Proceedings of 30th Indian Engineering Congress, the 21st Century Engineering: The Make in India Pathway, *December 2015*, pp. 123-128

Hydrodynamics of a Tapered Bubble Column for Two-phase Air-water and Air-electrolyte Systems

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Abstract

The hydrodynamic behaviors of a single-stage tapered bubble column using air-water and air-electrolyte two-phase systems have been reported in this article. Experimental results indicate that the hold up is increased with the increase in the superficial gas velocity. The gas flow rate however, does not have appreciable effect on the pressure drop owing to the dynamic pressure recovery stemming from the increase in the flow area in the axial direction. The energy dissipation has been increasing with the gas flow rate. The trend of hold up and pressure drop, and energy dissipation are similar for both the systems. Finally, correlations are put forward for predicting the hold up and pressure drop for the air-water system and are statistically highly functional.

Keywords: Air-electrolute, Air-water, Hydrodynamics, Tapered Bubble Column

1. Introduction

Bubble column or slurry bubble column reactor has emerged as one of the most promising devices in chemical, biochemical and environmental engineering operations. Bubble columns provide several advantages over other gas-liquid contacting devices because of its simple construction and operation, absence of any moving parts, isothermal condition, high heat and mass transfer rates and online catalyst addition and withdrawal[1,6,9,14,19] though it has some drawbacks, such as back mixing between the phases and bubble coalescence. Some of the specific uses include hydrogenation, crystallization, fermentation, water treatment, air pollution control etc.

Depending on the shape, bubble columns are accordingly named as conventional (uniform cross-section with cylindrical or rectangular in shape) bubble column and tapered (varied cross-section) bubble column. Various aspects such as hydrodynamics, interfacial area of contact and mass transfer coefficients of conventional bubble columns have been reported in the literature[2,3,5,7,16]. The flow behavior in a tapered bubble column was reported in details elsewhere in the literature[1]. The principal feature of a tapered bubble column is the increase in the cross-sectional area continuously from bottom to top. The increase in the flow area in the upward direction of the column may also result in the dynamic pressure recovery during operation

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that cannot be normally achieved in a conventional column.

The research investigation carried out on the tapered bubble column so far is scanty in the existing literature. Some studies of available literature are reviewed here. Zhang[17] investigated the distribution of axial solid concentration in tapered and cylindrical slurry bubble columns using air as the gas phase, tap water as the liquid phase and quartz sand as the solid phase and predicted axial solid concentration by developing an empirical correlation using the Peclet number. Zhang et al.[19] investigated the gas hold up characteristics for two and three phases in a 3 m long tapered bubble column having a tapered angle of 1.91^0 with internal diameters of 0.10 m at the bottom and 0.20 m at the top. Zhang and Zhao[18] explored the tools for developing low temperature methanol synthesis in circulating slurry bubble column reactors for commercial application. Bandyopadhyay and Biswas[1] studied the hydrodynamics of a single stage tapered bubble column with a tapered angle of 7^O using an air-water two phase system. Critical appraisal of the existing literature revealed that hydrodynamics of the tapered bubble column at varied tapered angle was not studied in details. Also the effect of presence of electrolytes in the aqueous phase has not yet been explored.

2. Experimental Methods

A single stage tapered bubble column was designed and fabricated with an angle of divergence of 10.84°. The top and bottom diameters of the 1.00 m column were 0.269 m and 0.08 m respectively. A maximum vertical height of 0.564 m was used in the present experiment. A sparger disc of 80 mm diameter was placed at the bottom of the tapered column containing 93 numbers of holes each having 0.8 mm of diameter. The experiments were conducted at 297± 2 K under various operating conditions as follows: static liquid volume (V_{QL}) from 2.00×10^{-3} m^3 to 8.00×10^{-3} m^3 and gas flow rates from 3.3×10^{-4} m^3/sec to 16.6×10^{-4} m^3/sec. The hold up (ε_g) was determined from the ratio of the difference in the volume of the dispersion (V) and volume of the quiescent liquid (V_{QL}) to the volume of the dispersion (V) as given below

$$\varepsilon_g = \frac{\left(V - V_{QL}\right)}{V} \tag{1}$$

The respective oblique heights were recorded from various experimental conditions and by using the principle of solid geometry corresponding volumes were determined as given below[1]:

$$\varepsilon_g = \frac{\left(V - V_{QL}\right)}{V} = \left(\frac{h_d}{h_d + h_q}\right)\left[\frac{\left(D_T^2 + D_T D_{Tq} + D_{Tq}^2\right)}{\left(D_T^2 + D_T D_B + D_B^2\right)}\right] = \left(\frac{H_d}{H_d + H_q}\right)\left[\frac{\left(D_T^2 + D_T D_{Tq} + D_{Tq}^2\right)}{\left(D_T^2 + D_T D_B + D_B^2\right)}\right] \tag{2}$$

