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The Influence of Channel Orientation and Flow Rates on the Bubble Formation in a Liquid Cross-Flow

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ABSTRACT

For gas turbines burning liquid fuels, improving fuel spray and combustion characteristics are of paramount importance to reduce emission of pollutants, improve combustor efficiency and adapt to a range of alternative fuels. Effervescent atomization technique, which involves the bubbling of an atomizing gas through aerator holes into the liquid fuel stream, has the potential to give the required spray quality for gas turbine combustion. Bubbling of the liquid stream is presently used in a wide range of other applications as well such as spray drying, waste-water treatment, chemical plants, food processing and bio- and nuclear-reactors. In order to optimize control of the required aeration quality and thus the resulting spray quality over a wide range of operating conditions, it is important that the dynamics of bubble formation, detachment and downstream transport are well understood under these circumstances. The paper reports on an experimental study conducted to investigate the dynamics of gas bubbles in terms of bubble detachment frequency when injected from an orifice that is subjected to a liquid cross-flow. The experiments were conducted over a range of gas and liquid flow rates and at various orientations of the liquid channel. Analyses presented here are based on shadowgraph images of two-phase flow, acquired using a high speed camera and a low intensity light source. An image processing algorithm was developed for the detection and characterization of the bubble dynamics. Results show that bubble detachment frequency is a function of both liquid cross-flow rate and the gas-to-liquid flow rate ratio.

INTRODUCTION

Some of the pressing challenges faced by the gas turbine industry are: reduction in emissions of pollutants; improvement of combustion efficiency thus reducing fuel burn and green house gas emissions; and adaptation to fuel flexibility. For gas turbines burning liquid fuels, the solution lies in the ability to control fuel spray quality and thus in turn improve combustion characteristics. The effervescent atomization technique, which involves the bubbling of an atomizing gas (air in most cases for gas turbines) through aerator holes at a very low velocity into the liquid fuel stream, has the potential to give the required spray quality for gas turbine combustion [1]. The bubbly flow improves atomization by reducing the characteristic liquid dimensions within the discharge orifice. The atomization is further improved by the rapid expansion of gas bubbles at the orifice exit, which shatters the issuing liquid stream into finer droplets [2]. Bubbling of the liquid stream has utilization in a wide range of other industrial applications as well. It is presently being used for spray drying, waste-water treatment, chemical plants [3], food processing and bio- [4] and nuclear reactors [5].

A considerable amount of work has been done in the last two decades on understanding the effects of liquid injection pressure [6], gas-to-liquid ratio [7] and the internal configuration of the effervescent injector [8] on the quality of atomization both under atmospheric as well as high pressure environments [9]. However, most of the work has been restricted to study of sprays and atomization characterization external to the atomizer. In order to optimize controllability of the required spray atomization quality of an atomizer over a wide range of operating conditions, it is equally important to investigate the aeration or bubble dynamics internal to the injector. This involves understanding of bubble formation and detachment; downstream transport of the two-phase flow including coalescence and interaction of the bubbly flow with the final orifice. In this context, with the exception of a few studies [10, 11], not much work has been done in the atomizer community. As a result the current understanding of effervescent atomization internal flow is rather limited.

On the other hand, bubble dynamics in general have been studied in great details in other application areas of two-phase flow. These studies include bubble formation and transport from a submerged orifice [12]. As a result there now exist reliable models to predict the effects of such parameters as the gas and liquid physical properties and flow rate and the orifice geometry. However, most of the efforts have been limited to gas bubbles issuing in a stagnant liquid phase and very limited data is available [13, 14, 15] on bubble behavior within a liquid which is in motion relative to the gas phase (as for example from aeration holes exposed to a liquid cross-flow within an effervescent atomizer). Although these limited studies were conducted using different experimental setups, all showed that under liquid cross-flow conditions and depending on the liquid flow rate, there may exist three bubble formation modes namely, single-bubble; pulse-bubble and jetting modes. They also found that the drag force due to liquid motion and not the buoyancy force controlled the bubble detachment from the gas orifice and that the detachment frequency was significantly higher compared to that under stagnant liquid conditions.

