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Motivation and results of a long-term research on pool boiling heat transfer in low gravity [☆]

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Abstract

This paper summarises the main results of a long-term research, begun more than ten years ago, about the influence of gravity and electric fields on heat transfer. After a somehow detailed analysis of the impact of heat transfer on modern society and of the motivation of low gravity research on this subject, the authors describe their own research work on the effects of gravitational and electric forces on single-phase convection and pool boiling. This research has the twofold aim to investigate the basic mechanisms of convective heat transfer, without the masking effect of gravity, and to identify methods to make free convection possible also in the absence of buoyancy, for space applications. It has been experimentally shown that the application of an external electric field generally enhances the heat exchange between a heated wire and a liquid pool. The single-phase heat transfer coefficient is improved, the nucleate boiling region is extended to higher heat fluxes, by increasing the critical heat flux, CHF, as well as the heat transfer rate in film boiling is augmented. The convective heat exchange is an increasing function of gravity, therefore heat transfer generally deteriorates in low gravity. The application of a sufficiently intense electric field restores the same value of heat transfer coefficient and critical heat flux measured on earth, thus demonstrating the progressive overwhelming of the electrical force on the buoyancy one. © 2002 Éditions scientifiques et médicales Elsevier SAS. All rights reserved.

Keywords: Pool boiling; Microgravity; Heat transfer active enhancement techniques; Spacecraft thermal control

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1. Introduction

1.1. Premise

Several times in the past we have been asked to deliver a keynote lecture on boiling in microgravity [14,18,19], thanks to the politeness of our colleagues. Most of the times we dedicated these lectures to show a general picture of the work done by the international community in this field, and the interested reader can easily refer to the previously quoted papers. The approach followed in the present article is rather different. This is motivated by three main reasons:

- most relevant, the quite crucial moment for the "space community" in connection with the ongoing construction of the International Space Station and the next Ministerial European Space Conference (to be held next autumn) that will make quite fundamental decisions for the future space activity;
- the effort that one of the authors (Grassi) is performing to make "Heat Transfer" accepted by the European (ESA) and the Italian (ASI) Space Agencies as a self consistent topic;[1]
- the need of people like us, involved in low gravity research since a long time,[2] to discuss our findings opinions and future work within a highly qualified scientific environment and to increase the interest for this sort of unique opportunity of experimentation (weightless test campaigns).

[☆] This article is a follow-up to a communication presented by the authors at the ExHFT-5 (5th World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics), held in Thessaloniki in September 24–28, 2001.

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[1] An ESA Topical Team on Boiling (as one of the most relevant heat transfer mode, including also condensation) chaired by Pisa has been instituted and works at present.

[2] In particular we have been the first authors investigating the combined effects of electric field and gravity on boiling.

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Nomenclature

Bo	Bond number $= (L/l_L)^2$	
d	wire diameter	m
d_{eq}	bubble equivalent diameter $= (6V/\pi)^{1/3}$	m
E	electric field intensity	$\mathrm{V \cdot m^{-1}}$
El^*	electrical influence number, see Eq. (13)	
El'	electrical influence number, see Eq. (3)	
El''	electrical influence number, see Eq. (4)	
F_e	volumic force	$\mathrm{N \cdot m^{-3}}$
g	actual gravity acceleration	$\mathrm{m \cdot s^{-2}}$
g_0	gravity acceleration, standard earth value	$\mathrm{m \cdot s^{-2}}$
Gr	Grashof number	
h_{lg}	latent heat of vaporization	$\mathrm{J \cdot kg^{-1}}$
I	current intensity	A
L	characteristic length	m
K	Kutatelatze number, see Eq. (8)	
l_{L}	Laplace length	m
Nu	Nusselt number	
p	pressure	Pa
Pr	Prandtl number	
q''	heat flux	$\mathrm{W \cdot m^{-2}}$
R	radius of the wire	m
R_{B}	bubble radius	m
r	radius	m
R'	dimensionless radius $= R/l_{\mathrm{L}}$	
t	time	s
T	temperature	°C, K
V	applied high voltage	V
α	heat transfer coefficient	$\mathrm{W \cdot m^{-2} \cdot K^{-1}}$
ΔT	temperature difference	K
ΔT_{sat}	wire superheat $= T_{\mathrm{w}} - T_{\mathrm{sat}}$	K
ε	relative dielectric permittivity	
ε_0	vacuum dielectric permittivity	$\mathrm{F \cdot m}$
λ_{u}	most unstable oscillation wavelength	m
μ	dynamic viscosity	$\mathrm{Pa \cdot s}$
ρ	density	$\mathrm{kg \cdot m^{-3}}$
ρ_E	free electric charge density	$\mathrm{C \cdot m^{-3}}$
σ	surface tension	$\mathrm{N \cdot m^{-1}}$
σ_E	electric conductivity	$\mathrm{S \cdot m^{-1}}$

Suffixes

0	in the absence of the electric field
b	bubble, buoyancy
c	critical
CHF	critical heat flux
cyl	cylinder
E	in the presence of the electric field
g	vapor
I	interface
l	liquid
ref	reference
sat	saturated
w	heated wall

Owing to this, we dedicate the rest of this section to describe the reasons which led us to get involved in the research that we have been pursuing for around twelve years. Some more details can be found in [24].

1.2. Heat transfer: An exciting challenge for low gravity science and technology

A large debate (not yet completely concluded [48]) took place in the past with regard to the mechanisms of heat transfer and in particular on heat conduction in gases. According to Brush [4] Benjamin Thompson, Count of Rumford "made a more important contribution to the *development of science* by his researches (published in the last decade of the 18th century) on the various modes of heat transfer; he helped to make this subject one of the major scientific concerns of the 19th century". Unfortunately his conclusions were affected by the problem of distinguishing between the contribution of conduction and convection. Around sixty years later Gustav Magnus, after his experiments (still affected by convective flows) on heat exchange in hydrogen, concluded that "*… this gas can transmit heat from particle to particle, in other words conduct it …*".[3] James Clerk Maxwell, who introduced a kinetic theory of heat conduction in 1860, made the real step forward.[4] This notwithstanding, Maxwell treated this subjects quite incidentally, due to his pessimism about the possibility of measuring gas thermal conductivity experimentally: "*… It would be almost impossible to establish the value of the conductivity of a gas by direct experiment, as the heat radiated from the sides of the vessel would be far greater than the heat conducted through air, even if currents could be entirely prevented …*". Such an opinion was caused by some errors Maxwell made, that led him to heavily underestimate the gas conductivity, as pointed out by Clausius (for air Maxwell gave a value of 10^{-7} of that of copper while after correction Clausius estimated it as $1/1400$

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[3] This statement might be misleading: Magnus did not recognize the possibility of molecular motion and attributed this particle interaction to molecular radiation. In addition he could not exclude a further influence of radiation in his experiments.

[4] Maxwell adopts the concept of mean free path proposed by Clausius two years before.

that of lead).[5,6] Due to the lack of experimental data Narr in 1871, Stefan in 1872 and Kundt and Warburg in 1875 tried to set up a satisfactory method to perform measurements. In particular the latter authors decided to perform low-pressure tests to strongly reduce *convective motions* without affecting the conductivity value, according to Maxwell's theory.

At this point we might wonder how much the above scientists would appreciate the chance of getting rid of gravity and how beneficial would this possibility be to make that long process shorter and easier. Asking such a question is what historians call historical anachronism, but it is easy to imagine weightless experiments to measure thermal conductivity of fluids.[7]

In any case, the heat transfer science was not only heat conduction in gases. It was fundamental to formulate the Principles of Thermodynamics, Planck's radiation theory, quantum physics etc. Nowadays it also plays a key role for on-earth and space technology and has a crucial impact on social and economic development of modern countries. To emphasise this we should make a step behind and briefly discuss some major challenges issued by the future society development.

1.3. *Sustainable development*

"Sustainable development" with all its implications, is probably the most important problem that modern society has to cope with. The attention of the world is focussed on the climate change that can be induced by the anthropogenetic activity with particular regard to the production of greenhouse gases (CO_2, CH_4, NO_2, CFCs, ...). They are mostly, 80% in the US [37], associated to energy and heat transfer technology. The first step was the Montreal protocol (1987), later on reinforced in London (1990) and Copenhagen (1992), aimed at eliminating the production of ozone depleting gasses like CFCs. These gases are mainly employed in refrigeration technology for an investment in the related equipment of about 75 billion Euro per year. The transition to HCFC and HFC with a lower or nil Ozone Depletion Potential could partially solve the problem. Anyway the last revision of the Kyoto Protocol imposed the elimination of several of these transition substances (HCFC22 in particular) within 2030 at the latest, while the new regulations of the European Union (CE n. 2037/2000) are much more severe on this respect. Due to this, the use of "natural" fluids like ammonia[8] is strongly encouraged by some authors [27]. After a rather long procedure (Rio de Janeiro, 1992, Kyoto, 1997, and Buenos Aires, 1998) some decision was made, at a world level, with regard to greenhouse gases (among which also HCFCs are included). Most of the industrialised countries are today committed to fulfil the Kyoto protocol directions, thus reducing the production of climate altering gasses. In particular the European Union is committed to reduce CO_2 emissions of 7% within 2010. The 17th Congress of the World Energy Council [42], held in Houston in 1998, has been focused on how technology could face the challenges of energy supplying and use for the next fifty years. It made the conclusion that: "... *The increased efficiency in the use of energy constitutes the most immediate, wide and economic opportunity of reducing resource consumption and environment degradation ... Efficiency should become mandatory in any aspect of the energetic business ...*".

In addition the Fifth Framework Programme[9] (funded for around 15 billion Euro) includes within its 4 thematic programmes "*Energy Environment and Sustainable Development*".

As most of the energy-dedicated equipment involves heat transfer, the enhancement of heat exchange performances becomes mandatory.

1.4. *Space technology development*

Satellite services play an essential role in the human kind daily life. They include communications and broadcastings, global positioning systems (GPS) for aeroplanes, ships and cars, meteorological forecasts, earth observation etc. A trend towards more sophisticated use of satellites is easily foreseeable (like, for example, Real Time Emergency Management via Satellite, REMSAT project, whose first demonstration was held on 13–14 May 2000 with the aim of helping bring a forest fire under control). Furthermore there is a strong interest in deep space exploration and *in situ* resources utilisation on Mars and Moon. All the related equipment undergoes thermal requirements as stringent as severe are the conditions of the surrounding environment where they should operate. For example on the ESA Web site one reads about the Mars Express[10] thermal control: "... *the spacecraft has to provide a benign environment*

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[5] Maxwell recognized his mistake with a very appreciable fair play, unfortunately not so common nowadays: "... It is Professor Clausius, of Zurich, that we owe the most complete dynamical theory of gases, ... there were several errors in my theory of the conduction of heat in gases which Clausius has pointed out in an elaborate memoir on the subject".