In the present study, the cross-sectional area was calculated from logarithmic mean column diameter obtained from the top of the dispersion and the bottom of the column as follows:

$$\text{LMCA} = \frac{\pi}{4}\left[\text{logarithmic mean column diameter}\right]^2 = \frac{\pi}{4}\left[\frac{\left(D_T - D_B\right)}{\ln\left(D_T / D_B\right)}\right]^2 \tag{3}$$

Therefore, superficial gas velocity was calculated from the following expression

$$U_g = \frac{\text{volumetric gas flow rate}}{\text{LMCA}} = \frac{Q_g}{\frac{\pi}{4}\left[\frac{\left(D_T - D_B\right)}{\ln\left(D_T / D_B\right)}\right]^2} \qquad 4)$$

3. Results and Discussion

3.1 Effect of Superficial Gas Velocity on the Hold Up

The effect of superficial gas velocity on the hold up for air-water two-phase system is shown in Figure 1 at various quiescent liquid volumes. The hold up was increased with the increase in the superficial gas velocity, U_g. It might be attributed to the fact that as the gas was moving upward, its velocity was reduced owing to increase in the cross-sectional area that induced lower bubble velocities leading to longer residence time that resulted in the higher gas hold up in the column. Increase in the holdup might also be due to the increase in the number of smaller bubbles stemming from higher bubble breakup frequency at higher values of the superficial gas velocity.

Experiments were also conducted for air-electrolyte (salt) two-phase system at a constant liquid volume of 4×10^3 m^3. The effect of superficial gas velocity on the hold up for this system is also shown in Figure 1. It can be seen from the figure that the hold up was higher in case of salt solutions at higher gas flow rates than in air-water system alone and thus the upper cross-section of the dispersion was increased resulting in the drop in velocity at that plane resulting in the recovery of dynamic pressure. Also the hold up was increased with the increase in concentration of the electrolyte solution. Furthermore, the hold up was higher in case of Na_2SO_4 and $CaCl_2$ than NaCl solution as well as air-water two phase system.

3.2 Effect of Quiescent Liquid Volume on the Hold Up

It was reported earlier in the literature Bandyopadhyay and Biswas[1] that higher values of the hold up could be observed for lower values of quiescent liquid volumes within the range of superficial gas velocities studied. This was due to the fact that the fraction of liquid in the column was increased with the increase in the V_{QL}, thus the holdup was reduced at higher values of V_{QL} under similar operating conditions. In the present investigation, similar effect was resulted without showing any transition zone (Figure 1). It might be owing to the lower and narrower range of U_g used in the present study than investigated by Bandyopadhyay and Biswas.

3.3 Effect of Gas Flow Rate on the Pressure Drop

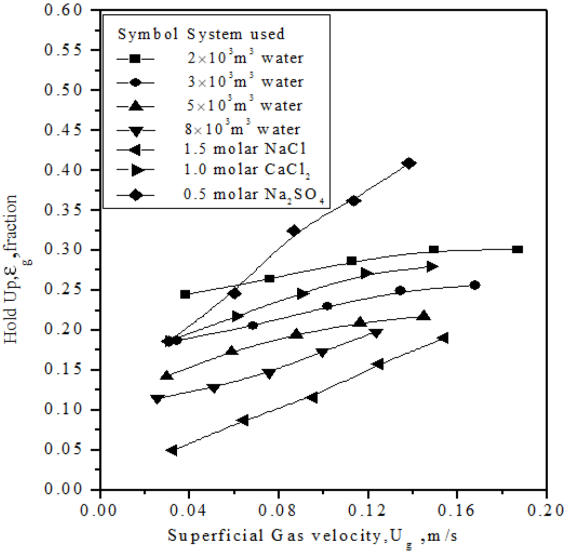

Figure 1. Effect of superficial gas velocity on the hold up for air-water and air-electrolyte solution two phase system in the tapered bubble column.

