BUBBLE AND SLURRY BUBBLE COLUMNS

I-1. Hydrodynamics of Slurry Bubble Columns using Computer Automated Radioactive Particle Tracking (CARPT) and Computed Tomography (CT)

A. Problem Definition

Slurry bubble column reactors are gaining wide importance in chemical, petrochemical, and biochemical industries. Although these reactors are simple in construction, the flow field and fluid dynamics of these reactors are not well understood due to the complex interaction among the three dynamic phases. Successful scale-up and design of these reactors require the understanding of the effect of operating conditions on phase holdups, velocity, and turbulent parameters profiles.

There have been numerous efforts to study the hydrodynamics of bubble/slurry bubble column reactors, however most of these studies provide information regarding global hydrodynamics. The only investigations to study the detailed hydrodynamics of bubble and slurry bubble column reactors at operating conditions of industrial interest were performed using air-water and air-water-150 μm glass beads system (Ong, 2003; Rados, 2003). No work has been reported that studies the detailed hydrodynamics of slurry bubble column reactors at the conditions as well as system of industrial interest. That motivates us to study detailed fluid dynamics and mixing characteristics at the conditions of industrial interest.

B. Research Objectives

The current study investigates the effect of superficial gas velocity, operating pressure, and solids loading on the flow field, particularly phase holdups, solids axial velocity and turbulent parameters profiles via existing CARPT and CT.

C. Research Accomplishments

The experiments were performed in a stainless steel column with an inner diameter of 16.15 cm and a height of 2.5 m. The dried air was used as gas phase while Therminol LT (μ = 0.88 cP, ρ = 886 kg.m^{-3}, σ = 17 dyne.cm^{-1}) was used as the liquid phase. Glass beads with an average diameter of 150 μm and particle density of 2500 kg.m^{-3} constituted the solids phase. The solids loading (defined as the ratio of volume of solids to volume of slurry) of 9.1 and 25 % vol. was employed. The superficial gas velocities were varied from 8 to 30 cm/s and operating pressure from 0.1 to 1 MPa.

The details of Computed Tomography setup are provided elsewhere (Kumar et al., 1997). CT/Overall gas holdup methodology (Rados, 2003) that was utilized to reconstruct three dynamic phase holdups. The details of CARPT setup and experiments are given by Degaleesan (1997) and Rados (2003). CARPT consists of two steps: calibration and experiments. The calibration has been performed with the aid of automatic calibration device using Sc 46 (t_{half} = 88 days, ρ = 3 g.cc^{-1}) tracer particle. The particle has diameter 136 μm covered by 7 μm thick Paralyne N making its density and size as 2.5 g.cc^{-1} and 150 μm. Newly developed position reconstruction algorithm has been used for CARPT data processing. The obtained reconstructed tracer particle location time series is used to calculate,

i) solids velocities,
ii) 'Reynolds' stresses,
iii) 'turbulent' kinetic energy,
iv) eddy diffusivities.

This work represents one of the tasks set for High Pressure Slurry Bubble Column Consortium; hence a brief outline has been presented. The goals set in this task are completed and reported to Consortium members.

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D. Acknowledgements

The authors are thankful to the High Pressure Slurry Bubble Column Reactor (HPSBCR) Consortium [ConocoPhillips, EniTech, Sasol, Statoil] grant that made this work possible.

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Rados, N. (2003), Slurry Bubble Column Hydordynamics, *D.Sc. Thesis*, Washington University, St. Louis, MO.

I-2. Phase Distribution, Solids/Liquid Velocity, and Solids/Liquid Turbulence in a High Pressure Slurry Bubble Column Reactor Operated at Mimic Fischer-Tropsch Conditions

A. Problem Definition

In the effort of better understanding the hydrodynamics of slurry bubble column (SBC) reactors, it is of great importance to investigate the effects of operating conditions and physical properties on the distribution and interaction of phases via experimentation.

The gas phase holdup distribution dictates the local buoyancy, which drives the slurry into convection and turbulence. Therefore, measuring the gas holdup distribution has become the focus of many hydrodynamics studies using various techniques. The hydrodynamics and mixing of liquid and solids are also determinants of the reactor performance, which need to be better understood. In the recent years, the development and implementing of nuclear-based techniques greatly contributed to the knowledge of the hydrodynamics in multi-phase reactors (Chaouki et al., 1997; Dudukovic, 2000). The gamma-ray based techniques developed at CREL, Computed Tomography (CT) and Computer Assisted Radioactive Particle Tracking (CARPT), provide measurements of time-averaged phase holdups, liquid/solids velocity filed, and liquid/solids turbulence parameters. The previous CT/CARPT studies (Degaleesan, 1997; Ong, 2003; Rados, 2003; CREL, 2003) in bubble columns/slurry bubble columns remarkably provided knowledge of phase hydrodynamics and mixing which could not be achieved with other techniques. However, these studies mostly used water as the liquid phase except CREL(2003) using an air-Therminol LT-glass beads systems; and almost all these studies used glass beads as the solids phase. It is of great importance to investigate the hydrodynamics in SBC using materials and operating conditions that can more closely represent industrial operations, particularly the Fischer-Tropsch (FT) process.

B. Research Objectives

The objective of this work is to investigate the cross-sectional phase holdup, liquid/solids velocity field and turbulence parameters in a high pressure slurry bubble column reactor using air at high pressure which has similar density as the syngas in FT slurry rectors; C_9C_{11} hydrocarbon which at room temperature mimics FT wax; and FT catalyst provided by ConocoPhillips. The experimental study is focused on operations at high gas velocity (churn-turbulent flow regime), high pressure, and high solids loading.

C. Accomplishment

CT/CARPT experiments were performed at the mimic FT conditions proposed to the HPSBC Consortium. The data of phase holdup, liquid/solids velocity, liquid/solids turbulence parameters were obtained and formulated. Effects of superficial gas velocity, operating pressure, solids loading, and physical properties of liquid/solids on the studied hydrodynamic parameters were observed, analyzed, and reported in the recently completed HPSBC Consortium final report.

Detailed information is only available to the HPSBC Consortium members.

D. Future Work and Milestones

It was found in this work that the FT catalyst (provided by ConocoPhillips) made an observable difference in solids hydrodynamics and mixing compared with glass beads. Therefore, experiments using different types of FT catalyst may help further understand the effect of catalyst properties on the hydrodynamics in FT slurry reactors.

