Figures 3.11 and 3.12 further confirm that gas holdup increases with pressure, except at low superficial gas velocities (below and up to 5 cm/s) when it is rather insensitive to pressure as reported in the literature (Kölbel *et al*., 1961; Deckwer *et al*., 1980). At atmospheric pressure, the cross-sectional average gas holdup seems almost constant after certain gas superficial velocity is reached as indicated by Figure 3.10. This leveling off effect seems to occur at higher gas velocities at higher pressures, as evident from Figures 3.11 and 3.12.

3.4. Comparison with Various Correlations in the Literature

Numerous correlations for overall gas holdup in bubble columns have been reported and those that seem applicable to the conditions investigated in this study are summarized in Table 3.3. Since Kumar (1994) has shown that the cross-sectional average holdup measured at heights above the distributor larger than 4 to 5 column diameters is in close agreement with the overall gas holdup in the column, the cross sectional average holdup determined in this study was compared to the prediction for overall gas holdup obtained from the reported correlations. Table 3.4 lists gas holdup values obtained using the correlations shown in Table 3.3 and the error in predictions. Figure 3.13 shows the predictions for the overall gas holdup at P = 1 atm as a function of superficial gas velocity based on various correlations. It can be concluded that none of the correlations, except Akita and Yoshida's (1973), agrees closely with the experimental data. At U_g = 5 cm/s, even Akita and Yoshida's prediction deviates from the observed holdup.

Since the superficial gas velocity of 5 cm/s is close to the transition velocity at P = 1 atm that changes bubbly flow into churn turbulent flow, and the precise value of the transition velocity is a function of the unmeasurable water quality, it is possible that the deviation between data and correlation predictions at U_g = 5 cm/s is caused by the fact that the correlations predict the holdup in one flow regime while the data reflects the other flow regime. It is evident from Figure 3.13 that the experimental holdup value at U_g = 5 cm/s at P = 1 atm is considerably higher than the value predicted by any of the correlations indicating perhaps a different flow regime during our experiment than observed in the data used to develop the correlations.

Table 3.3: Correlations for Gas Holdup

References	Gas-Liquid System	Apparatus	Conditions	Correlations
Akita & Yoshida (1973)	$He/CO_2/O_2$/air-H_2O/ Glycol/Methanol/CCl_4/ Na_2SO_3/NaCl	D = 0.152, 0.301, 0.6 m Sparger (5.0 mm)	P = 0.1 MPa T = 283 - 313 K U_g = 0.5 - 40 cm/s	$\frac{\bar{\varepsilon}}{(1-\bar{\varepsilon})^4} = 0.2\left(\frac{gD^2\rho_l}{\gamma}\right)^{0.125}\left(\frac{gD^3}{\nu_l}\right)^{0.083}\frac{U_g}{(gD)^{0.5}}$
Hikita *et al*. (1981)	$H_2/CO_2/CH_4/C_3H_8/H_2+N_2$/ air-$H_2O$/Sucrose/ Methanol/n-Butanol/ Aniline/i-Butanol/NaCl/ $Na_2SO_4/CaCl_2/MgCl_2$/ $AlCl_3/KCl/K_2SO_4/K_3PO_4$/ KNO_3	D = 0.10 m Nozzle (1.1 cm)	P = 0.1 MPa H/D = 15 U_g = 4.2 - 38 cm/s	$\varepsilon = 0.672 f\left(\frac{U_g\mu_l}{\gamma}\right)^{0.578}\left(\frac{\mu_l^4 g}{\rho_l\gamma^3}\right)^{-0.131}\left(\frac{\rho_g}{\rho_l}\right)^{0.062}\left(\frac{\mu_g}{\mu_l}\right)^{0.107}$ where $f = \begin{cases} 1.0 & \text{for non-electrolyte solution} \\ 10^{0.0414I} & \text{for } 0 < I < 1.0 \text{ kg ion/m}^3 \\ 1.1 & \text{for } I > 1.0 \text{ kg ion/m}^3 \end{cases}$
Hammar *et al.* (1984)				$\frac{\bar{\varepsilon}}{1-\bar{\varepsilon}} = 0.4\left(\frac{U_g\mu_l}{\gamma}\right)^{0.87}\left(\frac{\mu_l^4 g}{\rho_l\gamma^3}\right)^{-0.27}\left(\frac{\rho_g}{\rho_l}\right)^{0.17}$
Idogawa *et al.* (1985)	Air-H_2O	D = 0.05 m Porous plate (2, 100 μm) Capillary tubes (1, 3, 5 mm) Perforated plate (19 holes of 1 mm)	P = 0.1 - 15 MPa T = 288 - 293 K, H/D = 16.6 U_g = 0.5 - 5 cm/s	$\frac{\bar{\varepsilon}}{1-\bar{\varepsilon}} = 1.44U_g^{0.58}\rho_g^{0.12}\sigma_l^{-0.16\exp(-P)}$
Reilly *et al.* (1986)	He/Ar/air-H_2O/solvent/ trichloroethylene-glass beads	D = 0.3 m Perforated plate (293 holes,1.5 mm) Single sparger Multiorifice sparger (13.4 mm)	P = 0.1 MPa T = 283 - 323 K U_g = 0.4 - 40 cm/s	$\bar{\varepsilon} = 296U_g^{0.44}\rho_l^{-0.16}\rho_g^{0.19} + 0.009$
Idogawa *et al*. (1987)	H_2/He/Air-H_2O/Methanol/ Ethanol/Acetone/Aqueous alcohol solution	D = 0.05 m Perforated plate (19 holes of 1 mm)	P = 0.1 - 5 MPa T = 284 - 293 K, H/D = 16.6 U_g = 0.5 - 5 cm/s	$\frac{\bar{\varepsilon}}{1-\bar{\varepsilon}} = 0.059U_g^{0.8}\rho_g^{0.17}\left(\frac{\sigma_l}{72}\right)^{-0.22\exp(-P)}$

