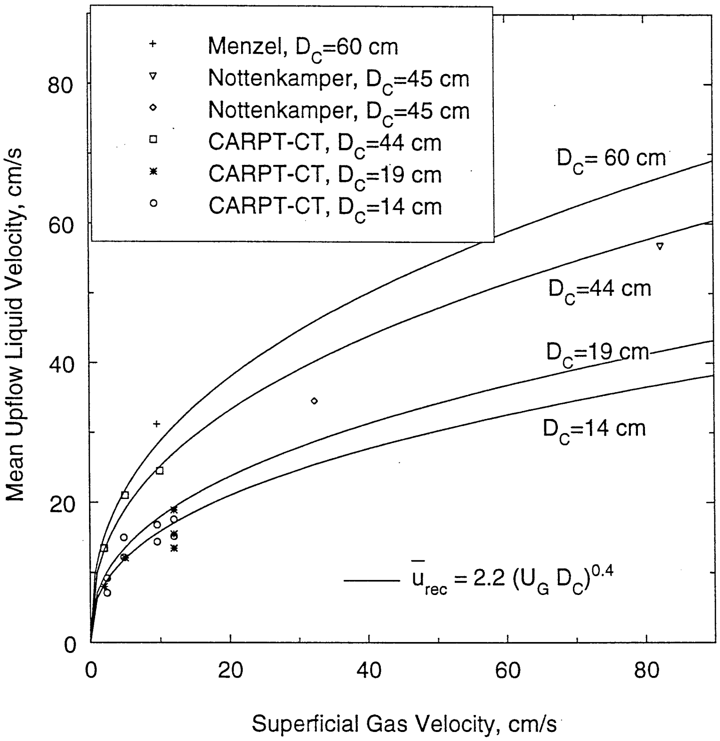

Figure 5.2: Effect of Superficial Gas Velocity and Column Diameter on Mean Liquid Recirculating Velocity

(1994), described in Appendix A, is considered here. An estimate of the mixing length profile (Kumar et al. 1994) is assumed and used in the one dimensional model, along with a known holdup distribution, to calculate the liquid recirculating velocity profile, $u_z(r)$. The centerline velocity, $u_z(0)$, and therefore the mean, $\bar{u}_{rec}$ will depend on the mixing length profile used. The average recirculating velocity, $\bar{u}_{rec,calc}$, calculated from $u_z(r)$ using Equation 5.3, is compared with the estimated mean recirculation velocity, $\bar{u}_{rec,est}$, obtained from Equation 5.5, for a given superficial gas velocity and column diameter. The mixing length profile is suitably adjusted until $\bar{u}_{rec,calc} = \bar{u}_{rec,est}$, which then yields an approximate value for the required axial liquid velocity profile. Using the above procedure, the liquid velocity profile can be evaluated, provided the holdup profile in the column is known.

