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Review of Reduced Gravity Boiling Heat Transfer: European Research

Paolo Di MARCO

Abstract

The first section of this paper (overview on boiling heat transfer characteristics) is directed to those who are not specialists in the field of boiling heat transfer, in order to make them aware of the fundamental physical mechanisms, the advantages and the main problems of this technique. Next, some of the basic knowledge achieved on terrestrial boiling heat transfer is outlined, along with the benefits and the problems raised from its application in space. Finally, the past and forthcoming research activities of the European teams in this field are reported, in addition to the main results achieved and a short overview on the available test facilities.

1. Introduction

The safe operation of spacecrafts relies on the efficiency of their heat removal systems; besides, several sophisticated scientific apparatuses require very precise temperature control. The ultimate heat sink is constituted by the cold outer space, to which, being in vacuum, heat can be transferred by radiation uniquely. As the outer surface of the spacecraft has in most cases poor heat exchange characteristics, in the absence of dedicated systems the internal temperature would rise to unacceptably high values for both system operation and human survival. Furthermore, systems are needed to route heat from internal utilities, like electronic equipment, payloads, air conditioning systems and so on, to outer heat sink.

To date, spacecraft active thermal control has been accomplished using pumped single-phase liquid loops. Systems of this kind (termed Active Thermal Control Systems, ATCSs) have been used on Mercury, Gemini, Apollo, MIR space station and are currently used on US Space Shuttle, and Russian Soyuz spacecraft. However for larger spacecrafts, like the International Space Station (ISS), some basic differences with respect to the actual systems are present:

- the total heat load will pass from a few kilowatts to tens of kilowatts;
- the heat transport distance will be longer (tens of meters);
- a greater flexibility is required to accommodate the needs (heat load, sink temperature) of different modules as they are put into operation.

Heat removal in a spacecraft is generally pursued via a *thermal bus*, i.e. a loop in which a fluid transports the rejected heat from the utilities to the external radiators where power is radiated to space. Thermal control systems of individual modules are connected to it. Thermal bus concept must provide stable thermal regime at any number of attached module and at any variation of thermal load. At present, thermal buses are generally mechanically-pumped ones, in which a single-phase fluid is operated, hence their heat removal capability is based on the so-called *sensible heat* of the fluid, i.e. in its capacity of absorbing energy by rising its own temperature. However, as well known, a fluid can exchange energy in a different way as *latent heat*, i.e. changing its aggregation state from liquid to vapor and vice versa (boiling and condensation, respectively); the Gibbs' rule states that, as long pressure is kept constant and the substance is pure, this process is isothermal. The main advantages of boiling systems are that they are nearly isothermal, require smaller heat exchange surface, have high power density removal and consequently require lower pumping power. As a result, boiling is recognized as a very effective technique to exchange high heat fluxes from heated bodies and is widely applied in on-earth technology in component heating and cooling.

As detailed in the following, boiling systems are distinguished in *forced-convection* ones, in which the fluid is driven by an external device like a pump, and *natural convection* or *pool boiling* systems, in which the motion of the fluid is originated by the thermal gradients within it: these in turn induces variations of other properties like density, electrical or magnetical permittivity etc., on which an external force field can act to induce motion. Pool boiling systems require no external pumping power, henceforth their interest is

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LOTHAR, Department of Energetics ''L. Poggi'', University of Pisa, Italy via Diotisalvi 2, I–56126 Pisa, Italy
(E-mail lothar@ing.unipi.it)

even greater for low-power demanding environments.

Summarizing, the adoption of boiling systems may yield substantial saving of weight, space and power aboard spacecrafts in order to work out the crucial problem of heat rejection. However, as detailed in the following, a number of problems have still to be solved to adapt these systems to microgravity environment. The former arguments, recently surveyed by Delil[1] stress the need and the importance of research in this field.

2. Overview on Boiling Heat Transfer Characteristics

In any heat transfer process between a solid surface and a fluid, the heat rate Q is commonly expressed by the convection law (usually referred to as Newton's)

$$Q = \alpha A (T_w - T_{ref}) \qquad (1)$$

where α is the so-called heat transfer coefficient, A is the heater area and (T_w-T_{ref}) is the difference between the temperature of the surface and a convenient reference one taken in the fluid; in boiling phenomena, the saturation temperature T_{sat} is generally adopted for T_{ref}. Both the heat transfer area and the temperature difference should be kept as small as possible, the former to minimize weight and investment costs, and the latter to minimize entropy generation and avoid surface overheating, which in turn may lead to equipment failure. Consequently, the heat transfer coefficient has to be as high as possible to accommodate large heat fluxes.

Boiling heat transfer coefficients are order of magnitude higher than in single-phase flow. This makes it a very suitable technique for applications requiring very efficient, compact and lightweight devices. However, especially at low fluid velocity, the vapor removal mechanisms are influenced by buoyancy forces, which of course are lacking in the absence of gravity: in such conditions the remaining forces (mainly inertial and superficial ones) acquire a dominant role. This might lead to a different behavior and even to early heat transfer degradation (the so-called critical heat flux or dryout phenomena, i.e. a surface blanketing by a layer of vapor).

Although a considerable amount of research has been carried out over the last forty years in normal gravity conditions, and to some extent with different gravity accelerations, our predictive capability is still very limited for conditions that do not exist on Earth. Generally, a choice is given to develop either heuristic or mechanistic models for predictive purposes, and although the former can be very effective, only the latter can be used to confirm physical understanding, which in turn gives opportunity for new and improved applications.

A large amount of boiling heat transfer correlations were developed in the past to fit the needs of industrial designers. These correlations are mostly empirically based and, although they have proven very effective in developing terrestrial equipment, their validity diminishes very rapidly outside their range of validity, that is they might poorly represent the situation at different gravity levels, and in particular in microgravity conditions.

As a consequence, an extensive and careful experimental activity under conditions as close as possible to the actual ones is required to improve design of boiling equipment in space. The physical insight gained in this way in conditions different from the ground ones may also lead to a substantial improvement of the comprehension of physical mechanisms governing boiling phenomena and their interaction, which, as shown later on, is still an open question.