As the above literature review shows, the studies on the bubble formation in liquid cross-flow are scarce. Furthermore, the effects of orientation of the liquid flow channel and the gas orifice were not investigated in the previous studies. In practical applications, the orientation of the orifice may not necessarily be aligned with the gravity and thus, it is important to investigate the bubble dynamics under different orientations of the orifice and liquid cross-flow with respect to the gravity.

The present research is focused on a comprehensive experimental investigation of the dynamics of gas (air) bubbles injected from an orifice that is submerged and subjected to a liquid (water) cross-flow under different channel orientations with respect to gravity. In the present paper, we present the results describing the influence of channel orientation on the bubble detachment frequency under different liquid and gas flow conditions.

EXPERIMENTAL SETUP

The experiments were conducted in a two-dimensional rig fabricated using Plexiglas and comprising a settling chamber, a contraction section, the test section and an outlet scoop, as shown in Fig. 1. The contraction section was designed using a cubic profile [16] and the contraction ratio was 25:1, while the length of the contraction section was 200 mm. The scoop at the exit of the test section was used to provide the required pressure drop across the test section. A water manifold was used to provide water uniformly to the rig, while an orifice tube was used to inject air in the test section. The water and air flows were both metered. The experiments were conducted over a range of gas and liquid flow rates and at various orientations of the liquid channel (see Table 1 for details). These flow rates were chosen to ensure that the bubble formation mode is maintained in the pulse-bubbling regime. Analyses presented here are based on flow and bubble images acquired using a back-lit shadowgraph-imaging set-up, which comprised a high speed camera from Canadian Photonic Labs with a 180 mm lens (Tamaron 1:3.5 Macro 1:1) and a low intensity light source powered by a DC source. The images were acquired at a rate of 6000 frames per second.

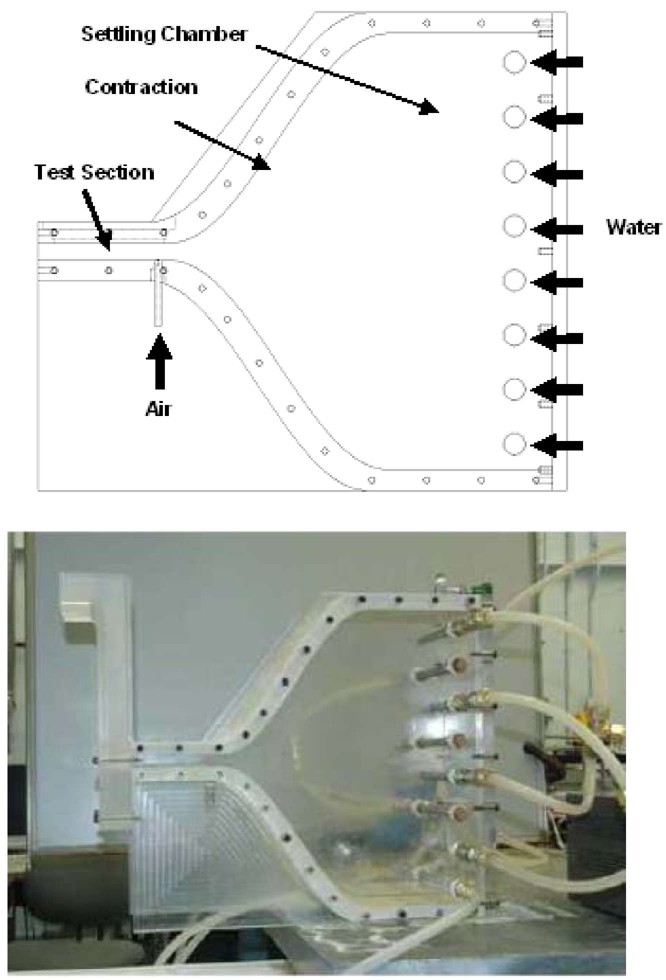

Fig. 1: Top: Schematic of the test section. Bottom: photograph of the experimental setup.

