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Nucleate Pool Boiling in the Presence of an Electric Field: Effect of Subcooling and Heat-up Rate

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■ The purpose of the paper is to experimentally assess the effect exerted by subcooling degree and heat-up rate (i.e., the rate of increase of thermal flux) on the phenomenon of nucleate boiling in the presence of an electric field. To this aim, an experimental facility was set up to investigate pool boiling on a heated platinum wire of 0.2-mm diameter. The working fluid was R-113 ($C_2Cl_3F_3$). A cylindrical electric field (up to 21 MV/m at the heater surface) was imposed. The power was increased along a linear ramp, at a rate ranging from 2.5 mW/s to 6 W/s. Subcooling degrees up to 22 K (Ja = 0.146) were investigated. The results of zero-field measurements are in agreement with previous ones in the literature. The effect exerted by the electric field consists mainly of a strong increase in critical heat flux, whereas, for a given heat flux, the nucleate boiling performance can be either weakly degraded or slightly enhanced. The critical heat flux was found to remain nearly constant with increasing transient velocity up to a given heat-up rate and then to increase with it. The effect of subcooling on nucleate boiling is quite complex but, in any case, quite weak in the entire investigated range. © Elsevier Science Inc., 1997

Keywords: *pool boiling, electric field, subcooling*

INTRODUCTION

Effect of the Electric Field on Nucleate Pool Boiling

The effect of an electric field on boiling heat transfer was evidenced many years ago, as reported in Ref. 1. Nevertheless, controversy still exists on some related phenomena, such as the enhancing effect in nucleate boiling [2], and further investigation in "classical" geometry is needed to clarify these topics.

The electric field affects many boiling features such as bubble shape, detachment diameter, frequency, and number of nucleation sites. In addition, the fluid flow around the bubble and thus the thermal field can be modified. Moreover, changes in physical properties, such as surface tension and wettability, can be expected, even if they are usually discounted. Generally speaking, the volume of the detaching bubbles decreases at increasing value of the group [3]:

$$G_E = \frac{\varepsilon_0 E^2 L}{\sigma}. \qquad (1)$$

The detachment volume also shows a separate dependence on ε_l for nonpolar fluids [3], with an increasing prolate bubble eccentricity versus the liquid permittivity. Furthermore, in nonuniform electric fields, a net force acts on the bubbles that, for a tiny spherical bubble, can be given as [4]

$$\mathbf{F}_E = 2\pi r_b^3 \frac{\varepsilon_g - \varepsilon_l}{\varepsilon_g + 2\varepsilon_l} \varepsilon_0 \varepsilon_l \nabla E^2. \qquad (2)$$

This force tends to move the bubble, which generally has a lower dielectric permittivity, toward regions with weaker electric-field intensity. Therefore its effect depends on how it is directed with respect to gravity. For example, for upward-oriented surface and field strength decreasing from the surface outward, it accelerates the bubble detachment. To account for the relative magnitude of this force, referred to the buoyancy force, a dimensionless group can be introduced:

$$G_{b,e} = \frac{|\mathbf{F}_E|}{|\mathbf{F}_b|} = \frac{3(\varepsilon_l - \varepsilon_g)\varepsilon_0 \varepsilon_l |\nabla E^2|}{2(\varepsilon_g + 2\varepsilon_l)(\rho_l - \rho_g) g}. \qquad (3)$$

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

The overall effect of the electric field on nucleate boiling is still not completely established. Baboi et al. [4] reported an increase in boiling performance at low heat fluxes. For higher fluxes, they asserted quite weakly that

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"there is no effect on the relative heat exchange coefficient, but on further increase of the heat flux, the latter decreases somewhat."

For geometries similar to the present one, Cooper [5] proposed a correlation providing an electric-field enhancement of the heat-transfer coefficient decreasing with increasing heat flux:

$$\frac{\alpha_E}{\alpha_0} = 0.3\, G_{\mathrm{be}}^{0.165} \left(\frac{2 r_b q''}{h_{fg}} \right)^{-0.16}, \tag{4}$$

where the group in brackets is a Reynolds number in the form proposed by Rohsenow. This correlation was obtained by fitting previous data sets by other authors [4, 6, 7].

Uemura et al. [8] reported a little enhancement at very low heat fluxes for saturated pool boiling of R113 on a flat, horizontal, upward-facing surface. Beyond this range of fluxes, all the data (with and without electric field) collapse on a single curve.

