POOL BOILING IN REDUCED GRAVITY

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Abstract. The main outcomes of the worldwide experimental activity dealing with pool boiling in reduced gravity are summarized. The currently available experimental facilities and experimental opportunities are examined, the main results obtained by the various experimental teams are reviewed, and highlights of current and future applications of boiling in space systems are given. The work initiated by several groups around the world seems to indicate that pool boiling (especially the subcooled one) may be safely sustained in micro-g conditions with appropriate measures and that improvements in performances (e.g. by application of other force fields) are possible. However, due to the high cost and low availability of flight opportunities, and to their limitations in space and time, a final assessment has yet to be completed, and some results are still controversial.

In the second part of the paper, a review of the main pool boiling features and of the related models is carried out. The main effects of gravity and other force fields are stressed and compared with the above mentioned experimental results on earth and under reduced gravity conditions. The most commonly accepted viewpoints are reported for each aspect. The empirical correlations developed for boiling heat transfer in terrestrial conditions do not trivially extend their validity outside their range of application. Thorough experimentation in microgravity is thus needed to assess the performance of boiling heat transfer in such conditions.

It is believed that, after further experimental activity, it will be possible to design efficient boiling systems for future spacecrafts. The research in microgravity, by eliminating the dominant effect of the buoyancy forces, may also help clarify the role played by the various mechanisms in the boiling phenomenon.
1. AVAILABLE MICRO-g FACILITIES

The state of microgravity is not the result of suppression of the gravity force, but rather of being in free fall. In such conditions, in fact, the inertia force counterbalances gravity. Microgravity conditions can thus be created by letting an object fall freely in a so-called drop tower or by flying a ballistic trajectory (parabolic flight) with an aircraft, the only limitation being that in these facilities, micro-g conditions can only be established for a limited time. Longer duration can be obtained in an orbital flight. More precisely, total gravity suppression is impossible, due to the mechanical perturbations in the system, so that, depending upon the technique, values of mean residual gravity acceleration ranging from $10^{-2}$ to $10^{-5}$ g are attained. Thus, it would be more appropriate to speak about “reduced gravity” rather than “microgravity”, although the latter term has gained popularity. Several kinds of facilities are currently available for microgravity experimentation and boiling experiments have been carried out in all the facilities described in the following.

Attention should be drawn not only to the duration and to the mean level of microgravity phase, but also to its quality: the so-called g-jitter, i.e. the small oscillations (which may also imply changes in direction) of the acceleration of gravity around its mean value, which can substantially affect bubble behavior. An example of g-jitter is given in Fig.1.

Drop towers and Dropshafts (dropshafts are wells in the ground) can provide a good quality microgravity ($10^{-5}$ g) for a limited time. From the very simple physical relationship of free fall motion, the drop height required to have a duration $\Delta t$ of microgravity is given by $H = 0.5 g \Delta t^2$. This means that several hundreds meters are

![Figure 1](image-url)  
*Figure 1* Example of g-jitter in parabolic flight (Di Marco & Grassi, 19991a)
necessary to have an appreciable duration of microgravity. Additional deceleration spaces should be also provided at the bottom, to allow for a safe recovery of the facility. As an example, the droptower of ZARM, Bremen, Germany, provides 4.7 s of microgravity with a free fall of 110 m, and the dropshaft of JAMIC in Hokkaido, Japan, yields 10 s of free fall, with a total depth, including the braking zone, of 790 m. Shorter facilities are operated in some laboratories. According to the formula above, a facility of 20 m height is able to provide 2 s of microgravity. Partial values of gravity can be obtained with appropriate braking systems.

Ballistic Flights encompass both parabolic flights and sounding rockets flights. In parabolic flight, an aircraft describes a (parabolic) free-fall trajectory in which inertia force counterbalances gravity. Around 20 s of relatively poor quality microgravity (around \(10^{-2}\)g, with a strong jitter, due to both atmospheric conditions and pilot’s skill) are available. The main advantage is that a number of repetitions are possible (classically, 30 parabolas per day for three days), allowing extensive testing, parameter adjustments and even failure recovery. Besides, scientists can control the experiment directly aboard the aircraft, more or less in the same way as in their laboratory. For these reasons, parabolic flights are generally considered as the first step in setting up an experimental program. Currently available aircrafts may accommodate very large experiments (up to 20 m in the European Airbus 300). A particular technique is the so-called free-floating one, in which the apparatus is free to move inside the cabin to reduce the influence of the g-jitter. Weight and time of micro-g are more limited in this case, due to the eventual impact of the apparatus on the walls. Different values of gravity can also be obtained by flying particular trajectories.

In sounding rocket flights, a rocket is launched in an almost vertical trajectory, which can provide from 6 to 20 minutes of very good quality microgravity \((10^{-4}-10^{-5}\) g\), depending on the height reached. Generally, the experiment can be controlled from ground via telemetry, and even video images, which are very useful in boiling experiments, can be obtained. Costs are however high, and space and weight limitations are more stringent. The payload mass is around 300 kg, shared among several experimental facilities. Some examples: the NASA carrier Orion yields 200 s of microgravity with an apogee of 170 km; the German carrier, TEXUS, the Swedish MASER, and the Japanese TR-1A can provide 6 min of microgravity (with an apogee of about 250 km), while 15 minutes can be attained with the Swedish MAXUS.

Orbital Flights can provide a good level of microgravity: \(10^{-4}\) to \(10^{-5}\) g, with the g-jitter depending mainly on the crew movements inside the spacecraft and on operation of on-board systems. Although the time duration is potentially very long, a limit is often found in the available power. Generally, the experimental facilities have to be self-powered, and space and weight limitations may be substantial. It must be taken into account that for most satellites the visibility from ground is limited to a few minutes per day, and the possibility of interaction with the experiment is thus reduced. Some facilities, like GetAway Special (GAS) are flown on the NASA Space Shuttle in place of ballast. In such a case, the experiment is simply switched on and off by the crew and everything, from the automated control of the experimental sequence to the energy needed, must be pre-loaded into the container. Data are available only upon retrieval of the container. The possibility of experimentation in orbital flight will greatly improved with the placing into service of the International Space Station, whose operation is
foreseen to start in the near future. Several multi-purpose facilities for the study of fluid behavior and heat transfer will be placed in it, e.g. the Fluid Science Laboratory (FSL) by ESA.

