Experimental study on bubble absorber with multiple tangential nozzles

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Abstract

Visualization study of bubble growth with multiple tangential nozzles is investigated in a bubble absorber. Bubble behavior is studied with different flowing condition like still, co-current and counter-current flow of water. Effect of air flow rate, water flow rate, nozzle diameters, number of nozzles and orientation of nozzle angle with reference to vertical plane on bubble diameter is studied. Results are compared with the available information which is found to be in good agreement. Bubble diameter during detachment increases with increase in gas flow rate in all the above flow conditions. Performance between single and double nozzle also compared and presented in this paper. Based on this study non-dimensional correlations are proposed.

1. Introduction

Formation and growth of gas bubbles and their rise due to buoyancy are very important to the hydrodynamics of gas-liquid interference study. The phenomenon of bubble formation decides the primitive bubble size in the system whereas the rise velocity decides the characteristic contact time between the phases which govern the interfacial transport phenomena as well as mixing. The use of bubbling devices, where in bubbles is produced by injecting gas through submerged nozzles or orifices occurs in a large number of technical applications like bubble absorber, water treatment, metallurgy, and chemical processing plants. Bubble absorber is an important component of vapour absorption refrigeration system for heat and mass transfer. Absorption process is one of heat and mass transfer process occurs in bubble absorber in which a gas bubble with the liquid to increase heat and mass transfer. Kang *et al.* (2000) carried out analytical investigation of falling film and bubble type absorbers and found that absorption rate of the bubble type absorber was found to be always higher than that of the falling film mode. Bubble type absorber provides better heat and mass transfer coefficients, also good wettability and mixing between the liquid and the vapor. Elperin and Fominyk (2003) studied combined heat and mass transfer mechanisms at all stages of bubble growth and rise in a bubble absorber, which can be useful in design calculations of gas–liquid absorbers. A number of fluid combinations used in bubble absorber for bubble dynamic as well as VAR system study, suggested by number of investigator. Different combination used for bubble dynamic study like air-water, glycerol-air, methanol-air, ethanol-air, etc and for VAR system ammonia–water, water-lithium bromide, R134a-DMF, etc.

A wide range of research have been reported in the literature about bubble formation from a nozzle and the effect of orifice diameter, air flow rate and liquid properties, flowing condition on bubble formation, growth and detachment have been considered. Bubble dynamic study started with numerical models developed for bubble formation with different properties of gas and compared experimentally under constant flow, Ramakrishnan *et al.* (1969) and under constant pressure condition, Satyanaryan *et al.* (1969). A simulation and experimental study conducted for single and multi orifice to know various effect bubble dynamics for different fluid under constant gas flow conditions by Li *et al*. (2000). Bari and Robinson (2013) proposed the bubble growth and pressure field adiabatically in submerged orifice at low gas flow rate by image processing. Bubble formation from single horizontal orifices submerged in Newtonian liquids has been investigated for chamber pressure and flow rate which are time dependent by Khurana and Kumar (1969). Gaddis and Vogelpohil (1986) developed an equation theoretically to predict the bubble detachment diameter in quiescent liquids under constant volumetric gas flow conditions in bubbling regime to transition regime with viscosity Wraith (1971) proposed a two stage model for the formation of gas bubbles and bubble coalescence between detaching bubble from a plate orifice submerged in an inviscid liquid at high gas injection rates. Jamialahmadi *et al.* (2001) done experimental and theoretical investigation on bubble formation under constant flow conditions for air and variety of solutions. A numerical simulation and experiment study done for bubble formation at submerged orifices under constant inflow conditions with variation of fluid properties, Gerlach *et al.* (2007). Das *et al.* (2011) investigated experimentally and analytically on bubble dynamic as a function of gas flow rate for three different submerged orifice sizes at various pool heights. Effect of nozzle shape and operating parameter on bubble formation from vertically downward nozzle study was investigated, Tsuge *et al.* (2006). This study shows the bubble formation and bubble size are influenced by the edge angle of nozzle, inner and outer diameters of nozzle and gas flow rate. Experimental and numerical investigations have been carried out by Suresh and Mani (2010) by visualing bubble behavior and studying the effect of gas flow rate and liquid concentration on bubble characteristics of R134a– DMF solution in a glass absorber. Bubble behavior was studied in still and flowing solution. Different measuring techniques were used in many literatures to measure the bubble shape, bubble diameter and bubble frequency. Akita and Yoshida (1974) measured bubble size by using photographic method for fluid pairs. Single and two phase heat transfer in a vertical flow with tangential injection nozzle with heat transfer study done by Guo and Dhir (1989).