[6] For a more detailed discussion of these and several other aspects the reader is referred to the valuable paper by Brush [4] already quoted.

[7] We take profit of this opportunity to stress how badly we need reliable data on thermophysical properties of several cooling fluids at their operating temperatures.

[8] Besides being already used in earth technology, ammonia is also used in the secondary cooling loop of the Russian segment of the International Space Station.

[9] Framework programme of the European Union that defines the strategic priorities for research and technological development for the period 1998–2002. Among its goals we enumerate, for example: increasing of industrial competitiveness, job opportunities creation and quality of life.

[10] Mars Express is a spacecraft designed to take a payload of scientific instruments, a data relay system for communicating with Earth and a lander to Mars. Its launch is foreseen for June 2003.

for the instruments and on-board equipment. That means keeping some parts of the spacecraft warm and other parts cold. Two instruments … have infrared detectors that need to be kept at very low temperatures (*about* 180 °C) … . *But the rest of the instruments and on-board equipment function best at room temperatures* (10–20 °C)". In this case the chance of making experiments in a low gravity environment is fundamental to test heat transfer equipment suited for space applications.

1.5. Heat transfer and fluid physics

There is a fortunate large convergence of goals between earth and space technology requirements discussed above:

- on earth, more effective thermal equipment means less energy consumption and a consequent reduction of environmental pollution;
- for space, it leads to lighter and more compact equipment and can better match the increasing need of dissipating larger heat fluxes. This need is clearly demonstrated by Hughes satellite HS 702 that produces a power of 18 kW and the new one HS 702, to date under design, which will have a power production of 25 kW [22].

Within the field of fluid physics the most effective heat exchange technologies are those involving phase change and in particular boiling and condensation. Their use on earth is very widespread and includes power generation plants, cooling of electronics, building air conditioning, food conservation etc. Their importance in daily life and their impact on economics is quite well established. For instance it has been estimated [27] that up to 25% of the total food world production is interested by refrigeration (home refrigerators included). In order to stress the importance of two phase mixtures, and in particular of bubble behavior in space, we can report a few sentences written in an amusing paper appeared in the New Scientist Journal [36]: "*In space gas bubbles affect everything from rocket fuel and life-support systems to human digestion and excretion … in space bubbles do not rise and so can block tubes that carry liquid. They cannot be bled away … because there is not enough gravity to separate gas from vapor … NASA astronauts on the shuttle recently asked for the amount of gas in fizzy drinks to be reduced … they had trouble burping. But if bubbles were to block pipes carrying liquid in a life support system, the problem could be disastrous. The Russians are designing a gas turbine power system* (much more energy efficient than photovoltaic cells) *that will keep equipment working and astronauts alive on the ISS. Solar rays will boil a liquid and the vapor used to power a turbine to generate electricity … but its success, and ultimately astronauts lives, will depend on understanding bubble behavior*".

2. Boiling in the absence of weight

One never fully appreciates how much his way of thinking is conditioned by his daily life on earth, until he starts dealing with the preparation of low gravity. We are so used to think in terms of gravity that it is often difficult even to conceive theories (and experiments) not accounting for its effect.

Thus the very first contribution of undertaking a research in weightless conditions consists in changing our mental attitude, long before than simply giving the opportunity of a very special experimental approach.

Whoever has been even occasionally involved in boiling or condensation heat transfer has easily learnt how much usual correlations are affected by the acceleration of gravity, g. On the other hand, gravity on earth (for our normal purposes) is practically constant and its force is the dominating force in several cases. Now one can wonder whether the use of g in correlations always catches the real physical nature of phenomena and how much the presence of gravity leads to underestimate some other small scale effect that could play a fundamental role in phase change heat transfer. Herein we will devote our attention just to boiling. The main physical aspects in which gravity acceleration could be involved are summarised in Table 1.

The boiling process involves extremely complicated, non-linear physical processes, operating over length scales ranging from 10 nm to 1 m or more. Strictly speaking it is intrinsically a non-stationary, non-equilibrium process, although it shows a sort of "regularity" only on a statistic basis.

As a consequence, a satisfactory description of the whole phenomena in terms of conservation and constitutive equations (plus obviously boundary and initial conditions) is unaffordable at present. Thus engineering design is still

Table 1
Boiling phenomena affected by gravity

Phenomena including gravity	Heat transfer and fluid dynamics
Bubble detachment diameter and frequency	Nucleate boiling. Film boiling (bubble detaching from the liquid–vapor interface).
Bubble terminal velocity	Transition from single bubble to fully nucleate boiling regime.
Bubble and drop oscillations	Bubbly flows. Sprays.
Bubble coalescence	Vertical coalescence: transition from single bubble to column regimes.
Liquid–vapor interface instability	Mechanism leading to CHF according to the hydrodynamic theory and to macrolayer theory. Transition boiling. Minimum film boiling point, MFB. Stable film boiling. Transition from film-wise to drop-wise condensation and viceversa. Counter current flow limiting condition, CCFL.

based on simplified correlations of experimental data, with limited range of validity. Over the next years increase in computing power will make it feasible to replace, or at least supplement, the correlations by large-scale models. The development of successful models depends on advances in understanding the physics of boiling: experiments in low gravity can play a fundamental role by modifying the balance between gravity-dependent forces and other interacting forces. This is why, from the very pioneering, but somehow solitary, work of a few scientists in the past (like, for example, Prof. Merte in the US and Prof. Straub in Europe), we passed to a very alive and increasing interest of the boiling community in this sort of experimentation, nowadays.

The statistic nature of boiling as a whole has some consequences for low gravity experiments. For example it implies that a sufficiently large number of bubbles must exist on the heating surface, that appropriate time and space averages of the phenomenon must be taken into account and that a steady fluid dynamic and thermal regime, both in the bulk fluid and in the heater, must take place. While all these conditions can be easily attained on earth (in some cases, like flow boiling, on a large length scale), a great care has to be paid to their fulfilment during low gravity experiments. This is because of the intrinsic limitations in size, power, and time (in case of short duration tests[11]) of the different experimental conditions available on low gravity platforms to date. Therefore any experimental apparatus to fly has to be properly designed to match the above constraints. Otherwise we can only speak of vapor bubbles behavior, but not of boiling.

One more mandatory requirement has to be the gravity relevance of the proposed experiment. Roughly speaking this, for instance, means that, whenever other field forces are recognised to be absolutely prevailing on gravity in the phenomenon, there is not enough scientific motivation for its testing in low gravity. This might be the case for strongly forced flows, which are already used in some space application (i.e., in the Russian segment of the International Space Station) just thanks to their insensitivity to the force of gravity.

Last, but unfortunately not least, the competition is so hard and funding from space agencies so desirable that Maxwell's fair play and correctness (see note 5) is some times ignored. Thus an appropriate, strict selection has to be done by the space agencies and the scientific community to avoid wasting of the limited resources available.

3. Lessons we learned from experiments conducted in weightless conditions

Our team in Pisa is conducting a broad spectrum of studies on the effects of force fields on single-phase convection and boiling. In general, the main force fields we can refer to are: gravitational, electric, magnetic, and acoustic fields. In these case we can adopt a twofold viewpoint:

- Gravity, on earth, is likely to mask the effects of the other force fields (scientific motivation for low gravity experiments);
- The force fields can be used to replace the gravity force in space applications (technological motivation for low gravity experiments).

At present we have a large amount of data related to the influence of the former two fields for a cylindrical geometry, and we are at an advanced stage of preparation of an experiment on flat surfaces to be flown next year on the Russian satellite Foton 13. In addition a co-operation has started with the University of Timisoara for a joint work on magnetic force fields. Furthermore we defined a collaboration with Alenia Aerospazio to develop a heat exchanger for space application.

In the following we will deal with the effect of gravity and electric fields on single-phase convection and pool boiling.

3.1. Experimental apparatus and procedure

The basic experimental set-up we have been using for our tests is shown in Fig. 1. Of course it has been adapted from time to time, depending on the particular environment where it has been used (laboratory, aeroplane parabolic flight, sounding rocket, drop shaft). It consisted of an aluminium vessel containing the test section, heated by Joule effect by a direct current up to 12 A. A bellows, connected to the main vessel, was operated by pressurised nitrogen in the secondary side, to compensate for volume variation due to thermal dilatation and vapor production, and to maintain the pressure constant. The main vessel had windows to allow visualisation of the phenomenon by means of video cameras (both normal and high-speed camera). An external heating system, controlled by a PID device, kept the fluid temperature constant within ± 0.1 K.

Experiments were carried out using a horizontal platinum wire of several diameters ranging from 0.2 to 0.6 mm and about 45 mm in length, which served as both a resistance heater and a resistance thermometer. In case of bubbling experiments the wire has been substituted with a capillary tube, with an orifice on its generatrix, to inject nitrogen bubbles into the liquid.

The electric field was obtained by imposing a DC voltage drop (up to 30 kV) between an 8-rod cylindrical "squirrel cage", of 60 mm diameter and 200 mm length, surrounding the heater, and the heater itself. It was shown that the length

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[11] Drop towers and drop shafts: 5 to 10 seconds. Parabolic flights on airplanes: 20 seconds for each parabola. Sounding rockets: from 6 (Texus and Maser) to 15 (Maxus) minutes. Tests in orbital flight are sometimes limited by battery lifetime.

