POOL BOILING IN THE PRESENCE OF AN ELECTRIC FIELD AND IN A VARIABLE GRAVITY FIELD: RESULTS OF EXPERIMENTS IN PARABOLIC FLIGHT

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ABSTRACT

The electric field has an influence on boiling heat transfer, as evidenced many years ago, and can act as a replacement of buoyancy in the absence of gravity. An experimental facility was set up to investigate pool boiling on a Pt heated wire of 0.2 mm diameter in the presence of an electric field and in microgravity. The working fluid was R-113 ($C_2Cl_3F_3$). On-earth experiment revealed that the critical heat flux undergoes a three-fold increase or more by applying a high voltage cylindrical electrostatic field around the wire: this effect was suitably scaled by means of an electric influence number. Nucleate boiling performance is on the contrary slightly affected in the present configuration. The facility was then operated in parabolic flight at an acceleration level of 0.03 *g*. The results indicates that, notwithstanding the dramatic alteration of bubble size, the nucleate boiling performance is weakly affected by gravity acceleration both in the presence of the electric field or less. The critical heat flux is decreased in microgravity with respect to ground values, but the electric field substantially improves it also in this condition. The analysis of the data on the basis of the available scaling groups indicates that the scaling based on Bond number seems to be effective, while a more thorough analysis is needed to test the validity of the electrical influence number.

1 INTRODUCTION

A non-uniform electric field (E.F) exerts a net force on bubbles, pushing them towards the zones of weaker field [0]. In this sense, it can be intended also as a “replacement” force in the absence of gravity. To assess this, experiments of pool boiling of R113 on a thin wire in the presence of an E.F. were carried out in variable gravity during parabolic flight. Data were recorded in normal gravity (1 g), macro gravity (up to 3 g) and micro-gravity (roughly 0.03 g).

The aim of the research is to answer the following questions:

- How is pool boiling affected by force fields?
- Is the effect of an E.F. on pool boiling the same at any value of gravity acceleration?
- Does the improvement in CHF due to E.F. hold in micro-g too?

Effect of gravity acceleration on pool boiling

Regardless of the modelling, the correlation for critical heat flux on flat plates has been often put in the form

$$q''_{CHF} = K\, q''_0 \qquad (1)$$

where

$$q''_0 = \rho_g^{0.5} h_{fg} \left[\sigma g \left(\rho_f - \rho_g\right)\right]^{0.25} \qquad (2)$$

In Eq. (1), if the heater is large with respect to the Taylor wavelength, *K* (often referred to as Kutatelatze number) is a constant: *K* can vary in the range 0.119-0.157, [0] and for flat plates was assumed 0.131 by

Zuber and 0.149 by Lienhard [0]. For horizontal wires, on the basis of the hydrodynamic theory, values of K have been proposed by Lienhard and Dhir [0] in the following form

$$\begin{cases} K = 0.118 & \text{for } \sqrt{Bo} \geq 1.2 \\ K = 0.123\, Bo^{-1/8} & \text{for } 0.15 \leq \sqrt{Bo} \leq 1.2 \end{cases} \tag{3}$$

where the Bond number, which can be interpreted as the ratio of the buoyancy to the capillary forces, is given by

$$Bo = \frac{R^2\, g\, (\rho_f - \rho_g)}{\sigma} \tag{4}$$

The prediction of Eqs.(3-4) was successfully tested against more than 900 data, obtained both in normal and in enhanced gravity (inside a centrifuge) with an accuracy better than ±15% [0]. Within $0.01 < \sqrt{Bo} < 0.15$ the experimental values have been found to be overestimated by Eq.(3). For very small wires ($\sqrt{Bo} < 0.01$) the conventional boiling curve, with its well known maxima and minima, is replaced with a monotonic curve [0], from boiling inception up to stable film boiling (provided that this traditional definition still holds) with neither a minimum in the heat flux nor a jump in the wall superheat. In this case the mechanism leading to a complete blanketing of the surface is possibly related to the vapor front propagation on the surface or to the coalescence of the bubble population; other factors, rather than the hydrodynamic instability, seem to control the phenomenon.

