Effect of temperature variation on the fluctuation of a sessile bubble rising in a stagnant medium

A M E D Faik* and A A Mohammed

Mechanical Engineering Department, Mustansiriayah University, Baghdad, Iraq
*a.faik@uomustansiriyah.edu.iq

Abstract. The present work represents an experimental investigation of the flow dynamics and features of a rising isolated bubble within a stagnant water column under variable temperature. The experimental tests have been carried out using high speed imaging with backlighting. Five different values of the water temperature (namely 10, 20, 30, 40, and 50°C) have been implemented during the experiments. The studied features are the bubble size (diameter and circumference), bubble shape (sphericity and aspect ratio), bubble rising velocity, in addition to the bubble zigzag motion features (angle, maximum horizontal diameter, velocity, and occurrence time portion). The obtained results showed that as the temperature increases, the degree of bubble zigzag motion from its vertical path increases, which means the flow of the bubble becomes less stable. Bubble diameter is shown to be irresponsible to temperature for small value increase, whereas, for greater temperature magnitudes (from 30 to 50°C) it is shown to be proportional. All other features are shown to be proportional to temperature variation. The zigzag motion features are also shown to be proportional to water temperature variation except the average occurrence time is inversely proportional to this change.

Keywords: Water, temperature, bubble dynamics, bubble fluctuation, image processing.

1. Introduction

The importance of bubbles and their dynamics is apparent in a variety of natural and industrial processes with multiphase flow natures. Flotation, distillation, absorption and boiling are among these processes in which bubbles and bubble dynamics are essential in defining the nature of the process [1]. Even in combustion, recent articles by the first author show that bubble generation inside the fuel droplet affects the combustion behavior in diesel-based fuel blends and emulsions [2–4]. Additionally, a diverse collection of physical, chemical, and engineering processes encompass bubble flow in the course of the process such as bubble columns, gas-solid fluidized beds, and gas-slurry bubble columns. The relative motion between the surrounding environment and gas bubbles in such systems is of fundamental importance in deciding the modes of heat and mass transfer to and from these systems. However, the dynamics of the fluids which is the key factor that controls the mixing and heat and mass transfer in such systems is relatively complex and not well understood [5]. Bubble dynamics include rising, coalescence, and collision, in addition to initial bubble formation, bubble growth, and detachment [6]. And the key parameters in defining these dynamics are bubble rise velocity (or terminal velocity) [7], bubble size variation [8], bubble shape and other parameters [9]. Therefore, the fundamentals of bubble dynamics have been the subject of a large number of studies [10–16]. One of
the parameters covered is the effect of liquid temperature on the bubble dynamics [6,17–20]. Zhen et al., [11] investigated the effect of high pressure and high temperature environment on bubble shape (in terms of aspect ratio) and rising velocity. They found that bubble velocity is proportional to temperature and inversely proportional to pressure of the liquid. Liu et al., [18] proved theoretically that bubble growth strongly depends on liquid temperature in binary mixtures. Robinson and Judd [16] also came with the same finding for bubble growth through a liquid with uniform temperature filed. However, despite the large number of studies performed for describing bubble dynamics, there still some aspects have not been covered, such as bubble flow path fluctuation or zigzag motion during its rise. This motion has been described be a number of researchers [20–26] to take place for bubbles of intermediate size range due to the effect of lift force [22]. The bubble zigzag motion is the periodic deviation of the bubble from the center of its path towards the right and left directions [23]. Despite of being described in literature, comprehensive analysis of this zigzag movement has not been found. Hence, the scope of this work will be devoted to carry out such analysis for bubble flow in stagnant liquid. Therefore, the main objectives of the present work are the implementation of imaging techniques and high speed imaging on the tracking and experimental study of the flow and dynamics of air bubbles in a stagnant water column under variable temperature, these dynamics include bubble size, shape, velocity, and zigzag motion.