Ogata and Yabe [9] reported data on nucleate boiling on a copper smooth pipe of 22.4-mm diameter. The investigated fluids were R-11 and a binary mixture of R-11 and methanol, to alter the electric relaxation time. A dc field up to 8.3 MV/m was established by means of a wire mesh 3 mm from the surface; that is, in a situation closer to the plane geometry than to the cylindrical one. The following main conclusions were drawn: (1) for $q'' = 5.8 \times 10^3$ W/m^2, a large heat transfer enhancement (8.5 times) took place for the binary mixture and a smaller one for pure R-11; (2) the interaction between bubble generation frequency and electrical relaxation time was found to be significant; (3) theoretical and experimental investigations of bubble behavior in a uniform field showed the importance of the field distortion, due to the bubble itself, in making predictions.

The effects of an electric field in natural convection, nucleate boiling, and critical heat flux on a wire were reported in a previous paper [10]. Field intensities up to 21 MV/m (for $V = 15$ kV) were investigated. The electric fields greatly enhanced the heat transfer in natural convection, in agreement with previous works. The onset of nucleate boiling appeared at lower superheats when increasing the electric field. Nevertheless, it was observed that, for some values of the heat flux, the heat transfer coefficient in nucleate boiling decreases when an electric field is externally imposed, showing the opposite trend with respect to other experiments. The effect of the system pressure was partially investigated in experiments at saturation temperature at pressures from 0.45 to 1.0 bar. The degradation observed in nucleate boiling at atmospheric pressure (102 ± 2 kPa) was reduced and even disappeared at low pressures.

Effect of Subcooling and Heat-up Rate on Nucleate Pool Boiling

The effect of subcooling on nucleate boiling performance was the subject of few but significant studies in the past —for example, Judd and Merte [11], Fand and Keswani [12], Ibrahim and Judd [13], Ulucakli and Merte [14], and Judd et al. [15]. In all these works, bulk subcooling was found to have a weak effect on nucleate boiling. The value of critical heat flux, on the other hand, is strongly increased with increasing subcooling. When ΔT_{sat} is plotted vs ΔT_{sub} for a given heat flux, the surface superheat, ΔT_{sat}, first increases and then decreases. The location of the maximum is shifted to higher subcoolings with increasing heat flux. At very high subcoolings, boiling is suppressed and the aforementioned curve approaches the natural circulation one. This behavior has been observed in both plane and cylindrical heater geometry for water and R113. As far as is known, no experiments were carried out about subcooled nucleate boiling in the presence of an electric field.

The effect of heat-up rate on nucleate pool boiling and critical heat flux was experimentally investigated by Sakurai and Shiotsu [16, 17] for an exponentially increasing heat input. They reported an increase in temperature overshoot at onset of boiling (attributed to a time lag in the activation of the originally unflooded cavities) and an increase in critical heat flux, which was neglectable below a threshold value of the time constant of the exponential process. Furthermore, two distinct processes were identified. In the so-called regular boiling, the transient nucleate boiling curve is shifted to higher values of ΔT_{sat} for the lower values of heat flux but recovers to the steady-state one before the steady-state critical heat flux value and remains along its extension until the transient critical heat flux is reached. In irregular boiling, the steady-state boiling curve is never recovered, and the entire boiling curve is shifted to higher values of ΔT_{sat}. The transition from the regular process to the irregular one is promoted by the increase in heat-up rate and the decrease in system pressure. Pasamehmetoglu et al. [18] proposed a model for transient critical heat flux based on Katto's macrolayer model [19] (referred to as a multistep model) that accounts for modified macrolayer thinning mechanisms and is in good agreement with experimental data concerning small wires.

Purpose of the Paper

The purpose of this paper is to assess the effect exerted by subcooling degree and heat-up rate (i.e., the rate of increase in thermal flux) on the phenomenon of nucleate boiling in the presence of an electric field. To this aim, an experimental facility was set up to investigate pool boiling on a heated wire. The study is also intended to establish the significance of short-time experiments, as are most of those carried out in microgravity conditions.

EXPERIMENTAL APPARATUS

Test Setup and Measurements

The experimental setup is shown in Fig. 1. It consisted of a stainless steel cylindrical vessel with lateral windows for visual observation.

