COMBINED EFFECT OF ELECTRIC FIELD, SUBCOOLING AND MICROGRAVITY ON CRITICAL HEAT FLUX ON A WIRE IN POOL BOILING

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ABSTRACT
An experimental facility was set up to investigate pool boiling on a heated wire in the presence of an electric field and in reduced gravity. The arrangement allowed achieving various pressure and subcooling combinations, independently of the environmental conditions. The test section was an electrically heated platinum wire with diameter of 0.2 mm. The working fluid was R113 (C₂Cl₃F₃). A cylindrical electric field was generated imposing 0 to 10 kV d.c. to a 60 mm diameter “squirrel cage” mounted coaxially to the heater.

Ground experiments were mainly devoted to assessing the combined influence of subcooling and electric field on critical heat flux at different pressures. The two factors seem to act independently of each other in the tested range, and the pressure has no influence. Experiments in reduced gravity were run in a parabolic flight campaign, covering mostly the nucleate boiling and critical heat flux (CHF) region at a pressure of 1 bar and with slightly subcooled liquid. An improvement in CHF due to electric field is evident both in normal gravity (as well known) and in micro-g. However, the relative enhancement of the critical heat flux, with respect to the zero-field one, is the same both in normal and in reduced gravity. No further improvement at lower electric field, as predicted by a theory based on scaling groups, seems to take place in reduced gravity with respect to normal gravity.


INTRODUCTION
The effect of an electric field on boiling heat transfer has been evidenced many years ago (Jones 1978; Di Marco & Grassi, 1993). On-earth experiments revealed that the critical heat flux on a thin wire undergoes a more than three-fold increase by applying a high voltage cylindrical electrostatic field around the wire. In contrast, nucleate boiling performance is only slightly affected in this geometry (Carrica et al. 1995). The electric force may also act as a replacement for buoyancy in the absence of gravity, leading to significant technological developments in the field of design of boiling equipment and separation devices for space stations, considering also that the energy consumption is negligible. Thus, an experimental facility was set up to investigate 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 mainly to generate a cylindrical non-uniform electric field around the heater, allowing also for small dimensions and weight and easy data handling. Subcooled conditions are always required in microgravity experiments to avoid facing the unpredictable behavior of a large volume of vapor. The present paper deals with the effect of the above mentioned parameters (subcooling, gravity acceleration and electric field) on critical heat flux in pool boiling on a wire.

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

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

where

\[ q''_{ref} = \rho_s \alpha_s h_f \left[ \sigma g (\rho_f - \rho_v) \right]^{0.25} \]  

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).
Pool boiling on wires has been extensively studied in a number of papers in the 60-70s. Remarkably, experimental data concerning chlorofluorocarbons are lacking. A non-trivial dependence of critical heat flux on the diameter has been reported for small wires or tubes. 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,

\[ R' = \sqrt{\frac{Bo}{R}} = \frac{R}{\sqrt{\frac{g(\rho_f - \rho_g)}{\sigma} \frac{1}{l_e}}} \]

A variation in gravity acceleration affects Bo as well as a variation in diameter of the wire: some of the experimental data were obtained in reduced or enhanced gravity. 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 increasing \( R' \). 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 one author to another: some of them are reported in Table 1.

### 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>

It is generally agreed that in the second zone \( (R_1 < R' < R_2) \) 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 \( R' > 0.15 \).
Mohan Rao and Andrews (1976) have correlated the data for water in the second zone in a semi-empirical way in the form

\[ K = \frac{0.21}{R} \left[ 1 + \frac{0.5}{(CR')^2} \right]^{-0.75} \quad \text{for} \quad 0.02 \leq R' \leq 0.15 \]  

(4)

where \( C \) is a constant taking 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.

