Visual analysis of flow boiling at different gravity levels in 4.0 mm tube

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Abstract. The aim of the present paper is to describe the results of flow boiling heat transfer at low gravity and compare them with those obtained at earth gravity, evaluating possible differences. The experimental campaigns at low gravity have been performed during the parabolic flight campaign of October-November 2013. The paper will show the analysis of differences between the heat transfer coefficients and vapour bubble parameters at normal and at zero gravity. The results of 4.0 mm tube are presented and discussed. With respect to terrestrial gravity, heat transfer is systematically lower at microgravity in the range of the experimental conditions. Heat transfer differences for the two gravity conditions are related to the different bubble size in each of them. The size of a bubble in flow boiling is affected by the gravity level, being larger at low gravity, unless inertial forces are largely predominant over buoyancy and other forces acting on the bubble itself when detaching from a heated wall. Vapour bubble parameters (bubble diameter, bubble length, width, and nose velocity) have been measured.

1. Introduction
Flow boiling heat transfer (FBHT) is encountered in many engineering fields (energy conversion, environmental applications, food, chemical and other process industries, etc.) and in particular, in space applications. In the coming years, expectations for space-based systems such as communication satellites and manned space-platforms or missions will grow rapidly. Due to the increasing size and capabilities of these systems, their power requirements will also greatly increase. More sophisticated thermal management systems capable of dealing with greater loads will have to be designed. FBHT may offer the solution for increasing heat transfer rates under future, challenging space conditions, at least under certain conditions and/or in certain areas of the system. High performance boiling heat transfer systems, which take advantage of the large latent heat transportation, are therefore important to reduce the size and weight of space platforms and satellites. Nonetheless, FBHT knowledge is also very important for the safe operation of existing single-phase liquid systems that may enter this mode of operation in case of accidental increase of the heat generation rate. An accurate understanding of the off-design situations is therefore essential for properly managing accidental situations.

Among the available platforms for microgravity experiments, such as parabolic flight (gravity level $10^{-2}$g, duration 20 s, repeated for about 30 times in a day), sounding rocket (gravity level $10^{-3}$g, duration 2-15 min), orbital flight (gravity level $10^{-2}$-$10^{-3}$g, duration unlimited), drop tower (gravity level $10^{-5}$g, duration 2-10 s), because of the complexity of an experimental loop for flow boiling heat transfer tests the most widely used microgravity platform is the parabolic flight.
The few data available shows small coherence, maybe due to severe restrictions in the test apparatus specification, strict prescription of experimental conditions and not enough chance to repeat experiments for repeatability, short lasting of 0-g conditions, etc. A complete overview (including pool boiling) can be found in Ohta et al. [1], Ohta [2], Di Marco [3], Kim [4], Ohta [5], and Baldassarri and Marengo[6].

Although the available experimental data are limited, some general conclusion may already be drawn: i) results on heat transfer are contradictory, spanning from increase to decrease with respect to terrestrial gravity, and include no effect of gravity level; ii) the effect of gravity level on heat transfer strongly depends on the flow pattern; therefore, its knowledge is crucial and systematic visualisation tests are required; iii) forced convection flow (inertial effects) plays a fundamental role in microgravity flow boiling heat transfer as, added up to the buoyancy force, it may overcome it; the thresholds beyond which inertial effects are dominant over buoyancy effects have to be carefully determined; iv) a systematic study of flow boiling heat transfer is necessary in order to create a consistent data set for design purposes and to better establish the flow boiling heat transfer knowledge at microgravity.

The aim of the present paper is to describe the results of flow boiling heat transfer at low gravity and compare them with those obtained at earth gravity, evaluating possible differences. The experimental campaigns at low gravity have been performed during the 59th ESA parabolic flight campaign of October-November 2013.

2. Experimental loop

The activity is carried out on the experimental facility called MICROBO (MICROgravity BOiling), specifically designed and built to be boarded on the Airbus A300 ZERO-Gravity managed by Novespace for parabolic flight experiments of ESA, French and German Space Agencies. The loop, schematised in Figure 1, consists of a gear pump (Gmax=500 mL/min), a filter, a Coriolis flow-meter, two electric pre-heaters, the test section (where boiling phenomena occurs), two condensers, a bellows, and a tank for the storage of the process fluid (FC-72).

