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BUBBLE RISE VELOCITY IN AN INCLINED CHANNEL AND THE EFFECTS OF CHANNEL WIDTH

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ABSTRACT

The behaviour of gas bubbles under a downward facing surface is of importance in a number of industrial operations including certain heat transfer equipments and the electrolytic cells. The movement of these gas bubbles provide the stirring necessary for fluid mixing. However, there is very little published data on the behaviour of bubbles under submerged inclined surfaces. In this work, data on the rise velocity of air bubbles in an inclined channel filled with water is presented. The entire range of angle from the horizontal to the vertical position, and the effects of changing the side wall width were examined. The rise velocity increases to a maximum at an inclination between 40 and 70°, although for smaller bubbles, this maxima is less obvious. Beyond this angle, the velocity decreases as the vertical is approached. It is also somewhat surprising to find that for the same bubble volume, the rise velocity increases as the channel width is reduced. The variation in the rise velocity with channel width when the channel is placed in the vertical orientation is also discussed.

INTRODUCTION

Studies of bubble rise in inclined cylindrical tubes have been reported by Zukoski(1966), Spedding & Nguyen(1978) and Bendiksen(1984). In some industrial equipments, the movement of gas bubbles occur under a flat surface. For example, in electrolytic cells, gas bubbles are formed underneath an essentially flat anode (Keiha & Welch 1988, Kasherman & Skyllas-Kazacos 1988). The subsequent movement of these bubbles greatly affect fluid mixing, temperature homogenization and the rate of mass transfer.

In nucleate pool boiling, it is known that the heat flux is affected by the inclination of the heater plate (Githinji & Sabersky, 1963, Nishikawa *et al.*1983, Cooper, 1988, and Tong *et al.* 1988). The variation of the heat flux with the heater orientation was shown to be due to the different bubble flow behaviours.

Weber *et al.*(1986), Maneri & Zuber (1974), Couet & Strumulo (1987) and Maxworthy (1991) have studied the rise velocity of gas bubbles in an inclined channel. A summary has been given in Che *et al.* (1991). Chen *et al.* (1992) have presented bubble rise results for inclinations up to 12° to the horizontal at various channel gap width. This paper is an extension of that work, but covering the entire range of angle including the vertical case.

EXPERIMENTAL EQUIPMENT

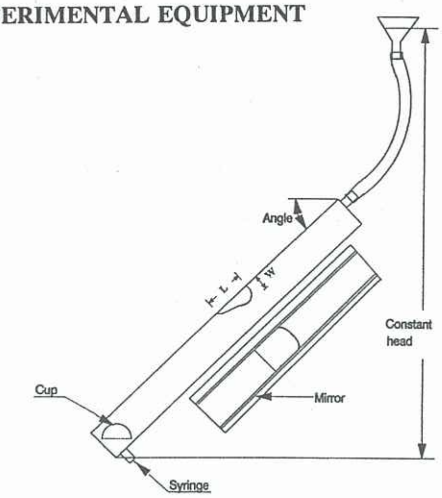

Figure 1. Schematic diagram of the experimental equipment.

As shown in Figure 1, the test section consists of a channel made of clear perspex which is 1250mm long and has a depth b of 102mm. The width of the section, a, may be adjusted to 100, 55, 25 or 16mm with the insertion of a perspex partition. A constant head of 1.28m of water was maintained as the box was inclined at various angles. A mirror was provided so that a plan view of the bubble may be observed simultaneously.

A known volume of air may be introduced into the cup through a septum by using a syringe. The cup may be inverted to release the air bubble. The relevant dimensions of the bubble L and W are also indicated in Figure 1.

A video camera was used to record the bubble rise motion. With a stop-watch placed along side the test section, the time during which the bubble tranvels a prescribed distance may be obtained when the video pictures were re-played in slow motion.

RESULTS AND DISCUSSIONS

Rise velocities for bubble volumes of 1, 3, 5, 7, 10, 20, 40, 100 and 200mL were measured at channel inclinations of 2, 3, 5, 7, 10, 12, 30, 50, 70 and 90°. The channel width, a, examined were 100, 55, 25 and 16mm. Only selected results relevant to the discussions will be presented here. Details are given in Chen *et al.* (1991).

Figures 2 & 3 show that bubble velocities increase with the bubble volume in general. The effects of the channel inclination appears to be more complicated since the velocities initially increased with inclination, but beyond a certain angle, the velocity becomes lower as the vertical position is approached. Furthermore, there is a definite channel width effect. In Figure 3 where *a*= 100mm, the rise velocity in the 90° case becomes effectively constant when the bubble volume exceeds about 20mL.