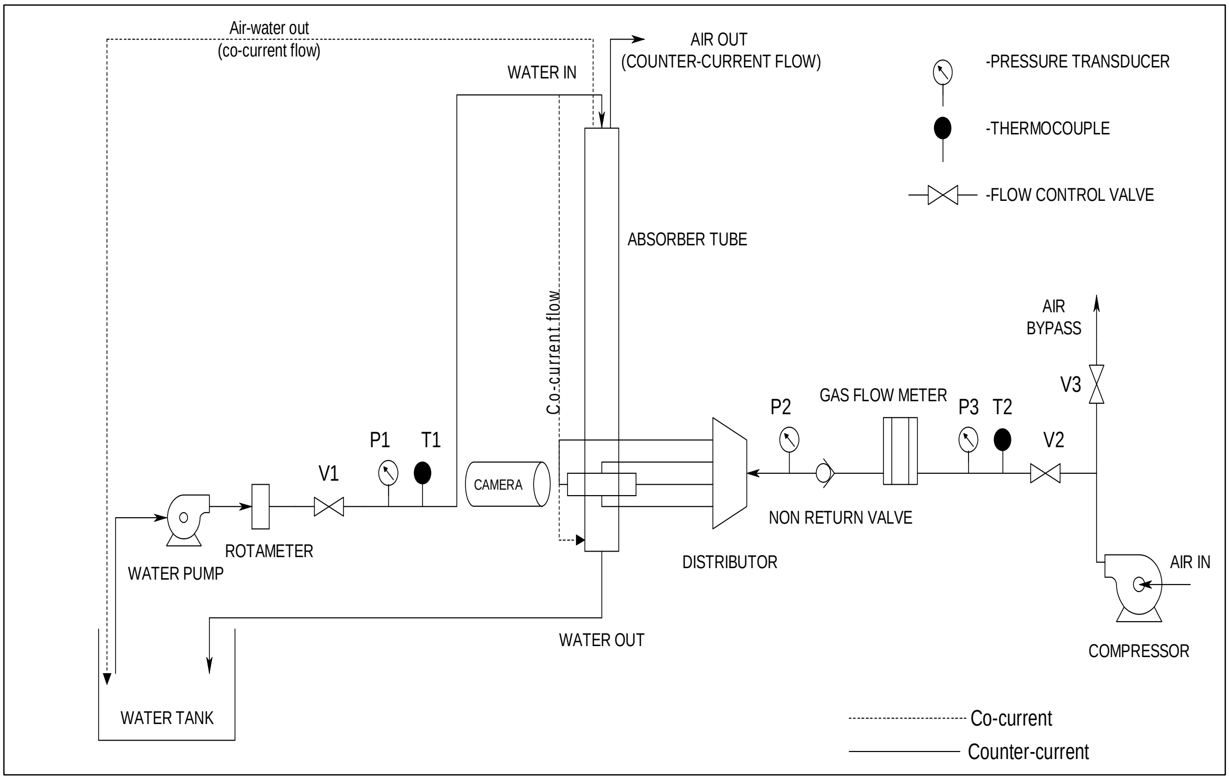

Figure 1 Schematic diagram for bubble absorber set up.

2. Experimental study

A Schematic diagram of bubble absorber experimental set up is shown in Fig.1 and a photograph of the experiment set up is shown in Fig. 2. The set up consists of bubble absorber, angle measurement device, water tank, water pump, air compressor, nozzles with polymer bearing, flow distributor, pressure, temperature and flow measuring instruments, and various control valves. Bubble absorber and angle measurement device are made up of acrylic (Polymethyl methacrylate). Acrylic tube is used for observing of bubble phenomena in the absorber to enable visualization and capture photographs while release from nozzles. A centrifugal pump to supply water to the water circuit is connected at bottom and top of the tube to realise co-current and counter-current flow configurations respectively, while other end is connected back to tank. A glass tube rotameter, flow control valve and bypass valve in water circuit are used to control the flow rate of water. At room temperature water flow rate was varied between 1 lpm to 3.72 lpm. A two stage reciprocating compressor with storage tank capacity of 220 liters and maximum