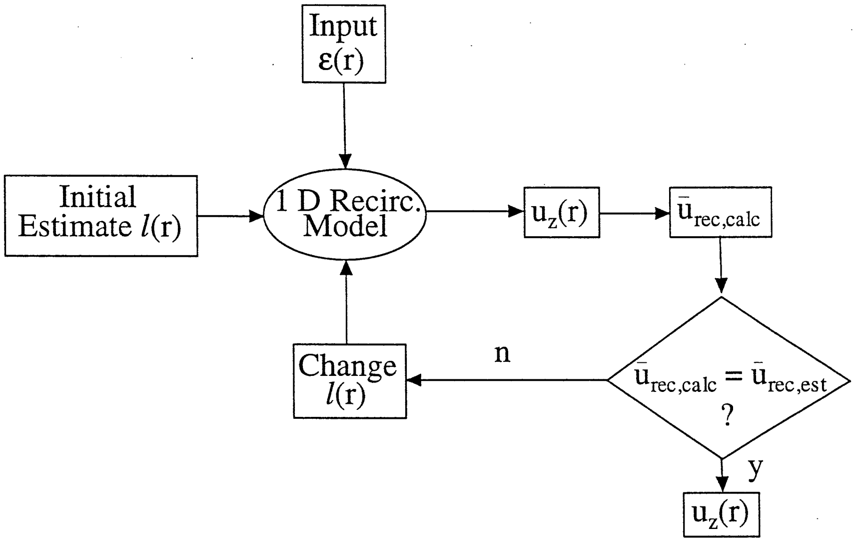

Figure 5.3: Determination of the Liquid Recirculating Velocity Profile, $u_z(r)$, With Knowledge of $\epsilon_l(\xi)$ and $\overline{u}_{rec}$

## 5.3 Turbulent Eddy Diffusivities

A similar method is used for scaling the cross-sectional averaged axial and radial turbulent eddy diffusivities defined, respectively, as

$$\overline{D}_{zz} = 2\int_0^1 D_{zz}(\xi)\xi d\xi \tag{5.6}$$

$$\overline{D}_{rr} = 2\int_0^1 D_{rr}(\xi)\xi d\xi \tag{5.7}$$

In this case, the present results from CARPT data in an air-water system and three column sizes, 14 cm, 19 cm and 44 cm, are considered. The data points shown in Figures 5.4 and 5.5 for $\overline{D}_{zz}$ and $\overline{D}_{rr}$ are rather limited in their range of $U_g$. Therefore, this represents only a preliminary attempt at scaling (extrapolating) $\overline{D}_{rr}$ and $\overline{D}_{zz}$, and needs to be substantiated with further experimental data at higher gas velocities, especially in the largest diameter (44 cm) column.

The following dependencies have been observed for $\overline{D}_{zz}$ and $\overline{D}_{rr}$ (based of CARPT data), on a similar basis as for $\overline{u}_{rec}$, and apply to large diameter columns (> 10 cm) in the churn-turbulent flow regime ($U_g > 5$).

$$\overline{D}_{zz} \;\; (cm^2/s) = -\frac{2325}{D_c^{0.8}} + 106.6 D_c^{0.3} U_g^{0.3} \tag{5.8}$$

$$\overline{D}_{rr} \;\; (cm^2/s) = -\frac{350}{D_c^{0.8}} + 13.0 D_c^{0.3} U_g^{0.3} \tag{5.9}$$

It is emphasized again, that due to the limited number of data points available, these equations represent only a preliminary development for the effects of scale and superficial gas velocity on the turbulent diffusivities.

CARPT results for the radial and axial eddy diffusivities in the churn-turbulent flow regime, indicate that the radial profiles of the turbulent diffusivities can be approximately expressed as follows:

$$D_{zz}(\xi) = \overline{D}_{zz} P_4(\xi) \tag{5.10}$$

$$P_4 = -3.4979\xi^4 + 3.2704\xi^3 + 0.4693\xi^2 + 0.005035\xi + 0.5847 \tag{5.11}$$

$$D_{rr}(\xi) = \overline{D}_{rr} P_2(\xi); \;\; P_2 = -5.0929\xi^2 + 5.0717\xi + 0.1653 \tag{5.12}$$

where $P_4$ and $P_2$ are fourth order and second order polynomials which are independent of gas velocity and column diameter. This is illustrated in Figures 5.6 and 5.7, which show the profiles evaluated using Equations 5.10, 5.10 and 5.12. The reasonably good comparisons suggest that the above equations ( 5.10 and 5.12) in combination with Equations 5.8 and 5.9 can be used to estimate the profiles for the axial and radial eddy diffusivities as a function of $D_c$ and $U_g$ in air-water bubble columns operating in the churn-turbulent flow regime.

