Investigating the Bubble Behavior in Pool Boiling in Microgravity Conditions

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In space, objects float without falling down. The floating effect happens because of the absence of gravity which is "No-Gravity", also known as Zero-gravity. Even though it is mentioned as zero-gravity, there is small portion of gravity level available; it is in micro level (10^{-6}). Therefore it is known as Microgravity. It is important to study and conduct microgravity research in order to understand the outer space environmental behaviors. Liquids (fluids) behave differently in microgravity level than the earth's gravity. Experimental research on "Boiling" was done in microgravity conditions to study the "Kelvin force effect in microgravity". Experimental Research was mainly funded by NASA-WV Space Grant Consortium. The bubble behavior, which is deformation (change in shape) and the change in radius of a bubble, and the velocity of a bubble in microgravity conditions, was studied. Parabolic path of an aircraft (going approximately 45° nose up and down) can create microgravity conditions inside an aircraft within a period of 20-30 seconds. That method was used to create microgravity conditions in a short period of time to carry out the experiment. Several parabolas were done to get the required microgravity periods to conduct the research. Boiling was done in two cylindrical tanks with fixed boiling pads in the bottom of the tank. Thermo couples were used to determine the temperature while running the experiment and temperature data was stored in the computer. While the experiment was running, video cameras were used to capture the boiling behavior which includes the bubble behavior. After conducting 40 parabolas of microgravity levels, most of the successful microgravity level parabolas were examined by reviewing the video clips. Frame by frame analysis of half a second time-frame captures of the clip were used to determine the bubble position. Center of the bubble, shape of the bubble (maximum radius and minimum radius in vertical and horizontal axis), rate of change of radius, vertical and horizontal displacement of the center, rate of change of the position of the bubble coordinates and the vertical component of the bubble velocity were determined by manually analyzing the data. Bubble displacement and the coordinates were measured in pixels. A couple of softwares such as Power DVD and Photoshop image processing softwares were used to examine the characteristics of the bubble frames. In one particular parabolic path (a parabolic path with a most clear and detectable bubble visibility) one single bubble was selected in microgravity boiling period from the bottom of the tank and until it reached the top of the tank to determine the data. After producing the Excel spread sheets of data, results were gathered. As an outcome of the results, bubble radius in vertical and horizontal direction was calculated with the average radius. Under the microgravity conditions bubble's vertical

displacement was in a spiral path. It could be expressed graphically in 2-D coordinate system.

Index Terms—Bubble Behavior, Microgravity, Pool Boiling.

I. INTRODUCTION

One of the goals of study of this research is to get proper understanding of bubble behavior in microgravity level and compare the characteristics of bubble behavior in microgravity conditions to the earth's level of gravity which is 9.81 ms^{-2} and observe the similarities and differences. In order to understand and see how the bubbles behave in microgravity conditions, it was necessary to create microgravity environment artificially. This artificial environment of microgravity was prepared by using an aircraft which flies in a parabolic path that creates microgravity environment in short period of time. After creating a microgravity environment, pool boiling was done in two identical tanks; one fixed with a permanent magnet beneath the heater surface, and one without a magnet. While the boiling process was taking place, video clips of the boiling process were captured. Out of those video clips, one bubble was selected and captured. The movement of the selected bubble and the bubble path was examined. As a result of that, the center of the bubble, radius of the bubble and the vertical component of the velocity were calculated. In order to determine the center location of the bubble in the coordinate system, eyeball approximation was used.

II. METHODOLOGY

Inside the two identical tanks, one tank had a magnet that attached to the bottom of the tank and both tanks were filled with paramagnetic liquid. The paramagnetic liquid was made by dissolving $MnCl_2$ in distilled water. Inside of the bottom of each tank, a heating pad was attached to heat the liquid to the desired boiling temperature. Both tanks were held in the same environment conditions such as temperature and pressure and both tanks experienced the same gravity level at the same time until they experienced the microgravity levels in the parabolic path of aircraft. There were two thermocouples fixed in each tank, one which was touching the heating pad and one that was in the middle of the tank to determine the temperature of the liquid. The one that was touching the heating pad determined the temperature of the heating pad, which is the maximum temperature inside the tank. **Fig. 1** illustrates the experimental apparatus before the flight.