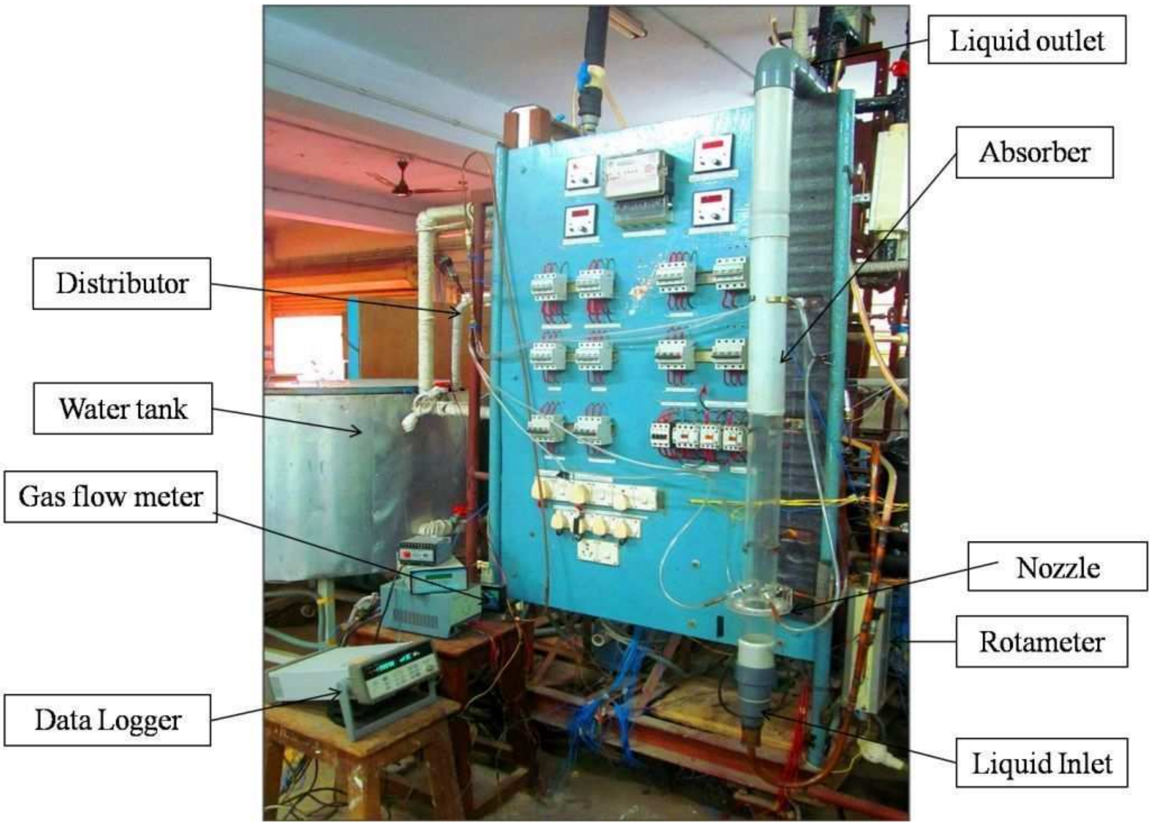

Figure 2 Photograph of bubble dynamic experimental set up

working pressure of 12.5 bar is used to supply air. Experiments were conducted under constant inlet pressure; which was achieved by bypassing a portion of compressor discharge to surrounding. A thermal mass flow controller based gas flow meter is used to measure air flow rate before it is admitted to distributer. Distributer is assumed to distribute flow equally to nozzles; a non-return valve is fitted to ensure that water does not flow back to gas flow meter when no air supply. Bubbles grow at the bottom of absorber tube where air is injected through copper nozzles. Standard copper tubes of inner diameter 1.7 mm, 3.2 mm, 4.8 mm are fitted on the periphery of absorber tube to inject air. The nozzles are fitted using spherical bearing so that it can be tilted in vertical and horizontal plane to study effect of inclination on bubble detachment diameter. Flexible plastic tubes connect distributor outlets to nozzles which also allow free movement of nozzles in bearings. Air, after bubbling through the tube passes along with water stream in case of co-current flow and is vented out through air vent at the top of absorber tube in case of counter-current flow and still water. Pressure and temperature of air are measured at inlet and outlet of the bubble absorber by sensors. A camera placed adjacent to transparent absorber tube was used to take still photographs. All the measuring instruments are pre-calibrated. Three numbers of copper-constantan thermocouple are used with an uncertainty up to ±0.5°C. Four numbers of piezo-electric type pressure transducers and a pressure gauge are used as pressure sensors with a measurement uncertainty up to ±1%. Glass rotameter used to measure the flow rate of water with uncertainty up to ±3%. Mass flow controller unit is used to measure the volume flow rate of air with a measurement uncertainty of ±2%.

Experiments are started by positioning the nozzles at 0° with reference to horizontal using the nozzle holder. The compressor is turned on and discharge valve is kept closed until pressure of 5 bar is reached in the storage tank; then air bypass valve and flow control valve is opened to allow air flow thorough the non-return valve to the absorber tube. Typical air pressure at the inlet of nozzle was recorded in the range of 1.1 to 1.5 bar atmospheric temperature. Water pump is turned on then and a desired co-current, counter-current flow or still water as the case may be; is maintained using rotameter and flow control valve. Air flow is always started before water flow to avoid back flow of water in air circuit and subsequent damage to air flow meter. For a set nozzle angle; air flow rate is accurately measured and varied between 400-900 ccm, water flow rate varied between 1-3.72 lpm for both co-current and counter-current configurations. Then nozzle angle is increased in step of 10° up to 30° and all above variations are repeated. All the parameters viz., water inlet and outlet pressure, temperature, water flow rate, gas flow rate, pressure and temperature, are monitored using a data acquisition logger unit. Photographs are taken for every different set of variables with shutter speed varying from 1/8-1/2500 seconds. A number of photographs are taken to capture detachment stage of bubble. Bubble photographs are taken along with reference objects (measured by a calibrated scale) inside and beside the bubble absorber, which are in parallel with the absorber. These photos are uploaded and zoomed in Adobe Photoshop software version 7.0. Bubble shape either spherical or hemispherical or elliptical is divided into number of segments with different radii. Circles are drawn corresponding to respective radii and superimposed on the zoomed-in profile of bubble image uploaded in Photoshop software Suresh and Mani (2010).

Equivalent volume of sphere
$$V_b = \frac{\frac{\pi}{6}\left(d_1^{\,3} + d_2^{\,3} + d_3^{\,3} + \ldots d_i^{\,3}\right)}{i} \qquad (1)$$

Bubble diameter
$$D_b = \left(\frac{6V_b}{\pi}\right)^{\frac{1}{3}} \qquad (2)$$

The method of estimating bubble diameter is based on the assumption that the bubble is a sphere and the measured diameter is volumetric bubble diameter, based on equivalent volume of a sphere. Also the diameter of nozzle in the photograph was measured using Photoshop software and compared with its actual bubble diameter. This method used as calibration scale to measure the bubble diameter in glass absorber. An uncertainty of 2-3% found in the bubble diameter during number of repeated measurements. Errors due to distortion of the bubble surface and location are taken into account to estimate the bubble diameter. Image processing techniques have been used to read the color value of pixels in the image, to adjust color balance, brightness, contrast and image sharpness of the available quality of the bubble images taken account for the accuracy of measurement.