![Figure 1. Schematic of the experimental loop.](image)

The experiments were performed on a vertical tubular test section made of a Pyrex tube with a transparent metal layer deposited on the outer surface (Figure 2). Inner tube diameter is 4.0 mm. The metal layer is made of ITO (Indium Tin Oxide) and its thickness is of the order of 100-150 nanometers. The heated length is 155 mm. The test section is heated by Joule effect by an electric supplier. This configuration allows obtaining constant heat flux at the inner surface of the test section.
The metal layer is transparent in order to allow tube heating as well as boiling phenomena visualization. Flow pattern visualisation is performed with a high speed digital video camera and images are analysed with an image processing software. This test section and the visualisation system allow the observation of flow patterns in diabatic flow conditions directly along the boiling channel. Wall temperatures are measured by a set of 10 thermocouples attached to the outer tube wall. The picture in Figure 2 shows the transparent test section with the wall thermocouples. The inlet section is at the left of the image. Working fluid is FC-72, perfluorohexane C₆F₁₄, a fluorinert liquid manufactured by 3M, used in electronic cooling. To reduce the heat losses, the test section is confined in a special box made of ERTACETAL® closed with two transparent plates made of polycarbonate. The test matrix for the experimental campaign presented in the paper are summarised in Table 1.

The experiments were conducted with a constant mass flux $G$ of 173 kg/(m$^2$·s) and a heat flux $q''$ which stretches from 7.6 kW/m$^2$ in single phase convection regime up to 65 kW/m$^2$ in flow boiling regime. The maximum heat flux causes the dryout of the liquid film. In this heat flux range the analysis of video images gives detailed observations of flow patterns and measurements of bubble parameters as dimensions, frequency, and velocity. At the same time, heat transfer is measured through the wall thermocouples and correlated with the flow pattern observations and bubble parameter measurements.

| Table 1. Test matrix |
|---------------------|
| D, [mm]             | 4                     |
| L, [mm]             | 155                   |
| $\Delta T_{\text{sub}}$, [K] | 24                   |
| P$_{\text{in}}$, [bar] | 1.8                  |
| G, [kg/m$^2$·s]    | 173                   |
| Re$_{\text{in}}$ [-] | 1472                 |
| $q''$, [kW/m$^2$]   | 7.6 - 65.9            |
| $x_{\text{out}}$, [-]| -0.22 - 0.48          |

3. Vapour bubble parameters
High frequency video has been registered through the transparent wall of the tube, at the position of thermocouples 7, 8, 9 and 10, the closest thermocouples to the tube outlet. Bubble video clips are recorded at frequency of 600 Hz. Video analyses are performed with the aim to measure the bubble geometry (width and length), nose velocity, frequency, and distance between two consecutive bubbles (liquid slug length in slug flow).
The measured parameters are shown in Figure 3. For each specified parameter, five bubbles have been analysed and their measurements are averaged. Measurements and analysis of video images are performed by the operator with the aid of video analysis software. For each thermocouple, all bubble measurements are carried out in an analysis zone centred on the thermocouple position for an extension of $D_i/2$ upwardly and $-D_i/2$ downwardly. When a bubble enters the analysis zone, then the operator starts the bubble measurements during the period of bubble transit in the analysis zone. Nose velocity is the velocity measured in the direction of the channel axis. Bubble length, the distance between the nose and the tail, is measured when the geometrical centre of bubble is inside the analysis zone.

