INFLUENCE OF ELECTRIC FIELD ON SINGLE GAS-BUBBLE GROWTH AND DETACHMENT IN MICROGRAVITY


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ABSTRACT

In order to separate the mechanical effects from the thermal and mass exchange ones in bubble dynamics, adiabatic two-phase flow conditions were established by injecting gas (nitrogen) bubbles in a fluoroinert liquid (FC-72) at ambient temperature and pressure through an orifice (about 0.1 mm diameter) drilled in a horizontal tube. An electric field of nearly cylindrical geometry was generated around the tube by imposing a d.c. potential drop $V$ (0-18 kV) to a 8-rod cylindrical “squirrel cage” surrounding it. The apparatus was operated in microgravity conditions in the dropshaft of JAMIC in Hokkaido, Japan. Bubble size, detachment frequency and velocity were measured by digital processing of high speed images. The results showed that in the absence of electric field bubble detachment did not take place at low gas flowrate; conversely at higher gas flow, the dynamical effects were sufficient to induce bubble detachment even in absence of the buoyant force. The application of electric field showed effective in promoting bubble detachment at values of diameter greater but of the same order of magnitude as in normal gravity, and in providing a force to remove the bubbles away from the orifice.

INTRODUCTION

State of the art

It is well established that the application of an external electric field enhances pool boiling performance and defer the critical heat flux to higher values, see e.g. Di Marco and Grassi (1993), Allen and Karayiannis (1995). These effects were largely tested in normal gravity applications since early 60s and are now mature for industrial development. Furthermore, this technique may have important application in microgravity heat transfer devices, since a very low amount of energy is required to establish the electrostatic field. Besides an electric field of appropriate geometry may replace the lacking buoyancy force in reducing the size of bubbles and in driving them away from the surface. The tests conducted in parabolic flight by Di Marco & Grassi (1999) demonstrated that pool boiling was stabilized by the action of the field and, for higher enough applied voltage, the same beneficial effect on critical heat flux enhancement as in normal gravity application was encountered.

The modeling of boiling in the presence of an electric field is not straightforward due to the great complexity of the involved physical phenomena and requires a clear identification of the forces acting on the generated bubbles. Therefore it was considered appropriate to perform experimentation in a more simple configuration, in order to better clarify the effect of the electrical force on bubbles, getting rid from the effects of thermal gradients and mass transfer between the two phases. Thus, an experimental facility has been set up to investigate the evolution of nitrogen bubbles in an isothermal pool of FC-72 in the presence of an externally applied electric field, under the action of terrestrial gravity or less.

The phenomena of detachment and rise of gas bubbles in a still fluid were extensively studied experimentally starting from 60s, see e.g. the pioneristic studies of Datta et al. (1950), Peebles and Garber (1953) and Davidson and Schuler (1960a,b), Ramakrishnan et al. (1969), Khurana and Kumar (1969), Satyanarayan et al. (1969), Wraith (1971), Terasaka and Tsuge (1973). The earlier works were summarized by Clift et al. (1978). All of these studies are performed using two-component immiscible fluids (gas into liquid), in adiabatic conditions, and most of them were related to the motion of air bubbles in water or water-based mixtures. Only a few works were focused on different fluids (e.g. Park et al., 1977, Tsuge and Hibino, 1972) and, as far as known, none of them on organic refrigerants. To the authors’ knowledge, bubbling phenomena in a stagnant fluid (water) in microgravity were experimentally investigated only by Pamperin and Rath (1995) and by Tsuge et al. (1997).

Models for bubble dynamics

A large amount of theoretical models for bubble formation, detachment and rise are available, see e.g. Peebles and Garber (1953) Davidson and Schuler (1960a,b), Ramakrishnan et al. (1969), Satyanarayan et al. (1969), Kumar and Kuloor (1970), Wraith (1971), Tsuge (1986), Tomiyama (1998), Tomiyama et al. (1998). None of them, though, account for the presence of an electrical force. The evolution of a gas bubble immersed in a liquid of different nature and attached to an orifice supplying gas to it (see Fig.1) can be studied by considering the gas volume $V_g$ bounded by the surface $A_g$ (gas-liquid interface) and (orifice inlet), joined by the three-phase contact line $L$. If the evaporation of the liquid into the gas and the dissolution of
gas in the liquid are negligible, the surface $A_b$ can be considered adiabatic to mass. The mass and momentum balance applied to this system are

