Lateral motion and interaction of dissolved gas bubbles growing over spherical and plate heaters

This work investigates the motion of CO₂ bubbles emerging in n-heptane when a heat pulse given to a submerged heater creates local supersaturation. The ensuing slow diffusion-induced bubble expansion makes bubble motion easy to observe. The low gravity environment of a parabolic flight allows bubbles to reach large sizes without departing from the heater while rendering their spherical shape. A fast lateral displacement of single bubbles has often been noticed on both type of heaters. In cases where many bubbles grow adjacent to each other, they soon start to interact. Phenomena such as bubbles clusters, coalescence and lift-off from the heater of a large bubble being picked up by neighboring small ones, have been repeatedly observed. An interesting thermocapillary mutual attraction has also been noticed between bubbles adhered to the heater and others free-floating in the nearby liquid.

1. Introduction

Bubble generation and growth in liquids plays a key role in diverse fields of technology e.g. glass processing, flotation separations, pumps and hydraulic power recovery systems [1,2,3]. It is also very important in human physiology e.g. blood oxygenation and decompression illness [4] and has a critical value in studying physical phenomena, such as cavitation, nucleation, desorption of dissolved gas, boiling and electrolysis [5, 6]. In boiling and electrolysis there is evidence that bubbles do not always grow at their nucleation site but sometimes perform a sweeping lateral motion across the heaters/electrodes and so interact with other bubbles [7,8,9]. This activity creates agitation of the local liquid layers and leads to a redistribution of bubbles over the heater/electrode surface which can affect directly the performance of the heater/electrode. In electrolytic gas bubble evolution, such phenomena are driven by buoyancy and concentration temperature gradients.

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In boiling, buoyancy has a minor contribution –this motion has been observed also in microgravity [6]– but bubble displacement is often too fast to observe with confidence.

This work aims to shed some light in these phenomena. Bubbles are produced from a gas which is initially dissolved in a liquid. At a certain point, a short heat pulse is given to a submerged heater which suddenly increases the temperature of the liquid locally, yet below its boiling point. Due to the local supersaturation, gas desorbs into bubbles which grow slowly in contact with the heater. However, not all of them stay pinned at their nucleation site during the heat pulse but some move around across the surface of the heater. As a result, these bubbles interact with their neighbors in a few different ways such as forming clusters, coalescing with them, making them to detach from the heater etc. The experiments of this work are conducted in microgravity conditions but also on the ground. Microgravity is essential not only to prevent bubbles distortion from sphericity and avoid their buoyant detachment from the heater but also to suppress natural convection at the liquid layers which would otherwise mask the agitation created by bubble motion and also alter the temperature distribution around the bubbles.

2. Experiment

The experimental set up is described in detail by Divinis et al. [10]. Here the major components are briefly presented. The core of the equipment is a thermostat unit, a CPF-2 type, into which an exchangeable sample cell unit is inserted. The thermostat operates under the gradient reduction principle and can provide precise temperature stability in the order of ±0.005°C.

A sample cell unit is essentially a sealed tube the lower part of which is made of special spectrometer glass cuvette with an internal diameter of 1.5 cm. The liquid volume in the cell is approx. 22 cm³. Two types of heaters are accommodated inside the test cells, placed apart by 5.5 cm in the longitudinal direction: a small axisymmetrical glass coated NTC thermistor (Thermometrics, Inc.) to serve as a smooth point spherical heater and a glass coated flat platinum resistor to serve as a smooth plate heater. Bubble images from these heaters are recorded by a CCD color camera with 1k x 1k pixels, 24-bit resolution RGB and acquisition rate of 25 frames per second.

For the ground experiments, two flat disc heaters with different surface morphologies are used. One has concentric circular grooves in a regular annular
pattern, Figure 1, whereas the other has straight micro scratches of random orientation.