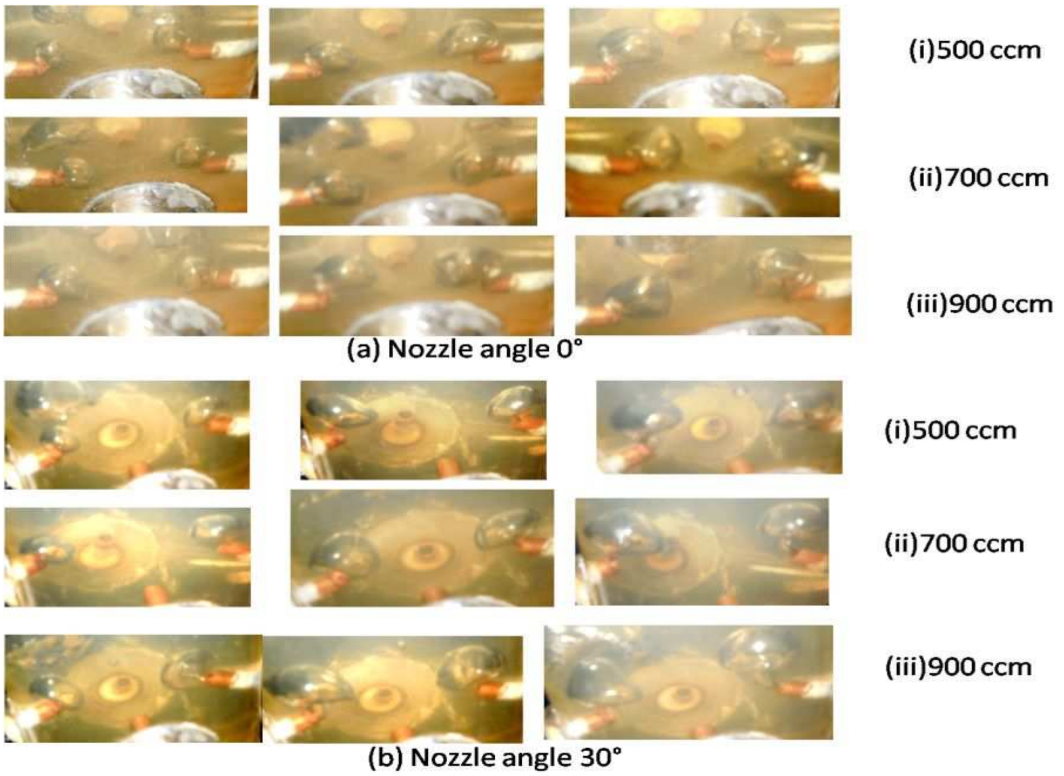

Figure 3 Stages of bubble growth at different air flow rate with still water

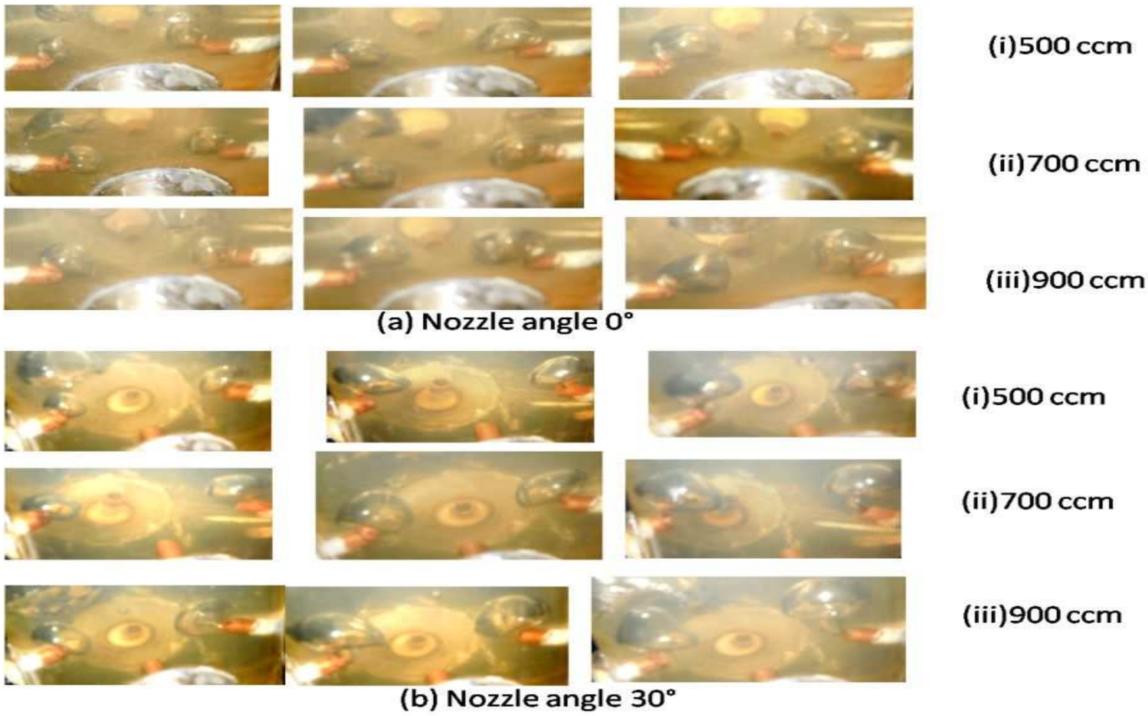

Figure 4 Stages of bubble growth at different air flow rate with co-current water

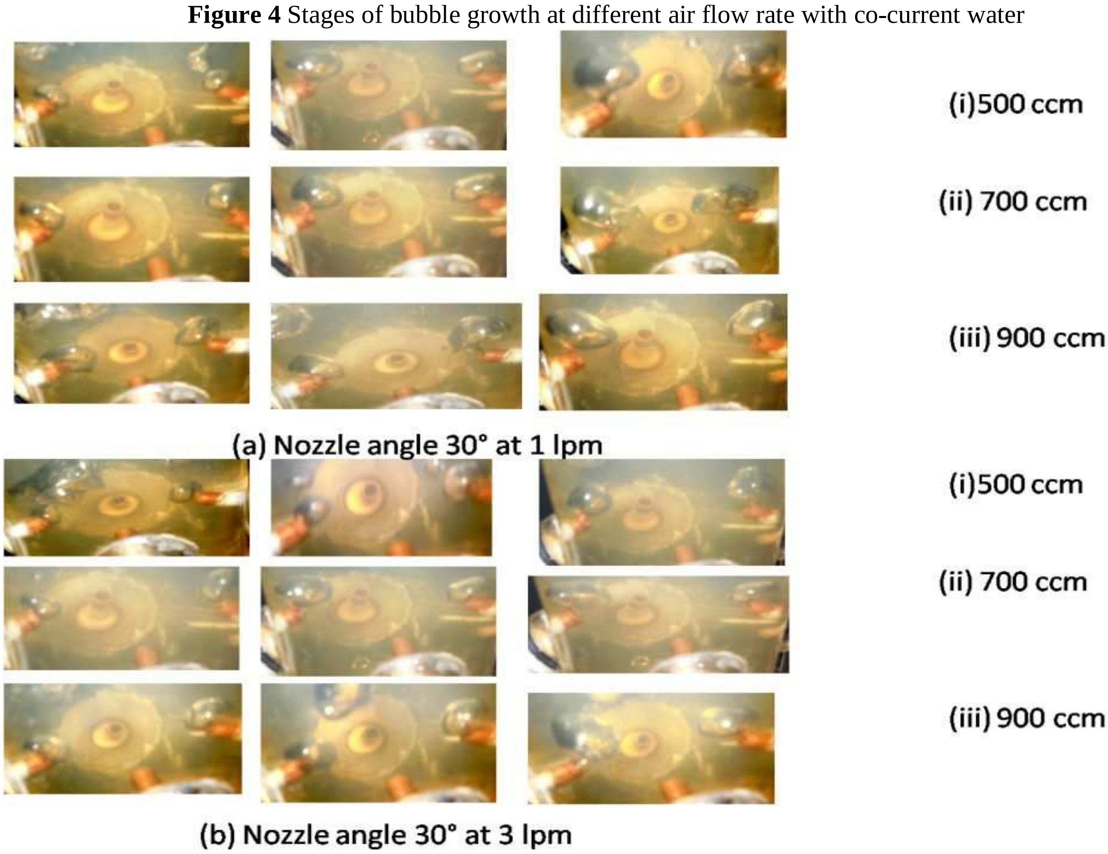

Figure 5 Stages of bubble growth at different air flow rate with counter-current water