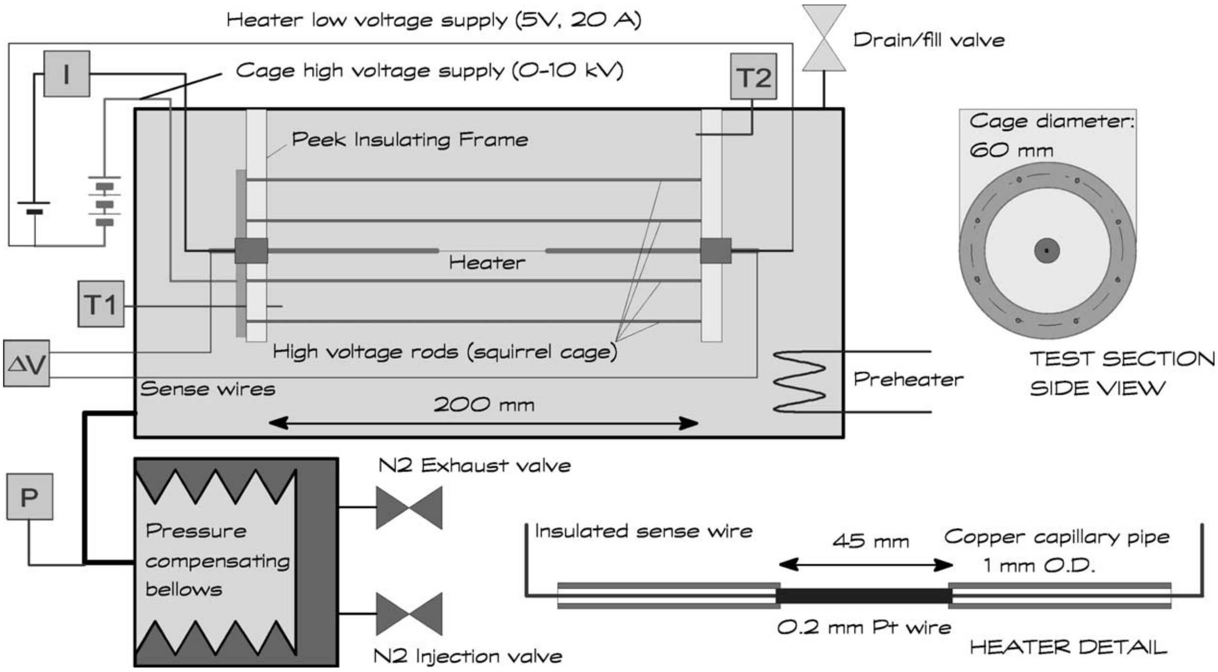


Fig. 1. Sketch of the experimental apparatus.

of the cage is sufficient to avoid side effects along the active part of the heater. The analysis showed also that, up to 10 mm from the wire axis, the field has the same $1/r$ trend as the one generated by a solid cylindrical electrode surrounding the heater, although with a lower intensity. The use of such a small test section is due to the above-mentioned limitation in space, power and time (a little thermal inertia is required) imposed by flight experiments constraints. So far we have been using used three fluids: R113, FC72 (trade mark by 3M) and Vertrel XF (trade mark by Dupont). The first and second ones are non-polar with a relative dielectric constant equal to around 2, while the third is polar with an estimated constant around 9, but its thermophysical and electric properties are hardly available. Different operating pressures as well as different values of liquid subcooling have been tested.

The whole set of pool boiling regimes, except for transition boiling, has been analysed, included single-phase convection prior to boiling inception. Moreover gas bubbling has been performed. All this has been done both on earth and in low gravity. In the following pages we will shortly report the main results obtained. For each of the analysed heat transfer regime we will summarise the most relevant achievements with regard to the scientific (Fundamentals) and the technological (Technology) point of view.

3.2. Single phase convection

Two parabolic flight campaigns were partly dedicated to this subject, respectively using R113 and FC72 as test fluid. A very good agreement exists between the related sets of experimental results. A preliminary study on EHD enhancement of free convection in R113 in microgravity condition was performed in a former parabolic flight campaign [15], for the first time in weightless experiments. The following discussion mainly describes the FC72 data taken in the second campaign [16]. Some tests were run at constant heat flux during the entire parabola. Thus we could collect data both in the low and in the high gravity phases. Other tests were performed increasing the heat flux linearly with time during the low gravity phase. Part of these tests led to the onset of nucleate boiling. No significant tests of single-phase convection were carried out in low gravity in the absence of electric field. Transient conduction to the surrounding fluid followed by transition to boiling may occur in such conditions. In this case, tests in microgravity resulted in a very early onset of nucleate boiling.

Constant heat flux tests. Figs. 2 and 3 show the trend of the heat transfer coefficient, with the wall heat flux kept constant, and vertical acceleration versus time for an applied voltage of 1.5 and 3 kV, respectively. Single-phase convection is still influenced by gravity in the former case, while the phenomenon is independent of the value of gravity within the data accuracy in the latter. The trends of the heat transfer coefficient versus time, at different values of the applied electric field and for a constant heat flux of 20 $\text{kW}\cdot\text{m}^{-2}$, are compared in Fig. 4. The weightless phase starts at 0 s, and the recovery one starts at around 20 s. The heat transfer coefficient increases with the value of the electric field and is independent of gravity for an applied voltage larger than 3 kV.

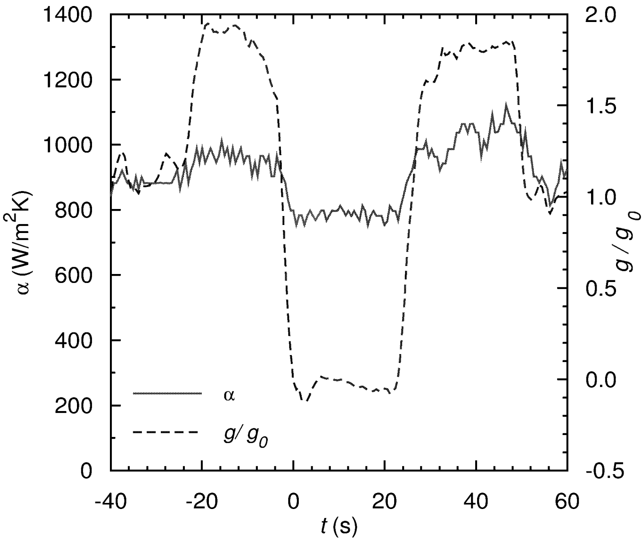


Fig. 2. Heat transfer coefficient in single-phase convection and gravity acceleration for $q'' = 21.3$ kW·m^{-2}, $V = 1.5$ kV, FC72.

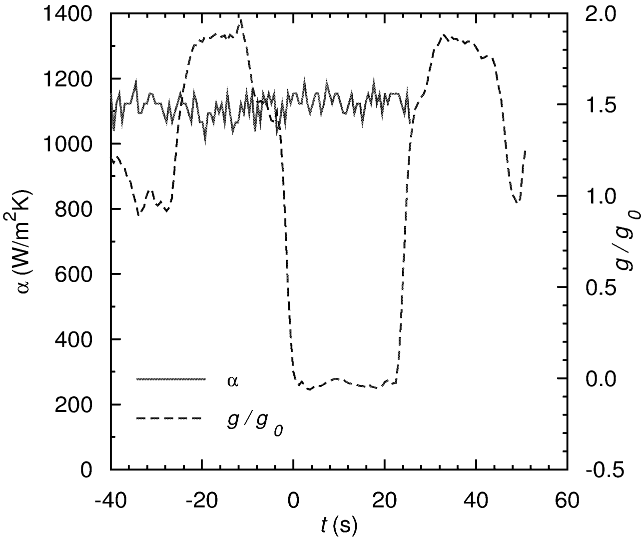


Fig. 3. Heat transfer coefficient in single-phase convection and gravity acceleration for $q'' = 21.3$ kW·m^{-2}, $V = 3$ kV, FC72.

Variable heat flux tests. During these tests the heat flux was increased linearly, starting from 0 at the onset of low gravity, and then it was kept at a constant value at the beginning of the recovery phase (enhanced gravity). Rates from 100 to 175 kW·m^{-2}·s^{-1} were adopted. The heat transfer coefficient increased with the heat flux during the microgravity phase and remained constant through the following recovery and levelled flight phases, i.e., when the heat flux was no longer increased and the gravity acceleration passed from 10^{-2} to 1.8 g_0, and later on to g_0. A comparison made with steady state conditions (constant heat flux conditions included) proved that, thanks to the low thermal inertia of the heater, quasi-steady conditions were reached at each step. Finally, the data obtained in normal gravity during pre-flight and in-flight tests were compared with those obtained in microgravity. It further proved that the heat transfer coefficient in the presence of an electric field, beyond a certain threshold, keeps independent of gravity. Besides, the presence of an electric field greatly improves the heat transfer. Enhancements up to 4-fold in the heat transfer coefficient could be obtained, with respect to zero-field conditions.

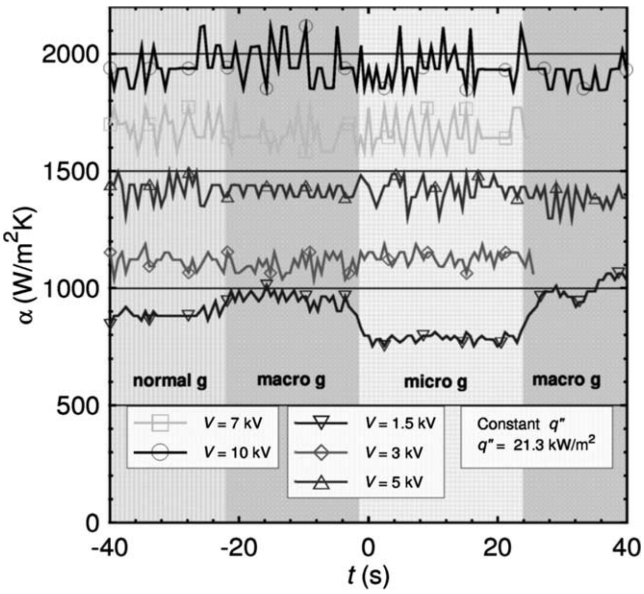


Fig. 4. Trend of the heat transfer coefficient in single-phase convection vs. time (during a parabola) for different high voltage values. The low gravity phase is located within 0 and 20 seconds.

Fundamentals. Once an electric field is applied to a fluid an electrical force arises, that reads

$$\boldsymbol{F}_{\mathrm{e}} = \rho_E \boldsymbol{E} - \frac{1}{2} E^2 \,\mathrm{grad}\, \varepsilon_0 \varepsilon + \frac{1}{2} \,\mathrm{grad}\left[E\rho \left(\frac{\partial \varepsilon_0 \varepsilon}{\partial \rho} \right)_{\mathrm{T}} \right] \tag{1}$$

The first RHS term (Coulomb's force) depends on the sign of the electric field and is present when charge build-up occurs. In many cases it predominates over the other electrical forces. The second term is a body force due to non-homogeneities of the dielectric constant (e.g., related to thermal gradients) and the third term is caused by non-uniformities in the electric field. The last term of the RHS of Eq. (1) is irrotational and can be lumped with pressure in the Navier–Stokes equations. Thus, in an incompressible flow, the onset of convection is only affected by the first two terms in the RHS of Eq. (1). Charge build-up may occur [11] even in poorly conducting fluids, as the one considered here.

