AREA I

MULTIPHASE REACTORS AND PROCESSES:

EXPERIMENTAL AND MODELING

BUBBLE AND SLURRY BUBBLE COLUMNS

I.1 Investigation of Bubble Properties with Four-Point Optical Probes in Bubble Columns

A. Problem Definition

The knowledge of bubble properties, including bubble velocity and chord length distribution, gas holdup and specific interfacial area, are of considerable importance for the proper design and operation of bubble columns. The microprobes (optical and conductivity probes) are the most frequently employed techniques for investigation of bubble dynamics in recent years (Korekazu *et al.*, 1980; Grunn and Al-Doori, 1985; Lee, De Lasa and Bergougnou, 1986; Choi and Lee, 1990; Chabot *et al.*, 1992; Wu and Ishii, 1999; Magaud *et al.*, 2001). Multi-point probes offer the possibility of measuring bubble size, shape and velocity simultaneously. At present, the optical probes have mainly been used to determine bubble chord length and velocity for individual bubbles in bubbly flows of modest gas holdup. There is no firm experimental data or algorithm that can guide us as to how to use these probes and interpret their signals in churn-turbulent flow with significant bubble coalescence and re-dispersion and with wide distribution of bubble sizes. It is the scope of this work to examine what information can be obtained in churn-turbulent gas-liquid flows. The objective of this research is to obtain some measures of bubble velocity and chord length distribution as well as local gas holdup and specific interfacial area.

B. Research Objectives

The overall objective of this work is to investigate the bubble velocity and chord length distribution, local gas holdup and specific interfacial area in bubble columns both in bubbly flow and in churn-turbulent flow as a function of operating conditions. A four-point optical probe, originally developed by Frijlink and his colleagues (1987) at the University of Delft in the Netherlands, was adapted to achieve this purpose. A modification of the data processing algorithm was developed to improve the capability of the probe (Xue et al., 2003). The measurements of the probe need to be validated versus video imaging at different conditions before applying it to practical bubble columns. By doing this research, we hope to set up a practical tool (four-point optical probe) for investigating bubble dynamics in bubble columns. This tool should provide us with more accurate bubble velocity and bubble chord length distribution, local gas holdup and specific interfacial area data, which are scarce in the literature up to now, especially in churn-turbulent flow. By analyzing bubble properties obtained by the probe and combining with the liquid velocity profile obtained by CARPT, a better understanding of hydrodynamics in bubble columns can be reached.

C. Research Accomplishments

The probe was validated and then applied in a 6.4” bubble column at superficial gas velocity of 2~60 cm/s, at atmospheric and high pressures up to 1.0 MPa and for three different spargers. It was found that the probe worked well in the highly churn-turbulent flow. Some examples of the bubble properties obtained by the four-point probe are shown in Figure 1.

Some findings in this study are:

1. The four-point optical probe and the new data processing algorithm is a practical tool for investigating bubble properties in bubble columns. By validation against video imaging, it was proved that the bubble velocity distribution, bubble chord length distribution, local gas holdup, and specific interfacial area obtained by the new four-point optical probe algorithm are reliable. Difficulties exist in the measurements of bubbles of very low velocity approximating to zero.

2. In bubbly flow, the radial profiles of specific interfacial area, bubble frequency, and mean bubble velocity are all flat. With an increase in superficial gas velocity, Ug, these profiles became more parabolic. In the column center, the bubble chord length distribution spreads wider with an increase in Ug. The mean bubble chord length increases with Ug until it is in deep churn-turbulent flow and then remains almost identical with Ug. In the wall region, the bubble chord length distribution does not change much with Ug. The mean bubble chord length in the wall region is much smaller than that in the column center, and it increases mildly with Ug between the bubbly flow and the transition flow regime, then decrease slightly with Ug.

3. At very low gas velocity, e.g. 2 cm/s, all bubbles move upwards in bubble column. In churn-turbulent flow (Ug>8cm/s), some bubbles move downwards even in the column center. In the wall region, the number of bubbles moving downwards is equal to or even larger than that of bubbles moving upwards. The percentage of bubbles moving downwards increases slowly with Ug in both the wall region and in the core of the column. In the wall region, the bubbles moving downwards are dragged down by the liquid, while in the core of the column the flow direction is generally upwards most of the time, and the bubbles moving downwards most likely come from the wakes of large bubbles and large 3D flow structures.

4. In bubbly flow, the bubble velocity distribution and bubble chord length distribution are alike at different radial positions, including the wall region. In churn-turbulent flow, in the core of the column the bubble velocity and chord length distributions are alike at different radial position, but in the wall region they are very different from the core of the column.

5. With an increase in pressure, the global liquid recirculation is enhanced, and the radial profiles of specific interfacial area, bubble frequency, and mean bubble velocity become more parabolic. The gas holdup increases with the axial position, possibly due to the accumulation of bubbles at the upper zone of the column at high pressure. The pressure effect is strong at 1.0 MPa, but it becomes weaker at pressures higher than 0.4 MPa.

6. In this study, the sparger effect disappears with an increase in the axial position in bubble column at z/D>5.1. However, at atmospheric pressure, the range of the sparger zone for the specific interfacial area is beyond z/D=5. Hence, the definition of the sparger zone based on gas holdup profiles may not apply to other bubble properties

under some conditions. In other words, the range of the sparger zone for different bubble properties may be different.

7. The Sauter mean bubble diameter cannot be calculated without assumptions that are not met and it is subject to large errors. Qualitatively it can be used for comparison of "mean" bubble size at different conditions.

8. The bubble size distributions observed are single modal. Hence, the suggested bimodal bubble size distribution postulated for churn-turbulent flow was not detected.

9. In this study, the mean gas-liquid slip velocity is almost identical for different spargers and at different superficial gas velocities in churn-turbulent flow, it decreases with pressure, due to a decrease in the bubble size.

D. Future Work

It is suggested that: (1) using data obtained by the probe for validation and refinement of CFD codes; (2) applying the four-point optical probe to wider range of operating conditions, such as the superficial gas velocity, pressure, column diameter and spargers, to expand the data base and get better understanding of the hydrodynamics in bubble columns; (3) validating and applying the four-point probe in organic systems of industry interest, and at high temperature and pressure higher than 1.0 MPa, e.g. in supercritical conditions; (4) applying the probe in slurry bubble columns to test the durability of the probe against the collision of the particles, in the cases that the glass probe can not stand long enough, e.g. systems with solid particles and high gas velocity, a plastic probe should be used; (5) commercializing the four-point probe technique to provide a tool which is simple and easy to use for the on site measurements of bubble properties, e.g. monitor the quality of the flow in multiphase reactors.

For additional information, please contact Professor M. P. Dudukovic at CREL.