E. Acknowledgement

The financial support of the High Pressure Slurry Bubble Column (HPSBC) Consortium provided by ConocoPhillips (USA), EniTecnologie (Italy), Sasol (South Africa), and Statoil (Norway) are gratefully acknowledged.

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I-3. Scale-Up of Bubble Column Reactors

A. Problem Definition

Bubble column reactor is a device in which a gas phase is bubbled through a column of liquid to promote a chemical or biochemical reaction in the presence or absence of a catalyst suspended in the liquid phase. Bubble columns have been widely used in chemical, petrochemical, biochemical, and mineral process industries due to their simple construction and ease of operation.

Extrapolation of small diameter behavior to larger one is an important and challenging task. Such task needs a reliable criterion for hydrodynamic similarity that can be subsequently applied for scale-up of bubble column reactors. In literature, various methodologies were proposed for similarity in bubble columns. A detailed overview of these methods suggests that, the reported studies are based on similarity of global parameter for hydrodynamic similarity. During their similarity studies, Macchi et al. (2001) found that though overall gas holdup in two systems was close within an acceptable engineering error, power spectra calculated using pressure fluctuation studies was quite different in two systems. They attributed this difference to the use mono- and multi-component liquid in two systems.

B. Research Objectives

In this work, a new hypothesis for similarity in bubble columns was proposed based on the reported similarity studies and the state of understanding developed from hydrodynamic studies at CREL. The main motive of this study is an experimental evaluation of the proposed hypothesis utilizing existing Computed Tomography (CT) and Computer Aided Radioactive Particle Tracking (CARPT).

C. Research Accomplishments

Figure 1 shows the gas holdup radial profile in an air-water system (Ong, 2003, Kemoun et al., 2001) at different operating conditions with similar overall gas holdup (i.e. 0.41). Though these systems have similar overall gas holdup, the gas holdup radial profiles in theese are different, which may lead to different mixing and flow patterns. The conclusions of Macchi et al. (2001) and the data presented in Figure 1 suggest that two systems may have similar global hydrodynamics but still can have different local flow behavior. Hence, we propose a hypothesis that,

"*not only overall gas holdup but its radial profile also should be the same in two reactors to be hydrodynamically similar*".

The proposed methodology consists of two steps:

i) Experimental evaluation of the proposed hypothesis using CT and CARPT.

ii) Development of Artificial Neural Network (ANN) correlations for the needed hydrodynamic parameters, such as gas holdup, radial profile of gas holdup, liquid axial velocity.

The first step consists of identifying the similarity conditions that have similar overall gas holdup and gas holdup radial profiles from the available database. In addition, experimental conditions that have similar overall gas holdup but different radial gas holdup profiles were also identified (mismatch conditions). The liquid circulation and mixing at identified similarity/mismatched conditions was studied via CARPT measurements.

Figure 2 shows the conditions of similarity where overall gas holdup (~ 0.36) as well as gas holdup radial profiles are similar. Figure 2a shows the similar gas holdup radial profiles that resulted into close axial liquid velocity profiles as shown in Figure 2b. The average absolute relative difference[*] (AARD) in gas holdups and axial liquid velocities for the set in Figure 2 was found to be 4 and 15 % respectively. Figure 3 shows the condition of mismatch where overall gas holdup at both the conditions is the same (~ 0.36) while the radial gas holdup profiles are mismatched. Figure 3a shows the mismatched gas holdup radial profiles. This mismatch results into different liquid axial velocity profiles and hence recirculation. AARD in gas holdups and axial liquid velocities in Figure 3 was found to be 25 and 48 % respectively. In both, similarity as well as mismatch conditions, one system has pure liquid while the other has a mixture of liquid.

We experimentally show that, to be hydordynamically similar two systems need to have similar gas holdup and its cross-sectional distribution. The similarity based only on overall gas holdup does not necessarily ensure similar hydrodynamic performance.

The second part of this method consists of developing ANN based correlations for needed hydrodynamic parameters such as overall gas holdup, gas holdup and axial velocity radial profile, and center line velocity. The correlations for these parameters are developed based on the reported experimental data.

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D. Acknowledgments

The authors are thankful to the High Pressure Slurry Bubble Column Reactor (HPSBCR) Consortium [ConocoPhillips, EniTech, Sasol, Statoil] grant that made this work possible.

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Kemoun , A., Ong, B. C., Gupta, P., Al-Dahhan, M. H., and Dudukovic', M. P., (2001). *IJMF*, 27 (5), 929.

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[*] Average absolute relative difference = $\frac{1}{N}\sum_{i=1}^{N}\left|\frac{x_i(r)-y_i(r)}{x_i(r)}\right|$

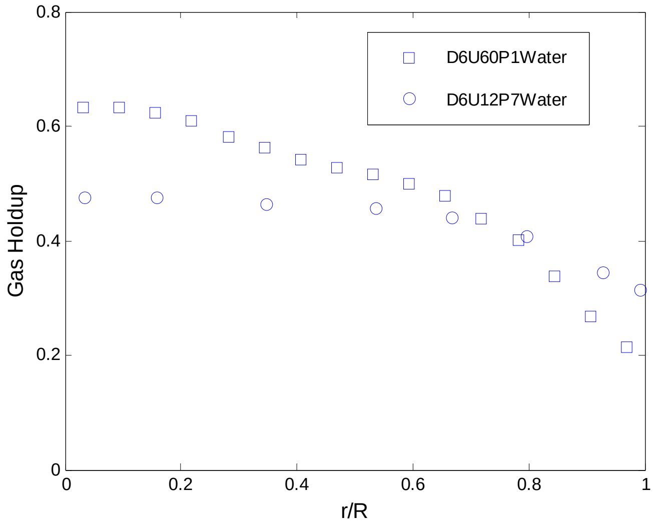

Figure 1: Comparison of gas holdup radial profile in 6” column using air-water system at two different operating conditions (◊ 7 bar and 12 cm/s, □ 1 bar, 60 cm/s) with similar overall gas holdup (ε_G = 0.41).