On earth, the electric force usually adds to gravity enhancing the heat exchange between the heater and the fluid [11,14,30]. Relations have been proposed of the form [30]

$$Nu = F_1(Pr\,Gr) + F_2(Pr\,El) \tag{2}$$

to evaluate the contribution of the electric force to free convection. If the EHD effect is solely attributed to the dielectrophoretic forces, *El* is defined as

$$El' = \rho \frac{\frac{\partial \varepsilon_0 \varepsilon}{\partial T} L^2 \Delta T E^2}{\mu^2} \tag{3}$$

accounting for the effect on ε of temperature variations in space. If the charge build-up mechanism dominates (DC field), the *El* number is expressed as

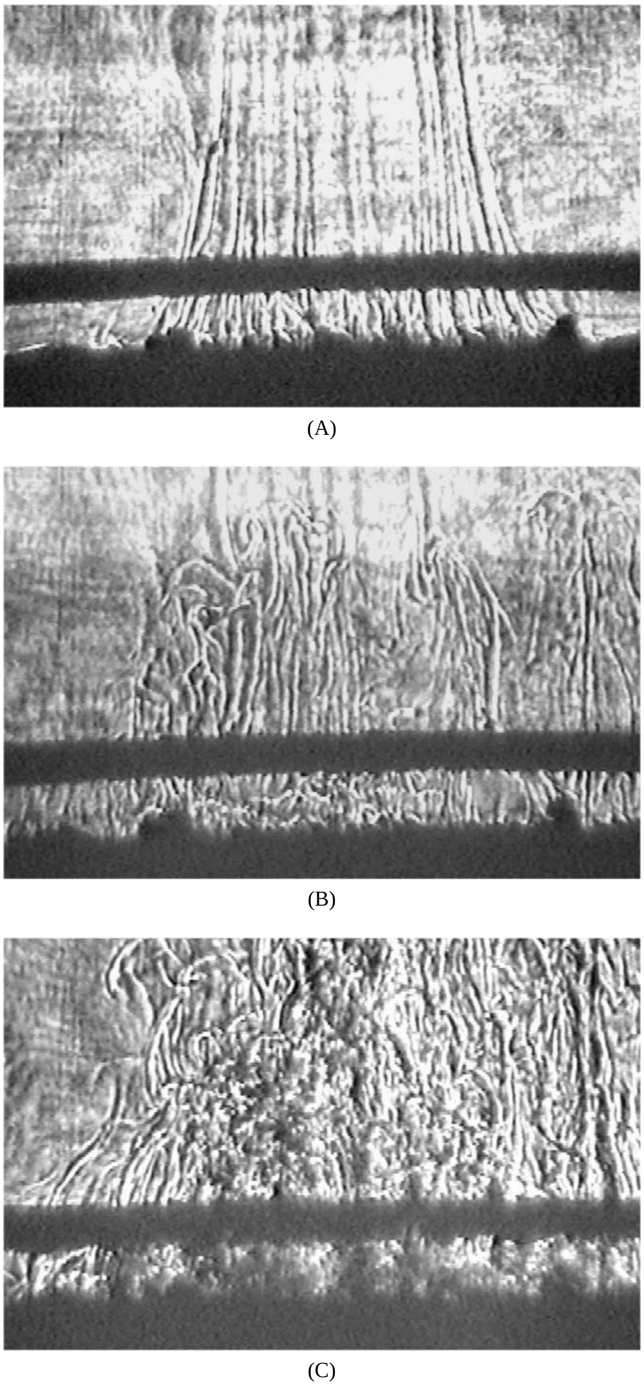
$$El'' = \rho \tau \frac{\frac{\partial \sigma_E}{\partial T} L^2 \Delta T E^2}{\mu^2} \tag{4}$$

In the absence of gravity and interfaces, the electric force is the only body force that promotes the motion of a pure liquid, thus allowing convection heat transfer to occur.

The comparison with correlations of the type reported in Eq. (4) is at present awkward, since no reliable data for the value of $\partial \sigma_E / \partial T$, appearing in El'', are available for the tested fluid. It is anyway evident that the second term in the right-hand side of Eq. (2), F_2, dominates the heat transfer starting from relatively low values of the applied potential. The availability of "zero-g" allows for evaluating this term, thus checking the reliability of such kind of correlations.

Fig. 5 qualitatively shows the effect of the electric field on the flow structure close to the heater. These pictures refer to very preliminary visualisation tests on a plane heater (20 × 40 mm) performed with a thermoplastic camera at the "Optical Laboratory" of Alenia Aerospazio, Torino, Italy. An electric field was applied by means of a wire mesh parallel to the plate, 3 mm apart. At the present stage it is not possible to draw any quantitative conclusion, but the bulk effect is quite clear from the photos. The flow field is completely modified by the electric field: it looks like a change from an ordered plume with a "large" characteristic length scale to a less ordered structure with much smaller length scale. Roughly speaking, it resembles something like a turbulence transition. Of course a situation like this should occur not only in single-phase convection, but also around bubbles, at least in the isolated bubble regime in nucleate boiling. We plan to investigate the whole phenomenon with the necessary detail in the near future, eventually applying a tomographic technique.

Technology. The application of an electric field strongly enhances convection on earth, in agreement with the conclusions shown in the literature. Besides we demonstrated that it can be used to obtain rather large (same as on ground for high fields) heat transfer coefficient in space application, of the acceleration level, with no need of pumping devices. In addition the value of this coefficient can be easily adjusted by simply tuning the high voltage value. Another remarkable result is that, in case of static fields, a quite small power consumption is needed. In fact in our tests the energy consumption in the high voltage circuit was negligible: the related electric current was always below the sensitivity threshold of the ammeter (5 μA), thus allowing to estimate that the power absorption did not exceed 50 mW.


(A)

(B)

(C)

Fig. 5. Effect of an electric field on the flow field over a flat heater, on ground: (A) convective plume in the absence of electric field; (B) flow field immediately after the electric field application (10 kV); (C) flow structure with electric field (10 kV) after regime is reached.

4. Nucleate boiling

The nucleate boiling regime extends from boiling inception up to the so-called critical heat flux (CHF). Preliminary

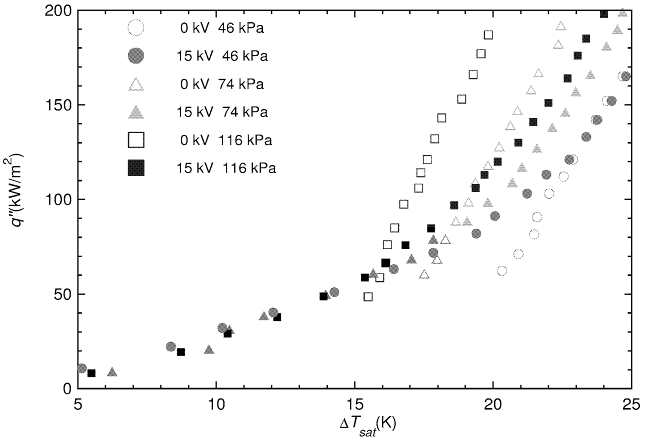


Fig. 6. Heat transfer coefficient at normal gravity for different pressure and applied electric fields, R113.

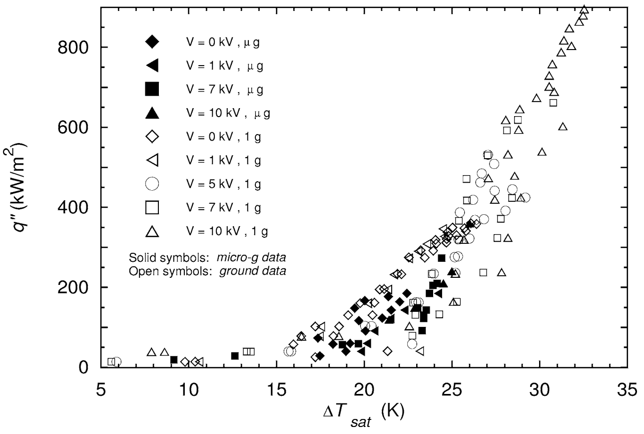
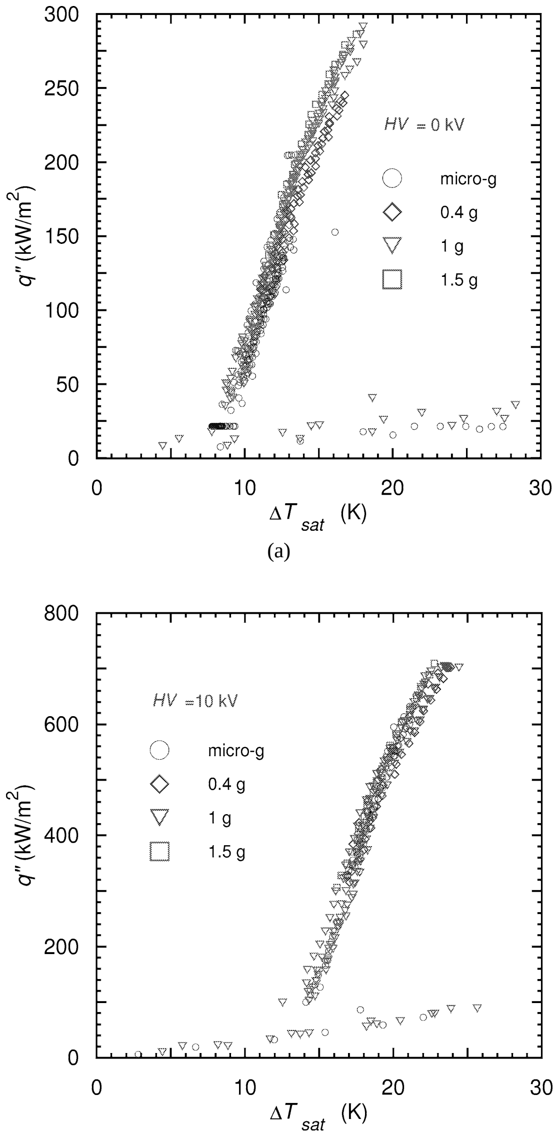


Fig. 7. Boiling curves in normal gravity and in low gravity for different applied voltages, R113, atmospheric pressure.

ground experiments suggest a favourable effect of the electric field in reducing the temperature overshoot at the onset of boiling [6]. This notwithstanding we did not perform yet a systematic study of the effect of gravitational and electric forces on this point. Thus this aspect will not be treated here. On the other hand nucleate boiling has been rather extensively studied. Test on a wire with R113, at normal gravity and different system pressures (atmospheric pressure included) are shown in Fig. 6 [6]. Boiling is enhanced by the electric field at low heat flux and marginally deteriorated at the higher heat fluxes. This may be attributed to the weakening of the field due to the presence of large masses of vapor.

A complete data set showing the combined influence on nucleate boiling of gravity and electric field is shown in Fig. 7 [13] for R113 and in Fig. 8 [17] for FC72. Video records showed that the vapor pattern (bubble size and velocity) is dramatically altered by the variation of the acceleration. Surprisingly, such a change is not reflected in an appreciable change of boiling performances, i.e., in the location of the related curve on the q'' vs. ΔT_{sat} plane, as shown in Fig. 6.