The effect of the gas flow rate on the Pressure drop for the air-water and air-electrolyte systems across the tapered column under varied quiescent batch operating conditions is shown in Figure 2. It can be seen from the figure that the pressure drop was practically remained almost constant with the increase in the gas flow rate. The pressure drop was varied between 2028.747 N/m^2 and 5071.868 N/m^2 within the framework of the present investigation. The pressure drop observed and reported by Bandyopadhyay and Biswas[1] was varied from 289.04 N/m^2 to 496.83 N/m^2 in a tapered bubble column with lower divergence angle as discussed earlier. Clearly, it can be seen that higher superficial gas velocities ($2.5\times10^{-3} m^3/s$ - $6.67\times10^{-3} m^3/s$) used yielded lower ΔP than in the present case.

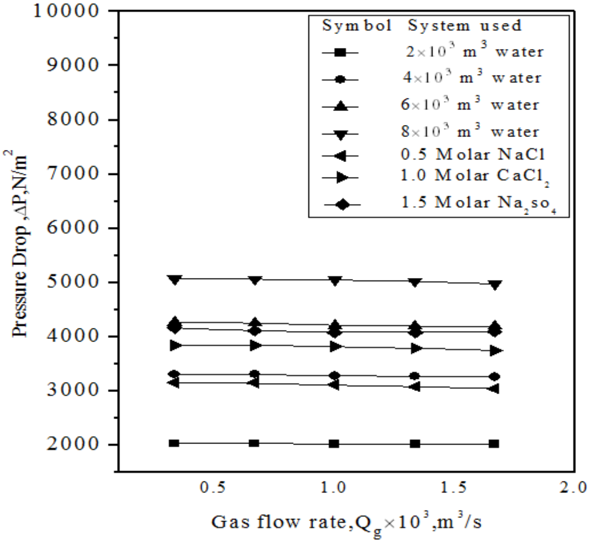

Figure 2. Effect of gas flow rate on the pressure drop for air-water and air-electrolyte two phase system in the tapered bubble column.

3.4 Effect of Gas Flow Rate on the Energy Dissipation

The effect of gas flow rate on the energy dissipation is shown in Figure 3. It can be seen from the figure that the energy dissipation in increasing with the gas flow rate. It can further be seen from Figure 3 that the energy dissipation for air-water two phase systems was slowly decreased with the quiescent liquid volume initially and thereafter increased. The energy dissipation in the air-water system was varied between 789.72 W/m^3 and 1135.4 W/m^3 of dispersion at gas flow rate 16.66×10^{-4} m^3/sec. The range of energy dissipation however, reported by Bandyopadhyay and Biswas[1] to be varied between 127 and 356 W/m^3 of the dispersion for air-water system alone. The effect of gas flow rate on the energy dissipation for air-electrolyte system is also shown in Figure 3 at a constant batch liquid volume of 4×10^3 m^3. The energy dissipation was increased linearly with the increase in gas flow rate in all the cases similar to air-water system. However, the energy dissipation observed for 1.0 M NaCl and 0.5 M NaCl solutions were relatively lower than others since the pressure drop was relatively lower in these cases as elucidated earlier.

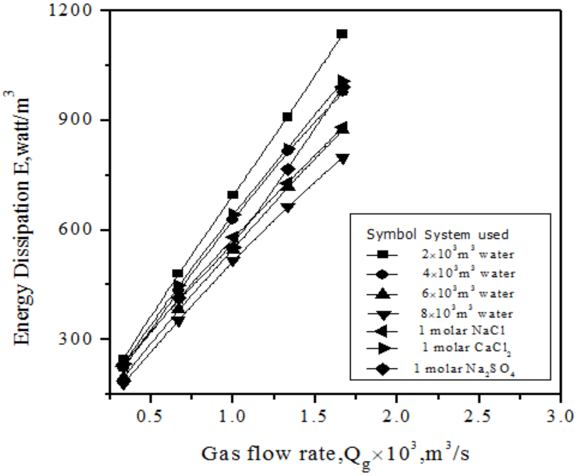

Figure 3. Effect of the energy dissipation for air-water and air-electrolyte two phase system at various gas flow rates in the tapered bubble column.