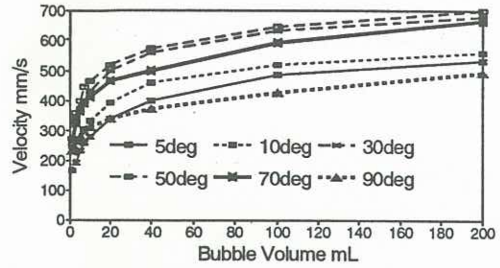

Figure 2. Bubble velocity plotted versus bubble volume with the inclination as a parameter for *a*=16mm.

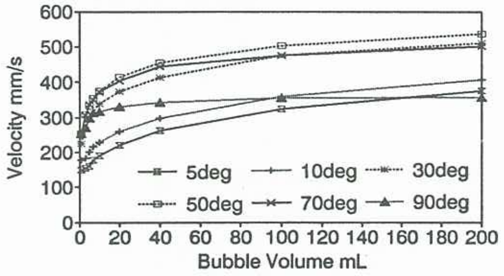

Figure 3. Bubble rise velocity plotted versus bubble volume with the inclination angle as a parameter with *a*=100mm.

The channel width effect is better illustrated when the data are re-plotted as in Figures 4, 5 and 6. The velocities showed a maximum somewhere in the range of 50-70° depending on *a* and the bubble volume. The existence of a maxima had already been reported by numerous authors including Spedding & Nguyen(1978), Weber *et al.* (1986). Maneri & Zuber (1974) attempted to explain the phenomena by considering two competing effects: variation of the bubble shape which affects the drag forces and the changes in the axial component of the buoyancy force. Bendiksen(1984) attempted a correlation involving the sum of a sine and a cosine term.

However, it is worth noting that Maneri & Zuber(1974) obtained their result using a channel which may be varied from 10.1 to 13.8mm in gap, and inferred that the rise velocity increases with increasing gap spacing.

Maneri's conclusions should be compared with the result presented in Figures 4, 5 and 6. In the case of small bubble volume, say 3mL, with inclinations less than about 50°, decreasing *a* from 100 to 55mm caused initially a decrease in the bubble rise velocity. However, further decrease in *a* from 55 to 25 and to 16mm showed a progressive increase in the bubble rise velocity. The latter trend is consistent for larger bubbles at inclination <50° over the entire range of *a* tested as shown in Figures 5 & 6.

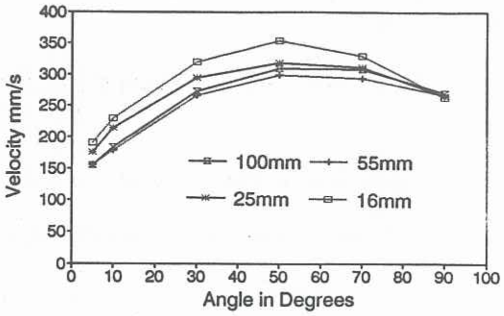

Figure 4. Bubble velocity plotted versus channel inclination with the *a* as a parameter for a 3mL bubble.

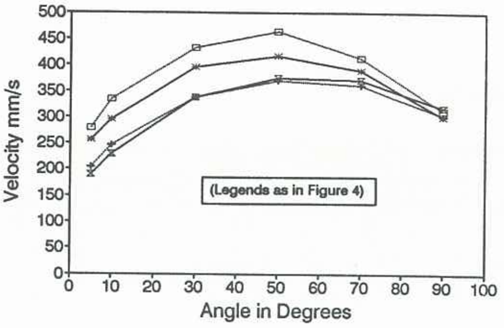

Figure 5. Bubble velocity plotted versus channel inclination with *a* as a parameter for a 10mL bubble.

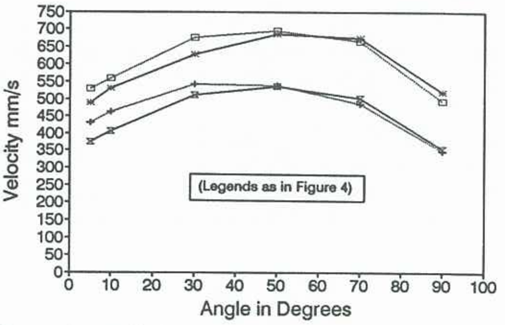

Figure 6. Bubble velocity plotted versus channel inclination with *a* as a parameter for a 200mL bubble.

In order to more clearly illustrate this behaviour, the data for the 30 and 90° inclinations are re-ploptted. In Figure 7, for small bubbles, e.g. less than 10mL, the rise velocity showed a minimum over the range of *a* examined. However, for larger bubbles, the rise velocity decreased with an increase in *a*.