2. Experimental work

Figure 1 (a) shows the schematic diagram of the experimental setup. A square-base transparent glass (15*15*40 cm) water tank equipped with a domestic water heater, thermostat for temperature control, and thermometer (temperature reading range 0-100°C) is used for experimentation. An Rs-150 Electrical bubble generator with 2.5 L/min maximum flow rate, 3 Watts power consumption, and 25 dB noise has been used for bubble generation. The diameter of the nozzle attached to the bubble generator is (4mm) with de-ionized water being the medium fluid, and the average generated bubble diameter is 1.4±0.3mm. The optical setup is based on backlighting imaging, where a (25 volts and 290 mAmps) light source is placed behind the water tank and the high speed camera (720HD IPhone7 mobile camera) is placed in front of the tank. The camera is set to (240 fps) imaging rate, (720*1280 pixle) image size covering a (191*107mm$^2$) of the tracked area, which covers the overall flow field of the bubble from the nozzle to almost the water surface. A plain white rectangular light diffuser is used for reducing the light intensity and insuring uniform distribution of the light all over the imaging area. This sheet is placed between the light source and the water tank.

![Figure 1](image-url)

*Figure 1. (a) Experimental setup, (b) Sequential tracking of bubble rise at 20°C water temperature.*

The fish tank is filled with a sufficient amount of distilled water so that the heater is fully merged and the view field of the camera is fully covered with water. This water is then heated to the set temperature (10, 20, 30, 40, and 50°C respectively). Continuous mixing is performed throughout the heating period to ensure uniform temperature distribution all over the water quantity in the tank. Once the set point is obtained, the bubble generator (that is set to produce a single bubble per pulse) is
turned on. Meanwhile, the imaging system is set and ready to work, once the bubble is ejected, the flow of this bubble is tracked and photographed using the high speed imaging system. Figure 1 (b) shows a set of successive images of an air bubble rising within the water column at 20°C environmental temperature. The above procedure is repeated for five times for each set temperature, this means, five different bubbles are generated and tracked for each of the five selected set temperature values. The images of each test are saved in a clip form in the MP4 format. These clips are then converted using MATLAB into odd frames in the JPEG format. Each of the obtained frames is post-processed according to a sequence of processes that include: (i) reading and cropping the RGB raw image, (ii) image enhancement, (iii) segmentation and morphological operations, (iv) feature extraction, and (v) data saving. The extracted features are the instantaneous bubble equivalent diameter, bubble projected area and circumference, instantaneous major and minor diameters of the rising bubble, in addition to the centroid and orientation of the bubble center. Then, the terminal velocity, Reynolds number, bubble deviation from vertical flow path are all calculated. Further details on the image enhancement, segmentation and morphological operation processes carried out for extracting the flow features can be found in [27]

3. Results and Discussion
The left upper part of Figure 2 shows the bubble shape change during the rising process. As it is shown, the bubble takes different shapes as it flows through the water depending on the drag force.

![Figure 2. Bubble shape change sequence (upper left), and bubble path tracking for 5-bubbles at: T=10ºC (upper middle), T=20ºC (upper right), T=30ºC (lower left), T=40ºC (lower middle), and T=50ºC (lower right).](image)

![Figure 3. Bubble Size variation (D/D₀) with normalized time (t/t_total).](image)
The other images in Figure 1 show the flow-path of 5-bubbles at each water temperatures with the temperatures being (10, 20, 30, 40, and 50ºC) respectively. It can be inferred from the images that as the temperature increases, the degree of bubble deviation (zigzag motion) from its vertical path increases, which means the flow of the bubble becomes less stable. This is in agreement with the findings of [28] for the effect of water temperature on bubble coalescence. Additionally, it can be shown from the images that for a specific temperature, the flow path followed by all the bubbles is almost the same even though the bubbles are not generated together. This gives an indication on the dependency of the bubble flow path on the properties of the liquid they are rising within.

Figure 3 shows the normalized bubble diameter variation ($D/D_0$) with normalized time at water temperatures (10, 30, and 50ºC respectively). Bubble diameter is obtained through image processing by evaluating the equivalent diameter of the projected area on every image, this method is further discussed in [27]. From the figure, it can be seen that increasing the temperature from 10 to 30ºC did not result in a sensible variation in bubble diameter, but when the water temperature is increased to 50ºC, a relatively sharp increase in diameter is resulted. From this, it can be inferred that bubble diameter is irresponsive to temperature for small value increase. This is in agreement with the findings of [20] for incremental temperature increase. Whereas, for greater temperature magnitudes (from 30 to 50ºC) is shown to be proportional, which is in agreement with [16] both experimentally and theoretically. However, this contradicts the findings of both [6,18] for higher temperatures.