$$\frac{d}{dt} \int_{A_b} \rho_g \, dV = - \int_{A_b} \rho_g \left( u_g \cdot n \right) \, dA \tag{1}$$

$$\frac{d}{dt} \int_{A_b} \rho_g \, u_g \, dV = - \int_{A_b} \rho_g \left( u_g \cdot n \right) \, dA + \int_{A_b} \rho_g \, u_g \, dV$$

$$- \int_{A_b} (\sigma_{ij} \cdot n) \, dA - \int_{A_b} \left( \Sigma_{ij} \cdot n \right) \, dA + \int_{A_b} (\sigma_{ij} + \sigma_{23} + \sigma_{31}) \, dL \tag{2}$$

where $\rho_g$ is the gas density, $V_b$ the bubble volume, $\Sigma$ the stress tensor acting on the bounding surfaces, $\sigma_{ij}$ the surface tension (vector, oriented tangentially to the surface separating the phases i and j and perpendicular to the contact line), n the unit outward normal to the bubble surface and g the acceleration of gravity. When the bubble detaches, the surface area of the orifice, $A_o$, is set to zero. The momentum jump condition across the interface, neglecting the gradients of surface tension, is (Delhaye, 1980)

$$\Sigma_{ij} \cdot n = \Sigma_{ij} \cdot n + \sigma \kappa n \tag{3}$$

where $\kappa$ is the sum of the two principal surface curvatures

$$\kappa = \frac{1}{R_1} + \frac{1}{R_2} \tag{4}$$

It has to be accounted that the pressure of the liquid $p_l$ is due to the contribution of the hydrostatic pressure, of the form drag and of the inertial action of the liquid surrounding the bubble, which counteracts its expansion. Such an approach meets with several difficulties in calculating the integrals in RHS of Eq.(2) along a moving boundary and, at present, is useful only for numerical modeling purposes. The momentum balance along the vertical ($z$) direction is thus rewritten as

$$\frac{d}{dt} \left[ V_z \left( \rho_g + C_M p_l \right) u_z \right] = \left( \rho_l - \rho_g \right) V_{gb} g - F_d \tag{5}$$

$$- \pi d o \sigma \sin \theta + \int_{A_b} \left( \rho_g \, u_m \right) \, dA + \frac{\pi d o^2}{4} \left( p_g - p_l \right) + F_E$$

where $u_o$ is the velocity of the center of the bubble and $d_o$ the diameter of the injection orifice. The hypotheses underlying this approach are thoroughly reviewed by Buyevich and Webbon (1996). The terms in RHS represent the buoyancy, the drag, the contact force along the three-phase line (where $\theta$ is the actual contact angle at the surface, not necessarily the equilibrium one), the momentum inflow through the orifice, the excess of internal pressure and the expansion force, respectively. All the models proposed for bubble growth and detachment are based on Eq.(5), often by neglecting some terms. To make use of Eq.(5), a geometry for the growing bubble has to be assumed: the bubble is generally schematized as a segment of sphere, or a sphere attached to a cylindrical stem. Semi-empirical constitutive models are necessary to represent at least the terms $C_D$ (virtual mass coefficient), $F_D$ (drag force), $F_E$ (expansion force). Generally $C_M$ is given as 0.5 for a nozzle orifice and 11/16 for a sphere attached to a plane (Milne Thompson, 1996); a correction factor to these values has been introduced by Buyevich and Webbon (1995).

The contribution due to the inertia of the gas, represented by $\rho_g$ on LHS of Eq.(5), is always neglected.

The expansion force over a gas sphere expanding in a quiescent liquid is modeled after Rayleigh (1920) as (Buyevich and Webbon, 1996)

$$F_E = - \frac{\pi d o^4}{16} \rho_l \left[ R_b \frac{d^2 R_b}{d t^2} + \frac{3}{2} \left( \frac{d R_b}{d t} \right)^2 \right] \tag{6}$$

It is worth noting that only the contribution pertinent to the orifice is not self-balanced and has to be considered here.