In the following, a short review of the main aspects of pool boiling heat transfer will be carried out, mainly devoted to those who are not specialists in the field. The process of boiling is intrinsically a non-stationary, non-equilibrium one, although quasi-cyclic repetitions are typical. Its study has to do with the most complex transport phenomena encountered in engineering, and several complex factors are involved, like interaction between the solid surface of the heater and the fluid, interaction between liquid and vapor phases, and phase transport mechanisms. As a consequence, a satisfactory description of the transport phenomena in the fluid in terms of the differential equations of conservation laws is still unaffordable.

2.1 General Aspects of Pool Boiling Heat Transfer

Following the approach originally developed by Nukiyama[2] in his early experiment, heat transfer performance in pool boiling is commonly reported in a heat flux-temperature difference plot (boiling curve). The curve generally exhibits the trend shown in **Fig. 1**. In the boiling curve (solid line in Fig. 1) several heat transfer regimes can be identified. In a first zone (AB) no boiling exists and heat transfer is by natural convection. In microgravity, if buoyancy and other driving forces are excluded, natural convection cannot take place and is replaced by transient conduction in the liquid layer. When temperature at the surface exceeds the saturation value of a required amount, bubbles are generated in surface cavities by heterogeneous nucleation and boiling starts. This implies a strong increase in heat transfer performance, and temperature difference is suddenly decreased, path BC. The *temperature overshoot* in point B may be so high as to compromise the operation of temperature sensitive equipment, like electronic devices. Along the path CD (nucleate boiling), more and more nucleation sites are activated and the heat flux q'' steeply increases with wall superheat $\Delta T_{sat} = T_w - T_{saT}$; this heat transfer mode is termed *nucleate boiling* and is the most important for industrial applications due to its high efficiency. However, it cannot be sustained indefinitely: beyond a maximum

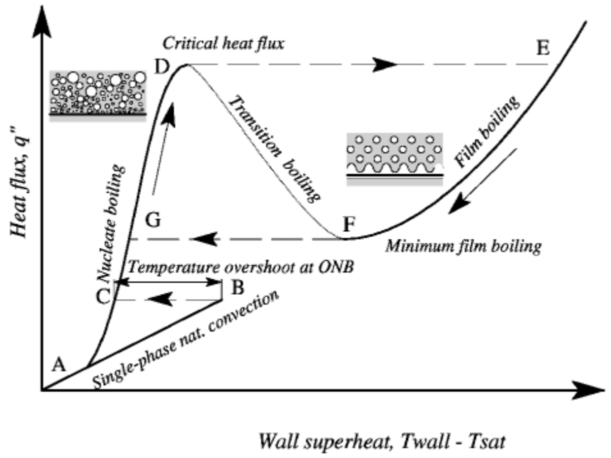

Fig. 1 Pool boiling curve.

value named *critical heat flux* (CHF, point D), it is suppressed (current theories about this phenomenon will be outlined later). Afterwards, two paths can be followed depending on the controlling variable. If this variable is heat flux, as in electric or nuclear equipment, a small rise in q'' causes a sudden jump from point D to E with a very large increase in wall temperature which can even lead to the destruction of the heater (the so-called *burnout* phenomenon). Beyond point F the curve has a much slighter slope than CD and the heat transfer regime is termed *film boiling*. In film boiling, the surface is completely blanketed with vapor and at most sporadic liquid contacts may occur: this is the reason for the strong heat transfer degradation. An unstable vapor film covers the heater, oscillating with an assigned wavelength; bubbles, spaced one wavelength, detach periodically from the film surface; radiation contributes significantly to total heat transfer in this regime, especially at high superheat. If heat flux is now progressively reduced (see the arrows), this curve can be covered down to point F, the minimum film boiling heat flux (MFB), where a further decrease takes the system back to G (hysteresis loop). On the other hand, if the wall temperature is the controlling variable, as in heat exchangers, also the unstable path DF (termed *transition boiling*) can be covered, by increasing or decreasing the wall superheat.

To summarize, although nucleate boiling is a very suitable heat transfer regime, it must be carefully operated: Caution must be taken in establishing it from cold conditions without damaging the equipment due to temperature overshoot, and heat flux must always be maintained safely under the critical heat flux value, beyond which heat transfer degradation takes place which is generally unacceptable.

2.2 Pool Boiling Correlations and Their Extrapolation to Different Gravity Levels

Though several mechanistic models of boiling phenomena have been developed, they encounter difficulties because they retain parameters given on an empirical basis. Thus, prediction of heat transfer performance in nucleate pool boiling still relies on empirical correlations. A large amount is available in open literature. Generally, the dependence on gravity of the so-called heat transfer efficiency α' (Straub[3]) can be expressed by a power law

$$\varepsilon = \frac{\alpha}{\alpha_0} = \left(\frac{g}{g_0}\right)^n \tag{2}$$

The exponent is different if constant heat flux or constant wall temperatures are compared. Straub et al.[3,4] reported that n can range from -0.35 to 0.5; a few examples are given in the following.

One of the most widely used correlations is Rohsenow's[5], which can be rearranged as

$$Nu = \frac{q'' l_L}{\Delta T_{sat} k_l} = \frac{1}{C_{sf}} \left(\frac{q'' l_L}{\eta_l h_{fg}}\right)^{-0.67} Pr_l^{-0.7} \tag{3}$$

which theoretically implies $n = 0.83$, for the same value of q''. If a constant value of ΔT_{sat} is retained, $n = 0.5$ is got. Nonetheless, advice is given to consider gravity acceleration as a mere dimensional constant in it (Dhir[6]). Thus, the correlation has been successfully used to predict pool boiling performance in microgravity, by leaving the terrestrial value of g in it (Motoya et al.[7]). This is consistent with pool boiling performance being poorly affected by gravity value. However, questions could be raised about the mechanistic models assumed to justify the form of Eq. (3). Zhang & Chao[8] proposed to retain the Rohsenow's model also in microgravity, supplementing it with the actual bubble departure diameter in place of the Laplace length.