2. EXPERIMENTAL RESULTS

In the following, highlights of the experimental activity carried out on pool boiling in microgravity are given. Their main features are summarized in table 1. 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 the formation of bubbles. 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. Siegel and coworkers (Siegel and Usiskin, 1959; Usiskin and Siegel, 1961; Siegel and Howell, 1965) used a 2.5 m-high droptower. Merte and Clark (1964) studied transient boiling of nitrogen on a sphere in a 10 m-high droptower. Studies up to 1990 were surveyed by Straub (Straub et al., 1990).

Merte and coworkers (Lee et al., 1997, 1998) reported on experiments carried out (adopting the same hardware) in five different missions in a GAS facility on Space Shuttle, in the period 1992-96. Pool boiling of R113 on a rectangular plate (19x38 mm) was investigated at heat flux up to 80 kW/m², for different subcoolings (up to 22 K) and a duration of up to 280 s. The authors claim to have attained steady state conditions in 27 of 45 runs. The mechanism of steady state boiling was described, and there is a substantial agreement on these observations also by other authors, as detailed in subsequent sections of the paper. A large bubble resides a short distance from the heater and acts as a reservoir, engulfing bubbles forming on the surface, see Fig. 2. This large bubble maintains its size due to balance of condensation at its cap and coalescence of 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 the liquid renewal under the large bubble and thus the possibility of maintaining steady state conditions. Subcooling was found effective in enhancing boiling performance, and the probability of having steady state conditions increased with subcooling. In these experiments, the heat transfer coefficient was increased up to about 30% with respect to terrestrial conditions at low and intermediate heat flux (40 kW/m²), while at higher heat flux degradation took place, see Fig.3.

The group leaded by Abe (Oka et al., 1992, 1995, 1996) performed several tests on square plates with R113, water and pentane both in droptowers and in parabolic flight in the period 1989-1996. A boiling mechanisms quite analogous to the one described by Lee et al (1997) is reported. However, for R113, the bubbles tended to maintain a hemispherical shape with a large contact area with the surface, they remained attached to the surface at higher heat fluxes, and as a consequence, a situation of surface dryout was gradually attained (no sudden transition was observed, however). In contrast, water
Table 1  Main features of the experimental activities

<table>
<thead>
<tr>
<th>REFERENCE</th>
<th>FLUID</th>
<th>HEATER</th>
<th>NOTES</th>
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<tbody>
<tr>
<td>Siegel &amp; Usiskin, 1959, 1961</td>
<td>DT</td>
<td>Water</td>
<td>Wires, 0.4 - 4 mm, Ribbon, 5x63 mm</td>
</tr>
<tr>
<td>Siegel &amp; Keshock 1964</td>
<td>DT</td>
<td>Water</td>
<td>22 mm round nickel heater</td>
</tr>
<tr>
<td>Zell, Straub et al. 1984, 1986</td>
<td>SR</td>
<td>R113</td>
<td>Flat plate 20x40 mm</td>
</tr>
<tr>
<td>Straub et al., 1991</td>
<td>PF</td>
<td>R12</td>
<td>Wire, 0.2 mm 0.05 mm Pipe, 8 mm o.d. Flat plate 40x20 mm</td>
</tr>
<tr>
<td>Oka et al., 1992</td>
<td>PF</td>
<td>R113, pentane, water</td>
<td>Flat plate 40x40 mm</td>
</tr>
<tr>
<td>Abe et al. 1994, 1999</td>
<td>DT</td>
<td>Water-ethanol</td>
<td></td>
</tr>
<tr>
<td>Oka; Abe, Mori &amp; Nagashima, 1995, 1996</td>
<td>DT</td>
<td>Water, R113, pentane</td>
<td>Flat square plate, 30, 40 and 80 mm</td>
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<tr>
<td>Tokura et al., 1995</td>
<td>DT</td>
<td>Methanol</td>
<td>Wire</td>
</tr>
<tr>
<td>Shatto et al. 1996</td>
<td>PF</td>
<td>Water</td>
<td>Flat and cylindrical heaters</td>
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<tr>
<td>Straub, Steinbichler et al., 1996, 1998</td>
<td>OF</td>
<td>R134a</td>
<td>Wire, 0.2 and 0.05 mm</td>
</tr>
<tr>
<td>Straub &amp; Picker, 1996, 1998, 1999</td>
<td>OF</td>
<td>R123</td>
<td>Hemispherical heater 1.41 mm diameter</td>
</tr>
<tr>
<td>Di Marco &amp; Grassi, 1996, 1999</td>
<td>PF</td>
<td>R113, FC72</td>
<td>Wire, 0.2 mm diameter</td>
</tr>
<tr>
<td>Lee, Merte &amp; Chiaramonte, 1997, 1998</td>
<td>OF</td>
<td>R113</td>
<td>Flat plate, 19x38 mm</td>
</tr>
<tr>
<td>Ohta, Kawaji et al., 1998</td>
<td>SR</td>
<td>Ethanol</td>
<td>Flat plate, 50 mm diameter</td>
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<tr>
<td>Motoya et al., 1999</td>
<td>DT</td>
<td>Water</td>
<td>Wire, 0.2 mm diameter</td>
</tr>
<tr>
<td>Suzuki et al, 1999</td>
<td>PF</td>
<td>Water</td>
<td>Ribbon 0.1 mm thick, 20x5 mm</td>
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Table 1 (Cont’d)

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<th>REFERENCE</th>
<th>FLUID</th>
<th>HEATER</th>
<th>NOTES</th>
</tr>
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<tr>
<td>Qiu et al., 1999</td>
<td>PF</td>
<td>Water</td>
<td>Single bubble studied</td>
</tr>
<tr>
<td>Ahmed &amp; Carey, 1998</td>
<td>PF</td>
<td>Water-propanol</td>
<td>Binary mixture</td>
</tr>
<tr>
<td>Snyder &amp; Chung, 2000</td>
<td>DT</td>
<td>FC-72</td>
<td>Electrostatic field applied, Duration 2 s</td>
</tr>
<tr>
<td>Kim et al., 2000</td>
<td>PF, SR</td>
<td>FC-72</td>
<td>Multi array heater with imposed surface temperature</td>
</tr>
</tbody>
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Legend: OF: orbital flight; SR: sounding rocket; PF: parabolic flight; DT: droptower/ dropshaft.

