IN SEARCH OF PARAMETERS TO SCALE
CRITICAL HEAT FLUX WITH GRAVITY ACCELERATION

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ABSTRACT
An experimental facility was set up to investigate the critical heat flux pool boiling on a heated wire. The facility could be operated in parabolic flights experiments, allowing to collect data in variable gravity conditions. The arrangement allowed to achieve various combinations of pressure and subcooling, independently of the environmental conditions. The test section was an electrically heated platinum wire with different diameters (0.1 to 0.6 mm). The working fluid were R113 and FC-72. Ground experiments were carried out with wires of different diameters. Experiments in microgravity were run in a parabolic flight campaign, with a wire of 0.2 mm, covering mostly the nucleate boiling and CHF region at a pressure of 1 bar and with slightly subcooled liquid. A degradation of CHF (as expected) took place in micro-g. The correlations available in literature gave acceptable predictions. The Bond number was able to scale both the size and gravity effect satisfactorily.


1. INTRODUCTION
The prediction of boiling crisis is of paramount importance to evaluate the operational safety margins of pool boiling equipment. Quite reliable correlations have been developed in the past, giving good results in terrestrial conditions. In the prospect to install boiling devices on future space stations, the question is raised whether their validity can be extended to microgravity conditions. As detailed in the following section, the acceleration of gravity appears in CHF correlations, but it is still unclear if it is simply a dimensional constant or a real physical parameter. Experiments at different gravity levels are needed to assess this. Thus, an experimental facility was set up to investigate critical heat flux (CHF) in pool boiling on a heated wire in the presence of an electric field and in microgravity. A wire geometry has been selected for this kind of experiment; for its simplicity, small dimensions and weight and easy data handling, since severe limitations in weight and power are prescribed for microgravity experiments. Besides, this allowed also to generate a cylindrical non-uniform electric field around the heater, to study its effect on boiling (reported elsewhere, Di Marco & Grassi, 1996, 1997). Slightly subcooled conditions are always required in microgravity experiments to avoid facing the unpredictable behavior of a large mass of vapor. The present paper reports the outcomes of a quite wide experimentation on the effect of physical parameters, including gravity acceleration, on CHF in pool boiling.

2. STATE OF THE ART
Regardless of the modeling approach, critical heat flux data on flat plates have been often correlated in the so-called Zuber-Kutatelatze form

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

where

\[ q''_{\text{ref}} = \rho_{\ell}^{0.65} h_{\ell} \left[ \sigma g \left( \rho_{\ell} - \rho_{g} \right) \right]^{0.25} \]

In Eq. (1), if the heater is large with respect to the Taylor wavelength, \( K \) (often referred to as Kutatelatze number) is a constant: \( K \) can vary in the range 0.119-0.157, (Grassi, 1985) and for horizontal flat plates was assumed 0.131 by Zuber and 0.149 by Lienhard (Lienhard & Dhir, 1973). For small heaters, \( K \) is a function of Bond number, which scales buoyancy to capillary forces

\[ B_o = D^2 \frac{g \left( \rho_{\ell} - \rho_{g} \right)}{\sigma} \leq \frac{D^2}{l_{\ell}} \]

where \( D \) is a characteristic dimension of the heater. This dependence become significant at small values of \( B_o \) (typically, \( B_o < 3 \)). This may alter the relationship between CHF and \( g \) as predicted simply by Eq.(2), since a
variation in gravity acceleration affects $Bo$ as well as a variation in the dimensions of the heater. Hence, heaters that can be considered “large” in terrestrial conditions may become “small” in reduced gravity.

Pool boiling of wires has been extensively studied in a number of papers in the 60-70s. Remarkably, experimental data concerning chlorofluorocarbons, and of course fluoroinerts, are lacking. 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 radius, i.e. the square-root of the Bond number

$$ R' = \sqrt{Bo} \frac{R}{l_k} $$

(4)

Basically, four different ranges were identified with increasing $R'$, see also Fig.1. In the first zone ($R' < R_1$) the boiling curve has a continuously increasing trend and no transition can be identified. In the second one ($R_1 < R' < R_2$) CHF decreases with increasing $R'$. In the third one ($R_2 < R' < R_3$), CHF increases with $R'$, and finally in the fourth one ($R' > R_3$) CHF decreases again with increasing $R'$. A constant value close to the one for infinite plate is asymptotically approached for large values of $R'$. The scattering of the experimental data in literature is quite high in the two intermediate zones, allowing Lienhard and Dhir (1973b) and Sun & Lienhard (1970) to claim that they can no longer be correlated by $R'$ alone. The reported values for $R_1$, $R_2$ and $R_3$ differ slightly from an author to another: some of them are reported in Table 1.

