5. PREDICTION OF MASS TRANSFER COEFFICIENT IN BUBBLE COLUMNS OPERATED AT HIGH PRESSURE BASED ON ATMOSPHERIC PRESSURE DATA

The liquid volumetric mass transfer coefficient is considered an important design parameter for bubble columns. Consequently, many authors have experimentally determined the values of mass transfer coefficient and developed empirical equations for their estimation (Akita and Yoshida, 1973; Hikita et al., 1981; Hammer et al., 1984; Ozturk et al., 1987). However, these published empirical equations do not account for the effect of pressure, in spite of the fact that the increase in gas hold up and decrease in bubble size with increased pressure leads to a higher interfacial area and mass transfer coefficient. Therefore, the mass transfer coefficient in a high-pressure bubble column will be underestimated by the published empirical correlations. Thus, an accurate estimation of the volumetric mass transfer coefficient for high pressure conditions requires experiments at high pressure, which are more complicated than those at atmospheric pressure.

Very few studies of the mass transfer coefficient at high pressure condition have been reported in the literature. Letzel et al., (1999) measured the mass transfer coefficient in bubble column reactors at elevated pressure by using the dynamic oxygen desorption method. They found that the ratio of volumetric mass transfer coefficient to gas holdup (k_La / ε_g) is constant and equal to approximately one half up to system pressure of 1.0 MPa. However when gas hold up is larger than 35%, the scatter in k_La increases due to the problems with the probe. Kojima et al., (1997) measured the volumetric mass transfer coefficient in bubble columns under pressurized conditions with different liquid phases and with different diameters of the single nozzle used as gas disperser. An empirical correlation was obtained for volumetric mass transfer by considering the effect of pressure and diameter of single nozzle with four empirical constants as fitted parameters, in addition, gas hold up correlation is needed to calculate the mass transfer coefficient. Dewes and Schumpe (1997) reported very strong effects of gas density on gas-liquid mass transfer and the gas density effect increased with the gas velocity. The pressure range in their study was similar to that used by Letzel (1999) and Kojima (1997).

The objective of this study is to develop a procedure for prediction of the volumetric mass transfer coefficient at any pressure based on atmospheric pressure data.

5.1. Procedure development

Wilkinson (1991) recommended accounting for the pressure effect by using the following equation:

$$\frac{(k_L a)_P}{(k_L a)_a} = [\frac{(\varepsilon_G)_P}{(\varepsilon_G)_a}]^M \quad (5.1)$$

where subscript P means pressure conditions and a indicates atmospheric conditions. This allow one to calculate k_La in pressurized bubble columns from atmospheric data for k_La and gas hold up, provided the gas hold up at elevated pressure is also known. However, due to the complex hold up structure, M depends on physical properties and flow regime (Deckwer et al.,1993). Therefore, the approach suggested by Wilkinson is of limited applicability (Grund et al., 1992). To improve the procedure recommended by Wilkinson, a correlation for M was developed by considering physical properties, column dimension and operation conditions. The following approach was used :

a. Chose proper correlations for the quantities in equation (5.1).

At atmospheric conditions, Akita and Yoshida's correlation is chosen for k_La calculation since it has been proven to be applicable for scale up (Deckwer et al.,1993)

$$\frac{k_L aD^2}{D_L} = 0.6(\frac{\mu_L}{\rho_L D_L})^{0.5}(\frac{g\rho_L D^2}{\sigma})^{0.62}(\frac{g\rho_L^2 D^3}{\mu_L^2})^{0.31}\varepsilon_G^{1.1} \qquad (5.2)$$

To predict gas holdup the correlation of Luo et al.(1999) was used at both low pressure and high pressure since it can cover a wide range of operating conditions and systems of different physical properties,

$$\frac{\varepsilon_G}{1-\varepsilon_G} = 2.9\frac{(\frac{U_G^4\rho_G}{\sigma g})^{\alpha}(\frac{\rho_G}{\rho_L})^{\beta}}{[cosh(Mo_L)^{0.054}]^{4.1}} \qquad (5.3)$$

