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Rise Velocity and Drag Coefficient of Collapsing Two-Phase Bubble Condensing in an Immiscible Liquid

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Abstract

Collapse of the vapor bubble condensing in an immiscible is investigated for n-pentane and n-hexane vapors condensing in cold water and n-pentane in two different compositions of glycerin- water mixture. The rise velocity and the drag coefficient of the two-phase bubble are measured.

Keywords: rise velocity, drag coefficient, two phase bubble, collapse of two phase bubble.

Introduction

The collapse of a vapor bubble in an immiscible liquid is encountered during the process of direct contact heat transfer by condensation of a vapor bubble in an immiscible liquid. As many investigators, [1-5] showed that dynamics of a collapsing two-phase bubble in addition to the heat transfer mechanism encountered between the two phases are more complex than the condensation of a bubble with constant radius.

In 1965, Sideman and Hirsch [1] showed their results of a collapsing isopentane bubble in water. The result was a condensing two-phase bubble with the condensate accumulated at the bottom of the bubble. They assumed that the heat transfer is accomplished only across the interface between the condensate and the continuous phase. In 1970, Isenberg and Sideman [7] assumed the collapsing two-phase bubble to have a constant velocity and the flow is to be potential or the bubble to be a rigid sphere. The transfer area was assumed to be in the front part of the condensate. In 1970, Sideman and Hirsch [1] proposed an analytical solution for bubble collapse. This was based on quasi-steady state and potential flow assumption. A velocity correction factor was also introduced.

In 1978, Jacobs [8] observed that in a two component system, the condensate film would contribute to about 30% of the heat transfer resistance.

In 1982, Sideman and Moalem [9] and Sudhoff et al [10] discussed in details the heat transfer characteristics of a bubble collapsing in an immiscible liquid.

To give a good representation of the process of heat transfer and dynamics of a collapsing two-phase bubble in an immiscible liquid, it is necessary to calculate the transfer area and transfer coefficients and to incorporate the velocity of the bubble.

The hydrodynamics behavior of such a bubble was studied by Clift et al [11]. According to Wanchoo and Sharma [12], it can be seen from the literature that no conclusive work on the momentum transfer involved in the collapse of a two-phase bubble in an immiscible liquid was available. Most of the authors assumed the behavior of the collapsing two-phase bubble is similar to that of a pure bubble with constant radius, and used the corresponding correlation of the drag coefficient to predict the bubble velocity. They also stated that due to the complex nature of the two-phase bubble involving the condensate film formation, internal circulation, and the bubble deformation during the course of collapse, the available correlations of the drag coefficient and velocity do not match the actual phenomena. A further complication is the presence of the noncondensables in the dispersed phase.

Experimental Work

The experiments involved the use of a light hydrocarbon as the dispersed phase to condense in an immiscible liquid. The pairs were n-pentane in water, n-hexane in water, n-pentane in 50% glycerin-water mixture and n-pentane in 100%glecyrin. The experimental apparatus is shown in Fig. 1. It consisted of a QVF column of 0.1 m in radius and one meter long, situated in a rectangular container filled with water to ensure a constant temperature bath. A high-speed camera of 120 frames/s was used to record the velocity and the height of the collapsing bubble.

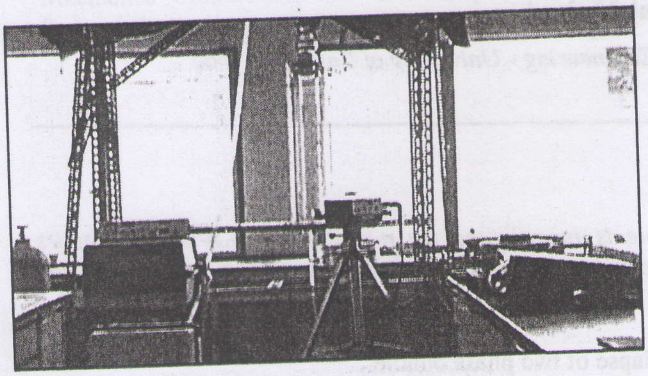

Fig. 1 Experimental apparatus

The column was filled with water at a low temperature say 12°C. Calibrated thermocouples were used to measure the change in the temperature of the continuous phase. The dispersed phase was introduced through a nozzle at the bottom of the column. Nozzles of two different diameters were used to get two different starting bubble diameters, these were (0.35cm and 0.3cm respectively).

The heating of the dispersed phase, which was placed in a QVF flask, made the vapor of the dispersed phase to be generated in the QVF flask. The vapor passed from the flask through a heated copper tube to the column.