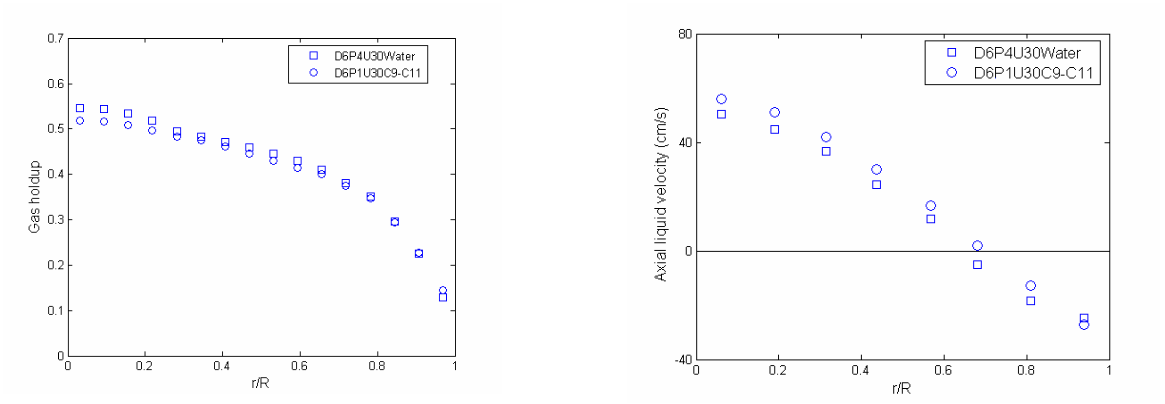

Figure 2: a) Gas holdup and b) Axial liquid velocity radial profile in 6” diameter stainless steel column (D6P1U30Sasol: 1 bar, 30 cm/s, and air-Sasol fluid system, D6P4U30water: 4 bar, 30 cm/s, and air-water system) [Overall gas holdup ~ 0.36]

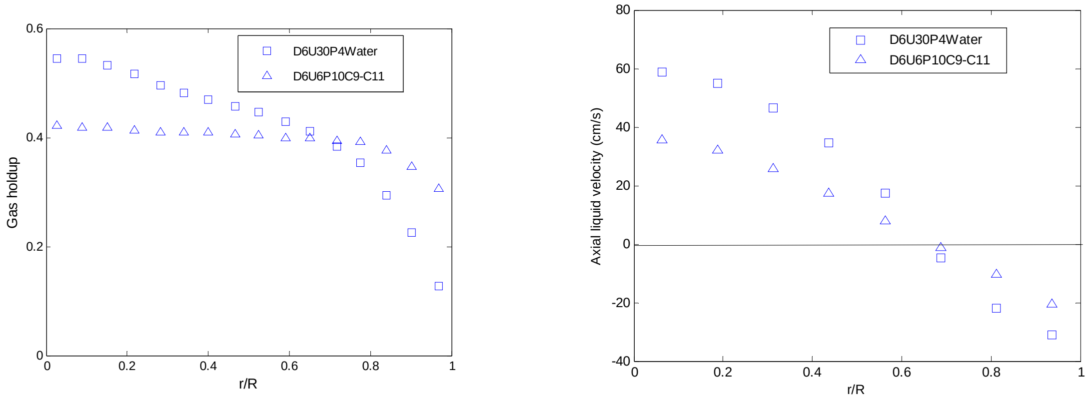

Figure 3: a) Gas holdup and b) Axial liquid velocity radial profile in 6” diameter stainless steel column (D6P1U30water: 1 bar, 30 cm/s, and air-water system, D6P10U6water: 10 bar, 6 cm/s, and air-Sasol fluid system) [Overall gas holdup ~ 0.36]

I-4. Characterization of Hydrodynamic Flow Regime in Bubble Column Reactors via Computed Tomography (CT)

A. Problem Definition

Bubble column reactors are emerged as the attractive two- or three-phase contacting devices, and have been widely used in various chemical, petrochemical, and biochemical applications. Although bubble column reactors are simple in construction, the proper design and scale-up of such reactors require a thorough understanding of the prevailing hydrodynamic and mixing characteristics. There are two basic flow regimes occur in such reactors, viz; homogeneous (bubbly flow) and heterogeneous (churn-turbulent flow). These regimes differ in many aspects of hydrodynamic and transport phenomena that make an identification of flow regime transition as an important task in scale-up and design of bubble column reactors.

With advances in measurement techniques for multiphase reactors, there are few attempts in characterizing flow regime using such imaging techniques. Bennett et al. (1999) and Dong et al. (2001) applied Electrical Capacitance Tomography (ECT) and Electrical Resistance Tomography (ERT) to study flow regimes in bubble columns. These studies depend on assessment of obtained tomograms rather than quantification in terms of simple secondary parameter. Later, Olomos et al. (2003) and Nedeltchev et al. (2003) applied instantaneous velocity data obtained using Laser Doppler Velocimetry (LDV) and Computer Automated Radioactive Particle Tracking (CARPT), respectively, to study flow regime transition.

A. Research Objectives

The current study evaluates the potential of single source γ-ray Computed Tomography for hydrodynamic flow regime characterization. Such a characterization can be potentially used to identify flow regime transition. The method will then be verified with Drift Flux model due to Wallis (1969).

B. Research Accomplishments

The experiments were performed in a stainless steel column with an inner diameter of 16.15 cm and a height of 2.5 m. The dried air was used as gas phase while Therminol LT ($\mu = 0.88$ cP, $\rho = 886$ kg.m^{-3}, $\sigma = 17$ dyne.cm^{-1}) was used as the liquid phase. The superficial gas velocities were varied from 1 to 20 and 30 cm/s with an interval of 1 cm/s. The operating pressures used are 0.1, 0.4, and 1 MPa.

The software and hardware details of the single source γ-ray CT have been explained elsewhere in detail (Kumar, 1994). The obtained CT data was processed using EM algorithm implemented by Kumar (1994). The quantification of flow regime was performed using a secondary parameter characterizing gas holdup radial profile. The break-point in the secondary parameter indicates the flow regime transition. This was evaluated using drift flux model based on cross-sectional gas holdup calculated from the obtained gas holdup radial profiles. The results obtained in this work are found to be in agreement with the reported literature studies.

This work represents one of the tasks set for High Pressure Slurry Bubble Column Consortium, hence a brief outline has been presented. The goals set in this task are completed and reported to Consortium members.

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C. Acknowledgements

The authors are thankful to the High Pressure Slurry Bubble Column Reactor (HPSBCR) Consortium [ConocoPhillips, EniTech, Sasol, Statoil] grant that made this work possible.