Tests were run at atmospheric pressure (102 ± 2 kPa), both in saturated and subcooled conditions. The working fluid was R113 ($C_2Cl_3F_3$). Operation temperature was achieved by using a 300-W electric preheater, and a copper-finned condenser, cooled by tap water, condensed the vapor back to the pool. The pressure was controlled by means of a reflux condenser open to the atmosphere. In subcooled runs, the pool temperature was controlled by means of a PID regulator, achieving a variation lower

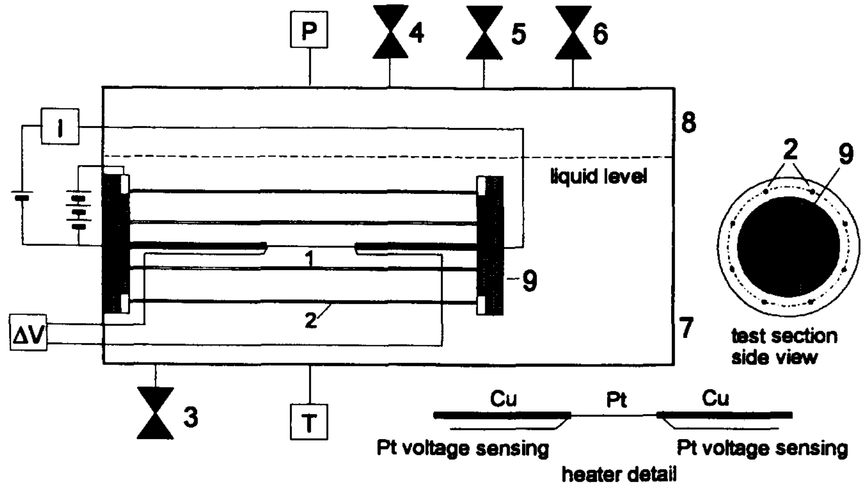

Figure 1. Sketch of the experimental apparatus: (1) heater, (2) high voltage cage wires, (3) drain valve, (4) fill valve, (5) to reflux condenser, (6) to vacuum line, (7) preheater, (8) condenser, (9) PTFE insulation.

than 0.2 K from the set point. Subcooling degrees up to 22 K (Ja = 0.146) were achieved, corresponding to a bulk temperature of 25.3° C.

Experiments were carried out by using horizontal platinum wires of 0.2-mm diameter and 49-mm length. The heaters were made by coaxially brazing the platinum wire to a 0.6-mm copper wire, designed to work at 1 K superheat at the maximum current rate in the experiments. Two additional thin wires (0.1-mm diameter) were used for direct voltage sensing the measurement at the two copper-platinum junctions, as can be seen in Fig. 1.

The electric field was generated by imposing from 0 to 15 kV dc to a 60-mm diameter, 8-wire cylindrical cage surrounding the heater. This configuration yielded a cylindrical field in the surrounding of the heater. The length of the cage was 240 mm to prevent side-end effects on the heater. Maximum care was taken in minimizing the size of the welding and sensing wiring to prevent big distortions on the electric field. The electric-field distribution was calculated by a finite-elements method and is reported in Fig. 2. It shows how the field stays cylindrical to a distance of 10 mm away from the heated wire; that is, in the region where the field influence should be stronger. The value of the electric field at the surface of the heater was $E = 1.4V_0$ (MV/m), where V_0 is the voltage applied to the outer cage in kilovolts.

The heat flux was calculated from the power given to the heater and the heater area. The temperature in the heater was measured by using the standard method of detection of the resistance of the platinum wire and making reference to the 0° C resistance from

$$R = R_0(1 + \beta T_w - \gamma T_w^2), \tag{5}$$

with $\beta = 3.908 \times 10^{-3}\ \mathrm{K}^{-1}$ and $\gamma = 5.802 \times 10^{-7}\ \mathrm{K}^{-2}$ [20]. The reference resistance, R_0, was calculated before the tests by least squares from many measurements at very low heat flux to ensure no superheat in the heater and reduced to 0° C by using the same Eq. (4). The temperature in the pool was measured by means of an AD590 transducer, giving an accuracy of ±0.1 K. All the experimental data were collected by a computer-based acquisition system with a 12-bit AD converter. Every data point was the result of an average of 100 measurements, to reduce high-frequency noise. The computer system, by means of a DA converter, was able to control the power supplied to the wire by the dc feeder. The heat input was increased step-by-step, and both the increase and the duration of each step could be preset by software. Owing to the very small steps used, the power increase could be considered linear with time, and the heat-up rate could be varied from 2.5 mW/s to 6 W/s.