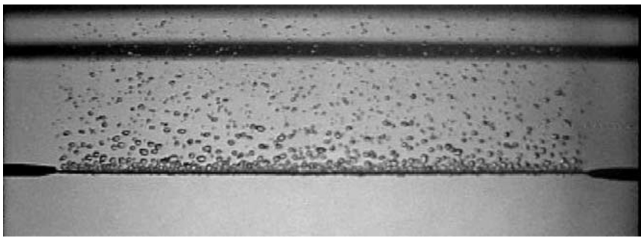


(a)

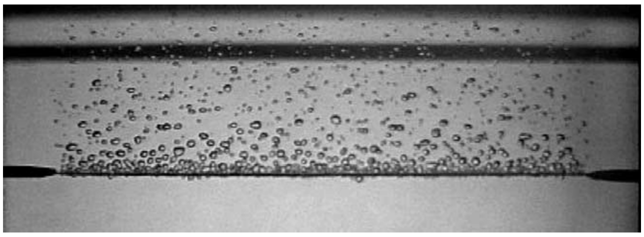
(b)

Fig. 8. Boiling curves at different values of gravity acceleration (a) at 0 kV (b) at 10 kV applied voltage, FC72, $p = 115$ kPa

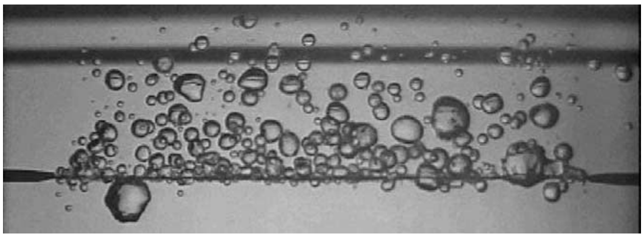
For the tested geometry we can in general state that both the electric and the gravity field do not have any major effect on the nucleate boiling heat transfer coefficient, while they heavily modify the vapor pattern at the wall. In fact the presence of an electric field reduces bubble size and increases their detachment frequency. Gravity has a similar effect so that in low gravity bubbles grow to very large diameters. Through appropriate combinations of electric and gravity forces it is possible to control bubble size and frequency (see also paragraph on Bubbling). All this can be clearly observed in Fig. 9. In this figure bubble size can be, at least qualitatively, appreciated with reference to length of the boiling wire (the amperometric contacts, about 45 mm apart, are clearly visible on the left and right sides of the photos).



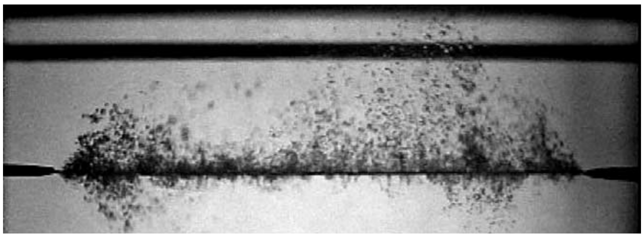
(A) $g = 2g_0$, 0 kV



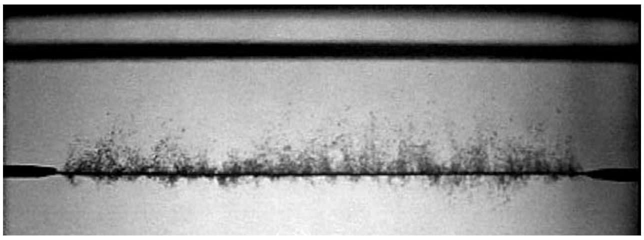
(B) $g = g_0$, 0 kV



(C) $g = 0.02g_0$, 0 kV



(D) $g = 0.02g_0$, 10 kV



(E) $g = g_0$, 10 kV

Fig. 9. Vapor patterns with different gravitational and electric fields (indicated below each picture) for FC72 and wall heat flux of 100 kW·m^{-2}. The two amperometric contacts are 45 mm apart.

Fundamentals. The electric field affects many boiling features such as bubble shape, detachment diameter, frequency and number of nucleation sites. Also the fluid flow around the bubble, and thus the thermal field, can be modified according to what has been previously said about natural convection. Moreover changes in physical properties, like surface tension and wettability, can be expected, even if they are usually discounted. Generally speaking, the volume of the detaching bubbles decreases at increasing value of the group

$$G_E = \frac{\varepsilon_0 E^2 L}{\sigma} \tag{5}$$

The detachment volume shows also a separate dependence on ε_l for non-polar fluids, with an increasing prolate bubble eccentricity versus the liquid permittivity. Furthermore, in case of non-uniform electric fields, a net force acts on the bubbles that, for a tiny elliptical bubble, can be given as [32]

$$F_{\mathrm{DEP}} = \frac{2}{3}\pi R_{\mathrm{B}}^3 \frac{\varepsilon_g - \varepsilon_l}{n_1\varepsilon_g + (1-n_1)\varepsilon_l}\varepsilon_0\varepsilon_l \nabla E^2 \tag{6}$$

The constant n_1, which can be calculated with an elliptic integral related to the eccentricity of the bubble, is $n_1 = 1/3$ for a perfect sphere, while $n_1 > 1/3$ for an oblate ellipsoid. The validity Eq. (6) suffers 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 [40,43]. These drawbacks were recently removed by Karayiannis and Xu [31] which developed a more general relationship in the form of a surface integral. 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 force like the one in Eq. (6) tends to move the bubble towards regions with weaker electric field intensity. Therefore its effect depends on how it is directed with respect to gravity. For example, for upward oriented surface and field strength decreasing from the surface outwards, it accelerates the bubble growth and detachment, while the opposite occurs for downward oriented surface. Besides, this force has generally a little magnitude, however in the absence of buoyancy it might be an important tool for phase separation. To account for the relative magnitude of this force referred to the buoyancy force, a new dimensionless group can be introduced:

$$G_{b,e} = \frac{|F_E|}{|F_b|} = \frac{3(\varepsilon_l - \varepsilon_g)\varepsilon_0\varepsilon_l|\nabla E^2|}{2(\varepsilon_g + 2\varepsilon_l)(\rho_l - \rho_g)g} \tag{7}$$

For a cylindrical heater, like the one studied herein, this force tends to increase the circumferential symmetry of the boiling heat transfer and bubbles can detach also from the lower side of the heating surface.

The overall effect of the electric field on nucleate boiling is still not completely established. The general opinion is either that there is no practical influence or that a little enhancement of the heat exchange takes place [30].

However, Baboi et al. [1] have reported an increase in boiling performance at low heat fluxes. For higher fluxes, they have asserted quite weakly that “there is no effect on the relative heat exchange coefficient, but on further increase of the heat flux, the latter decreases somewhat".

For geometries similar to the present one, Cooper [9] proposed a correlation providing an electric field enhancement of the heat transfer coefficient decreasing with increasing heat flux. This correlation was obtained by fitting old data sets [1,3,7].

The reduction of enhancing EHD effect with increasing heat flux is a well assessed phenomenon [31]. As some examples, Uemura et al. [49], have investigated saturated pool boiling of R113 on a flat, horizontal, upward facing surface. They report a little enhancement at very low heat fluxes. Beyond this range of fluxes all the data (with and without electric field) collapse on a single curve. Recently, Zaghdoudi and Lallemand [51] experimenting pool boiling on a flat heater with R113, n-pentane and R123, reported enhancement factors up to 5 (for R123), decreasing with increasing heat flux.

In the absence of applied electric field, Straub et al. [45] noted a very weak influence of gravity acceleration on pool boiling on wires. The importance of having a statistically meaningful number of bubbles on the heater in order to be able of dealing with boiling (as a process) is worth stressing once more. This happened in our case, as clear from the pictures of Fig. 7, taken during parabolic flight experiences. The contribution of the electric field to this aspect is absolutely favourable as it increases the bubble number decreasing their size: thus "the heater behaves as a very large (in some cases practically infinite) surface if compared to bubbles diameter". In addition bubbles can "escape" in any direction from a small (not necessarily a wire) cylinder. All this is generally not true for a flat heater, where horizontal coalescence is likely to occur. This, joined with some local field gradient (e.g., at the surface edge), can make bubbles slide along the surface with a beneficial effect on the heat transfer. Anyway the behavior of flat surfaces needs a much deeper insight. Among other things it is worth emphasising that they are much more (respect to cylinders) sensitive to g-jitter.[12] Oka et al. [38] reported a significant dependence on gravity of boiling heat transfer on flat plates at high heat flux; the surface overheating was also correlated the variation of direction of the residual gravity in the micro-g phase: bubbles can be either pushed toward the surface or moved away from it. Nucleate boiling seems to be generally enhanced on flat plates; non-etheless, opposite results have been reported as well. The general tendency is to have an increase at lower values of heat flux and decrease at higher ones (see, e.g., [33,44]). The different nature of the heating surface and its contamination may play a role in this frame. Regardless of enhancement or degradation, the heat transfer performance is less dependent on gravity than flow patterns and bubble size, and the dependence on gravity is far less than predicted by the boiling correlations [19].

In conclusion we can state, at present, that according to most of the studies about fully nucleate boiling (thus not the single bubbles region) heat transfer does not exhibit a major sensitivity to electrical and gravitational forces. As these forces strongly affect the vapor fluid dynamics, it is possible to infer that fluid dynamics is not the dominating mechanism in fully developed nucleate boiling.

Technology. In any case the above findings mean that fully developed nucleate boiling is a very effective heat transfer means also for space applications. This is a very good news for space thermal device improvement, but can we keep boiling stable without buoyancy, i.e., without a force lifting bubbles away from the heating surface? In general the answer is as follows. Steady-state long-term nucleate pool boiling can be attained in micro-g. The possibility is higher with larger subcoolings and low heat fluxes. A debate is still open on the possibility of maintaining it indefinitely, and on the role played by fluid properties and size and shape of the solid surface. At the present state of knowledge it would be advisable to keep the liquid at least slightly subcooled. Moreover the electric field can help removing vapor from the heater, thus directing vapor towards appropriate regions (vapor management).

5. Critical heat flux

As well known, the critical heat flux, CHF, is the maximum value of heat flux that a boiling surface can "safely" reach, once wall heat flux is the controlled variable. Beyond this point the wall temperature can suddenly and dramatically rise, eventually causing the physical burnout of the heater. Therefore it is an important limit to the boiling performances of any apparatus. To understand the mechanisms leading to CHF and to find appropriate means for improving its value constitute fundamental issues for enhancing the effectiveness of any heat exchange equipment.

Fundamentals. The interpretation of this phenomenon is still controversial. Several approaches have been attempted among which we can recall: the *bubble coalescence model* (proposed by Rohsenow and Griffith in [41]), the *hydrodynamic theory* (proposed by Zuber in 1959 [52] and modified by Lienhard and Dhir in 1973 [34] for finite size heaters), the *macrolayer theory* (defined by Haramura and Katto in [25]) which anyhow implies the hydrodynamic instability of vapor stems and the *hot spot theory* (proposed by Unal et al. [50]). Unfortunately, only the model of the hydrodynamic theory has been extended to the case of boiling with an electric field (by Johnson in [28] and refined by Berghmans [2]). For a detailed discussion on the whole matter the reader can refer to Di Marco and Grassi [11,14,18] Carrica et al. [6].

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[12] g-jitter represents the time variation of the acceleration with respect to its mean value. In parabolic flights it may be of the order of the mean value. According to the authors' experience it is much lower in sounding rocket (no effect of air turbulence to be compensated, of course) and in drop-shafts.