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I-5. A New Methodology to Measure the Solids Axial Dispersion in a High Pressure Slurry Bubble Column Reactor

A. Problem Definition

The solids dispersion and distribution in slurry bubble columns (SBC) play an important role in deciding the reactor performance, and remains difficult to be predicted in reactor design and scale-up due to the complicated interaction of phases. Although the solids mixing in SBCs has been the focus of a number of studies over decades, the reported method to measure the solids dispersion and distribution is mostly limited to sample-withdrawing or bed sedimentation methods. The majority of the studies measured the solids axial distribution by withdrawing samples from ports (Nakao et al., 2000; Zhang et al., 2002; etc.), while some others by settling the solids onto several shutter plates (Matsumo et al., 1989 and 1992). These methods are invasive and are limited to steady state measurements. The computer assisted radioactive particle tracking (CARPT), developed at CREL, is a gamma-ray based technique that provides abundant information of the solids hydrodynamics. However, no effort has been made to estimate the solids axial dispersion coefficient using this technique. The sedimentation-dispersion model (SDM) (Cova, 1966; Imafuku et al., 1968) can well predict the solids axial distribution and is widely employed in reactor modeling (Nakao et al., 2000; Zhang et al., 2002; etc.). However, no solids dispersion studies at high pressure were found, and many of the previous studies were conducted at low gas velocities. The application of the SDM at high pressure and high gas velocity in SBCs has not been evaluated.

B. Research Objectives

The objective of this work is to develop a methodology to measure the solids axial dispersion in slurry bubble column reactors based on the computer assisted radioactive particle tracking (CARPT) technique. This method inherits CARPT's non-invasiveness, and provides tracer responses that can be considered as almost ideal tracer injections. With this new method, the application of the SDM at high pressure and high gas velocity is evaluated; the axial dispersion coefficient is then estimated at various conditions.

C. Accomplishment

The new methodology to measure the solids axial dispersion coefficient with the CARPT technique was developed. Both dynamic response data and steady solids axial distribution data were obtained based on the CARPT data, as shown in Figures 1 and 2. Accordingly, values of the solids axial dispersion coefficient were obtained separately using both the transient SDM and the steady state SDM (model fits shown in Figures 1 and 2). It was found that the model predictions well fit both the transient responses and the steady solids distribution at high pressure and high gas velocity. Compared with the steady state method, the transient method is recommended for its much less sensitivity on the u_{st} values. Considering the difficulty of precise u_{st} measurement or estimation in a three-phase system, the results of the transient method gives more confidence than that of the steady state method, since the fitted D_s values with the steady state method are greatly affected by the u_{st} estimation. The values of D_s were measured at various superficial gas velocities and operating pressures using the transient method. The solids axial dispersion increased with the superficial gas velocity due to both the enhanced solids circulation and solids axial eddy diffusivity. Increasing the operating pressure yielded higher solids axial dispersion as a result of significantly enhanced solids global circulation, although the solids axial eddy diffusivity became lower.

D. Future Work and Milestones

Since the experiments were performed in a reactor with large length-to-diameter ratio (L/d_c=11), this work implemented the one-dimensional SDM on the reactor and estimated the solids axial dispersion coefficient. However, similar method can also be applied to measure other dispersion coefficients in a different reactor model, such as axial and radial dispersion coefficients in a two-dimensional axial dispersion model, or other dispersion coefficients in a mechanistic model.

E. Acknowledgement

The financial support of the High Pressure Slurry Bubble Column (HPSBC) Consortium provided by ConocoPhillips (USA), EniTecnologie (Italy), Sasol (South Africa), and Statoil (Norway) are gratefully acknowledged.

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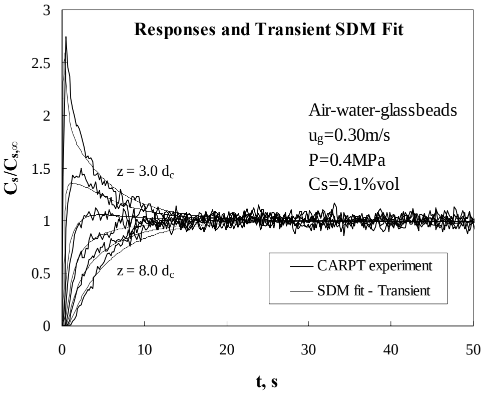

Figure 1. Transient solids concentration profiles and SDM fit
(Curves from up to down are fits at $3.0d_c$~$8.0d_c$)

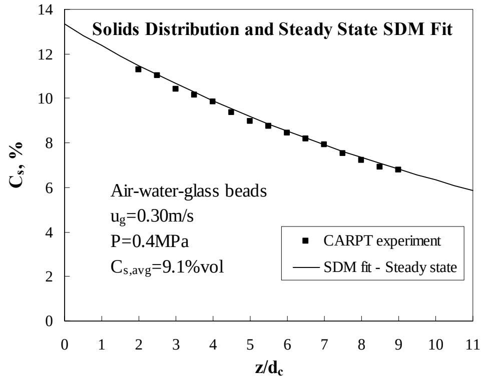

Figure 2. Steady state solids distribution and SDM fit.

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I-6. Gas-Liquid Mass Transfer in a High Pressure Bubble Column Reactor with Different Gas Sparger Designs

A. Problem Definition

Bubble column (BC) reactors are widely employed in chemical, biochemical, and petrochemical industrial processes due to their advantages such as simple construction and excellent heat and mass transfer. Yet successful design and scale-up of BC reactors remains difficult due to the complex interaction and mixing of phases. One of the key determinants of BC reactor performance, the gas-liquid mass transfer, is directly affected by the hydrodynamics, phase mixing, and physical properties. In the ongoing effort to reduce uncertainty, there has been a large body of mass transfer research covering various conditions. However, reports (Abraham et al., 1989; Han et al., 2003) on the effect of gas distributor (sparger) designs on the gas-liquid mass transfer are limited. The gas distributor is important in reactor design and has been proven to directly affect the hydrodynamics and phase mixing in BCs at certain conditions (George et al., 2000; Vial et al., 2001; Ong, 2003, Rados, 2003). Hence, the sparger effect on gas-liquid mass transfer needs to be further characterized. Furthermore, only a limited number of mass transfer studies separately measured the liquid side mass transfer coefficient, k_l, and the interfacial area, a, although these two parameters help understand the underlying phenomena. More importantly, the reported effects of pressure and gas velocity on the liquid side mass transfer coefficient, k_l, are not consistent.