The correlation by Cooper[9]

$$\alpha = C \left(\frac{p}{p_{crit}}\right)^{0.12 - 0.091 \ln R_p} \left(-0.4343 \ln \frac{p}{p_{crit}}\right)^{-0.55} \times M^{-0.5} q''^{\,0.67} \tag{4}$$

is in dimensional form (R_p is the roughness in μm and M the molecular weight of the fluid) but has no gravity acceleration in it, so $n = 0$. Several other models have this feature, e.g. Yagov's[10], and Cornwell's and Houston's[11]. Another well established correlation proposed in VDI Heat Atlas[12] (1993) is due to Stephan and Preusser

$$Nu = \frac{q'' D_d}{\Delta T_{sat} k_l} = 0.1 \left(\frac{q'' D_d}{T_{sat} k_l}\right)^{0.674} \left(\frac{\rho_g}{\rho_l}\right)^{0.156} \times \left(\frac{h_{fg} D_d^2}{a_l^2}\right)^{0.371} \left(\frac{a_l^2 \rho_l}{\sigma D_d}\right)^{0.35} Pr_l^{-0.16} \tag{5}$$

where D_d is the bubble detachment diameter, given by

$$D_d = C\Phi \sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}} = C\Phi l_L \tag{6}$$

Hence, the gravity acceleration appears through the capillarity length inside D_d, resulting in a very little value of n ($n = -0.033$ for the same heat flux). Once a reference value α_{ref} is determined by experiments, or by tables given in VDI Heat Atlas, or by Eq. (5), the value of α for other heat fluxes can be determined as:

$$\alpha = \alpha_{ref}\left(\frac{q''}{q''_{ref}}\right)^{m} \text{ where } m = 0.9 - 0.3\left(\frac{p}{p_{crit}}\right)^{0.3} \tag{7}$$

Di Marco & Grassi[13] found a good agreement with VDI correlation, Eq. (7) for low and intermediate heat fluxes on a wire, both in normal and in reduced gravity.

2.3 Critical Heat Flux

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 modeling, critical heat flux data on flat plates have often been correlated in the so-called Zuber-Kutatelatze form

$$q''_{CHF} = K\rho_g^{0.5} h_{fg}[\sigma g(\rho_f - \rho_g)]^{0.25} \tag{8}$$

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, (Grassi[14]) and for flat plates was assumed 0.131 by Zuber[15] (1959) and 0.149 by Lienhard & Dhir[16].

Pool boiling on wires and small bodies has been extensively studied in a number of papers over the 60–70s. 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

$$R' = \sqrt{Bo} = r\sqrt{\frac{g(\rho_f - \rho_g)}{\sigma}} = \frac{r}{l_L} \tag{9}$$

The scattering of experimental data in literature is quite high for $Bo < 0.15$, allowing Lienhard & Dhir[16] and Sun & Lienhard[17] to claim that they can no longer be correlated by R' alone. As a result of photographic studies on wires, Bakhru & Lienhard[18] concluded that for $R' < 0.07$ the obtained boiling curve exhibits a continuous trend, from boiling inception up to stable film boiling (provided that this traditional definition still holds) with neither a minimum in heat flux nor a jump in wall superheat. This implies that the very concepts of critical heat flux and minimum film boiling become questionable. In this case the mechanism leading to complete blanketing of the surface is possibly related to the vapor front propagation on the surface or to the coalescence of the bubble population. Also the properties of the material of the heater may play a role.

It is very important to note that a variation in gravity acceleration affects Bo as well as a variation in size of the heater: the scaling length in Bond number is again the capillarity length. If true, this has a strong physical implication, since heaters that are considered ''large'' in normal gravity may become utterly ''small'' as gravity decreases. On the other hand, in the currently available microgravity experimental facilities, the adoption of very large heaters is prohibited by space, power and weight limitations. Even assuming that the present correlations can be extended to reduced gravity conditions, expressions for K (e.g. Lienhard and Dhir[16]) yield a non-trivial dependence of critical heat flux on gravity. This means that for very reduced gravity, a simple ''power law'' dependency, like $g^{1/4}$ or $g^{1/8}$ is not necessarily valid.

2.4 General Aspects of Forced Convective Boiling Heat Transfer

In forced convective boiling the phenomenology is more complicated due to additional system effects. Generally, taking as reference a vertical heated pipe, two kinds of regimes are possible, depending on inlet subcooling and flow rate, as sketched in **Fig. 2** (the vertical scale is purely indicative). Referring to situation A (low flow rate) in the figure, starting from single-phase liquid heat transfer, in which the heat transfer coefficient is essentially constant, nucleation is initiated at the wall when the bulk of the fluid is still subcooled (subcooled nucleate boiling). Afterwards, a point is attained in which the bulk of the fluid becomes saturated (quality $x = 0$), and saturated nucleate boiling takes place. The flow pattern in this region is gradually modified from bubbly to slug and annular, with a progressive increase in heat transfer coefficient. When the liquid film at the wall is destroyed due to thinning and instability, the liquid deficient region is entered, with a sudden decrease of heat transfer coefficient and a consequent increase of wall temperature. The flow regime is now dispersed drop. The droplet evaporation

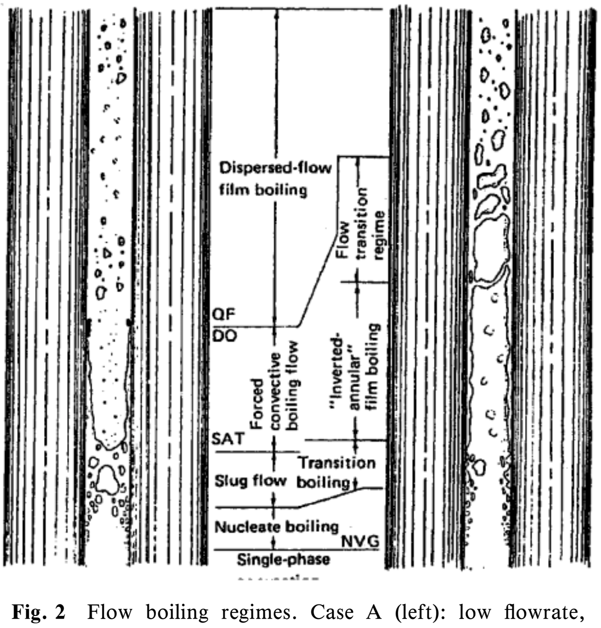

Fig. 2 Flow boiling regimes. Case A (left): low flowrate, Case B (right): high flowrate.