In the remaining two ranges (\( R' > R_2 \)) values of \( K \) have been proposed by Lienhard and Dhir (1973b) in the following form

\[
\begin{cases} 
K = 0.123 \cdot Bo^{-1/6} & \text{for } 0.15 \leq R' \leq 12 \\
K = 0.118 & \text{for } R' \geq 12 
\end{cases}
\]

(5)

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

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

(6)

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 (4) and (6). 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 enhanced gravity conditions (in a centrifuge) and only the data of Siegel & Howell (1965) (as reported by Sun & Lienhard, 1970) were obtained in very early microgravity experiments, in a free-falling apparatus of about 2.5 m height. A characteristic trend with a minimum and a maximum is evident in almost all the reported data series, although the scatter is very high. The minimum separating zones 1 and 2 lies in the range 0.02<\( R' <0.08 \) for all the reported data.

Terrestrial experiments revealed that the critical heat flux on a thin wire undergoes a strong increase by applying a high voltage cylindrical electrostatic field around the wire. Johnson (1968), assuming the validity of the hydrodynamic theory and that the only parameter affected by the electric field is the Taylor wavelength, derived theoretically the following relationship

\[
\frac{q''_{\text{CHF,E}}}{q''_{\text{CHF,0}}} = \sqrt{\frac{E^2 + E^{*2} + 3}{3}}
\]

(7)

where

\[ E^* = \frac{\varepsilon_{\text{eq}} E^2}{\sqrt{(\rho_1 - \rho_g) \sigma g}} \]

(8)

and \( \varepsilon_{\text{eq}} \) is a combination of dielectric permittivities of liquid and gas (e.g., defined in Di Marco & Grassi, 1993). Since the electric field varies as 1/r around the wire, the electric field intensity, \( E \), is a reference value determined in the following assumptions: the field distribution is evaluated in absence of vapor and \( E \) is calculated at a distance from the heater roughly equal to the average size of the detaching bubbles. Equation (7) has given very satisfactory results in modeling the increase of CHF with electric field in on-earth experiments (Carrica et al., 1995). A significant implication of Eq.(7) is that a substantially lower electric field intensity and, consequently, applied voltage may be needed to obtain the same enhancement in CHF in microgravity conditions.

The effect of subcooling in increasing critical heat flux is well assessed, and correlations expressing a linear increase with subcooling, like the one of Ivey and Morris (Carey, 1992)

\[ \frac{q'_{\text{CHF,sub}}}{q'_{\text{CHF,sat}}} = 1 + 0.1 \left( \frac{\rho_1}{\rho_g} \right)^{0.75} \frac{c_p \Delta T_{\text{sub}}}{h_{\text{fg}}} \]

(9)

have always been found satisfactory. As far as known, the only paper dealing with the combined effect of subcooling and electric field on critical heat flux on a wire is by Masson & Carrica (1995), who claim that the enhancing effect of an electric field is reduced in the presence of subcooling.

A limited amount of experimental data is available for CHF in reduced gravity on a wire. On a theoretical basis, Eq.(5) implies a dependence of critical heat flux on \( g^{1/8} \) for small wires, provided that the lower threshold of \( Bo \) for the validity of equations is not crossed.

For a flat plate, or large tubes, correlations like Eq.(1) lead to infer a dependence of critical heat flux on \( g^{0.25} \); this fact was never 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 occasional, since further experiments carried on at 10^5 g deviated significantly from the one-fourth power relationship. Straub et al. (1990) investigated nucleate pool boiling in microgravity in several geometrical configurations (small plates and wires) and have claimed that the critical heat flux measured on wires during parabolic and sounding rocket flights are higher than those predicted by the theory (or its extrapolation). Besides, the trend of critical heat flux versus gravity acceleration decreased monotonically and no reduction in CHF could be observed for \( R' <0.1 \), in disagreement with most of the data shown by Lienhard & Dhir (1973).

**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
A bellows, 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 phenomena with appropriate back-illumination. An external heating system, governed by a PID controller, maintained the fluid temperature constant up to ± 0.1 K.

Experiments were carried out using a horizontal platinum wire (of 0.2 mm diameter and 45 mm length) which served as both a resistance heater and a resistance thermometer. The heater was made by brazing coaxially the platinum wire (the active heater) to a 0.6 mm copper wire, designed to work at 1 K superheat at the maximum current rate in the experiments. Two further thin wires (0.1 mm diameter) were used for direct voltage sensing and measurement at the two copper-platinum junctions, as can be seen in Fig.2.