Table 3.3: Correlations for Gas Holdup (Continued)

References	Gas-Liquid System	Apparatus	Conditions	Correlations
Wilkinson *et al.* (1992)	N_2-H_2O/n-Heptane/Mono-ethylene glycol	D = 0.158, 0.23 m Sparger ring 7(4 holes of 7 mm)	P = 0.1 - 2.0 Mpa H = 1.2 m U_g = 0 - 60 cm/s	$U_g < U_{trans}$ $\quad \bar{\varepsilon} = \frac{U_g}{U_{s.b.}}$ $U_g > U_{trans}$ $\quad \bar{\varepsilon} = \frac{U_{trans}}{U_{s.b.}} + \frac{U_g - U_{trans}}{U_{l.b.}}$ where $\frac{U_{trans}}{U_{s.b.}} = 0.5\exp(-193\rho_l^{-0.61}\mu_l^{0.5}\gamma^{0.11})$ $\frac{\mu_l U_{s.b.}}{\gamma} = 2.25\left(\frac{\gamma^3\rho_l}{g\mu_l^4}\right)^{-0.273}\left(\frac{\rho_l}{\rho_g}\right)^{0.03}$ $\frac{\mu_l U_{l.b.}}{\gamma} = \frac{\mu_l U_{s.b.}}{\gamma} +$ $2.4\left[\frac{\mu_l(U_g - U_{trans})}{\gamma}\right]^{0.757}\left(\frac{\gamma^3\rho_l}{g\mu_l^4}\right)^{-0.077}\left(\frac{\rho_l}{\rho_g}\right)^{0.077}$
Kojima *et al.* (1997)	Air-H_2O/Aqueous buffered solution/Aqueous enzyme solution	D = 0.045 m Nozzle (1.38, 2.1, 2.9, 4.03 mm)	P = 0.1 - 1.1 MPa T = 290 - 300 K, H/D = 20 - 26.7 U_g = 0.005 - 0.15 cm/s	$\bar{e} = 1.18 U_g^{0.679}\left(\frac{g}{g_0}\right)^{-0.546} \exp\left[1.27\times10^{-4}\left(\frac{r_l Q^2}{d_o^3 g}\right)\left(\frac{P}{P_0}\right)\right]$

Table 3.4: Comparison of Cross-Sectional Average Gas Holdup with Predictions of Different Correlations (and Percent Error in Predictions)

$$\text{Error} = \frac{\text{measured value - predicted value}}{\text{measure value}} \times 100$$

P = 1 atm

U_g, cm/s	Expt'l data	Akita (1973)	Hikita (1980)	Hammer (1984)	Idogawa (1985)	Reilly (1986)	Idogawa (1987)	Wilkinson (1992)	Kojima (1997)
2	0.069	0.063 (8.7)	0.050 (28)	0.040 (42)	0.052 (25)	0.059 (14)	0.056 (19)	0.050 (28)	0.083 (20)
5	0.191	0.106 (44)	0.084 (56)	0.084 (56)	0.085 (56)	0.084 (56)	0.110 (42)	0.096 (50)	0.155 (19)
12	0.193	0.181 (6.2)	0.140 (28)	0.165 (14)	0.134 (31)	0.120 (38)	0.200 (3.6)	0.162 (16)	0.286 (47)