A novel image processing algorithm was developed to automatically compute the detachment frequency of gas bubbles. In this algorithm, a region-of-interest (ROI) was defined at and around the orifice exit. The image segmentation was performed next, to convert the gray-scale original image into a binary image. The threshold for image segmentation was selected based on the histogram of the gray-scale values in the ROI. Due to the good contrast between the bubbles and the background liquid, the histogram showed bimodal distribution i.e. one corresponding to the bubble and other corresponding to the background liquid. The minima between the two modes were selected as the threshold. The binary image was inverted and a series of morphological operations was performed to remove the noise. While the bubble stayed attached to the orifice, the ROI contained only one detected object. As soon as the bubble detached from the orifice, the ROI contained two objects which was set as the criterion to detect the bubble detachment. Because the ROI contained two objects until the detached bubble completely moved out of the ROI, there exists a possibility of multiple detection of the same bubble. To avoid this double counting, another criterion was set to ensure that a given bubble was detected only in the image where it is detached from the orifice. The image frame numbers in which the bubbles were detached were recorded. By knowing the camera frame rate, the bubble detachment frequency was computed.

In order to validate the detection algorithm, the bubble detachment frames were manually detected through visual inspection of the images. The visual inspection was carried out for 12 cases that comprised of three liquid flow rates and four gas flow rates (at each liquid flow rate). 8000 images for each case were visually inspected. The comparison of the visually detected image frames with those detected by the algorithm showed excellent agreement. Both techniques detected identical frames in over 95% cases. In 5% cases, the difference between the two techniques was by one frame which is still considered as an excellent agreement.

TABLE 1: Matrix of air and water flow rates for experiments at each flow-channel inclination angle.

Water flow rate [slpm]	Air flow rate [slpm]			
0	0.006	---	---	0.057
6.96	0.006	0.023	0.040	0.057
13.91	0.006	0.023	0.040	0.057
16.67	0.006	0.023	0.040	0.057

RESULTS AND DISCUSSION

The investigations on bubble detachment frequency were conducted at a number of flow-channel orientation angles. Results presented and discussed here are for 10^o, 45^o and 90^o inclinations with respect to the horizontal. Fig. 2 shows three sample back-lit shadowgraph images captured at the above three inclination angles at a liquid and gas flow rates of 16.67 slpm and 0.04 slpm, respectively. The images show significantly different flow trajectories that bubbles follow during their downstream transport with the liquid flow. The trajectory angle with respect to the gas-orifice axis increases with the increase in the inclination angle which is likely due to the change in the gravity direction with respect to the channel orientation.

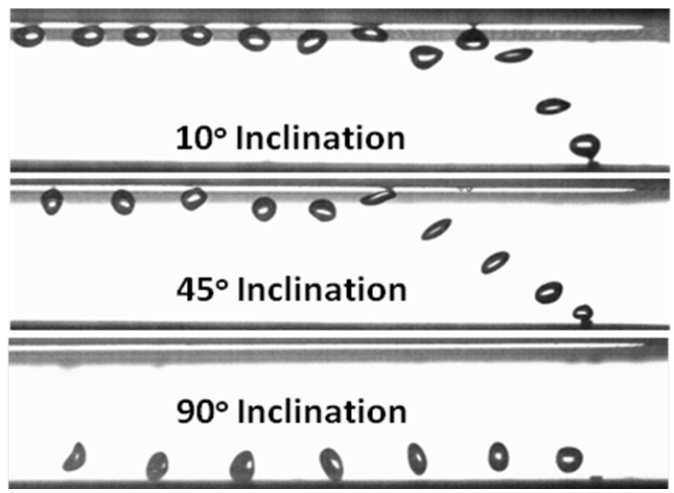

Fig. 2: Back-lit shadowgraph images showing bubble transport trajectories at three flow-channel inclinations: 10^o, $45^o$and 90^o, at a liquid flow rate (Q_L) of 16.67 slpm and a gas flow rate (Q_G) of 0.04 slpm.