Several models have been developed for the drag force accounting for the system geometry and the flow regime. The drag force has been neglected during the growth and detachment phase by several authors (Wraith, 1971; Satyaranan et al, 1960, Buyevich and Webbon, 1996). This force can be expressed as (Tomiyama et al., 1998)

$$F_D = \frac{1}{2} C_D \rho_l \frac{\pi d o^2}{4} u_o^2 \tag{7}$$

where $C_D$ is the drag coefficient and $d_o$ is the bubble equivalent diameter, i.e. the diameter of the sphere having the same volume as the bubble

$$d_o = \sqrt[3]{\frac{6 V_b}{\pi}} \tag{8}$$

As an example, Ramakrishnan et al. adopted for $C_D$ the Stokes’ equation for a viscous flow past a solid sphere

$$C_D = \frac{24}{Re} \tag{9}$$

Gaddis and Vogelpohl (1986) adopted

$$C_D = \frac{24}{Re} + 1 \tag{10}$$

and Pamperin and Rath (1995), considering the modified Stokes’ equation for a viscous flow past a sphere corrected with the Hadamard-Rybczynski factor, proposed

$$C_D = \frac{2}{3} \left( \frac{24}{Re} + \frac{4}{\sqrt{Re}} \right) + 0.4 \tag{11}$$

where the velocity to be used in Eq.(7) is calculated at the bubble top ($u = 2 u_o$).

It has to be remarked that Eq.(5) is able to account only in a simplified way for the actions exerted on the interface by the surrounding fluid. Equation (5) keeps its validity after bubble detachment: in such a case, all the forces originating from the contact of the bubble with the orifice, namely the momentum...
Different bubble detachment criteria were adopted. For Ramakrishnan et al. (1969), the detachment occurs when the bubble neck reaches a length equal to the bubble radius. A similar criterion (i.e., a limit distance between the bubble center and the orifice) was adopted by Davidson and Schulter (1960a,b) Khurana (1969) and Wraith (1971). Buyevich an Webbon (1996) proposed that the hydrodynamic instability in the stem should be considered, without actually applying this consideration in their model, and ended up in adopting the Ramakrishnan’s hypothesis. Other authors have assumed that detachment occurs when a force balance like Eq.(5) cannot anymore be satisfied in the presence of the forces originating from the contact of the bubbles with the orifice. As an example, Pamperin and Rath (1995), by considering a force balance like Eq.(5) in which the buoyancy the excess internal pressure and the expansion force are neglected, have determined that bubble detachment in the absence of gravity occurs only if

\[ We^* = \frac{\rho_g d_b u_n^2}{\sigma} > 8 \]  

They claim that the data from their experiment in droptower (referring to air bubbles in water, with injection orifices of 0.39 and 0.80 mm diameter) are in agreement with the derived criterion.

To start the bubble formation, an excess pressure is necessary inside the gas injection chamber underlying the inlet orifice. The amount of such excess can be estimated by means of a static balance as

\[ \Delta p = \frac{4 \sigma}{d_b} \]  

The inlet flow and pressure at the orifice, and thus the entire phenomenon, are influenced by the dynamics of the compressible gas volume constituted by the chamber. This is generally accounted for through the capacitance number (Hughes, 1955)

\[ N_c = \frac{4 g \rho_g V_{ch}}{\pi d_b^2 (p_{ch} + \Delta p / 2)} \]  

where \( p_{ch} \) is the pressure in the chamber and \( \Delta p \) is given by Eq.(8). It is generally agreed (Ramakrishnan et al. 1969) that low values of the capacitance number \( (N_c < 1) \) correspond to the so-called constant flow conditions, in which the inlet flow through the orifice is constant and there is no or very little waiting time between the detachment of a bubble and the beginning of formation of the next one; conversely, for \( N_c > 10 \) constant pressure conditions are established, in which the pressure in the chamber is nearly constant and the flowrate through the orifice undergoes significant oscillations.

For bubbles originating from the same orifice, it has been found experimentally that the detachment volume has a characteristic trend with increasing gas flowrate: initially the detachment volume is nearly constant with increasing flowrate (and thus the detaching frequency increases linearly with it) and almost independent of liquid viscosity. Afterwards, the detachment volume grows with inlet flowrate and according to Clift (1978) it depends on liquid viscosity and increases with it. The data collected on ground with the present experimental apparatus are in agreement with this trend (Danti et al., 2000)

Effect of an electrostatic field on bubble dynamics

The most generally accepted expression for the volumic electric force that acts on a fluid, to be included in the momentum equation, is (Landau, 1986)

\[ F_e = \rho_g E - \frac{1}{2} E^2 \frac{\partial}{\partial \rho} \]  

Only the first term (Coulomb's force) depends on the sign of the electric field. It is present when free charge buildup occurs and in such cases it generally predominates over the other electrical forces. The other two terms depend on the gradient of the electric field and of the dielectric constant (related to thermal gradients or phase discontinuities), and on the magnitude of \( E^2 \), thus being independent of the field polarity. The second term is a body force due to non-homogeneities of the dielectric constant and the third term is caused by non-uniformities in the electric field distribution.