4. Results and discussion

4.1. Flow pattern

Flow patterns were determined as a result of video and images analysis operated by a human operator. The results are shown in Figure 4 for normal gravity and Figure 5 for low gravity tests. The graphs in these figures show local thermodynamic quality (calculated at the thermocouple position along the channel axis) on the horizontal axis, and mass flux on the vertical axis. Flow images recorded with the high speed video camera have been analysed frame by frame in order to study the flow patterns at different heat fluxes and positions along the flow channel. The vapour-liquid structures observed in the images are classified according to the flow pattern classifications in upward two-phase flow, given by McQuillan and Whalley [7]. These flow patterns are shown in Figure 6. The only exception is that in the present article, “plug flow” is called “slug flow”. In order to give an extended description of vapour-liquid structures, a number of additional flow patterns have been introduced between these fundamental flow patterns at normal gravity conditions. At low gravity the evolution of flow patterns is simpler and does not need additional flow patterns. As it is well known, this method of analysis is affected by a degree of subjectivity of the operator in the identification of the flow patterns and this causes a certain level of uncertainty in the flow pattern transitions.

The two groups of pictures in Figure 7, show a complete view of the evolution of two-phase flow, from ONB up to annular flow and CHF, for increasing values of heat fluxes (from left to right). The right portion of Figure 7, shows the images recorded at normal gravity, while the left portion shows the images recorded at low gravity.

![Flow patterns, and their boundaries for 1-g tests](image)

Flow pattern evolution is progressive, i.e., is in evolution as seeing through the tube, being the bubbles larger as they flows toward the outlet. Taking into the account the axial position 10 ($z/L=89 \%$), i.e., the closest position with respect to the outlet, the corresponding flow patterns are: a) and b) bubble
coalescence flow, c) bubbly to slug flow, d) and e) slug coalescence flow, f) slug to annular flow, g) annular flow, and h) annular flow (up to critical heat flux, CHF).

Figure 7 Right, shows the pictures of all flow pattern characteristics for tests at microgravity. In bubbly flow, the vapour phase is distributed as discrete bubbles in a continuous liquid phase and the bubble diameters are smaller than the diameter of the tube as shown in Figure 7 Right a,b,c.

Figure 5. Flow patterns, and their boundaries for 0-g tests

Bubbles at low gravity are larger than those at normal gravity and characterised by lower velocity (due to the absence of buoyancy) and almost linear trajectories and absence of deformation (spherical shape) in comparison to those at 1-g. This leads to a more ordered flow with a reduced relative velocity among the vapour bubbles. In these conditions (ordered flow, linear trajectories, spherical shape of bubble) it is reasonable to expect a reduction of the turbulence level due to the absence of bubble-induced turbulence.

Figure 6. Flow pattern schematization in two-phase flow according to McQuillan and Whalley [7]

An interesting issue for discussion concerns the larger diameter of bubbles at zero-g. It is assumed that two mechanisms control the bubble diameter: detachment diameter and coalescence rate. Detachment diameter is expected larger due to the absence of buoyancy in the balance of forces acting on a bubble during the nucleation phase. In order to have the bubble detachment, the diameter of the bubble must be large enough to generate the drag force sufficient to detach the bubble from the nucleation site. The other mechanism responsible for the increase of bubble diameter at low gravity could be the higher rate of coalescence. The coalescence of two bubbles is strongly dependant on their approaching velocity (Ribeiro and Mewes [8]). For low relative velocities, coalescence of bubbles occurs; for approaching velocities higher than a given value (critical velocity), bubbles do not coalesce but bounce.

At low gravity conditions, bubbles in bubbly flow were observed to be larger, with spherical shape (without deformation), following linear trajectories and lower velocities. These conditions seem ideal for promoting coalescence of bubbles. In fact, linear trajectories reduce the lateral motion of bubbles.
Therefore, for the same flow conditions low gravity bubbly flow shows higher coalescence rate and larger bubble diameters in comparison to the flow in similar conditions at normal gravity conditions.

In bubbly/slug flow, bubbly flow and slug flow are both present as shown in Figure 7 Right, d,e. This is a transition from pure bubbly to pure slug flow.