At present, it is unclear if just one mechanism determines the occurrence of critical heat flux (CHF) in any geometrical and thermodynamic condition. Regardless of the previously quoted models, critical heat flux data on flat plates have been often correlated in the so-called Zuber–Kutatelatze form

$$q''_{\mathrm{CHF}} = K q''_{\mathrm{ref}} \tag{8}$$

where

$$q''_{\mathrm{ref}} = \rho_g^{0.5} h_{lg} \left[\sigma g (\rho_l - \rho_g)\right]^{0.25} \tag{9}$$

In Eq. (8) 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, and for flat plates was assumed 0.131 by Zuber and 0.149 by Lienhard.

Pool boiling on wires and small bodies has been extensively studied in a number of papers in the 60–70 s. A non-trivial dependence of critical heat flux on the diameter of the wire has been reported. The most suitable group to scale the effect of the diameter is the so-called dimensionless length, i.e., the square root of the Bond number

$$R' = \sqrt{Bo} = R\sqrt{\frac{g(\rho_f - \rho_g)}{\sigma}} = \frac{R}{l_{\mathrm{L}}} \tag{10}$$

and it is assumed that the factor K is a decreasing function of R': $K = K(R')$. This means that gravity and heater size have a sort of interchangeable role, as a change in their value has the same qualitative effect on R'. Thus “large” heaters become “small” in low gravity and vice versa. For large heaters (R' above a critical value R'_{c}) the proposed mechanism is the vapor–liquid interface instability, that proved to be the leading mechanism also for film boiling. For small heaters ($R' < R'_{\mathrm{c}}$) hydrodynamics no longer dominates the phenomenon and the vapor front propagation mechanism comes into play. In this case the effects of surface tension and liquid and wall thermophysical properties play a major role. For example $R'_{\mathrm{c}} = 0.07$–0.1 was proposed in the past.

The available CHF data are reported in the K–R' plane in Fig. 10 together with the most commonly accepted correlations. It is worth mentioning that a reduction in the Kutatelatze number, K, does not directly imply a corresponding reduction in the value of critical heat flux: since q_{ref} (a function of fluid properties) increases with pressure (for low values of reduced pressure) and with gravity acceleration. The overall effect is an increase of CHF with pressure and a reduction with decreasing gravity.

The space within the two dotted curves represents a further large amount of data mainly obtained at normal gravity (changing either fluid properties or heater diameters) or in a centrifuge. The symbols with no references are experimental results due to the present authors with different gravity levels. It can be seen that the correlation of Sun and Lienhard [46], is still acceptable up to $R' = 0.08$ although it slightly underestimates the data for fluorocarbons at high R'. A different value of the constant or of the exponent might yield better results. The modification proposed by Hong et al. [26] provides better results for intermediate values of R', but worst performance in the range $0.06 < R' < 0.3$.

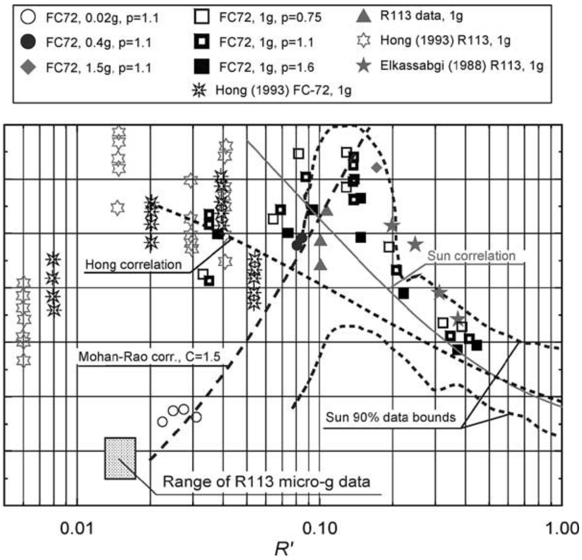


Fig. 10. Values of K in Eq. (8) and comparison with available correlations. All the data not countersigned with a reference belong to the present authors. The symbol p represents the system pressure in bar. The data of Elkassabgi et al. are reported in [23] and those of Hong et al. in [26].

For $R' > 0.08$, the data obtained in reduced or increased gravity lies in the range of most of the other experimental data. Thus it seems that the Bond number is a suitable parameter to scale the effect of gravity for $R' > 0.08$. However, it should be noted that the data obtained with higher system pressure systematically lie below the others: a secondary effect of this variable should not be excluded.

The situation appears to be drastically different for $R' < 0.04$: the data obtained in low gravity are very well separated from the ones of thinner wires, corresponding to the same value of R', obtained in normal gravity. Thus, it must be concluded that the Bond number (or the equivalent parameter R') is not able to scale adequately both the effects, and separate groups containing the gravity acceleration and the wire diameter seem to be needed. Alternatively, the mechanism itself of CHF could be different in the two situations. The correlation by Mohan-Rao and Andrews [35] is able to fit the data obtained for fluorocarbons in microgravity, and could be considered acceptable up to $R' = 0.2$, but it is not able to predict the data obtained in normal gravity on thin wires for the same fluids. These conclusions seem to hold for the whole range of tested accelerations ($g/g_0 = 1.5$, 1, 0.4 and 0.02). The data obtained during a sounding rocket experiment ($g/g_0 = 10^{-4}$) are still under evaluation.

Once an electric field is applied it influences the physics of the vapor–liquid interface instability. Consequently the relation for the heat flux becomes [28]

$$\frac{q''_{\mathrm{CHF},E}}{q''_{\mathrm{CHF},0}} = \sqrt{\frac{\lambda_{u0}}{\lambda_{uE}}} \tag{11}$$

Where $\lambda_{u0}, \lambda_{uE}$, represent the instability wavelength without field and in the presence of the field, respectively. According to Johnson [28]

$$\frac{\lambda_{u0}}{\lambda_{uE}} = \frac{El^* + \sqrt{El^{*2} + 3}}{\sqrt{3}} \tag{12}$$

with the electric influence number given by

$$El^* = \frac{\varepsilon_0 \varepsilon_{\mathrm{eq}} E_{\mathrm{I}}^2}{\sqrt{(\rho_l - \rho_g)\sigma g}} \tag{13}$$

where E_{I} is the electric field at the gas–liquid interface and $\varepsilon_{\mathrm{eq}}$ an equivalent relative electric permittivity. The proper value of $\varepsilon_{\mathrm{eq}}$ to be used mostly depends on the actual physical situation, as discussed in [12]. Eq. (12) is strictly valid for a plane interface only, although it can be extended to cylindrical geometry.

The trend of critical heat flux data versus the applied high voltage, for FC72 at atmospheric pressure, is shown in Fig. 11. Similar trends have been obtained for R113 and, on ground, for Vertrel XF. These results clearly demonstrate that

- CHF is very sensitive to gravity and undergoes a strong reduction with a decrease of the above acceleration;
- the electric field is very effective in improving CHF both on ground and in low gravity;
- for large enough electric fields the values of the critical heat flux on earth and in weightless conditions become indistinguishable.

Fig. 12 reports the same data as Fig. 11, but non-dimensionalised with respect to the critical heat flux (corresponding to g_0 and to low g) at zero high voltage. This allows for concluding that the relative enhancement of CHF is larger at low g than on earth.

The above trends are very well fitted by the following relation, deriving from the hydrodynamic theory and obtained by combination of Eqs. (11), (12)

$$\frac{q_{\mathrm{CHF},E}}{q_{\mathrm{CHF},0}} = \sqrt{\frac{El^* + \sqrt{El^{*2} + 3}}{\sqrt{3}}} \tag{14}$$

with

$$El^* = \frac{\varepsilon_0 \varepsilon_l E^2}{\sqrt{(\rho_l - \rho_g)\sigma g}} \tag{15}$$

In El^*, the electric field E is calculated at a distance from the wire of the order of the bubble size. This is done as an attempt to obtain the value of the field actually present at the "liquid–vapor" interface. So far these results with electric field seem to support the validity of the hydrodynamic theory to some extent and for the tested geometry. It is worth recalling that, in this case, bubbles become much smaller with the increasing of the field. Thus the ratio between the heater size and the bubbles one becomes larger. Probably, in this case, we should refer to a modified R', that becomes larger for the effect of the electric field.

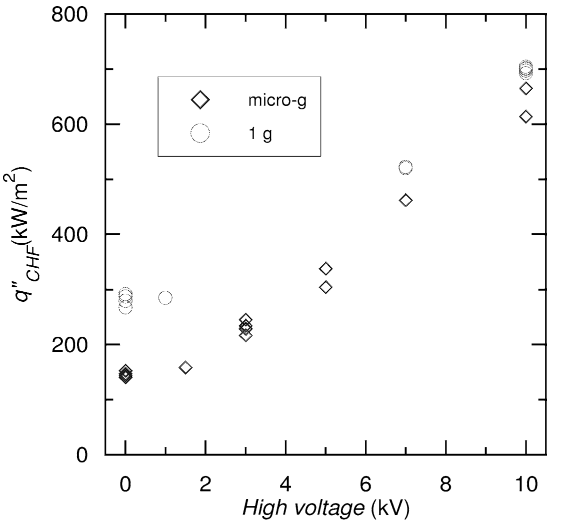


Fig. 11. Critical heat flux values vs. high voltage for FC72 on ground and in low gravity.

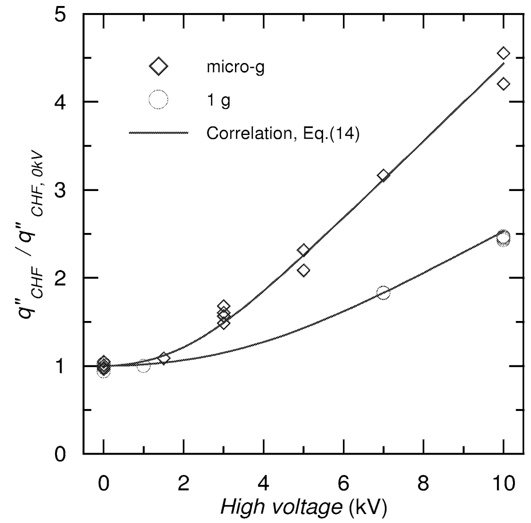


Fig. 12. Dimensionless (respect to the corresponding flux at 0 kV) critical heat flux at low g and on ground vs. the applied high voltage, for FC72.

Technology. The importance of the achieved results for technology are quite clear. As already said the location of CHF on the boiling curve defines the extension of the nucleate boiling regime. We established that this region narrows when gravity decreases. Conversely the same region widens with the application of an electric field both on ground and in weightless conditions. Therefore the CHF value can be controlled by simply controlling the applied voltage. With regard to space it offers an active technique for improving the performances of some heat transfer equipment with a very limited energy consumption.