Uncertainty Assessment

With the use of the standard error propagation procedure, the errors in measurements of heat flux, wire superheat, and heat transfer coefficient can be expressed as, respec-

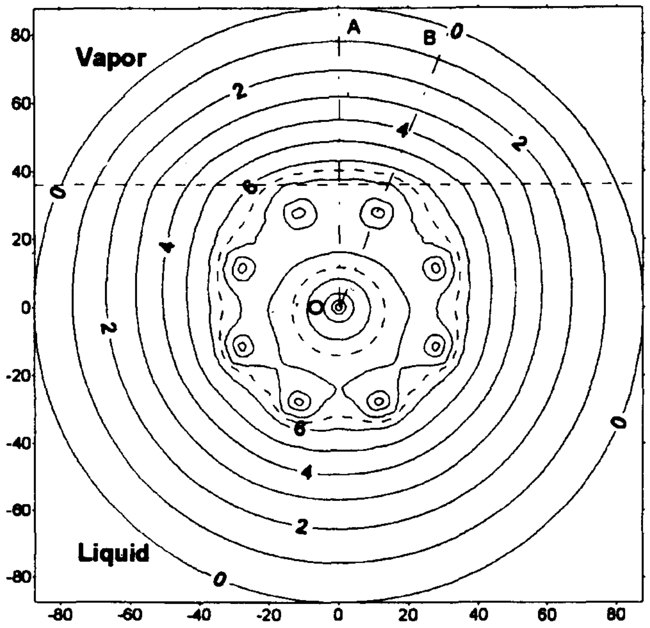

Figure 2. Electric-field distribution around the heater.

tively,

$$\delta_{q''}^2 = \delta_{\Delta V}^2 + \delta_I^2 + \delta_{A\text{h}}^2, \tag{6}$$

$$\delta_T^2 = \left(\frac{r'}{T_w}\right)^2 \left(\delta_{R_0}^2 + \delta_I^2 + \delta_{\Delta V}^2\right), \tag{7}$$

$$\delta_\alpha^2 = \delta_{A_h}^2 + \left(1 + \frac{r'}{T_w + T_b}\right)^2 \delta_I^2 + \left(1 - \frac{r'}{T_w - T_b}\right)^2 \delta_V^2 + \left(\frac{r'}{T_w - T_b}\right)^2 \delta_{R_0}^2 + \left(\frac{T_b}{T_w - T_b}\right)^2 \delta_{T_b}^2, \tag{8}$$

where

$$r' = \frac{1 + \beta T_w - \gamma T_w^2}{\beta - 2\gamma T_w}, \tag{9}$$

where δ_x represents the relative uncertainty in the generic quantity x. The estimated uncertainties are reported in Table 1. In nucleate boiling, the resulting random uncertainties are $\delta_{q''} = 0.2$–0.5%, $\delta_{\Delta T} = 1$–2%, and $\delta_\alpha = 3.5$–7.0%, with the largest values at the lowest heat fluxes. The error in heat-transfer area was not taken into account in this evaluation, because it is a bias and affects only the comparison with data sets by different authors. Only the random uncertainty is significant in comparing the data presented here, all of which refer to the same experimental setup and the same heater. The overall uncertainties are $\delta_{q''} = 4.1\%$, $\delta_{\Delta T} = 1$–2%, and $\delta_\alpha = 5$–8%, respectively.

A further source of uncertainty, which should be accounted for, is due to the heat losses by conductivity through the wire side ends. This leads to an underestimation of both the wire maximum temperature and the actual heat flux to the fluid and to an overestimation of the heat-transfer coefficient. This error can be shown to be less than 1.5% in nucleate boiling conditions [21]. Another consideration is that, in power transients, the heat released to the fluid is less than the heat input, owing to the thermal storage in the heater. However, because of the very small heat capacity of the wire, this effect was negligible even in the fastest power transients tested.

EXPERIMENTAL RESULTS

Heat-up Rate

Figure 3 shows the general trend of nucleate pool boiling with an applied electric field: heat-transfer enhancement takes place for very low heat fluxes and for very high ones. In the intermediate zone, heat transfer is slightly degraded. Consequently, the curves can show two crossover points (the first one is located at low heat flux and may not appear in the plots). The effect on pool boiling performance is quite low in every case, except for the very marked increase in the critical heat flux value.

Table 1. Estimated Uncertainties in Measurements

Quantity	*Reference Value*	$\delta_{\max}$
Voltage drop, ΔV		2.5 mV
Current, I		10 mA
Heater area, A_h	0.308×10^{-4} m^2	0.04
Reference resistance, R_0	0.156 Ω	0.005
Pool temperature, T_b	25–48° C	0.004

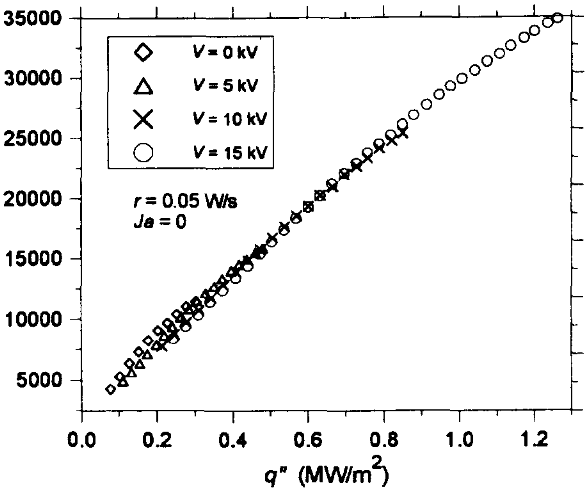

Figure 3. Heat-transfer coefficient vs heat flux for various values of V, at saturation (Ja = 0).

