

EFFECT OF AN EXTERNALLY APPLIED ELECTRIC FIELD ON POOL FILM BOILING OF FC-72

Massimiliano Cipriani, Paolo Di Marco, Walter Grassi

LOTHAR, Dipartimento di Energetica, Università di Pisa,
Via Diotisalvi 2 - 56126 PISA, Italia, Tel. +39-50-569639, FAX +39-50- 830116
E-mail: lothar@ing.unipi.it

ABSTRACT

The paper reports the results obtained during an experimental study on film boiling on wires in the presence of an externally imposed electrostatic field. 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 diameters of 0.1 and 0.2 mm. The working fluid was FC-72. The results showed that two different film boiling regimes, separated by an additional boiling transition, can exist in the presence of an electric field. The first regime, at low wire superheat, was strongly influenced by the electric field, showing a remarkable heat transfer enhancement with increasing voltage. The second regime, at higher superheat, was weakly dependent on the field strength and almost coincident with the zero field one. These results are analogous to the ones previously obtained using R113 as working fluid. The reasons for the occurrence of the transition were investigated. A simple model of the effect of the electric field on the interface behavior was developed, taking into account the variation of the thickness of the vapor layer with the increase of the heat flux, thus providing a possible explanation for the occurrence of the transition.

KEYWORDS: Pool Boiling – Film Boiling – Electric Field – Enhanced Heat Transfer.

INTRODUCTION

It is very well established that during saturated film boiling on a horizontal cylinder a stable vapor layer separates the heater surface from the surrounding liquid. At the lowest heat fluxes, the vapor-liquid interface oscillates (with well defined wavelength) originating equally spaced vapor bubbles which rise into the liquid. The heat exchange between the heating surface and the interface takes place by conduction-convection across the vapor layer and radiation. The importance of the last mechanism increases with wall superheat.

The first theoretical model of film boiling on a horizontal cylinder was proposed by Bromley (1950, 1952). Several further models, all based on refinements of Bromley's one, were proposed in the following years: among them, the ones by Breen and Westwater (1962), Pomerantz (1964), Baumeister and Hamill (1967a, 1967b), Siviour and Ede (1970), Nishikawa *et al.* (1972). Sakurai (1990) reviewed most of the former models and developed the most comprehensive correlation for film boiling on wires, able to fit a large amount of experimental data both in saturated and in subcooled conditions (Sakurai *et al.*, 1990a,

1990b). The comparison of the predictions of these models, applied to the geometry investigated herein, evidenced big discrepancies (up to 350%) in their predictions (Cipriani, 1999), see fig.1.

Sakurai *et al.* (1988) collected data on film wavelength, bubble diameter and detachment frequency in film boiling.

Once an electric field is applied to the system the interface dynamics changes, owing to the destabilizing effect of this field (Di Marco e Grassi, 1993, 1994). The oscillation wavelength tends to decrease at increasing field intensity, with a corresponding increase of the oscillation frequency. The net effect is an improvement of the heat flux at a given wall superheat that applies also to the Minimum Film Boiling point (MFB).

The effect of an externally applied electric field on film boiling was experimentally investigated by Choi (1962), Bonjour *et al.* (1962), Markels and Durfee (1964, 1965), Baboi *et al.* (1968), Jones and Schaeffer. (1976) and Jones and Hallock (1978). Markels and Durfee (1964, 1965) reported unique measurements of current in the high voltage circuit, indicating a possible intermittent wetting of the heated surface induced by the electric field. Most of these experimenters, as pointed out by Jones (1978), did not design their experiments with concern to the relevant physical parameters involved (e.g. relaxation time, wire radius, electric field frequency).

Baboi *et al.* (1968) carried out experiments of pool boiling of toluene and benzene on a wire heater, applying an electric field between the heater and a parallel wire. They reported an exponential increase of the heat transfer coefficient with the applied field. The MFB heat flux was found to increase almost proportionally to the field intensity. A few measurements of the film wavelength were also taken: it was found to decrease with field intensity. The film boiling regime was reported to disappear for a field intensity higher than 50 MV/m. The shift from a two-dimensional flow pattern to a three-dimensional one was observed too: bubbles departed also from the lower side of the heater and the hydrodynamic structure disappeared.

