Coalescence of Bubbles Generated from Single Nozzle in Stagnant Water

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Abstract— **Different conditions and phenomena for the coalescence of bubbles generated from single nozzle in pool water were studied and compared with the prior analysis. Research was done for the bubbles ranging 0.100 to 2.700 mm bubble diameter. It was found that the coalescence and non-coalescence processes of the bubbles depend upon size of the bubbles and bubble to bubble distances. For small bubbles 0.100 to 0.500 mm bubble diameter, the coalescence occurred for larger bubble distance and bubble diameter ratio than the coalescence between larger bubbles 0.500 to 2.700 mm bubble diameter. There were always a vertical and horizontal velocities of the bubbles rising in the water pool. The vertical velocity of the upper coalescing pair became always slower and the velocity of the lower coalescing pair was higher than the non-coalescing bubbles of the same condition. The smaller horizontal displacement was favorable for the occurrence of the coalescence of the bubbles. The wakes of the bubbles influenced during the coalescence between the bubbles pairs. According to the horizontal displacement, bubble flow patterns were divided into TYPE I and TYPE II. In the TYPE I coalescence of the bubbles occurred in the line but in the TYPE II coalescence of the bubbles occurred after this line. When comparing the experimentally obtained vertical velocities of bubbles with the prior theories, the bubbles in the range 0.500 to 2.100 mm had higher velocities than the theoretically predicted. The higher velocities of these bubbles were found to be due to the larger horizontal fluctuations.**

Index Terms— **Bubble, Coalescence, Two Phase Flow, Vertical and horizontal velocities, Wake**

I. INTRODUCTION

Flow patterns are very much important in Two Phase Flow. In the cooling system of Nuclear Power plant scientists are facing problems due to the fluctuation of the flow pattern. The change in flow pattern cause the variation in thermal exchange property in the system. Thus if the flow patterns are known, thermal exchange property could easily be found out. The problems concerning the flow pattern are very much wide. In the present research paper, deals with the conditions and other phenomena for the occurrence of coalescence of the bubbles. Thus knowing these conditions and phenomena, model could be developed, where bubble flow pattern could be allowed to change into slug flow pattern, which must be the great deal in the Two Phase Flow dynamics.

There are millions of literature devoted for the bubble rising in the liquid. In the beginning, formation and the detachment of the bubbles were performed by. Oguz et al.[4)], Boultione et al.[6)], Sridhar et al.[3)] and Buyevich et al.[14)]. They concluded that buoyancy, kinetic energy of the injected gas and injector nozzle are the controlling factors. Huttenhuis et al.[9)] had shown the effect of the gas phase density on the process of bubble formation. Ran et al.[1)] said that the soluble gases had no detectable effect on the behavior of the air bubble.

Many researchers concluded that impurities in the liquid pool, were the cause of decrease in the coalescence of the rising bubbles. Literatures like, Nevers et al.[8)]; Solanki et al.[7)]. Sridhar et al.[3)], Park et al.[13)], Katz et at.[5)], Nevers et al.[8)] did experiment on a single pair of bubble rising in line and wake induced relative motion. Kirkpatric et al.[11)]; Solanki et al.[7)] explained about the film rupture during coalescence of bubbles. Most interesting one is that by Katz et at.[5)], they explained the relative velocity for the coalescence and its dependence on bubble diameter and bubble to bubble distance for small bubbles only. They still left a gap for the coalescence behavior of different sizes of bubbles and bubble to bubble distances, horizontal fluctuation, vertical fluctuation in terms of velocity time factor of bubbles rising in line.

II. METHODOLOGY

Various measuring techniques has been developed for the measurement in Two-Phase Flow, using probes are disturbing flow pattern. Measurement techniques can be classified into two categories depending on the nature of sensors contacting the flow fields, namely internal sensors and external sensors (Liu et al.[12)]). Internal sensors include probes, such as optical probes and static probes. External sensors include photographic, X-ray and γ-ray methods. In the present experiment, visualization method followed by image processing method was performed, using CCD video camera and still camera were used to observe flow field around the bubble trains.

