Saturated Pool Boiling in Microgravity in ARIEL Experiment

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Abstract

The ARIEL experiment was flown on May 2005 aboard of Foton-M2 satellite and was dedicated to the study of nucleate boiling of dielectric fluids on a flat plate, in the presence of an external electric field or less. The experiment was run for four days, however the unexpected high vapor production caused the early exhaustion of the nitrogen of the pressure compensation system. The experiment runs were continued in off-nominal conditions, at subatmospheric pressure, allowing for testing saturated pool boiling in microgravity. The results reported herein show that saturated pool boiling in microgravity can occur without originating immediately surface dryout. The application of a moderate electric field increases the surface wetting and decrease the size of departing bubbles. For the highest applied electric field, nucleation is suppressed and only single phase heat transfer takes place, at least in the power range investigated here, with degradation of the performance.

Keywords: Microgravity, Boiling Heat Transfer, Electric Field

1. Introduction

In boiling heat transfer, buoyancy has been found to affect the removal, rather than the detachment, of bubbles from a heated plate. In the lack of gravity, bubbles reside close to the surface, coalescing in a large mass of vapor that is difficult to condense, due to the low surface to volume ratio, and prevents the liquid to reach the surface. This big bubble may sporadically get in contact with the heated surface, and eventually may lead to an anticipated dryout of the surface. This impairment of heat transfer performance, verified during several experimental tests, joint with the difficulties in removing vapor from the heating surface, complicates the application of boiling heat transfer in micro-g. The application of an electric field may provide an additional volume force, reducing the size of detaching bubbles and leading them away of the surface, thus restoring good heat transfer conditions. The effectiveness of this technique was already demonstrated by several experiments carried out in microgravity, both in gas-liquid systems [0], [0] and in boiling systems [0], [0], [0].

Saturated boiling was seldom investigated in microgravity due to the erratic behavior of the large masses of uncondensed vapor. According to some opinions, saturated pool boiling in microgravity is considered impossible, and surface dryout should take place immediately. This work is dedicated to the analysis of saturated pool boiling in microgravity that, although not originally programmed, occurred during the ARIEL experiment on Foton-M2.

2. The ARIEL experiment on Foton-M2

The Foton-M2 unmanned space mission was organized by ESA in cooperation with Russian Space Agency. A total of 39 experiments in physical and biological science were housed aboard of a Foton satellite, for a total payload mass of 385 kg, and put into orbit by a Soyuz-U Russian launcher, on 31 May 2005, from the cosmodrome of Baikonur. The satellite remained in orbit for 15.6 days, and the re-entry module was successfully recovered after the landing. During the mission, a significant sub-set of the experimental data was transmitted to ground, at each passage of the satellite over the ground antenna of the base of Esrange (Kiruna, Sweden) typically 4-5 times per day. The scientists had also the possibility to modify the experimental parameters via telemetry, upon analysis of the observed experimental trends. ARIEL was part of the Fluidpac reusable facility [0], containing a total of 4 fluid-physics experiments, sharing power subsystems, optical diagnostics and data storage. During the flight, different experiments were activated at different times: ARIEL was operated for a total of 92 hours.

The main objectives of ARIEL experiment, can be summarized as follows:
- testing boiling heat transfer at high heat rate on a flat surface, whose size is of technical relevance;
- investigating the role played by an electrostatic field in improving boiling performance in different gravity conditions;
- obtain a visualization of the boiling patterns in reduced gravity.

3. Experimental apparatus and test procedure

The apparatus, shown in Fig. 1, contained a 10 mm thick plate of zinc sulphide (ZnS) of 50 mm diameter, placed in an aluminum container of about 1 liter volume. The entire facility had an overall mass of about 9.5 kg. The container was provided with a glass window and an illuminating system which allowed for the visualization in the visible range from the lateral side. The active
heating element consisted of a square layer of 20x20 mm, with a thickness of gold of 40 nm, deposited by sputtering over a ZnS substrate. The gold layer was transparent to visible light: in this way, images of the boiling patterns in the visible range could also be obtained from the lower side of the apparatus via the flexible optical diagnostics system of Fluidpac.

The gold layer was electrically heated by dc current. The voltage drop across the gold layer was monitored via two sense wires soldered at its sides. The heating element proved to be very adherent to ZnS and resistant throughout repeated series of tests; no significant degradation of the coating and of its electrical properties was observed. The upper side of the heater was facing a pool of FC-72 (C₆F₁₄), a dielectric fluid manufactured by 3M and used for electronics cooling. The fluid was thoroughly degassed before the filling of the apparatus, which was sealed. A bellows, connected to the main vessel, was operated by pressurized nitrogen in the secondary side, in order to compensate for volume variation due to thermal dilatation and vapor production, and to keep the pressure constant at 100±3 kPa (corresponding to a saturation temperature of 56.6±0.8°C for FC-72). An external electrical heater and a plate heat exchanger, connected to FLUIDPAC cooling loop, allowed for the heat removal and the set up of the bulk fluid temperature, which was regulated within ±0.5 K before the start of each test. Other measurements included the pressure in the cell, by means of an extensimetric transducer, and the fluid bulk temperature, obtained as the average of the output of two AD-590M transducers placed inside the cell at 3 mm and 10 mm from the heater, respectively. Finally a Pt-100 sensor, stuck on the external surface of the ZnS plate, monitored its temperature.