![Figure 4. Normalized bubble size fluctuation ($\Delta D/D_0$) versus normalized flow time ($t/t_{\text{total}}$).](image)

Additionally, it can be seen that during its movement through the medium, the bubble experiences slight fluctuations in its size; these fluctuations have been evaluated as the net difference between two successive size values for all the tested bubbles for all temperatures. A sample of these values is
shown in Figure 4 for the same bubbles presented in Figure 3. From the figure, it can be noticed that bubble size fluctuation takes place in almost whole of the bubble rising time, and that sometimes it is being relatively in the same order of magnitude of the bubble initial size. The average values of bubble size fluctuations are evaluated and shown in Figure 5. From the figure, it can be noticed that the average bubble size fluctuation is in the \(10^{-3}\) order of magnitude of the initial bubble size, and it is proportionally responsive to the variation in water temperature. However, the repeatability of fluctuation values (expressed in terms of the standard deviation bars) is slightly diverging with the increase in water temperature. The increase in bubble size fluctuation is attributed to the decrease in buoyancy and surface tension forces of the water with increasing its temperature [6].

![Figure 6. Bubble terminal velocity (m/s) versus normalized time \((t/t_{total})\).](image)

Figure 6 shows sample results of the variation of bubble rise terminal velocity with respect to time (normalized with the total time) for (10, 30, and 50ºC) water temperature respectively. These velocity values are for the same bubbles shown in Figure 3 and Figure 4. Bubble rising velocity is obtained through image processing by evaluating the vertical displacement of the bubble for each image and dividing the difference in displacement between two successive images on the time difference between them. The obtained velocity values are highly comparable in order and magnitude to those corresponding velocity values published in literature, such as those in [11]. This in turn gives a high confidence in the implemented processing algorithm and the obtained results. It can be depicted from Figure 6 that the bubble terminal velocity is proportional to the temperature variation. This is attributed to the decrease in water surface tension and buoyancy by increasing its temperature [11,20,28]. In addition to the above presented results, some of the bubble flow characteristics are evaluated and averaged over the results of 5-bubbles for each of the (10, 20, 30, 40, and 50ºC) water temperature values. These flow characteristics include average bubble size (expressed in terms of bubble diameter and perimeter), average bubble shape (in terms of its sphericity and aspect ratio), and average rising velocity and Reynolds number. These characteristics are shown in Figure 7. The upper left and middle graphs of Figure 7 present the effect of water temperature on the average bubble size (diameter and perimeter) respectively. Both diameter and perimeter values are normalized by the initial bubble diameter to eliminate its effect on the results. As explained previously, the diameter is obtained by evaluating the equivalent diameter of the bubble projected area. Hence, the diameter and perimeter represent both boundaries of the bubble. From the graphs, it can be seen that bubble size is susceptible to water temperature variation, and that increasing water temperature results in an increase in both bubble perimeter and projected area (presented as equivalent diameter). To estimate the repeatability of these results, the standard deviation (STD) of each case has been evaluated, hence the maximum and minimum STD for each case are 0.7 (at 20ºC) and 0.15 (at 40ºC) in the case of the diameter, and 1.2 (at 50ºC) and 0.16 (at 40ºC) in the case of perimeter. The upper right and lower left graphs of Figure 7 show the variation of bubble shape (sphericity and aspect ratio) with varying water temperature. Sphericity is defined as the ratio of the surface area of a sphere of an equivalent volume to
the real surface area of the particle [29], whereas the aspect ratio of the bubble is the ratio between the major diameter and minor diameter of the bubble as it takes the elliptical shape [11]. These two parameters are essential in evaluating how much the bubble is close to spherical geometry. Hence, the closer each of these parameters to unity the closer the bubble is to spherical shape. From the graphs in Figure 7, it can be deduced that the bubbles in the present study are slightly far from spherical configuration, and that both parameters are proportional to water temperature since they are slightly increasing by the increase in water temperature. Additionally, the results of both parameters are highly repeatable with maximum and minimum SD values being 0.23 (at 50ºC) and 0.09 (at 10ºC) for sphericity, and 0.17 (at 10ºC) and 0.03 (at 40ºC) for aspect ratio.