Nucleate pool boiling in microgravity was investigated in several geometrical configuration by Straub *et al.* [0] and on flat plates by Oka *et al.* [0]. For a flat plate, correlations like Eqs.(1-2) lead to infer a dependence of critical heat flux on $g^{0.25}$: this fact was never satisfactorily tested. Oka *et al.* [0] have reported a decrease of CHF with g in parabolic flights, which matches the dependence on $g^{0.25}$ within the experimental error, but they have considered this fact as occasional, since further experiments carried on at 10^{-5} g deviated significantly from the one-fourth power relationship. For thin wires, as the ones considered here, Eq.(3) implies a dependence of critical heat flux on $g^{1/8}$, provided that the lower threshold of Bo for the validity of equations is not crossed. Straub *et al.* [0] have claimed that the critical heat flux measured on wires during parabolic and sounding rocket flights are higher than those predicted by the theory (or its extrapolation). Besides, the trend of critical heat flux *vs.* Bo was monotonically decreasing and no reduction in CHF could be observed for $\sqrt{Bo} < 0.1$, in disagreement with most of the data shown in [0].

Effect of electric field on pool boiling

The effect of electric field on boiling heat transfer has been evidenced many years ago, as reported in [0]. On-earth experiment revealed that the critical heat flux on a thin wire undergoes a three-fold increase or more by applying a high voltage cylindrical electrostatic field around the wire. Conversely, the effect on nucleate pool boiling is quite weak in the tested geometrical configuration [0],[0]. If the hydrodynamic theory is assumed and the only parameter affected by the electric field is the Taylor wavelength [0], [0], the following relationship holds

$$\frac{q''_{CHF\,E}}{q''_{CHF\,0}} = \sqrt{\frac{El^* + \sqrt{El^{*2} + 3}}{\sqrt{3}}} \tag{5}$$

where

$$El^* = \frac{\varepsilon_{eq}\, E^2}{\sqrt{(\rho_l - \rho_g)\, \sigma\, g}} \tag{6}$$

and ε_{eq} is a combination of dielectric permittivities of liquid and gas defined in [0]. Since the electric field varies as $1/r$ around the wire, the electric field intensity, E, is a reference value determined in the

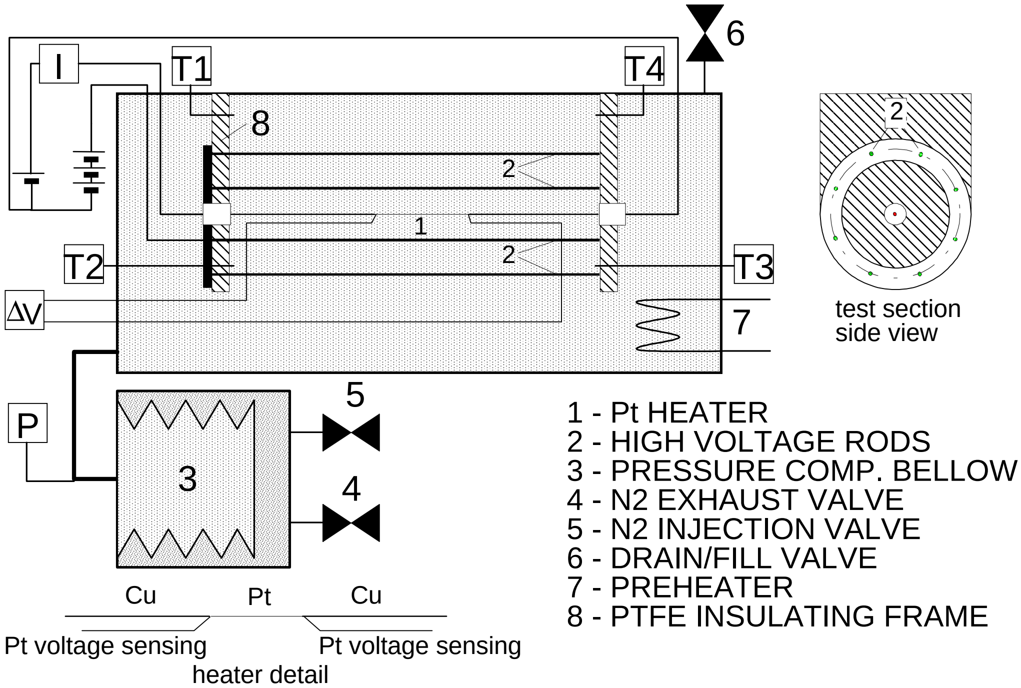

Fig. 1: Sketch of the GABRIEL apparatus

following assumptions: the field distribution is evaluated in absence of vapor and E is calculated at a distance from the heater roughly equal to the average size of the detaching bubbles.