The two-phase bubble starts to form as the vapor enters the column were the cold continuous phase. The condensate forms the lower part of the bubble and the remaining vapor in the upper part of it. To measure the change or the decrease in the dimensions of the two-phase bubble and its velocity, a high-speed camera of 120 frames/s was used where the timer showed the time related to each picture successively. With the measured position of each bubble, the velocity was calculated. A digital camera with a 3.5" floppy disk was also used to get clear photographs of the two-phase bubble. The shape of the two-phase bubbles ranged from spherical to elliptical and sometimes had a deformed shape. Their equivalent radii were measured. A schematic representation of the two-phase bubble is shown in Fig. 2 [13].

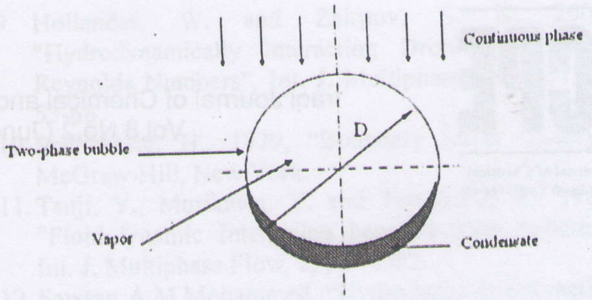

Fig. 2 Two-phase bubble

During the experiments the condensing two-phase bubble always looked as in Fig. 2, where the vapor phase was in the upper part of the bubble while the liquid or condensate was accumulated at the rear back of the two-phase bubble.

For the collapsing bubble it was always seen that the velocity of the two-phase bubble always changed and it got less and less as the bubble was encountering the condensation process as it descended upward.

Results and Discussion

According to Wanchoo and Sharma [12], equilibrium of the drag, gravity and buoyancy forces was assumed. The equation of motion for the collapsing two-phase bubble can be given as:

$$\frac{U^2}{gD}=[\frac{4}{3}Cd][1-\frac{\rho_{av}}{\rho_c}] \quad (1)$$

The average density given in eq.(1) can be calculated according to the mass balance around a constant mass bubble of two phases. In 1987, [14] used the following equation to calculate the average density:

$$\rho_{av}=\frac{\rho_v}{\left(\frac{D}{D_o}\right)^3} \quad (2)$$

If the above two equations are combined with the use of the defenition of Archimedes number given as follows:

$$Ar=\left[\frac{D^3 g\rho_c^2}{\mu_c^2}\right]\left[1-\left(\frac{D_o}{D}\right)^3\frac{\rho_v}{\rho_c}\right] \quad (3)$$

The final equation to calculate the drag coefficient for the two-phase bubble is given in the following equation:

$$Cd=\left[\frac{4}{3}\right]\frac{Ar}{\mathrm{Re}^2} \quad (4)$$

The drag coefficient of a rigid sphere was also calculated to be compared with the one calculated from eq.(4). The following equations were used to calculate the drag coefficient based on the values of the Reynold's number, [11]:

$$
\begin{aligned}
Cd &= {}^{24}\!/_{\mathrm{Re}} && \text{for } \mathrm{Re} \le 1 \\
Cd &= {}^{24}\!/_{\mathrm{Re}}\,[1+.102\mathrm{Re}^{0.855}] && \text{for } 0.2 < \mathrm{Re} \le 2 \\
Cd &= {}^{24}\!/_{\mathrm{Re}}\,[1+0.125\mathrm{Re}^{0.802}] && \text{for } 2 < \mathrm{Re} \le 21 \\
Cd &= {}^{24}\!/_{\mathrm{Re}}\,[1-0.189\mathrm{Re}^{0.632}] && \text{for } 21 < \mathrm{Re} \le 200 \\
Cd &= 0.28 + {}^{6}\!/_{\mathrm{Re}^{0.5}} + {}^{21}\!/_{\mathrm{Re}} && \text{for } 200 < \mathrm{Re} < 4000
\end{aligned}
\tag{5}
$$

The values of Re were calculated using the physical properties of the continuous phase and the velocity of the two-phase bubble with its equivalent diameter. The velocity and the bubble equivalent diameter were determined from the high speed camera readings.

The rise velocity of the studied two-phase bubble were represented for each pair of fluids and for each initial diameter of the bubble in Fig. 3, 4, 5 and 6.