Where $Mo_L = g\mu_L^4 / (\rho_L - \rho_G)\sigma^3$, $\alpha = 0.21 Mo_L^{0.0079}$ and $\beta = 0.096 Mo_L^{-0.011}$

Substituting equations (5.2) for $(k_La)_a$ to equation (5.1), and assuming $(\varepsilon_G^{1.1}/\varepsilon_G^{M})_{atm} = 1$ to simplify the problem, one can obtains the following equation:

$$\frac{k_L aD^2}{D_L} = 0.6Sc^{0.5}Eo^{0.62}Ga^{0.31}(\varepsilon_G)_P^M \qquad (5.4)$$

where $(\varepsilon_G)_P$ can be evaluated from equation (5.3).

b. Develop a correlation for M

In equation (5.4) parameter M depends on physical properties and flow regime which is associated with the operating conditions and column dimensions as mentioned above. To account for these factors, a correlation was developed by Wu et al.(1999):

$$n = 2.188\times 10^3 \,\mathrm{Re}^{-0.598} Fr^{0.146} M_{oL}^{-0.004} \qquad (5.5)$$

for prediction of the exponent n in the gas radial gas hold up profile which is usually represented by

$$\varepsilon_G = \tilde{\varepsilon}_G(\frac{n+2}{n})[1 - c(r/R)^n]$$

n indicates the steepness of hold up profile and reflect the intensity of liquid circulation. It is depends on flow characteristics and nature of system used as well. n and M must be somehow related. Then M= f (n) can be obtained by fitting part of the experimental data reported in the literature using equation (5.1). We have obtained 155 sets of experimental data available from the literature and chosen 65% of the points to obtain the M dependence on n as follows:

$$M = 0.3\,ln(n) + 0.044 \qquad (5.6)$$

Now one can predict the mass transfer coefficient based on gas hold up data only by using equations (5.3)-(5.6). We have compared the model predictions with experimental data at the range of pressure 0.1MPa -1.1MPa. Some of results are shown below.

5.2. Comparison of model prediction and experimental data

At elevated pressure, experimental data has been reported by Letzel (1999) at 0.1MPa to 1.0 MPa system pressure with column diameter equal to 0.15 m using dynamic oxygen desorption method. The comparison of model prediction and the reported experimental data by Letzel (1999) at 0.2MPa system pressure is shown in Figure 1. From Figure 1 one can see that the model predicts the experimental data well. The prediction by the correlation of Akita (1973) under-estimates the experimental data even if using hold up data at 0.2MPa. This correlation usually provides for a conservative estimate as reported by Deckwer et al.(1993). For the pressure at 0.3, 0.4 MPa or higher, the comparison of model prediction and experimental data is similar to what is discussed above and mass transfer coefficient increases with increasing system pressure due to small bubble size and an increase in the number of small bubbles which results in higher gas hold up. In addition, parameter M in equation (5.1) was reported by Wilkinson(1992, 1994) to be equal to 1-1.2. If M is set equal to 1.1, one can apply equation (5.2) and (5.3) in equation (1), then the correlation of Akita returns the same formula except that the hold up needs to be calculated by the correlation obtained at elevated pressure condition. From this point of view, one can argue that the procedure suggested by Wilkinson does not predict the experimental data well without considering the dependence of M on physical properties and flow regime. When the dependence of M on physical properties and flow regime, as suggested by Deckwer et al.(1993), is accounted for the prediction for k_La is good. In this study M was found to vary from 0.4 to 1.1 depending on system pressure and superficial gas velocity.

The other sets of experimental data for volumetric mass transfer coefficient at high pressure was obtained by Kojima (1997) using oxygen electrode (Oxi-96WTW) to measure dissolved oxygen. The column diameter used was small (0.045 m) and the system pressure range employed was 0.1-1.1 MPa. The comparison of model prediction and experimental data at 0.6 MPa is shown in Figure 5.2. From Figure 5.2, it is clear that the model proposed in this work can predict experimental observation well. Again either Akita's correlation or equation (1) with M=1.1 predicts a lower mass transfer coefficient than experimental data.