In one particular parabolic path (a parabolic path with a most clear and detectable bubble visibility) one single bubble

was selected during microgravity boiling and its motion was followed for the period from the bottom of the tank and until it reached the top of the tank to determine the data.
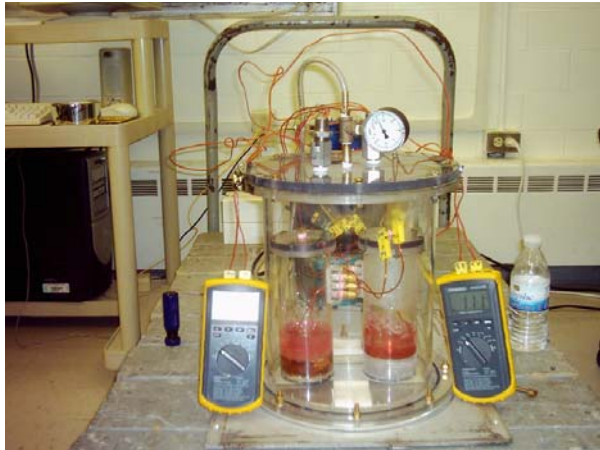

Figure 1.

One of the parabolic paths of flight that was chosen is parabola 36 out of 40 parabolic paths that were flown throughout the entire experiment. In that parabola 36, bubble behavior was very clear compared to the other parabolas. It was the main reason to choose this particular parabola to analyze the bubble behavior. In that particular parabola, one bubble had a very clear visual image which started from the bottom of the tank and reach the top of the tank. There were several conditions to be considered when choosing a certain bubble. Those conditions follow as below.

- The bubble must be clearly visible to the eye from the start to the end of the path.
- The bubble must be visualized from the bottom of the tank and that should reach the top of the tank (Not from the half way of the path).
- The bubble must not collapse with another bubble and it should not merge together while it is moving upward.

After considering those main three characteristics of the bubble movement, one single bubble was chosen from parabola 36. (parabola 36 is the 36th parabolic path of the aircraft). As it shown in **Fig. 2**, the bubble that was chosen was very clearly visible to the eye from the bottom of the tank until the bubble was reached the top of the tank without collapsing or merging to another bubble.

Figure 2.

The next step was editing the video clip and capturing still images from the clips as the bubble traveled from the bottom of the tank to the top. In order to capture video clips, Power DVD software was used. By using one of the tools available in Power DVD, still pictures of the clips were taken with half a second time interval with help of Power DVD special features. After gathering half a second time frames of pictures they were uploaded into Photo Shop software.

In Photo Shop software, frame size of the picture was determined for the best resolution of the picture and kept as constant for the every picture frame. Size of the picture for every frame was fixed as 640 X 480 pixels. After ten times magnification of the bubble, bubble edges were able to seen clearly in the Photo Shop image window as shown in **Fig. 3**. In Photo Shop software, there is an option to choose the axial coordinates and the location of a point with respect to the movement of the mouse cursor.
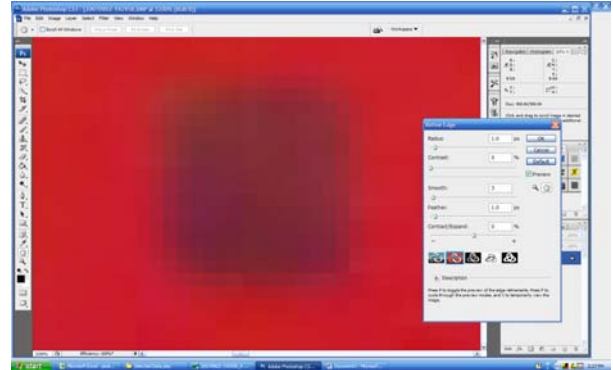

Figure 3.