B. Research Objectives

The objective of this work is to investigate both the volumetric gas-liquid mass transfer coefficient, k_la, and the liquid side mass transfer coefficient, k_l, in a high pressure bubble column with three different sparger designs at various conditions.

C. Accomplishment

The gas-liquid mass transfer in a 0.162 m high pressure stainless steel bubble column was investigated using a perforated plate sparger with small holes; a perforated plate sparger with large holes; and a cross sparger. An oxygen-enriched-air dynamic method and an optical oxygen probe technique were implemented to measure the k_la values in the bubble column reactor. Using the interfacial area (a) values measured by a 4-point probe technique at similar conditions (Xue, 2004), the k_l values were estimated. Axial dispersion model (ADM) and continuous stirred tank reactor (CSTR) model were used to calculate k_la as a fitted parameter with the measured data. The ADM gave better fits to the experimental data than the CSTR model, especially at high axial locations and for the bubble column used with a large L/d_c ratio. Hence, the ADM was selected for the k_la measurement in this study. As shown in Figure 1, the sparger design was found to have a noticeable effect on k_la in the low gas velocity range (u_g<0.15 m/s) but only a slight effect in the high gas velocity range (u_g>0.20 m/s). The sparger design showed almost no effect on the liquid side mass transfer coefficient, k_l, at high gas velocity (u_g=0.30 m/s) (Figure 2), where no significant variations of the bubble size distribution and hydrodynamics were obtained using different sparger designs. Although the k_la values increased with the operating pressure (Figure 3), the pressure change from 0.1MPa to 0.4MPa yielded lower k_l values (Figure 4), as a result of the reduced bubble size. However, as the pressure further increased to 1.0MPa, the a and k_la values increased while the k_l values negligibly decreased. In addition to the pressure and sparger design effects, the superficial gas velocity had effect of increasing the k_l values, while such effect became small and flattened out at high superficial gas velocities (Figure 2).

D. Future Work and Milestones

The $k_l a$ values of various gases (O_2, CH_4, CO_2, and Ar) in a 0.162m slurry bubble column using an air-paraffin-catalyst system were obtained at high gas velocity, high pressure, and high solids loading, using the optical probe technique and a gaseous tracer technique. If 4-point probe experiments are performed at these conditions, the values of k_l can be estimated in the slurry bubble column that mimics the Fischer-Tropsch slurry reactor operation.

E. Acknowledgement

The financial support of the High Pressure Slurry Bubble Column (HPSBC) Consortium provided by ConocoPhillips (USA), EniTecnologie (Italy), Sasol (South Africa), and Statoil (Norway) are gratefully acknowledged.

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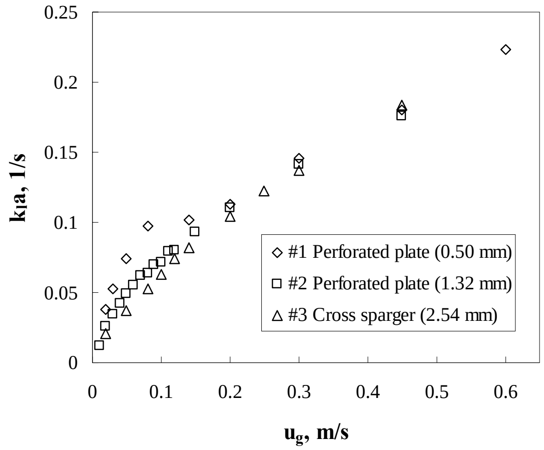

Figure 1. Measured $k_l a$ values
Effect of sparger design and u_g

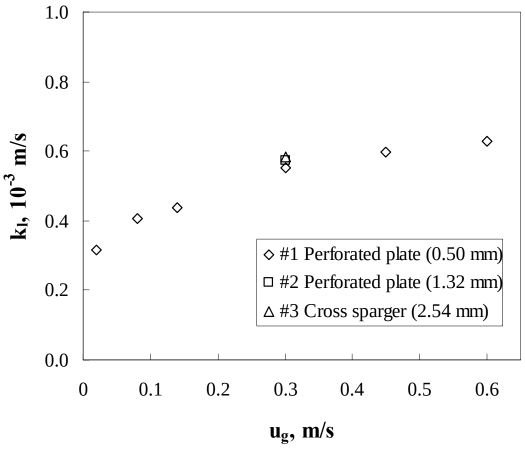

Figure 2. Measured k_l values
Effect of sparger design and u_g

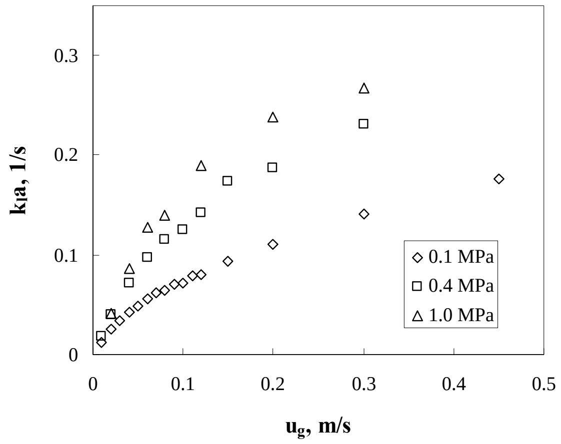

Figure 3. Measured $k_l a$ values
Effect of operating pressure

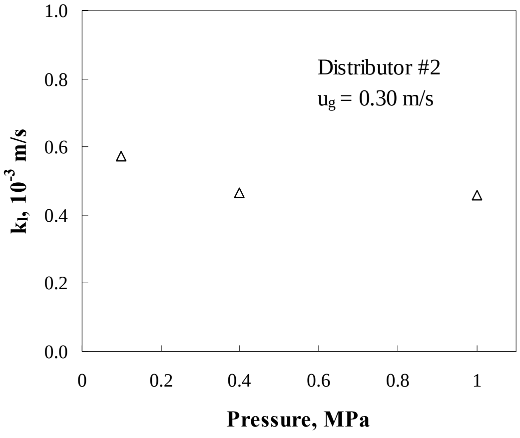

Figure 4. Measured k_l values
Effect of operating pressure

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I-7. Heat Transfer Coefficients in a High Pressure Bubble Column

A. Problem definition

Bubble column and slurry bubble column reactors are widely employed in petrochemical, chemical, and biochemical processes due to their easy installation, easy operation, and high heat and mass transfer rates caused by strong gas-liquid interactions. These reactors are operated under high pressure in many industrial applications, such as heavy oil upgrading, Fischer-Tropsch synthesis, and methanol synthesis. A number of studies have been performed on the heat transfer coefficient in bubble columns[1-6]. However, heat transfer coefficient studies in high pressure bubble columns are scarce.