Figure 2  Saturated or quasi-saturated boiling pattern encountered in microgravity over a flat plate.

bubbles exhibited “necking”, and were readily detached by the surface. The difference is attributed to the different consumption rate of the liquid film underlying the bubbles and to the forces that deform the bubbles from hemispherical shape with a large contact area into a nearly spherical shape, which in turn allows detachment due to the motion of the surrounding fluid. Latent heat of vaporization and surface tension are mainly responsible of these effects. Thus, it appears that surface and fluid properties play an even greater role in micro-g boiling than in normal gravity. In parabolic flight on horizontal plates
Figure 3 Heat transfer coefficient in microgravity ($a = 10^{-4}$ g) on a flat plate (19x39 mm), fluid: R113. (from Lee and Merte, 1998).

(Oka et al., 1995) a significant effect of g-jitter on surface temperature was observed. Abe et al. (1994) investigated boiling in binary mixtures in a dropshaft: enhancement of boiling heat transfer was reported.

Ahmed and Carey (1998) who conducted experiments on boiling of subcooled or nearly saturated binary mixtures (water/2-propanol) on a flat copper surface in parabolic flight. Nucleate boiling heat transfer and critical heat flux were found to be independent of gravity level in the range $10^{-2}$ g - 2 g, and this was attributed to the strong contribution of favourable Marangoni convection. Currently available correlations for binary mixtures were found to be acceptable at twice the normal gravity, but inadequate when the gravity is reduced of orders of magnitude.

Some remarkable discrepancies are present between the results of Lee et al. (1997) and those of Oka et al. (1995, 1996). In the former case, bubbles of R113 were observed to detach from the surface, and enhancement of heat transfer was reported, while Oka et al. claimed degradation of heat transfer in pool boiling. The different nature of the heating surface and its contamination may play a role in this frame.

Di Marco and Grassi (1996, 1997, 1999a) conducted experiments in parabolic flight of pool boiling of R113 and FC-72 on a 0.2-mm platinum wire, in slightly subcooled
conditions. High values of heat flux, up to CHF, were tested. Data were recorded also 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. The experiments have been recently repeated on a sounding rocket flight (MASER-8) with results in good agreement with the former ones. Despite a very evident change in bubble size and velocity, no effect of gravity acceleration on the heat transfer coefficient in nucleate boiling was found. Critical heat flux (CHF) was clearly detected (Fig. 4) and it was found to be reduced of about 50%. A cylindrical electrostatic field around the wire was also imposed in some 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 in 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. It is also important to point out that the detachment of the 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.

Snyder and Chung (2000) reported on experiments carried out in a droptower (1.5 s of free fall) for pool boiling of FC-72 (5 K of subcooling) on a flat heater (25x25 mm). An electrostatic field was also generated by imposing a voltage drop up to 23 kV in three
electrode geometries: flat parallel plate, flat diverging plate, perpendicular pin. The heat transfer coefficient was found to decrease drastically in microgravity in the absence of an electric field. The application of the electric field increased the heat transfer coefficient from 40% to 70% in microgravity; in some cases, at low heat fluxes, a heat transfer coefficient even larger than in normal gravity conditions was measured. The most efficient geometrical configuration was the diverging plate. The electric field was found to also decrease the average bubble size (about 1 mm with respect to 70 mm in the absence of EF).

Tokura et al. (1995) performed pool boiling experiments in JAMIC dropshaft on boiling of methanol on thin platinum wires (0.1 and 0.05 mm diameter). Two boiling regimes were observed: in the first, bubbles of relatively small size sprung out from the wire and quasi-steady-state conditions were attained, and in the second the bubbles coalesced laterally along the wire to eventually form large spherical bubbles that enclosed the wire without detaching. The first regime took place typically in low heat flux conditions, the second at higher ones. Due to the near absence of liquid, the wire glowed white inside the large bubble. Coexistence of the two regimes was also observed. In the first regime, the heat transfer coefficient was quite close to the expected terrestrial value. The authors concluded that it is not possible to attain steady state boiling at high heat flux in microgravity.

Shatto et al. (1999) experimented in parabolic flight with water at reduced pressures. Some data at Martian gravity level (0.4 g) were also collected. Two heaters, a flat and a cylindrical one, were employed. Nucleate boiling heat transfer was found to be increased in reduced gravity. A significant reduction in critical heat flux under reduced gravity was measured.

Motoya et al. (1999) studied boiling of saturated water on a platinum wire (0.2 mm diameter) in the JAMIC dropshaft. The effect of scale deposition (calcium carbonate) on the wire was also studied. In the bare wire, the same boiling mechanism described by Tokura above was observed, with a large coalescing bubble causing burnout at high heat flux. Conversely, on the scaled surface, the bubbles kept on detaching even at high heat flux. The pool boiling performance in microgravity was almost the same as in normal gravity for the bare wire, with reduction in CHF. For the scaled surface, modest degradation took place. Agreement with the Rohsenow correlation (Eq. 10) was found, by using terrestrial value of $g$ in the equation even for microgravity condition. Significantly, the authors measured the ratio of the latent heat transport to the total in their experiments. The values for the terrestrial conditions agreed well with the ones reported in literature (increasing with heat flux), while in microgravity this ratio was found to be consistently very low (below 0.1).

Suzuki et al. (1999) performed a test of subcooled boiling (10 to 40 K) on water in parabolic flight. The heater was a stainless steel ribbon of 0.1 mm thickness, 20x5 mm, cooled on both sides. Bubbles were observed to remain attached to the surface at low heat flux and to detach at higher ones. Only critical heat flux is reported, which was lower than in terrestrial conditions, but 200% to 400% higher than the one predicted by Zuber and Ivey-Morris correlations. However, no corrections to the above correlations seem to have been made to account for the small size of the heater (see section 3.2.4). The authors underline that the same value of CHF was measured in terrestrial conditions by placing a cover plate with a small clearance (1 mm) over the heater.
Ohta et al. (1998) reported on pool boiling experiments carried out in a Japanese sounding rocket (TR-1A n.5). The test fluid was ethanol, under pressure from 0.01 to 0.48 MPa, and temperature from 25 to 30 °C. The surface was a flat disk of sapphire glass, 50 mm diameter, indirectly heated by a ITO layer. Heat fluxes up to 80 kW/m² were tested. Small Pt sensors were coated directly on the heated surface, for local temperature and film thickness measurements. The same boiling mechanism as described by Merte, with a large coalesced bubble, was observed. At the heated surface, a microlayer under the primary bubbles was occasionally replaced by dry patches. The measured thickness of the microlayer (variable in space and time) was between 100 and 10 µm. Enhancement in heat transfer (with respect to terrestrial conditions) was encountered. The authors claim to have obtained steady subcooled pool boiling conditions, and that it is difficult to maintain them over a long period in nearly saturated states, due to the microlayer evaporation.