The behaviour of bubbles at inclination exceeding about 50° appears to be different but follows very closely the behaviour for the vertical case. Thus, in Figure 8 which shows data for the 90° inclination, small bubbles exhibited velocity increase with increasing *a*. However, with larger bubbles, the velocity undergoes a minima within the range of *a* investigated.

Inclination Less Than About 50°

At low inclinations, typically less than 50°, bubble rise velocity generally increases with decreasing gap spacing except for the very small bubbles. To ascertain that this was in fact due to a change in the bubble frontal shape which affect the drag characteristics, measurements were taken from still pictures of the bubbles. Typical results for the case of a 200mL bubble rising at a 5° inclination are given in Figure 9.

The bubble length *L* and the bubble thickness *W* are plotted versus their respective velocities. The point corresponding to the lowest velocity is that for *a*=100mm, and for the highest velcoity, *a*=16mm. It is obvious that the frontal thickness and the length of the bubble increase with decreasing channel width. However, when these length terms are multiplied by the width of the channel *a* and replotted as shown in Figure 10, it becomes clear that the bubbles have a reduced frontal area and a reduced area of contact with the top wall as *a* is decreased. This therefore confirmed that the form and frictional drags are both reduced as the channel width is decreased.

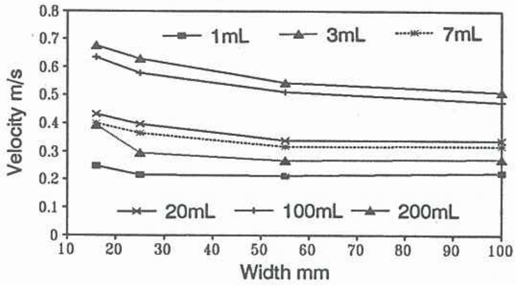

Figure 7. Bubble velocity plotted versus *a* with bubble volume as the parameter for channel inclination of 30°.

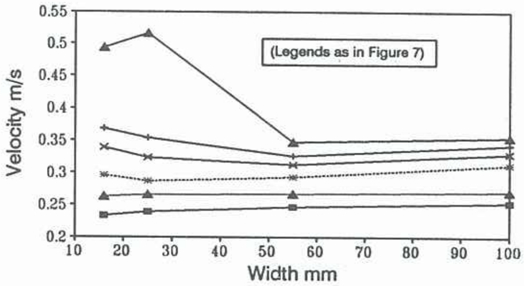

Figure 8. Bubble velocity plotted versus channel width with bubble volume as the parameter for channel inclination of 90°.

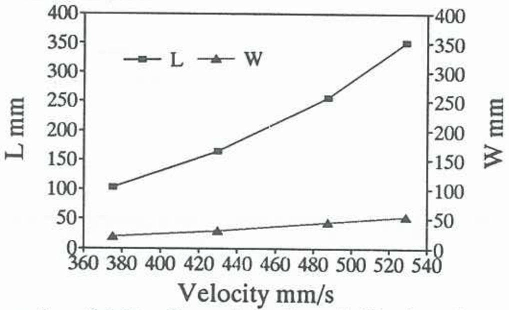

Figure 9. Bubble dimensions L and W plotted versus velocity. The four points correspond to, from left to right, channel width of *a* = 16, 25, 55, and 100mm.

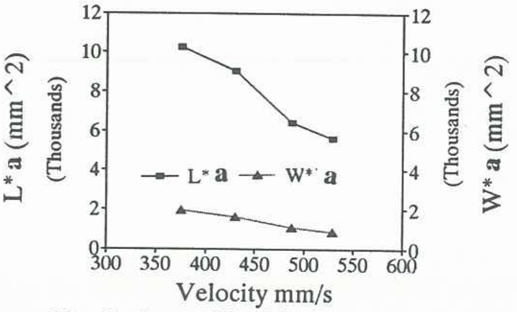

Figure 10. Products of bubble dimensions and channel width *L*a* and *W*a* plotted versus velocity. The four points correspond to channel width of *a* = 16, 25, 55, and 100mm.

Inclination Greater Than About 50° / Vertical Channel

For the purpose of discussions, only the vertical situation will be discussed as it is believed that the predominant forces in this situation is also dominant for inclination above about 50°. Wall effects for bubbles rising in a containing vessel whose cross-sectional dimensions are of the same order as the equivalent spherical diameter of the bubble, $\mathbf{d_{eq}}$, are considered in Cheremisinoff(1986). At $\mathbf{d_{eq}/D_{hy}} < 0.125$, where $\mathbf{D_{hy}}$ is the hydraulic diameter of the channel, effects due to the containing vessel may be neglected. However, at $\mathbf{d_{eq}/D_{hy}} > 0.125$ the bubble rise velocity with wall correction may be estimated as follows.