3.5 Prediction of Hold Up and Pressure Drop through Correlations

A correlation was developed for predicting the hold up for air-water system analogous to the well known Akita-Yoshida[11] correlation as a function of various pertinent variables of the system by multiple non-linear regression analysis. The correlation developed was statistically highly significant (at 99.0% confidence range with correlation coefficient of 0.9893 and coefficient of determination of 0.9788). The predicted values agreed excellently well with the measured values (standard error 0.0579). The developed correlation with the coefficient and exponents are given as follows

$$\left[\frac{\varepsilon_g}{(1-\varepsilon_g)^4}\right] = 1.0\left(\frac{gD^2\rho_L}{\sigma_L}\right)^{-1.36}\left(\frac{gD^3}{v_L^2}\right)^{0.2708}\left(\frac{U_g}{\sqrt{gD}}\right)^{0.5507} = 1.0[N_{BO}]^{-1.36}[N_{Ga}]^{0.2708}[N_{Fr}]^{0.5507} \quad (7)$$

A correlation was also developed for predicting the pressure drop for air-water system as a function of various pertinent variables of the system by multiple non-linear regression analysis. The correlation developed was statistically highly significant (at 99.0% confidence range with correlation coefficient of 0.9997 and coefficient of determination of 0.9995). The predicted values agreed excellently well with the measured values (standard error 0.0117). The developed correlation with the coefficient and exponents are given as follows

$$\left[\frac{\Delta P}{\rho_g U_g^2}\right] = 8.09\times10^4\left[\left(N_{ReG}\right)^0.\left(N_{Fr}\right)^{-3.0313}.\left(N_{We}\right)^{0.5140}.\left(\varepsilon_g\right)^{-0.1830}\right] \quad (8)$$

4. Conclusion

In this article, the performances of a tapered bubble column for air-water and air-electrolyte two-phase systems under batch operating conditions were reported. Experimental results revealed that the hold up was increased with the increase in the superficial gas velocity. The hold up was varied between 5.526 % ($V_{QL} = 4\times10^{-3}$ m^3; $Q_G = 2\times10^{-4}$ m^3/s) and 17.865 % ($V_{QL} = 3\times10^{-3}$ m^3; $Q_G = 8\times10^{-4}$ m^3/s) for air-water system. The pressure drop for air-water system was practically remained almost constant with the increase in the gas flow rate for both systems. The pressure drop was varied between 2028.74 N/m^2 and 5071.86N/m^2 within the hydrodynamic regimes studied. The energy dissipation was increased with the increase in the gas flow rate for air-water system. The energy dissipation in the air-water system varied from 789.72 to 1135.4 W/m^3 of dispersion. The effect of superficial gas velocity on the hold up at various electrolyte concentrations indicated that the hold up was increased with the concentration of electrolyte and also with the increase in the ionic strength of the solution. It was attributed to the fact that electrolyte had reduced the surface tension of water and thereby causing smaller bubbles to stable for longer period of time and as a result, bubble coalescence as well as bubble bursting was prevented compared to that occurred in case of air-water system alone. Finally correlations were developed for predicting the hold up and pressure drop for air-water two phase systems which were statistically highly functional.