In the absence of free charge, the net force acting on a spherical gas bubble is (Landau, 1986),

\[ F_{DEP} = 2 \pi R_g \left( \frac{e_{g} - e_{l}}{n_l e_{g} + (1 - n_l) e_{l}} \right) e_i \nabla E^2 \]  

The constant \( n_l \), which can be calculated with an elliptic integral related to the eccentricity of the bubble, is equal to 1/3 for a perfect sphere, while \( n_l > 1/3 \) for an oblate ellipsoid (Landau, 1986).

If the bubble is immersed in a liquid of higher electrical permittivity, this yields a net force driving it towards the zone of weaker electric field. This force has generally a little magnitude, however in the absence of buoyancy it might be an important tool for phase separation. The validity Eq.(16) is subjected to several limitations: the dielectric must be isotropically, linearly and homogeneously polarizable, and both the fluids must have zero conductivity; besides, the bubble must be small enough to obtain the amount of polarization by approximating the field as locally uniform (Pohl, 1958, Snyder and Chung, 2000). It must also be considered that the presence of bubbles may substantially alter the local electric field distribution with respect to the one in the all-liquid situation, so that all these effects should be carefully evaluated. A dimensionless parameter, scaling the effect of electric force to buoyancy one, can be identified as

\[ G_{be} = \frac{F_{DEP}}{F_{BU}} = 3 \left( \frac{e_{g} - e_{l}}{n_l e_{g} + (1 - n_l) e_{l}} \right) ( \rho_{g} - \rho_{l} ) g \]  

EXPERIMENTAL APPARATUS

Experimental facility

As previously said, in order to separate the mechanical effects from the thermal and mass exchange ones, adiabatic two-phase flow conditions were established by injecting gas bubbles in a liquid through an orifice. Each experimental cell consisted of an aluminum box of about 2.5 dm³ volume monitored by temperature and pressure sensors, connected to a bellows in order to allow for volume dilatation due to temperature changes and gas injection, without leaving a free
To achieve a good level of microgravity conditions, the apparatus was operated in the Japan Microgravity Center (JAMIC) dropshaft, located at Kamisunagawa in Hokkaido. The working fluid was FC-72 ($C_{6}F_{14}$), a fluoroinert liquid manufactured by 3M, used in electronics cooling. The geometry of the test section was derived from the one of an analogous apparatus operated at Pisa University, to study boiling phenomena (Di Marco and Grassi, 1999), in order to compare the results. It consisted mainly of an horizontal copper tube (1 mm o.d, 0.2 mm i.d.) connected to the gas injection device. The nitrogen was injected from a pressurized vessel into the fluid via an orifice (0.13 mm diameter) drilled in the upper part of the tube. The electric field was generated by imposing a d.c. potential drop $V$ (0-18 kV) to a 8-rod cylindrical squirrel cage surrounding the tube, which was grounded. The resulting electric field was nearly cylindrical in geometry:

$$E = k \frac{HV}{r}$$  \hspace{1cm} (18)

where $V$ is the applied potential and $r$ the distance from the tube axis. Finite elements calculations (Danti, 1999) showed that the validity of such a dependence is valid up to a distance of 12 mm from the orifice and the constant value is $k = 0.172$.

To measure and control nitrogen mass flow a digital mass flow controller (model El-Flow by Bronkhorst) was used in each cell: this device guaranteed a stable inlet flow (proportional to an input voltage) in the chamber below the orifice. The outlet flow rate from the orifice stabilized at the orifice. The conditions to ensure "fixed-flow" operation are compared in detail by Danti et al. (2000).