E. Nomenclature

Ug: the superficial gas velocity, cm/s

F. References

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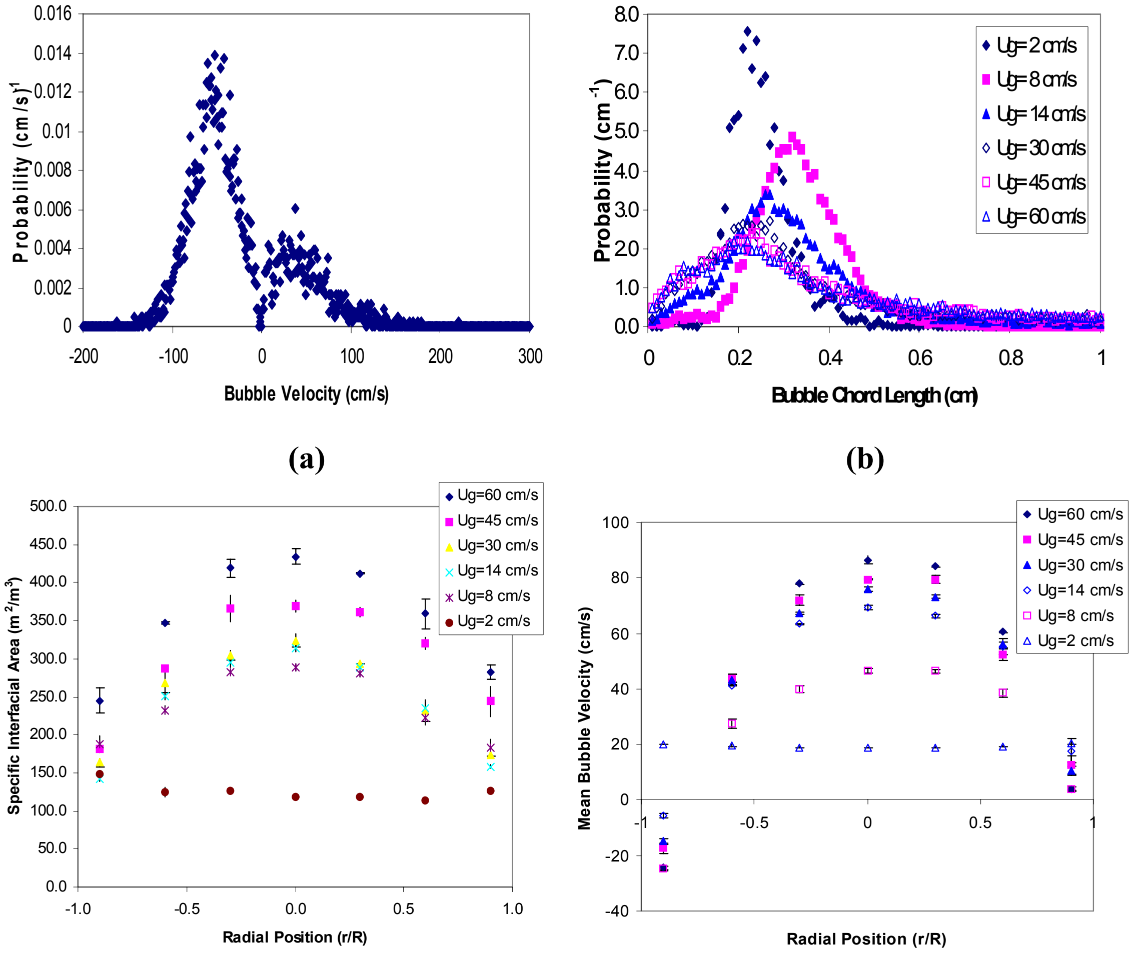

(a) **(b)** **(c)** **(d)**

Figure 1: Examples of the Bubble Properties Obtained by the Four-Point Optical Probe: (a) Bubble Velocity Distribution, (b) Bubble Chord Length Distribution, (c) Specific Interfacial Area and (d) Mean Bubble Velocity

I-2. Modeling of Liquid Phase Methanol Synthesis in Slurry Bubble Column Reactors

A. Motivation

Slurry bubble column reactors are presently used in a wide range of processes in chemical, petrochemical, biochemical, and other industries. Amongst these processes, the emerging application of slurry bubble column reactors are for liquid phase methanol synthesis and Fischer-Tropsch synthesis. The main advantages of bubble column reactors for these processes are an efficient removal of high exothermic heat, smaller catalyst particle size that results in higher effectiveness factor, lower catalyst deactivation rate, and capability of operating at high pressure.

In reactor modeling of slurry bubble columns, the gas phase has been generally modeled using either plug flow (PF) or axial dispersion model (ADM) while liquid/slurry phase has been modeled using either completely stirred tank (CST) or ADM. Additionally, compartmental models (Degaleesan, 1997; Gupta et al., 2003; Rados et al., 2003) have also been developed for slurry bubble columns. Although axial dispersion model can mathematically describe the systems that approach perfect mixing; it is an extrapolation of its original intention of describing minor deviation from plug flow. The hydrodynamic studies in bubble column suggest that the liquid phase mixing behavior is neither plug flow nor perfectly mixed. Also, the use of axial dispersion coefficient as a single parameter describing the complex bubble column flow behavior is questionable. Any non-ideal flow behavior lies within the two ideal flow behaviors i.e. plug flow and perfectly mixed flow. The basic concept that infinite mixed flow reactors in series give the same performance as plug flow while varying intermediate values of number of tanks give non-ideal reactor performance, is well known for many years in chemical engineering.

B. Research Objectives

The objective of this work is to develop a mixed cell model for slurry bubble column reactors and utilize the developed model to study the performance of liquid phase methanol synthesis. The mixed-cell model is developed to incorporate multi-component multi-reaction network. The mixed cell model provides a simple and flexible way to gain insight into the trends of the effect of various operating and design parameters on the process performance.

C. Research Accomplishments

Methanol synthesis consists of the following three reactions,

$$CO + 2H_2 \Leftrightarrow CH_3OH \qquad \Delta H^0_{298} = -94{,}084 J/mol$$

$$CO \ + H_2O \Leftrightarrow CO_2 + H_2 \qquad \Delta H^0_{298} = +41{,}270 J/mol$$

$$CO_2 + 3H_2 \Leftrightarrow CH_3OH + H_2O \qquad \Delta H^0_{298} = -52{,}814 J/mol$$

The main process features of liquid phase methanol synthesis are, control and removal of exothermic heat of reaction and overcoming equilibrium constraint to maximize per pass conversion.

The mixed cell model was developed based on the following assumptions, 1) the reactor has been visualized as consisting of *N* number of tanks in series, in each of which the liquid is completely mixed and the gas is in plug flow. The plug flow performance for whole reactor corresponds to $N = \infty$ or large while completely backmixed reactor corresponds to N=1. The intermediate values of *N* will correspond to liquid phase flow pattern between plug flow and perfectly mixed flow, 2) Due to change in moles, the gas flow rate varies over the length of the reactor. Therefore, total gas phase balance has been considered in the current analysis, 3) Constant slurry velocity was assumed. The model can be used for co- and counter-current liquid flow. In the current case, only co-current upward flow has been used, 4) The liquid and solids phase form a pseudo-homogeneous phase whose properties can be predicted from the pure liquid and solids phases, 5) The axial solids distribution has been calculated using Sedimentation Dispersion Model (SDM). In this case, the slurry concentration in a cell is assumed to be constant while it varies from cell to cell, 6) The liquid-solid mass transfer and intraparticle resistances are neglected. In addition, the temperature difference between the catalyst and the liquid is assumed to be negligible, and 7) Only heat transfer from the slurry phase to wall has been considered.

The application of mass and energy balance yields following system of dimensionless equations for cell *j*, which is a combination of n+1 Ordinary Differential Equations (ODEs) and n+1 Non-linear Algebraic equations (NLAs).