III. EXPERIMENT SET UP

The bubble trains were generated in a tank (325×135×114 mm^3) filled with filtered water at a depth of 250 mm. Glass capillaries of 50μm (nozzle 1) to 258μm (nozzle 66) internal diameters, were used to generate bubbles of 0.103 mm to 2.131 mm in diameters, respectively. Nitrogen gas was used to generate the bubbles. Flow of Nitrogen gas was controlled by changing only the pressure in the gas buffer, which was connected just upstream of the nozzle. The control system of the pressure consisted of the needle valve, bypass valve and the water manometer.

The behaviors of the bubble trains were recorded by CCD camera with back lighting. Observations were carried out for various heights *H*, from the nozzle tip in the bottom of the tank and recorded for various seconds for each of the heights with constant nozzle inlet pressure. The original view area was 40(w)×50(h) mm^2, and the zooming was imposed for the measurement. The measurement accuracy is estimated as ± 30 μm.

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The experimental conditions are shown in Table 1, where *Pg* is the gauge pressure at the nozzle inlet and *Dn* is inner diameter of capillary nozzle and bubble diameters *D*.

Table 1:

Nozzle Dia. Dn, μm	Bubble Dia. D, mm	Pressure gauge MPa, p
50	0.103	0.022
70	0.201	0.020
163	0.801	0.017
160	0.957	0.021
67	1.212	0.030
258	1.243	0.020
150	2.131	0.017

In this experiment a 500W photo-chromatic lighting is used at the back of the observation tank facing in the opposite direction (back lighting) to provide a smooth and even background. It was found that the three dimensional movement is more prominent in the bubbles of larger sizes at the smaller bubble to bubble distances, so it was taken in both X-Y and Y-Z planes by using mirrors.

IV. RESULTS AND DATA ANALYSIS

Bubbles of smaller size were spherical in shape. It is observed that even for the larger bubbles too, shape of these bubbles were spherical in shape close to the detachment point. In this experiment small bubbles (0.100 to 1.00 mm), are considered as spherical. For the large bubbles (1.000 to 2.696 mm) the mean of the lateral and longitudinal diameter is considered as the bubble diameter, *D*. Origin in the figure is taken as nozzle tip throughout the experimental result and analysis. Reference lines and planes were taken as horizontal and vertical lines and planes passing through the origin i.e. nozzle tip.

4.1 Vertical and horizontal displacement of coalescing and non-coalescing bubbles bubble in the train:

The vertical displacement *Lv*, of the numbers of coalescing and non-coalescing bubbles of different diameters, *D* and different ratios of bubble distance and bubble diameter, *L/D* were drawn with respect to the time in Fig. 1(a) and Fig.1(b). In these figures, when a bubble became close enough to the other bubble then the wake between the bubbles became effective. Due to the wake the upper bubble moved slowly so that the lower bubble rose close to get coalescence. It was found that the non-coalescing bubbles also rose in approximately the same speed as the lower coalescing bubble pair.

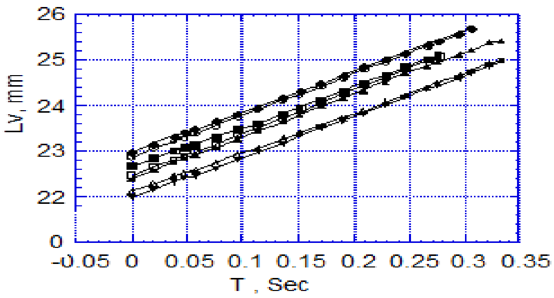

Fig. 1(a) Vertical displacement *Lv* of seven successive bubble train, vs time duration, *T*

In Fig. 1(a) for bubble train of 0.103 mm diameter and ratios of bubble distance and bubble diameter, *L/D* as1.948 mm were taken. Among them successive bubble 1-2, 3-4 and 6-7 coalesced. Whereas bubble 5 did not coalesce with any bubbles. Vertical velocity of non-coal. Bubble 5 was 20.33mm/s. Average vertical velocity of upper coal. Bubbles were 19.38mm/s and average velocity of lower coal. bubbles were 20.27mm/s. It was clearly seen the wake of the bubbles were effecting during the coalescence between the bubbles pairs.