3. Results and discussion

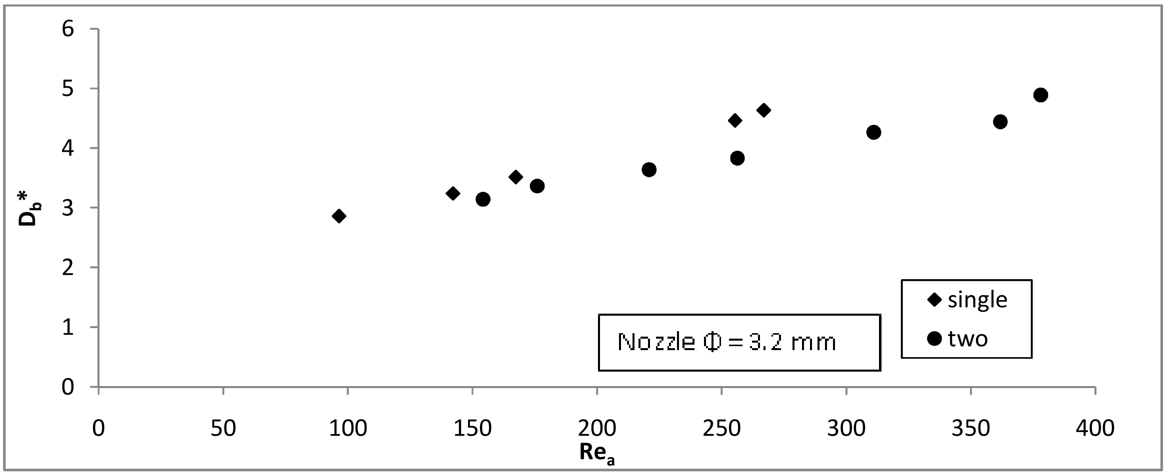

Figure 6 Effect of gas flow rate on bubble diameter in still water for single and two nozzles

Experiments with visualization study were carried out on a bubble absorber system by varying the operating parameters, viz. air flow rate from 300 to 1000 ccm, water flow rate from 1 to 3.72 lpm, three nozzle of inner diameters (4.8 mm, 3.2 mm and 1.7 mm), vertical nozzle angle 0° to 30°, three types water flowing condition (still, co-current and counter-current), one and two number of nozzle used for bubble diameter during detachment at normal pressure and temperature. Figures 3-5 show the visualization of air-water bubble growth at different stage in still, co-current and counter-current water flow with different air flow rate at two different nozzle angles 0° and 30°. Based upon the observations recorded of image at low and continuous gas flow rates, bubble dynamics takes place, bubble growth at the tip of nozzle and detachment from nozzle, then travel to the top due to buoyancy force. Figures 3-5 show three different stages of bubble growth at three different flow rates (500, 700, 900 ccm).

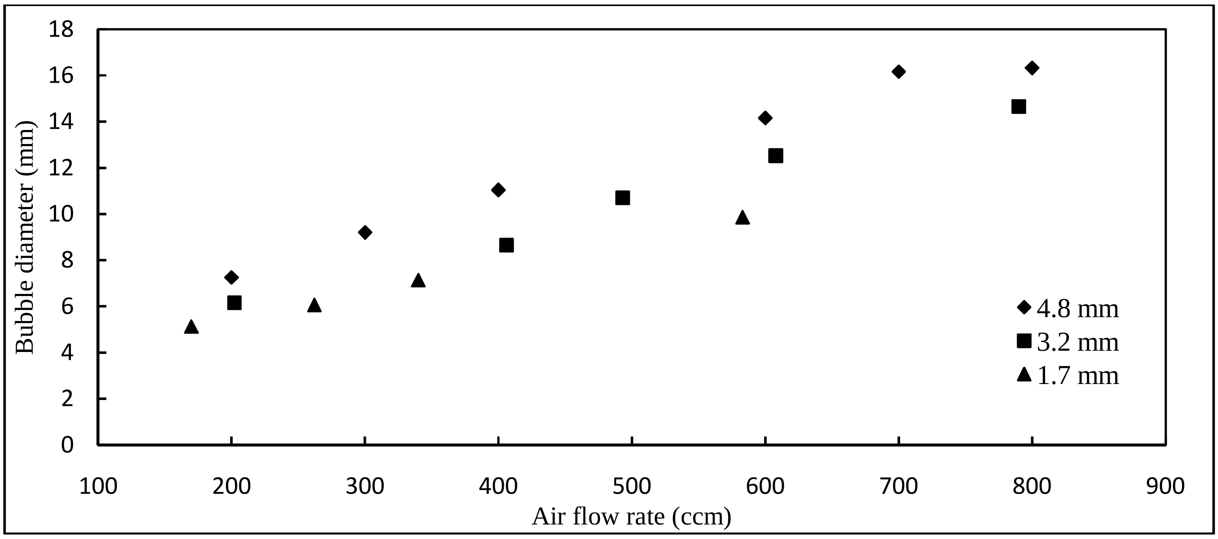

Figure 7 Effect of gas flow rate and nozzle diameter on bubble detachment diameter in still water (Panda and Mani, 2014)

Figure 6 shows the non-dimensional bubble diameter (D_b*) increases with increasing the air flow rate for different nozzle diameters in still water and single nozzle produces more or less same diameter bubble compare to two nozzles. Due to frictional loss the pressure of injecting air decrease so it affects the bubble diameter. Figure 7 shows the bubble diameter comparison between different nozzle diameter for air mass flow rate (Panda and Mani, 2014). It is seen from Figs. 8 and 9 that the non-dimensional bubble diameter for the same Reynolds number of air (Re_a) is tends to increase in co-current flow and decrease in counter-current flow with increase in water flow rate. This decrease in bubble diameter within the tested range of liquid flow rate can be attributed to increased upward force acting on bubble surface caused by liquid; which tends to detach the bubble earlier. Liquid flowing in counter-current flow exerts force on bubble downwards and hence delays the detachment which results in decreased diameter of bubble.