When the mouse cursor moves along the picture, the location of the cursor is indicated in X and Y coordinates. By taking the mouse cursor to the desired location of the bubble, the position of the bubble was determined in the X and Y Cartesian coordinate. A desired location of the bubble depends on the place that supposes to get exact coordinate of the location. As an example, if the center of the bubble needs to be determined, the cursor will be moved the center of the bubble and X and Y coordinates will be shown in the coordinate box. The other important locations are top of the bubble and bottom of the bubble and left edge of the bubble and right edge of the bubble. After gathering those edge locations and the center location of the bubble of each frame of the bubble until it reaches the top of the tank, spread sheet analysis of the data was done to visualize the bubble path by making the graphs of the bubble properties

As shown in **Fig. 4**, bubble perimeter was examined digitally. Using the image processing tool by changing the color contrast of the image in Photo Shop software, bubble perimeter was digitally examined.
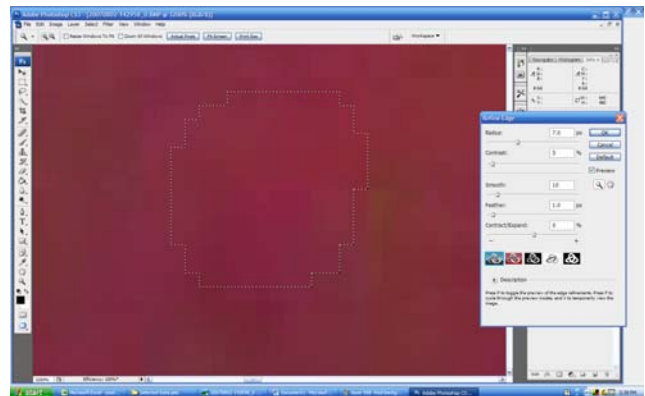

Figure 4.

It was ten times magnified and that is ten times clearer than to the naked eye. In **Fig. 4**, bubble perimeter was determined digitally by dotted line and it demonstrates the deformation of the bubble shape from circular shape to a slightly close to a oval shape.

Average radius of the bubble was determined from the left and right coordinates and top (upper) and bottom (lower) coordinates in the X and Y plane. Vertical radius, which is half distance from the top to bottom (half distance from upper position on the bubble perimeter to the lower position on the bubble perimeter), was calculated. This half distance from the upper position to the lower position on bubble perimeter, which is termed as the "vertical radius" (r_y) was calculated for the each frame that captured from the video. Following the same method, horizontal radius was determined. Half of the distance from the left side location on the perimeter of the bubble to the right side location on the perimeter of the bubble was determined. That distance is termed the "horizontal radius" (r_x). Analyzing the vertical radius of the bubble for each frame that captured from the video, rate of change of vertical radius of the bubble was determined. From the vertical and the horizontal radius of a bubble, the average radius (r_{Avg}) of the bubble was determined.

$$r_x = \frac{x_R - x_L}{2} \quad \ldots (1)$$

$$r_y = \frac{y_U - y_L}{2} \quad \ldots (2)$$

$$r_{Avg} = \sqrt{\left(\frac{x_R - x_L}{2}\right)^2 + \left(\frac{y_U - y_L}{2}\right)^2} = \left(\frac{\sqrt{r_x^2 + r_y^2}}{2}\right) \quad \ldots (3)$$

Equation (1) was used to calculate the bubble radius in horizontal direction which is r_x and equation (2) was used to calculate the vertical radius which is r_y. After determining the location of the left and right edges and bubble the top and bottom locations, the average radius of the bubble for that particular frame can be calculated by using equation (3). After calculating the average radius of the bubble for each frame, rate of change of radius of the bubble was calculated in a spread sheet. By knowing the locations of the four edges of the bubble for each frame, due to the change in bubble radius, it was possible to figure out the deformation of the bubble when compared to the previous time. Since every picture frame has a half a second time period and within that time period of time, displacement of the bubble center was already known, the vertical component of the velocity was computed by dividing the displacement in pixels by time in seconds. As a result of that, vertical component of the bubble velocity was determined in pixels per second. The average radius verses the frame number was graphed to determined the change in the radius with respect to the distance. This graph provides a general idea of how the bubble radius was increased and changed with the deformation that took place while the bubble was moving upwards. The results of the calculated averaged bubble radius and the graphs of the radius verses bubble frame number are presented in the results section of this report.

III. RESULTS

In the **Table (i)**, the X and Y coordinates were determined for every 10 frames that were captured from the video clip. In this table, X1,X2,X3… shows the x coordinates of the picture frames. Also the Y1,Y2,Y3… shows the Y coordinates of the picture frames.