Images acquired at all the operating conditions (as given in Table 1) and at the three inclination angles were processed using the specially developed algorithm (described earlier) to obtain the bubble detachment frequency at each condition. Shown in Fig. 3 are the detachment frequencies (f_d) as a function of gas-to-liquid flow rate ratio (Q_G/Q_L) for the three liquid flow rates and at a flow-channel inclination of 10^o. At a given liquid flow rate, f_d increases linearly with the increase in Q_G/Q_L. Similarly at a fixed Q_G/Q_L, increase in liquid flow rate results in an increase of f_d. However, as may be noted this increase is not linear. This observation may be seen more clearly in Fig. 4, where now f_d is plotted against liquid-to-gas flow rate ratio (Q_L/Q_G). The influence of increasing liquid flow rate on f_d diminishes asymptotically beyond a threshold value of Q_L/Q_G. For the operating conditions shown in Fig. 4, this threshold value of Q_L/Q_G was found to be above 1000.

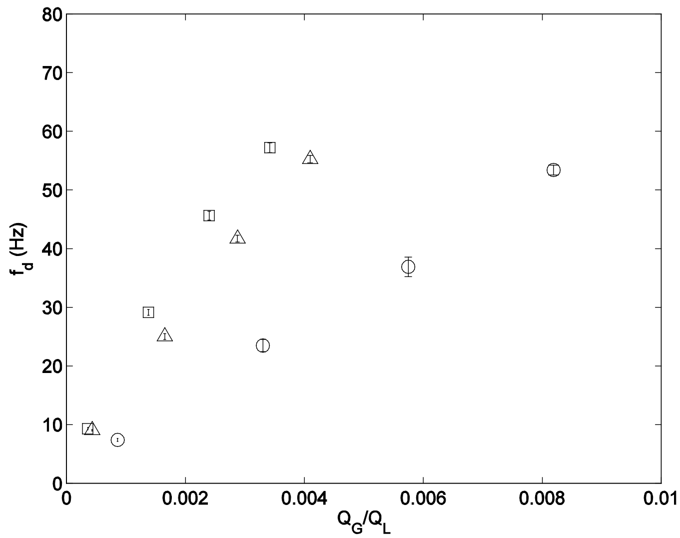

Fig. 3: Bubble detachment frequency (f_d) versus Gas-to-Liquid flow rate ratio (Q_G/Q_L) at the channel inclination of 10^o for various liquid flow rates (Q_L). Symbols: o for Q_L = 6.96 slpm; Δ for Q_L = 13.91 slpm; and, □ for Q_L = 16.67 slpm. The error bar is based on the standard deviation.

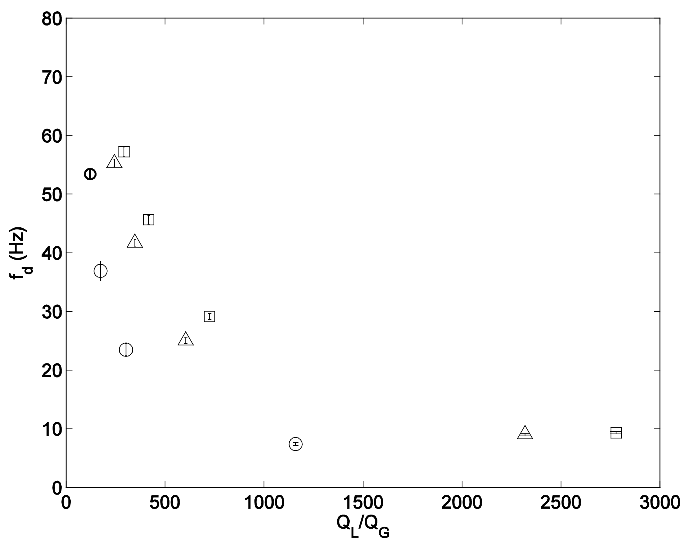

Fig. 4: Bubble detachment frequency (f_d) versus Liquid-to-Gas flow rate ratio (Q_L/Q_G) at the channel inclination of 10^o for various liquid flow rates (Q_L). Symbols: o for Q_L = 6.96 slpm; Δ for Q_L = 13.91 slpm; and, □ for Q_L = 16.67 slpm. The error bar is based on the standard deviation.