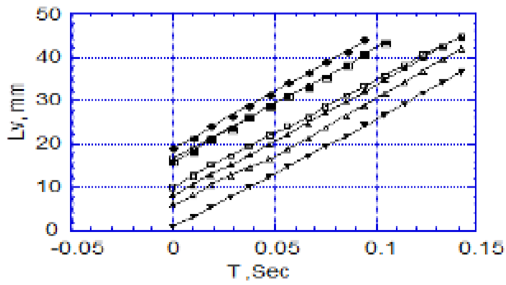

Fig. 1(b) Vertical displacement *Lv* of seven successive bubble train, vs time duration, *T*

Similarly, in Fig. 1(b) for bubble train of 0. 0.801 mm diameter and ratios of bubble distance and bubble diameter, *L/D* as1.815 mm were taken. Among them successive bubble 2-3 and 4-5 coalesced. Whereas bubbles 1, 6 and 7 did not coalesces with any bubbles. Average vertical velocity of non-coal. Bubbles 1, 6 and 7 were 253.827mm/s. Average vertical velocity of upper coalesced bubbles were 246.03mm/s and average velocity of lower coalesced bubbles were found 258.995mm/s. In this coalescing bubble pairs, it was clearly seen the wakes of the bubbles were effective during the coalescence between the bubbles pairs.

Further, Fig. 2 was drawn to represent the difference between vertical displacements of the same bubbles of the same train as shown in Fig. 1. The distance between non-coalescing bubble pairs 2-3, 4-5 and 5-6 were large in compression to that between coalescing bubble pairs 1-2, 3-4 and 6-7.

As the bubble rose with time distance between bubble pairs 2-3, 4-5 and 5-6 increased or remained constant but the distance between bubble pairs 1-2, 3-4 and 6-7 decreased and time would come that they become zero. Which means that the wakes were working between coalescing bubble pairs but the wakes were not much effective between non-coalescing bubble pairs. As described in the above paragraph, the wakes between the coalescing pairs caused the upper pair to rise slowly thus the lower pair roses close to get coalescence.

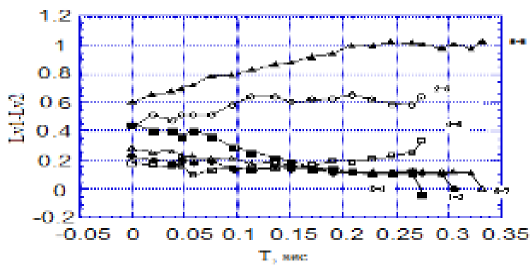

Fig. 2 Difference between vertical displacement *Lv* between bubbles vs time, *T*

It was observed that bubble train were not always vertical, further devotion occurred for bubbles larger than 0.5 mm in diameter. The horizontal displacement of the some of the coalescing and non-coalescing bubbles of same diameters, *D* and different bubble distance and bubble diameter, *L/D* were drawn with respect to the time in Fig. 3. It was observed that coalescing bubbles also entered in the wake of its pair horizontally before coalesce.