Gas phase balance

Component balance:

$$\frac{dy_i}{dz^*} = -\frac{(\alpha_{i,j}/N)}{N^*_{T_j}}\left(\frac{y_i(z^*)}{T^*_j} - C^*_{L,i,j}\right) + \frac{y_i}{N^*_{T_j}}\sum_{i=1}^{n}(\alpha_{i,j}/N)\left(\frac{y_i(z^*)}{T^*_j} - C^*_{L,i,j}\right) \qquad \text{(a)}$$

total gas phase balance:

$$\frac{dN^*_{T_j}}{dz^*} = -\sum_{i=1}^{n}(\alpha_{i,j}/N)\left(\frac{y_i(z^*)}{T^*_j} - C^*_{L,i,j}\right) \qquad \text{(b)}$$

Liquid/Slurry phase balance

$$(N^*_{T,i}y_i)_{j\pm1} - (N^*_{T,i}y_i)_j = \beta_i[C^*_{L,i,j} - C^*_{L,i,j\pm1}] + (\gamma_{i,j}/N)\sum_{1}^{k=nr}\nu_{ik}R^*_{i,k} \qquad \text{(c)}$$

Energy balance

$$(\delta_j/N)\sum f^*_k - \varphi_j(T^*_j - T^*_w) = T^*_j - T^*_{j\pm1} \qquad \text{(d)}$$

where, $\alpha_{i,j} = (k_L a)_i L / u_{G,0} m_i$, $\beta_i = u_{SL} / u_{G,0} m_i$, $\gamma_{i,j} = w_j \varepsilon_{SL} \rho_{SL} (L/N) R^{ref} / C_G^{ref} u_{G,0}$, $\delta_j = w_j \varepsilon_{SL} \rho_{SL} (L/N)(-\Delta H_R)^{ref} R^{ref} / u_{SL} (\rho Cp)_{SL} T_w$, $f_k = \upsilon_{i,k} R_k (-\Delta H_R)_k / R^{ref} (-\Delta H_R)^{ref}$ $\varphi_j = h(a_{cooler}/N)(L/N)/u_{SL}(\rho Cp)_{SL} T_w$, $N^*_{T_j} = N_{T_j} / N_{Tin}$, $T^*_j = T_j / T_w$, $C^*_{L_i} = m_i C_{L,i} / C_G^{ref}$, $z^* = z/L$, $R^*_{i,k} = R^*_{i,k} / R^{ref}$, N = number of mixed cells.

For any cell j, the concentration of entering streams $C^*_{L,i,j-1}$ and $y_{i,j-1}$, the temperature of entering stream T^*_{j-1} and $N^*_{T,j-1}$ are known. The unknown quantities are $C^*_{L,i,j}$, $y_{i,j}$, $T^*_{i,j}$, and $N^*_{T,j}$ that can be calculated by solving equations a, b, c, and d. The set of ODEs and NLAs were solved by using Runge-Kutta method (RK4) and modified Newton-Raphson method (HYBRD), respectively. The subroutine RK4 is integrated with HYBRD to simultaneously predict species mole fraction, concentration, temperature, and total molar flow rate at the exit of each cell.

The model developed in this study can accommodate multicomponent multireaction network. The backmixing in slurry phase can be adjusted by varying number of mixed cells, N. In this case, one need not to rely on the correlations developed based on data of either limited range or industrially irrelevant conditions (in some cases, correlations are nonexistent) for prediction of axial dispersion coefficient (in case of ADM model) and/or other turbulent parameters (in case of compartmental models). In such cases, mixed cell model provides more robust tool to study the performance of slurry bubble column reactors. Also, the solution is faster in mixed cell model compared to other above mentioned models.

Following L-H type of kinetic model developed by Vijayaraghavan and Lee (1993) for liquid phase methanol synthesis has been used in this study,

$$r_{MeOH} = \frac{k_0 \exp(-E/RT)(p_{H_2}^2 p_{CO} - p_{MeOH}/K_L)}{(K_0 + K_{H_2} p_{H_2}^{0.82} + K_{CO} p_{CO}^{0.82} + K_{MeOH} p_{MeOH}^2)^n}$$

Figure 2 shows dimensionless liquid concentration, gas phase mole fraction, dimensionless molar flow rate, and dimensionless exit temperature as a function of number of cells considering the total gas phase balance as well as the energy balance at Ug = 20 cm/s, and u_{SL} = 2 cm/s. An increase in number of cells reduces mole fraction of reactants (H_2, CO) and increases mole fraction of product (CH_3OH). The increase in methanol formation is significant up to number of mixed cells, N = 4, after that an addition of cells results in an insignificant change as it shows asymptotic behavior approaching the plug flow. The change in exit molar flow rate as well as temperature is also insignificant after N = 4. The reduction of molar flow rate was found to be higher in non-isothermal case compared to isothermal case. Also, high CO conversion was observed when total gas phase balance has been considered compared to using constant superficial gas velocity.

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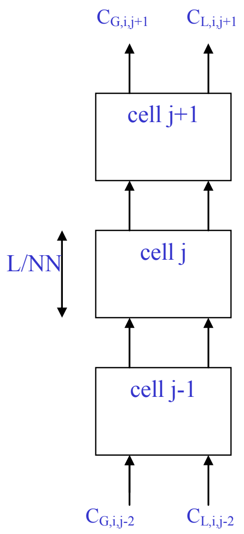

Figure 1: Schematic representation of mixed cell model

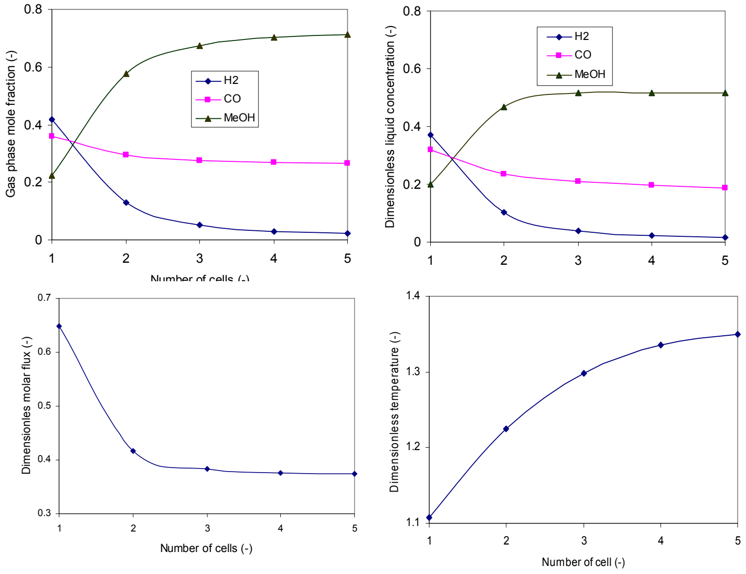

Figure 2: Gas phase mole fraction, dimensionless liquid concentration, dimensionless molar flow rate, and dimensionless temperature as a function of number of mixed cells at non-isothermal conditions and with total gas phase balance: U_G = 20 cm/s, u_{SL} = 2 cm/s, D = 2.3 m, L = 23 m, T = 521 K.

D. References

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2. Gupta, P (2001), *D.Sc. Thesis*, Washington University, St. Louis, MO.
3. Rados, N., Al-Dahhan, M. H., Dudukovic, M. P. (2003), *Catalysis Today*, 79-80, 211.
4. Vijayaraghavan, P.and Lee, S. (1993). *Fuel Sci. Technol. Int.*, 11, 1459 – 1481.