The vertical velocity is obtained from two frames (not necessarily two consecutive ones) taken at times $t_{1}$ and $t_{2}$

$$u = (x_{g2} - x_{g1})/(t_{2} - t_{1})$$  \hspace{1cm} (21)

This value is assigned at the point whose vertical coordinate is $x = (x_{g2} + x_{g1})/2$, and errors are thus calculated by propagation as

$$\left( \frac{\Delta u}{u} \right)^{2} = 2 \left( \frac{\Delta x_{g2}}{x_{g2} - x_{g1}} \right)^{2} + \frac{\Delta t_{2}^{2}}{(t_{2} - t_{1})^{2}}$$  \hspace{1cm} (22)

The volume of the bubble is evaluated as

$$V = 2/3 \cdot (\text{projected area}) \cdot \text{(max axis)} = 2/3 \cdot ((N - p/2 - 1) \cdot (b-1))$$  \hspace{1cm} (23)

**Data reduction and measurement uncertainties**

The measurements taken from the video images for this study are detachment frequency, center of mass velocity and bubble equivalent diameter.

Time measurements with the camera are affected by one frame resolution, which corresponds to $\delta_{t} = 2 \text{ ms}$ or $1 \text{ ms}$ for the frame rates used, i.e. 500 or 1000 fps.

The detachment frequency comes from the period, defined as the temporal distance between two completely detached bubbles; since these are not always detected at the same distance from the orifice, a statistical treatment is needed to get a consistent value and calculate the error. The number of bubbles considered to get a period measurement was so chosen to reduce the contribution of statistical fluctuations lower than the resolution limit, when possible. Error was then calculated as the sum of the two contributions as

$$\Delta f = \sqrt{\delta_{t}^{2} + \sigma_{f}^{2}}$$  \hspace{1cm} (19)

where $\sigma_{f}$ is the sample standard deviation over the measurements.

Image processing was then performed using a free-ware software (Scion Image), working with binary images. A threshold method was used for edge detection (after contrast enhancing). The brightness histogram showed two peaks corresponding to the background and the grey level typical of the bubbles. The threshold level was chosen in midway between the two peaks.

This method was tested with good results on spherical and elliptical objects of known volume and permits to measure $N$ (number of pixels in a bubble) and $p$ (number of pixels in its perimeter). The center-of-mass coordinates of a bubble were defined as

$$x_{g} = \frac{1}{N} \sum_{j} x_{j} \Theta(x_{j}, y_{j}) , \hspace{0.5cm} y_{g} = \frac{1}{N} \sum_{j} y_{j} \Theta(x_{j}, y_{j})$$  \hspace{1cm} (20)

where $x$ and $y$ are pixel coordinates ($x$ axis in the gravity direction) and $\Theta(x, y)$ is a function whose value is 1 if $(x, y)$ is in the considered bubble and 0 elsewhere.

The error on these measurements is mainly due to lines/columns counting: if the bubble is enclosed in a rectangular frame whose dimension in pixels are $a$ (x direction) and $b$ (y direction), the uncertainties in the coordinates center of mass are $\delta_{x_{g}} = 1/\sqrt{a}$ and $\delta_{y_{g}} = 1/\sqrt{b}$.

The vertical velocity is obtained from two frames (not necessarily two consecutive ones) taken at times $t_{1}$ and $t_{2}$.
considering the contour passing in the middle of each perimetral pixel and bubbles as oblate ellipsoids with $b$ as the major axis. The calculated values showed a plateau as long as the bubble path kept rectilinear. A mean over this region was taken as the detachment volume. The error was derived (considering $p/2$ as the area error) as

$$\Delta V = \frac{p}{2(N - p/2 - 1)} V$$

Finally, the equivalent diameter was obtained by Eq.(8) and the error on it from

$$\frac{\Delta d_{eq}}{d_{eq}} = \frac{1}{3} \frac{\Delta V}{V}$$

The so obtained distances are in pixels (velocities in pixel/s and volumes in pixel$^3$), a conversion factor is needed to change them into metrical units. This was measured from a gauge image, taken before the test in the same optical conditions, featuring a steel bar with ticks at known distances and introduces in calculations a new source of errors to be propagated. This error was added at the final stage to the previous ones and is mainly statistical (due to mechanical differences in ticks, differences in the light distribution etc.).