causes an increase in vapor velocity, and in heat transfer coefficient, up to the point where the conditions of heat transfer to single-phase vapor are eventually reached. In the situation B, at higher flow rate, the crisis is reached directly from nucleate boiling conditions: a vapor layer is formed at the wall (reversed annular flow regime).

Both conditions were extensively studied, mainly in the field of nuclear reactor safety and design, and the reader is addressed to specialized literature (e.g Delhaye et al.[19)], Collier and Thome[20)]) in which appropriate correlations for each regime are given.

In both the outlined situations, nucleate boiling regime cannot be sustained indefinitely. A *boiling transition* is eventually reached, which leads to severe heat transfer degradation. Usually, this transition is generally termed *dryout* in conditions of type A in Fig. 2 and *departure from nucleate boiling* (DNB) in condition of type B in the same figure. Differently from pool boiling situation, the crisis in this case depends not only on local conditions, but on the whole evolution of the fluid before the point of the crisis. In forced convective boiling inertial effects are expected to dominate over buoyancy in driving phases, except at low flow conditions: this threshold, however, has still to be determined in micro-g conditions. Besides, some basic mechanisms governing bubble evolution in the near-wall region are common to pool boiling regimes.

3. European Research

3.1 Boiling experiments in microgravity

In the following, highlights of the experimental activities carried out in the field by European teams are given. Their main features are summarized in **Table 1**; research was mainly focused on pool boiling. In fact, due to space and power limitations in available facilities, so far most of the experiments worldwide performed concerned pool boiling heat transfer. A common feature of all the experimental facilities must be stressed: due to the absence of gravity, a free surface separating liquid and vapor must be avoided. All the experimental containers were thus initially filled with liquid, and connected to a bellows to allow for thermal dilatation of the fluid and for volume compensation due to bubble formation. In this way, pressure and subcooling conditions could also be varied during the experiments.

The first experiments of pool boiling in microgravity were initiated in the late 50s in US. Siegel and coworkers (Siegel et al.[21–23)]) used a 2.5 m-high droptower. Since then, experiments were carried out in all the available facilities, namely droptowers and dropshafts, parabolic flights, sounding rockets and orbital platforms. Different heater shapes were used. Thin wires were used for their low thermal inertia, allowing for fast transients like in parabolic flights, and for simple data conditioning (they can be used as resistance thermometers). Plates (up to 50 mm diameter) are more difficult to operate, but have more practical significance for applications; finally, small heaters were adopted to investigate individual bubble behavior. Worldwide studies up to 1990 were surveyed by Straub[4)] and up to 2000 by Di Marco and Grassi[24)].

The mechanism of steady state pool boiling in reduced gravity in saturated or slightly subcooled conditions was described by several authors, and there is substantial agreement on these observations (e.g. Kim et al.[25)], Lee et al.[26)], Oka et al.[27)]). A large bubble resides at a short distance from the heater and acts as a reservoir, engulfing bubbles forming on the surface, see **Fig. 3**. This large bubble maintains its size due to balance of condensation at its cap and coalescence of

Table 1 Pool boiling in microgravity: main features of the European experimental activities
Legend: OF: orbital flight; SR: sounding rocket; PF: parabolic flight; DT: droptower/dropshaft.

REFERENCE		FLUID	HEATER	NOTES
Straub et al., 3	SR	R113	Wire 0.2 mm	Subcooled conditions
Zell, Straub et al., 3, 28, 62	SR	R113	Flat plate 20 × 40 mm	Saturated and subcooled conditions
Straub et al., 3, 63, 4, 62	PF	R12	Wire, 0.2 mm 0.05 mm Pipe, 8 mm o.d. Flat plate 40 × 20 mm	Several flights Saturated and subcooled conditions
Straub and Micko, 3, 30	OF	R134a	Wire, 0.2 and 0.05 mm	Saturated and subcooled conditions
Straub at al, 3, 64, 65, 66	OF DT	R11 R123	Hemispherical heater 0.26 mm diameter Circular heaters, 1, 1.5 and 3 mm dia.	Saturated and subcooled conditions Mainly devoted to study individual bubble behavior
Di Marco and Grassi, 13, 24, 33, 36	PF	R113, FC72	Wire, 0.2 mm diameter	Partial g-level tested Electrostatic field applied
Di Marco and Grassi, 13, 34	SR	FC72	Wire, 0.2 mm diameter	Electrostatic field applied

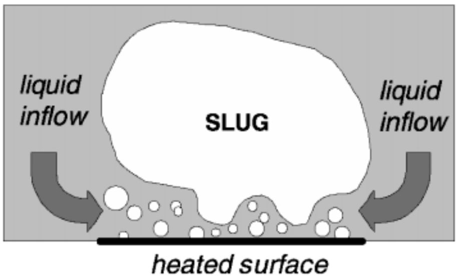

Fig. 3 Saturated or quasi-saturated boiling pattern encountered in microgravity over a flat plate.

new, small bubbles at the base. Lateral coalescence of bubbles along the surface was observed, with consequently induced motion in the fluid, causing small oscillations in the heater temperature. It is inferred that the dimensions of the surface may affect liquid renewal under the large bubble and thus the possibility of maintaining steady state conditions. The probability of having steady state conditions increased with subcooling. Both enhancement and degradation of performance with respect to terrestrial conditions were encountered, as detailed in the following.