Notations

$C^*_{G,i}$	dimensionless gas phase concentration of species, i ($= C_{G,i} / C_G^{ref}$)
$C^*_{L,i}$	dimensionless liquid phase concentration of species, i ($= m_i C_{L,i} / C_G^{ref}$)
m_i	dimensionless Henry constant, ($= He_i / RT_j$)
z^*	dimensionless length, ($= z/L$)
n	number of species
N	number of mixed cells
N_T	molar flow rate, mol m^{-2} s^{-1}
T_j	temperature of cell, j
L	length of reactor, m
a_{cooler}	specific heat exchanger area, m^{-1}
$U_{G,0}$	inlet superficial gas velocity, m s^{-1}

I.3 Mass Transfer and Hydrodynamics in Catalytic Slurry Reactors

A. Problem Definition

Slurry reactors like stirred tanks and bubble columns are increasingly used in industrial practice (as absorbers, fermenters, strippers, coal liquifiers, and chemical reactors). These low-cost reactors are easily made and therefore rather popular. In gas-liquid-solid (GLS) slurry processes, segregation of catalyst particles from the liquid phase can take the form of *Catalyst Particle Agglomeration*, whereas the attachment of catalyst particles to gas bubbles can take the form of *Particle-to-Bubble Adhesion* (PBA). PBA is determined by a plethora of parameters, e.g., gas properties (composition, density), liquid properties (surface tension, viscosity, density, surface-active components, and aqueous or organic liquid), and catalyst particle properties (diameter, lyophobicity, surface roughness, partition coefficient, i.e., adsorption capacity between liquid and solid), process parameters (reactant pressure, mixing intensity, catalyst concentration). The significant influence of catalyst particle properties on adhesion and agglomeration is of utmost importance for a proper design of catalytic slurry reactors, in terms of reactant conversion and product selectivity, where the reactor size is largely determined by mass transfer and the selectivity of the reaction is strongly dependent on mixing time and residence time. However, the influence of agglomeration and adhesion has been difficult to predict until now.

B. Research Objectives

The aim of the PhD project was to understand the influence of catalyst particle properties and the influence of liquid properties on the mass transfer, the hydrodynamics, and the reaction rate in catalytic slurry reactors. The goal was to understand and exploit the mechanism for the increase in the rate of GL mass transfer. A phenomenological mass transfer model must be developed which incorporates the properties of gas, liquid, and solid phases together with the reaction kinetics. To meet these objectives, the research has been carried out in three types of slurry reactors: a surface aeration stirred slurry reactor (SAR) with a known flat gas-liquid interface, a gas-inducing stirred slurry reactor (GIR), and a slurry bubble column (SBC).

C. Research Accomplishments

A mass transfer model is constructed that describes the influence of catalyst particles on mass transfer, hydrodynamics, and reaction rate in the slurry reactors. The model is a combination of a particle-interface-adhesion-dehesion (PIAD) model[3,6] and the GLS-GS-model[6]. The PIAD model is a dynamic description of the equilibrium between the particle adhesion rate and the particle dehesion rate at the GL interface. The adhesion and dehesion rates (ratio giving the PIAD equilibrium constant) determine the average residence time of the particles at the GL interface. The GLS-GS-model is a combination of the classical resistances-in-series gas-to-liquid-to-solid (GLS) mass transfer model and direct gas-to-solid (GS) mass transfer model. It is shown that the average residence time at the GL interface, the solid-liquid partition coefficient, the particle diameter, and the reaction rate determine the mass transfer rate by shuttling of the particle between the GL interface and the bulk liquid.

Four possible mechanisms for the enhancement of GL mass transfer are proposed and studied[7,8]: (1) boundary layer mixing, (2) shuttling, (3) coalescence inhibition, and (4) boundary layer reaction. The model parameters are determined from mass transfer and reactivity experiments, with aqueous oxidation (glucose) and organic hydrogenation (α-methyl styrene) reactions. The experiments are performed at various mixing intensities, oxygen partial pressure, and catalyst concentrations. The PBA equilibrium constant and the gas-to-solid mass transfer coefficient during reaction are estimated as a function of mixing intensity. The mass transfer model is able to predict physical and reactive mass transfer rates as a function of particle diameter, liquid-solid partition coefficient, stirring speed, and catalyst concentration. Experimental and theoretical enhancement factors for non-reactive and reactive mass transfer agree well.

In (slurry) bubble columns (SBC), a unique and unambiguous flow regime transition identification method is developed based on the coherent standard deviation and the average frequency of pressure fluctuations[4]. The method is verified in a 2D SBC and the physical interpretations are based on the large bubble characteristics, quantified by a high speed video camera. The coherent standard deviation clearly marks the first and the second transition points. The average frequency can be used to confirm the second transition point. The methods are also successfully applied to pressure time series in a 3D SBC.

In the aqueous 2D SBC, the influence of carbon and silica particles, electrolyte, and the combination of electrolyte and particles on regime transition, gas hold-up, and volumetric mass transfer coefficient have been studied. It is shown that the volumetric mass transfer coefficient increases with gas velocity, increases with electrolyte concentration, and decreases with slurry concentration. The liquid side mass transfer coefficient increases with gas velocity, bubble diameter, and is higher for lyophobic particles. A new mass transfer correlation is proposed for the heterogeneous regime[2].

In the GIR and in the 2D SBC with organic liquids, it is found that the influence of particle lyophobicity on the gas hold-up, the mass transfer, and the reaction rate is negligible[5]. The GLS-model is sufficient to describe the mass transfer and the reaction rate with varying catalyst concentration and mixing intensity in both the GIR and the SBC. The phenomenon of PBA is significant but similar for both catalysts in organic liquids.

In summary, the results presented in the thesis[1] provide a foundation for understanding the relationships between the catalyst particles properties and the liquid properties on the hydrodynamics and the mass transfer behavior of slurry reactors. By modifying the surface properties of catalyst particles, the particles can be made to adhere more to gas bubbles. This way, the catalyst is exposed to higher dissolved gas concentrations, which increases the reaction rate. Thus, the catalyst efficiency increases and lower amounts of expensive catalyst are required. In some cases, it is undesirable to expose the catalyst to high dissolved gas concentrations; the catalyst may deactivate. Contrarily, in this situation, those catalyst particles should be used that do not adhere to the gas bubbles. The acquired knowledge leads to improved designs and consequential cost-reductions for these reactors. This improves the competitiveness of the chemical industry.

D. Future Work

Apart from the accomplished research work, author in his Thesis[1] has claimed various vibrant research topics, in order to better understand and model the catalytic slurry reactor systems.

E. Publications

1. *K.C. Ruthiya*, Mass transfer and hydrodynamics in catalytic slurry reactors, PhD Thesis, Eindhoven University of Technology, The Netherlands, ISBN: 90-386-2936-2, pp 229, (2005)
2. *K.C. Ruthiya*, J. van der Schaaf, B.F.M. Kuster, J.C. Schouten, “Influence of particles and electrolyte on gas hold-up and mass transfer in a slurry bubble column”, *Int. Journal Chem. Reactor Eng.,* submitted, (2005)
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I-4. Implementation of Bubble Population Balance Model in CFD

A. Problem Definition

Design and scale-up of bubble column reactors rely on understanding of the hydrodynamics of gas-liquid flow. The need to establish a rational basis for the interpretation of the interaction of fluid dynamic variables is the primary motivation for bubble column modeling based on computational fluid dynamics (CFD). Currently Eulerian and other CFD models do not predict gas holdup well even in 3D simulation, the “mean” bubble size parameter needs to be tweaked to fit the experimental data. Moreover, interfacial area density profiles have not been predicted.

B. Research Objectives

1. By introducing breakup and coalescence (B&C) models into a population balance equation for the bubbles, and by incorporating this into CFD, we hope to avoid having to specify bubble size as such a model will internally predict the bubble sizes on which drag calculations should be based. This model will predict the interfacial area density as well.
2. Compare the computed results with CARPT/CT/Optical Probe data.