The comparison of additional experimental data and model prediction is shown in Figure 5.3. From Figure 5.3, one can see that for most of the available experimental data the error between predicted mass transfer coefficient by this work and experimental data reported in the literature is less than 20% within the pressure range 0.1 to 1.1 MPa. There is another set of experimental results reported by Dewes et al.(1997), The data was not included in Figure 5.3 due to insufficient information on physical properties to be used in the proposed model. However, Dewes et al.(1997) reported that $k_L a \propto \rho_G^{0.45-0.5}$ and this is comparable with this work regarding the dependence of mass transfer coefficient on gas density.

5.3. SUMMARY

Based on the approach that mass transfer coefficient and gas hold up data obtained at lower pressure and gas hold up obtained at high pressure conditions can be used to predict the mass transfer coefficient at high pressure, we have chosen the widely accepted mass transfer correlation and newly reported gas hold up correlation which covers wide operating pressure conditions to form a new correlation for the prediction of mass transfer coefficient at wide range of operating conditions. The correlation can be used to predict the mass transfer coefficient up to 1.1 MPa system pressure with error within 20%.

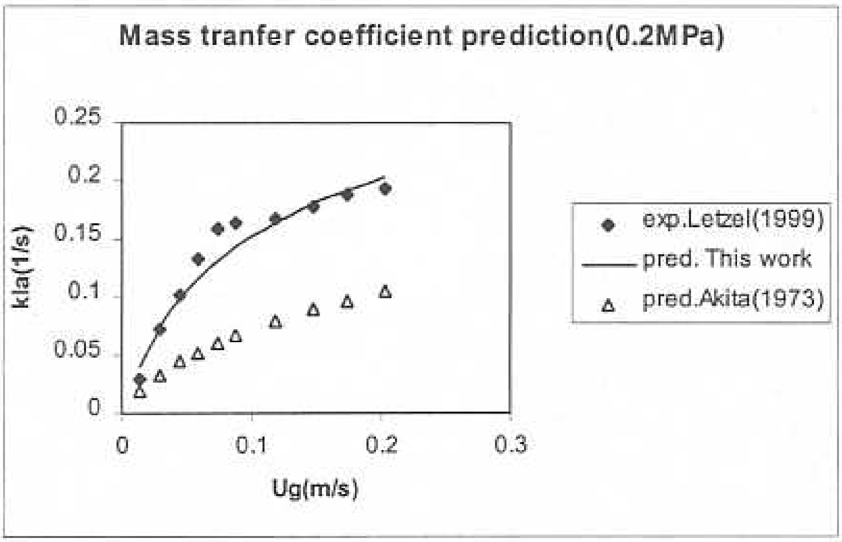

Figure 5.1 Comparison of model prediction and experimental data of Letzel (1999)

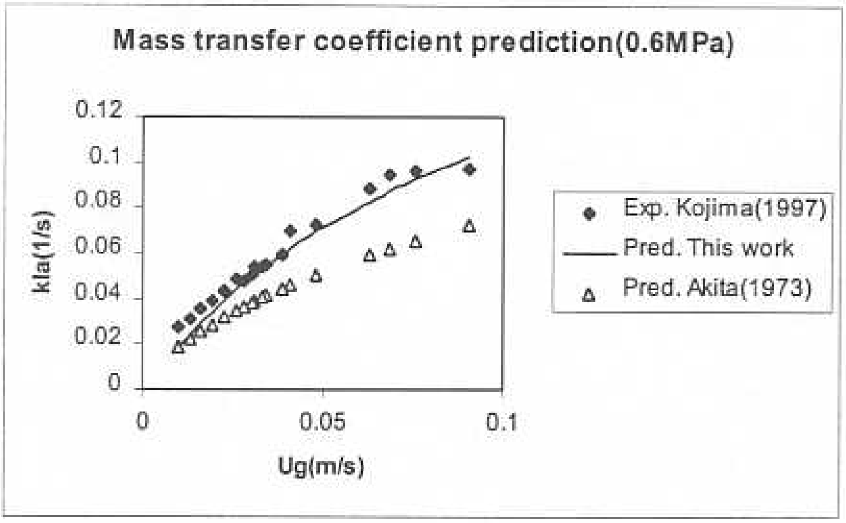

Figure 5.2 Comparison of model prediction and experimental data by Kojima(1997)

