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

This work investigates the motion of CO_2 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 retaining 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 clustering, coalescence and lift-off from the heater of a large bubble induced by neighboring small ones, have been repeatedly observed. An interesting thermocapillary attraction has also been noticed between bubbles adhering to the heater and others free-floating in the nearby liquid.

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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 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 pinned at their nucleation site but occasionally 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 the

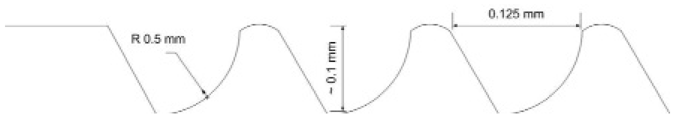


Figure 1: Geometry of the circular grooves.

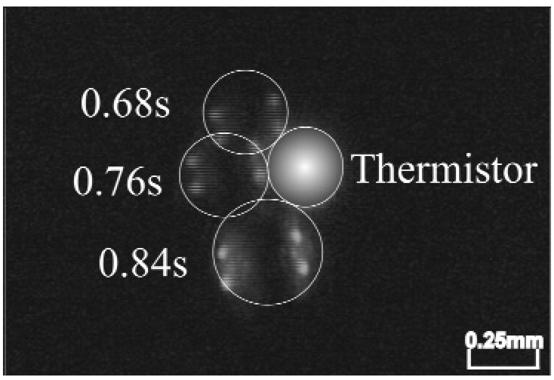
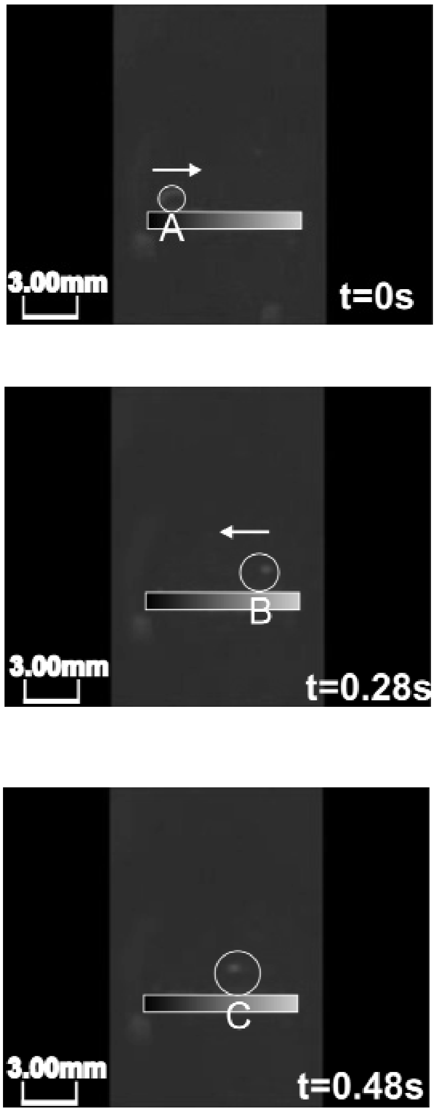


Figure 2: Instants during bubble displacement across the surface of the spherical heater (thermistor), $T_{thermistor}$ =45°C, (~0 g).

performance of the heater/electrode. In electrolytic gas bubble evolution, such phenomena are driven by buoyancy and concentration or temperature gradients.

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

The present work aims to shed some light in these phenomena. Bubbles result from desorption of a gas which is initially dissolved in the liquid. At a certain point, a short heat pulse is given to a submerged heater, which suddenly increases the local temperature of the liquid to a value above saturation but below the liquid boiling point. Due to the local supersaturation, gas desorbs into bubbles which grow relatively slowly (growth rate less than 1 mm/s) in contact with the heater. Depending on the temperature of the heater, bubble growth is also influenced by inevitable vapors of the liquid. However, this is always a secondary effect. Not all of the growing bubbles stay pinned at their nucleation site during the heat pulse, but some move around across the surface of the heater giving rise to the aforementioned interaction phenomena. The experiments of this work are conducted in microgravity conditions as well as 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 in the liquid, which would mask the agitation created by bubble motion and would also alter the temperature distribution around the bubbles. In this short communication, we report only qualitative information, leaving quantitative results for a forthcoming publication.