The electric field is obtained by imposing a d.c. potential drop up to 10 kV to a 8-rod cylindrical “squirrel cage”, of 60 mm diameter and 200 mm length, surrounding the heater. The electric field was thoroughly characterized via finite element (Grassi & Mazzoni, 1996) and finite difference (Ambrosini, 1996) analyses, which showed that the length of the cage is sufficient to avoid side effects along the active part of the heater. The trend in a section perpendicular to the wire is shown in Fig.3. The analyses showed also that, up to 10 mm from the wire axis, the field has the same 1/r trend as the one generated by a solid cylindrical electrode surrounding the heater, although with a lower intensity. The field obeyed the law $E = C V/r$, where $E$ is the field intensity at the wire surface, $V$ the high voltage applied to the rods and $C = 0.1034$ (while for a solid outer electrode $C = 0.1735$).

Measurements included:
- The bulk temperature, by averaging the readings of 4 AD-590 transducers located at various positions inside the cell;
- The pressure, by an absolute transducer, 3.5 bar full scale;
- The heat flux, from $\Delta V \times I$ measurement;
- The wire superheat, from wire resistance and platinum temperature-resistance calibration curve (Carrica et al., 1995).

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. In particular, the wire resistance was continuously monitored shutting off the power within 0.01 s at the achievement of the critical heat flux, to avoid severe wire overheating. To reduce the random error in measurements, the reported data were averaged over 125 to 500 samples.

Due to the above mentioned averaging procedure, the uncertainty on the data is thus mainly due to fixed errors, so the comparison among the results inside this data set is only slightly affected. The uncertainties 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 intrinsic variability, which could be quantified as roughly 10% in on-earth experiment (Grassi & Mazzoni, 1996) and 15% in low-gravity ones.

The facility was also operated in reduced gravity in parabolic flights carried out on a Cessna Citation II aircraft, owned jointly by T.U. Delft and National Aerospace Laboratory of the Netherlands. The parabolic trajectory allowed roughly 10 s of good quality microgravity (± 0.03 g). Although the term “reduced gravity” may be more appropriate to designate these conditions, the word “microgravity” has gained popularity in the field. Microgravity was achieved in the upper part of the trajectory, while during the two pull-ups before and after this phase the vertical acceleration was roughly 3 g and 2 g, respectively. Forty one useful parabolas were carried out during the three-day campaign, seven of which resulted in occurrence of CHF.

EXPERIMENTAL RESULTS AND DISCUSSION

Effect of subcooling

Ground experiments were mainly devoted to assess the combined influence of subcooling and electric field on critical heat flux. Data were obtained for fluid bulk temperatures ranging from 22 to 55 °C, and pressures of 0.075, 0.105, 0.155 MPa (\( p/p_c = 0.022, 0.031, 0.046 \), respectively). Figure 4 reports the values of the critical heat flux versus the dimensionless subcooling (often referred to as Jakob number, \( Ja \)). The data were normalized to the theoretical value for no electric field, obtained by Eqs (2), (6) and (9)

\[
q'_{\text{CHF, sub}} = 0.131q'_{\text{ref}}
\]

\[
\left[0.89 + 2.27\exp(-3.44\sqrt{R'})\right] 
\left[1 + 0.1Ja \left(\frac{\rho - \rho_f}{\rho_f}\right)^{0.25}\right]
\]

\( (10) \)

It is evident that in the tested range the enhancing effect on CHF due to the electric field is almost independent of both pressure and subcooling. The data are also in good agreement with the correlation for no electric field, taken from literature. However, a slight underestimation of the data for high \( Ja \) seems to take place. It should also be noted that the actual values of \( R' \) (0.105-0.098) are slightly below the threshold of validity of Eq.(6).

Former data, obtained in a different apparatus for higher values of electric field (Grassi & Mazzoni, 1996), indicate that the two factors act independently of each other up to a certain threshold, beyond which a sort of apparent asymptotic behavior starts to take place: the enhancing effect of electric field is reduced for high values of voltage or subcooling. Weak evidence of this fact may be observed also in Fig.4: the ratio of CHF in the presence of the electric field to the zero field one seems to be systematically reduced for the higher values of \( Ja \).