B. Objectives

The objective of this study is to investigate the effects of pressure, superficial gas velocity, and orientation of the probe on the heat transfer coefficient and its radial profile in a 0.16 m diameter air-water bubble column.

C. Accomplishments and Current Work

The experiments were performed in a 0.16 m diameter and 2.50 m high stainless steel bubble column. Tap water was the liquid phase, and compressed air was the gas phase. The superficial gas velocity was varied from 0.03 m/s to 0.30 m/s. A thermocouple probe was used to measure the bulk temperature of the media in the column adjacent to the heat transfer probe. The heat transfer probe (Figure 1), manufactured at Washington University, was a modified version of the probe developed by Li and Prakash[3].

During the experiments, the heat transfer probe was horizontally installed in the fully developed region of the bubble column, and it can used to measure both the local heat flux and the surface temperature of the probe simultaneously. Since the heat flux, the temperature of the probe surface, and the bulk media temperature could be directly measured, the local instantaneous heat transfer coefficient and local averaged heat transfer coefficient could be estimated as follows:

$$h_i = \frac{q_i}{T_{si} - T_{bi}} \qquad (1)$$

$$h_{ave} = \frac{1}{n}\sum_{i=1}^{n}\frac{q_i}{T_{si} - T_{bi}} \qquad (2)$$

where
h_i = instantaneous local heat transfer coefficient (kW/(m^2. K)),
q_i = instantaneous heat flux across the sensor (kW/(m^2. K)),
T_{bi} = instantaneous bulk temperature of the media (K),
T_{si} = instantaneous surface temperature of the probe (K),
h_{ave} =time averaged heat transfer coefficient (kW/(m^2. K)), and
n = total number of the samples.

The effects of the superficial gas velocity (up to 0.30 m/s), pressure (up to 10 bar), probe position and orientation were investigated. The heat transfer coefficient increased with superficial gas velocity, and at high velocities the increase became smaller. At the same operating conditions, the heat transfer coefficient in the center of the column was larger than near the wall region, and the differences at low superficial gas velocities were smaller than those at high superficial gas velocities.

Figure 2 shows the effect of pressure on the heat transfer coefficient in bubble column. With increased pressure, the heat transfer coefficient decreased, whereas, the differences at low superficial gas velocities were larger than those at high superficial gas velocities. The overall decrease trend of the heat transfer coefficient with increasing pressure is mainly due to the decrease of bubble size. However, the bubble frequency and bubble number increase with elevated pressure, which enhance the liquid circulation in the bubble column. At low gas velocity, although the total number of bubbles increases under high pressure, the liquid circulation does not change much because bubble coalescence and break up are insignificant in this bubbly regime. At high superficial gas velocity, more large bubbles are formed in the transition flow regime and churn turbulent flow regime. Even though the average size at high pressure is smaller than that under atmospheric pressure, the enhanced bubble frequency and increased bubble number under high pressure cause intense interaction between bubble-bubble, bubble-liquid, liquid-wall, and liquid-probe surface. Such enhanced interactions due to pressure decrease the thickness of the contact film between the probe and the bulk and then increased the heat transfer coefficient to some extend. It is noteworthy that these enhancements on heat transfer coefficient due to increasing bubble number and bubble frequency with increasing pressure are not as strong as the effect of the bubble size reduction (Yang et al. 2000).

The orientation of the probe reflects the flow direction in different region of the column. For the first time the radial profiles of the heat transfer coefficient under high pressure was investigated, and it was found that the radial profiles of heat transfer coefficients become flatter at high pressure due to decreasing bubble size and shrinking bubble size distribution with an increase of pressure.

D. Future work

The effects of the solids loading will be investigated under both atmospheric pressure (1bar) and high pressure (10 bar) in the same column.
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E. Acknowledgements

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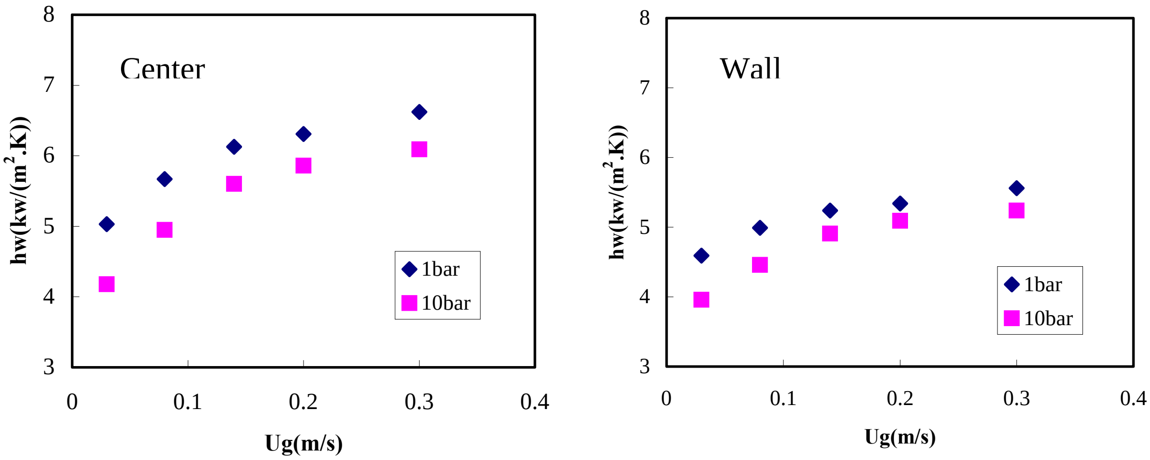
Figure 1. Picture of the heat transfer measurement probe
1: Teflon tube, 2: brass shell, 3: heat flux sensor, 4: Teflon cap.



(a)
(b)

Figure 2. Effect of pressure on heat transfer coefficients in the fully developed region of a bubble column
a) In the center of the column (r/R=0), b) Near the wall of the column(r/R=0.9).