Table (i).

Frame #	X - position	X-coordinate	Y - position	Y-coordinate
1	X1	173	Y1	143
2	X2	184	Y2	147
3	X3	188	Y3	159
4	X4	185	Y4	176
5	X5	186	Y5	183
6	X6	195	Y6	186
7	X7	188	Y7	192
8	X8	181	Y8	206
9	X9	176	Y9	223
10	X10	190	Y10	230
11	X11	188	Y11	259

In the **Table (ii)**, the "ΔY" is the difference between two center points of consecutive two bubble frames in vertical direction. Since the time difference between two consecutive frames is half a second, bubble vertical velocity is calculated with respect to the vertical displacement as it shown in the **Table (ii)** below.

Table (ii).

ΔY	ΔY value (virtical)	Time ,t	t (seconds)	Δt constant = 0.5	Vertical Velocity (Vv) pixels/s
Y2-Y1	4	t1	0	t2-t1=0.5	0
Y3-Y2	12	t2	0.5	t3-t3=0.5	24.00
Y4-Y3	17	t3	1	t4-t3=0.5	17.00
Y5-Y4	7	t4	1.5	t5-t4=0.5	4.67
Y6-Y5	3	t5	2	t6-t5=0.5	1.50
Y7-Y6	6	t6	2.5	t7-t6=0.5	2.40
Y8-Y7	14	t7	3	t8-t7=0.5	4.67
Y9-Y8	17	t8	3.5	t9-t8=0.5	4.86
Y10-Y9	7	t9	4	t10-t9=0.5	1.75
Y11-Y10	29	t10	4.5	t11-t10=0.5	6.44

In **Fig. 5,** shown in below, the bubble vertical displacement is shown with respect to the bubble frame number. This graph shows that the bubble does not move linearly in vertical direction. In other words, bubble displacement for a half a second time period in vertical direction is not constant for every frame and as displacement increases in frame to frame. According to the observation, bubble jumps from one position to another position within half a second period of time. This sudden jump and change in location in the coordinate system per constant time periods shows the nonlinear behavior of the bubble in vertical direction. This can be verified by looking at the vertical velocity component of the bubble velocity with respect to the constant time frames.
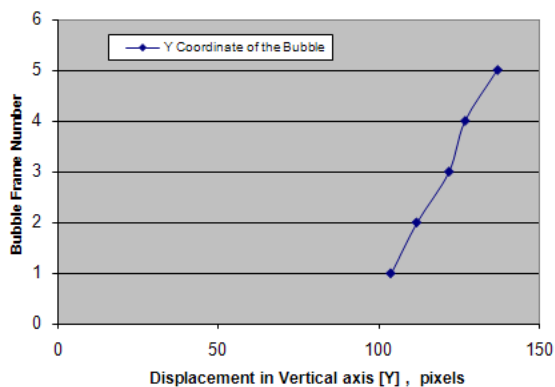
Figure 5.
Bubble Frame Number Vs. Vertical Displacement.

The vertical velocity component graph shows that bubble displacements in the vertical direction are not linear with respect to constant time frame periods. By carefully studying this graph in **Fig. 6**, the kinetic energy level of the bubble can be recognized. Frame numbers represents the position of the bubble in constant time periods.
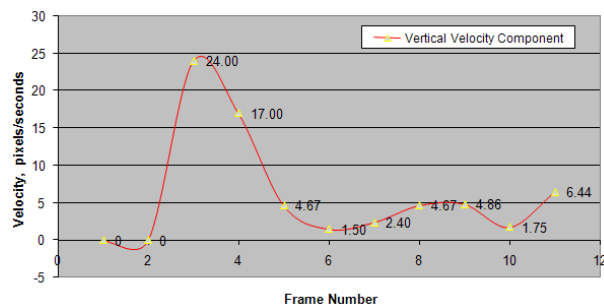

Figure 6.
Vertical Velocity vs. Frame Number.