It is generally agreed that in the second zone the boiling transition is triggered locally by an isolated bubble spreading as a patch: surface tension effects rather than hydrodynamics seem to control the phenomenon. The properties of the material of the heater may play a role in this range. As a result of photographic studies, Sun & Lienhard (1970) have concluded that for $R' > 0.07$ bubble coalescence rather than hydrodynamics is responsible for CHF and that the hydrodynamics mechanism is well established only for $R' > 0.15$.

![Fig. 1](image_url) Experimental data available in literature concerning CHF on wires.

Table 1 - Values of $R_1$, $R_2$ and $R_3$ according to different authors

<table>
<thead>
<tr>
<th>Authors</th>
<th>$R_1$</th>
<th>$R_2$</th>
<th>$R_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mohan Rao &amp; Andrews, 1976</td>
<td>0.02</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Lienhard &amp; Dhir, 1973b</td>
<td>0.01</td>
<td>0.03</td>
<td>0.12</td>
</tr>
<tr>
<td>Shimizu et al., 1993</td>
<td>0.02</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>Fujita &amp; Bai, 1996</td>
<td>0.03</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>
Mohan Rao and Andrews (1976) have correlated the data in the third zone in a semi-empirical way in the form

\[
K = \frac{0.21}{R} \left[ 1 + \frac{0.5}{(CR)^{0.75}} \right]^{0.75} \quad \text{for } 0.02 \leq R \leq 0.15 \quad (5)
\]

where \( C \) is a constant which takes into account the thickness of the so-called vapor blanket around the wire, to be determined experimentally. A range of \( C \) from 1 to 1.5 is proposed. The model is based on the hydrodynamic theory.

In the remaining two ranges \( (R>R_1) \) values of \( K \) have been proposed by Lienhard and Dhir (1973b) in the following form

\[
\begin{align*}
K &= 0.123 Bo^{-\frac{1}{2}} \quad \text{for } 0.15 \leq R \leq 1.2 \\
K &= 0.118 \quad \text{for } R \geq 1.2
\end{align*}
\]

An alternate formulation, (Sun & Lienhard, 1970) which is almost as satisfactory as the former one, is the following

\[
K = 0.117 + 0.297 \exp(-3.44 \sqrt{R'}) \quad \text{for } R' \geq 0.15 \quad (7)
\]

In deriving Eq.(7), a hydrodynamic mechanism of CHF was presumed, seeking the onset of the instability of vapor jets, of radius \( R+\delta \), leaving the heater. The parameter \( \delta \) was estimated by interpolation of a great number of experimental data.

Some of the experimental data obtained in the past for low values of \( R' \) for different fluids are reported in Fig.1, together with the predictions of Eqs. (5) and (7). The values of \( K \) have been normalized to 0.131, i.e. the generally agreed value for an infinite flat plate. Most of the data have been obtained in normal gravity; some of them refer to environmentally-safe perfluorinated fluid, trade mark by 3M.

In Search of Parameters to Scale Critical Heat Flux with Gravity Acceleration

3. EXPERIMENTAL APPARATUS

The experimental apparatus is shown in Fig.2. It consisted of an aluminum box containing the test section, which was heated by Joule effect by a direct current up to 30 A. A bellow, connected to the main vessel, was operated by pressurized nitrogen in the secondary side, to compensate volume variations due to vapor production and to maintain the pressure constant. The main vessel had two windows to allow video recording of the phenomenon with appropriate back-illumination. An external heating system, driven by a PID controller, maintained the fluid temperature constant up to ± 0.1 K.

Experiments were carried out using a horizontal platinum wire, which served as both a resistance heater and a resistance thermometer. The wires had a length of 45 mm and different diameters, namely 0.1, 0.127, 0.2, 0.3 0.5 and 0.6 mm, but only the 0.2 mm wire was tested at non standard gravity. The heater (see Fig.3) was made by brazing coaxially the platinum wire (the active heater) to two copper capillary tubes (1 mm O.D., 0.15 mm I.D.), designed to work at less than 1 K superheat at the maximum current rate in the experiments. Two further thin insulated wires (0.08 mm diameter) were passed inside the copper tubes and brazed to the copper-platinum junctions for direct voltage sensing and measurement at the two copper-platinum junctions, as can be seen in Fig.2. The facility was operated on ground and in microgravity, in two different parabolic flights campaigns.

Two fluids were tested: R113 (C Cl F) and FC-72, an environmentally-safe perfluorinated fluid, trade mark by 3M.