Figure 1. Geometry of the circular grooves

Images are recorded by a high speed digital video camera (Motion Scope PCI 8000S, Redlake Inc) with a frame rate of 250 frames/second. The disc heaters are placed in the liquid facing downwards in order to minimize natural convection effects and keep the bubbles attached to the surface for longer times. Constant-power ($\pm 2\%$) heating pulses are applied to the heaters through a special circuitry. Registering the voltage drop across the heaters with a sampling frequency of 10 Hz, allows the delivered power and temperature of the heater to be calculated. For all runs the bulk liquid temperature is maintained at 32°C. The main characteristics of the heaters used in this work are presented in Table 1.

<table>
<thead>
<tr>
<th>Geometry Description</th>
<th>Nominal Dimensions, mm</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spherical</td>
<td>$D=0.250$</td>
<td>NTC thermistor (glass coated)</td>
</tr>
<tr>
<td>Smooth</td>
<td>$L\times W=7\times3$</td>
<td>Platinum resistor (glass coated)</td>
</tr>
<tr>
<td>Circular</td>
<td>$D=119$</td>
<td>Stainless steel resistor</td>
</tr>
<tr>
<td>Scratched</td>
<td>$D=132$</td>
<td>Stainless steel resistor</td>
</tr>
</tbody>
</table>

Table 1 Main characteristics of the heaters

The test liquid for the experiments is n-heptane (99.0%, Panreac quimica). A few other liquids (deionized water, glycerin/water mixture 42/58%w/w and phosphate buffered saline at pH 7.2) have been also examined in microgravity conditions [11] but no major bubble motion—beside growth—was ever observed. It must be noted that among these liquids, n-heptane has the lowest surface tension (20.1 mN/m at 20°C and $T_{\text{boiling}}=98°C$ at 1atm). N-heptane is initially saturated with CO$_2$ (99.99%, Air metal), a gas which due to its large solubility in liquids gives easy birth to the phenomena we wish to investigate.

The low gravity experiments are performed during the 35$^{th}$ and 38$^{th}$ Parabolic Flight Campaigns of ESA (European Space Agency) with an average low gravity level during a parabola of $\pm 2.6\times10^{-2}$ g. Unfortunately, there were no other flight opportunities under the same contract to fly the disc heaters in low gravity.

3. Results

Single bubble lateral motion

Figure 2 presents a series of instants where a bubble moves around the thermistor. The bubble grows initially at its nucleation site for 0.68s, followed by a short living (0.16s) trip to another position where it continues to grow without any further movement. The estimated bubble angular velocity is 12.5 rad/s which corresponds to a linear velocity at the base of the bubble equal to 27.3 mm/s. It is noted that the bubble starts to move when it gets roughly as large as the thermistor. This is always the case for all runs and manifests the significance of the relative curvatures of the thermistor and the bubble along with the low values of interfacial tension and contact angle in the system n-heptane/CO$_2$/glass, in destabilizing the three phase contact line. However, this alone would only lead to a new contact line without any significant lateral motion. Therefore, it seems reasonable to assume that the motion once triggered it is sustained by thermocapillarity which drags the loose bubble towards hotter regions around the thermistor.

![Fig. 2 Instants during bubble displacement across the surface of the spherical heater (thermistor), $T_{\text{thermistor}}=45°C$, (~0 g).](image)

A more intense lateral movement is observed with bubbles growing over the smooth plate heater. In Figure 3, the bubble starts travelling at much larger size (smaller curvature). In addition, it travels faster (average velocity between A and B: 17mm/s) while continuing to grow and, most importantly, when it reaches the edge of the heater it reverses direction and moves towards the hotter center of the heater, (average velocity between B and C: 7mm/s). Both the above arguments are in line with those made regarding Figure 1. At some instant (0.48s) the bubble comes to rest but continues to grow.