6. Film boiling

Film boiling was studied both for gaining a better understanding of the mechanism leading to CHF and in view of its technological importance in processes like metal treatment and power production (e.g., the suppression of film boiling in large boilers).

Carrica et al. [6] performed experiments of film boiling of R113 on platinum wires, 0.2 and 0.3 mm in diameter. For the first time, it was clearly identified that the electro-hydro-dynamic (EHD) enhanced film boiling regime cannot be sustained indefinitely in this configuration. A second transition takes place for large enough wall superheat, bringing the system back to a film boiling regime which is practically unaffected by the presence of the field. A weak evidence of this can be also found in the data by Jones and Schaeffer [29]. Later on, a confirmation that the application of an electric field has a poor influence on film boiling performance at high wall superheats was found by Di Marco et al. [14], who adopted R113 and Vertrel as testing fluids. For both the tested wire diameters, data were obtained in saturated and subcooled (10 K) conditions, at pressures of 0.075, 0.115, 0.16 MPa and with an applied high voltage ranging from 0 to 10 kV.

The most striking feature is the clear evidence of a boiling transition, separating two distinct film boiling regimes. The first one, at lower wire superheat, was strongly influenced by the presence of the electric field, with an increase of the heat transfer coefficient up to 400%. The second film regime (taking place at superheats higher than about 550 K) was almost unaffected by electrical forces. All this is shown in Fig. 13 for saturated film boiling on a 0.2 mm wire at an operating pressure of 115 kPa. Similar trends were encountered for different pressures, fluids and wire diameters [5,8,14].

Visual observation, with the aid of the CCD camera, showed the presence of the following three distinct fluid-dynamic regimes.

- For an applied high voltage up to 2 kV, the liquid-vapor interface had an oscillatory motion and a dominating wavelength was clearly identifiable (Fig. 14).
- With increasing electric field, the wavelength and bubble size decreased up to a condition where no dominating wavelength was identifiable (Fig. 15). The oscillatory phenomenon was likely two-dimensional in these conditions, with a circumferential oscillation superimposing to the axial one. The vapor pattern was more similar to that occurring in nucleate boiling. Bubbles started to detach also from the lower part of the wire and were of irregular size; lateral coalescence was observed. The authors have also proposed a model for this transition [8].
- For high values of the wire superheat, the second film-boiling regime took place (Fig. 16). The interface oscillated with high values of the wavelength, and

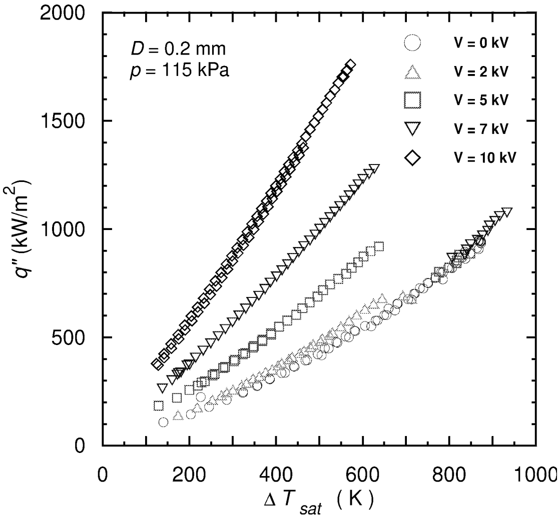


Fig. 13. Film boiling curves at different electric field levels.

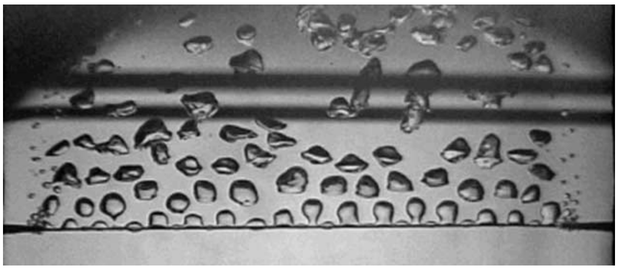


Fig. 14. First film boiling regime, monodimensional oscillatory pattern; $p = 115$ kPa; $d = 0.2$ mm; $V = 0$ kV; $q'' = 400$ kW·m^{-2}; $\Delta T_{\mathrm{sat}} = 449$ K.

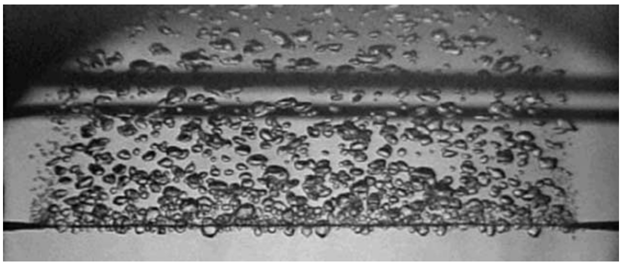


Fig. 15. EHD enhanced film boiling regime, multidimensional oscillatory pattern; $p = 115$ kPa; $d = 0.2$ mm; $V = 7$ kV; $q'' = 400$ kW·m^{-2}; $\Delta T_{\mathrm{sat}} = 201$ K.

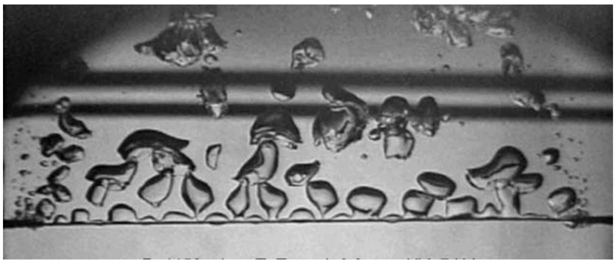


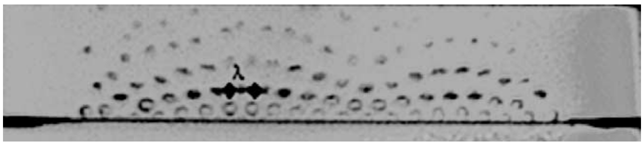
Fig. 16. Second film boiling regime, independent of applied voltage; monodimensional oscillatory pattern; $p = 115$ kPa; $d = 0.2$ mm; $V = 7$ kV; $q'' = 850$ kW·m^{-2}; $\Delta T_{\mathrm{sat}} = 781$ K.

bubbles were larger than in the former two regimes. Both the heat transfer coefficient and the vapor pattern were substantially independent of the applied electric field in this regime.

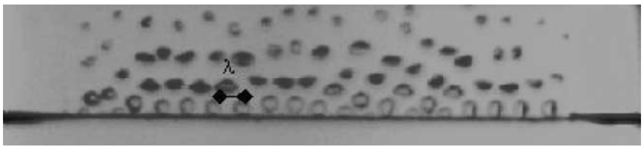
Very recently, film boiling has been investigated during a parabolic flight campaign [21,47] organised by ESA. The preliminary data indicate that the above mentioned two different regimes persisted even in microgravity. While film boiling at low values of applied electric field was sensitive to the acceleration of gravity and it showed degradation at low values of g, it became insensitive to the value of gravity for a high enough applied voltage (above 3 kV). This obviously means that the effect of the electric field becomes absolutely prevailing beyond a certain threshold. The only effect of gravity on the vapor pattern in film boiling is shown in Fig. 17. Both bubble size and horizontal spacing (smallest wavelength) increase with decreasing of the acceleration value. It is worth remarking that also at low gravity bubbles regularly detach from the liquid-vapor interface, even if almost no buoyancy forces are present. This might suggest that even very small dynamic actions, like the forces caused by interface oscillations or the effect of g-jitter are sufficient to maintain bubble motion. In fact, during our low gravity campaigns, we found that bubbles are extremely sensitive to the very small (less than one hundredth of g_0) residual accelerations, usually experienced during parabolic flights. In Fig. 17(D) horizontal coalescence phenomena can be observed: this phenomenon becomes more important at larger heat fluxes. The whole matter, outlined above, is discussed in more detail in [19].

Fundamentals. Besides giving a general better insight into the phenomena involved by film boiling, this research has, in particular, evidenced what follows.

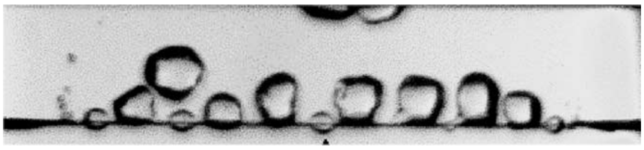
- Film boiling keeps its characteristic features (same as on ground with regard to vapor pattern, electric field influence and so on) also at very low gravity levels, at least for the experimental conditions tested. This is the first time that such a point has been demonstrated during a low gravity campaign [19]. A further parabolic flight campaign, with different levels of acceleration, is planned for the very next future in order to obtain more data that could eventually reinforce this conclusion.
- What exposed in the above item gives some more consistency to the hypothesis that (still in the tested conditions) critical heat flux occurrence could be explained according to the Hydrodynamic Theory. Of course we are quite aware of the objective limits of our experimentation. This is one more reason why we are planning experiments, for instance, on flat surfaces.
- A still partly open question is the second film boiling transition. We proposed a model for the transition from the one-dimensional to the two-dimensional regime (first film boiling transition) occurring with increasing the electric field value [8]. On the other hand no fully satisfactory models are presently available for the collapse of the film boiling curves at different electric fields on a single one at high wall superheat.



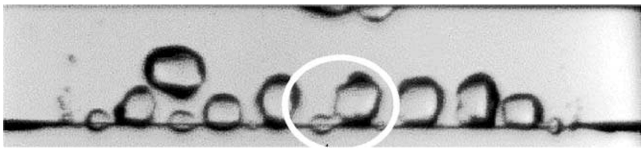
(A) $g/g_0 = 1.8$, wall heat flux $g'' = 190$ kW·m^{-2}



(B) $g/g_0 = 1$, $g'' = 190$ kW·m^{-2}



(C) $g/g_0 = 10^{-2}$, $g'' = 190$ kW·m^{-2}



(D) $g/g_0 = 10^{-2}$, $g'' = 190$ kW·m^{-2}

Fig. 17. Influence of gravity on vapor pattern in film boiling in slightly subcooled (3 K) FC72 at atmospheric pressure and zero electric field. Wire diameter 0.2 mm, length 47 mm. Gravity level and heat flux are indicated below each picture. Lateral coalescence phenomena are visible from (C) and (D) (e.g., white circle).

Technology. Film boiling generally constitutes a very undesirable boiling regime for any heat transfer equipment, ranging from air conditioning to power stations boilers, due to the high temperature reached by the heating surface. EHD enhanced film boiling (first film boiling regime) significantly reduces the surface overheating, and safety margins (accounting also the already mentioned increase of critical heat flux) are consequently extended. This is one more reason why the application of an electric field should be an attractive technique both on ground and in space.

In addition, film boiling is anyway encountered in metal treatments processes. In this case, the availability of an external electric field to tune the heat transfer coefficient (for example, in tempering metals) is doubtless interesting.