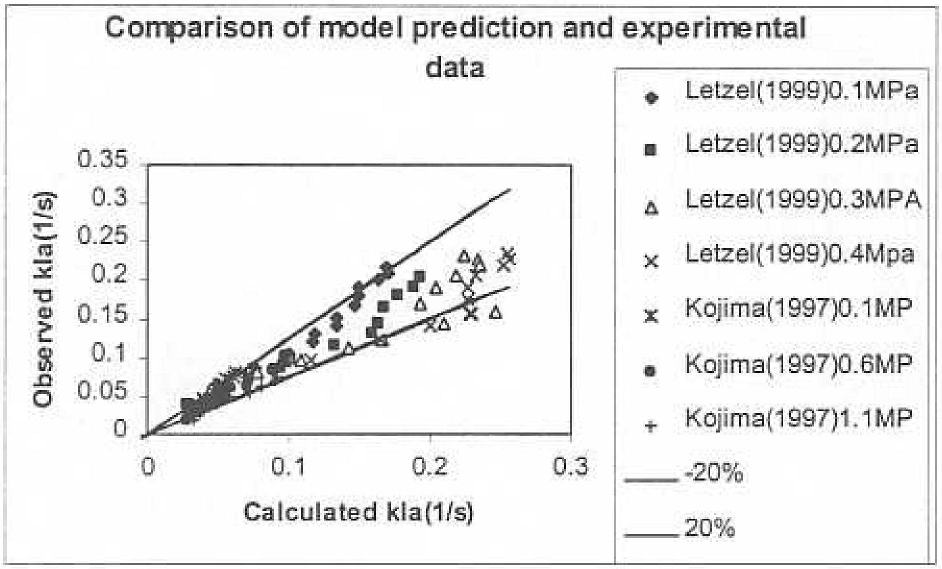

Figure 5.3 Comparison of predicted k_La and observed k_La

5.4 *NOMENCLATURE*

a	special interfacial area, m^2/m^3
D	Column diameter, m
D_L	Molecular diffusivity, m^2/s
Eo	Eotvos number, dimensionless
Fr_g	Gas Froude number, dimensionless
g	Acceleration due to gravity, m/s^2
Ga	Galico number, dimensionless
k_La	Volumetric mass transfer coefficient, 1/s
Mo_L	Liquid Morton number, dimensionless
n	Parameter in Eq(5)
Re_G	Reynolds number, dimensionless
Sc	Schmidt number, dimensionless
U_{Sg}	Superficial gas velocity, m/s

Greek letters

ε_G	Cross-sectional average gas hold up
μ_L	Liquid viscosity, Pa.s
ρ_G	Gas density, kg/m^3
ρ_L	Liquid density, kg/m^3
σ_L	Liquid surface tension, N/m

6. REFERENCES

Akita, K.,and F. Yoshida, Gas holdup and volumetric mass transfer coefficient in bubble columns, Ind. Eng. Chem. Proc. Des. Dev., 12, 76, 1973.

Allen, M. P. and D. J. Tildesley. *Computer Simulation of Liquids*, Clarendon Press, Oxford, 1987.

Bukur, D.B., Models for Fischer-Tropsch reaction in slurry bubble column reactors, *Chem. Eng. Sci.*, 38(3), 441, 1983.