Qiu et al. (1999) conducted experiments in parabolic flight with saturated and slightly subcooled water on a flat surface with a single, controlled-size nucleation site to investigate on the growth of a single bubble, for gravity values from 10⁻² g to 1.8 g. A dependence of detachment diameter on \( g^{-0.5} \) was found. On this basis, a detachment diameter of 280 mm is predicted for a water bubble at a gravity level of 10⁻⁴ g, but the authors have no experimental confirmation of this. Remarkably, the authors note also that a little variation in subcooling has no effect on the detachment diameter, but greatly affects the growth time.

Kim et al. (2000) used a sophisticated flat multi-array heater (made up by 96 0.27-mm square micro heaters) to conduct pool boiling experiments on FC-72 in parabolic flight and sounding rocket at imposed surface temperature. Local mapping of heat flux underneath growing bubbles was thus possible.

Straub and coworkers (Straub et al., 1990, 1991; Straub, 1992; Straub, 1994) performed extensive tests with various organic refrigerants (R11, R12, R22, 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 hemispherical heater). Sounding rocket (TEXUS) experiments investigated boiling of R113 on wires and flat plates (Zell et al., 1984). The same boiling mechanism as reported above was described for flat plates; and a decrease of 50% in heat transfer coefficient was found. For wires, the detachment of bubbles 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 independent of the gravity level in both sounding rocket and parabolic flight experiments (Straub, 1992).

Recently, Straub (Straub and Micko, 1996; Steinbichler et al., 1998) 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/m² 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 a wire geometry. Critical heat flux was not reached at a heat flux of 350 kW/m² (at a reduced pressure of 0.55), i.e. well above the predictions of the hydrodynamic theory. However, the value of CHF in terrestrial conditions was even higher, though its value was not reported in the paper.
Experiments with R123 and a hemispherical heater (1.41 mm diameter) were also conducted in the BDPU facility, owned by ESA (Straub et al., 1996; Steinbichler et al., 1998) for heat flux up to 300 kW/m², 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, collapses rapidly restarting the process.

According to the wide experience of Straub, nucleate boiling is determined by primary and secondary mechanisms (Straub, 1992). The primary mechanisms are independent of gravity, and they are determined by the evaporation in the so-called microwedge underneath the bubble and by capillary forces. The secondary mechanisms are responsible for vapor transport: they are buoyancy, coalescence processes, momentum of bubble growth and formation, and thermocapillary flow for subcooled states. In microgravity, buoyancy can largely be replaced by the other secondary mechanisms.

3. DISCUSSION OF RESULTS

3.1 Main experimental outcomes

Due to the limited availability of flight opportunities, the experimental activity is still quite fragmentary and a general picture of the phenomenon has yet to be completed. However, an attempt is made to draw some general conclusions, as reported in the following.

- Steady-state long-term nucleate pool boiling can be attained in micro-g. The possibility is higher with greater subcoolings and low heat fluxes. Debate is still open on the possibility of maintaining boiling indefinitely, and on the role played by fluid properties and surface dimension. To the authors’ knowledge, steady state pool boiling was maintained for a maximum time of 280 s by Merte (1998). Straub (1998) points out that the limited size of the test containers used so far may also play a role.

- Due to power limitations, and cooling difficulties, the maximum value of the imposed heat flux is limited.

- The results on nucleate pool boiling performance are puzzling: nucleate boiling seems poorly affected by gravity acceleration for wire geometry, while it is generally enhanced on flat plates. Nonetheless, 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. Lee and Merte, 1998, and Steinbichler et al., 1998).

- 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, as shown in the following.

- Bubbles are definitely larger in microgravity. Mechanisms of lateral coalescence of bubbles along the heater surface have often been observed: the results is an enhancement of heat transfer. Vertical coalescence was observed as well.

- In several conditions, including boiling of binary mixtures, Marangoni convection plays a fundamental role, which has still to be completely assessed.

- Critical heat flux in pool boiling is reduced in low gravity. The validity of the available correlations and models for low gravity conditions has still to be verified.

3.2 The influence of gravity on boiling mechanisms

In the following, the most accepted mechanisms of boiling will be briefly reviewed in the attempt to identify the possible role played by gravity in them. As a very large number of theories about pool boiling mechanisms exists, only a very schematic treatment will be provided herein, to stress the main features.

3.2.1 Bubble growth at the wall

Several mechanisms have been proposed for bubble growth and it is not possible to deal with all of them exhaustively in a very limited space. During the very first bubble growth period, the bubble is entirely immersed in the highly superheated thermal boundary layer close to the wall and the growth is essentially inertia controlled and independent of liquid superheating and gravity. As time elapses, the growth is mainly governed by energy exchanges (asymptotic growth), and the bubble is attached to the wall through a small vapor stem, while a very thin layer of superheated liquid is placed under the bubble base (evaporation microlayer). Moreover the lower part of the bubble interface is also surrounded by superheated liquid with very strong temperature gradients directed towards the interface. In case of saturated boiling, the bubble top is in touch with a very slightly superheated liquid with smaller thermal gradients (relaxation microlayer according to Van Stralen and Cole, 1979) and the interface is practically isothermal (Beer et al., 1977). In case of subcooled boiling, the bubble top is in contact with subcooled liquid and the thermal gradient value depends on the degree of subcooling.

One more mechanism plays a role in supplying heat to the bubble in the region close to the wall where large temperature gradients are present and the liquid-vapor interface is not isothermal. In fact in this case thermal convection exists in the liquid, due both to buoyancy and to surface tension gradients, which enhances heat transfer between the two phases (Delhaye et al., 1980, Mc Grew et al., 1966) and between the heated wall and the liquid in the non-boiling region (i.e. among the bubbles).