Effect of microgravity

Experiments in microgravity were run at a pressure ranging from 0.97 to 1.07 bar. To ease the condensation of

![Fig.4. Effect of subcooling on CHF at various pressures and electric field intensities (terrestrial conditions)](image1)

![Fig.3. Map of the electric field in a plane perpendicular to the wire for an applied potential of 10 kV (calculated via FE technique).](image2)
the generated vapor, the tests were carried out in slightly subcooled conditions (2 to 4 K).

The data are reported in Fig. 5, together with the ones obtained in a ground test, with the same subcooling, at normal gravity before the flight. In Fig. 6 the same data are normalized to the average value with zero electric field. The values were also divided by the factor given by Eq. (9) to account for the effect of subcooling.

An improvement in CHF due to electric field is evident in micro-g. However, the ratio of the critical heat flux with respect to the zero-field one is the same both in normal gravity and in micro-g. No further improvement at lower electric field, as predicted by a simple theory based on the scaling groups (see Eqs. 7-8) seems to take place in micro-g with respect to normal gravity.

The data obtained with zero field are also reported in the $K-R'$ plane, see Fig. 7. This figure is analogous to Fig. 1, but the data of other experimentalists (except the ones obtained by Siegel in reduced gravity) were omitted for the sake of clarity. It can be seen that the correlation of Sun &
CONCLUSIONS

The occurrence of CHF on a wire in pool boiling was studied in a variety of experimental conditions. On the basis of the reported data, the following two main conclusions can be drawn.

The effectiveness of an externally applied electric field in improving the CHF has never been questioned in all the experiments reported in the literature. The enhancing effect of electric field is confirmed in this work, for the particular geometry tested, in a quite wide range of variation of experimental parameters (pressure, subcooling, gravity acceleration).

Some preliminary conclusions may be drawn about the behavior in reduced gravity, notwithstanding that the amount of available data is too limited and the uncertainties are quite high. In the absence of an electric field, the validity of the correlations and scaling groups reported in the literature seems to be confirmed also in this case. In the presence of an electric field, the scaling criterion based on the group $El^*$ does not seem to be applicable, at least not in a trivial way. According to our research program, more data on CHF on wires at different levels of reduced gravity, both in the presence of an electric field or without, will become available in the near future to further clarify this point.

NOMENCLATURE

- $B_0$: Bond number (see Eq.3)
- $E$: electric field intensity (V/m)
- $El^*$: electrical influence number (see Eq.8)
- $c_p$: liquid specific heat (J/kg K)
- $g$: acceleration of gravity (m/s²)
- $I$: current intensity (A)
- $h_{fg}$: heat of vaporization (J/kg)
- $Ja$: Jakob number ($c_p \Delta T_{sat} \rho_f / h_{fg} \rho_s$)
- $K$: Kutateladze number (see Eq.1)
- $l_{L}$: Laplace length ($\sigma / g (\rho_f - \rho_s)0.5$) (m)
- $q^*$: heat flux (W/m²)
- $q_{ref}$: reference heat flux (see Eq.2) (W/m²)
- $r$: radial coordinate (m)
- $R$: radius of the wire (m)
- $R^*$: dimensionless radius of the wire, see Eq.(3)
- $T$: temperature (K)
- $\Delta T_{sat}$: wire superheat $T_w-T_{sat}$ (K)
- $\Delta T_{sub}$: subcooling (K)
- $\Delta V$: voltage drop across the wire (V)
- $\varepsilon$: dielectric permittivity (F/m)
- $\rho$: density (kg/m³)

$\sigma$: surface tension (N/m)

Suffixes

- 0: in the absence of electric field
- $CHF$: critical heat flux
- $f$: liquid
- $g$: gas
- $eq$: equivalent
- $E$: in the presence of electric field
- $sub$: subcooled
- $sat$: saturated
- $w$: wire

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