C. Research Accomplishment

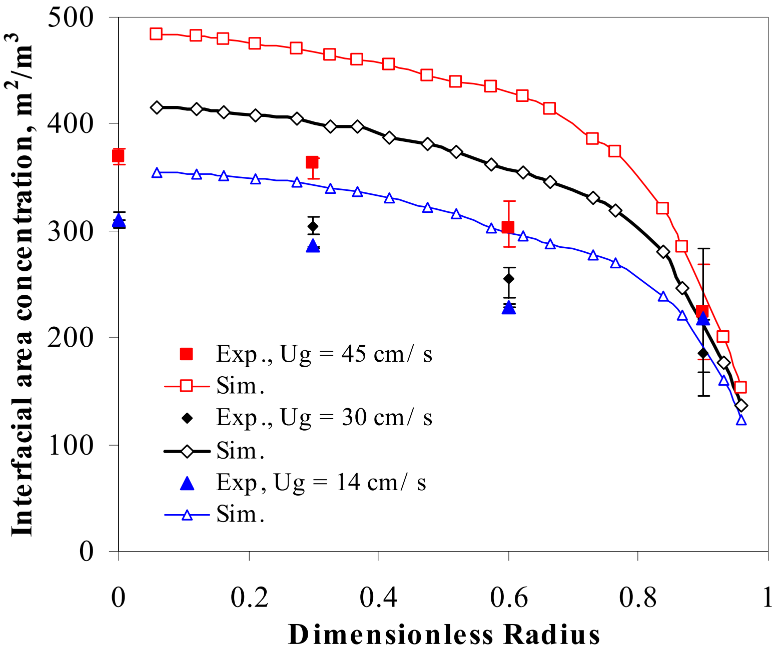
C1. Model Equations and Closures

In the present work, the flow in bubble columns was modeled using the Eulerian two fluid model. The Bubble Population Balance Equation (BPBE) is solved simultaneously with the Euler-Euler model equation to calculate the needed local and time-dependent mean bubble diameter.

The breakup kernel as given by Luo and Svendsen (1996) is used. The coalescence model is divided into two parts, the collision frequency and the coalescence efficiency. The collision rate is given by Saffman and Turner (1956) and the coalescence efficiency is given by Luo (1993). We do not use the wake-induced collision because the coalescence efficiency models are all based on the turbulence-induced collision. Full three-dimensional simulation was performed.

C2. Results and Discussion

Figure 1 shows the comparison between the simulated gas-liquid interfacial area concentration profile and those obtained by four point optical probe in a 16.2-cm diameter column at U_g = 14.0, 30.0 and 45.0 cm/s superficial gas velocity and 1 bar. The prediction is reasonably well (within 20-30%) but systematically over-estimated the interfacial area concentration. This, together with the fact that the simulation correctly predicted the gas holdup and liquid velocity profile (Chen et al., 2005), indicates the drag law used in the current work may need to be improved.



D. Future Work

1. The fluctuating velocity components are not well captured in this work. In order to capture better the small scale structure in bubble column flows, Large Eddy Simulation (LES) is desirable.
2. New drag laws need to be proposed.

For detailed information, contact Peng Chen at Corning Incorporated at chenpe@corning.com.

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I-5. High Pressure Slurry Bubble Column Reactor (HPSBCR) Consortium

(January 1, 2003 – December 31, 2005)

The High Pressure Slurry Bubble Column Consortium has been extended to additional 3 years. The consortium is sponsored by Conoco Phillips (USA), Eni Technology (Italy), Sasol (South Africa) and Statoil (Norway). The overall objective of this study is to further advance the fundamental understanding of the effect of various design and operating variables on the mixing and transport in high pressure slurry bubble column reactor (SBCR) operated at the conditions that mimic FT synthesis. The results should advance the design, scale-up and operation of SBCR and improve prediction of CFD simulations. The following outline of the tasks will be performed in a collaboration effort between Washington University (WU), Ohio State University (OSU) and Rennselear Polytechnic Institute (RPI).

NOTE: The studied conditions for the tasks listed below will be finalized with the consortium members.

Washington University (WU)

The current 6-inch high pressure slurry bubble column units (one for CARPT/CT and one for probes which is equipped with ports and windows) that can be operated at pressure up to 10 bar, high gas velocity of air and room temperature will be used for the following tasks:

TASK 1: Experimental investigation of the effects of pressure, gas velocity, solids loading and FT catalyst type and size on the mixing, flow pattern, turbulent parameters and holdup distribution in slurry bubble column reactor (SBCR) using the conditions that mimic FT reaction via CARPT and CT techniques

Investigate at a range of pressure and gas velocity the effects high solids loading and catalyst type and sizes that cover the desired range of FT catalyst on the three phases distribution via computed tomography (CT) and 3D flow field pattern of solids, velocity distribution, turbulent parameters, kinetic energy, eddy diffusivity, etc. via computer automated radioactive particle tracking (CARPT). The final studied conditions will be selected within the consortium members.

Systems to be used:

Solids:	selected FT catalyst(s) - **Conoco**
Gas:	air at pressures that provide the same density of the syngas at FT conditions, if possible
Liquid:	selected liquid(s) that cover the range of physical properties at room temperature of FT waxes at FT conditions; e.g. Therminol fluid (Solutia, (i.e., previously called Monsanto fluid)) and a mixture of parafins which will be identified by **Sasol**.
Gas Sparger:	Perforated plate, 1.0% open area

TASK 2: Overall gas holdup and flow regime transition

- Conduct experimental investigation on identifying the region for flow regime transition in slurry bubble column reactor (SBCR) at selected conditions via overall gas holdup measurement, pressure fluctuation measurements from the differential pressure transducers, Kolmogorov entropy analysis, CT measurements for gas holdup profile (if possible).
- Identify the transition regime by these techniques and compare the findings.
- Evaluate different criteria obtained by these techniques to predict flow regime transition and establish a methodology, correlation, model or criterion for predicting flow regime transition in SBCR.

TASK 3: Heat and mass transfer coefficients study

Develop heat and mass transfer coefficients measurement techniques. Investigate at selected conditions the effects of flow field pattern on the heat and mass transfer coefficients in the high pressure 6" slurry bubble column. The available correlations to predict the coefficient will be evaluated and a new one will be developed if necessary.

TASK 4: Computational fluid dynamics (CFD)

Examine at the selected conditions that will be studied in this program the recommended closures and related findings in bubble column which will be obtained from the current CFD effort in CREL as a part of other projects on the predictions of slurry bubble column hydrodynamics using the available CFD codes at CREL

NOTE: High temperature and high pressure SBCR could be developed with column diameter equal or larger than 1 ft that can be used with CT/CARPT techniques if the needed funds will be available.

Ohio State University (OSU)

TASK 1: Overall gas holdup, flow regime transition and bubble size distribution and rise velocity study

This task complements task 2 at WU. The effects of pressure, solids loading, gas velocity on the overall gas holdup, flow regime transition and bubble size distribution and rise velocity will be investigated. The effects of a pressure range higher than 10 bar, high range of solids loading and catalyst type would be considered. The studied parameters will be measured as follows:

1. Flow regime transition. The pressure fluctuation sign from the differential pressure transducer and overall gas holdup will be used to determine the regime transition.
2. Bubble size distribution and rise velocity: These parameters will be measured by two points optical probe.

3. Mean gas holdup: The mean gas holdup is determined by measuring the change in dynamic height of the slurry.

TASK 2: Mass coefficient study

Investigate at selected conditions of high pressure and high temperature and locations inside the 4-inch SBCR the mass transfer coefficients. The measured values will be evaluated against the available correlations. If necessary, a new correlation will be suggested.

TASK 3: Entrainment study

Liquid and solid entrainment will be studied in a slurry bubble column at a range of pressure and temperature that mimic FT conditions.

Rensselaer Polytechnic Institute (RPI)

The following tasks will be performed at RPI.

TASK 1: Evaluating of NPHASE code and its closures to simulate SBCR

This includes evaluating the NPHASE and its closure capabilities to simulate slurry bubble column reactors. The newly obtained data by CARPT and CT will be used as a benchmark for simulations comparison and validations.