**RESULTS AND DISCUSSION**

A total of eight drops were performed in JAMIC during four days (two in the year 2000 and two in 2001), for a total of sixteen combinations of experimental parameters. The test matrix, referring to the eleven tests relevant for this study, is reported in Tab.1. The injection of nitrogen was started 40 s before the drop: in this way, the flow controller stabilized the flowrate to the desired value before the onset of microgravity. Video recording was started about 1 s before the drop, and a recording time of 6.9 or 8.3 s was achieved, depending on the adopted field of view and frame rate. Immediately before delivering the apparatus to JAMIC personnel, tests in normal gravity were performed in the same experimental conditions for comparison.

The results without electric field indicated that as soon as microgravity was established no detachment of the bubble occurred in both cells in the test at low flowrate (tests 17-1-1, 17-2-2): the bubble grew as a perfect sphere attached to the orifice during all the drop. Conversely, by increasing the flowrate (test 18-2-2), the detachment took place (with a bubble diameter of 6.8 mm), presumably due to the momentum transfer by the inlet gas flow. The trend of the bubble volume vs. time in the three tests with no electric field applied is shown in Fig.3. The trend of the volume vs. time of the growing bubble attached to the orifice is compared with the gas volume entering the test tube, obtained as the measured inlet volumetric flowrate multiplied by the elapsed time. It can be seen that the volume of the bubble is always greater than the second one. This might be ascribed to the inertia of the chamber underneath the orifice or to the difference in density between the gas in the chamber and the gas in the bubble, due to the pressure drop across the orifice. Besides, the trend of the bubble volume vs. time is not linear, thus evidencing the delaying effect of the chamber and possibly the inertial effects of the surrounding liquid.

As outlined in the introduction, Pamperin and Rath (1995) on the basis of a simple force balance evidenced that the detachment of the bubble in microgravity should occur when the modified Weber number (see Eq.12) exceeds a critical value, $We^* > 8$. In the present case, no detachment occurred at low flowrate ($We^* = 0.006$), but detachment occurred at the higher value of flowrate for a $We^* = 0.147$, i.e. far less than the above mentioned theoretical value. This difference might be due to the action of different forces than the ones considered by Pamperin and Rath (1995), taking also into account the different geometry. In particular, from the analysis of the image it is observed that interfacial waves on the bubble surface started to develop before its detachment (see Fig.4). This superficial instability may trigger an earlier bubble detachment than predicted by the above mentioned model.

By applying the electric field, detachment of bubbles was obtained in all the microgravity tests: however, the bubble size and detachment frequencies changed with gravity acceleration, and these changes were less evident at the higher values of the applied voltage. The values of the detachment diameter in normal gravity normalized to the one at zero electric field are plotted vs. the applied voltage in Fig.5. The prediction of a model derived (Danti et al. 2000) after Baboi (1968) is also shown for comparison.
The detachment diameter in micro-gravity condition, normalized to the one in terrestrial gravity for the same value of the electric field, are plotted vs. the applied voltage in Fig.6. Detachment of bubbles occurred for all the values of the applied field. It can be seen that for the highest values of high voltage, there was no change in detachment diameter with gravity acceleration: this demonstrates the dominance of the electrical force over the buoyancy one in these conditions. For decreasing values applied voltage, the detachment diameter increased in microgravity: presumably the threshold where detachment ceases to occur is a little below the lowest value of voltage tested (1 kV, test 18-1-2): only very few and large bubbles detached in these conditions.

The rising velocity of the bubbles is shown in Fig.6 for normal gravity conditions and in Fig.7 for microgravity conditions. For the higher values of the applied electric field, the velocity exhibited a peak and then decreased with distance: this is ascribed to the fact that the intensity of the electrical force, due to the field geometry, decreases with increasing radius at it was almost negligible at a distance from the tube greater than about 2-3 mm, where all the curves merged with the zero-field one. Afterwards, the geometry of the field results in a slowing-down effect on bubbles. For the same reasons, in microgravity conditions the rising velocity of the bubbles decreased to zero with increasing distance from the orifice. It should be noted that the peak velocity at 18 kV in normal gravity (about 0.22 m/s, see Fig.6) was still greater than the
one reached in microgravity (about 0.2 m/s, see Fig.7): this indicates a residual sensible action of the buoyancy force in the process of bubble lifting. This was not contradictory with the results concerning detachment diameter, due to the already mentioned weakening of electric field with increasing distance from the orifice.