Equation (5) has given very satisfactory results in modeling the increase of CHF with electric field in on-earth experiments. A significant implication of Eq. (5) is that a substantially lower electric field intensity, and consequently applied voltage, may be needed to obtain the same enhancement in CHF in microgravity conditions.

2 EXPERIMENTAL CONDITIONS

The GABRIEL experimental apparatus is shown in Fig.1. It consisted of an aluminum box containing the test section, which was heated by Joule effect by a direct current up to 12 A. A bellow, connected to the main vessel, was operated by pressurized nitrogen in the secondary side, to compensate volume variations due to vapor production and to maintain the pressure constant. The pressure ranged from 0.97 to 1.07 bar. To ease the condensation of the generated vapor, the tests were carried out in slightly subcooled conditions(2 to 4 K). The main vessel had two Lexan windows to allow video recording of the phenomenon with appropriate back-illumination. An external heating system, controlled by a PID regulator, maintained the fluid temperature constant up to ± 0.1 K.

Experiments were carried out using an horizontal platinum wire of 0.2 mm diameter and 45 mm length, which served as both a resistance heater and a resistance thermometer. The heater was made by brazing coaxially the platinum wire (the active heater) to a 0.6 mm copper wire, designed to work at 1 K superheat at the maximum current rate in the experiments. Two further thin wires (0.1 mm diameter) were used for direct voltage sensing and measurement at the two copper-platinum junctions, as can be seen in Fig.1.

The electric field is obtained by imposing a d.c. potential drop up to 10 kV to a 8-rod cylindrical “squirrel cage”, of 60 mm diameter and 200 mm length, surrounding the heater. The electric field was thoroughly characterized via finite element [0] and finite differences [0] analysis. The trend in a vertical section containing the heater is shown in Fig.2: the length of the cage is clearly enough to avoid side

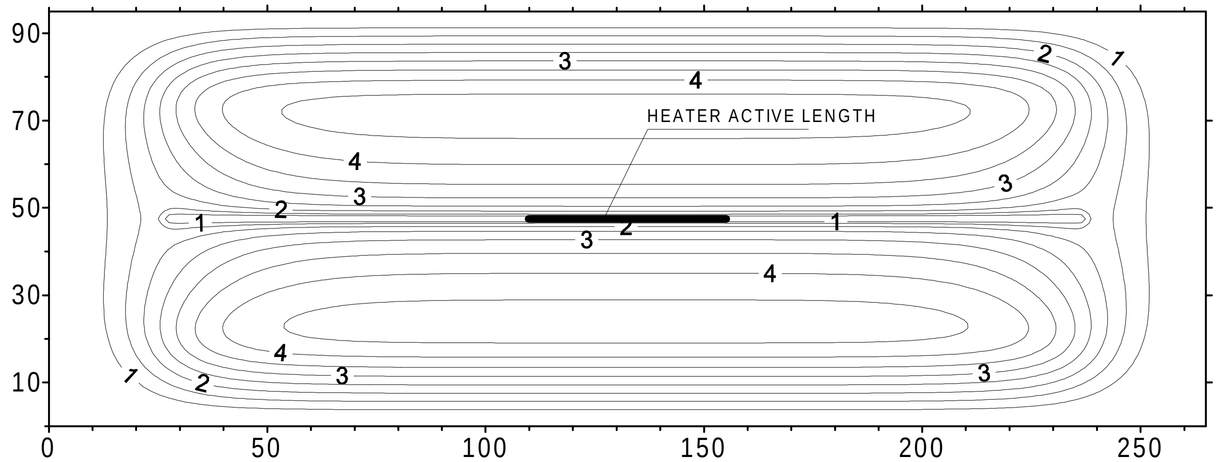

Fig.2: Isopotential contours in a vertical plane containing the heater for an applied potential of 10 kV.

effects along the active part of the heater. The trend in a section perpendicular to the wire is shown in Fig.3. The analysis showed that the field did not differ appreciably from the one produced by a solid cylindrical electrode surrounding the heater (for which the analytical solution is available) up to 10 mm from the wire axis and obeyed the law $E = C\ V/r$ where E is the field intensity at the wire surface, V the high voltage applied to the rods and $C = 0.1034$.