The spatial-averaged temperature of the heating surface, \( T_w \), was evaluated by means of a linear relationship between the heater electrical resistance and its temperature

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R = R_0 [1 + \alpha (T_w - T_0)]
\]

where the reference resistance at \( T_0 = 0 \) °C, \( R_0 \) and the temperature coefficient, \( \alpha \), were determined via experimental calibration during the setup of the apparatus; their stability in time was checked by means of a short standard step at low power before each power step.

The electrostatic field was imposed by means of a grid of five stainless steel rods, 1 mm in diameter, laid parallel to heater, at a distance of 5 mm from it (from rod axis to plate). The grid was connected to a high voltage power supply, able to provide up to 10 kV dc.

Each experimental sequence was organized in a series of power steps with increasing heat flux, at the same fluid bulk temperature and high voltage. The heater control system was able to maintain the power constant throughout each step, of the duration of 240 s. After each power step, the heater was switched off and the bulk temperature was restored to the initial value. Power cutoff was foreseen in case of critical heat flux or system overheating. After the maximum foreseen power was achieved, a new sequence was started with a different value of applied high voltage or fluid temperature.

According to the original test planning, two kinds of experimental sequences were foreseen, the first mainly devoted to single-phase flow and the second to pool boiling conditions. The parameter range included five different bulk temperatures of the fluid (36, 40, 44, 48 and 50°C), four different applied voltages (0, 1, 5 and 10 kV), and values of heat flux up to 200 kW/m², i.e. of the same order of magnitude as critical heat flux in FC-72. As far as known no tests over a large surface at so high heat flux levels were ever run before. A complete counterpart sequence was carried out before the flight in terrestrial gravity conditions. However, during the flight, as a consequence of the increased vapor production, the nitrogen consumption to operate the pressure compensation bellows was much higher than foreseen, and the nitrogen reserve was fully consumed before the nominal end of the test sequence. The runs were continued at reduced power in off-nominal conditions, in the lack of pressure control system. In the lack of nitrogen supply, the compensating bellows set stably to its minimum extension, and the
pressure thus stabilized at the saturation value corresponding to the bulk temperature of 36 °C, i.e. about 50 kPa. A large mass of uncondensed vapor was continuously present in the cell. In total, 22 of the originally foreseen 28 experimental steps were completed, with 6 of them in off-nominal conditions. Results on subcooled nucleate boiling, in the presence of electric field or less, have already been reported in [0], [0]. The present paper is dedicated to the analysis of the last three runs in off-nominal conditions, where saturated (or nearly-saturated) heat transfer at sub-atmospheric pressure took place.

4. Results

Figs. 2-3 report the boiling curves for the first two runs analyzed here (applied voltage 0 and 5 kV): it can be seen that boiling heat transfer is slightly enhanced for an applied voltage of 5 kV, compared to the case with no electric field. This is better appreciated in Fig.4, where the heat transfer coefficients are compared. In the latter figure, heat transfer coefficient at 10 kV is also included, where no nucleation took place.

The analysis of the side-view images (Figs.5-6) shows that for an applied voltage of 5 kV, the average size of the detaching bubbles is significantly reduced.

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**Fig. 2** Pool boiling curve, saturated boiling, \( T_f = 36 °C \), no applied voltage.

**Fig. 3** Pool boiling curve, saturated boiling, \( T_f = 36 °C \), applied voltage 5 kV.

**Fig. 4** Comparison of heat transfer coefficients for different applied voltages, saturated conditions, \( T_f = 36 °C \). No nucleation took place for \( HV = 10 \text{kV} \).

**Fig. 5a** Flow pattern at \( q'' = 30 \text{kW/m}^2 \), with no applied electric field, lateral view (image width: 30 mm).

**Fig. 5b** Flow pattern at \( q'' = 30 \text{kW/m}^2 \), with an applied electric field of 5 kV, lateral view (image width: 30 mm).

**Fig. 6a** Flow pattern at \( q'' = 47 \text{kW/m}^2 \), with no applied electric field, lateral view (image width: 30 mm).
Images from the bottom of the test section (Figs. 7a, 8a) show that, for no applied EF, the boiling surface is covered by dry patches, originated by bubble coalescence, when no voltage is applied. The analysis of subsequent images (not reported here for reasons of space) shows that the extension of these patches varies periodically. The formation of patches is suppressed when a voltage of 5 kV is applied, see Figs. 7b, 8b, and nucleation on the surface is more similar to the one in terrestrial gravity.

For an applied voltage of 10 kV, a different situation takes place: nucleation on the heated surface is almost entirely suppressed, and no boiling occurs, see an example in Fig. 9. Heat transfer performance is degraded in this last case, as it can be appreciated in Fig. 4. The increase in heat transfer coefficient around 40 kW/m$^2$ is accompanied by a change in the aspect of the bubble surface, that becomes wavy, (see Figs. 10-11) indicating that increased fluid flow takes place around it: the reasons for this behavior are currently being investigated.

5. Conclusions

The ARIEL facility, flown aboard of Foton-M2 on May 2005, was aimed to investigate the effect of an electrostatic field on pool boiling in microgravity, in the presence of electric field or less. Some runs of saturated pool boiling at subatmospheric pressure, although
originally unscheduled, were performed at low heat flux due to the exhaustion of the nitrogen operating the pressure control system.

The results reported herein show that steady saturated pool boiling in microgravity can occur, without originating immediately surface dryout. The application of a moderate electric field increases the surface wetting and decrease the size of departing bubbles, with a slight improvement of heat transfer performance at the highest values of heat flux. For the highest applied electric field, nucleation is suppressed and single phase heat transfer takes place, at least in the heat flux range investigated here, with degradation of the performance.

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