Straub and coworkers performed extensive tests with various organic refrigerants (R11, R12, R113, R123, R134a) in parabolic flights, sounding rockets and orbital facilities from the early 1980s to date, using various heater geometries (flat plate, wires, small circular and hemispherical heaters) in a wide range of reduced pressure (up to 0.68). Straub3) recently issued a comprehensive review of his own activity, whose results can only shortly be summarized below.

Sounding rocket (TEXUS) experiments investigated boiling of R113 on wires and flat plates (Zell et al.28)). The same boiling mechanism as above was described for flat plates; and a decrease of heat transfer coefficient was found. For wires, bubble detachment in subcooled conditions was attributed to Marangoni flow. When vapor production was high enough, surface tension forces were no longer able to rewet the surface and a film boiling situation was maintained throughout. The heat transfer coefficient for wires was found to be almost independent of gravity level in both sounding rocket and parabolic flight experiments (Straub3,29)). The onset of nucleate boiling was slightly influenced by gravity acceleration, and tended to occur at lower superheating in micro-g due to the lack of free convection, which mitigates the temperature of the superheated layer.

Straub (Straub and Micko30); Steinbichler et al.31)) reported results of experiments on a Get Away Special (GAS) payload on the Space Shuttle: pool boiling of R134a on platinum wires (0.05 mm and 0.2 mm diameter). A range of heat flux from 50 to 350 kW/m^2 was investigated both in saturated and subcooled conditions (up to 50 K). For the first time, a slight enhancement (15%) of pool boiling heat transfer was reported for wire geometry.

Experiments with R123 and a hemispherical heater (1.41 mm diameter) were also conducted in the BDPU facility, owned by ESA (Straub et al.32), Steinbichler et al.31)) for heat flux up to 300 kW/m^2, reduced pressures from 0.04 to 0.21 and subcooling up to 60 K. Also in this case, enhancement of pool boiling heat transfer with respect to terrestrial gravity was encountered, decreasing with increasing heat flux. At low subcooling, strong thermocapillary flow was observed around the bubbles attached to the surface. At higher subcooling, this mechanism ceased due to the small bubble size and was replaced by the ''pumping effect'' of growing bubbles: the bubble grows, pushing outwards the heated liquid in the thermal boundary layer, then, once its surface gets in contact with the cooler liquid, it rapidly collapses restarting the process. This process was too fast to allow the establishment of thermocapillary flow.

On the basis of his experiments, Straub3) identified three basic boiling configurations: saturated or slightly subcooled boiling, characterized by bubble detachment and coalescence; subcooled boiling, with bubbles adherent to the surface acting as heat pipes, with strong thermocapillary flow along their surface; and highly subcooled boiling, with very small bubbles growing and collapsing very quickly, acting as little pumps, with no thermocapillary flow again. It is still an open question whether nucleate pool boiling is enhanced or degraded in micro-g. Straub3) has recently summarized the main outcomes from his research: a) enhancement or degradation are anyway limited (±30 % max); b) the heat transfer efficiency α' (see Eq. 2) always decreases with increasing heat flux; it can be greater than one at low heat flux and lower than one at high heat flux; c) subcooling seems not to influence the value of α'; d) α' drops off at high reduced pressure.

Di Marco and Grassi24) conducted experiments of pool boiling of R113 and FC–72 on a 0.2-mm platinum wire, in slightly subcooled conditions, both in parabolic flight and in sounding rocket. High values of heat flux, up to CHF, were tested. Data were also recorded in the enhanced gravity phase of trajectory and during special trajectories resulting in a constant gravity value of 1.5 g for 40 s. Pool boiling data at Martian gravity level (0.4 g) were also collected. Despite a very evident change in bubble size and velocity, no appreciable effect of gravity acceleration on the heat transfer coefficient in nucleate boiling on a wire was found. Critical heat flux (CHF) was clearly detected and it was found to be reduced of about 50% in low gravity; analysis of high speed images indicated that the boiling crisis was triggered by bubble coalescence along the wire (Di Marco and Grassi33)). For $R' > 0.08$, the CHF data obtained in reduced or enhanced gravity lie in the range of most of the other experimental data. Thus the

Bond number (or alternatively its square root, R', see Eq. 9) seems to be a suitable parameter to scale the effect of gravity for $R' > 0.08$. The situation appears to be drastically different for $R' < 0.04$: the data obtained in microgravity are very well separated from those of thinner wires, corresponding to the same value of R', obtained in normal gravity. This leads to conclude that at low values of the Bond number this parameter is no more suitable to scale critical heat flux, as it could be inferred by extending the model of Lienhard and Dhir[16)] to low gravity conditions, and the effects of gravity and size have to be accounted for separately[24)]. Straub[3)] recently has reported that his own CHF data for wires in parabolic flight and orbital flight were consistently lower than the corresponding terrestrial values, and could be succesfully correlated adopting a value of K (see Eq. 8)

$$K = 0.94R'^{-0.25} \tag{10}$$

for values of R' as low as 5×10^{-4}. However, no fitting of CHF values at different gravity levels was made.

A cylindrical electrostatic field around the wire (up to 10 MV/m at the heater surface) was also imposed by Di Marco and Grassi[24)] in part of the parabolas. No significant effect was detected on the heat transfer coefficient, but the imposition of an electric field was found to be effective in drastically reducing bubble size and increasing CHF also in microgravity. At high values of applied voltage, the same value of CHF as in terrestrial conditions was measured, thus demonstrating the dominance of the electric force on buoyancy in these conditions. However, existing models of CHF in the presence of electric field revealed their limitation when applied in reduced gravity[33)]. It is also important to point out that the detachment of bubbles from the heated surface took place in both the presence and absence of an electric field, the difference being that in the former case the bubbles slowed down and stopped at a small distance from the surface and started to coalesce. The experiments were repeated on a sounding rocket flight, MASER-8[34)] confirming the same results even in high micro-g (about 10^{-5} G) conditions.