Therefore, in **Fig. 6**, the frame numbers 1, 2, 3 represents the bottom positions inside the tank. The liquid layers in the bottom of the tank have a higher temperature than the top liquid layers. That is because the heating pad is fixed to the bottom and it is constantly providing heat to the bottom of the tank. Liquid molecules, including $MnCl_2$ molecules and air molecules in the bottom section of the tank have higher temperature than the upper top molecules in the tank. When the temperature is high, it increases the random molecular vibration between the molecules by increasing the molecule energy. Increasing in random molecule energy, increase in kinetic energy of the molecules and it increases kinetic energy in liquid layers. The above graph in **Fig. 6**, which is the vertical velocity component graph, shows that when the bubble is in the lower section of the tank, it has a higher velocity. Specially the bubble position respect to the frame number 3 and 4 has velocity 24 pixel/s and 17 pixel/s. Frame numbers one and two have almost 0 velocity component in Y direction (vertical direction) and it suddenly increase in 24 units when it reach the position 3 respect to the frame number. Therefore, by looking at the graph and the analyzing the data values, the reason for the sudden jump can be explained. Sudden increase in velocity causes the sudden jump between the positions of the bubble path. Since the kinetic energy is linearly proportional to the square of

velocity, it is very clear that bubbles have higher kinetic energy in lower positions of the tank and it gradually decreases with respect to the position when it reaches the top of the tank. It is straightforward to visualize the change in velocity in vertical direction and decrease in the gradient.

In order to calculate the displacement in the horizontal direction, bubble location needed to be calculated. Bubble location was calculated in horizontal direction by taking the average of the distance in left side and right side location on the perimeter of the bubble. After determining the left and right location and the center point of the bubble, average distance, which is average length, was calculated. Half length of the distance from left point location on the perimeter and to the right hand side perimeter will be taken as the average radius in horizontal direction. Also the average change of length in horizontal direction will be determined. Finally the rate of change of displacement in horizontal direction with respect to the bubble fame number was calculated and presented in a graph.

Table(iii).

Frame Number	x_{LEFT} x_L coordinate	x_{RIGHT} x_R coordinate	y_{UPPER} y_U coordinate	y_{LOWER} y_L coordinate	(r_x) $(x_R-x_L)/2$	(r_y) $(y_U-y_L)/2$	$r = sqrt\ (([\ (r_x)^2 + (r_y)^2\ ])/2)$ (pixels)
1	173	196	125	104	11.5	10.5	11.011
2	172	196	136	112	12	12	12.000
3	171	200	170	122	14.5	24	19.827
4	173	204	158	127	15.5	15.5	15.500
5	170	203	169	137	16.5	16	16.252

The following graphs in **Figs. 7, 8 and 9** will show the vertical, horizontal and average radius respect to bubble frame number.
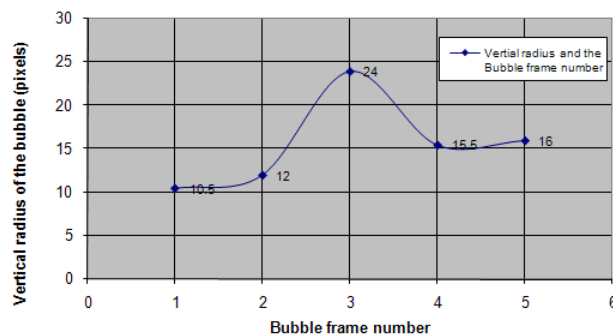

Figure 7.
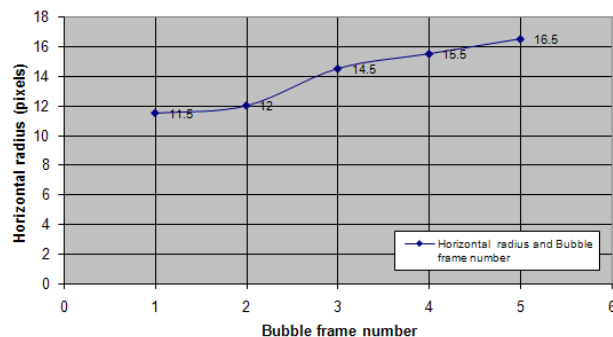**Bubble frame number Vs. Vertical radius of the bubble.**