Jones and Schaeffer. (1976) and Jones and Hallock (1978) performed experiments in an apparatus quite similar to the present one, adopting R113 as the working fluid, and mainly focusing on MFB conditions. Data for film boiling were also reported, showing a clear heat transfer enhancement in this regime due to the electric field, in agreement with former experimentalists. The decrease of the film oscillation wavelength with increasing electric field was also verified.

Theoretical models for MFB enhancement on wires were reported by Jones and Schaeffer (1976). They argued that d.c. coupling should be substantially greater than a.c. coupling, but they did not find experimental evidence for this. On the contrary, in their experiments a.c. and d.c. couplings were quite similar. They were not able to develop a satisfactory model for d.c. electric coupling, and concluded that some further physical mechanism had to be present. On this basis they recommended additional experiments with d.c. fields. Their theoretical work was improved by Berghmans (1978), who accounted for the three-dimensional wave pattern around the wire.

Recently, Verplaetsen and Berghmans (1999) modeled the effect of electric field on pool film boiling on a plane heater, developing a correlation in good agreement with the experiments.

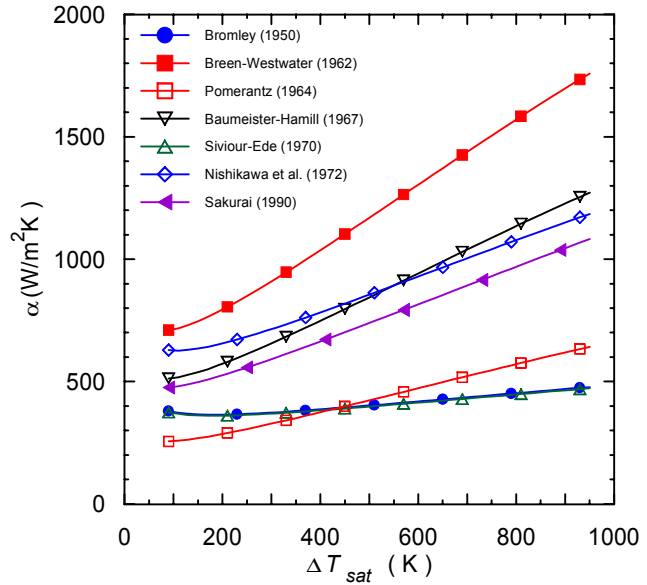


Fig. 1: Comparison of different correlations from literature, as applied to the tested conditions (fluid: FC-72, saturated, $p=115$ kPa, $D=0.2$ mm).

Carrica *et al.* (1996) performed experiments of film boiling of R113 on a platinum wire, 0.2 and 0.3 mm diameter. For the first time, it was clearly identified that the electro-hydro-dynamic (EHD) enhanced film boiling regime cannot be sustained indefinitely in this configuration, and for high enough wire superheat a second transition takes place, bringing the system back to a film boiling regime which is rather unaffected by the presence of the field. A weak evidence of this can be also found in the data by Jones and Schaeffer (1976). Later on, a confirmation that the application of an electric field has a poor influence on film boiling performance at high wall superheats was found by Di Marco *et al.* (1997), who adopted R113 and Vertrel as testing fluids.

The aim of the paper is to investigate in detail the effect of electric field on pool film boiling on wires in FC-72. This study constitutes a part of a broader research program on pool boiling under microgravity conditions in the presence of an electric field, which might act as a replacement field force to drive the vapor. In fact, the choice of the type of heater (i.e. wires) was due mainly to the need to accommodate an analogous test section in the relatively small flight facilities available for microgravity experiments.

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. A bellows, connected to the main vessel, was operated by pressurized nitrogen in the secondary side, to compensate for volume variation due to the vapor production and to the thermal dilatation of the fluid, and to maintain constant pressure. This configuration allowed to test any desired combination of pressure and subcooling. The main vessel had two windows to allow visualization of the phenomenon by means of a video camera, with appropriate back-illumination. An external heating system, governed by a PID controller, maintained the fluid temperature constant within ± 0.1 K.

