Dynamics of a Single Condensing Two-Phase Bubble

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Abstract

The dynamics of a single condensing two-phase bubble of two different dispersed-continuous systems were studied. The systems were, CCl_4 - water and CCl_4 - 100% glycerol. Cinephotography was used to determine the change in height, diameter and time. These results were used to determine the experimental rise velocity of the bubble, which was compared with a theoretical one based on some equations used. It was found that the velocity of the first system remained almost constant, while it decreased gradually for the second system.

Keywords: condensing bubble, two-phase bubble, dynamics of bubble.

Introduction

When a vapor is bubbled through a cooler immiscible liquid, direct – contact heat transfer takes place. With the continuous phase below equilibrium temperature, condensation of the vapor will occur around the vapor bubble giving two – phase bubble. Buoyant force cause this bubble to rise and create convective motion of the fluid. At the same time the continued condensation causes bubble collapse [1].

"Two – phase bubble" each comprising a vapor or gas phase and a liquid phase in a medium of another immiscible liquid have an importance in various kinds of heat and mass transfer processes. A number of studies, both theoretical and experimental, have been done to study the phenomenon of a single moving bubble condensing in a stagnant column of immiscible liquid [2].

Direct – contact heat transfer occurs when immiscible fluids (liquid and vapor) are brought into contact, resulting in the condensation of the vapor that has a higher boiling point. Also, it occurs when immiscible fluids (liquid and liquid) are brought into contact, resulting in the evaporation of the liquid that has a lower boiling point. It has been studied by many researchers because it has many advantages over conventional heat exchangers [2].

Direct – contact heat transfer in process equipment occurs between two process streams, which can either be identical media or different ones [3]. It deals mostly with contact of immiscible fluids as a dispersed and continuous fluid. Heat transfer occurs as condensation or evaporation of the dispersed fluid, which is in direct contact with the continuous one.

The advantages of the direct – contact heat exchangers according to different studies and authors [1], [4], [5], [6], and [7] are summarized below:

- Smaller required temperature differences.
- Smaller mass flow rate of the transfer fluid.
- Convenient separation of the fluid.
- Eliminating metallic heat – transfer surfaces between fluids, which are prone to corrosion and fouling.
- If phase change occurs, a large heat capacity for heat absorption is available because of larger contact area between the fluids.

This study was undertaken to observe the dynamics of a two-phase bubble, condensing in an immiscible liquid, such as change of the velocity of rise of the two-phase bubble with time and comparison of theoretical rise velocity with the experimental data. The experimental observations involved the use of cinephotography to record the collapse of different dispersed phase bubble in different continuous phase liquids. The dynamics of the two-phase bubble was determined.

Experimental Work

The experimental study was carried out to investigate the hydrodynamics associated with the phase change of vapor bubbles condensing while rising in a stagnant medium of an immiscible liquid whose temperature is moderately less than the saturation temperature of the bubble. As the condensation starts, the vapor bubble turns into a "two – phase bubble" composed of a growing liquid phase and a reducing vapor phase, and it continues to rise in the medium due to decreasing buoyancy.

Experimental apparatus

The experimental apparatus is shown photographically in Figure, 1 and schematically in Figure, 2. The main components of the experimental setup are:

- Main column.
- Dispersed – phase vaporizer.
- High – speed video camera.
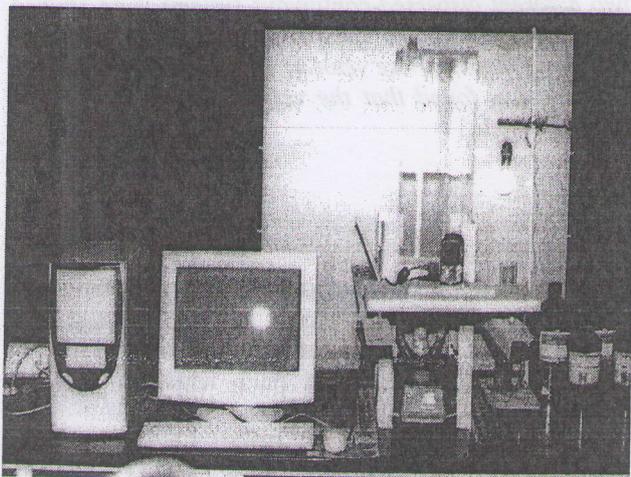
Figure 1, General photographic view of the experimental apparatus