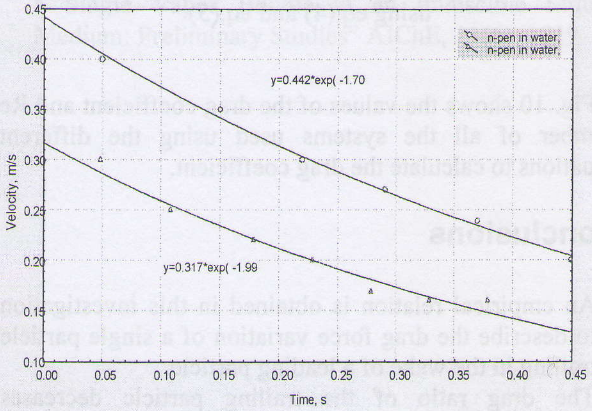

Fig. 3 Rise velocity vs time for n-pentane/water system

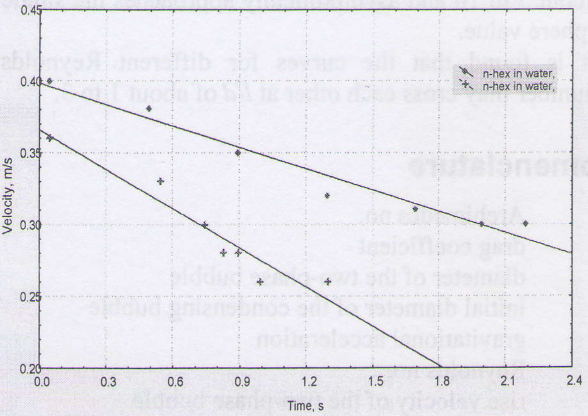

Fig.4 Rise Velocity vs Time for n-hexane/water system

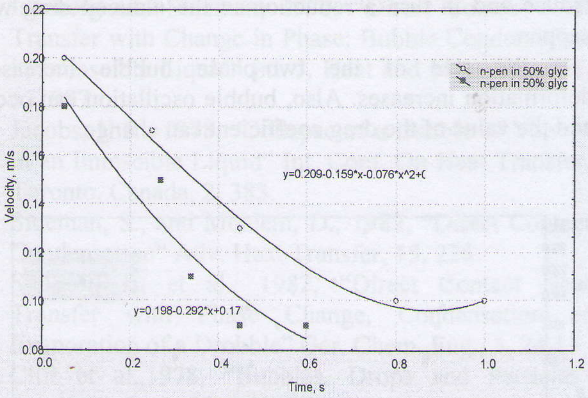

Fig. 5 Rise Velocity vs Time for n-pentane in 50% glycerin system

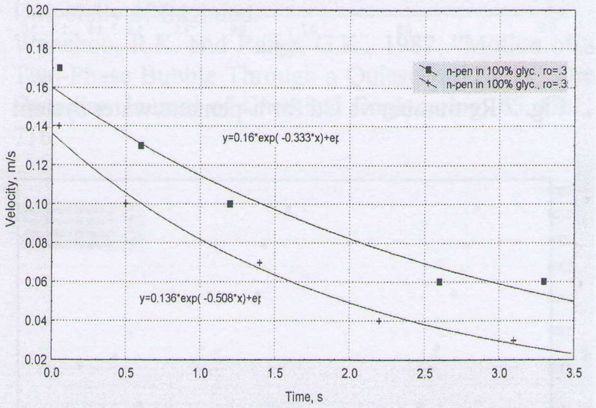

Fig.6 Rise Velocity vs Time for n-pentane in 100% glycerin system

All the figures above showed clearly a decrease in the value of the rise velocity for the two-phase bubble. It is also evident that the larger bubble always has the lower velocity. For the systems of n-pentane glycerine, the velocity was much less than the other two systems. This is due to the large difference in the physical properties of the continuous phase (i.e. pure water and different compositions of glycerine).

The relation between Re number and the drag coefficient for different pairs of fluids is clearly shown in Fig. 7, 8, and 9.

From the above figure, it is clear that the two-phase bubble experiences a reduction in the drag coefficient. According to [11], the reduction in drag coefficient of collapsing two-phase bubble is due the presence of mobile interface (condensate film) and a high degree of internal circulation present within the bubble.

This circulation might reduce the skin friction and the form drag. The size of wake behind the bubble may reduce and in turn a reduction in the induced drag will happen.

If the size of the two-phase bubble increases, deformation increases. Also, bubble oscillation can occur and the value of the drag coefficient can change.