Some significant flow patterns can be seen in Fig.9: it can be noted that with no electric field the bubble grows spherically in micro-g (Fig.9A). For an applied field of 5 kV, the detachment diameter is still greater in micro-g (Fig.9B), while at 15 kV the detachment diameter is almost independent of gravity level (Fig.9C). When the electric field is applied, slowing down and coalescence of bubbles start to take place 3-4 mm away from the orifice (Fig.9 B and C).

CONCLUSIONS

An experimental apparatus was set up and operated in the JAMIC droptower to study the influence of electrical forces on bubble dynamics in microgravity. In order to separate the mechanical effects from the thermal and mass exchange ones, adiabatic two-phase flow conditions were established by injecting nitrogen gas bubbles in a fluoroinert liquid through an orifice. The geometry of the test section and of the electric field was chosen in order to allow a future comparison with the results of a similar apparatus operated by the LOTHAR laboratory of the University of Pisa and dedicated to the investigation of boiling phenomena. Bubble size, detachment frequency and velocity were measured by digital processing of high speed images in a total of eleven different experimental conditions during four drops.

The results showed that in the absence of electric field bubble detachment did not take place at low gas flow rate; conversely at higher gas flow, the dynamical effects were sufficient to induce bubble detachment even in absence of the buoyant force. The application of electric field showed effective in providing a force to remove the bubbles away from the orifice and in promoting bubble detachment at values of diameter greater but of the same order of magnitude as in normal gravity. For the higher values of the tested electric field, the detachment diameter was almost the same as in normal gravity.

In this way, the effectiveness of the electric forces in promoting bubble detachment and their progressive dominance over buoyancy force were experimentally demonstrated. The results obtained so far in this relatively simple experimental configuration will help in elaborating mechanistic models of phase separation, bubble formation and detachment, both for adiabatic gas liquid flows and for the more complex boiling phenomena.

NOMENCLATURE

\begin{itemize}
\item $A$ area (m$^2$)
\item $C_D$ drag coefficient
\item $C_M$ virtual mass coefficient
\item $d$ bubble diameter (m)
\item $E$ electric field intensity (V/m)
\item $f$ frequency (Hz)
\item $F$ force (N)
\item $g$ gravity acceleration (m/s$^2$)
\item $g_0$ gravity acceleration, earth value (m/s$^2$)
\item $G_{be}$ dimensionless group, see Eq.(17)
\item $HV$ applied high voltage (V)
\item $n$ outward normal unit vector
\item $n_1$ coefficient, see Eq.(16)
\item $N_c$ capacitance number, see Eq.(14)
\item $p$ pressure (Pa)
\item $r$ distance from the tube axis (m)
\item $R$ radius (m)
\item $Re$ bubble Reynolds number
\item $T$ temperature ($^\circ$C, K)
\item $T_0$ period (s)
\item $t$ time (s)
\item $u$ velocity (m/s)
\item $V$ volume (m$^3$)
\item $We^*$ modified Weber number, see Eq.(12)
\item $x$ vertical coordinate (m)
\item $y$ horizontal coordinate (parallel to tube) (m)
\end{itemize}
δi error in measurement i  
ε dielectric permittivity (F/m)  
θ contact angle (rad)  
κ surface curvature (1/m)  
μ dynamic viscosity (Pa s)  
ρ density (kg/m³)  
ρF free electric charge density (C/m³)  
σ surface tension (N/m)  
Σ stress tensor (Pa)

Suffixes  
B bubble  
BU buoyancy  
ch chamber  
D drag  
DEP dielectrophoretic  
E expansion  
eq equivalent  
g vapour  
G center of gravity  
in inlet  
l liquid  
o orifice

ACKNOWLEDGEMENTS

Thanks are due to Mr. Roberto Manetti for the design and the assembling of the electronics and for technical assistance. Authors would also like to thank the student Michele Danti who set up the apparatus and took part in the experiments in the frame of the activities of his graduation thesis. The cooperation of the direction and the personnel of JAMIC is gratefully acknowledged, as well as that of JSUP, which provided the two high-speed cameras. The work was partly funded by the Italian Space Agency (ASI) under contract ARS–99–66.

REFERENCES


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**Tab. 1**: Test matrix (flow rate is referred to normal conditions, 0°C and 101.325 kPa, and g-level was evaluated by JAMIC)