Based on the findings the following may be needed:

- improve the predictions of gas holdup profiles,
- examine how to properly treat the presence of the solids,
- examine how to account for the pressure effects,
- develop procedure of how to account for the presence of the internals.

TASK 2: Develop or suggest improved mechanistic models for closures to simulate churn turbulent flow regime in SBCR.

NOTE: **NPHASE code with its mechanistic models for closures will be available to be used by the consortium members at their premises.**

The results of this study will only be available to CREL general sponsors after they are released by the mini-consortium sponsors.

I-6. Solids Flow Visualization in Slurry Bubble Columns using Computer Automated Radioactive Particle Tracking (CARPT) and Computed Tomography (CT)

A. Motivation

Slurry Bubble column Reactors are gaining wide importance in chemical, petrochemical, and biochemical industries. Though Slurry Bubble Columns 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 velocity, turbulent parameters profiles, and phase holdup profiles.

Most of the studies reported in literature have been performed at atmospheric pressure and /or low superficial gas velocity. There is little information available on the solids velocity and turbulent parameter profiles and phase holdup profiles at industrially relevant conditions. Also, in such systems, probe measurement techniques such as hot wire anemometry and 'see through' measurements techniques such as Particle Image Velocimetry (PIV) and Laser Doppler Velocimetry (LDV) can not be applied due to the presence of solids and high opacity of the flow. CARPT and CT are recognized as one of a few techniques that can be reliably and accurately used in highly turbulent and opaque flow systems. The only available data in such system exists in air-water-glass beads system using CARPT and CT (Rados, 2003).

B. Research Objectives

The current study investigates the effect of superficial gas velocity, operating pressure, and solids loading on the solids axial velocity and turbulent parameters profiles and phase holdup profiles using a liquid, which at room temperature, mimics Fischer-Tropsch (FT) wax at FT reaction conditions.

C. Research Accomplishments

The experiments have been 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. The physical properties of Therminol LT at ambient conditions are close to FT wax at FT reaction conditions. 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 used. The superficial gas velocities were varied from 8 to 30 cm/s and operating pressure from 0.1 to 1 MPa.

The details of CARPT and CT setups and experiments have been 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 of 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 phase holdup profiles have been measured using existing single source CT. In this work, CT/Overall gas holdup methodology (Rados, 2003) was utilized to reconstruct the phase holdup profiles of three dynamic phases using single source CT.

The combination of CARPT and CT experiments is useful to get insight into the effect of superficial gas velocity, operating pressure, and solids loading on the following parameters:

- Solids instantaneous and time-averaged velocity field
- Solids instantaneous and time averaged turbulent parameters and eddy diffusivities
- Time averaged gas and solids holdup profile

This work represents one of the tasks set for High Pressure Slurry Bubble Column Consortium. The results are reported first to the Consortium members at this time and hence, a brief outline has been presented here.

For additional information, contact Ashfaq Shaikh (Phone: 314-935-4729, E-mail: ashfaq@che.wustl.edu)

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I-7. Hydrodynamics Similarity in Bubble Column Reactors

A. Motivation

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 a difficult and challenging task. Such task needs a reliable criterion for hydrodynamics similarity that can be subsequently applied for scale-up of bubble column reactors. In literature, various methodologies have been proposed for similarity in bubble columns. Degaleesan (1997) proposed one of the early procedures for similarity based on overall gas holdup. Inga (1999) developed a method based on similarity of a dimensionless parameter which is a function of overall mass transfer coefficient and pseudo first-order rate constant. The group of Prof. Krishna developed two different methods to study the behavior of large diameter bubble columns based on Computational Fluid Dynamics (CFD). Safoniuk et al. (1999) proposed a scaling method for three-phase fluidized beds with the aid of Buckingham pi theorem. They successfully demonstrated their method by maintaining five proposed dimensionless groups the same in two reactors which resulted in similar overall gas holdup. Macchi et al. (2001) extended Safoniuk et al. (1999) scaling methods to three-phase fluidized beds where in one system they used a pure liquid while in other, it was a mixture of liquids. They found that though overall gas holdup in two systems was within engineering error, pressure fluctuation studies in two systems revealed quite different power spectra. 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 has been proposed based on the reported similarity studies and the state of understanding developed from studies at CREL. The main motive of this study is experimental evaluation of the proposed hypothesis for hydrodynamic similarity utilizing existing Computed Tomography (CT) and Computer Aided Radioactive Particle Tracking (CARPT).

C. Research Accomplishments

Figure 1 shows the gas holdup radial profile in 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 the two systems are different, which may lead to different mixing and flow patterns. The conclusions of Machhi et al. (2001) and the data presented in Figure 1 suggest that two systems may have similar overall gas holdup as a global hydrodynamic parameter but still can have different flow pattern and mixing. 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 validation 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 holdups and gas holdup radial profiles from the available database. To complete the needed set of conditions for evaluation of the proposed hypothesis, additional CARPT experiments were performed. In addition, experimental conditions that have similar overall gas holdup but different radial gas holdup profiles have also been identified.

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 overall gas holdup and gas holdup radial profile have been developed. The development of axial velocity profile and centerline velocity correlations is in progress.

This work represents of the tasks set for high pressure slurry bubble column consortium. The results are presented first to the consortium members and this time and hence, a brief outline has been presented here.

For additional information, contact Ashfaq Shaikh (Phone: 314-935-4729, E-mail: ashfaq@che.wustl.edu

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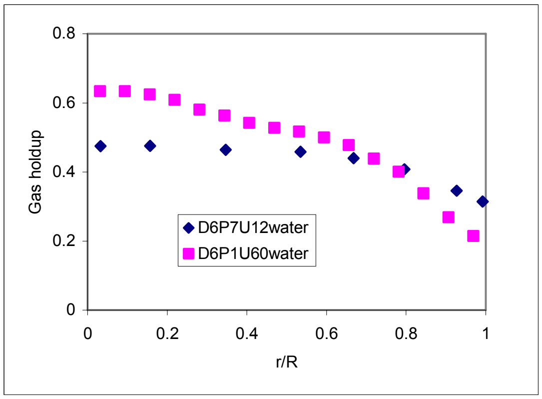

Figure 1: Comparison of gas holdup radial profile in 6” column using air-water system at two different operating conditions (◊ 7 bar and 12 cm/s, □ 1 bar, 60 cm/s) with similar overall gas holdup ($\varepsilon_G = 0.41$).

I-8. Combination of Computed Tomography (CT) and Electrical Capacitance Tomography (ECT) for Flow Visualization Investigation in Slurry Bubble Column Reactors

A. Motivation

Slurry Bubble column Reactors are cylindrical vessels where gas is sparged through a distributor into a suspension of liquid and fine solids catalyst. These reactors offer excellent mixing without moving parts and markedly low power consumption, though back mixing in such reactors is one of its main disadvantages. In order to accomplish desired flow pattern, and thus reactor performance, an improved understanding and quantification of key hydrodynamic phenomena are required. Most literature studies on distribution of phase holdups have focused on gas-liquid systems. Few studies have investigated the effect of operating parameters on the phase holdup profiles in slurry bubble columns (Warsito, 1997, George et al., 2001, Warsito and Fan, 2003).

Although many tomographic techniques have been developed during last decade, few are readily applicable to three-phase systems. In three-phase systems, the requisite sensed signal contains information that is a function of more than one parameter in the object space. Most tomographic techniques are single modal systems that can not be applied for multiple sensing in three phase flows. Approaches adopted by the researchers to tackle this problem can been classified in the following three categories:

I) combining two single-modal systems (dual modality)
II) using an inherently multi-modal system such as Ultrasonic tomography
III) improving reconstruction techniques of single-modal system to accommodate three dynamic phases.