Experiments were carried out using a horizontal platinum wire of 0.1 and 0.2 mm diameter and 45 mm length, which served as both a resistance heater and a resistance thermometer. The heater (see Fig.2) was made by brazing coaxially the platinum wire (the active heater) to two copper capillary tubes (1 mm O.D., 0.2 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. This design was chosen to eliminate the distortion effects on the electric field that might arise in the presence of external sensing wires at the junctions.

The fluid adopted in the tests was FC-72 (C_6F_{14}) a fluoroinert liquid, trade mark by 3M used for electronics cooling.

The electric field was obtained by imposing a d.c. potential drop up to 10 kV to an 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 and finite difference analysis (Di Marco & Grassi, 1996), assuming that the fluid was single-phase and homogeneous in the investigated domain. It was shown that the length of the cage is sufficient to avoid side effects along the active part of the heater. For the 0.2 mm wire, the analysis showed that, up to 10 mm from the wire axis, the field obeyed the law $E = C V/r$, where E is the field intensity

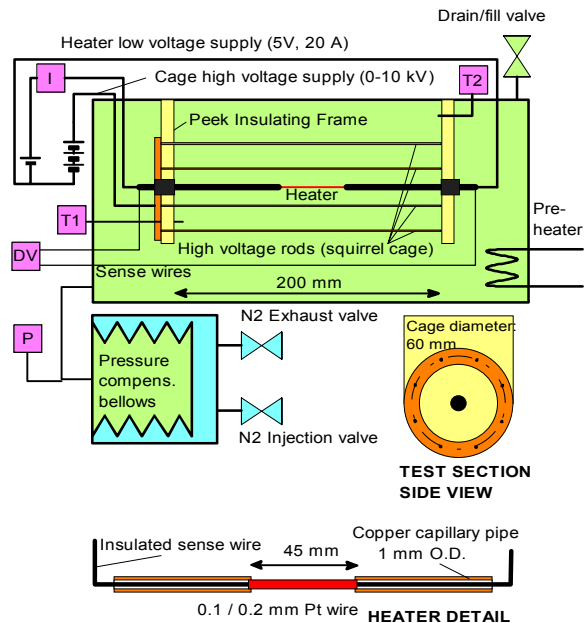


Fig. 2: Experimental apparatus.

at the wire surface, V the high voltage applied to the rods and $C = 0.1034$. For a solid cylindrical electrode of the same diameter the constant can be calculated analytically and its value is $C = 0.1735$; thus, the actual field is less intense than the one generated by a solid outer electrode.

Measurements and accuracy

Measurements included:

- The bulk temperature, by averaging the readings of 2 AD590M transducers located at different positions inside the cell;
- The pressure, by an absolute transducer, 3.5 bar full scale;
- The voltage drop across the wire, ΔV
- The electric current flowing in the wire, I , by means of a calibrated shunt,
- The value of the applied high voltage, V , by means of a calibrated shunt.

The following quantities were derived from the above-mentioned measurements:

- The heat flux, as $\Delta V \times I / A_h$;
- The wire temperature T_w , from ohmic resistance of the wire, $R = \Delta V / I$ and from the temperature-resistance calibration curve of platinum

$$R_E = R_0 (1 + \beta T_w + \gamma T_w^2) \quad (1)$$

where the coefficients β e γ were determined by calibration in the pre-test phase and the wire cold resistance, R_0 was measured before the tests.

- The heat transfer coefficient, as

$$\alpha = \frac{q''}{T_w - T_{sat}} \quad (2)$$

Table 1- Measurements and estimated uncertainties.