Measurements included:

- The bulk temperature, by averaging the readings of 2 AD-590 transducers located inside the cell;
- The pressure, by an absolute extensimetric transducer, 3.5 bar full scale;
- The acceleration in the x (roll) and y (yaw) axes of the aircraft, for in flight experiments, by means of piezoresitive accelerometers, 5g and 2g full scale, respectively;
- The voltage drop across the wire, \( \Delta V \)
The electric current flowing in the wire, $I$, by means of a calibrated shunt. The following quantities were derived from the above-mentioned measurements:
- The heat flux, from $\Delta V \times I$ measurement;
- The wire superheat, from wire resistance and platinum temperature-resistance calibration curve (Carrica et al., 1995)

$$R = R_0 \left( 1 + \beta T + \gamma T^2 \right)$$

where the temperature coefficients $\beta$, $\gamma$ and the cold resistance $R_0$ were obtained by calibration for every new wire.

The data were recorded on a PC equipped with a data acquisition system based on a 12 bit A.D. converter. The same computer controlled the operating parameters during each test. The electrical resistance wire was continuously monitored by a dedicated device, which shut off the power within 0.01 s at the achievement of the critical heat flux, to avoid severe wire overheating and the consequent damage. This allowed to reuse the same wire for many different CHF tests with no need to replace it. To reduce the random error in measurements, the reported data were averaged over a minimum of 20 samples.

The uncertainty in derived quantities were calculated by the error propagation formulae given in (Carrica et al., 1995b): the uncertainty in heat flux was 4%, mainly due to the evaluation of the heat transfer area. Besides, it must be noted that the critical heat flux had an inherent variability, which, for R113, could be quantified in roughly 10% in on-earth experiment (Grassi & Mazzoni, 1996).

4. EXPERIMENTAL RESULTS AND DISCUSSION

Ground Experiments
Terrestrial experiments were mainly devoted to assess the combined influence of the wire diameters and of the fluid properties on critical heat flux. Data were obtained in saturated or slightly subcooled conditions, at pressures of 0.075, 0.105, 0.155 MPa for R113 ($p_r = 0.022, 0.031, 0.046$, respectively), and of 0.075, 0.115, 0.16 MPa for FC-72 ($p_r = 0.04, 0.06, 0.09$, respectively).

The data obtained in subcooled conditions were reduced to the theoretical value for saturation by means of the Ivey-Morris correlation

$$q'_{CHF, sat} = q'_{CHF, sub} \left[ 1 + 0.1 J_a \left( \frac{\rho_r}{\rho_f} \right)^{0.25} \right]$$

which has been shown to give good predictions, at least for small subcoolings, for the tested fluids (Di Marco & Grassi, 1997b).

In all the ground tests, the heat flux was increased linearly up to reach the critical heat flux. The heat up rate ranged from 100 to 175 kW/m$^2$ s.
In Search of Parameters to Scale Critical Heat Flux with Gravity Acceleration

The data collected in ground experiments are shown in Fig. 3, where the value of CHF is plotted versus the dimensionless wire radius, $R'$. Tests in microgravity

The first parabolic flight campaign was carried out with R113 on a Cessna Citation II aircraft, owned jointly by T.U. Delft and National Aerospace Laboratory of the Netherlands. The second one was performed with FC-72 during the 24th ESA Parabolic Flight Campaign, aboard of the A300 “Zero-G” operated by Sogerma.

The parabolic trajectory allowed roughly 20 s of relatively good quality microgravity (0.02-0.03 g). Microgravity was achieved in the upper part of the trajectory, while during the two pull-ups before and after this phase the vertical acceleration was beyond 2 g. The residual acceleration during the micro-g phase was affected by oscillations (the so-called g-jitter) due to the pilots’ maneuvers and to the atmospheric turbulence. In the second campaign, the standard deviation in z-acceleration during micro-g phase ranged from 0.037 to 0.016 g. Spectral analysis revealed significant peaks at 35, 70 and 140 Hz. In the second campaign, some parabolas were performed at a level of 0.4 g (gravity acceleration on Mars), and in other instances the aircraft followed a spiraled trajectory, resulting in about 40 s of constant 1.5 g acceleration. This gave the unique opportunity to collect data at values of gravity acceleration different from standard and microgravity ones. To ease the condensation of the generated vapor, all the tests in flight were carried out in slightly subcooled conditions (2 to 4 K).

Experiments with R113 were run at a pressure ranging from 0.97 to 1.07 bar. The values were also divided by the factor given by Eq. (9) to account for the effect of subcooling. During this campaign, the software was not capable to perform test with increasing heat flux. The tests were thus run at constant heat flux, and the corresponding values of CHF are affected by a greater uncertainty.

Experiments with FC-72 were performed at a pressure of 1.15 bar, with almost 3 K of subcooling. In this series of experiments, the heat flux was increased linearly at the same rate as in ground experiments up to CHF. A very good repeatability of the results was obtained during the three days.