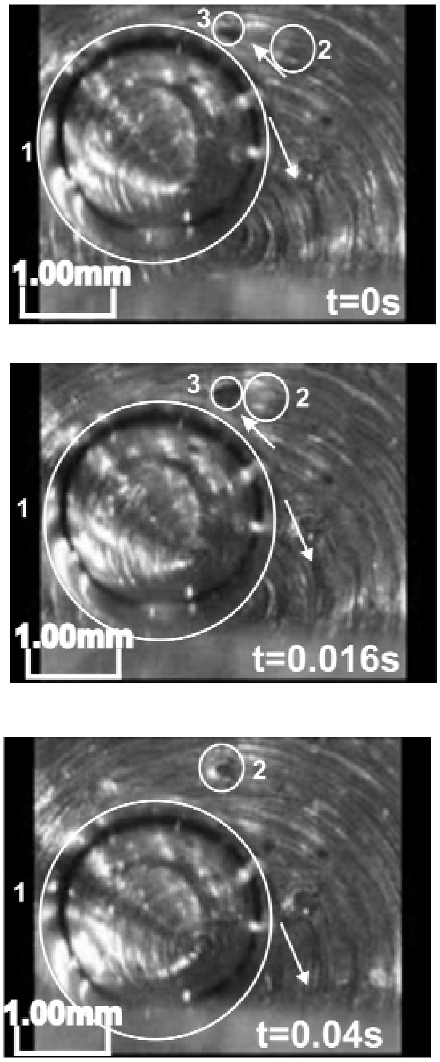


a)

b)

c)

Figure 3: Bubble motion over the smooth plate heater (a) t=0s, (b) t=0.28s and (c) t=0.48s, $T_{thermistor}$ =40°C, (~0 g).).



a)

b)

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Figure 4: Bubble motion over the circular grooved disk heater, (a) t=0s, (b) t=0.016s and (c) t=0.04s, $T_{thermistor}$ =40°C, (1 g).

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 a temperature stable within ±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 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.

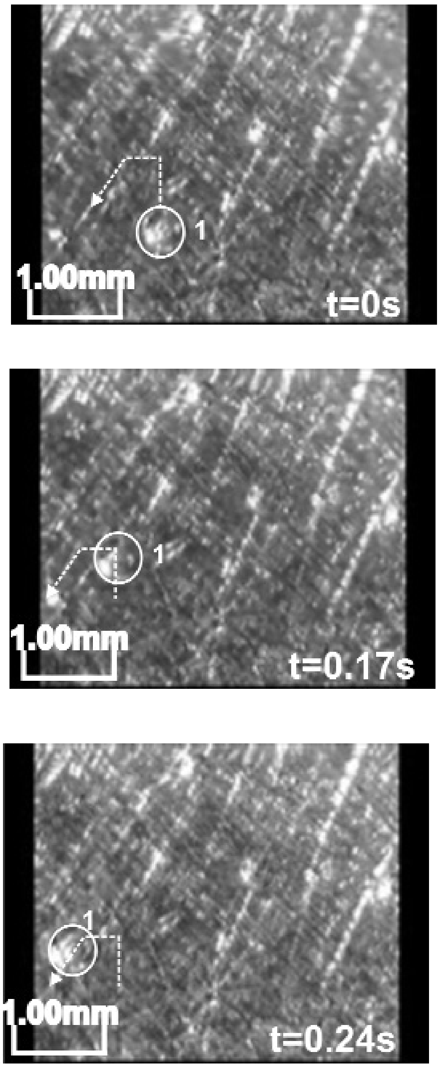
For the ground experiments, two flat disc heaters with different surface morphologies are used. One has concentric circular grooves in a regular annular pattern, Figure 1, whereas the other has straight micro scratches of random orientation.

The main characteristics of the heaters used in this work are presented in Table1.

Images from the disc heaters 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.