P = 7 atm

U_g, cm/s	Expt'l data	Hikita (1980)	Hammer (1984)	Idogawa (1985)	Reilly (1986)	Idogawa (1987)	Wilkinson (1992)	Kojima (1997)
2	0.077	0.056 (27)	0.055 (29)	0.084 (9.1)	0.081 (5.2)	0.077 (0.0)	0.054 (30)	0.083 (7.8)
5	0.227	0.103 (55)	0.114 (50)	0.135 (40)	0.117 (48)	0.147 (35)	0.106 (53)	0.159 (30)
12	0.410	0.158 (62)	0.215 (48)	0.206 (50)	0.168 (59)	0.258 (37)	0.181 (56)	0.326 (20)

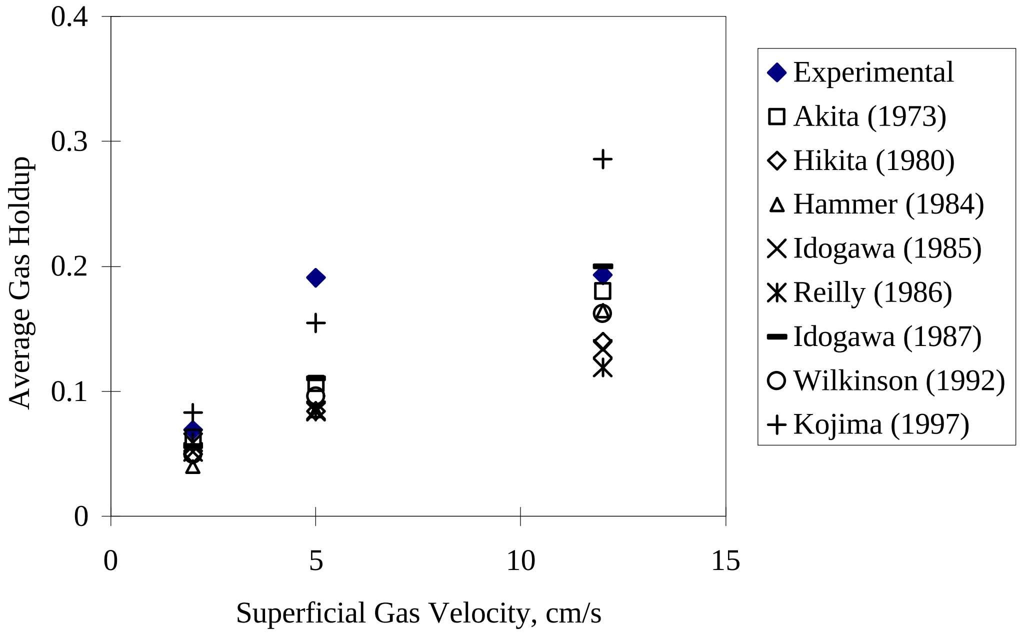

Figure 3.13: Cross-sectional Average Gas Holdup as a Function of Superficial Gas Velocity at Atmospheric Pressure

Figure 3.14 shows the predictions for the overall gas holdup as a function f superficial gas velocity at P = 7 atm and compares these predictions to our data. The numerical comparison is shown in Table 3.4. At elevated pressure the correlation of Kojima et al., 1997 comes the closest to the data.