It was seen that in Fig. 3(a) the horizontal displacement, *Lh* of the bubbles had unpredictable zigzag type of motion for 0.103 mm bubble diameters. Here, upper line was for non-coalescing and rest two lines were displacements for coalescing pair. It was found that for small bubbles *Lh* did not have large fluctuation, rather a zigzag line. But for middle and large sized bubbles, *Lh* were found large and some curves were clearly obtained as shown in Fig. 3(b) for 0.0.801 mm bubble diameters. It was observed that coalescing bubble pairs were orientated to some fixed reference lines. It was observed from recorded CCD images, both *X-Y* and *Y-Z* planes are important to be measured for bubbles larger than 2.0 mm, which were not remarkable in 0.103 mm and 0.801 mm bubbles diameters. Fig. 4, was drawn to show large horizontal displacement of 2.696 mm diameter bubble in both *X-Y* and *Y-Z* planes, using mirrors in the experiment.

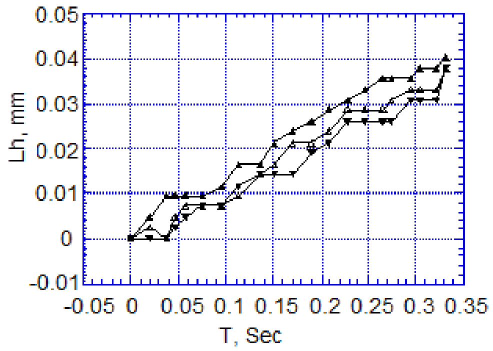

Fig. 3(a) Horizontal displacement *Lh* vs time duration, T

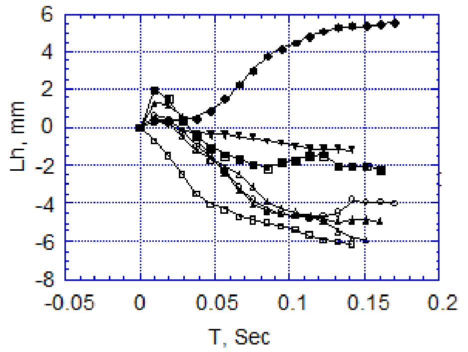

Fig. 3(b) Horizontal displacement *Lh* vs time duration, *T*

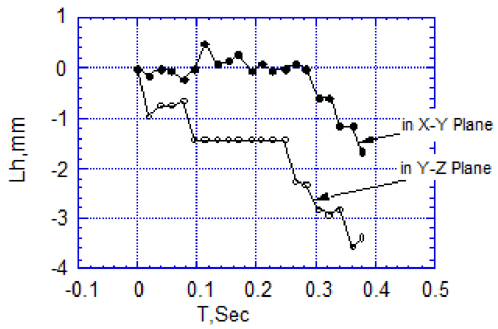

Fig. 4 Horizontal displacement of bubble in *X-Y* and *Y-Z*

4.2 Bubble to Bubble Distance (L) Vs Bubble Diameter(D):

It was observed from recorded CCD images, bubbles of the smaller sizes (0.100 to 0.500mm), coalescence occurred at the large ratio of bubble to bubble distance and bubble diameter, *L/D*. The occurrence of the coalescence for the medium sized bubbles (0.500 to 2.000mm) occurred at the lower value of *L/D*. For the larger bubbles (2.000 to 2.600 mm), the coalesced at much lower value of *L/D*. But in this later case *L/D* did not vary sharply with respect to the bubble size. For the smaller sized bubbles (0.100 to 0.500mm) the horizontal displacements were small (named as TYPE I), so that even for the larger *L/D* also the bubbles easily entered into the wake of the other bubbles, resulting coalescence. But for the medium (0.500 to 2.000) mm and large sized (2.000 to 2.600 mm) bubbles the horizontal displacements were larger (named as TYPE II), so that smaller *L/D*s were needed to obtain the good effect of the wake for coalescence bubbles.

According to the horizontal displacement of the bubble flow patterns, were separated into two main types.