Chen, J., A. Kemoun, M.H. Al-Dahhan, M.P. Dudukovic, D.J. Lee, L.S. Fan. Comparative hydrodynamics study in a bubble column using CARPT/CT and PIV. *Chem. Eng. Sci*, 1999.

Chen, J., F. Li, S. Degaleesan, M.H. Al-Dahhan, M.P. Dudukovic, B. Toseland. Fluid dynamic parameters in bubble columns with internals. *Chem. Eng. Sci*, 1999.

Daly, J.G., Patel, S.A. and Bukur, D.B., Measurements of gas holdups in a three phase bubble column by gamma-ray densitometry, *Fluidization VIII*, 647, 1996.

de Swart, J.W.A, Krishna, R., Sie, S.T., Selection, design and scale up of the Fischer-Tropsch reactor, *Stud. Surf. Sci. Catal.*, 107(Natural Gas Conversion IV), 213, 1997.

de Swart, J.W.A. Scale-up of a Fischer-Tropsch slurry reactor. Ph.D. Thesis, University of Amsterdam, The Netherlands. 1996

Deckwer W.-D and A. Schumple, Improved tools for bubble column reactors design and scale up, Chem. Eng. Sci., 48, 889-911, 1993.

Deckwer, W.-D., Serpemen, Y, Ralek, M. and Schmidt B., Modeling the Fischer-Tropsch Synthesis in the slurry phase, *Ind. Eng. Chem. Process Des. Dev.*, 21, 231, 1982.

Degaleesan, S., Dudukovic, M.P., Toseland, B.A. and Bhatt, B.L., A two-compartment convection-diffusion model for slurry bubble column, *Ind. Eng. Chem. Res.*, 36, 4670, 1997.

Degaleesan, S., Turbulence and liquid mixing in bubble columns, *D.Sc. Thesis*, Washington University, St. Louis, MO, 1997.

Devanathan, N. Investigation of liquid hydrodynamics in bubble columns via computer automated radioactive particle tracking (CARPT). D.Sc Thesis, Washington University, St. Louis, 1991.

Dewes I. And A. Schumpe, Gas density effect on mass transfer in the slurry bubble column, Chem. Eng. Sci., 52, 4105-4109, 1997.

Dry, M.E., Advances in Fisher-Tropsch chemistry, *Ind. Eng. Chem. Prod. Res. Dev.*, 15, 282, 1976.

Fan, L.-S., Gas-liquid-solid fluidization engineering, *Butterworths Series in Chemical Engineering*, Boston, 1989.

Fan, L.-S. and K. Tsuchiya. *Bubble Wake Dynamics in Liquids and Liquid-Solid Suspensions*. Butterworth-Heinemann, Stoneham, MA, 1990.

Fan, L.-S., G.Q. Yang, D.J. Lee, K. Tsuchiya and X. Luo. Some aspects of high-pressure phenomena of bubbles in liquids and liquid-solid suspensions. *Chem. Eng. Sci.*, 54, 4681, 1999.

Gormley, R.J., Zarochak, M.F., Deffenbaugh, P.W. and Rao, K.R.P.M., Effect of initial wax medium on the Fishcer-Tropsch slurry reaction, *Applied Catalysis*, 161, 263-279, 1997.

Grevskott, S., B.H. Sannaes, M.P. Dudukovic, K.W. Hiarbo, and H.F. Svendsen. Liquid circulation, bubble size distribution and solids movements in two- and three-phase bubble columns. *Chem. Eng. Sci.*, 51, 1703-1713, 1996.

Grund, G., A. Schumpe and W.D. Deckwer. Gas-liquid mass transfer in a bubble column with organic liquids, Chem. Eng. Sci., 47, 3509-3516, 1992.

Hammer, H, H. Schrag, K. Hektor, K. Schonau, W. Kuster, A. Soemarno, U. Sahabi, and W. Napp, New subfunctions on hydrodynamics, heat and mass transfer for gas/liquid and gas/liquids/solid chemical and biochemical reactors, Front. Chem. Reac. Eng., 464, 1984.