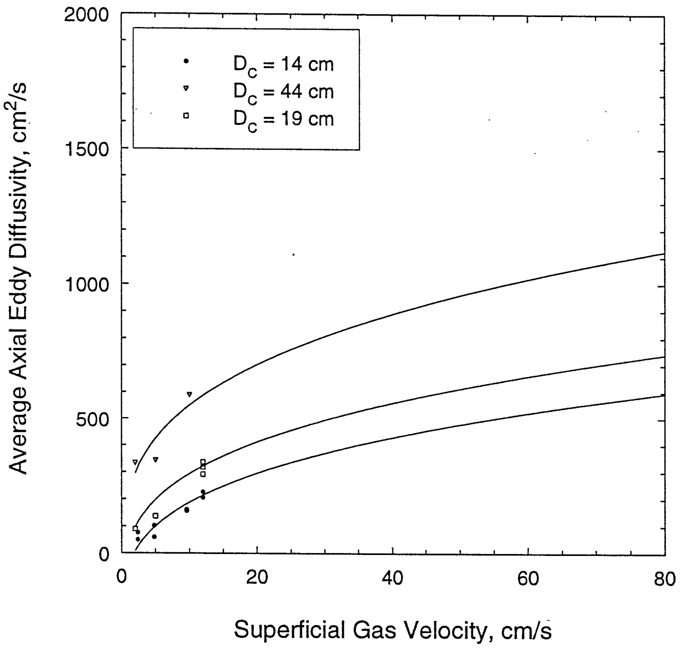

Figure 5.4: Effect of Superficial Gas Velocity and Column Diameter on the Average Axial Eddy Diffusivity

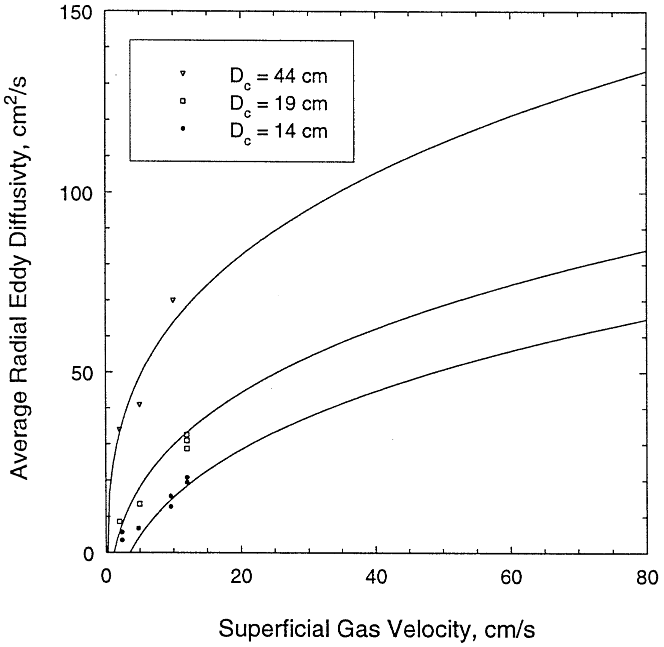

Figure 5.5: Effect of Superficial Gas Velocity and Column Diameter on the Average Radial Eddy Diffusivity