TYPE I: The horizontal displacement, *Lh* of the bubbles had very small and displacement of zigzag type, under the condition of *Lh<3D* and *Lh/Lv*<1. In these type of bubble flow patterns, coalescence of the bubbles occurred within the line. These type of bubble flow patterns were very much favorable for the coalescence of the bubbles. Here the bubbles remained on the line, so that due to the wake effect, there were higher chance of bubbles to get close for coalescence. The size range found for this type of bubble was 0.100 to 0.500 mm bubble diameter. Displacements of this type of bubbles were shown in Fig. 5 for 0.103mm bubble diameter *D* and 0.02335 mm vertical displacement *Lv*. Coalescing pair was indicated by arrow heads. At the beginning the pair rose normally and later come closer and finally coalesced as wake between them became effective.

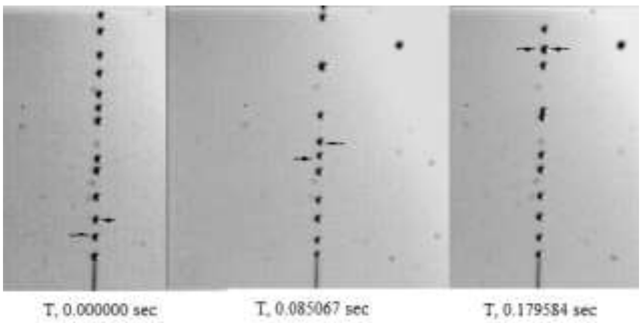

Fig. 5 TYPE I Bubble Flow Pattern
(High Speed Camera Image)

TYPE II: In this type of the flow pattern, bubbles first flowed in the line for some distances and later the line broke, bubbles move zigzag direction. In these type of the flow patterns the coalescence of bubbles occurred after breaking the line. The size range found for these type of bubble flow patterns was 0.500 to 2.700 mm bubble diameter. Due to the higher horizontal displacements, the coalescences of the bubbles were less favorable than the TYPE I. Displacement of these type of bubbles are shown in Fig. 6 for 0.949mm bubble diameter *D* and 1.449 mm vertical displacement *Lv*.

Coalescing pair was indicated by arrow heads. At the beginning the pair rose normally and later come closer and finally coalesced as wake between them became effective.

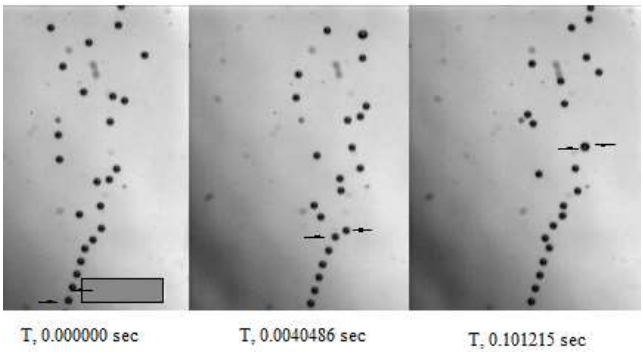

Fig.:6 TYPE II Bubble Flow Pattern
(High Speed Camera Image)

4.3 Theory and Analysis of Results:

Thousand many literatures were written in the behavior of single gas bubbles. In Clift et al.10) had given a chart, showing the shapes of the bubbles and particles for different Reynolds numbers and Galileo number. Peebles et al.[2]. concluded some important equation for the terminal velocity of the bubbles. They had separated the behaviors of the bubbles into four regions.

Case I $R_e < 2$ $(R_e = \rho_L D u/\mu)$

A spherical bubbles moving in rectilinear paths, drag coefficient agrees with the result predicted by Stroks' Law. Thus the equation for the steady rate rising velocity and drag coefficient for bubbles with in this region is,

$$C_D = \frac{24}{R_e}$$

$$u_B = \frac{g \rho_L D_e^2}{18 \mu_L}$$

Case II $2 \le R_e \le 4G_1^{-0.214}$ (Where $G_1 = g\mu_L 4/(\rho_L \sigma^3)$)