I-8. Modeling of Gas Distributor for 3 D Simulation of Bubble Columns

A. Problem Definition

Bubble column reactors have variety of applications in the chemical, biochemical and petrochemical industries due to their relative simple construction; favorable heat and mass transfer properties and low operating cost. Although simple in construction, the hydrodynamics of bubble columns is largely affected by global operating parameters such as reactor configurations, superficial gas velocity, distributor, operating pressure, temperature and liquid height. Among these multiple influences, the selection and design of the gas distributor has a decisive influence on the hold-up, the interfacial area and the level of mass transfer. The hydrodynamics and therefore, performance of the bubble columns can be controlled by proper designing of distributor. Therefore, for scale-up of bubble column reactors, it is essential to develop qualitative as well as quantitative understanding of distributor design using CFD techniques.

The effect of gas distributor on the hydrodynamics of bubble column has been studied experimentally by many researchers for cylindrical; (e.g. Degaleesan et al.[1]) as well as for rectangular (e.g. Ranade et al. [2]) bubble column reactors. Based on these findings several hydrodynamic simulations have been performed both for 2D and 3D geometries[3, 4]. However, in most published simulations, the sparger is assumed to distribute the gas uniformly through the sparger region and was modeled as an inlet. In some cases (e.g. special configurations such as ring spargers), an appropriate sparger area was considered by selecting the computational grid[2]. Therefore, hydrodynamic modeling with real distributor has been largely ignored for 3D simulations (and even for 2D simulations), and in most cases only axi-symmetric results have been obtained from simulation (up-flow in the centre of column and down-flow near the column walls). Although these computational results are useful in providing overall guidelines for bubble column reactor design, in order to account for non-uniform gas sparging at the sparger and to capture unsteady recirculatory flow structures in bubble columns, there is need to include the actual design of gas distributor in simulations [3].

B. Research Objectives

In this work, the effect of a sieve plate gas distributor has been investigated using Computational Fluid Dynamic simulations. Two-fluid (Eulerian–Eulerian) model of FLUENT 6.1 software is employed for 3D simulations of cylindrical bubble column reactor.

C. Accomplishments

In the first step of CFD simulation, GAMBIT 2.1.1 (preprocessor for FLUENT) is used to create 3 D geometries of the bubble column reactor as well as for its meshing. In order to reduce the number of grids and thus to minimize computational resources, cylindrical geometry is splitted into two sections. Small size tetrahedral (unstructured) mesh is created for the area close to the distributor while a hexahedral (structured) mesh is used for the rest of the area (Figure 1).

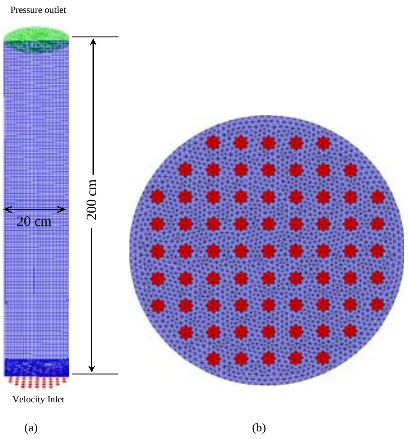


Figure 1: Computational Domain of the Bubble column reactor. (a) Grid on an iso- surface at X=0, Y=20 cm, Z=200 c m (b) Gas distributor model

The flow field in the bubble column is solved in FLUENT 6.1 using the standard *k-ε* model for turbulence. Water and air are taken as the continuous and dispersed phase respectively and simulations are performed for unsteady state condition. In order to study the distributor effect on the hydrodynamics of bubble column, simulations with different size distributors and superficial gas velocities are performed. Figure 2 shows snapshots of velocity vectors of water for a typical distributor at a superficial gas velocity of 17 cm/s. These velocity vectors are compared with the experimental flow field for a similar bubble column obtained using a radio-active particle technique. In an earlier study, Sanyal et al^3 performed 2D simulations for similar experimental setup. They used same modeling approach as the current study (Two-Fluid Eulerian), but ignored the distributor effect and modeled the perforated plate distributor as a uniform source of gas phase. As a result no asymmetric or meandering pattern was observed at the distributor (which is shown in the left most picture in Figure 2). In order to capture clear picture of the swirling motion near gas distributor, they not only emphasized the need for the inclusion of real spargers for simulation but also on 3D simulations. Simulations performed in this study clearly demonstrate this is indeed possible to capture the meandering behavior using the Eulerian-Eulerian approach provided the distributor effect is included.

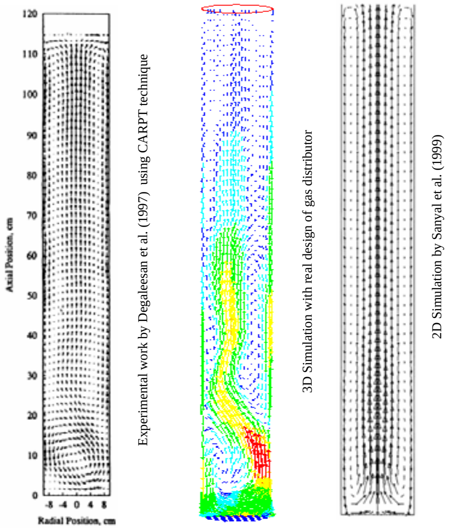


Figure 2: CFD simulation with gas distributor (Model validation

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I-9. Multiple Particle Tracking (MP-CARPT) Implementation: Low L/D Slurry Bubble Column Reactor

A. Problem Definition

Slurry bubble column reactors (SBCR) are three phase gas-liquid-solid systems. They are extensively used in chemical industry applications. Traditionally in bubble columns, liquid height to column diameter ratio (L/D) is more than four. But for industrial applications it is difficult to build very tall reactors and thus the reactor height needs to be reduced, which lowers the L/D ratio. Most of the information of SBCR is for high L/D ratio, thus it is of particular interest to study the hydrodynamics of low L/D SBCR. Since, multiple-particle tracking (MP-CARPT) was validated successfully to track liquid phase using two radioactive particles simultaneously in an airlift internal loop reactor. MP-CARPT can also be tested to track two different phases simultaneously, such as solid and liquid in SBCR.

B. Objectives

1. To test and implement the MP-CARPT to track two different phases simultaneously.
2. To obtain the hydrodynamics of low L/D SBCR using MP-CARPT.