The nucleate boiling performance was not affected by the variation in the heat-up rate in the tested conditions. This is evidenced in Figs. 4 and 5, in which the trends are almost undistinguishable.

On the other hand, a sensible effect was observed on the value of the critical heat flux, which was increased for heat-up rates greater than a threshold. Below this value of heat-up rate, the critical heat flux value was nearly constant (Fig. 6), although a little decrease can still be noted for the 0-kV case. The threshold tends to shift at higher values when the electric field is applied.

The effect of heat-up rate, in the tested interval, was negligible even in subcooled conditions, as shown in Fig. 7.

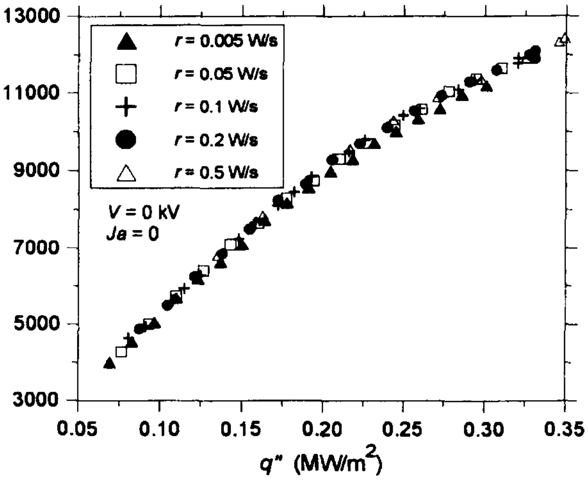

Figure 4. Heat-transfer coefficient vs heat flux for $V = 0$ kV and different heat-up rates, at saturation (Ja = 0).

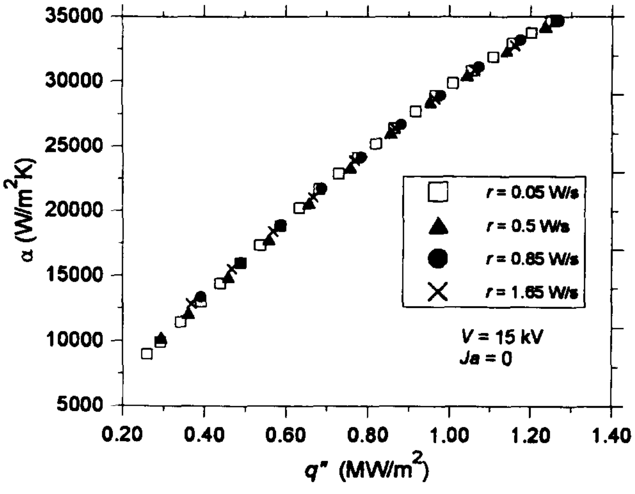

Figure 5. Heat-transfer coefficient vs heat flux for $V = 15$ kV and different heat-up rates, at saturation (Ja = 0).

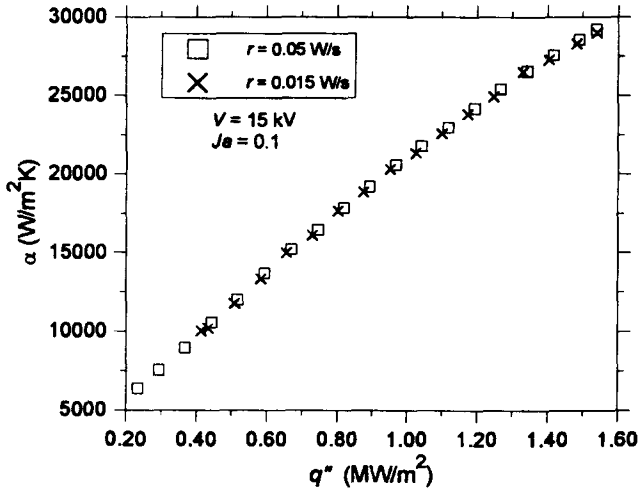

Figure 7. Heat-transfer coefficient vs heat flux for $V = 0$ kV and different heat-up rates, in subcooled conditions (Ja = 0.1).