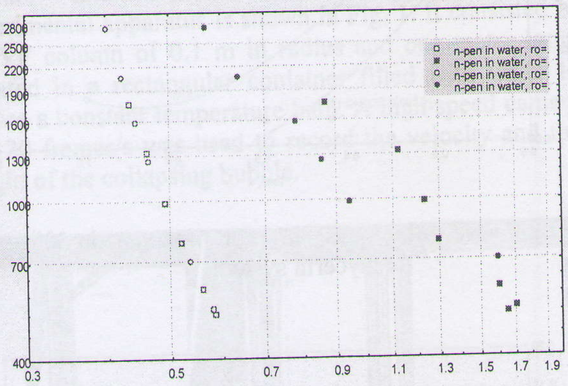

Fig. 7 Re number vs Cd for n-pentane/water system

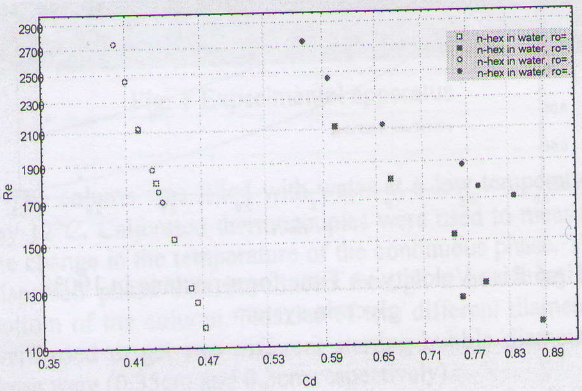

Fig. 8 Re number vs Cd for n-hexane/water system

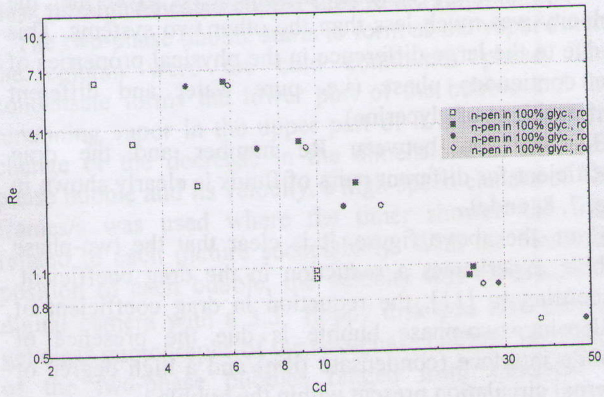

Fig. 9 Re number vs Cd for n-pentane in different glycerin systems

The difference in the values of drag coefficient calculated according to the rigid sphere model or eq.(4) may be attributed to the use of physical properties of the continuous phase and the equivalent diameter of the two-phase bubble.

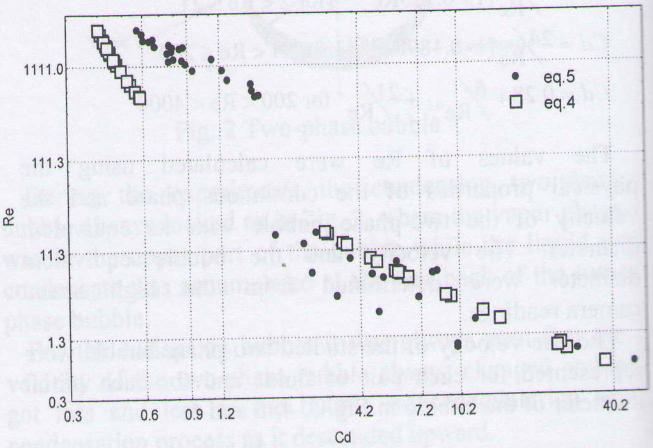

Fig. 10 Re. Number vs Cd for all the systems studied using eq.(4) and eq.(5)

Fig. 10 shows the values of the drag coefficient and Re number of all the systems used using the different equations to calculate the drag coefficient.

Conclusions

1. An empirical relation is obtained in this investigation to describe the drag force variation of a single particle trailing in the wake of a leading particle.
2. The drag ratio of the trailing particle decreases exponentially with decreasing *l/d* and reaches a minimum at the contact position, but the effect of interaction disappears at a distance larger than *l/d* of about 5 to 10 and asymptotically approaches the single sphere value.
3. It is found that the curves for different Reynolds number may cross each other at *l/d* of about 1 to 3.

Nomenclature

Ar	Archimedes no.
Cd	drag coefficient
D	diameter of the two-phase bubble
Do	initial diameter of the condensing bubble
g	gravitational acceleration
Re	Reynolds no.
U	rise velocity of the two-phase bubble
ρav	avearge density of the two-phase bubble
ρc	density of the continuous phase
ρv	density of the vapor phase

μc viscosity of the continuos phase.

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