C. Accomplishments and Current Work

A six-inch diameter acrylic cylindrical vessel with gassed liquid height of 22 cm (L/D=1.4) operated as SBCR was used for this study. The gas distributor plate had 139 holes of 1.32 mm diameter each, arranged in a triangular pitch of 1 cm. The distributor plate had open area of 1.04%. The tank was filled with 4 liters of water. 40 gms of 300 micron glass spheres (2.5 gm/cc density) were added to the water, such that slurry had 1 % (by weight) solids. Air was sparged at the rate of 50 SCFH, such that superficial gas velocity in the tank was 2.154 cm/sec. A 300 μm Sc-46 particle with approximate activity of 100 microCi was used to mimic the solid phase. A 100 μm Co-60 particle enclosed in a 1 mm polypropylene ball was used to mimic the water phase. Three sets of experiments were performed, all of them using MP-CARPT unit. Two experiments where Co-60 and Sc-46 particles were tracked separately as liquid phase and solid phase, respectively. Then both the particles were released in the system and were tracked together in the third experiment. This allowed the validation of results of dual-particle tracking of different densities against the single-particle tracking results. In each of the three experiments, particles were tracked for total of 20 hours at frequency of 50 Hz.

The flow patterns obtained for Sc-46 and Co-60 are shown in Figure 1a to 1b. The flow patterns for Sc-46 and Co-60 from single-particle and dual-particle tracking look the same as shown in Figure 1a and 1b, respectively. It is very interesting to note that the flow patterns for a low L/D SBCR are significantly different than the flow patterns of solid or liquid phase in a high L/D SBCR.

The flow patterns in a high L/D SBCR were obtained by Novica (2003). Figure 2 shows the radial profile of azimuthally averaged axial velocity at the center of the column. The error bars are also shown in Figure 2. The dual particle tracking experiment was repeated to obtain the error. It can be seen that the difference between velocities obtained from the single-particle and dual-particle tracking is not significant as it is less than the error associated with the reconstructed data. The error associated with Sc-46 reconstruction is more than the error associated with Co-60. The reasons for this were explained before. These results show the ability of the new MP-CARPT unit to track two radioactive particles of different densities. However, it has to be remembered that the solid fraction in the system was kept low to 1%, so that the collisions between the Sc-46 particle tracking liquid phase and the solids in the system can be kept to minimum. If the solids hold up is too high then the true hydrodynamics of liquid phase cannot be obtained due to the interference created by solids in the system to the tracer mimicking liquid phase.

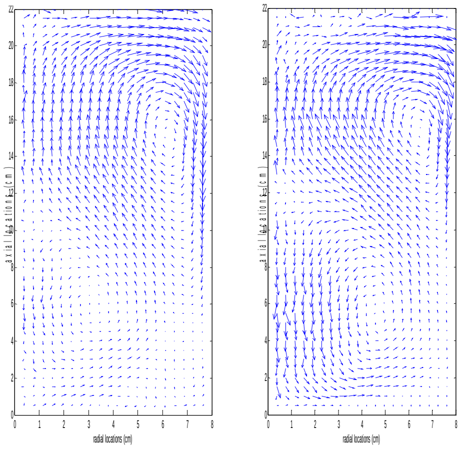

Figure 1 Flow pattern of (a) Co-60 and (b) Sc-46

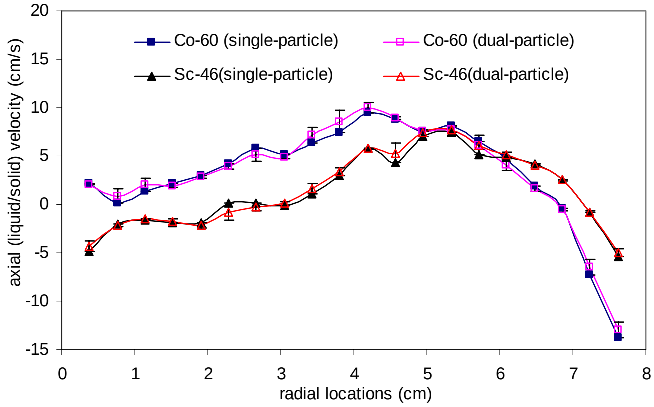

Figure 2 Comparison of axial velocity profiles obtained from single-particle and dual-particle tracking for Co-60 and Sc-46 with different densities.

Two radioactive particles of different densities, one mimicking liquid phase and other solid phase, were tracked in SBCR. The particles representing different phases could also be tracked simultaneously using MP-CARPT unit. The solids fraction is SBCR was kept low to 1% to obtain true hydrodynamic information of liquid phase. When tracking two different phases, ex. solid and liquid, care should be taken to design the experiment in such a way that the tracer follows the represented phase as closely as possible. Collisions of tracer representing liquid phase with the solid particles in the system can be minimized by using very low solids fraction. MP-CARPT can be used conveniently to track two or more solid phases in a system with different properties (for example size, shape or density). However, how much difference in size or density of tracers is required so that the tracers can provide true hydrodynamics of phase being tracked needs to be evaluated. This issue can be addressed by tracking tracers of same size and different densities or same density and different sizes and observing the difference in hydrodynamics. Since the technique is validated and the protocols for operation of MP-CARPT unit are understood, a manual for MP-CARPT is prepared (Vesvikar, 2006). This manual will help future novice users to understand and operate the MP-CARPT electronics and also and provide guidelines to process the raw data obtained from tracking experiments using the new electronics.

D. Future Work and Milestones

The error in the reconstruction of the MP-CARPT can be further reduced by some modifications of the experimental set-up, procedures, and the reconstruction algorithms. If the number of detectors for tracking are increased, such that the detector are packed closely together, then the error in the reconstruction will be reduced due to increased spatial resolution (CARPT manual, 2005). The current MP-CARPT reconstruction algorithm is based on the principle of addition of the calibration counts of Co-60 and Sc-46 obtained separately to represent the counts obtained together. Instead if the calibration is performed with the Co-60 and Sc-46 particles present together, keeping one particle fixed at one location and placing other particle at all the calibration locations one by one and thus covering all the possible permutations, then more accurate calibration region can be obtained. This calibration technique will take into consideration the effect of presence of two particles together on their total counts. The reconstruction method developed by Bhusarapu (2005) can be also be used for the increased accuracy.

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