A spherical bubbles moving in rectilinear paths, with outside of the Stroks' Law range and the equation for the steady rate rising velocity and drag coefficient for bubbles with in this region is,

$$C_D = \frac{18.7}{R_e^{0.68}}$$

$$u_B = 0.135 \left(\frac{\rho_L}{\mu_L} \right)^{0.52} g^{0.76} D_e^{1.27}$$

Case III $4G_1^{-0.214} \le R_e \le 3G_1^{-0.25}$

Bubbles deformed ellipsoidal in cross section, flattened in the horizontal direction, moving spiraling, zigzag path, the equation for the steady rate rising velocity and drag coefficient for bubbles with in this region is,

$$C_D = 0.0275 G_1 R_e^4$$

$$u_B = 1.35 \left(\frac{2\sigma}{\rho_L D_e} \right)^{0.5}$$

Case IV $R_e > 3G_1^{-0.25}$

Greatly deformed bubbles assuming an irregular mushroom like shape, rising in the rectilinear path, the equation for the steady rate rising velocity and drag coefficient for bubbles with in this region is,

$$C_D = 0.82 G_1^{0.25} R_e$$

$$u_B = 1.18 \left(\frac{\sigma g}{\rho_L} \right)^{0.25}$$

In Fig. 7, the experimentally obtained rising velocities of the bubbles were compared to the theoretically calculated velocities using Peebles et.al.[2]. For the bubbles up to 0.500 mm and above 2.100 mm the experimentally obtained velocities were close to the theoretically predicted velocities. But for the bubble diameters 0.500 to 2.100, mm the experimentally obtained velocities are higher than the theoretically predicted velocities.

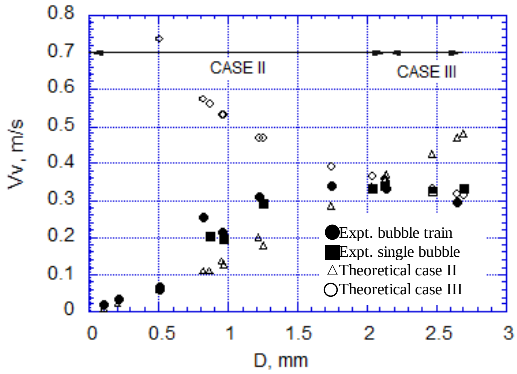

Fig. 7 Experimental and theoretical vertical velocity *Vv* for different bubble diameters

In the calculation comparing Reynolds numbers, obtained that 0.103 to 2.100 mm bubbles diameters falls in CASE II and 2.100 to 2.600 mm in CASE III. Again, 0.500 to 2.100 mm bubble diameter falls in the range of CASE II according to Reynolds number ($2 \le R_e \le 4G_1^{-0.214}$) using Peebles et.al[2]. equations. But in contrast to the predictions by them, here experimentally, the bubbles of this range had noticeable horizontal fluctuations rather than the theoretically predicted rectilinear motion when rising in the water pool. As shown in the Fig. 8, the horizontal velocities were higher in this range. That means it gradually transferred towards the CASE III. Hence the higher values of the experimental velocities of this range was due to the large horizontal fluctuation of the rising bubbles.

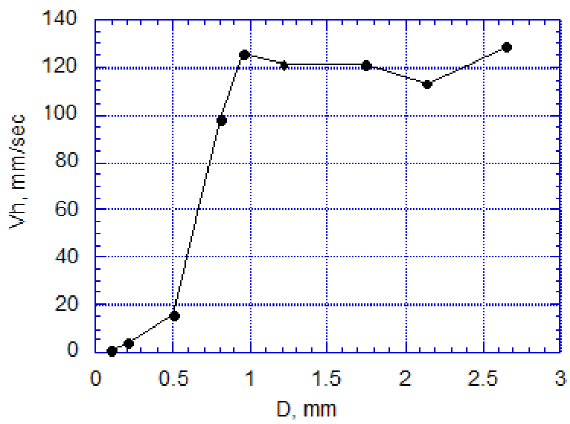

Fig. 8 Maximum absolute horizontal velocity for different bubble diameters

V. CONCLUSION

Diameter, vertical shift, horizontal shift, bubble to bubble distances and wake induced in rising bubble trains were important parameters for change of flow pattern from bubbly flow to slug flow pattern by coalescing between bubbles. The continuous and high rata of coalescence coverts the bubble flow pattern into slug flow pattern.