Bulk Subcooling

The approach of Judd and Merte [11] was adopted to describe the effect of bulk subcooling on nucleate boiling. If the surface superheat, at constant heat flux, is plotted vs the Jacob number, the resulting curves exhibit a maximum (Fig. 8). Afterward, the surface superheat decreases monotonically for low values of q'', whereas a minimum is shown for high values of q''. The electric field does not modify this general trend (Fig. 9). In the present test conditions, the variations are quite smooth anyway, thus indicating a weak effect of subcooling on nucleate boiling up to high Jacob numbers.

DISCUSSION

As can be seen from Fig. 3, the electric field affects the nucleate boiling performance, enhancing the heat transfer at both very low and very high heat fluxes and degrading it in the intermediate range. Remarkably, Cooper's correlation is not able to predict this trend, although it correctly predicts a decrease in the enhancement with increasing heat flux. The aforementioned effect is quite weak: this may help in explaining previous papers on the phenomenon, in which either low enhancement or no effect were reported in the present geometrical configuration. The most evident effect of electric field on nucleate boiling is the large increase in the critical heat flux. Up to this new value of critical heat flux, the boiling curve remains approximately along the extension of the zero field one, apart from the small deviations described earlier.

The data for zero-field saturated boiling were best fitted by the correlation

$$\alpha = Cq''^{n}, \tag{10}$$

with $C = 1$, $n = 0.74$, yielding a standard deviation of 1.3%. The results are shown in Fig. 10. The values of C and n are in good agreement with those given by Stefan and Abdelsalam [22] ($C = 1.05, n = 0.745$). For an applied

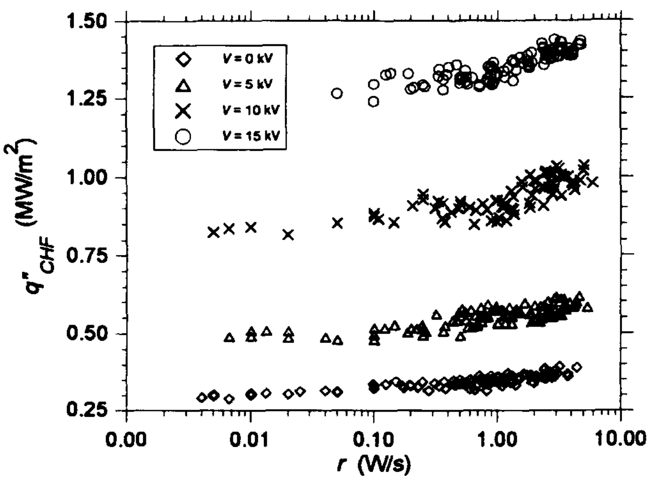

Figure 6. Critical heat flux vs heat-up rate, for various values of applied electric field, at saturation (Ja = 0).

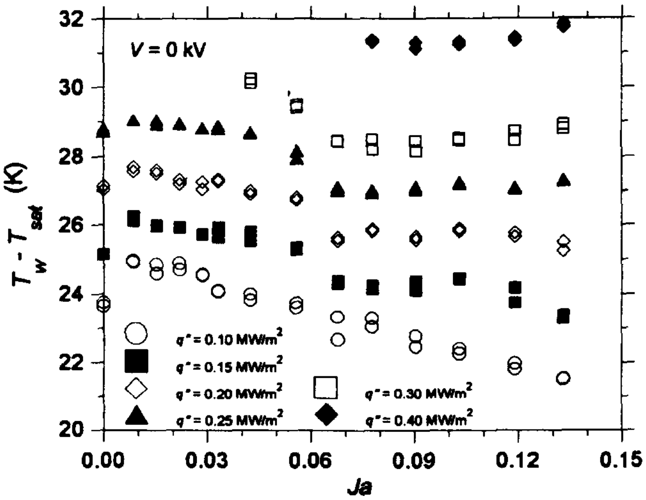

Figure 8. Wall superheat vs Jacob number for $V = 0$ kV and different values of heat flux.