The data collected in parabolic flight are shown in Fig. 3.

Discussion

The obtained data are reported in the $K$-$R'$ plane, see Fig. 4. This figure is analogous to Fig. 1, but the data of other experimentalists were omitted for the sake of clarity. It can be seen that the correlation of Sun & Lienhard, Eq.(6) is still acceptable up to $R'=0.1$ for R113, although, as foreseen, it overestimates slightly the data. Conversely, it seems to underestimate the value of CHF for FC-72. A different value of the constant or of the exponent might yield better results. The data obtained in micro-g lies in the range of most of the other experimental data, and are quite
well fitted by Eq.(4), which fits also the data obtained in normal gravity. Thus it seems that the Bond number is a suitable parameter to scale the effect of gravity in this case. On the other hand, it should be noted that the data obtained with higher system pressure systematically lie below the others: a secondary effect of this variable should not be excluded.

It is worth mentioning that a reduction in the Kutatelatze number, $K$, does not directly imply a corresponding reduction in the value of critical heat flux: since $q_{\text{ref}}$ (a function of fluid properties only) increases with pressure (see Eq.2). The overall effect is an increase of CHF with pressure and a reduction with decreasing gravity acceleration. This is clear from Fig.3.

5. CONCLUSIONS
The occurrence of CHF on a wire in pool boiling was studied in a variety of experimental conditions, encompassing heater size, fluid nature and pressure, and gravity acceleration, in order to seek a suitable scaling parameter for CHF occurrence. On the basis of the reported data, the following main conclusions can be drawn.

It is confirmed that the Bond number is the main scaling parameter in this context. It was capable to scale size effect as well gravity ones. This notwithstanding, secondary effects have been observed: the Kutatelatze number, $K$, seems to be systematically lower with increasing system pressure.

The validity of the correlations and scaling groups reported in the literature seems to be confirmed also in variable gravity, although some refinement would be desirable to obtain a better accuracy.

The results allows to infer that the reduction of critical heat flux in reduced gravity conditions may be estimated quite well with the correlations already tested in terrestrial conditions. This conclusion might not extend to very low gravity acceleration, i.e. for very low Bond numbers, in a zone in which models and correlations are still lacking.

**NOMENCLATURE**

- $Bo$ Bond number (see Eq.3)
- $c_p$ liquid specific heat (J/kg K)
- $g$ gravity acceleration (m/s$^2$)
- $I$ current intensity (A)
- $h_f$ heat of vaporization (J/kg)
- $Ja$ Jakob number ($c_p \Delta T_{sat} \rho_f / h_f \rho_s$)
- $K$ Kutatelatze number (see Eq.1)
- $l_L$ Laplace length
- $p$ pressure (Pa)
- $p_r$ reduced pressure = $p/p_{\text{ref}}$ (Pa)
- $q''$ heat flux (W/m$^2$)
- $q''_{\text{ref}}$ reference heat flux (see Eq.2) (W/m$^2$)
- $r$ radial coordinate (m)
- $R$ radius of the wire (m)
- $R'$ dimensionless radius of the wire, see Eq(3)

**Fig. 4. Values of K and comparison with available correlations.**

Range of R113 micro-g data

Sun (1970) 90% data bounds
Sun (1970) correlation
Mohan Rao (1976), C=1.6
FC72, 1g, p=0.75
FC72, 1g, p=1.1
FC72, 1g, p=1.6
FC72, 0.02 g, p=1.1
FC72, 0.4 g, p=1.1
FC72, 1 g, p=1.1
FC72, 1.5 g, p=1.1

R113 data, 1g tests

0.01 0.10 1.00
0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
0.01 0.10 1.00
R'

Range of R113 micro-g data
In Search of Parameters to Scale Critical Heat Flux with Gravity Acceleration

\[
T \quad \text{temperature} \quad \text{(K)}
\]
\[
\Delta T_{sat} \quad \text{wire superheat} \quad \text{(K)}
\]
\[
\Delta T_{sub} \quad \text{subcooling} \quad \text{(K)}
\]
\[
\Delta V \quad \text{voltage drop across the wire} \quad \text{(V)}
\]
\[
\rho \quad \text{density} \quad \text{(kg/m}^3\text{)}
\]
\[
\sigma \quad \text{surface tension} \quad \text{(N/m)}
\]

**Suffixes**

- 0 at 0 °C
- \text{CHF} \quad \text{critical heat flux}
- \text{f} \quad \text{liquid}
- \text{g} \quad \text{gas}
- \text{eq} \quad \text{equivalent}
- \text{sub} \quad \text{subcooled}
- \text{sat} \quad \text{saturated}

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