Pool film boiling on wires was tested by Straub and coworkers[3] in parabolic and orbital flights. A dependence of the heat transfer efficiency α' on $(g/g_0)^n$, with $n = 0.16$–0.33, valid for $g/g_0 > 10^{-2}$, was evidenced; this is in agreement with heat transfer correlations, like Bromley's[35)]. For lower values of g/g_0, like in orbital flights, α' is higher than predicted by the relationship above and ranges between 0.46 and 0.25. In subcooled film boiling, heat is removed by the film surface by thermocapillary convection. Di Marco et al.[36)] performed experiences of pool film boiling of FC72 on a wire in parabolic flight, in the presence of an electric field or less. The variation of the oscillation wavelength of the film, due to gravity and electric field, was evidenced. In particular, a reduction of gravity caused an increase of oscillation wavelength and a decrease in heat transfer, while the reverse occurred by applying the electric field. Beyond an electric field threshold, the heat transfer coefficient became insensitive to gravity changes, so even in this regime the dominance of electric forces was demonstrated.

Recently, Grassi and his coworkers have also performed experiments on a flat heater 20 × 20 mm in parabolic flight, imposing an electric field up to 2 MV/m. Preliminary results (still unpublished) showed that even in this geometry the electric field is effective in delaying boiling crisis in low gravity and in reducing the detachment diameter and coalescence of bubbles, thus easing the subsequent condensation of the produced vapor.

The research carried out so far worldwide allowed to draw a suitable qualitative picture of boiling in microgravity. Several experimental works lead to conclude that the phenomena in the area under the growing bubble gives a dominant contribution to the overall heat transfer in boiling. Sophisticated measurements with advanced techniques[37,38)] confirmed the above speculation. Remarkably, the governing phenomena in this region, namely intermolecular forces of adsorption, capillary forces, molecular interfacial phase change resistance and change of phase equilibrium, are independent of gravity. This was experimentally confirmed in parabolic flight experiments by Kim et al.[25)], who indicated that what they call ''small scale'' boiling, i.e. heat transfer in the zones where only small, uncoalesced bubbles exist, is independent of gravity level and subcooling. Straub[29,3)] also distinguishes boiling mechanisms in *primary* ones, which are independent of gravity and determined by evaporation and capillary forces in what he calls the microwedge underneath the bubble, and *secondary* mechanisms, which are responsible for mass and energy transport away from the surface: they are buoyancy, coalescence processes, momentum transfer due to bubble growth and formation, and thermocapillary flow for subcooled states. Gravity thus plays a role in the macroscale, for convective removal of energy away of the layer, and can largely be replaced by the other secondary mechanisms. Secondary mechanisms influence number and size of the bubbles residing close to the surface: when the vapor fraction is larger, vapor may adhere to the heated surface leading to substantial heat transfer degradation and eventually to CHF. Gravity may affect the two preceding factors, in a way which depends on subcooling and heater geometry, and this may explain why both enhancement and degradation of heat transfer in microgravity were reported. As a consequence, a correct prediction of the nucleation site density and of the bubble detachment diameter, associated to a gravity-independent bubble growth model (e.g. Dhir[39)], Bai and Fujita[40)], Stephan and Hammer[41)]) may lead to a substantially correct prediction of boiling heat transfer in any gravitational field, at least for low to intermediate heat fluxes. However, this is far an easy task to accomplish, and debate still exists about the dominating heat removal mechanism: as outlined by Stephan[42] several theoretical works lead to conclude that evaporation in a tiny area under the bubble where the liquid-vapor interface approaches the wall (the so-called micro-region) gives the dominant contribution to the overall heat transfer in boiling (e.g. Wayner[43]; Stephan and Hammer[41], Straub[3]). Conversely, according to Demiray and Kim[44], although microlayer evaporation plays a role in bubble heat transport, the heat transfer occurs mainly through transient conduction and microconvection during liquid rewetting after bubble departure.

3.2 Ancillary experiments in reduced gravity for boiling heat transfer

As already said, boiling heat transfer involves a blend of a large amount of physical mechanisms. The individual understanding of these mechanisms of course helps the comprehension of the whole phenomenon. As this review is focused on boiling, these experiments are defined as ''ancillary'' here, even though each of them has of course its own role and significance. In particular, experiences concerning thermocapillary convection (a form of Marangoni convection) and bubble dynamics will be outlined herein.

The role of thermocapillary convection in boiling has still to be completely assessed, and it is expected that this mechanism becomes more important in the absence of buoyancy. Straub points out that thermocapillary flow around the bubbles was observed in reduced gravity in subcooled boiling, but never in saturated conditions: the origin of this flow has still to be understood, and Marek and Straub[45] suggest that it is originated by the gradient of dissolved gas concentration along the bubble interface. Straub[46] also stresses that quantitative measurements indicated that the contribution of thermocapillary convection to overall boiling heat transfer is small, however he gives large evidence that thermocapillary flow is an important mechanism for transporting energy away from the liquid-vapor interface into the bulk fluid (and not from the heated surface to the fluid). In the absence of buoyancy and subcooling, like in reduced gravity saturated boiling, the energy transport into the bulk of the fluid uniquely relies on bubble motion.

Reynard et al.[47] experimentally studied thermocapillary convection around a single air bubble introduced under a heated horizontal wall in a silicone oil layer. Experiments were performed under normal gravity and microgravity conditions, in parabolic flight. For liquids with a low Prandtl number, different states of thermocapillary convection exist. When a critical threshold is exceeded, an oscillatory state follows the steady one and the initially axisymmetrical flow, in the shape of a roll around the bubble, becomes time dependent, with development of secondary rolls. The periodic 3D spatio-temporal structure of the thermocapillary rolls was visualized by shadowgraphy and tracer particles. It was shown that in the present configuration under reduced gravity, the stationary thermocapillary roll developed down to the bottom of the test chamber, due to the absence of the counteracting effect of buoyancy, and the convective heat transfer in the fluid was increased, while in normal gravity (for the same bubble size and thermal gradient) the contribution of thermocapillary convection was very small, due to the presence of secondary rolls.