Hikita, H., H. Sasai, K.Tanigawa, K. Segawa,and M. Kitao, The volumetric liquid phase mass transfer coefficient in bubble columns, Chem. Eng. J., 22,61, 1981.

Hills, J.H. Radial non-uniformity of velocity and voidage in a bubble column. *Trans. Inst. Chem. Engrs.*, 52, 1-9, 1974

Huff, G.A.Jr. and Satterfield, C.N., Intrinsic kinetics of the Fischer-Tropsch synthesis on a reduced fused-magnetite catalyst, *Ind. Eng. Chem. Process Des. Dev.*, 23(4), 696, 1984.

Idogawa, K., Ikeda, K., Fukuda, T., and Morooka, S., 'Effect of Gas and Liquid Properties on the Behavior of Bubbles in a Bubble Column under High Pressure,' *Kag. Kog. Ronb.*, 11, 432, 1985.

Idogawa, K., Ikeda, K., Fukuda, T., and Morooka, S., 'Effect of Gas and Liquid Properties on the Behavior of Bubbles in a Column under High Pressure,' *Int. Chem. Eng.*, 27, 93-99, 1987.

Iglesia, E., Design, synthesis, and use of cobalt-based Fischer-Tropsch sythesis catalysts, *Appl. Catal.*, 161(1-2), 59, 1997.

Jean, R.-H. and L.-S. Fan. Rise velocity and gas-liquid mass transfer of a single large bubble in liquids and liquid-solid fluidized beds. *Chem. Eng. Sci.,* 45, 1057, 1990.

Jennings, J.W.,Jr. and Pallas, N. R.., An efficient method for the determination of interfacial tensions from drop profiles, *Langmuir*, 4(4), 959, 1988.

Joshi, J.B. and M.M. Sharma. A circulation cell model for bubble columns. *Trans. Inst. Chem. Engrs*, 57, 244-251, 1979.

Kato, Y., Nishiwaki, A., Fukuda, T. and Tanaka, S., The behavior of suspended solid particles and liquid in bubble columns, *J. Chem. Eng. Japan*, 5, 112, 1972.

Kemoun, A., Ong, B. C., Gupta, P., Al-Dahhan, M. H., and Dudukovic', M. P., 'Gas Holdup in Bubble Columns at Elevated Pressure via Computed Tomography,' To be published in *International J. of Multiphase Flows*, 2000.

Kojima H., J. Sawai and H. Suzuki, Effect of pressure on volumetric mass transfer coefficient and gas hold up in bubble columns, *Chem. Eng. Sci.*, 52, 4111-4116, 1997.

Krishna, R., and Ellenberger, J., 'Gas Holdup in Bubble Column Reactors Operating in the Churn-Turbulent Flow Regime,' *AIChE J.*, 42, 9, 2627-2634, 1996.

Kumar, S.B., Computed tomography measurements of void fraction and modeling of the flow in bubble columns, *Ph.D. Thesis*, Florida Atlantic University, Boca Raton, 1994.

Kuo, J.C.W., Slurry Fischer-Tropsch/Mobil two-stage process of converting syngas to high octane gasoline, *U.S. DOE Final Report*, DOE/PC/30022-10, 1983.

Leib, T.M., Mills, P.L., Lerou, J.J. and Turner, J.R., Evaluation of Neural Networks for simulation of three-phase bubble column reactors, *Trans. Inst. Chem. Eng. (Part A)*, 73, 690, 1995.

Letzel, H.M., J.C. Schouten, R.Krishna, C.M. van den Bleek, Gas hold up and mass transfer in bubble column reactors operated at elevated pressure, Chem. Eng. Sci., 54, 2237-2246, 1999.

Luo, X., P. Jiang, and L.-S. Fan. High pressure three-phase fluidization: hydrodynamics and heat transfer. *AIChE J.,* 43, 2432, 1997a.

Luo, X., J. Zhang, J., K. Tsuchiya, and L.-S. Fan. On the rise velocity of bubbles in liquid-solid suspensions at elevated pressure and temperature. *Chem. Eng. Sci.*, 52, 3693, 1997b.