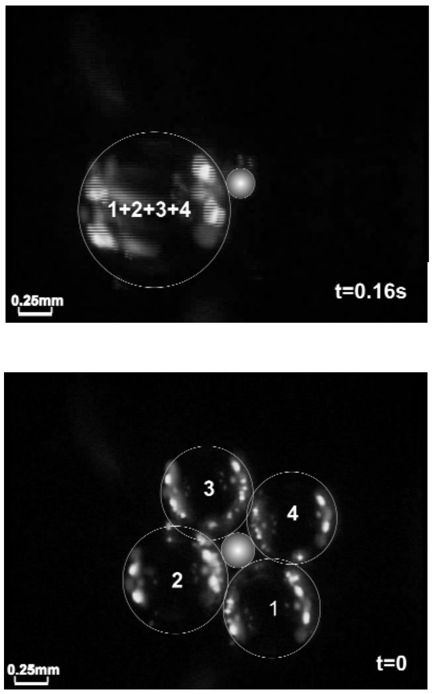
Constant-power (± 2%) heating pulses are applied to the heaters through a special circuitry. Registering the voltage drop across the heaters with a sampling frequency of 10 Hz, allows the delivered power and temperature of the heater to be calculated. For all runs, the bulk liquid temperature is maintained at 32°C.

The 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 –besides 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



a) b) c)

Figure 5: Bubble motion over the scratched disk heater (a) t=0s, (b) t=0.17s and (c) t=0.24s $T_{thermistor}$ =40°C, (1 g).).



a) b)

Figure 6: Coalescence of four (4) bubbles attached to the spherical heater at (a) t=0s and (b) t=0.16s, Tthermistor =80°C, (~0 g).

$T_{boiling}$=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. Apparently, the diffusion-induced bubbles include also some n-heptane vapor.

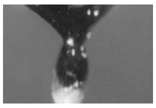
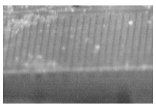
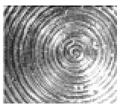
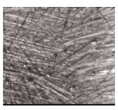
The low gravity experiments are performed during the 35th and 38th Parabolic Flight Campaigns of ESA (European Space Agency) with an average low gravity level during a parabola of ± 2.6×10^{-2} g. Unfortunately, there were no other flight opportunities under the same contract to fly the disc heaters in low gravity.

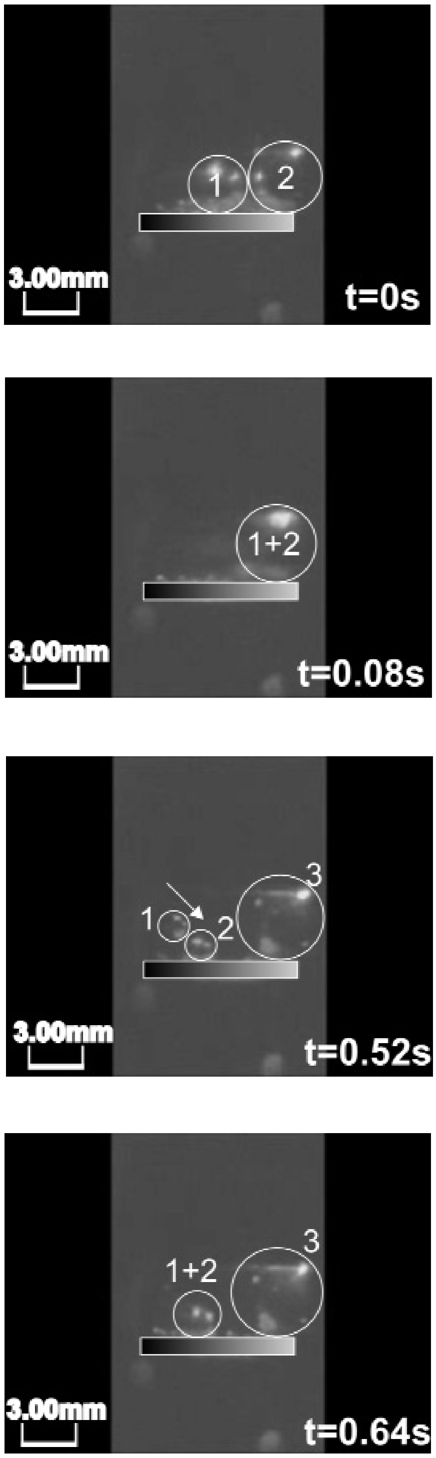
3. Results

Single bubble lateral motion

Figure 2 presents a series of instants with the corresponding bubble locations around the thermistor. The bubble grows initially at its nucleation site for 0.68s, then embarks in a short-duration (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 attains roughly the size of 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 destabiliz-