Betz and Straub[48] have set up recently a model for the study of Marangoni convection around a gas bubble either in microgravity or not, confirming that a strong enhancement of single-phase convection around the bubble can be obtained in microgravity, if the cell size is comparable with the bubble diameter. The model compared well with experimental results and the relevant dimensionless parameters were identified. The authors appropriately point out that Marangoni convection is strongly influenced by surface contamination, so the purity of the fluid or its degradation in time may substantially affect the experimental behavior of the system.

Studies on bubble dynamics in reduced gravity are important to understand bubble behavior, and in particular to asses the role of dynamic forces in bubble evolution in the absence of thermal ones.

Pamperin and Rath[49] performed experiments of injection of air bubbles in water with injection orifices of 0.39 and 0.80 mm diameter in the droptower of ZARM, Germany. By assuming that the bubble detachment in microgravity is ruled uniquely by a balance between surface tension at the bubble neck and inlet gas momentum forces, they developed a detachment criterion based on a modified Weber number

$$We^* = \frac{\rho_g u_o^2 d_o}{\sigma} = 8 \tag{11}$$

They claimed that their experimental data are in agreement with the derived criterion, as they observed detachment only for $We^* > 10$ during the 4.74 s of microgravity available in the tests.

Di Marco et al.[50] investigated the process of nitrogen bubble formation injected in FC72 from an orifice of 0.1 mm diameter drilled in a horizontal tube. The experiment was operated in the Japanese dropshaft of JAMIC, at a level of about 10^{-4} G. It was also possible to apply a non-uniform electric field around the tube, thus obtaining a geometrical configuration similar to the one adopted by the same authors for boiling experiments in reduced gravity: this allowed to study dynamical and electrical effects separately from thermal ones. Bubble size, detachment frequency and velocity were measured by digital processing of high-speed images. The results showed that, in microgravity and in the absence of electric field, bubble detachment did not take place at low gas flow rate at least throughout the duration of the drop; a bubble diameter up to 5 mm was obtained. Conversely at higher gas flow, the dynamical effects were sufficient to induce bubble departure. The value of detachment diameter was lower than predicted by available theoretical models and the role of surface dynamics in promoting detachment was evidenced in the high-speed images. For this well-wetting fluid, the detachment occurred for values of We^* far lower than prediction of Eq. (11); this was also confirmed in the experiences of Herman et al.51). The application of electric field proved effective in providing a force able to remove the bubbles away from the orifice and in promoting bubble departure at diameter values greater than, but of the same order of magnitude, as in normal gravity. For the higher values of the tested electric field, the detachment diameter was almost the same as in normal gravity. In this way, the effectiveness of the electric forces in promoting bubble detachment and their progressive dominance over buoyancy force was experimentally demonstrated.

4. Forthcoming European Activities: Experiments and Facilities

4.1 European Experimental Facilities

Several European facilities are available for microgravity experimentation in fluid physics. Among them, the A-300 ZERO-G52), the largest aircraft ever used in parabolic flights, with a test cavity of $20 \times 5 \times 2.3\ \mathrm{m}^3$, different models of sounding rockets (MASER, TEXUS, MAXUS53)) which can attain over 750 s of microgravity with MAXUS, and the droptower of ZARM in Bremen, Germany54), which, after the closure of the Japanese dropshaft of JAMIC, currently holds the record of the longest available micro-g time (9.5 s) in drop facilities.

Concerning the orbital facilities, the Fluid Physics Facility (FluidPac)55), to be installed on board of the retrievable Russian capsule FOTON, is a multi-user platform, originally conceived for observation of surface tension and thermal phenomena along a gas-liquid interface, which can be used also for different fluid physics experiments, including boiling. The platform hosts 13 different optical diagnostic tools; up to 4 experiment containers can be located on its caroussel and operated one at a time. Data collected in a 15-day orbital mission can be stored on board and partly transmitted to ground via telemetry. A new launch of FuidPac, in FOTON-M2 mission, is foreseen in 2005: it will carry four different fluid-physics experiments, and among them ARIEL, to study pool boiling in the presence of electric fields.

The most promising European facility for two-phase experiments is the Fluid Science Laboratory (FSL), which will be housed in the European Columbus laboratory of the International Space Station (ISS). FSL is a multi-user facility for conducting fluid physics research in microgravity conditions56). It can be operated in fully- or in semi-automatic mode and can be controlled on-board by the ISS astronauts, or from the ground in the so-called telescience mode. Each experiment (or experiment category) will be integrated in an individually-developed Experiment Container (EC), which will be separately transported on the Space Shuttle within the Multi-Purpose Logistics Module (MPLM) and stored on board. With a typical mass of 25-30 (max. 40) kg, and standard dimensions of $400 \times 270 \times 280\ \mathrm{mm}^3$, the EC provides space to accommodate the fluid cell assembly, including any necessary process stimuli and dedicated electronics. A very complete set of diagnostic instruments is integrated within FSL. It includes a set of cameras offering high-speed, high-resolution, infrared, and color recording, illumination with either white or monochromatic light sources, particle image velocimetry (including imaging of liquid crystal tracers for simultaneous velocity and temperature mapping), thermographic mapping, interferometric observation along two perpendicular axes utilizing a combination of state-of-the-art convertible interferometers. The Microgravity Vibration Isolation Subsystem (MVIS), developed by the Canadian Space Agency, will be implemented in the facility to isolate -via magnetic levitation- the experiment from space station g-jitter perturbations.