Luo, X., D. J. Lee, R. Lau, G. Q. Yang, and L.-S. Fan. Maximum stable bubble size and gas holdup in high pressure slurry bubble columns. *AIChE J.,* in press, 1998a.

Luo, X., G. Q. Yang, D. J. Lee, and L.-S. Fan. Single bubble formation in high pressure liquid-solid suspensions. *Powder Technology,* 100, 103, 1998c.

Luo X., D.J. Lee, R. Lau, G.Yang and L.S. Fan, Maximum stable bubble size and gas hold up in high pressure slurry bubble columns, AICHE J., 45, 665-680, 1999.

Marano, J.J. and Holder, G.D., Prediction of bulk properties of Fischer-Tropsch derived liquid, *Ind. Eng. Chem. Res.*, 36(6), 2409-2420, 1997.

Maretto, C. and Krishna, R., 1999. Modeling of a bubble column slurry reactor for Fischer-Tropsch synthesis. *Catalysis Today*. 52, 279-289.

Mendelson, H. D. The motion of an air bubble rising in water. *AIChE J.*, 13, 250, 1967.

Mills, P.L., Turner, J.R., Ramachandran, P.A. and Dudukovic, M.P., The Fischer-Tropsch synthesis in slurry bubble column reactors: analysis of reactor performance using the axial dispersion model, *Topics Chem. Eng.*, 8(Three Phase Sparged Reactors), 339, 1996.

Moslemian, D., Devanathan, N. and Dudukovic, M.P., Radioactive particle tracking technique for investigation of phase recirculation and turbulence in multiphase systems, *Rev. Sci. Instrum.*, 63, 4361, 1992.

Murray, P and Fan, L.-S., Axial solid distribution in slurry bubble columns, *Ind. Eng. Chem. Res.*, 28, 1697, 1989.

Ong, B.-C., N. Rados, P. Gupta, Y. Wu, M.H. Al-Dahhan, M.P. Dudukovic, R. Lau, L.S. Fan. Hydrodynamic of slurry bubble column. Internal report, Chemical Reaction Engineering Laboratory (CREL), Washington University, St. Louis, 2000.

Oukachi R., Singelton, A.H. and Goodwin, J.G., Comparison of patented Co F-T catalysts using fixed-bed and slurry bubble column recators, *Appl. Catal.*, 186(1-2), 129, 1999.

Ozturk, S.S., A. schumpe and W.D. Deckwer, Organic liquids in a bubble column: Hold up and mass transfer coefficients, AICHE J., 33, 1473-1480, 1987.

Patel, S.A., Daly, J.G. and Bukur, D.B., Bubble-Size Distribution in Fischer-Tropsch-Derived Waxes in a Bubble Column, *AIChE J.*, 36(1), 93, 1990.

Prakash, A., On the effect of syngas composition and water-gas-shift reaction rate on FT synthesis over iron based catalyst in a slurry reactor, *Chem. Eng. Commun.*, 128, 143, 1993.

Qicker, G., W.D. Deckwer. A further note on mass transfer limitations in the Fischer-Tropsch slurry process. *Chem. Eng. Sci.*, 36, 1577-1579, 1981.

Rados, N. Slurry bubble column hydrodynamics, D.Sc. Proposal, Washington University, St. Louis, 1999.

Rao, V.U.S., Stiegel, G.J., Cinquegrane, G.J. and Srivastava, R.D., Iron-based catalyst for slurry-phase Fischer-Tropsch process: Technology review, *Fuel Process. Technol.*, 30 (1), 83, 1992.

Rice, R.G., N.W. Geary. Prediction of liquid circulation in viscous bubble columns. *AIChE J.*, 36, 1339-1348, 1990.

Sannaes, B.H., Solids movement and concentration profiles in column slurry reactors, *Dr. Ing. Thesis*, Norweign University of Science and Technology, Trondheim, Norway, 1997.