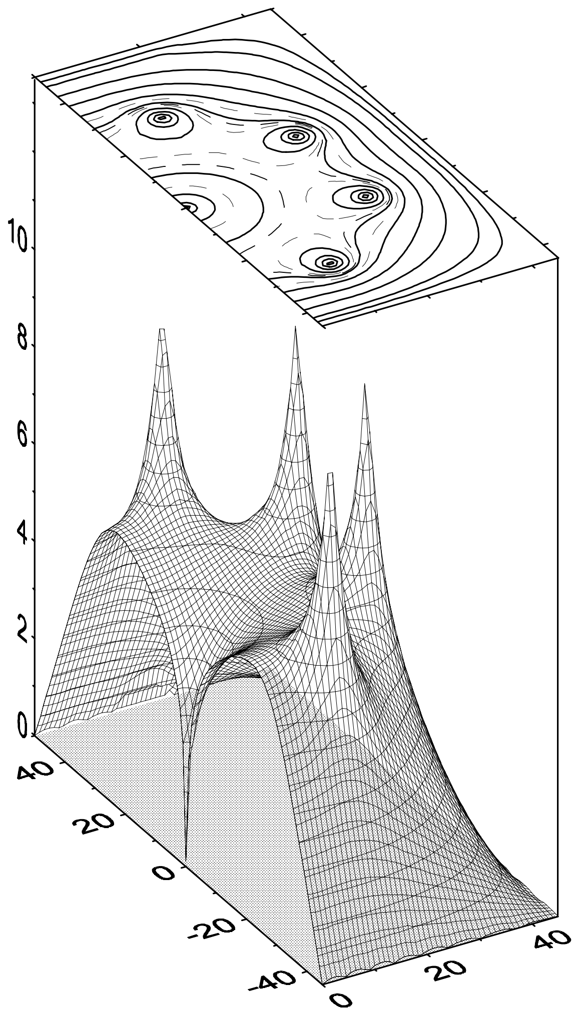

Fig. 3: Map of the electric field in a plane perpendicular to the wire, for an applied potential of 10 kV.

The tests were carried out on a Cessna Citation II aircraft, owned jointly by T.U. Delft and National Aerospace Laboratory of the Netherlands. The aircraft, equipped with two turbofan engines, had a maximum payload of 1400 kg, a maximum speed of 0.7 Mach at a ceiling of 13000 m. In the present configuration, it carried the two pilots plus a crew of four payload specialists and the experimental apparatus. The parabolic trajectory, sketched in Fig.4, allowed roughly 10 s of good quality microgravity (±0.03 *g*). Microgravity was achieved in the upper part of the trajectory, while during the two pull-ups before and after this phase the vertical acceleration was roughly 3 *g* and 2 *g*, respectively.

Experiments were run setting the current in the wire to a constant value before the beginning of a parabola, allowing data acquisition during 1 *g*, macro-g and micro-g phases. The electrostatic field was established adopting voltages of 1, 7 and 10 kV. Data at zero field were taken as well. The wire heating was started during the micro-g phase in some parabolas, to assess the effect exerted by the residual convective motion on the phenomenon. 41 useful parabolas were carried out during the three-day campaign, covering mostly the nucleate boiling region

Measurements included:

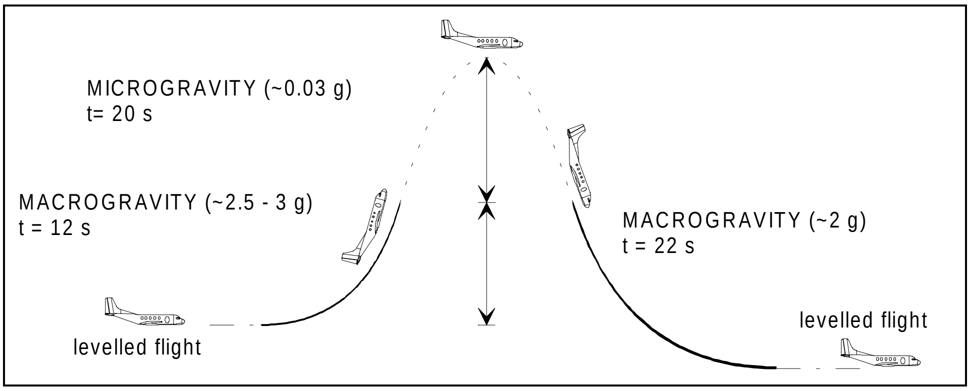

Fig. 4: Parabolic flight trajectory.

- The bulk temperature, by averaging the readings of 4 AD-590 transducers located at various positions inside the cell;
- The pressure, by an absolute extensimetric transducer, 3.5 bar full scale;
- The heat flux, from $\Delta V \times I$ measurement;
- The wire superheat, from wire resistance and -platinum temperature-resistance calibration curve [0].