**Figure 7. Left:** Flow patterns visualisation at 1-g (z/L from 66 to 89 %) with increasing the heat flux: a) 8.0, b) 16.7, c) 23.5, d) 29.5, e) 39.8, f) 44.9, g) 52.6 and h) 65.9 kW/m$^2$

**Right:** Flow patterns visualisation at 0-g (z/L from 68 to 93 %) with increasing the heat flux: a) 5.1, b) 9.6, c) 15.1, d) 20.6, e) 24.9 and f) 28.8 kW/m$^2$

In slug flow, vapour bubbles become elongated and reach approximately the same diameter as the tube as shown in Figure 7 Right, f. The nose of the bubble is characterised by a hemispherical shape and the vapour in the bubbles is separated from the tube wall by a thin film of liquid. The liquid flow is contained mostly in the liquid slugs, which separate successive vapour bubbles. The length of the vapour bubbles can vary considerably and is increased for increasing heat fluxes. At low gravity conditions the liquid film is significantly thinner than that at normal gravity. The tail of a Taylor bubble at low gravity is different from that at normal gravity (Figures 7 Left, e,f and Figure 7 Right, f). The shape of the bubble tail is more regular and the motion in the liquid slug is less chaotic. The length of Taylor bubbles at low gravity is significantly longer than those for the same conditions at 1-g.

**Figure 8.** Bubble nose velocity versus local quality at 1-g
4.2. Bubble parameters

Graphs of figures 8 and 9 show the results of bubble nose velocity and length measurements versus local quality at normal gravity. The figures show also the boundaries of the observed flow patterns. Bubble nose is represented (Figure 8) as the ratio of the bubble nose velocity on the liquid velocity (average liquid velocity calculated at the inlet of the test section). The bubble length is represented in Figure 9 as the ratio between the bubble length and the tube diameter (4 mm for the present case). In the bubbly and bubbly coalescence regions, bubbles are almost spherical and the reported length corresponds the bubble diameter.

Figure 9. Bubble length versus local quality at 1-g

The figures show the parameters measured at the different thermocouple positions along the tube (Tw7, Tw8, Tw9, and Tw10), characterised by different values of local quality. Figure 8 shows the effect of local quality on vapour bubble nose velocity. Although, the graph shows few results in the bubbly flow region, it exhibits a notable velocity increase for increasing values of thermodynamic quality. In the regions of bubble coalescence flow and bubbly to slug flow, bubble nose velocity is independent of local quality and has an almost flat slope with a value of 2.31.

In the slug flow region, nose velocity shows a dependence on local quality, and in the slug coalescence flow region, this dependency becomes significant. In the latter region, two associated effects cause the increase of the nose velocity slope: the acceleration of Taylor bubbles due to coalescence and liquid film evaporation. The region of slug to annular flow does not show any results because as the Taylor bubbles start the axial coalescence, they increase their length and the flow becomes a semi-annular flow; in these conditions it is almost impossible to distinguish the tail and the nose of two consecutive bubbles due to the reduced distances, high velocities, and more chaotic flow. The maximum measured bubble nose velocity on liquid velocity is 6.36, equivalent to bubble nose velocity of 682 mm/s.

Figure 10. Bubble velocity versus local quality at 0-g
The graph of figure 9 shows the effect of local quality on vapour bubble length at low gravity. In bubbly and bubble coalescence flow, bubble lengths show a linear dependence on local quality, with a small slope. In the bubbly to slug flow and slug flow regions the trend is not linear any longer, and the slope increases rapidly for increasing values of local quality (as shown in the slug coalescence region). Measurements in this region are affected by the same considerations made for the bubble nose velocity. Reduced distances between consecutive bubbles, high velocities, and more chaotic flow, result in more difficulties in parameter measurements from images. The longest measured bubble is 18.84 mm ($l_b/D_i = 4.71$).

The graph of figure 10 shows the results of vapour bubble nose velocity at microgravity. Nose velocity of bubbles increases linearly with local quality and shows two different regions characterised by different slopes. The first region is the region where bubbly flow occurs (local quality less than -0.20). In this region, the flow pattern evolves from sparse small bubbles, dispersed in the liquid phase to large bubbles (Figures 7 Left, a, b, c). The measured bubble nose velocity ratio is in the range from about 0.75 up to 1.25. In this flow pattern regime, it was expected to find a near zero slip velocity, i.e. $u_n/u_l = 1$ (due to the absence of buoyancy).