There have been few attempts to combine two single modal systems, eg., Bukur et al. (1996) used dual modal γ-ray densitometry, George et al. (2001) combined γ-ray densitometry and Electrical Impedance Tomography (EIT), Grassler and Wirth (2001) developed a dual energy X-ray tomography. Using the second approach, Warsito et al. (1995) implemented a dual-frequency ultrasonic method, and Warsito et al. (1999) developed an ultrasonic tomographic (UT) technique with two-parameter sensing, i.e., energy attenuation and sound speed to measure simultaneously the three dynamic phase holdups. There remains a discrepancy regarding the key assumption in reconstructing phase holdups using UT. In addition, due to its high signal non-linearity the technique is limited to bubbly flow and very low solids holdup.

In third approach, Nooralahiyan and Hoyle (1997) used Electrical Capacitance Tomography (ECT) for three phase imaging by developing an algorithm based on Neural Network with double sigmoid function. Warsito and Fan (2001) have developed a neural network based reconstruction algorithm that incorporates some assumptions to reconstruct the dynamic three phase distribution in an atmospheric slurry bubble column using ECT. Rados et al. (2005) reconstructed three dynamic phases using single source γ-ray Computed Tomography incorporating physically sound assumptions.

Third approach is an attractive option for phase holdup measurement in three-phase systems as it is easy to construct and implement. However, the obtained results need to be evaluated and the validity of the improved reconstruction technique and the assumptions used for the operating conditions therein need to be defined. As discussed above, with the current state of imaging techniques, while second approach remains to be in development stage, first approach can be used for such evaluation. This makes it necessary to demonstrate the possibility of coupling two single-modal tomographic techniques (i.e. dual modality CT) and to evaluate the assumptions incorporated in third approach.

B. Research Objectives

The current work focuses on the development of dual modality CT by combining a single source γ-ray CT and Electrical Capacitance Tomography (ECT) measurements to reconstruct phase holdup distribution of three dynamic phases in slurry bubble column reactors. The obtained results can be utilized to verify the assumptions in CT/Overall gas holdup methodology (Rados et al. 2005).

C. Research Accomplishments

The experiments have been performed in a plexi-glass column with an inner diameter of 10.12 cm and a height of 1.2 m. Air was used as gas phase while Norpar15 (μ = 2.53 cP, ρ = 773 kg.m^{-3}, σ = 26.4 dyne.cm^{-1}) was used as the liquid phase. Glass beads with an average diameter of 200 μm and particle density of 2500 kg.m^{-3} constituted the solids phase. Two superficial gas velocities were used i.e. 5, and 15 cm/s. CT and ECT scans were performed at axial height of 40 cm from the distributor. The single hole sparger with a hole of 5 mm size and a perforated plate with open area of 2 % has been used. The two solids were employed, i.e., 9.1 and 25 % vol.

Single source γ-ray CT experiments have been performed at CREL, Washington University while ECT experiments have been performed at Ohio State University at the same operating and design conditions. At Washington University, a holdup reconstruction methodology has been developed to combine CT and ECT measurements to measure the time-averaged cross-sectional holdup distribution of three phases without any assumptions. This algorithm essentially combines the single source CT equation with Two-Region Three Phase Capacitance Model proposed by Warsito and Fan (2003), which was modified for the current case.

This work represents one of the tasks set for High Pressure Slurry Bubble Column Consortium. The results are presented first to the consortium members at this time and hence, a brief outline has been presented here.

For additional information, contact Ashfaq Shaikh (Phone: 314-935-4729, E-mail: ashfaq@che.wustl.edu)

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I-9. Hydrodynamics and Mass Transfer in Slurry Bubble Columns

A. Problem Definition

Slurry bubble column reactors (SBCR) are vertical cylindrical vessels in which gas is dispersed by a distributor and bubbled through the slurry. They are gas-liquid-solid three-phase systems with solid particle sizes in the range 5-150 microns and solids loading up to 50% by volume (Krishna et al., 1997). SBCRs are widely used for carrying out reactions and mass transfer operations such as Fischer-Tropsch (FT) synthesis. FT chemistry is an acknowledged route for clean utilization of synthesis gas in production of fuels and chemicals. Due to various reaction engineering issues and economics, SBCR has been identified as an optimal commercialized reactor type for FT synthesis. For high productivity of industrial FT synthesis process, SBCR needs to be operated at large flow rate, high pressure, high catalyst loading and high catalyst activity. Hydrodynamics and mass transfer phenomena in slurry bubble columns have been subjects of great interest in reactor design and scale-up.

Due to the complex interaction of phases in SBCR, hydrodynamics of it has not been fully understood. Experiment conditions of industrial interest and importance need to be carried out to explore the transport and hydrodynamic parameters of these reactors. Moreover, most researchers have performed mass transfer studies based on simplified assumptions: perfectly mixed liquid and zero oxygen depletion. In this study, Axial dispersion model (ADM) and a mechanistic model are to be evaluated for describing the mixing and mass transfer behaviors in slurry bubble columns, interpreting the experimental data for volumetric gas-liquid mass transfer coefficient, k_la.

B. Research Objectives

This work is part of the tasks set for High Pressure Slurry Bubble Column Consortium supported by ConocoPhillips (USA), Enitechnology (Italy), Sasol (South Africa), and Statoil (Norway). The objective of this work is to study the liquid/solids and gas hydrodynamics of slurry bubble columns and to evaluate properly the mass transfer coefficients. Computed Tomography (CT) (Figure 1) and Computer Assistant Radioactive Particle Tracking (CARPT) (Figure 2) techniques are used to obtain profiles of hydrodynamic parameters. Two mass transfer measuring techniques, optical oxygen probe and gas tracer response, are being developed for estimation of mass transfer coefficients. Experiments are performed under Fischer-Tropsch (FT) mimic conditions by using suitable organic liquids, high-pressure air to mimic syngas density at FT conditions and FT catalyst. These experiments investigate the effects of pressure, superficial gas velocity, and solids loading on hydrodynamics and mass transfer rate and coefficients in slurry bubble columns.

C. Research Accomplishments

The results and findings of this work are only reported to the supporting companies and are not shared with other companies at this time.

CARPT and CT experiments have been performed in a 16.15cm (6 inches) stainless steel high-pressure slurry bubble column under FT mimic conditions. Liquid/slurry circulation velocity profiles were obtained by CARPT experiments. Non-intrusive time-averaged cross-sectional gas holdup profiles were obtained by CT technique.

An optical oxygen probe technique has been developed and implemented in an SBCR with identical geometry and conditions used in CARPT and CT experiments. Dissolved oxygen concentration in the liquid phase can be obtained to be used for mass transfer coefficient measurement. ADM model has been evaluated as a reactor model to fit the dissolved oxygen concentration profiles from an oxygen step change method. An example of the obtained data fitted using both ADM and CSTR models is shown in Figure 3. It can be seen that ADM gives better fitting to the experimental data.

A gaseous tracer technique and methodology were developed and implemented to measure the axial dispersion of gas phase in SBCRs. The gas phase axial dispersion coefficient, D_g, was obtained from minimum square error fitting of the axial dispersion model to the experimental tracer response data. This technique will be used for the 6" column under FT conditions.

D. Future Work

Eddy diffusivity of liquid/slurry, D_{zz} and D_{rr}, and turbulence parameters will be obtained from the CARPT experiments already performed under mimic Fischer-Tropsch conditions. Axial dispersion coefficient of liquid/slurry, D_l/D_s, will be obtained based on the CARPT results.

Gas dynamics information and gas phase axial dispersion coefficient, D_g, will be obtained by the gaseous tracer experiments. Correlation of gas phase axial dispersion coefficient will be developed based on the experimental data under FT conditions.