The effects of Q_G/Q_L and Q_L on bubble detachment frequency at the higher flow-channel inclination of 45^o are shown in Fig. 5. It may be observed that at this inclination angle, the relationship between f_d and Q_G/Q_L for the lowest and intermediate liquid flow rates deviates from its linear trend at the higher value of Q_G/Q_L. This tendency shows up more prominently when the inclination angle is further increased to 90^o, as shown in Fig. 6. This change in behaviour at the higher inclination angles may be attributed either to the influence of buoyancy effects or to the channel-wall effects, resulting from the change in bubble transport trajectory as seen in Fig. 2. Work is in progress to quantify the effect of these factors.

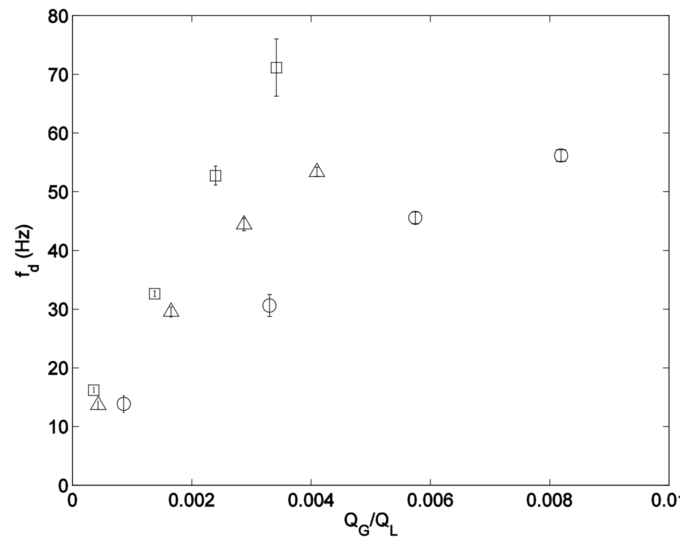

Fig. 5: Bubble detachment frequency (f_d) versus Gas-to-Liquid flow rate ratio (Q_G/Q_L) at the channel inclination of 45^o for various liquid flow rates (Q_L). Symbols: o for Q_L = 6.96 slpm; Δ for Q_L = 13.91 slpm; and, □ for Q_L = 16.67 slpm. The error bar is based on the standard deviation.

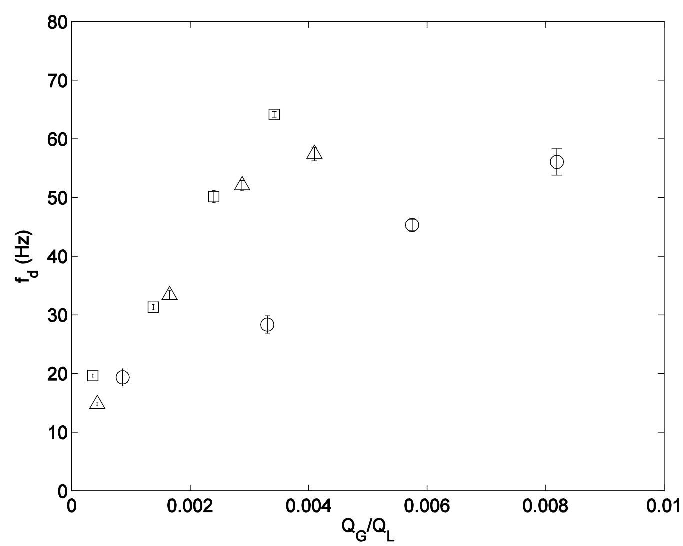

Fig. 6: Bubble detachment frequency (f_d) versus Gas-to-Liquid flow rate ratio (Q_G/Q_L) at the channel inclination of 90^o for various liquid flow rates (Q_L). Symbols: o for Q_L = 6.96 slpm; Δ for Q_L = 13.91 slpm; and, □ for Q_L = 16.67 slpm. The error bar is based on the standard deviation.

CONCLUSION

The influence of liquid and gas flow rates on bubble detachment frequency was investigated at different flow-channel inclinations. An experimental setup was developed having a submerged gas-orifice subjected to liquid cross flow. Analysis was done on flow images, acquired using back-lit shadowgraph technique. A novel image processing algorithm was developed and applied to determine the bubble detachment frequency.