![Fig. 3 Bubble motion over the smooth plate heater (a) t=0s, (b) t=0.28s and (c) t=0.48s, $T_{\text{thermistor}}=40°C$, (~0 g).](image)
The effect of the heater’s surface morphology is examined only on earth. Figure 4 presents results from the disc heater with circular grooves. On this heater, the movement of the bubbles depends on their size (in fact, the size of their contact area) with respect to the grooves’ size. If a bubble is large enough it can roll about over the grooves but if it is small it follows the pathline of the grooves. In Figure 4, bubble (1) moves freely around whereas bubble (2) moves along the grooves until it is trapped at a small pit (3). The linear velocity of bubble (2) is approximately 20mm/s. However, even minute scratches can detain and direct the movement of small bubbles as shown in Figure 5. Thus, while Marangoni convection may be once more responsible for the movement, it is not presently possible to accurately quantify the relative sizes of bubbles and surface irregularities that dictate this movement.

Wang et al., [8] and Lu and Peng [9] have noticed an intense lateral motion (30-40 mm/s) of bubbles during subcooled boiling of water and alcohol at 1 atm on very thin (0.1 mm) wires. However, this was not observed in the experiments with water on our heaters [14]. So, it seems again that the relative curvatures of the bubble and the heater together with the relevant interfacial properties determine whether such motion will take place or not.

**Fig. 4** Bubble motion over the circular grooved disk heater, (a) t=0s, (b) t=0.016s and (c) t=0.04s, T\text{thermistor} =40°C, (1 g).

**Fig. 5** Bubble motion over the scratched disk heater (a) t=0s, (b) t=0.17s and (c) t=0.24s T\text{thermistor} =40°C, (1 g).

**Clustering and coalescence**

When multiple bubbles grow simultaneously on the heaters, clustering and coalescence are often witnessed. Figure 6 shows four bubbles in contact with the thermistor and each other. It only takes a small disturbance (g-jitter) to rupture this cluster and make all four bubbles to coalesce. The violent embracement occurs so fast that due to our recording capacity we capture only blurred images (not shown). After 0.16 s, the newly formed large bubble is at rest and continues to grow until the heat pulse is over.

**Fig. 6** Coalescence of four (4) bubbles attached to the spherical heater at (a) t=0s and (b) t=0.16s, T\text{thermistor} =80°C (~0 g).

The coalescence of bubbles on the smooth plate heater happens chiefly between smaller, “tracer”, bubbles and larger, “attractor”, bubbles, Figure 7(a, b). This is in agreement with what Sides and Tobias [7] observed in their electrolytically evolved oxygen bubbles on a vertical tin oxide electrode. An interesting phenomenon is presented in Figure 7(c, d) where two bubbles of similar size coalescence. Bubble (1) which free-floats in the colder liquid is attracted towards the hotter bubble (2) due to Marangoni convection. Similar observations in microgravity boiling experiments have been reported by Straub [6].

**Fig. 7** Coalescence of bubbles over the smooth plate heater, (a) t=0s, (b) t=0.08s, (c) t=0.54s and (d) t=0.64s, T\text{thermistor} =50°C, (~0 g).

Intense coalescence between various sized bubbles is observed in the experiments performed on the ground with both disk heaters. It appears that surface roughness play a minor role in this. Figure 8 displays an interesting oscillation during the coalescence of two bubbles of comparable sizes. Despite the employed high recording speed (250 frames/s) the oscillation is still difficult to imprint. All in all, it seems that coalescence may act as a natural means to free once in a while part of the heating surface from gas bubbles. This may be significant in designing boiling equipment for microgravity applications.
Lateral movement across the heater, coalescence and lift-off are some of the interesting phenomena observed with CO₂ bubbles growing in n-heptane under microgravity conditions. These are observed on both smooth spherical heaters and smooth plate heaters. The role of the heater surface roughness is examined in ground experiments with specially constructed disk heaters of different morphology. It is seen that surface roughness can indeed affect lateral movement of bubbles below a certain size. Coalescence and lift-off are two phenomena that show potential with respect to microgravity applications where heating surfaces must be wiped from gas bubbles from time to time. Both phenomena can be tuned by proper selection of surface morphology (e.g., grooves or beads) and working fluid (interfacial properties).

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5. References