Figure 8.
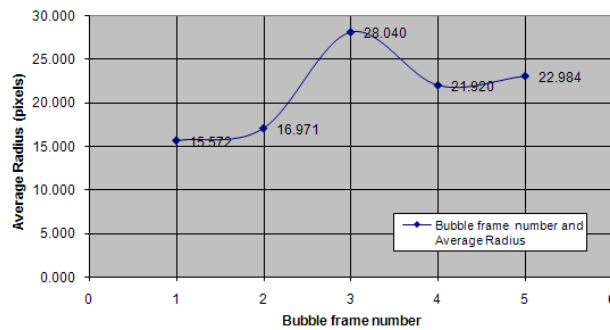**Bubble number Vs. Horizontal radius of the bubble.**

Figure 9.
Average radius of the bubble Vs Bubble frame number.

As a result of calculating the center, vertical and horizontal radiuses, graphical representation of the vertical and horizontal and average radius can be graphed in **Fig. 10** with respect to the bubble number (bubble frame number). This provides information about how the bubble behaves in the vertical horizontal directions as it changes the radius respect to the position on its path of traveling along the vertical direction.
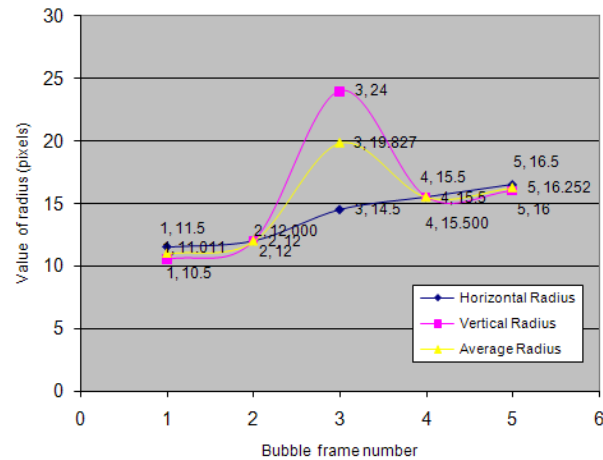

Figure 10.
Value of Radius Vs. Bubble frame number.

After determining the vertical and horizontal radiuses of the bubble and the center positions of the bubble for each frame, bubble path can be graphed in Cartesian coordinate system which is shown in **Fig. 11**.
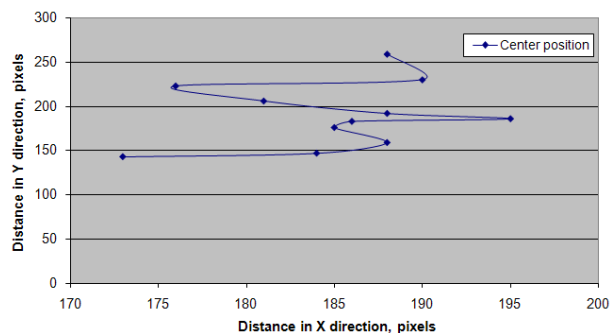
Figure 11.
Displacement Vs. Center of the Bubble.

This allows a better understanding of how the bubble behaves and the 2-D path of the bubble from the bottom of the tank to the top of the tank.

IV. CONCLUSION

Bubble behavior in microgravity conditions was observed by conducting pool boiling in two identical tanks. Bubble movement was analyzed by capturing still pictures from video clips and those pictures used to find the bubble location. After analyzing frame by frame of captured still pictures, the locations of the bubble center, left and right coordinates on the perimeter of the bubble were determined. Bubble center coordinate helped to determine the bubble displacement in horizontal and vertical direction. After calculating the bubble displacement in vertical direction, vertical component of bubble velocity was determined. The vertical component of the bubble velocity showed the sudden increasing in kinetic energy in vertical direction. Also horizontal and vertical radiuses were calculated. As a result of calculating the horizontal and vertical radiuses, the bubble's average radius was determined and graphed. Movement of the center locations of the bubble was graphed with respect to vertical and horizontal location. As result of that, the bubble path was determined in two dimensional coordinates and bubble center was moving in a spiral path in a two dimensional coordinate system.

V. APPENDIX

Boiling in Earth gravity.   Boiling in Microgravity.

VI. ACKNOWLEDGEMENT

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