The coalescence and non-coalescence process of the bubbles depended upon the size of the bubbles and the bubble to bubble distances. For the small bubbles between same sizes the coalescence occurred still for the large *L/D* relative to the coalescence between two same sized large bubbles.

The vertical and horizontal displacements were important in the course of the coalescence of the bubbles. It was found that the average vertical velocity of the upper coalescing pair became always slower and mostly the velocity of the lower coalescing pair was higher or almost same as the non-coalescing bubbles of the same conditions. The smaller horizontal displacements were favorable for the occurrence of the coalescence of the bubbles. As explained before TYPE I, flow pattern was more favorable for the occurrence of coalescence.

When comparing experimentally obtained velocities of bubbles with theoretical calculated velocities using the equations given by Peebles et.al[2)], it was observed that there are some bubbles (0.500 to 2.100 mm) do not obey the theoretical curve. It was found that the deviation of these bubbles were due to the large horizontal shifts in contrast to the rectilinear motion as predicted.

REFERENCES

[1]Bing Ran and Joseph Katz; *The response of microscopic bubbles to sudden change in the ambient pressure*; JFM, 1991, vol.224, pp91-115

[2]Feed N. Peebles and Harold J. Garber; *Study on the motion of gas bubbles in liquid*; ChemEngProg.,49-2, 1953, pp88-97

[3]G. Sridhar and J. Katz; *Drag and lift forces on microscopic bubbles entrained by a vortex*; Phys. Fluid 7(2), 1995

[4]Hasan N. Oguz and Andrea Prosperetti; *Dynamics of bubble growth and detachment from a needle*; JFM, 1993, vol.257 pp111-145

[5]J. Katz and C. Meneveau; *Wake-Induced Relative Motion of Bubbles Rising* In Line; Int. J. Multiphase Flow, 1996, vol.22, No.2, pp.239-258,

[6]J.M. Boultione and J.R. Blake; *Gas bubble bursting at a free surface* JFM (1993), vol.254, pp437-466

[7]M.K.S. Solanki, A.K. Mukherjee and T.R. Das; *Bubble formation at closely spaced orifices in aqueous solutions*; The Chemical Eng. Journal, 49, 1992, pp65-71

[8]Noel De Nevers and Jen-Liang Wu; *Bubble Coalescence in Viscous Fluids* AiChE Journal, 1971, pp182-186

[9]P.J.G. Huttenhuis, J.A.M. Kuipers and W.P.M. Van Swaaij; *The effect of gas flow density on bubble formation at a single orifice in a two dimensional gas-fluidized bed*, Che.Eng.Sci., 1996, vol.51, no.24, pp5273-5288

[10] R. Clift, J.R. Grace and M.E. Weber; *Bubbles, drops, and particles*, Academic Press, 1978

[11] R.D. Kirkpatric and M.J. .Lockett, *The Influence of Approach Velocity on bubble Coalescence*, Che.Eng.Sci.1974, vol.29, pp2363-2373

[12] W. Liu, Clark Nigel and A.I. Karamavruç, , *Relationship between bubble size distributions and chord-length distribution in heterogeneously bubbling system*, *Chemical Engineering Science*, 1997, pp.1267

[13] W.C. Park, J.F. Klausner, and R. Mei; *Unsteady forces on spherical bubbles*; Experiments in Fluids 19, 1995, pp167-172

[14] Yu.A. Buyevich and B.W. Webbon; *Bubble formation at a submerged orifice in reduced gravity*; Che.Engg.Sci., 1996, vol.51, no.21, pp4843-4857

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