Table 1: Main characteristics of the heaters

Geometry Description mm	Nominal Dimensions.	Material
 Spherical	D= 0.250	NTC thermistor (glass coated)
 Smooth	LxW=7x3	Platinum resistor (glass coated)
 Circular grooves	D=119	Stainless steel resistor
 Micro scratches	D=132	Stainless steel resistor

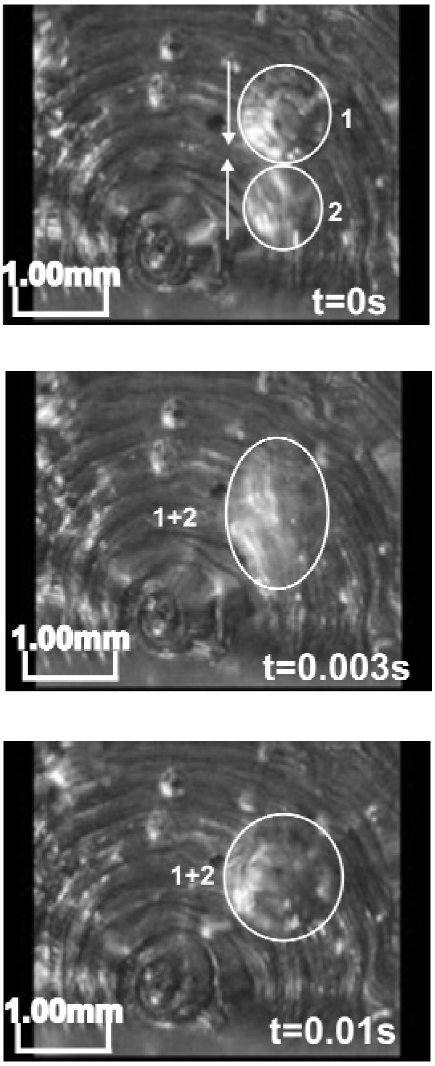


a)
b)
c)
d)

Figure 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, $T_{thermistor}$ =50°C, (~0 g).

ing 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, once triggered, the motion is sustained by thermocapillarity which drags the loose bubble towards hotter regions around the thermistor.

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 observations are in line with the arguments made regarding Figure 2. At some instant (0.48s) the bubble comes to rest but continues to grow.



a)

b)

c)

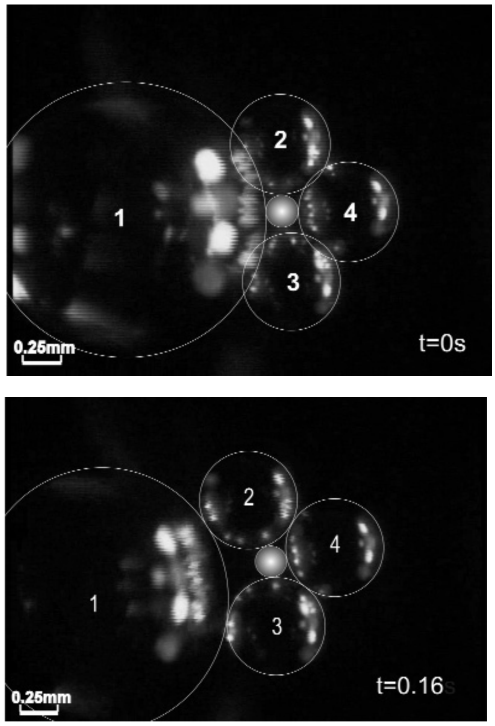
Figure 8: Coalescence of two (2) bubbles over the circular grooved disk heater (a) t=0s, (b) t=0.003s and (c) t=0.01s, $T_{thermistor}$=50°C, (1 g).

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 appears 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 [11]. 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.

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



a)

b)

Figure 9: "Pick up and lift-off" of a large bubble (1) by two smaller ones (2+3) attached to the spherical heater, at temperature. $T_{thermistor}$=85°C, (~0 g).

only takes a small disturbance (g-jitter) to rupture this cluster and make all four bubbles coalesce into one. The collapse occurs so fast that, with our recording capacity, we capture only blurred images of the intermediate events (not shown). After 0.16 s, the newly formed large bubble is at rest and continues to grow until the heat pulse is over.

The coalescence of bubbles on the smooth plate heater occurs predominantly between smaller, "tracer", bubbles and larger, "attractor", bubbles, Figure 7(a, b). This is in agreement with what Sides and Tobias [7] observed with their electrolytically generated oxygen bubbles on a vertical tin oxide electrode. In recent publications of the same group [12, 13], a quantitative explanation of such phenomena has been attempted with reasonable success. However, the present short report concerns only qualitative description of phenomena, so quantitative comparisons are left for the future.