It was found that the channel inclination angle influences the flow trajectory of the bubbles as they are transported downstream with the liquid flow. Steeper trajectories are observed with the increase in inclination angle.

At lower inclination angle of 10^o, a linear relationship was found to exist between the bubble detachment frequency and the gas-to-liquid flow rate ratio for all the three liquid flow rates used in the study. Deviation from this linear trend towards a non-linear behaviour was observed at higher inclination angles, especially for lower values of the liquid flow rates. This non-linear relationship may be attributed to buoyancy and wall effects that seem to play an influencing role at higher inclination of the flow-channel.

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REFERENCES

[1] Lefebvre, A. H., (1989), A novel method of atomization with potential gas turbine application, Journal of Propulsion and Power, 4 (4), 293-298.

[2] Sovani, S. D., Sojka, P. E. and Lefebvre, A. H., (2001), Effervescent atomization, Progress in Energy and Combustion Science, 27, 483-521.

[3] Kawamura, T., Takahashi, M., Hayashi, M., Murayama, K., and Gotoh, N., (2003), Synchronized vibrations of a circular cylinder in cross flow at supercritical Reynolds Numbers, Journal of Pressure Vessel Technology, 125, 97–108.

[4] Kim, J., Lee, C., and Chang, I., (2001), Effect of pump shear on the performance of a cross-flow membrane bioreactor", Water Research, 35, 2137–2144.

[5] Takemoto, M., Sahai, S., Wakai, K., Sumida, I., Kondou, T., and Inatomi, T., (2000), Investigation of two-phase flow mixing between two sub-channels, Heat Transfer - Asian Research, 29, 412–426.

[6] Wade, R. A., Sojka, P. E. and Gore, J. P. (1999), Effervescent atomization using high supply pressure, Proceedings of the 9th Annual Conference on Liquid Atomization and Spray Systems, San Francisco, CA, 263-270.

[7] Li, J., Lefebvre, A. H. and Rollbuhler, J. R., (1994), Effervescent atomizers for small gas turbines, Proceedings of International Gas Turbine and Aeroengine Congress and Exposition, The Hague, Netherlands.

[8] Wang, S. F., Chin, J. S. and Lefebvre, A. H., (1989), Influence of gas injector geometry on atomization performance of aerated-liquid nozzles, International Journal of Turbo Jet Engines, 6, 271-280.

[9] Chen, S. K., Lefebvre, A. H. and Rollbuhler, J. R., (1994), Influence of ambient air pressure on effervescent atomization, Journal of Propulsion and Power, 9 (1), 10-15.

[10] Huang, X., Wang, X. and Liao, G., (2008), Visualization of two phase flow inside an effervescent atomizer, Journal of Visualization, 11 (4), 299-308.

[11] Catlin, C. A. and Swithenbank, J., (2001), Physical processes influencing effervescent atomizer performance in the slug and annular flow regimes, Atomization and Sprays, 11, 575-595.

[12] Marshall, S. H., (1990), Air bubble formation from an orifice with liquid cross-flow, Ph.D. Thesis, University of Sydney, Australia.

[13] Rigby, G. D., Evans, G. M. and Jameson, G. J., (1995), Modelling of gas flow from a submerged orifice in a liquid cross-flow, Trans. Instn Chem. Engrs, 73 (A), 234-240.

[14] Forrester, S. E. and Rielly, C. D., (1998), Bubble formation from cylindrical, flat and concave sections exposed to a strong liquid cross-flow, Chemical Engineering Science, 53 (8), 1517-1527.

[15] Loubiere, K., Castaignede, V., Hebard G. and Roustan, M., (2004), Bubble formation at a flexible orifice with liquid cross-flow, Chemical Engineering and Processing, 43, 717-725.

[16] Sargison, J. E., Walker G. J. and Rossi, R., (2004), Design and calibration of a wind tunnel with a two dimensional contraction, 15th Australasian Fluid Mechanics Conference, Sydney, Australia.