Experimental procedure

The glass column was properly leveled and filled up to a pre – fixed height with either distilled water or aqueous glycerol solutions (25, 50, 75 and 100 wt.%). The continuous – phase liquid was maintained at the room temperature (20 °C). A calibrated thermometer was used to measures the temperature of the continuous phase. To ensure the constant temperature, the space between the inner column and the square Perspex was filled with water as a coolant.

The three – necked flask was filled with dispersed phase liquid (carbon tetra chloride or n – heptane). Heating of the flask was accomplished by using an electrical heating mantle. Enough amount of heat must be supplied to the flask so that the evaporation starts and no back condensation occurs. The vapor was generated and

left the flask through a rubber tube to the nozzle at the bottom of the column. In order to avoid any condensation inside the dispersed phase nozzle, glass wool covered by aluminum foil was wound around the upper part of the vapor – generating flask, and also round the rubber tube all the way to the nozzle entrance at the bottom of the column.

1.	Light source
2.	QVF column
3.	Perspex column
4.	Continuous phase
5.	Transparent scale
6.	Two-phase bubble
7.	Thermometer
8.	Nozzle
9.	Valve
10.	QVF flask (500 ml)
11.	Dispersed phase
12.	Electrical heating mantle
13.	Camera
14.	computer
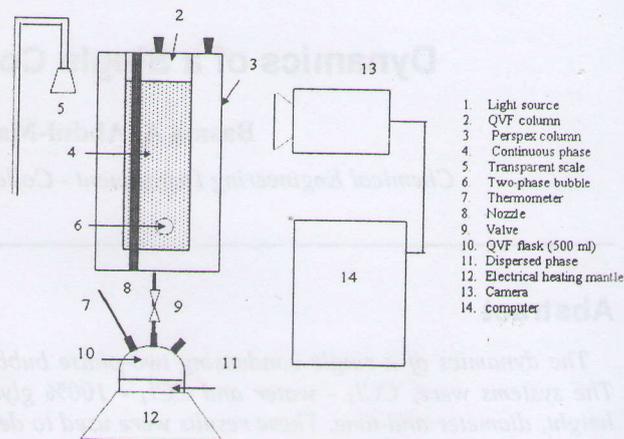
Figure 2 Schematic diagram of the experimental apparatus

The dispersed phase vapor bubble (*i.e.* carbon tetra chloride or n – heptane) formed started to move through the continuous phase, and its upward motion was recorded by a high speed video camera. The captured images were saved in computer and analyzed to calculate the variables changes (*i.e.* instantaneous height, time, diameter and rise velocity of the two – phase bubble) for all systems studied.

A backlight arrangement was used for proper exposure. Prior to the motion of the bubble, the camera was focused on the transparent millimeter plastic scale. Standard spherical glass balls of different and known sizes were fixed on the plastic scale and were photographed along with the bubble. Their images were projected and enlarged. These standard glass balls helped in getting the approximate value of the two – phase bubble diameter.

As the vapor bubble entered the column, it started to condense causing the temperature of the continuous phase to increase in the field around the two – phase bubble. This increase in temperature was measured using one thermocouple, which was embedded inside the glass column. The temperature increase of the continuous – phase was very small (0.5 – 1 °C), which did not affect the physical properties of the continuous phase.

Analysis of the experimental data

Studying and analyzing the photographs gave the instantaneous two – phase bubble height and time of ascent

from the nozzle tip. The inlet position of the nozzle was considered as the reference point and other readings were taken relative to it. Knowing the time and position, the instantaneous rise velocity of the bubble was determined.