For $\mathbf{0.125 \le d_{eq}/D_{hy} \le 0.6}$,

$$U=1.13U_{\infty}\exp(-d_{eq}/D_{hy}) \tag{1}$$

and for $\mathbf{(d_{eq}/D_{hy}) > 0.6}$

$$U=[0.23+0.13(a/b)]\sqrt{gD_{hy}} \tag{2}$$

The value for U_{∞} is calculated using the results of Davies & Taylor(1950), *a* and *b* are the channel width and depth respectively, and g is the acceleration due to gravity. In Figures 11 to 13, the predicted values of **U** using Equations (1) and (2) are compared with the measured values for bubble volumes of 1, 10 and 200mL, for the four values of *a*. For small bubbles, e.g. 1mL, the predictions of Equations(1) is very clase to the measured values in the low $(\mathbf{d_{eq}/D_{hy}})$ range, i.e. large *a*. For larger bubbles, the predictions of Equation (2) approach the measured values as the bubble volume is increased. For bubble volumes between 1 and 100mL, none of the equations were suitable for $(\mathbf{d_{eq}/D_{hy}})$ > about 0.3 to 0.5. It is interesting to note that Equation (1) predicts a decrease in velocity with increased $(\mathbf{d_{eq}/D_{hy}})$ in all cases while the reverse is true for Equation (2).

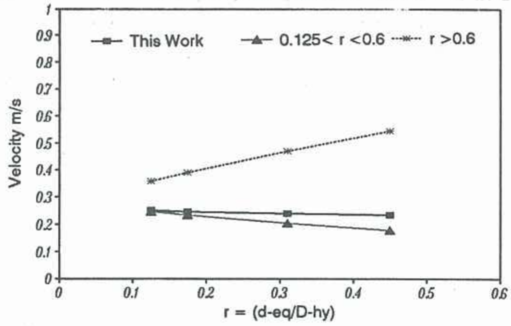

Figure 11. Comparison of measured vertical rise velocity for a 1mL bubble with predictions using Equations (1) and (2).

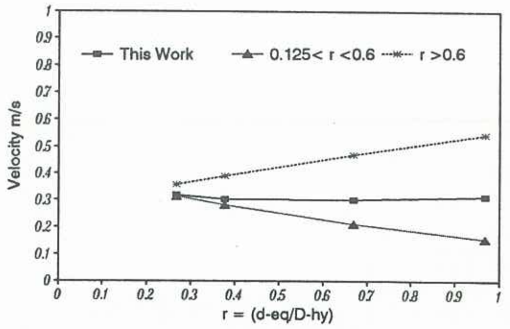

Figure 12. Comparison of measured vertical rise velocity for a 10mL bubble with predictions using Equations (1) and (2).

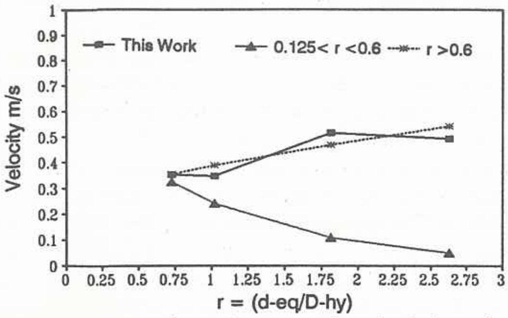

Figure 13. Comparison of measured vertical rise velocity for a 200mL bubble with predictions using Equations (1) and (2).

CONCLUSIONS

Experimental results for the rise velocity of bubbles in a channel at inclinations ranging between horizontal and vertical have been presented. While all bubbles exhibit a maximum velocity somewhere in the range of 50-70°, small bubbles showed a much weaker maxima.

The width of the channel affects the bubble rise velocity. At inclinations less than c 50°, while small bubble, e.g. <3mL in volume, showed a slight decrease in velocity with decreasing channel width *a* from 100 to 55mm, further decrease in *a* caused an increase in velocity. For larger bubbles, the velocity showed an increase with a decrease in the channel gap over the range examined.

The bubble behaviour for channel inclination >50° appears to be more complicated. The vertical case was chosen as a typical case for discussion. For small bubbles, the rise velocity increases with increasing channel spacing. On the other hand, at larger bubble volume, the rise velocity, in fact is decreased with an increase in the channel spacing. Existing correlations appear to correlate the results well for large bubbles. For bubbles in the intermediate range, the correlations hold only for small values of the bubble equivalent diameter to channel diameter ratio.

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