The last two graphs in Figure 7 show the variation of average rising velocity and average Reynolds number (Re) with water temperature. The average rising velocity is calculated as the average velocity of the bubble throughout its overall rising time. Then this value is averaged over the results of 5-bubbles for each of the water temperature values. The same is carried out for evaluating Re. As it is shown in the graphs, both rising velocity and Reynolds number are proportional to the variation in water temperature. This proportionality between the rising velocity and water temperature has already been discussed within Figure 6, whereas for Reynolds number, it can be explained with regard to the definition of Re as the ratio between the inertia force and viscous force, since Re is proportional to both the diameter and velocity of the bubble, and because both are shown to increase with increasing water temperature, as a result, Re will increase with increasing water temperature.

One more physical behavior of the rising bubble is investigated in the present work that is the zigzag motion of the bubble among its vertical path throughout its overall flow time. This zigzag motion is shown in Figure 2 for all the investigated bubbles. The main features of this motion have been tracked by image processing for all the bubbles in Figure 2. These features include the deviation
angle, maximum horizontal deviation diameter, deviation velocity, and the portion of zigzag motion occurrence time. The average values of these features have been calculated for all the bubbles presented Figure 8 with respect to water temperature. As the figure shows, each of the deviation angle, maximum deviation diameter, and velocity is proportional to the change in water temperature, whereas the occurrence time is inversely proportional to this change. This could be attributed to the decrease in water surface tension by increasing temperature which results in the increase in lift force. This could be combined with the previously discussed decrease in bubble size fluctuations with increasing temperature, giving an overall description of the bubble behavior with water temperature variation, where increasing temperature increases bubble zigzag motion and decrease its overall size fluctuation. Furthermore, it can be noticed that the zigzag motion occurrence time (that is normalized by the overall bubble rising time) is about 20% of the overall time, suggesting a relatively high portion of the overall bubble rising time. Hence, this phenomenon (zigzag motion) has to be further investigated for more in depth description.

4. Conclusions
The present work represents an experimental investigation of the flow dynamics of a rising isolated bubble within a stagnant water column under variable temperature. The experimental tests have been carried out using high speed imaging with backlighting. Five different values of the water temperature (namely 10, 20, 30, 40, and 50°C) have been implemented during the experiments to study the effect of varying environmental temperature on the flow dynamics of the rising bubbles. The studied features are the bubble size (diameter and circumference), bubble shape (sphericity and aspect ratio), and rising velocity, in addition to the main features of bubble zigzag motion. The main findings of the present work are:
1. As the temperature increases, the degree of bubble deviation (zigzag motion) from its vertical path increases, which means the flow of the bubble becomes less stable.

2. Bubble diameter is irresponsive to temperature for small value increase, whereas, for greater temperature magnitudes (from 30 to 50ºC) is shown to be proportional.

3. The average bubble size fluctuation is in the \(10^{-3}\) order of magnitude of the initial bubble size, and it is proportionally responsive to the variation in water temperature. The increase in bubble size fluctuation is attributed to the decrease in buoyancy and surface tension forces of the water with increasing its temperature.

4. Bubble terminal velocity is proportional to the water temperature variation. This is attributed to the decrease in water surface tension and buoyancy by increasing its temperature.

5. Both bubble sphericity and aspect ratio are proportional to water temperature since they are slightly increasing by the increase in water temperature.

6. The main features of the bubble zigzag motion throughout its rising path have been tracked and evaluated. These features include the deviation angle, maximum horizontal deviation diameter, deviation speed, and the portion of zigzag motion occurrence time. The average values of deviation angle, maximum deviation diameter, and velocity are proportional to the change in water temperature, whereas the average occurrence time is inversely proportional to this change.

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