5. References

1. Bandyopadhyay A, Biswas MN. Hydrodynamics of a Tapered Bubble Column. Chemical Engineering and Technology. 2011; 34:186–200.
2. Buffiere P, Moletta R. Some Hydrodynamic Characteristics of Inverse Three Phase Fluidized Bed Reactors. Chemical Engineering Science. 1999; 54(9):1233–42.
3. Comte MP, Bastoul D, Hebrard G, Roustan M, Lazarova V. Hydrodynamics of a Three Phase Fluidized Bed–the inverse turbulent bed. Chemical Engineering Science. 1997; 52:3971–7.
4. Deckwer WD. Bubble Column Reactors. Chichester, UK: John Wiley & Sons; 1992.
5. Deckwer WD, Schumpe A. Improved Tools for Bubble Column Reactor Design and Scale up. Chemical Engineering Science. 1993; 48(5):889–911.
6. Fan LS. Gas–liquid–solid fluidization engineering. Stoneham, USA: Butterworth Pub.; 1989.
7. Havelka P, Linek V, Sinkule J, Zahradnik J, Fialova M. Hydrodynamic and Mass Transfer Characteristics of Ejector Loop Reactors. Chemical Engineering Science. 2000; 55:535–49.
8. Hyndman CL, Larachi F, Guy C. Understanding Gas phase Hydrodynamics in Bubble Columns: a convective model based on kinetic theory. Chemical Engineering Science. 1997; 52(1):63–77.
9. Joshi JB. Computational Flow Modeling and Design of Bubble Column Reactors. Chemical Engineering Science. 2001; 56(21–22):5893–933.
10. Kantarcia N, Borakb F, Ulgen KO. Bubble Column Reactors. Process Biochemistry. 2005; 40:2263–83.
11. Akita K, Yoshida F. Gas Holdup and Volumetric Mass Transfer Coefficient in Bubble Columns, Effects of Liquid Properties. Industrial & Engineering Chemistry Process Design and Development. 1973; 12(1):76–80.
12. Maruyama T, Sato H. Liquid Fluidization in Con-

ical Vessels. Chemical Engineering Journal. 1991; 46(1):15–21.

13. Schumpe A, Grund G. The Gas Disengagement Technique for studying Gas Holdup Structure in Bubble Columns. The Canadian Journal of Chemical Engineering. 1986; 64(6):891–6.
14. Shah YT, Kelkar BG, Godbole SP, Deckwer WD. Design Parameter Estimation for Bubble Column Reactors. AIChE Journal. 1982; 28(3):353–79.
15. Thorat BN, Joshi JB. Regime Transition in Bubble Columns: Experimental and Predictions. Experimental Thermal Fluid Science. 2004; 8:423–30.
16. Ueyama K. Practical handbook of bubble column and three phase fluidized bed. Tokyo, Japan: IPC; 1993.
17. Zhang K. Axial Solid Concentration Distribution in Tapered and Cylindrical Bubble Columns. Chemical Engineering Journal. 2002; 86(3):299–307.
18. Zhang K, Zhao Y. A Scale up Strategy for Low Temperature Methanol Synthesis in a Circulating Slurry Bubble Reactor. Chemical Engineering Science. 2006; 61(5):1459–69.
19. Zhang K, Zhao Y, Zhang B. Gas Holdup Characteristics in a Tapered Bubble Column. International Journal of Chemical Reactor Engineering. 2003; 1:1–7.

Appendix

Nomenclature and Greek Symbols

D_B	diameter at the bottom of the tapered bubble column, m
D_T	diameter at the top of the tapered bubble column with dispersion, m
D_{Tq}	diameter at the top of the tapered bubble column with quiescent liquid, m
E	energy dissipation per unit volume of dispersion, W/m^3
g	acceleration due to gravity, 9.81 m/s^2
h_d	vertical height of the dispersion in the tapered bubble column, m
H_d	oblique height of the dispersion in the tapered bubble column, m
h_q	vertical height of the quiescent liquid in the tapered bubble column, m
H_q	oblique height of the quiescent liquid in the tapered bubble column, m
LMCA	logarithmic mean cross-sectional area, m^2
Q_g	volumetric flow rate of gas, m^3/s
T	temperature, K
U_g	superficial gas velocity, m/s
V	volume of the dispersion, m^3
V_{QL}	volume of the quiescent liquid, m^3
ε_g	gas hold up, dimensionless
$\rho_{glycerine}$	density of glycerine, kg/m^3
Δh	differential height in manometer, m
ρ_g	density of gas, kg/m^3
ρ_L	density of liquid, kg/m^3
$\boldsymbol{\sigma}_L$	surface tension of liquid, N/m
$\boldsymbol{\nu}_L$	kinematic viscosity of liquid, m^2/s
μ_L	viscosity of liquid, kg/ms
N_{BO}	Bond number $[gD^2\rho_L/\boldsymbol{\sigma}_L]$
N_{Ga}	Galileo number $[gD^3/\boldsymbol{\nu}_L^2]$
N_{Fr}	Froude number $[U_g/\sqrt{gD}]$
N_{ReG}	Gas phase Reynolds number $[DU_g\,\rho_L/\mu_L]$
N_W	Weber number $[DU_g^2\rho_g/\boldsymbol{\sigma}_L]$