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 have been reported by Straub [6] in microgravity boiling experiments.

Intense coalescence between bubbles of various sizes is observed in the experiments performed on the ground with both disk heaters. It appears that surface roughness plays a minor role in these phenomena. 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 follow. 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.

Lift-off

In the absence of external forces to destroy the liquid film between bubbles in a cluster, the following event –documented in Figure 9– is sometimes observed. A large bubble (1) is picked up by two adjacent small bubbles (2+3) and is lifted-off from the heater. After detachment, the large bubble stops growing. As with coalesence, this phenomenon may be particularly useful for operating boiling equipment in weightlessness, where bubbles need to be periodically removed from the heating surfaces.

4. Conclusions

Lateral movement across the heater, coalescence and lift-off are some of the phenomena observed with CO_2 bubbles growing in n-heptane under microgravity conditions. These are documented 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 surface morphology. It is seen that surface roughness can affect lateral movement only for 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 periodically wiped from gas bubbles. Both phenomena can be tuned by proper selection of surface morphology (e.g., grooves or beads) and working fluid (interfacial properties).

Acknowledgements

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5. References

[1] *Uhlmann, D.R.:* Glass processing in a microgravity environment. In:Rindone,G.E.(Ed.), Materials Processing in the reduced gravity environment of space. Elsevier, New York, USA, p269-278 (1982).

[2] *Payvar, P.:* Mass Transfer controlled bubble growth during rapid decompression of a fluid. Int. J. Heat Mass Transfer, 30, p699-706 (1987).

[3] *Clift, R, Grace, J. R., and Weber, M. E.:* Bubbles, Drops and Particles. Academic Press, New York, London, etc (1978).

[4] *Van Liew, H. D., Burkard, M. E.:* Simulation of gas bubbles in hypobaric decompressions: roles of O_2, CO_2, and H_20. Aviation, Space and Environmental Medicine 66, p50-55 (1995).

[5] *Westerheide, D.E. and Westwater, J.W.:* Isothermal growth of hydrogen bubbles during electrolysis. A.I.Ch.E. Journal, 7, p357-362 (1961).

[6] *Straub, J.:* Boiling Heat Transfer and Bubble Dynamics in Microgravity. Advances in Heat Transfer. Hartnett, J.P., Irvine, T. F., Cho, Y. I., Greene G. A.(Eds.), Academic Press, San Diego, vol. 35, p. 57 (2001)

[7] *Sides, P.J. and Tobias C.W.:* A close view of gas evolution from the back side of a transparent electrode. J. Electrochem. Soc.: Electrochemical science and technology, 132, p583-587 (1984).

[8] *Wang, H, Peng, X.F., Wang, B.X., Lee, D.J.:* Bubble sweeping and jet flows during nucleate boiling of subcooled liquids. Int. J. of heat and mass transfer, 46, p863-869 (2002).

[9] *Lu, J.F., Peng, X.F.:* Bubble separation and collision on thin wires during subcooled boiling. Int. Journal of heat and mass transfer, 48, p4726-4737 (2005).

[10] *Divinis, N., Karapantsios, T.D., Kostoglou, M., Panoutsos, C.S., Bontozoglou, V., Michels, A.C., Sneep, M.C., de Bruijn, R., Lotz, H.Th.:* Bubbles growing in supersaturated solutions at reduced gravity. A.I.Ch.E. Journal, 50, p2369-2382 (2004).

[11] *Divinis, N, Karapantsios, T.D., de Bruijn, R., Kostoglou, M, Bontozoglou, V, Legros, J.C.* Bubble dynamics during degassing of dissolved gas saturated solutions at microgravity conditions, submitted to A.I.Ch.E. Journal

[12] *H. Kasumi, S. Guelcher, Y. Solomentsev, P. Sides, J. Anderson.* Thermocapillary flow and aggregation of bubbles on a solid wall, J. Coll. Interf. Sci. 232 p111-120 (2000).

[13] *H. Kasumi, P. Sides, J. Anderson.* Interactions between two bubbles on a hot or cold wall, J. Coll. Interf. Sci., 276 p239-247 (2004).