Sannaes, B.H., M.P. Dudukovic, and H. Svendsen. Experimental and numerical investigation of solids dynamics in slurry bubble columns, in Hamid Amstoopour, Editor, *Fluidization and Fluid-Particle Systems*, preprints, 159-163, Particle Forum of AIChE, 1995.

Shah, Y. T., B. G. Kelkar, S. P. Godbole, and W.-D. Deckwer. Design parameters estimations for bubble column reactors. *AIChE J.*, 28, 353, 1982.

Soong, Y., Harke, F.W., Gamwo, I.K., Schehl, R.R. and Zarochak, M.F., Hydrodynamic study in a slurry-bubble column reactor, *Catalysis Today*, 35, 427-434, 1997.

Srivastava, R.D., Rao, V.U.S. Cinquegrane, G. and Stiegel, G.J., Catalysts for Fischer-Tropsch, *Hydrocarbon Porcess., Int. Ed.*, 69(2), 59, 1990.

Stern, D., Bell, A.T. and Heinemann, H., A theoretical model for the performance of bubble-column recators used for Fischer-Tropsch synthesis, *Chem. Eng. Sci.*, 40(9), 1665, 1985.

Storch, H.H., Golumbic, N. and Anderson, R.B., The Fischer-Tropsch and related synthesis, *John Wiley & Sons, Inc.*, New York, 1951.

Tomiyama, A., I. Kataoka, and T. Sakaguchi. Drag coefficients of bubbles (1st report, drag coefficients of a single bubble in a stagnant liquid). *Nippon Kikai Gakkai Ronbunshu B Hen,* 61(587), 2357, 1995.

Turner, J.R. and Mills, P.L., Comparison of axial dispersion and mixing cell models for design and simulation of Fischer-Tropsch slurry bubble column reactors, *Chem. Eng. Sci.*, 45(8), 2317, 1990.

van der Laan, G.P., Beenackers, A.A.C.M. and Krishna, R., Multicomponent reaction engineering model for Fe-catalyzed Fischer-Tropsch synthesis in commercial scale slurry bubble column reactors, *Chem. Eng. Sci.*, 54, 5013, 1999.

Wasan, D. T. and M. S. Ahluwalia. Consecutive film and surface renewal mechanism for heat and mass transfer from a wall. *Chem. Eng. Sci.,* 24, 1535, 1969.

Wilkinson, P.M., A.P. Apek, and L.L. van Dierendonck, Design parameters estimation for scale-up of high-pressure bubble columns, AICHE J.,38(4), 544-554, 1992.

Wilkinson, P.M., H. Haringa, L. Laurent and Van Dierendonck, Mass transfer and bubble size in a bubble column under pressure, Chem.Eng. Sci., 49(9), 1417-1427, 1994.

Wilkinson, P.M. Physical aspects and scale-up of high-pressure bubble columns", PhD thesis, University of Groningen, The Netherlands, 1991.

Wu, Y.X. and Al-Dahhan, Prediction of gas hold up profiles in bubble column reactors, Accepted in *Chem. Eng. Sci.*, 2000.

Zhang, J., L.-S. Fan, C. Zhu, R. Pfeffer, and D. Qi. Dynamic behavior of collinear collision of elastic spheres in viscous fluids, *Advanced Technologies for Particle Processing,* Vol. II, 44, Particle Technology Forum, AIChE; *Proceedings* of *PTF Topical Conference at AIChE Annual Meeting*, Nov. 15-20, Miami Beach, FL; *Powder Technology*, in press, 1998a.

Zhang, J., Y. Li, and L.-S. Fan. Numerical simulation of gas-liquid-solid fluidization systems using a combined CFD-DPM-VOF method: single bubble rise behavior, *Advanced Technologies for Particle Processing,* Vol. II, 509, Particle Technology Forum, AIChE; *Proceedings* of *PTF Topical Conference at AIChE Annual Meeting*, Nov. 15-20, Miami Beach, FL, 1998b.