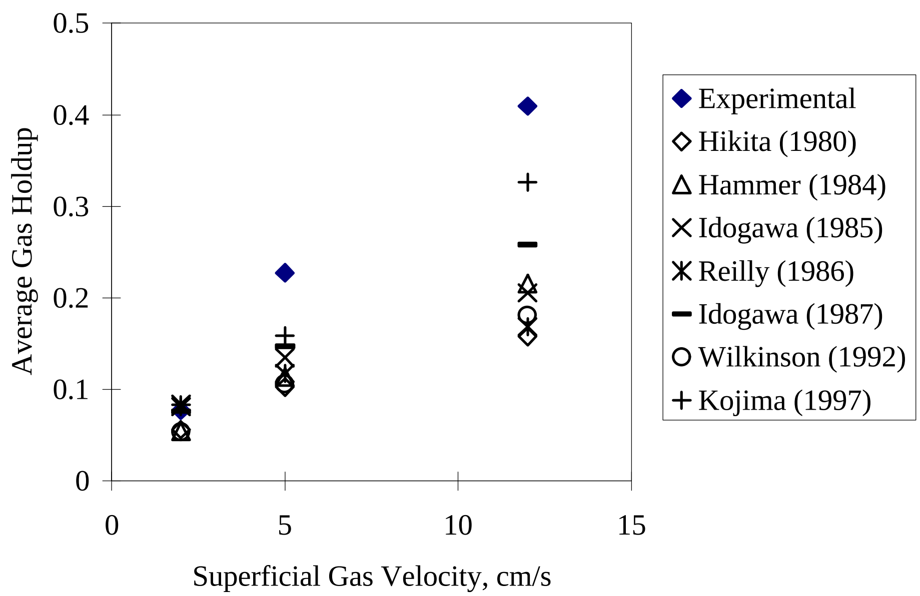

Figure 3.14: Cross-Sectional Average Gas Holdup as a Function of Superficial Gas Velocity at P = 7 atm

Among the correlations reported in Table 3.3 those of Idogawa *et al.* (1985), Idogawa *et al*. (1987), Wilkinson *et al*. (1992), and Kojima *et al.* (1997) were developed by considering high pressure data also. As evident from Figures 3.13 and 3.14 and Table 3.4, the gas holdup calculations based on Kojima *et al.* (1997)'s correlation have the least error compared to the observed cross-sectional gas holdup at elevated pressure.

3.5. Summary

The gas holdup and gas holdup cross-sectional distribution measurements were obtained at elevated pressure up to 7 atm using gamma-ray Computed Tomography (CT), which is available in CREL (Chemical Reaction Engineering Laboratory). Gas holdup increased as pressure increased due to a decrease in bubble sizes. Coalescence of bubbles decreased and the bubble breakup was promoted under pressurized conditions. The measured radial gas holdup distribution was flatter at a higher pressure than at atmospheric pressure. At atmospheric pressure at superficial gas velocity of 12 cm/s, the radial gas holdup distribution is parabolic, indicating churn-turbulent flow condition.

The cross-sectional average gas holdup was calculated using the collected data and compared with various correlations found in the literature. At atmospheric pressure, Akita and Yoshida's correlation was in the best agreement with data compared with other correlations, except for U_g = 5 cm/s. The calculated cross-sectional average gas holdup data is compared also with Shollenberger *et al.* (1995, 1997). The data is comparable except for U_g = 5 cm/s at atmospheric pressure. This value is near the transition point, and thus the discrepancies can be large due to flow regime transitions. At higher pressure, the correlation of Kojima *et al.* (1997) predicted gas holdup values in reasonable agreement with the observed cross-sectional average gas holdup.

3.6. Nomenclature

d_o	-	inner diameter of single nozzle, mm
D	-	column diameter, m
g	-	gravitational acceleration, m/s^2
P	-	system pressure, MPa
P_0	-	standard atmospheric pressure
Q	-	volumetric flowrate of gas under the condition in the bubble column, m^3/s
U_g	-	superficial gas velocity, m/s
U_{gc}	-	superficial gas velocity, cm/s
$U_{l.b.}$	-	slip velocity for large bubbles, m/s
$U_{s.b.}$	-	slip velocity for small bubbles, m/s
U_{trans}	-	velocity at regime transition, m/s
$\bar{e}$	-	cross-sectional averaged gas holdup
γ	-	liquid surface tension, N/m
ν_l	-	liquid kinematic viscosity, m^2/s
ρ_g	-	gas density, kg/m^3
ρ_l	-	liquid density, kg/m^3
σ_l	-	liquid surface tension, mN/m
σ_0	-	surface tension of water at 20 °C, mN/m

3.7. References

Adkins, D. R., Shollenberger, K. A., O'Hern, T. J., and Torczynski, J. R., "Pressure Effects on Bubble Column Flow Characteristics," ANS Proceedings, 1996 National Heat Transfer Conference, Technical Sessions sponsored by Thermal Hydraulics Division American Nuclear Society, 9, 318-325, Aug 3-6, 1996.

Akita, K., and Yoshida, F., 'Gas Holdup and Volumetric Mass Transfer Coefficient in Bubble Columns,' *Ind. Eng. Chem. Process Des. Dev*., 12, 76-80, 1973.

Deckwer, W.-D., Bubble Column Reactors, John Wiley & Sons, New York, 1992.