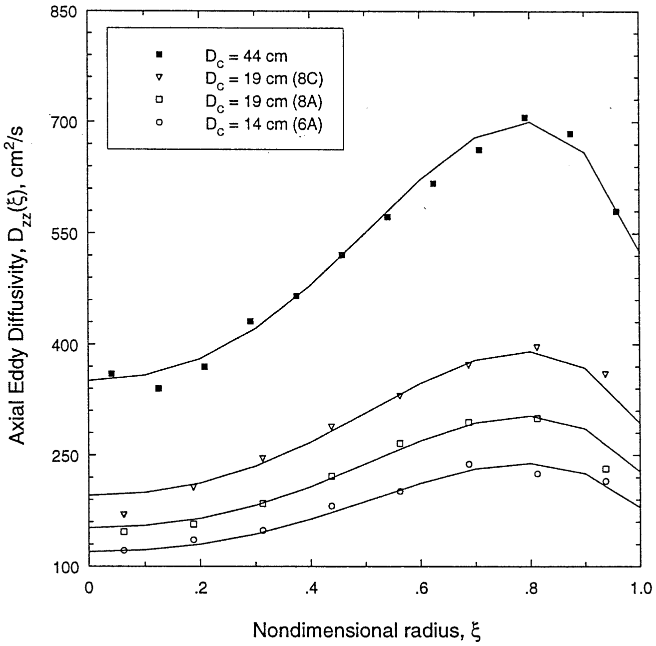

Figure 5.6: Radial Profile ($P_4$) for the Axial Eddy Diffusivity

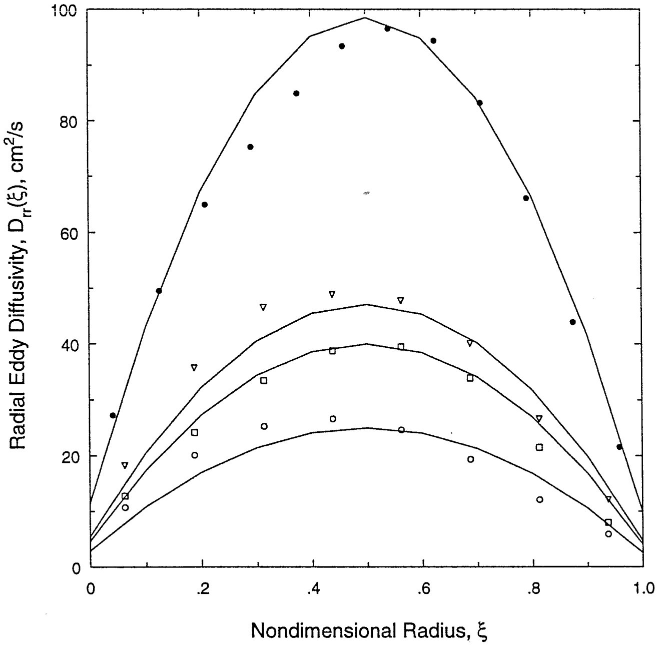

Figure 5.7: Radial Profile ($P_2$) for the Radial Eddy Diffusivity

## 5.4 Characterization of Churn-Turbulent Bubble Columns

The scale-up equations presented in the previous sections have been developed for air-water atmospheric systems, in the churn-turbulent regime. In this regime of flow, effects of distributor and trace contaminants in water are expected be small. It is therefore assumed that at sufficiently high gas velocities for air-water systems, the fluid dynamic parameters are predominantly a function of superficial gas velocity and column diameter.

A change in system properties (physical properties of the fluids, presence of solids, etc.) and operating conditions (pressure and temperature) directly affect bubble sizes and distribution, and thereby the global gas holdup and holdup distribution in the column. This in turn influences the extent of liquid recirculation and turbulence characteristics in the system, which are essentially dictated by the passage and interaction of bubbles. For example, an increase in the system pressure tends to reduce the bubble size, which delays transition to turbulent flow regime and therefore results in the increase in gas holdup, compared to values expected at atmospheric conditions. However, when the flow is in the churn-turbulent regime, it is typically characterized by the presence of large and small bubbles, irrespective of system pressure and other such factors (Krishna and Ellenberger 1996; De Swart 1996). Based on interpretation of DGD experiments Krishna et al. (1994) conclude that the characteristics of the large bubbles are unaffected by system properties and pressure. Independent measurements of the local holdup profile in high pressure bubble columns, at high gas velocities (Adkins et al. 1996), indicate that the holdup profile is parabolic ($m = 2$ in Equation 2.7) in shape, similar to the case for air-water systems at atmospheric pressure.