A comparison was made between the photographs of the standard spherical glass balls with different and known sizes, and the photographs of the two – phase bubbles for different systems studied. This comparison helped in the relative determination of the size of the two – phase bubble, *i.e.* its diameter.

Different photographs for the ascending two – phase bubble are shown in Figures, 3 to 5. These photographs show the evolution of the bubble during the condensation process.
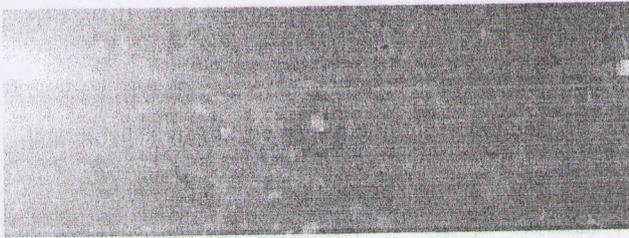
Figure, 3 Two – phase bubble at the beginning of the condensation process

Figure, 4 One of the stages of the condensation process of the two – phase bubble
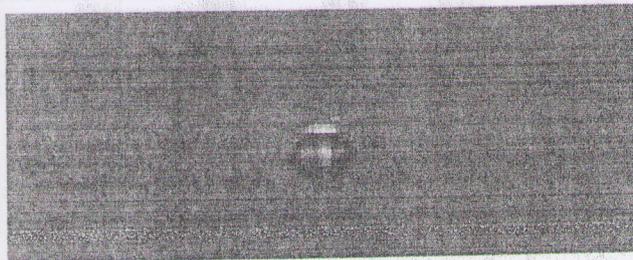
Figure, 5 Magnified two – phase bubble during the condensation process

Results and Discussion

Various forces that affect the two – phase bubble motion through an immiscible liquid are: inertial, viscous, buoyancy and interfacial tension. The difference in physical properties such as the density and viscosity between the continuous phase, being distilled water in the first case and different concentration solutions of glycerol in the second case,

causes the different changes in the behavior of the two – phase bubble, and among them is the velocity behavior.

The rise velocity was nearly constant for the CCl4 – water and n-heptane – water systems. A narrow range of bubble velocities was observed for the carbon tetra chloride – water system (0.205 – 0.198 m/s), as shown in figure (6.a), and for the n – heptane – water system (0.216 – 0.211 m/s). Also, it can be observed that the velocity of n – heptane bubble was higher than that of carbon tetra chloride bubble, this is because the vapor density for n – heptane is less than the vapor density for carbon tetra chloride.

A gradual decrease was observed in two – phase bubble velocity for carbon tetra chloride – 25% glycerol system (0.196 – 0.185 m/s) and for carbon tetra chloride – 50% glycerol system (0.143 – 0.122 m/s). A sharp decrease can be observed for carbon tetra chloride – 75% glycerol system (0.106 – 0.078 m/s) and for carbon tetra chloride – 100% glycerol system (0.023 – 0.003 m/s) as shown in figure (6.b). Also, it can be seen from these figures that the rise velocity decreases with the increase in viscosity of the continuous – phase.
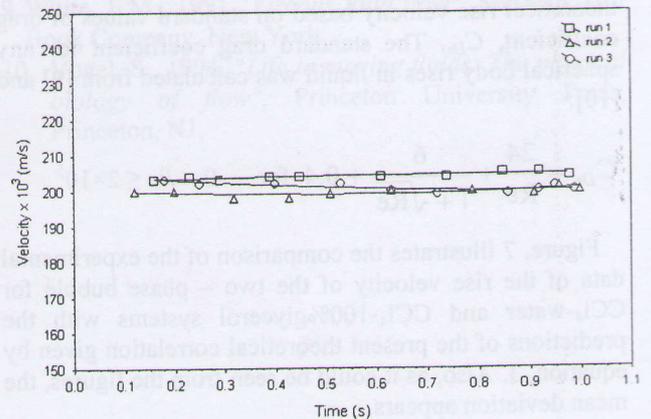
(a)
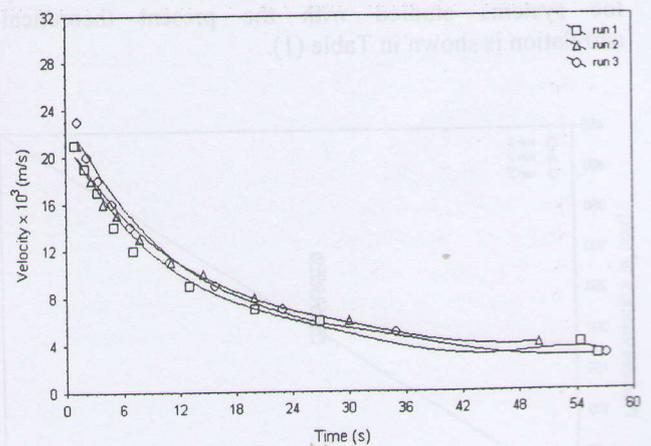
(b)