The data were recorded on a PC equipped with a data acquisition system based on a 12 bit A.D. converter, at a sampling frequency of 125 Hz. The same computer controlled the operating parameters during each test. In particular, it continuously monitored the wire resistance, shutting off the power within 0.01 s at the achievement of the critical heat flux, to avoid severe wire overheating. To reduce the random error in measurements, the reported data were averaged in a period ranging from 1 to 4 s (i.e. 125 to 500 samples).

Due to the above mentioned averaging procedure, the uncertainty on the data is thus mainly due to fixed errors, so the comparison among the results inside this data set is slightly affected; an esteem is given in Table 1. The uncertainty in derived quantities were calculated by the error propagation formulae given in [0]: the one in heat flux was 4%, mainly due to the evaluation of the heat transfer area, and the uncertainty in temperature ranged from 2 to 3 K (5 - 15%) at the highest and the lowest heat flux, respectively. Besides, it must be noted that the critical heat flux had an intrinsic variability, which could be quantified in roughly 10% in on-earth experiment [0] and 15% in low-gravity ones.

Table 1. Estimated uncertainties in measurements.

Quantity	**Reference value**	**Max. uncertainty**
Voltage drop, ΔV	0.25-2 V	6 mV
Current, I	1.5-11 A	5 mA
Heater area, A_h	27.5 mm^2	1.1 mm^2 (4 %)
Reference resistance, R_0	141 mΩ	0.7 mΩ (0.5 %)
Pool temperature, T_b	43 - 48 °C	0.1 K

3 EXPERIMENTAL RESULTS

Nucleate Boiling

A complete data set for nucleate boiling is shown in Fig.5. It can be noted that:

- After the first increase at onset of macro-g, nucleate boiling was weakly influenced by the gravity field.

* The pressure exhibited an increase with gravity acceleration, which was due to the variation of the hydrostatic head in the variable gravity field. Such variations were negligible at the level of the heater.

An examination of acceleration plots (see an example in Fig.6) revealed that microgravity was generally affected by a significant jitter, with frequent changes of vertical direction (up/down). Video records showed that the flow field (bubble size and velocity) is dramatically altered by the variation of the gravity acceleration. Surprisingly, such a change is not reflected in an appreciable variation of boiling performance, i.e. of the location of the curve on the *q"* vs. ΔT_{sat} plane, as shown in Fig.7. This is also in agreement with previous observations by Straub *et al.* [0]. On the contrary, Oka *et al.* [0] reported a significant dependence on gravity for boiling performance of flat plates at high heat flux; the surface overheating was also affected by the variation of direction of the residual gravity in the micro-g phase. Thus, it appears that the present configuration is intrinsically uninfluenced by g-jitter, due to the characteristics of the cylindrical geometry.