The mechanism of thermocapillary (or Marangoni) convection can be explained as follows: for most fluids, surface tension decreases with increasing temperature. Thus, if there is a temperature gradient along an interface, a force arises in the opposite direction bringing the liquid from hot to cold. In some cases the contribution of Marangoni
Convection is even greater than the one due to density gradients (of course, this last mechanism is lacking in the absence of gravity).

The liquid velocity can thus be estimated as due to two different components:

\[ u_\sigma = \frac{L}{\eta} |\text{grad } \sigma|, u_\rho = \frac{\beta g \Delta T L^2}{\nu} \]  

(1)

where the first term is due to surface tension gradients, the second one to buoyancy and \( L \) is a significant length of the problem. The ratio of the above quantities:

\[ G_I = \frac{\beta g \Delta T L \rho_l}{|\text{grad } \sigma|} \]  

(2)

gives an idea of the relative importance of the two terms. Large differences in the estimated values of \( u_\sigma \) in Eq.(1) exist in the open literature.

Once \( |\text{grad } \sigma| \) is given as \( \Delta \sigma / L \) and the buoyancy term is only attributable to thermal convection, the quantity reported in Eq.(2) represents the ratio of the Rayleigh to Marangoni number

\[ Ra = \beta g \frac{L^3 \Delta T}{\nu^2 \rho_l \text{Pr}}, \quad Ma = \frac{L \Delta \sigma}{\rho_l \nu^2 \text{Pr}} \]  

(3)

The contribution to the total heat transfer of Marangoni flow is usually assumed negligible in on-earth saturated nucleate boiling with respect to the latent and sensible ones. On the contrary it might play a significant role in subcooled boiling (Straub, 1992) and close to the peak heat flux for small heating surface (Lienhard and Dhir, 1973a, 1973b). Anyway there is not a general agreement on this point, also due to the difficulty of measuring the above quantities and to the fact that \( \Delta \sigma \) depends on \( \Delta T \) as all the other phenomena described so far.

Once a bubble is present in subcooled liquid, a Marangoni liquid flow develops along its surface, being directed (for fluids with negative \( d \sigma /dT \)) from the heated wall towards the bulk of fluid, forming a plume which is quite evident in interferometric mesurements. The reaction to Marangoni flux keeps the bubble pressed against the surface and hinder its detachment. However, once the bubble detaches, the drift Marangoni streams carry it away from the surface. The situation is reversed in the so called positive mixtures, where, due to a surface tension gradient of opposite sign than above induced by the concentration gradients, the Marangoni currents are directed towards the heating surface. In this case, the bubble detachment is eased and, according to Abe and Iwasaki (1999) this is the main cause of enhancement of boiling heat transfer in mixtures in microgravity. The direct (for pure fluids) and reverse (for mixtures) Marangoni flux along the bubble surface were experimentally detected by interferometric techniques. Similar considerations were developed by Ahmed and Carey (1998) and by Zhang and Chao (1999).
Bubble growth is influenced by a large number of factors, last but not least the cavity size distribution on the heater. It is worth quoting Hsu and Graham (1986) who wrote that “predicting individual bubble growth is as impossible as trying to predict the growth rate of a particular boy using a universal equation”. This has probably led, in the past, to capturing the contributions of the various mechanisms in a single dimensionless group, $Ja$, then tuning the correlations through the values of the empirical constants. More recently, statistical approach and evaluation by computer codes start to be pursued.

Under microgravity conditions (Straub et al., 1990) it was found (R113 at 26°C and reduced pressure $p/p_{cri} = 0.013$) that bubble growth rate can be expressed as

$$ D = 0.62 \sqrt{a \cdot t} $$

(4)

This is in close agreement with the case of bubble growth controlled by microlayer evaporation (Van Stralen and Cole, 1979) that provides a value 0.66 for the constant. Therefore, this mechanism, that is important at low pressure on earth, might the dominating mechanism at low pressure and reduced gravity ($g/g_0 = 10^{-4}$) for asymptotic bubble growth.

### 3.2.2 Bubble detachment diameter and frequency

As is well known, bubbles can detach from the wall or even condense before the detachment depending on the degree of liquid subcooling. In some cases, they stay attached at the surface, and act as sort of “heat pipes” with vapor production at their base and condensation at the top.

The phenomenon of bubble detachment has always been considered as the result of a competition between “attaching” forces and “detaching” ones. In the very early approach of Fritz (1935) the detaching force is buoyancy and the attaching one is surface tension at the bubble neck, resulting in the classical formula:

$$ D_d = C \cdot \Phi \left[ \frac{\sigma}{g \cdot (\rho_l - \rho_g)} \right]^{1/2} = C \cdot \Phi \cdot l_L $$

(5)

where $l_L$ is the Laplace (or capillarity) length. $C = 0.0208$ was proposed in the original formula if the contact angle $\Phi$ is in degrees.

Such a simple approach implies of course that in reduced gravity no detachment (or only detachment at very large diameter) could take place. It is however common experience that even in microgravity bubble detachment occurs at relatively small diameters if a thermal field is present. The problem is rather to remove the lifted bubbles away from the surface before coalescence occurs.

The explanation is that other forces, whose action is masked by gravity on earth, come into play. Different values of detachment diameters, than those predicted by Eq.(5), are to be expected even in terrestrial conditions if the other forces are significant. As a matter of fact, the classification of these forces (liquid and gas inertia;
thermocapillary convection; surface tension; fluid-dynamic interaction with previously detached bubbles) between the attaching or the detaching ones it is not unequivocal.

More sophisticated expressions than Eq.(5) have been proposed for detachment diameter: a dependence of $D_d$ on $Ja$, and still on $g^{1/2}$, has been found at low pressure; at high heat flux and elevated saturation pressure $D_d$ is made to depend on $Ja$ and $g^{-1/3}$ (Dhir, 1999).

Under reduced gravity pool boiling the following mechanisms of bubble departure was found (Straub et al., 1990): inertia force at low pressure, vertical and horizontal coalescence, lifting and replacement of the larger bubbles by smaller ones. If $D_0$ is the detachment diameter at earth gravity ($g_0$) the following relation (Straub et al., 1990) was found to hold:

$$
\frac{D_d}{D_0} = \left( \frac{g}{g_0} \right)^{-m}
$$

where $m=0.30-0.39$ for wires and cylinders and $m=0.24-0.31$ for plate. Qiu et al. (1999) found a value of $m = 0.5$, for gravity values from $10^{-2}$ g to 1.8 g, in agreement with Eq.(5). Siegel & Keshock (1964) found for boiling water values of $m$ between 0.33 and 0.5, with a better agreement with $m = 0.5$ for $0.01g < g_c < 0.1$ g. Moreover, the size of the bubbles depends on the size of the heater, in the sense that smaller bubbles correspond to smaller heaters, as it occurs on earth.