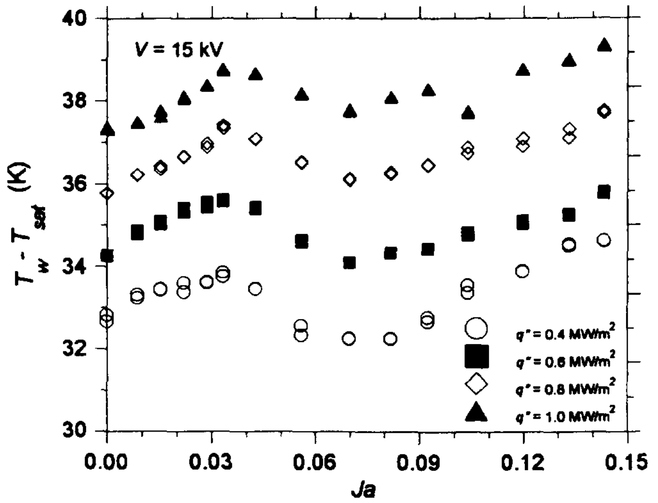

Figure 9. Wall superheat vs Jacob number for $V = 15$ kV and different values of heat flux.

potential of 15 kV and a heat flux of 1 MW/m^2, the same correlation underpredicts α of about 7% at high heat flux and overestimates it of 15% at low flux.

The effect of an increase of heat-up rate in the linear power ramp was in agreement with what was previously described by several authors for exponentially increasing power transients. In particular, the conditions referred to as "irregular boiling" by Sakurai and Shiotsu [17] were never reached in the present series of tests. This may help in evaluating the results of sounding rockets and parabolic flights experiments, where, owing to the short duration of the microgravity phase, boiling curves have to be obtained in relatively fast transients.

The increase in critical heat flux was found to be significant for heat-up rates greater than 0.05 W/s. Below this value, the effect was negligible, although according to Fontana [23], some decrease (within the experimental uncertainty) may be detected even for the slower transients.

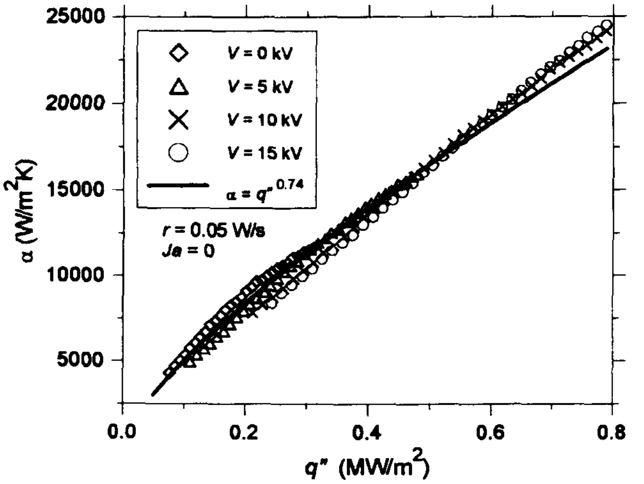

Figure 10. Comparison between the experimental data and the interpolation, Eq. (10), in saturated conditions.

The effect of subcooling on nucleate pool boiling is sometimes reported as a degradation in the heat-transfer coefficient. This might actually be detected by plotting α vs Ja for a given heat flux or by comparing Figs. 5 and 7. However, this is just an illusory phenomenon, which is substantially due to the decrease in the bulk temperature. As evidenced in Figs. 8 and 9, the surface superheat, which is often the most important parameter in applications, is weakly affected by subcooling. The preceding observations are equally valid when the electric field is applied, and, to the authors' knowledge, this fact has never been reported in the open literature. The results concerning the effect of subcooling are in partial agreement with previous experimental findings in zero-field conditions [11, 13–15]. Although the presence of a maximum in surface superheat vs Jacob number has been widely reported, no previous study detected the subsequent minimum for the higher heat fluxes. On the other hand, none of the previous work dealt precisely with boiling of R113 on a thin wire: this could be a peculiar feature of the present experimental conditions.

PRACTICAL SIGNIFICANCE / USEFULNESS

In recent years, a great deal of work has been carried out worldwide on the so-called EHD-enhanced boiling and condensation, and some configurations of practical interest have already been proposed. The reasons for this have to be found in the extreme simplicity of the technique, the reduced power consumption, and the considerable increase in heat-transfer performance. Additionally, much can be learned about the physical processes in boiling and condensation with simple experiments involving EHD enhancement. In this work, no appreciable enhancement was detected in nucleate pool boiling performance, although a dramatic and very interesting increase in the value of critical heat flux is shown in Fig. 6 with increasing applied electric field. The increase in the critical heat flux safety margin is itself a valid motivation to consider EHD boiling in applications and to continue the basic research to understand how this increase is produced.