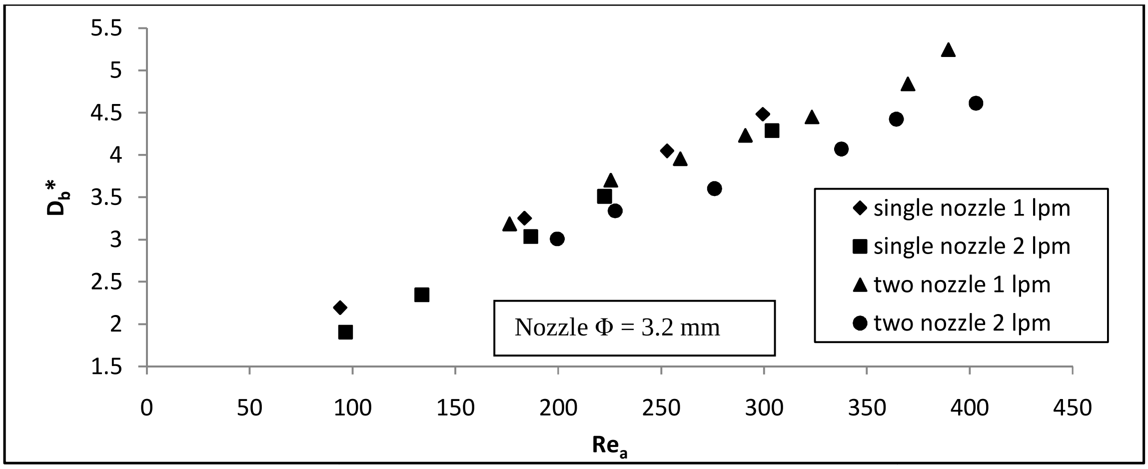

Figure 8 Comparison between one and two nozzle bubble diameter with different air flow rate for co-current water Flow

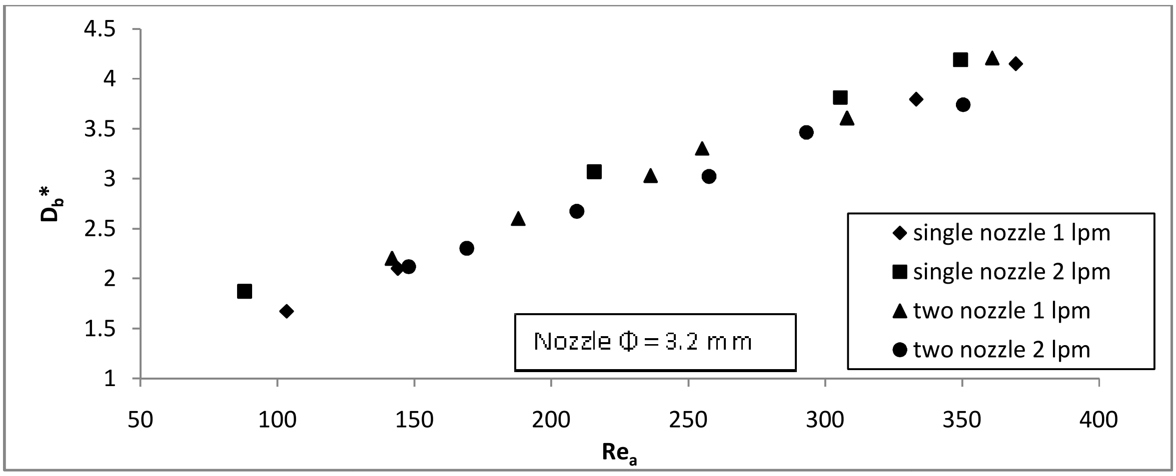

Figure 9 Comparison between one and two nozzle bubble diameter with different air flow rate for counter-current water flow

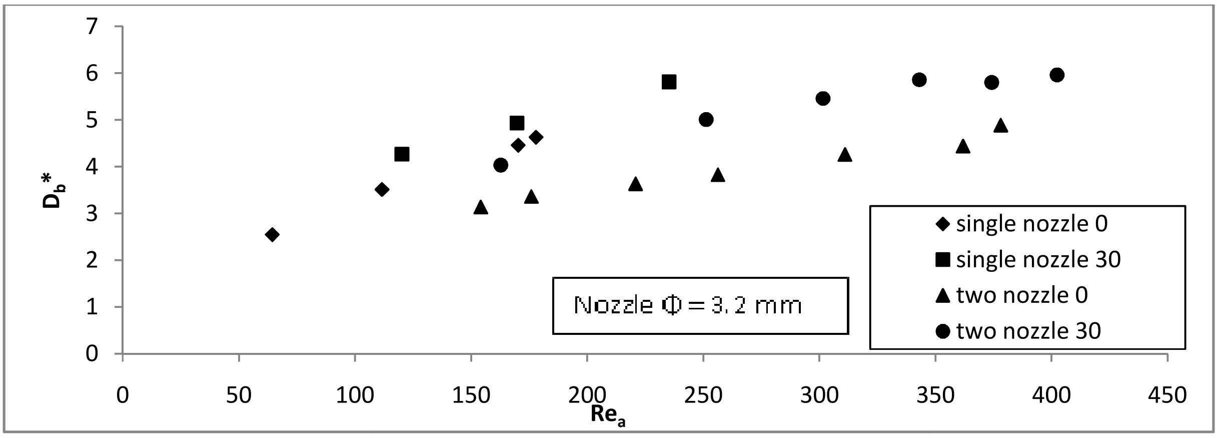

Figure 10 Comparison between one and two nozzle bubble diameter with on 0° and 30° orientation in still water