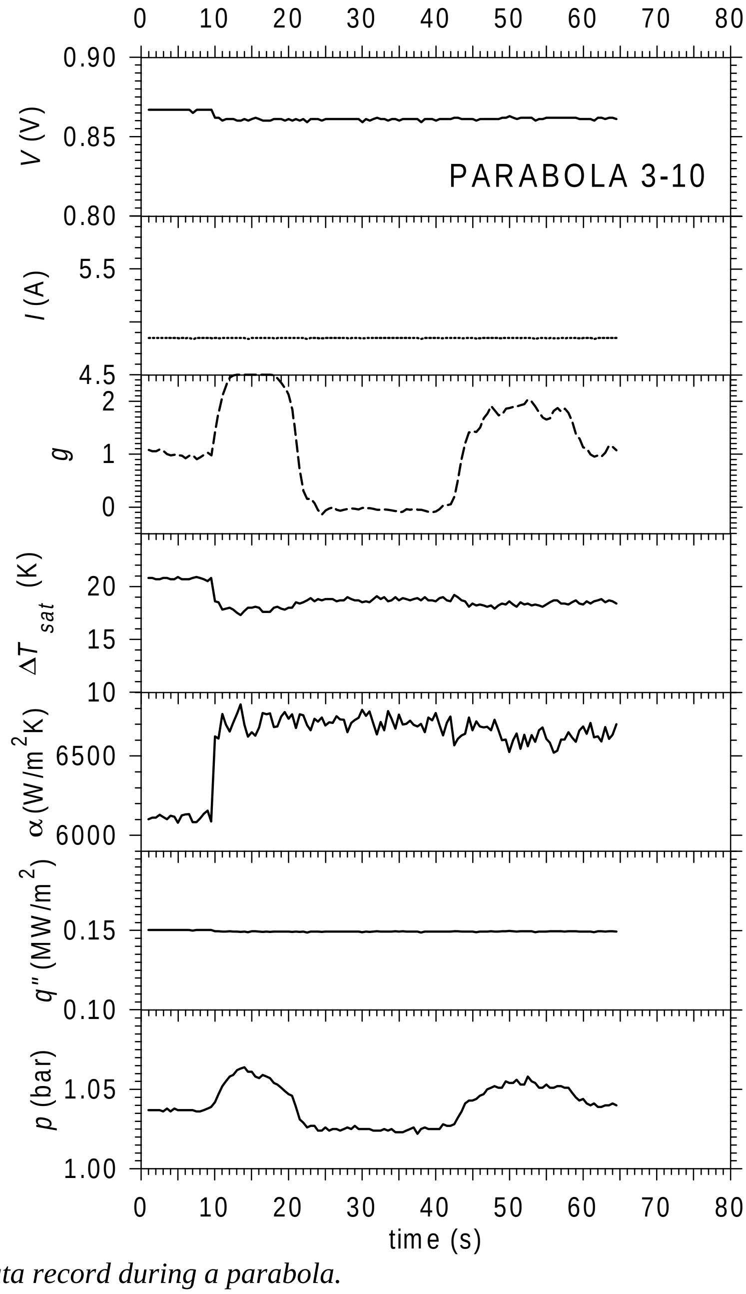

Fig. 5: Complete data record during a parabola.

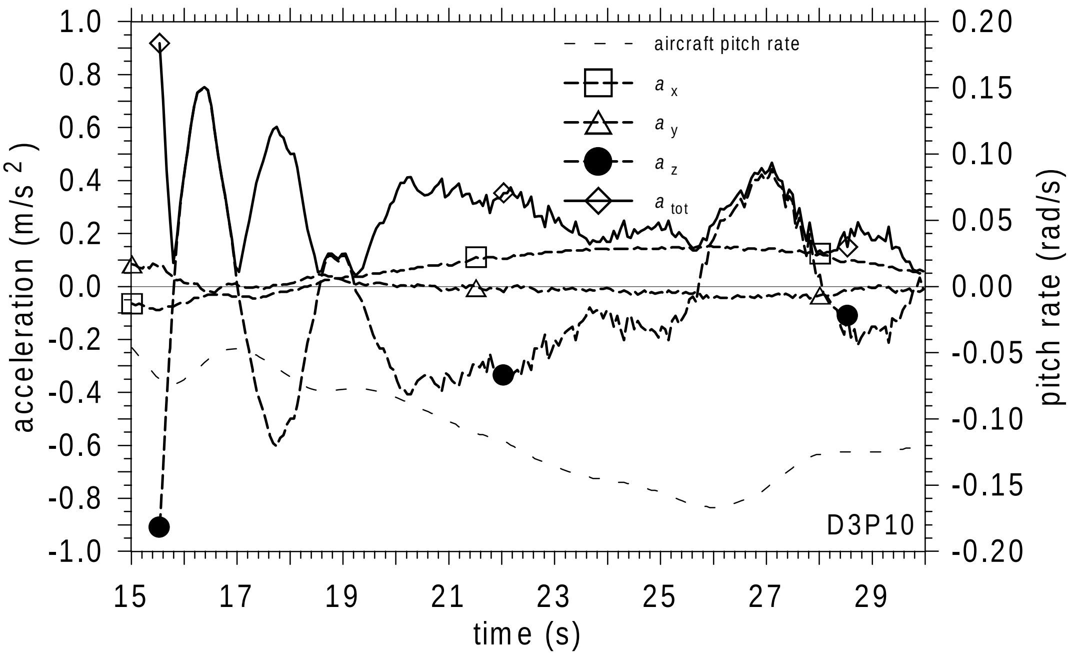

Fig. 6: Acceleration trends during the micro-g phase.