Another important field of application of EHD boiling is the heat transfer in microgravity: in such conditions, the electrical body force may supply a replacement of the gravity force for phase separation and boiling enhancement with a neglectable consumption of energy. Unfortunately, the current capability of experimentation in microgravity is heavily limited in space and time by the characteristics of the flight facilities available at present, and experiments must be simple and very carefully designed to comply with such limitations. The practical interest of the present work lies mainly in having supplied a complete and consistent data set on the effects of heat-up rate and subcooling on nucleate pool boiling, useful to define the operational range of parameters for future experiments on EHD boiling in microgravity.

CONCLUSIONS

The effect of some system parameters—namely, subcooling and heat-up rate—in pool boiling of R113 on a heated wire in the presence of an external electric field was experimentally studied.

Zero-field measurements were in good agreement with previous ones in the literature. The effect exerted by the electric field consisted mainly of a strong increase in the critical heat flux. In nucleate boiling, for a given heat flux, the heat-transfer performance can be either weakly degraded (for very low or very high heat flux) or slightly enhanced (in the intermediate range). This result is valid with reference to this particular geometrical configuration and should not be generalized. Currently available correlations cannot model this effect. The critical heat flux was found to increase with increasing transient velocity above a threshold, and this threshold was found to increase in the presence of the electric field. Conversely, the effect of the heat-up rate on nucleate boiling heat transfer was negligible in all the tested conditions. The effect of subcooling on nucleate boiling was, in any case, quite weak in the entire investigated range: the plots of ΔT_{sat} vs Ja for constant heat flux showed an initial increase followed by a decrease, either in the presence of the electric field or less.

RECOMMENDATIONS AND FUTURE RESEARCH NEEDS

The analysis reported herein should be extended to cover the effect of subcooling on critical heat flux and the effect of other parameters, such as the system pressure. This work is currently in progress. Some advanced measurements beyond the classical boiling curve, such as those of void fraction, bubble detachment frequency, size, distribution, and other two-phase flow quantities, would also be very valuable in studying the more basic physical mechanisms present in the critical heat flux under the effects of electric fields and the possible coupling between the boiling-condensation process and the electric field near the heated surface.

The geometry tested here, although a very classical one, has a practical interest limited to basic research. Nevertheless, it was chosen simply to accommodate an analogous facility in the very small microgravity rigs, such as sounding rockets. Of course, on ground experiments should be reoriented to geometrical configurations of greater technological concern. In this context, the research of an optimum field-surface coupling, allowing minimization of high voltage and power consumption, is an extremely interesting and open subject.

Although R113 has been a very popular and inexpensive testing fluid in the past and a considerable amount of data is available, experimentation with it is becoming increasingly difficult owing to limitations in its use imposed by environmental protocols. It is now necessary to start experimentation with the so-called environmentally safe fluids.

The visit of Dr. Pablo Carrica at Dipartimento di Energetica was funded by the Italian Ministry of Foreign Affairs, through the Italian-Argentinean Cultural Co-operation Agreement. Mr. Manrico Grassi and Mr. Gianni Mazzoni collected most collected most of the reported experimental data in the framework of their dissertation. Mr. Roberto Manetti gave a decisive contribution in setting up the experimental apparatus and the related electronics. This work was carried out with the financial support of the Italian Space Agency (contract no. ASI-94-RS-122).

NOMENCLATURE

A_{h}	heater area, m^2
E	electric field intensity, V/m
$\mathbf{F}_{\text{E}}$	electric force, Eq. (2), N
G_{E}	see Eq. (1)
G_{be}	see Eq. (3)
g	gravity acceleration, m/s^2
I	current, A
Ja	Jacob number $(= c_{\text{p}}\,\Delta T_{\text{sub}}/h_{\text{fg}})$
L	Laplace length $(= [\sigma/(\rho_{\text{l}} - \rho_{\text{g}})g]^{1/2})$, m
q''	thermal flux, W/m^2
R	wire resistance, Ω
R_0	cold wire resistance, Ω
r	heat-up rate, W/s
r_{b}	bubble radius, m
r'	see Eq. (9)
T	temperature, °C, K
V	high voltage drop, V

Greek Symbols

α	heat transfer coefficient, W/(m^2 K)
β	platinum temperature coefficient, K^{-1}
γ	platinum temperature coefficient, K^{-2}
ΔV	voltage drop across the wire, V
δ	relative measurement uncertainty
ε	relative electric permittivity
ε_0	vacuum absolute electric permittivity, F/m
σ	surface tension, N/m
ρ	density, kg/m^3

Subscripts

b	buoyancy or bulk
e	electric
E	with electric field
g	vapor
l	liquid
sat	saturation
sub	subcooling
w	wall (heater)

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