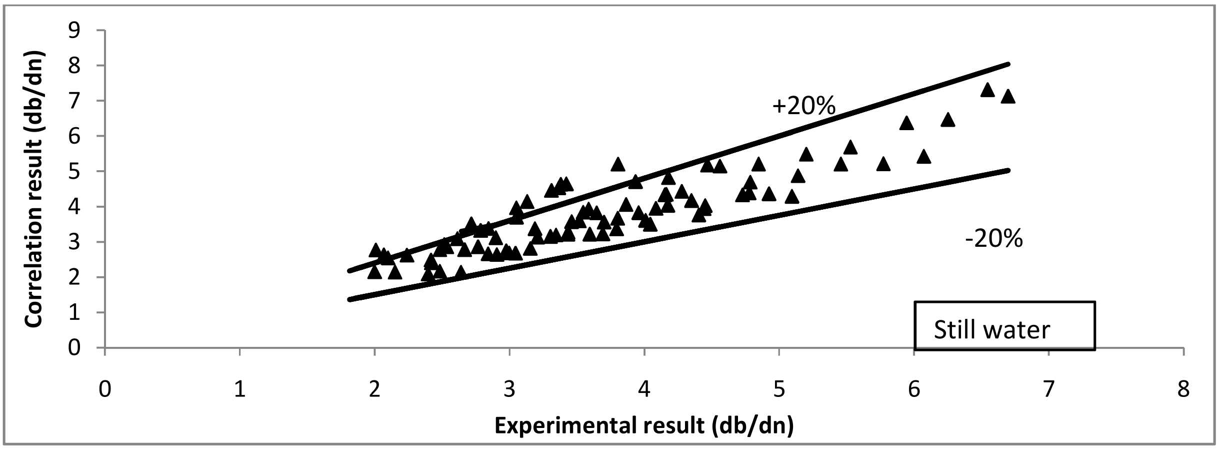

Figure 11 Comparison between experimental and correlation

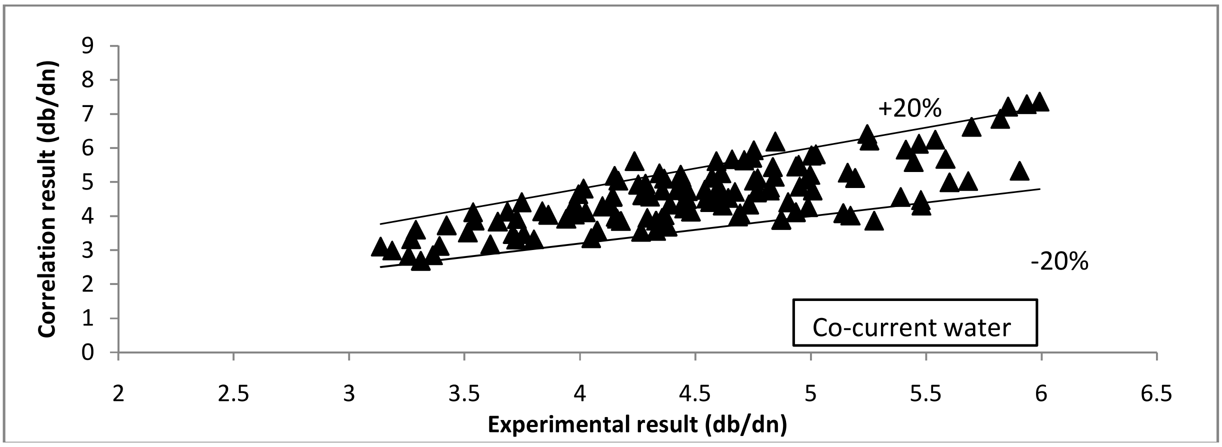

Figure 12 Comparison between experimental and correlation

Figure 10 shows the effect of nozzle angle on bubble diameter. Though the effect is small, it is observed that diameter ratio is smallest for nozzle at 0° angle orientation and it increases with increase in angle. A horizontal nozzle resembles to a cross flow situation, which tends bubble to break off earlier from nozzle resulting in smaller diameter. As the nozzle angle increase the diameter ratio of bubble increases during detachment.

Three correlations were developed for different flow condition like still, co-current and counter current. Figures 11-13 show the comparison between experimental results and correlation data, which is in good agreement within range of ±20% error.

For, Still
$$\frac{d_b}{d_n} = 0.29954(\mathrm{Re}_a)^{0.46774}(N)^{-0.07642}(\cos\theta)^{-0.56625} \quad (3)$$

Co-current
$$\frac{d_b}{d_n} = 0.77686\left(\mathrm{Re}_a\right)^{0.28198}\left(\mathrm{Re}_w\right)^{0.04339}\left(N\right)^{-0.06205}\left(\cos\theta\right)^{0.01288} \quad (4)$$

Counter-current
$$\frac{\mathrm{d_b}}{\mathrm{d_n}} = 0.9937\left(\mathrm{Re_a}\right)^{0.23272}\left(\mathrm{Re_w}\right)^{0.04229}\left(\mathrm{N}\right)^{-0.04783}\left(\cos\theta\right)^{-0.12207} \quad (5)$$