4.2 Research Programs

The CIMEX (Convection and Interfacial Mass Exchange) research program57) aims to investigate processes involving mass transfer through interfaces, and their coupling with surface-tension-driven flows and instabilities. During the first two-year phase of this MAP (Microgravity Application Promotion) project, funded by ESA, four experiments are being prepared for subsequent flight onboard the International Space Station (ISS), using the Fluid Science Laboratory (FSL). The main focus is on flows and instabilities with evaporation, and though only CIMEX-3 involves boiling directly, all the experiments are expected to provide useful information on boiling phenomena. Both single component and multi-component fluid systems are studied, in collaboration among several European teams, an industrial partner, and with the advice of non-EU collaborators. On a fundamental point of view, progress is expected in the understanding of different regimes of interfacial mass transfer processes, in the presence of several effects (inert gas, Marangoni convection, micro-regions or triple lines, surfactants). On the applied point of view, both direct and prospective researches are conducted, aiming to optimize heat pipes, thin-film evaporators, two-phase flow and boiling technologies in normal and reduced gravity. In particular, CIMEX-1 studies evaporative convection in liquid layers, and CIMEX–2 is devoted to the physical understanding of capillary phenomena in pipe grooves, for optimization of heat pipe performance using advanced structures. In CIMEX–3, a versatile loop system will be developed for the study of microgravity two-phase flows and heat transfer issues. This part of the program foresees the development of transparent swirl evaporators and a high-efficiency, low-pressure-drop condenser, to be used in a mechanically-pumped loop, the characterization of flow patterns and void fraction in reduced gravity by using different working fluids: the results may prove the viability of mechanically pumped two-phase loops and will be useful and for thermal-gravitational scaling1). In CIMEX–458), thermocapillary flows around vapor bubbles will be investigated using optical and thermal diagnostics; parabolic flight precursory experiments have been already performed, as previously outlined47).

ESA supports the creation of European networks, called 'Topical Teams' (TTs), to consolidate, optimize and promote plans for research programs in the space environment in anticipation of future announcements, also involving conventional industry for transfer of space technology. The TTs are composed of European scientists, but they are open to the (unsupported) cooperation of non-EU members. At present, a TT on Boiling and Two-Phase Flow is active. This TT is currently defining the requirements for future experiments of boiling, bubble dynamics and two-phase flow in microgravity, aimed to the realization of one or more ECs for FSL.

As reported by Delil (2003), European teams are currently involved in the development of two near-future mechanically pumped, two-phase heat transport systems applications in space, namely:

- The two-phase ammonia thermal control system of the Russian segment of ISS59,60),
- The hybrid two-phase CO_2 loop of the Tracker Thermal Control System of Alpha Magnetic Spectrometer (AMS-2)61), an international experiment searching for anti-matter, dark and missing matter, planned for a 5-years mission as attached payload on ISS.

5. Conclusions

In this paper, the fundamental characteristics of boiling heat transfer and its advantages for high demanding heat removal applications were outlined. The most significant European research in the field was recapitulated, while the activities carried on in US and Japan were described in detail in companion papers.

The main results achieved so far can be summarized as follows

- Although bubble dynamics and transport mechanisms are different in micro-g, bubbles detach equally from the heated surface and the heat transfer coefficients for saturated and subcooled nucleate pool boiling (up to medium heat fluxes) do not diminish appreciably with gravity reduction, contrary to the prediction of most heat transfer correlations. Occasionally, even enhancement up to 30% at low heat fluxes was observed.
- A sufficient evidence was gained that the phenomena taking place in the micro-region under the bubble, which is the major contributor to boiling heat transfer rate, are independent of gravity acceleration; gravity rules the mechanisms of heat and vapor removal from the surface in terrestrial gravity, affecting free convection and bubble-departure size and velocity, but may be replaced by different mechanisms in micro-g. This may expain why boiling is less sensitive than expected to gravity acceleration.
- In microgravity, different pool boiling regimes were identified with increasing subcooling: saturated/slightly subcooled boiling with bubble departure and coalescence, subcooled boiling with no bubble departure and thermocapillary convection, highly subcooled boiling with rapidly growing and collapsing bubbles acting as micro-pumps.
- Critical heat flux is reduced in low gravity, however it is higher than predicted by the extrapolation of correlations well assessed on earth. The scaling of CHF in microgravity based on Bond number revealed unsatisfactory so far, and a separate dependence on gravity and heater size seems to exist.
- The experiments in flow boiling are still insufficient to elaborate flow maps or to identify the minimum flow above which the role of gravity is still significant.

The research so far conducted worldwide allowed to gain sufficient qualitative knowledge about boiling heat transfer process in microgravity. Some of this knowledge was also useful for clarifying the fundamental mechanisms of boiling. It has now become quite clear that efficient boiling can be sustained in microgravity, especially in subcooled conditions, and that vapor removal from the proximity of the heated surface is the key problem to be solved to avoid early degradation of heat transfer performance. However, we are still far from the elaboration of quantitative models, for which extensive experimentation is still required.

6. Nomenclature

A	area	(m^2)
a	thermal diffusivity	(m^2/s)
Bo	Bond number, l/l_L	
C	generic constant	
d_o	orifice diameter	(m)
D	diameter	(m)
g	actual vertical acceleration	(m/s^2)
h_{fg}	saturation enthalpy	(J/kg)

k	thermal conductivity	(W/mK)
K	Kutatelatze constant, (see Eq. 8)	
l, L	length	(m)
l_L	Laplace length, $\sqrt{\dfrac{\sigma}{g(\rho_l-\rho_g)}}$	(m)
M	molecular weight	(kg/kmol)
n	power law exponent, (see Eq. 2)	
Nu	Nusselt number	
p	pressure	(Pa)
Pr	Prandtl number	
q''	heat flux	(W/m^2)
Q	heat rate	(W)
r	radius	(m)
R'	dimensionless radius	
R_p	surface roughness	(μm)
T	temperature	(K)
u_o	gas velocity at orifice	(m/s)
We^*	modified Weber number, (see Eq. 11)	
α	heat transfer coefficient	(W/m^{2}K)
α'	heat transfer efficiency, (see Eq. 2)	
ΔT_{sat}	wall superheat, T_p-T_{sat}	(K)
η	dynamic viscosity	(Pa s)
ρ	density	(kg/m^3)
σ	surface tension	(N/m)
Φ	contact angle	(rad)

Subscripts

0	referred to terrestrial gravity
crit	critical
CHF	critical heat flux
d	detachment
g	gas
l	liquid
ref	reference
sat	saturation
w	heated wall

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