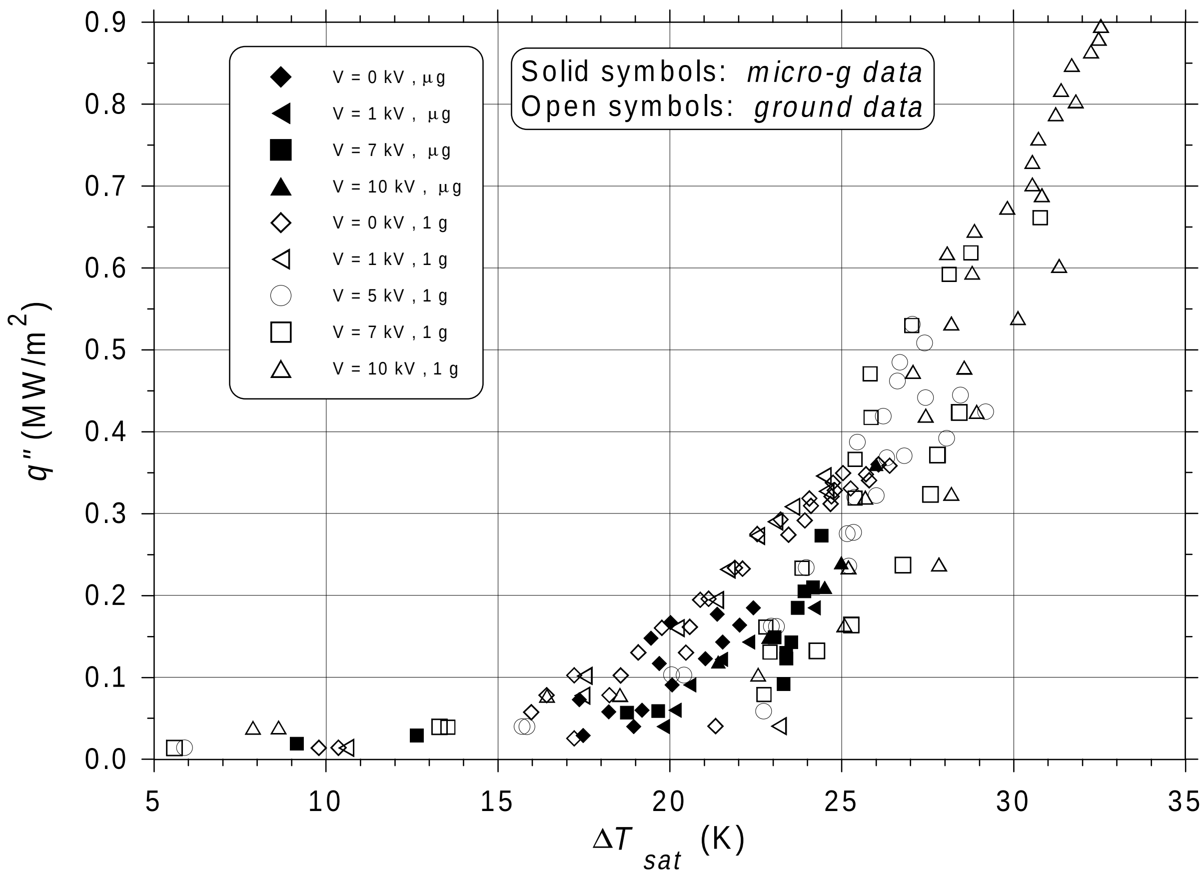

Fig. 7: Boiling curves in normal gravity and microgravity, for various values of the applied voltage.

Critical Heat Flux

CHF data are reported in Fig.8. An improvement in CHF due to electric field is evident both in normal gravity (as already well assessed, [0]) and in micro-gravity.

As shown in Fig.9, the ratio of the critical heat flux with respect to the zero-field one is the same both in normal gravity and in micro-g. No further improvement at lower electric field takes place in micro-g with respect to normal gravity, in contrast with the prediction based on the scaling group El^*, (Eqs. 5-6). To fulfill the dependence on E and g as given by Eqs.(5-6), at 0.03 g the same enhancing effect would have taken place at a value of applied voltage of 17% of the one required in normal gravity, which is definitely not the case. However, taking into account that the bubble size is different in micro-g, a different value of E could be required in Eq.(6), considering the assumptions made in the introduction.