Figure 6, change of velocity with time, (a) CCl₄-water system, (b) CCl₄-100% glycerol system

Now to predict the theoretical values of rise velocity, a mathematical model was derived for this purpose. Assuming equilibrium of the drag, gravity and buoyancy forces, the equation of motion for a condensing two-phase bubble can be written as [7]:

$$\frac{U_{theo}^2}{gD} = \frac{4}{3}\frac{1}{C_{Ds}}\left(1 - \frac{\rho_{dav}}{\rho_c}\right) \quad (1)$$

Based on the material balance around a constant mass two-phase bubble the average density of the two=phase bubble, [8] can be estimated as:

$$\rho_{dav} = \frac{\rho_{dv}}{(D/D_o)^3} \quad (2)$$

Combining Eqs, 1 and 2,

$$U_{theo} = \left[\frac{4}{3}\frac{gD}{C_{Ds}}\left(1 - \frac{\rho_{dv}}{\rho_c}\left(\frac{D_o}{D}\right)^3\right)\right]^{1/2} \quad (3)$$

Equation, 3 was used to determine the values of theoretical rise velocity based on standard values of drag coefficient, C_{Ds}. The standard drag coefficient for any spherical body rises in liquid was calculated from [9] and [10]:

$$C_{Ds} = \frac{24}{Re} + \frac{6}{1 + \sqrt{Re}} + 0.4 \quad for \quad 0 < Re \le 2 \times 10^5$$

Figure, 7 illustrates the comparison of the experimental data of the rise velocity of the two – phase bubble for CCl₄-water and CCl₄-100%glycerol systems with the predictions of the present theoretical correlation given by equation, 3. Also, as it could be seen from the figures, the mean deviation appears.

Some of the results of comparison of the rise velocity foe systems studied with the present theoretical correlation is shown in Table (1).

(a)

(b)
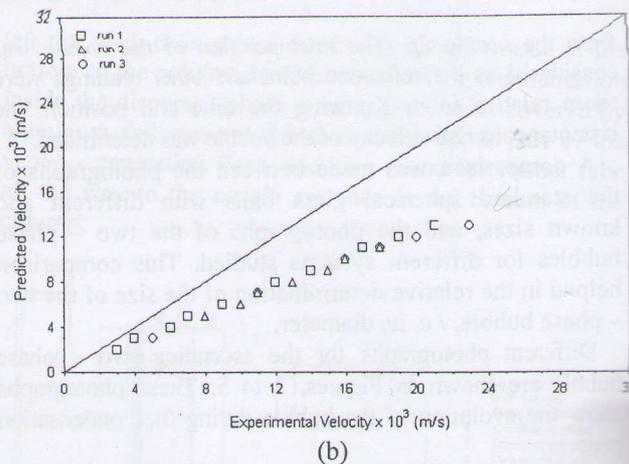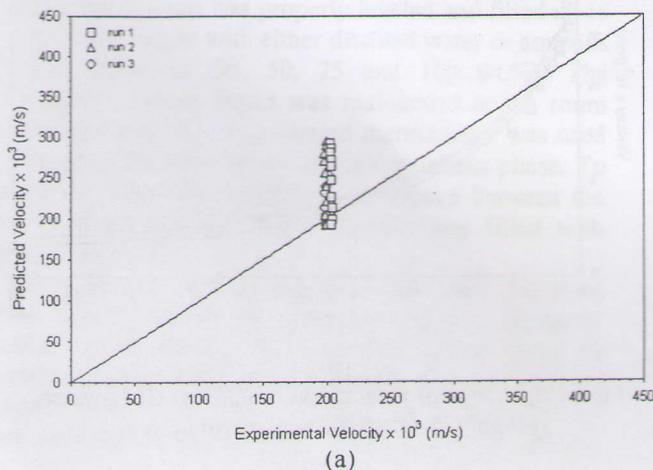
Figure 7, Comparison of theoretical rise velocity with the experimental data (a) CCl₄-water system, (b) CCl₄-100%glycerol system