The frequency of detachment of the bubbles is related to the waiting time $t_w$ and to the growth time $t_g$, $f = (t_w + t_g)^{-1}$. The former time, $t_w$, is the one needed to overheat a proper liquid layer close to the wall in order to activate the nucleation site. It mainly depends on the heater surface morphology and on the thermophysical properties of the liquid and the wall, and thus its evaluation is not straightforward (see e.g. Hsu and Graham, 1986, or Dhir, 1999). Theoretically the second one can be evaluated by combining the growth rate (Eq. 0) with the value of the detachment diameter (Eq. 0). Such an approach meets with little success (Dhir, 1999) due to the cavity size distribution, bubble interaction, and the difficulty to predict actual heat transfer rate. So, empirical correlations of the form $D_d f^{m} = const$ have been proposed. The most comprehensive one is due to Malenkov (1971):

$$
f = \frac{w}{\pi D_d} \left( 1 + \frac{q''}{\rho_l h_{fg} \rho_f w} \right)
$$

where $w$ has the dimension of a velocity and is given by

$$
w = \sqrt{\frac{D_d g (\rho_l - \rho_g)}{2(\rho_l + \rho_g)}} \frac{2\sigma}{D_d (\rho_l + \rho_g)}
$$

If the heat flux is sufficiently small to neglect the correction in the round bracket in Eq. (0), for large departure diameters the second term in Eq. (0) is small, and the $D_d f^{1/2}$
is found to be a constant. At intermediate diameters the two terms in square bracket balance each other and the classical relationship $D_A f = \text{const}$ is approached. At small detachment diameter, or at low gravity, the second term in Eq. (0) dominates and the relation is of the kind $D_A f^{2/3} = \text{const}$. As far as known, this model has never been tested in microgravity conditions. It is also worth remarking that the size of the nucleation sites is not accounted for by Eq. (0).

### 3.2.3 Nucleate boiling heat transfer

At least two vapor patterns can be recognized in nucleate boiling: the single bubble and the jets and columns ones. In the first one bubbles do not appreciably interact with each other and sufficiently wide regions of liquid are present on the wall among them. In the second region much of the wall is covered by swirling vapor columns. In between, single bubbles start coalescing and a transition from one to the other regime occurs (Zuber, 1963). The heat transfer from the heating wall can be estimated as the sum of three main contributions (Beer et al., 1977):

a) natural convection between the realms of influence of the bubbles, $q_{nc}$, which can be evaluated by the usual correlations of natural single-phase convection;

b) evaporation given by $q_e = N f h_{fg} \rho_g$, being $N$ the number of nucleation sites and $f$ the bubble frequency;

c) the drift currents which remove hot liquid (at an average temperature $T_m$) from the surface, $q_d = N f V_{dr} (T_m - T_{sat})$, where $V_{dr}$ is the drift current volume roughly approximated as $V_d/2$. This drift flow brings "cold" liquid to the wall, thus destroying the superheated liquid layer and causing transient heat conduction from the heater in order to restore this layer. This motion is caused by the wake flow of the detached rising bubble.

Different models for the three contributions exist, see e.g Dhir (1999).

The contribution of the Marangoni effect has been widely discounted in the classical boiling literature. A better understanding of this effect is being gained by microgravity related studies and, for example, it was been found that for subcooled boiling with R113 the total heat flux from the wall is mainly due to Marangoni effects both in micro-g and in normal gravity conditions (Zell et al. 1984).

Though several mechanistic models of boiling phenomena have been developed, they encounter difficulties because they themselves have employed empirical parameters. Thus, prediction of heat transfer performance in nucleate pool boiling still relies on empirical correlations. Generally, the dependence on gravity can be expressed by a power law

$$\frac{\alpha}{\alpha_0} = \left(\frac{g}{g_0}\right)^n$$  \hspace{1cm} (9)
The exponent is different if constant heat flux or constant wall temperatures are compared. Straub et al., (1990) have reported that $n$ can range from -0.4 to 0.5; a few examples are given in the following.

One of the most widely used correlations is the Rohsenow (1952) one, which can be rearranged as

$$
\frac{q''}{\Delta T_{sat} k_l} = \frac{1}{C_{sf}} \left( \frac{q''}{\eta f h_{fg} \sqrt{g (\rho_l - \rho_g)}} \right)^{-0.67} \text{Pr}_{l}^{-0.7} \tag{10}
$$

which theoretically implies $n = 0.83$, for the same value of $q''$ and $n = 0.5$ if a constant value of $\Delta T$ is retained. Nonetheless, the advice is given to consider the gravity acceleration as a simple dimensional constant (Dhir, 1999). Thus, the correlation that has been successfully used to predict pool boiling performance in microgravity, uses the terrestrial value of $g$ (Motoya et al., 1999). This is consistent with the fact that pool boiling performance is weakly affected by gravity value. However, questions could be raised on the mechanistic models assumed to justify the form of Eq. (10). Zhang and Chao (1999) propose to retain the Rohsenow model also in microgravity, supplementing it with the actual bubble departure diameter in place of the Laplace length.

The correlation by Cooper (1984)

$$
\alpha = C \left( \frac{pr}{p_{crit}} \right)^{0.12 - 0.091 \ln R_p} \left( -0.4343 \ln \frac{p}{p_{crit}} \right)^{-0.55} M^{-0.5} q''^{0.67} \tag{11}
$$

is in dimensional form ($R_p$ is the roughness in $\mu$m 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. the one of Yagov (1988).