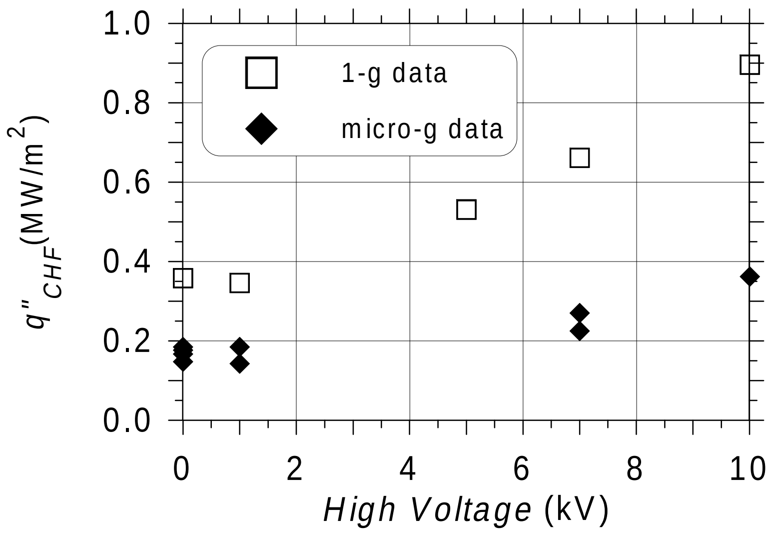

Fig.8: CHF values vs. applied high voltage, in normal gravity and in microgravity

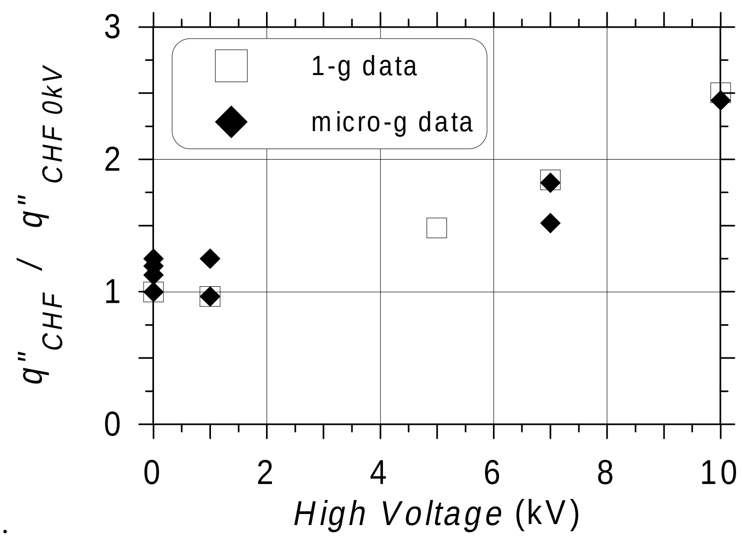

Fig.9: CHF values normalized to zero-field ones, vs. applied high voltage, in normal gravity and in micro-gravity.

The value of K, as given by Eq.(1-2), was 0.233 in normal gravity at zero field, in good agreement with the value of 0.220 predicted by Eq.(3). In reduced gravity, the measured K ranged from 0.1 to 0.123: in this conditions, the value of $\sqrt{Bo}$ was 0.017, well below the range of validity of Eq.(3), but still in a zone in which a boiling transition takes place, according to [0]. In Fig.59 of the same report [0], a certain amount of experimental data are reported for the value of $\sqrt{Bo}$ considered here, and, in spite of the considerable scattering, they are centered around the value of K=0.1. Thus, it seems that Bo is a suitable group to scale the gravity effect on wires.

4 CONCLUSIONS

In spite of the limited amount of data and the uncertainties due to the significant g-jitter, the following preliminary conclusions can be drawn:

- The flow pattern (bubble size and velocity) is strongly dependent on gravity and electric field (see video observations);
- Nucleate boiling performance is weakly dependent on gravity and electric field;
- A boiling transition (CHF) does exist in micro-g too;
- Critical heat flux was found to decrease in micro-g;
- The application of an electric field in micro-g is effective in increasing CHF;
- The scaling of electric field effect on CHF based on the group *El**, although effective in on-earth experiments, does not apply trivially in micro-g conditions;
- The scaling of CHF based on *Bo* seems to be effective in micro-g conditions too.

5 NOMENCLATURE

Bo	Bond number (see Eq.4)	
ΔT_{sat}	wire superheat	(K)
E	electric field intensity	(V/m)
El^*	electrical influence number (see Eq.6)	
g	gravity acceleration	(m/s^2)
h_{fg}	heat of vaporization	(J/kg)
K	Kutatelatze number (see Eq.1)	
q''	heat flux	(W/m^2)
q''_0	reference heat flux (see Eq.2)	(W/m^2)
r	radial coordinate	(m)
R	radius of the wire	(m)
ε	dielectric permittivity	(F/m)
ρ	density	(kg/m^3)
σ	surface tension	(N/m)

Suffixes

CHF	critical heat flux
f	liquid
g	gas
eq	equivalent

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