![Figure 11. Bubble length versus local quality at 0-g](image)

The explanation for this discrepancy can be caused by the fact that the velocities reported in the graph are the average value of velocities of all bubbles at certain condition of heat flux. This average value does not take into the account the position of the bubble in the tube (bubbles near the wall have a smaller velocity than the liquid, while bubbles in the centre have same mean liquid velocity). Further analysis will be performed on this point in the future.

![Figure 12. Comparison of bubble width at 1-g and 0-g](image)
The second region (local quality larger than -0.20) is characterised by the transition bubbly to slug flow and by slug flow. Bubble nose velocities are in the range 1.25 – 2.7. In this region the higher velocities could be caused by the acceleration of the vapour phase and axial coalescence of Taylor bubbles.

Figure 11 shows the effect of local quality on vapour bubble length (actually, the ratio $l_b/D_i$). Bubble length in bubbly flow region shows a linear dependence on local quality. Bubbly to slug flow and slug flow regions are characterised by data scatter caused by the effect of coalescence of bubbles. In fact, coalescence of two consecutive Taylor bubbles increases the bubble length with a large amount from one frame to the successive.

Figure 12 shows the comparison of bubble width at two different gravity levels. The effect of gravity is significant: the width of bubbles at low gravity is larger than that at earth gravity. It can be explained by both, the larger bubble diameter at detachment and higher rate of coalescence at low gravity condition as discussed in the previous section. The liquid film thickness for slug region (where the width does not increase any more) at normal gravity condition is significantly larger than in microgravity. At normal gravity the thickness is about 400 μm, double than that at low gravity.

Figure 13. Boiling curves for axial position of Tw10 (z/L=93%) at 1-g and 0-g

4.3. Heat transfer

Figure 13 shows the boiling curves for the two gravity conditions. The low gravity boiling curve shows the results of decreasing heat fluxes starting from the region of slug flow. The curve at normal gravity condition is built with increasing heat fluxes and shows the onset of nucleation. The behaviour of the two curves is quite similar in the nucleate boiling region. Here, the two curves show small differences of curve slope. The transition from bubbly to slug flow is evidenced by a large change of slope. This change in heat transfer mechanism occurs at lower superheating for normal gravity data.

Figure 14. Heat transfer coefficient for axial position of Tw10 (z/L=93%) at 1-g and 0-g
Figure 14 shows the local heat transfer coefficients measured at Tw10 next to the tube outlet. Both gravity heat transfer coefficients are strong functions of heat flux. Low gravity heat transfer is systematically lower than that at normal gravity for all values of local quality and for all the observed flow patterns (bubbly flow and slug flow).

The differences of heat transfer in bubbly flow at the two gravity levels, could be explained with the lower level of turbulence expected at low gravity, as described in the previous section.

5. Conclusions

The paper presents the results of a research dedicated to the study the effect of gravity level on flow patterns and heat transfer in flow boiling inside a small tube of 4.0 mm in diameter. The working fluid is FC-72. The test section and the visualisation system allow observing flow patterns and bubble behaviours in diabatic flow conditions. The observed flow patterns at earth gravity vary from bubbly flow up to the intermittent flow, annular flow and thermal crisis. At low gravity flow patterns are simpler than in earth gravity and vary from bubbly flow, slug flow to annular flow. Experiments provided detailed observation of flow patterns and measurement of vapour bubble dimensions and velocities at different flow patterns. At the same time, heat transfer is measured with the wall thermocouples and correlated with the flow pattern observations and bubble parameter measurements. At microgravity conditions, bubbles are found larger than those at normal gravity with lower velocity (due to the absence of buoyancy), almost linear trajectories and absence of deformation in comparison to those at 1-g. Larger bubble diameters are controlled by two mechanisms: detachment diameter and coalescence. Liquid film thickness of Taylor bubbles at normal gravity condition is found to be almost double (1.65) than that at low gravity condition.

Heat transfer coefficients and boiling curve are presented and discussed in details. Heat transfer data are correlated with the observed flow patterns and heat transfer mechanisms are highlighted in the different regimes. Heat transfer at low gravity condition is lower than that at normal gravity condition in the tested range. The reduction of heat transfer in nucleate boiling can be explained with the reduction of the turbulence level in bubbly flow at low gravity condition.

6. References

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