Hammer, H., Schrog, H., Hektor, K., Schönau, K., Küsters, W., Soemarno, A., Sahabi, U., and Napp, W., 'New Subfunctions in Hydrodynamics, Heat & Mass Transfer for Gas/Liquid and Gas/Liquid/Solid Chemical and Biochemical Reactors,' *Front. Chem. Reac. Eng*., 464, 1984.

Hikita, H., Asai, S., Tanigawa, K., Segawa, K., and Kitao, M., 'Gas Holdup in Bubble Columns,' *Chem. Eng. J*., 20, 59-67, 1980.

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., 'Behavior of Bubbles of the Air-Water System in a Column under High Pressure,' *International Chem. Engng*., 26, 3, 468-474, 1986.

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.

Jiang, P., Lin, T.-J., Luo, X., and Fan, L.-S., 'Flow Visualization of High Pressure (21 MPa) Bubble Column: Bubble Characteristics,' *Trans IChemE*, 73, Part A, 269-274, April 1995.

Kojima, H., Jun, S., and Hideyuki, S., 'Effect of Pressure on Volumetric Mass Transfer Coefficient and Gas Holdup in Bubble Column,' *Chem. Eng. Sci*., 52, 21/22, 4111-4116, 1997.

Kojima, H., Okumura, B., and Nakamura, A., 'Effect of Pressure on Gas Holdup in a Bubble Column and a Slurry Bubble Column,' *J. Chem. Eng. Japan*, 24, 1, 115-117, 1991.

Kölbel, H., Borchers, E., and Langemann, H., *Chemie -Ing. -Techn*., 33. 668. 1961.

Kumar, S. B., Computed Tomography Measurements of Void Fraction and Modeling of the Flow in Bubble Columns, PhD Thesis, Florida Atlantic University, Boca Raton, FL, 1994.

Kumar, S. B., Moslemian, D., and Dudukovic, M. P., ‘A Gamma Ray Tomographic Scanner for Imaging Void Fraction Distribution in Bubble Columns,’ *Flow Meas. Instr*., 6, 1, 61, 1995.

Kumar, S. B., Moslemian, D., and Dudukovic, M. P., ‘Gas Holdup Measurements in Bubble Columns Using Computed Tomography,’ *AIChE J*., 43, 6, 1414-1425, 1997.

Lin, T.-J., Tsuchiya, K., and Fan, L.-S., ‘Bubble Flow Characteristics in Bubble Columns at Elevated Pressure and Temperature,’ *AIChE J*., 44, 3, 545-560, March 1998.

Oyevaar, M. H., De La Rie T., Van Der Sluijs, and Westerterp, K. R., ‘Interfacial Areas and Gas Holdups in Bubble Columns and Packed Bubble Columns at Elevated Pressures,’ *Chem. Eng. Process*., 26, 1-14, 1989.

Oyevaar, M. H., and Westerterp, K. R., ‘Mass Transfer Phenomena and Hydrodynamics in Agitated Gas-Liquid Reactors and Bubble Columns at Elevated Pressures: State of the Art,’ *Chem. Eng. Process*., 25, 85-98, 1989.

Reilly, J. G., Scott, D. S., de Bruijn, T., Jain, A., and Diskorz, J., ‘Correlation for Gas Holdup in Turbulent Coalescing Bubble Columns,’ *Can. J. Chem. Eng*., 64, 705, 1986.

Shollenberger, K. A., Torczynski, J. R., Adkins, D. R., and O’Hern, T. J., “Bubble Column Measurements Using Gamma Tomography,” ASME FED, Fluid Measurement and Instrumentation, 211, 25-30, 1995.

Shollenberger, K. A>, Torczynski, J. R., Adkins, D. R., O’Hern, T. J., and Jackson, N. B., “Gamma-densitometry Tomography of Gas Holdup Spatial Distribution in Industrial-Scale Bubble Columns,” *Chem. Eng. Sci.*, 52, 13, 2037-2048, 1997.

Wilkinson, P. M., Spek, A. P., and van Dierendonck, Laurant L., ‘Design Parameters Estimation for Scale-Up of High-Pressure Bubble Columns,’ *AIChE J*., 38, 4, 544-554, 1992.

Wilkinson, P. M., and van Dierendonck, Laurent L., ‘Pressure and Gas Density Effects on Bubble Break-Up and Gas Hold-Up in Bubble Columns,’ *Chem. Engng. Sci*., 45, 8, 2309-2315, 1990.