Table (1) Some of the Experimental and Theoretical results

CCl₄-water system				
Instantaneous height, $H \times 10^{-3}$, m	Time, s	Diameter ratio D/D_o	Experimental rise velocity of two-phasw bubble, m/s	Theoretical velocity of two-phasw bubble m/s
32.5	0.16	0.976	0.203	0.293
47	0.23	0.941	0.204	0.286
59	0.29	0.906	0.203	0.280
79.5	0.39	0.859	0.204	0.271
92	0.45	0.823	0.204	0.264
124.5	0.61	0.741	0.204	0.247
151	0.74	0.647	0.204	0.226
174	0.85	0.588	0.205	0.213
188.5	0.92	0.529	0.205	0.198
200	0.98	0.506	0.204	0.192
CCl₄-100% glycerol system				
Instantaneous height, $H \times 10^{-3}$, m	Time, s	Diameter ratio D/D_o	Experimental rise velocity of two-phase bubble, m/s	Theoretical velocity of two-phase bubble m/s
20	0.96	0.988	0.021	0.013
38	1.99	0.965	0.019	0.012
56.5	3.35	0.906	0.017	0.011
70	5.06	0.882	0.014	0.009
88	7.12	0.823	0.012	0.008
120.5	13.10	0.741	0.009	0.006
144.5	20.11	0.670	0.007	0.005
168	27.00	0.588	0.006	0.004
190	54.45	0.529	0.004	0.003
200	56.28	0.506	0.003	0.002

Conclusions

The two – phase bubble rises almost at a constant velocity in low – viscosity liquids (viscosity ≤ 1 cP), while a gradual decrease in velocity was observed in other liquids. The condensing two – phase bubble maintains its sphericity in high – viscous continuous – phase immiscible liquid, while it changes it shape and traverses a zigzag path in a low – viscous continuous – phase liquid, like water. The amplitude of oscillations was found to decrease with increasing in the viscosity of continuous – phase liquid. Throughout the rise motion of the two – phase bubble, the vapor phase was always located on the top of the liquid phase, and the two phases were always in contact with each other. There was a

continuous decrease in the volume of the two – phase bubble with time because of the condensation process. As the condensation process continues the mass of condensate increases.

Nomenclatures

C_D	Standard drag coefficient
D	Diameter of the two-phase bubble, m
D_o	Initial diameter of the two-phase bubble, m
G	Gravitational acceleration, m/s^2
H	Instantaneous height of the two-phase bubble, m
M	Mass of the two-phase bubble $= \dfrac{\pi}{6} D^3 \rho_{dav}$, kg
Re	Reynolds number $= \dfrac{\rho U D}{\mu_c}$
U	Rise velocity of the two-phase bubble, m/s

Greek letters

P	Density. kg/m^3
M	Viscosity, kg/ms.

Subscripts

Av	Average value
C	Continuous phase
Dv	Dispersed phase vapor
$Theo$	Theoretical

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