A general correlation proposed in VDI Heat Atlas (1993) is

$$
\alpha = \alpha_{ref} \left( \frac{q''}{q''_{ref}} \right)^m \text{ where } m = 0.9 - 0.3 \left( \frac{p}{p_{crit}} \right)^{0.3} \tag{12}
$$

where $\alpha_{ref}$ is determined by experiments or by tables given in VDI Heat Atlas for several fluids. In the absence of data, $\alpha_{ref}$ can be evaluated by the correlation by Stephan and Preusser

$$
\text{Nu} = \frac{q'' D_d}{\Delta T_{sat} k_l} = 0.1 \left( \frac{q'' D_d}{T_{sat} k_l} \right)^{0.674} \left( \frac{\rho_g}{\rho_l} \right)^{0.156} \left( \frac{k_{fg} D_d^2}{a_l^2} \right)^{0.371} \left( \frac{a_l^2 \rho_l}{\sigma D_d} \right)^{0.35} \text{Pr}_{l}^{-0.16} \tag{13}
$$
where $D_d$ is given by Eq.(0). Hence, the gravity constant appears through the capillarity length inside $D_d$, resulting in a very little value of $n$ ($n = -0.033$ for the same heat flux).

Stephan and Abdelsalam (1980) improved the accuracy of Eq. (28) by fitting a large amount of experimental data, adding new dimensionless groups and formulating different values of the exponents $m_1, \ldots, m_8$ according to the class of fluids considered.

\[
\text{Nu} = \frac{q'' D_d}{\Delta T_{sat} k_F} = C \left( \frac{q'' D_d}{T_{sat} k_F} \right)^{m_1} \left( \frac{a_f^2 \rho_f}{\sigma D_d} \right)^{m_2} \left( \frac{c_{pl} T_{sat} D_d^2}{a_f^2} \right)^{m_3} \left( \frac{h_{fg} D_d^2}{a_f^2} \right)^{m_4} \left( \frac{\rho_g}{\rho_f} \right)^{m_5} \left( \frac{\rho_f - \rho_g}{\rho_f} \right)^{m_6} \left( \frac{\rho_f c_{pp} k_p}{\rho_f c_{pl} k_f} \right)^{m_7} \left( \frac{Pr_f}{Pr_g} \right)^{m_8}
\]

Depending on the value of the exponents (for the same value of $q''$), a value of $n$ from -0.08 (hydrocarbons) to 0.48 (water) is found. However, a simple extrapolation to microgravity conditions can be expected to be incorrect for an empirically based correlation.

Ohta et al. (1998) measured $\alpha = C q'' n$, where $n$ is 0.9-1 in microgravity and 0.8 in normal gravity. Grassi and Di Marco (1999a) found a good agreement with the VDI correlation, Eq.(12), for low and intermediate heat fluxes on a wire, both in normal and in reduced gravity.

### 3.2.4 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

\[
q''_{CHF} = K q''_{ref}
\]

where

\[
q''_{ref} = \rho_g^{0.5} h_{fg} \left[ \sigma g (\rho_f - \rho_g) \right]^{0.25}
\]

In Eq.(15), 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, 1985) and for flat plates was assumed 0.131 by Zuber (1959) and 0.149 by Lienhard (Lienhard and Dhir, 1973a).

Pool boiling on wires and small bodies has been extensively studied in a number of papers in the 1960-and 1970s. 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

\[ R' = \sqrt{\text{Bo}} = R \sqrt{\frac{g(\rho_f - \rho_L)}{\sigma}} = \frac{R}{l_L} \]  

(17)

As an example, for wires, values of \( K \) have been proposed by Lienhard and Dhir (1973b) in the following form for small values of \( R' \)

\[
\begin{cases}
K = 0.123 \text{Bo}^{1/6} & \text{for } 0.15 \leq R' \leq 1.2 \\
K = 0.118 & \text{for } R' \geq 1.2
\end{cases}
\]  

(18)

The scattering of the experimental data in literature is quite high for \( \text{Bo} < 0.15 \), allowing Lienhard and Dhir (1973b) and Sun and Lienhard (1970) to claim that they can no longer be correlated by \( R' \) alone. As a result of photographic studies on wires, Bakhru and Lienhard (1972) concluded that for \( R' < 0.07 \) the 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 the heat flux nor a jump in the 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 a complete blanketing of the surface is possibly related to the vapor front propagation on the surface or to the coalescence of the bubble population. 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 \( \text{Bo} \) as well as a variation in the size of the heater. Thus, heaters that are considered “large” in normal gravity may become utterly “small” as gravity decreases. This has a strong physical implication, since the scaling length in Bond number is the capillarity length, which governs several boiling phenomena, starting from bubble size. On the other hand, in the currently available microgravity experimental facilities, the adoption of very large test sections is prevented by space, power and weight limitations.

Even assuming that the present correlations can be extended to reduced gravity conditions, expressions like Eqs.(18) yield a non-trivial dependence of the critical heat flux on gravity. This means that for very low gravity, a simple “power law” dependency, like \( g^{1/4} \) or \( g^{1/8} \) is not necessarily valid.

For a “large” flat plate, correlations like Eqs.(15-16) lead to a dependence of critical heat flux on \( g^{0.25} \); this fact has never been satisfactorily tested. Oka et al. (1995) have reported a decrease of CHF with \( g \) in parabolic flights, which matches the dependence on \( g^{0.25} \) within the experimental error, but they have considered this fact as tentative, since further experiments carried on at \( 10^{-5} \) \( g \) deviated significantly from the one-fourth power relationship (Oka et al., 1996).

Straub et al. (1990) claimed that the critical heat flux measured on wires during parabolic and sounding rocket flights are higher than those predicted by the theory (or its
extrapolation). Besides, the trend of critical heat flux vs. $Bo$ was monotonically decreasing and no reduction in CHF could be observed for $\sqrt{Bo} < 0.1$, in disagreement with most of the data reported by Lienhard and Dhir (1973b) in normal and enhanced gravity. However, some data obtained in droptowers, reported by Straub (1999) seems to confirm the classical trend.

Di Marco and Grassi (1999b) collected critical heat flux data for pool boiling on wires for various values of the gravity acceleration: the data are compared with others obtained by Hong et al. (1995) on thin wires in normal gravity in Fig.5. For $R' > 0.08$, the data obtained in reduced or enhanced gravity lie in the range of most of the other experimental data. Thus the Bond number 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 for thinner wires obtained in micro-gravity are very well separated from the data obtained in normal gravity at the same value of $R'$. 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 of Mohan-Rao and Andrews (1976) 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.

### 3.2.5 Electric field effect on boiling

The effect of the application of an electrostatic field (with a potential drop of several kilovolts) in a boiling system were first observed around 1920. Since then, a large amount of research work has been done in earth gravity conditions on electro-hydrodynamic (EHD) enhanced pool boiling mainly in view of its potential applications, for example, in cryogenics and heat exchangers, (Allen and Karayiannis, 1995). Nevertheless many physical aspects are still not completely understood.