From these observations it is inferred that well into the churn-turbulent flow regime, similar (bi-modal) bubble size distribution characteristics are present in the column, irrespective of system properties (except when viscosity is very high). It is essentially the resulting gas holdup and its radial distribution that dictate liquid recirculation and turbulence. Therefore, this unified characterization of churn-turbulent bubble columns can be employed to approximately evaluate $\overline{u}_{rec}$, $\overline{D}_{zz}$ and $\overline{D}_{rr}$ in industrial systems of interest, based on the knowledge of these parameters in air-water systems, as shown in Figure 5.8. For a given process condition, with prior knowledge of the global gas holdup in the column, an equivalent superficial gas velocity, $U_{ge}$, that would exist at atmospheric conditions in such a column in an air-water system, can be evaluated using Equation 5.2. The calculated $U_{ge}$ can then be substituted in Equations 5.5 to 5.9 to estimate the average recirculation rate and turbulent diffusivities in the column under the specific conditions of interest.

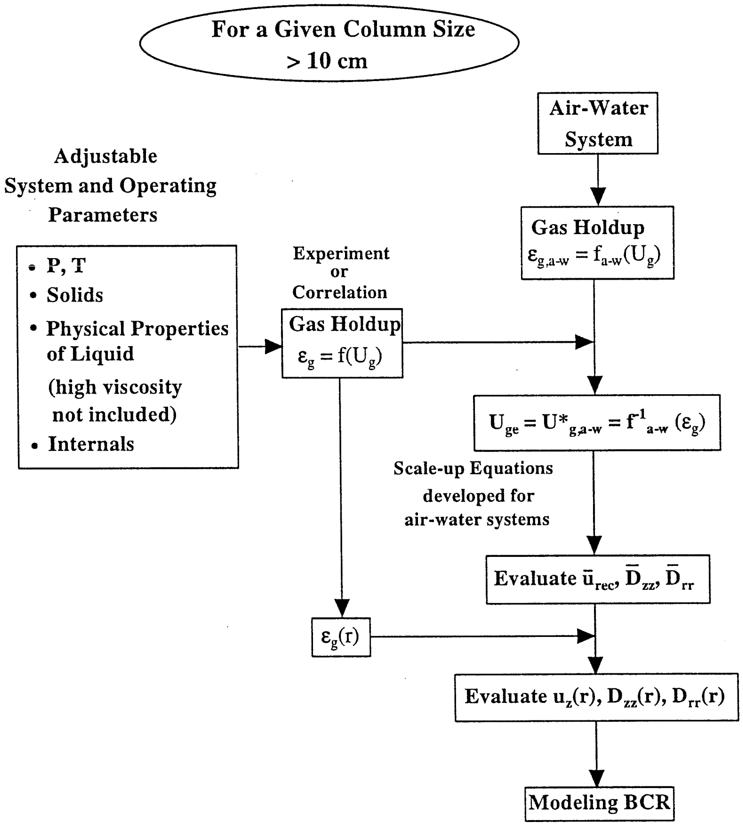

Figure 5.8: Method of Characterization of Churn-Turbulent Bubble Columns

The fluid dynamic parameters estimated from the above procedure are used in the phenomenological modeling of liquid mixing in an industrial slurry bubble column reactor, described in Chapter 6.

## 5.5 Summary

In this chapter 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, from the present work and from the literature, equations have been developed for the prediction of the mean liquid recirculating velocity and average eddy diffusivities in air-water atmospheric systems. Based on the unified characterization of churn-turbulent bubble columns a methodology has been proposed which enables the estimation of the mean liquid recirculating velocity and turbulent eddy diffusivities, in the churn-turbulent flow regime, in systems of industrial interest, e.g., high pressure and high temperature, using the data generated in air-water systems. This strategy requires a 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 in large columns, at higher gas velocities and in different systems. Once verified, this will serve as a tool by which data from a limited database can be utilized to model and scale-up bubble columns, under process conditions, in the churn-turbulent flow regime. In the present work, an indirect verification of the scale-up strategy is done, (discussed in Chapter 6) by using experimental liquid tracer data from an industrial bubble column reactor.