Volumetric gas-liquid mass transfer coefficient, k_la, will be obtained for mimic FT conditions. The k_la study will be performed for SBCR using ADM model and the experimental data obtained in the other studies mentioned above such as D_l/D_s, D_g, and gas holdup. Correlation of k_la will be developed for FT conditions.

Detailed information is only available for the HPSBC Consortium members.

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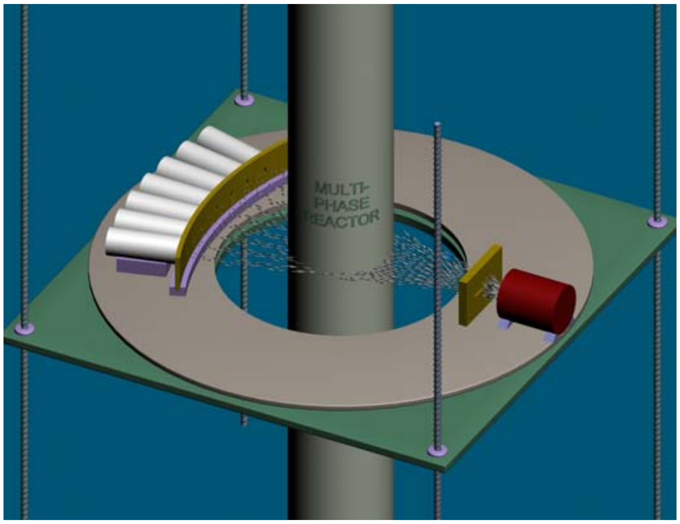

Figure 1. CT Experimental

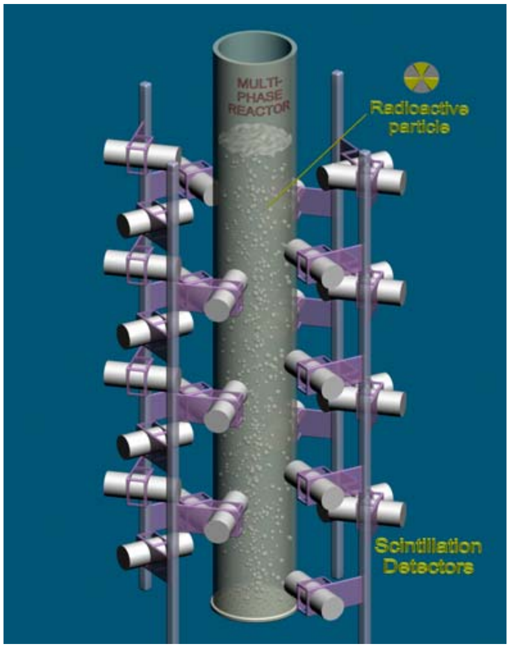

Figure 2. Diagram of CARPT Setup

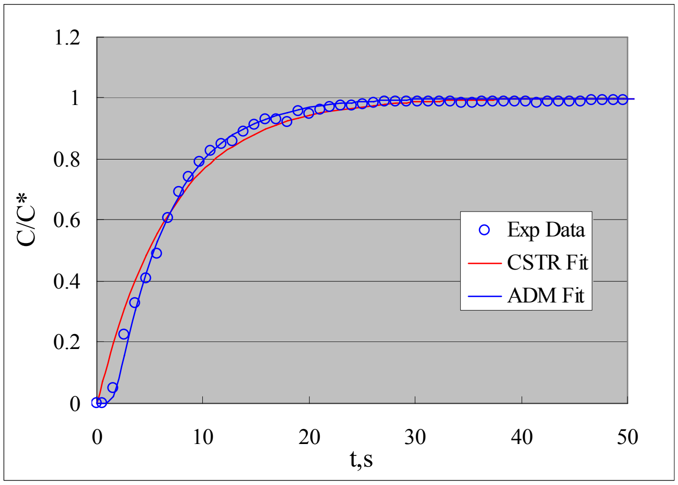

Figure 2. Comparison of data fittings with ADM and CSTR models (Air-water)

d_b=0.16m, SGV=0.30m/s, sampling location at z/L=0.9

(k_la=0.142 s^{-1} with ADM, k_la=0.102s^{-1} with CSTR)

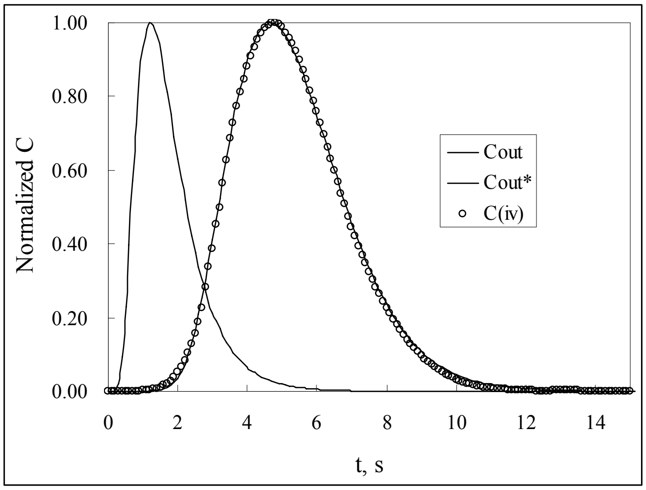

Figure 4. Fitting of outlet tracer response using ADM model (Air-water)

C_{out} – Calculated outlet tracer profile by ADM

C_{out}^* – Calculated outlet tracer profile by ADM after being corrected

$C_{(iv)}$ – Measured outlet tracer profile

I-10. Heat Transfer Coefficient Measurements in High Pressure Slurry Bubble Columns

A. Motivation

High heat and mass transfer rates are among the advantages of high-pressure slurry bubble column reactors due to the highly interacted flow structure induced by the bubble movement. Therefore, the design and scale-up of slurry bubble column reactors require detail knowledge of the hydrodynamics and transport characteristics. A growing numbers of studies have been performed on the mass and heat transfer behaviors in the slurry bubble column reactors [1~11]. However, there were few reports about heat transfer coefficient in high-pressure bubble/slurry bubble column reactors. Hence, heat transfer coefficient measurements in 6 inch high-pressure bubble/slurry bubble column will be performed at conditions that can mimic Fischer-Tropsch synthesis conditions.

B. Research Objectives

This project is apart of the tasks set for high-pressure slurry bubble column consortium supported by Conocophillips (USA), Enitechnology (Italy), Sasol (South Africa), and Statoil (Norway).

The main objectives of this project are shown bellow:

1. Develop a fast response heat transfer coefficient measurement probe.
2. Measure heat transfer coefficients at different locations inside the column, and investigate the effects of pressure, superficial gas velocity, sparger, solids loading, and physical properties on the heat transfer coefficients.
3. Check available correlations, and if it is necessary, new correlation will be developed based on the results obtained.

C. Research Accomplishments

This work is part of the tasks set for high-pressure slurry bubble column consortium. Therefore the results and findings of this work are only reported to the supporting companies and are not shared with other companies at this time. The following is just an outline of the progress made on this project this year.

Heat transfer probe has been developed and been tested using air-water system in a 19.0 cm column under atmospheric pressure conditions. The results compared well with those reported by other researchers [1,3,8,9]

Experiments using air-C9C11 system have been completed under both atmospheric and high pressure (up to 1.0 MPa). And the effects of superficial gas velocity, probe location, and pressure have been studied in a 6” stainless steel column.

D. Future Work

Heat transfer coefficient in high pressure slurry bubble column reactor will be investigated according to the goals set for the high pressure slurry bubble column consortium mentioned above.

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