The phenomenon of convective heat transfer in the presence of an electric field is described by the classical mass, momentum and energy fluid-dynamic conservation equations, to which the first two Maxwell equations, characterizing the electric field, and the free charge conservation equation must be added (Di Marco and Grassi, 1993). Appropriate constitutive models and boundary conditions are required too.

The most generally accepted expression for the volumic electric force that acts on a fluid, to be included in the momentum equation, is

$$F = \rho_E E \cdot \frac{1}{2} E^2 \text{grad} \, E + \text{grad} \left[ \frac{1}{2} \rho E^2 \left( \frac{\partial E}{\partial p} \right)_T \right]$$  \hspace{1cm} (19)$$

For a spherical gas bubble, this yields a net force driving it towards the zone of weaker electric field.
In the absence of free charge, this force is generally small. However in the absence of buoyancy it might be an important tool for phase separation.

Several basic mechanisms involved in the boiling process are expected to be influenced by the presence of an electric field. The main ones are: bubble growth on the wall and detachment, bubble buoyancy and rise velocity, liquid-vapor interface stability.

The main effects on boiling curve are the following:

- temperature overshoot at onset of boiling is reduced,
- critical heat flux is dramatically raised.
pool boiling heat transfer is generally enhanced, although the enhancement can be
minimal or cannot even take place in some geometrical configurations (e.g. wires).

film boiling is enhanced, the enhancement being larger at low heat flux.

All the above mentioned effects vary with the properties of the fluid, and the geometry
of the system and of the electric field: an optimal coupling has still to be identified. It is
noteworthy that imposing an electrostatic field requires a very limited level of electric
power, which can be very important in space applications.

4. CONCLUSIONS

The main results of the worldwide experimental activity on pool boiling in microgravity
have been summarized. It appears that pool boiling phenomena are less influenced by
gravity than might be expected. A review of the main pool boiling features has been
carried out and the primary effects of gravity and other force fields have been stressed
and compared with the available experimental results under microgravity conditions.
The most commonly accepted viewpoints have been reported for each aspect.

It has been observed that the empirical or semi-empirical models, developed for
boiling heat transfer in terrestrial conditions, do not trivially extend their validity outside
their range of application. Most of these models adopt as a scaling parameter the Laplace
length, whose value changes very strongly with gravitational acceleration. Hence, it has
to be assessed if its use has a real physical meaning.

If by “understanding” we mean that the behavior of the system can be predicted in
terms of the governing parameters, it should be concluded that boiling is a poorly
understood phenomenon, and many questions are still open. The “behavior” would
include the conditions for onset of boiling, the evolution of vapor bubbles and the
associated heat transfer, while the governing parameters range from the system
geometry, to the heater surface and fluid properties, and to system conditions like
pressure, temperature and, of course, gravity. All these issues still need refinement even
in normal gravity conditions.

At the beginning of microgravity studies, the question was whether at all pool
nucleate boiling can be maintained in the lack of buoyancy. Now the problem is shifting
on the limits of nucleate boiling in microgravity, on the mechanisms governing it in the
lack of buoyancy, on the methods to improve boiling performance in such conditions.
Thorough experimentation in microgravity conditions is thus needed to completely
assess the following aspects:

• possibility of steady state nucleate boiling heat transfer conditions. In this respect, the
  major problem to be faced is removal of vapor away from the surface rather than the
  bubble detachment;

• conditions for enhancement/degradation of nucleate boiling heat transfer in reduced
  gravity;
• heat transfer mechanisms and bubble flow structure at the surface;

• criteria for CHF transition.

Flow boiling mechanisms were found to be quite independent of gravity, and the design phase of components based on flow boiling has already started. On the other hand, equipment based on pool boiling is particularly suitable for space applications, since it is highly efficient and no power is required to circulate the fluid. The problem of phase separation in space has also to be considered: although centrifugal or capillarity based separators have already been realized, the task of improving their efficiency and minimize their power consumption and pressure drops has still to be pursued.

This work has already been initiated by several groups around the world, and encounters strong difficulties mainly due to the limited availability of test opportunities. The results obtained so far seem to indicate that boiling may be safely sustained in micro-g conditions with appropriate measures, and improvements in performances (e.g. by application of electric fields) are possible. However, such activity has still to be completed. It is believed that, after further experimentation, it will be possible to design efficient boiling systems for future spacecrafts.

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6. NOMENCLATURE

\( a \) \hspace{1cm} \text{thermal diffusivity}
\( \text{Bo} \) \hspace{1cm} \text{Bond number,} \; \ell/h_L
\( c_p \) \hspace{1cm} \text{specific heat capacity}
\( C \) \hspace{1cm} \text{generic constant}
\( D \) \hspace{1cm} \text{diameter}
\( E \) \hspace{1cm} \text{electric field intensity}
\( f \) \hspace{1cm} \text{frequency}
\( F \) \hspace{1cm} \text{volumic force}
\( g \) \hspace{1cm} \text{gravity acceleration}
\( h_{fg} \) \hspace{1cm} \text{saturation enthalpy}
\( \text{Ja} \) \hspace{1cm} \text{Jakob number}
\( k \) \hspace{1cm} \text{thermal conductivity}
\( K \) \hspace{1cm} \text{Kutatelatze constant, see Eqs. (15-16)}
\( l, L \) \hspace{1cm} \text{length}
\( l_L \) \hspace{1cm} \text{Laplace length}
\( \text{Ma} \) \hspace{1cm} \text{Marangoni number}
\( N \) \hspace{1cm} \text{number}
\( p \) \hspace{1cm} \text{pressure}
Prandtl number
heat flux
radius
dimensionless radius
Rayleigh number
temperature
time
velocity
volume

Greek Symbols

heat transfer coefficient
thermal dilatation coefficient
wall superheat, $T_p - T_{sat}$
electrical permittivity
dynamic viscosity
kinematic viscosity
density
free electric charge density
surface tension
contact angle
proportional

Subscripts

referred to earth conditions
bubble
critical
detachment
drift
film
gas
heater
Helmholtz
liquid
mean
heated wall
minimum film boiling
peak heat flux
reference
saturation
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