7. Bubbling

Part of the research performed in Pisa has been dedicated to the behavior of gas bubbles. The aim is to gain a better understanding on the influence of force fields on boiling and on gas (vapor) management, by separating the different effects that can play a role on the phenomenon.

To do this we used the same apparatus already described with the heating wire substituted by a small cylinder (1 mm diameter), with an orifice drilled on its upward generatrix. Nitrogen is injected into the fluid, FC72, through this hole [10]. Thus we are pursuing the following research programme.

(1) By using nitrogen bubbles issuing from a single hole we eliminate phase change and thermal gradients. Therefore we have neither Marangoni nor EHD convection around bubbles as well as no interaction with other bubbles growing on the surface at the same time. Under these conditions we can study the effect of gravitational and electric fields on single-bubble dynamics.
(2) As a second step a thermal field will be added to investigate its effect on bubble dynamics. The third will consist to analyse the influence of the interaction with other bubbles growing on the surface with and without thermal fields.
(3) At the end vapor bubbles, instead of gas bubbles, will be studied.

This is a very ambitious programme aimed at understanding very fundamental aspects and requiring a rather long time to be completed, both on earth and in low gravity. At present we have a rather large amount of experimental data regarding the first item, both on ground and in reduced gravity. The latter results have been obtained during two campaigns (January 2000 and January 2001) performed in the dropshaft of JAMIC, Hokkaido, Japan. The data are still under elaboration, nevertheless some macroscopic effects can be already reported herein, while more details on this subject can be found in [20].

Fig. 18 shows some photos, taken in FC72 at atmospheric pressure and at a liquid bulk temperature of 20 °C. The diameter of the cylinder (1 mm) from which bubbles stem out can be used as a qualitative reference length for the photos. The left side refers to micro-*g* conditions and the right one to normal gravity experiments. The first line (18A) refers to nitrogen bubbles issuing into FC72 with no electric field. Fig. 18(B) and 18(C) show the same situation, once an electric field (5 kV and 15 kV, respectively) has been applied. It is quite clear how in normal gravity (right side) the electric field modifies both bubble detachment diameter and frequency. In fact the bubble size is reduced, while frequency is increased, as demonstrated by the number of bubbles present in the frame. The left side of Fig. 18 shows the bubbles behavior during a low gravity experiment ($10^{-4}g_0$) conducted in dropshaft of JAMIC. Fig. 18(A) refer to the growth of a (big) bubble on the wall in low gravity in the absence of electric field. The quite spherical shape of the bubble and the absence of a “neck” at its base are worth stressing. At low gas flow rates no bubble detachment from the wall was observed during the low-*g* phase (8–10 seconds). A couple of tests were also performed at rather large nitrogen flow rate to verify whether the inertia effects, due to the fast injection of gas into the liquid, could cause the detachment of bubbles from the wall in reduced gravity. As expected [39], with increasing gas inlet velocity we observed bubbles detaching from the wall then keeping standing in the liquid and eventually coalescing with the following bubbles. We could not collect systematic data on this aspect due to the limited amount of drops available in the dropshaft and to the fact that our research was mainly finalised to investigate the influence of the electric force. Anyway, the inlet gas velocity yielding bubble detachment seems to be significantly lower

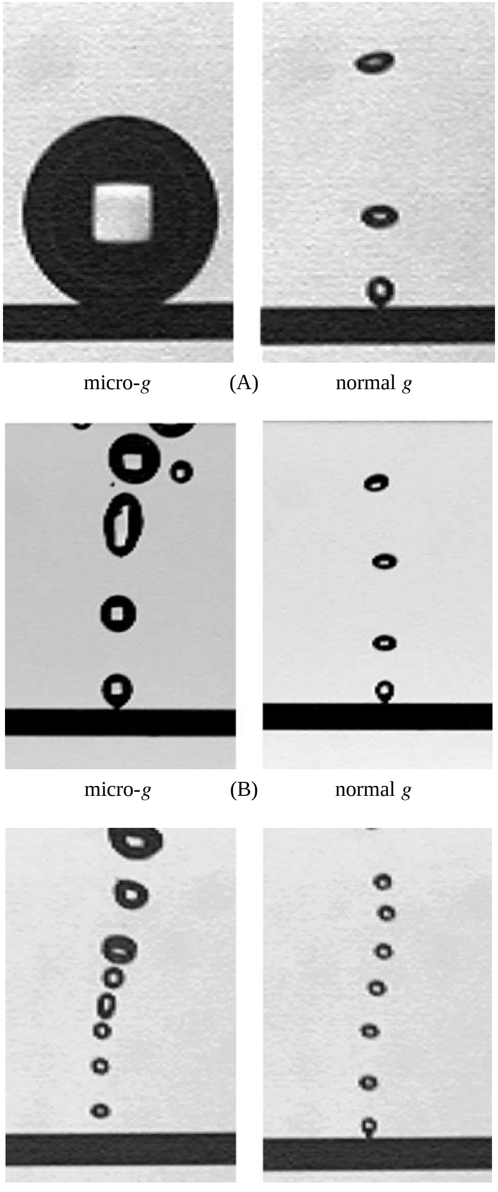


Fig. 18. Bubbling flow patterns in microgravity (left) and normal gravity (right) for: (A) no electric field, (B) 5 kV applied electric field, (C) 15 kV applied electric field The tube diameter (black line at the bottom) is 1 mm. Nitrogen bubbles in FC72, atmospheric pressure and ambient temperature (20 °C).

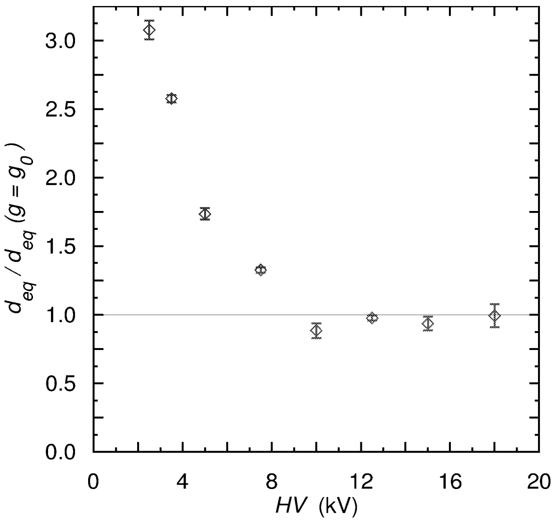


Fig. 19. Effect of applied electric field in micro gravity ($10^{-4}g_0$) on bubble detachment diameter (normalized to the value for the same field at normal gravity, g_0). Nitrogen bubbles in FC72, atmospheric pressure and ambient temperature (20 °C).

than the one predicted by Pamperin and Rath [39] on air-water systems [20].

The role played by the electric field in microgravity is shown in Fig. 18(B) and 18(C) (left side). In the presence of electric field, bubbles keep on detaching from the wall. In Fig. 18(C) it can be seen that the detachment diameter is the same as in normal gravity: this happens for the higher values of the applied electric field, as shown in Fig. 19, and demonstrates that even in this case the electrical force becomes the dominant one. From the Fig. 18 (left side) it is also clear how in microgravity bubbles start coalescing at some distance from the wall. This happens because of the cylindrical geometry of the electric field distribution. In fact, due to this, the field rapidly weakens with increasing distance from the cylinder, so that bubbles are progressively subjected to lower lifting forces. Among other things, this clearly demonstrates how it could be possible to use electric fields for gas and vapor management in space.

8. Conclusions

In this paper we analysed the main results we achieved so far about the effect of gravitational and electrical forces on single-phase natural convection and pool boiling heat transfer. At present, mainly due to space and power limitations, only wire geometry was investigated. The outcomes can be very shortly summarised as follows.

Single-phase. It is very much influenced by gravity, as obvious, as well as by electric fields. The obtained results can supply a quite fundamental contribution to the understanding of the actual role of the electrical forces and consequently to the improvement of the existing correlations. Reliable temperature correlations about the temperature dependence of the electrical properties of the fluids are really needed to this aim, by means of ad hoc measurements. For space applications the main result obtained is the possibility of controlling the heat transfer coefficient by tuning the applied high voltage.

Nucleate boiling. At least for the tested geometry, fully developed nucleate boiling heat transfer is practically insensitive to both the gravitational and electric fields. On the other hand the vapor pattern is dramatically influenced by both of them. This leads to the conclusion that this regime is not dominated by hydrodynamics. Both the fields, conversely, act on the extension (heat flux and wall superheat) of the nucleate boiling region, thanks to their effect on the critical heat flux value.

Critical heat flux. This flux is very sensitive to the two force fields examined. It increases both with gravity and electric fields. As both this forces have an instabilising effect on a vapor–liquid interface, this result seems to support the hydrodynamic theory, still for the type of heater tested (geometry, material surface morphology etc.) and above a certain Bond number. Below this value, the Bond number cannot be considered as the only parameter characterising the phenomenon. This is the first time that data on this subject are systematically obtained at different level of acceleration, from low to high gravity. The planned further experimental campaigns in low gravity on flat geometries will supply some further crucial information. The most important feature from the technological viewpoint consists in the possibility of strongly increasing the CHF value, thus enormously improving the performances of the heat transfer equipment. In micro-g, the application of a high electric field restores the same value of critical heat flux as on earth, thus demonstrating the dominance of electrical forces on the gravitational ones.

Film boiling. The related studies confirmed the fundamental action exerted by gravity and electric field on the vapor–liquid interface instability, thus giving many significant pieces of information on this mechanism, that might be fundamental for CHF. Two different film boiling regimes were evidenced: (a) one, occurring for lower heat flux (and wall superheat) showing a multi-dimensional interface oscillation pattern, with a high sensitivity of the heat transfer process to the electric forces, (b) a second one, for higher heat fluxes, showing a one-dimensional interface oscillation regime where the heat transfer coefficient keeps quite insensitive to the electric forces. In microgravity, film boiling in regime (a) is quite insensitive to gravity acceleration once the electric field value is above a certain value. It is also worth emphasising that film boiling, in low gravity, keeps its oscillatory features also in the absence of electric forces. With increasing wall heat flux coalescence of adjacent bubbles along the wire becomes progressively more important.

Bubbling. The action exerted by gravitational and electric forces on nitrogen bubbles has been investigated, mainly aimed at studying the basic involved physics. A clear effect of gravity and electric field on bubble size has been evidenced. The electric field plays also a major role on bubble detachment frequency and causes bubble detachment in the absence of gravity. Furthermore bubble coalescence starts in the region where the electric field is weak. All this is in agreement with the predictions of theory. It came also out that inertia forces due to the inlet gas flowrate could cause bubble detachment also in the absence of buoyancy. Beyond giving some more information on bubble dynamics, this study pointed out how an appropriate electric field distribution could be used for gas (and vapor) management in space.

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