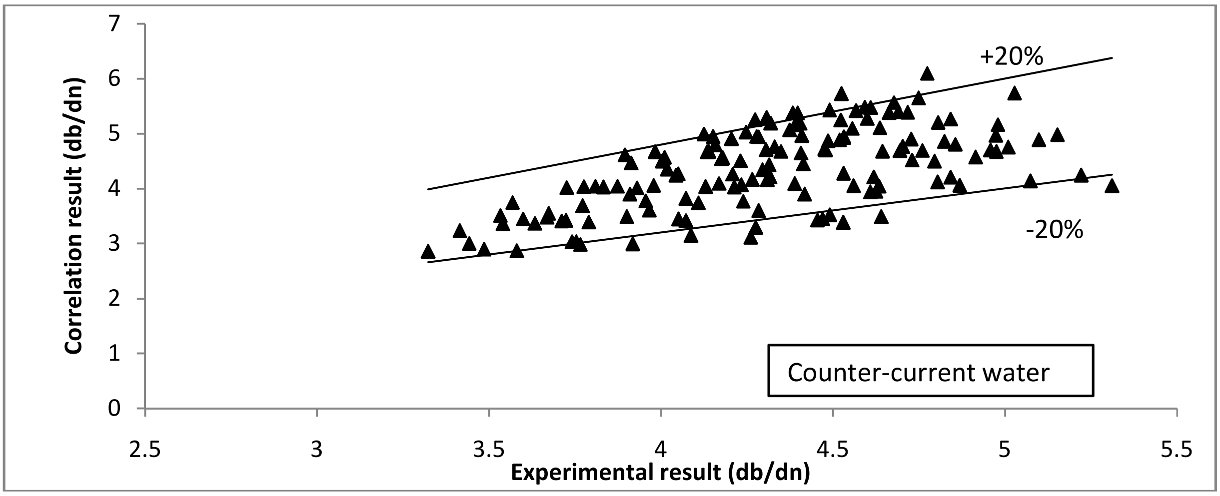

Figure 13 Comparison between experimental and correlation

4. Conclusions

Bubble dynamic study with visualization have been carried out on a bubble absorber experimentally to know the effect of air flow rate, water flow rate, flowing condition, different nozzle diameter, number of nozzles and orientation of nozzle angle. Bubble behavior was visualized using photographic and image processing studies. The diameter of bubble increase as the air flow rate increase with a constant diameter nozzle. As diameter of nozzle increase the bubble diameter also increase. As the number of nozzle increase the bubble diameter also effects. Bubble diameter increases more or less similar with two nozzles compared to one nozzle in a particular volume of liquid. The orientation of inject nozzle angle also affects the bubble diameter, as the nozzle angle increase the bubble diameter increase due to buoyancy effect. A number of correlation developed based on the flowing condition which will useful for bubble dynamic study.

5. References

1. Akita K., Yoshida F., 1974, Bubble size, interfacial area and liquid phase mass transfer coefficient in bubble columns, *Industrial and Engineering Chemistry Process Design and Development*, vol. 13, p. 84 – 91.
2. Bari Sergio Di and Robinson Anthony J., 2013, Experimental study of gas injected bubble growth from submerged orifices, *Experimental Thermal and Fluid Science*, vol. 44, p. 124-137.
3. Das A.K., Das P.K., Saha P., 2011, Formation of bubbles at submerged orifices – Experimental investigation and theoretical prediction, *Experimental Thermal and Fluid Science*, vol. 35, p. 618-627.
4. Elperin T., Fominyk A., 2003, Four stages of the simultaneous mass and heat transfer during bubble formation and rise in a bubbly absorber, Chemical Engineering Science, vol. 58, p. 355–3564.
5. Gaddis E.S., Vogelpohl A., 1986, Bubble formation in quiescent liquids under constant flow conditions, *Chemical Engineering Science*, vol. 41, p. 97-105.
6. Gerlach D., Alleborn D., Buwa V., Durst F., 2007, Numerical simulation of periodic bubble formation at a submerged orifice with constant gas flow rate, *Chemical Engineering Science*, vol. 62, p. 2109-2125.
7. Guo Z., Dhir V.K., 1989, Single- and two–phase heat transfer in tangential injection–induced swirl flow, *Int. J. Heat and Fluid Flow*, vol. 10, No. 3, p. 203 – 210.
8. Jamialahmadi M., Zehtaban M. R., Muller-Steinhagen H., Sarrafi A., Smith J. M., 2001, Study of bubbleformation under constant flow conditions, *Trans IChemE*, vol. 79, Part A p. 523.
9. Li Y., Yang G.Q., Zhang J.P., Fan L.S., 2000, Numerical studies of bubble formation dynamics in gas-liquid -solid fluidization at high pressures, *Powder Technology*, vol 116, 246-260.
10. Kang Y.T., Akisawa A., Kashiwagi T., 2000, Analytical investigation of two different absorption modes: falling film and Bubble types, International Journal of Refrigeration, vol. 23 no. 6, p. 430–443.
11. Khurana A., Kumar R., 1969, Studies in bubble formation-I Bubble formation under constant flow conditions, *Chemical Engineering Science*, vol. 24, p. 1711-1723.
12. Ramakrishnan S., Kumar R., Kuloor R., 1969, Studies in bubble formation-I Bubble formation under constant flow conditions, *Chemical Engineering Science*, vol. 24, p.731-747.
13. Satyanarayan A., Kumar R., Kuloor R., 1969, Studies in bubble formation-II Bubble formation under constant flow conditions, *Chemical Engineering Science*, vol. 24, p.749-761.
14. Santosh Kumar Panda, Mani A. 2014, Bubble dynamics study with tangential nozzles in a bubble absorber, International Sorption Heat Pump Conference at Maryland University, Maryland.
15. Suresh M., Mani A., 2010, Experimental studies on bubble characteristics for R134a – DMF bubble absorber, *Experimental Thermal and Fluid Science*, vol. 39, p. 79 – 89.
16. Tsuge Hideki, Tezuka Yusuke, Mitsudani Masae, 2006, Bubble formation mechanism from downward nozzle –Effect of nozzle shape and operating parameters, *Chemical Engineering Science*, vol. 61, p. 3290 – 3298.
17. Wraith A. E., 1971, Two stage bubble growth at a submerged plate orifice, *Chemical Engineering Sci*ence, vol. 26 p. 1659 – 1671.

Nomenclature

V	Volume of bubble	i	No of experiments
Re	Reynolds number	**Subscript**	
d	Bubble diameter	a	Air
D	Ratio of bubble diameter to nozzle diameter	b	Bubble
θ	Nozzle vertical angle	w	Water
N	No. of nozzle	n	Nozzle
lpm	Liter per minute	**Superscript**	
ccm	Cubic centimeter per minute	*	Non-dimensional