MEASUREMENT	RANGE	MAX. UNCERTAINTY
Current (I)	$1.5 < I < 4$ A *	0.331 % @ 1.5 A
	$4 < I < 12$ A **	0.128 % @ 12 A
Voltage (V)	$1.5 < V < 8$ V *	1.25 mV
	$1.5 < V < 5$ V **	
Bulk temp. (T_b)	$38.4 < T < 70.2$ °C	0.3 °C
Pressure (p)	$750 < p < 1600$ mbar	0.21 % @ $p = 1180$ mbar
High voltage (V)	$0 < HV < 10$ kV	50 V
Cold resistance (R_0)	$152 < R_0 < 605$ m Ω	< 0.11 %
Wall temp. (T_w)	$200 < T_w < 900$ °C *	4.3 % @ $T_w = 900$ °C
	$200 < T_w < 900$ °C **	3.3 % @ $T_w = 900$ °C
Wire overheat ($T_w - T_{sat}$)	$150 < \Delta T_{sat} < 850$ °C *	4.7 % @ $T_w = 900$ °C
	$150 < \Delta T_{sat} < 850$ °C **	3.5 % @ $T_w = 900$ °C
Heat flux (q'')	$120 < q'' < 2350$ kW/m ² *	10.24 % *
	$140 < q'' < 1850$ kW/m ² **	5.46 % *
Heat transfer coefficient (α)	$950 < \alpha < 5050$ W/Km ² *	11.3 % @ $T_w = 900$ °C
	$700 < \alpha < 3650$ W/Km ² **	6.5 % @ $T_w = 900$ °C

* 0.1 mm diameter wire

** 0.2 mm diameter wire

All the tests were run in the so-called “constant voltage” way, i.e. the voltage drop across the wire was the controlled parameter. This procedure may yield “two-mode boiling” conditions in some instances, (Di Marco and Grassi, 1995) that is coexistence of nucleate boiling on part of the wire and of film boiling on the other part can be observed: the relative data were discarded during the analysis.

The signals were pre-amplified and insulated electrically via a set of preamplifiers (Analog Device 5B, high bandwidth). A notebook PC equipped with a data acquisition system based on a 12 bit A.D. converter recorded the data (averaging each of them over 20 to 50 samples) and controlled the power input to the wire during each test.

The uncertainty in derived quantities was calculated by the classical error propagation formulae, reported by Di Marco and Grassi (1995). The most significant values are summarized in Tab.1; more details are reported by Cipriani (1999). It should be noted that a fixed error originates from the heat losses due to conduction through the clamped ends of the wire. A thorough evaluation of this error was carried out and (Di Marco and Grassi, 1995; Cipriani, 1999) and all the data reported in the following were corrected to get the values in the central zone of the heater, where they are unaffected by the side-end conduction (i.e., they can be considered as values on a wire of zero thermal conductivity).

Generally speaking, the relative uncertainty in heat flux increases with wire superheat, while the one in heat transfer coefficient decreases.

EXPERIMENTAL RESULTS AND DISCUSSION

Experimental procedures and results

The testing fluid was thoroughly degassed by boiling and flashing before introducing it in the cell. The wire resistance and the temperature coefficients were measured before the tests, and occasionally tested during the experiments: the variations were very limited, except for the temperature quadratic coefficient, γ . For both the tested wire diameters, data were obtained in saturated and subcooled (10 K) conditions, at pressures of 0.075, 0.115, 0.16 MPa ($p_r = 0.04, 0.06, 0.09$, respectively). The value of the applied high voltage ranged from 0 to 10 kV.

The tests were run by increasing the heat flux in constant steps at regular time intervals, up to a point where the wire temperature exceeded a safe value (about 900 °C), and then decreasing it until nucleate boiling was re-established: a good repeatability was always obtained in the ascending and descending data, except for the tests run at 10 kV: this was presumably due to the fact that the excessive heat input caused a rise of system pressure with time.

Some of the obtained boiling curves (q'' vs. ΔT_{sat}) are reported in figs.3-8 for the saturated case (the experimental parameters are indicated in the figures). The most striking feature is the clear evidence of a second boiling transition, separating two distinct film boiling regimes: the first one, at lower wire superheat, was strongly influenced by the presence of the electric field; an increase of the heat transfer coefficient up to 400 % was encountered. The second film regime (taking place at superheats higher than about 550 K) was almost unaffected by electrical forces. The transition point moved towards lower superheats with increasing applied voltage. A hysteresis cycle is clearly visible in the curves.

Visual observation, with the aid of the CCD camera, showed the presence of the following three distinct fluid-dynamic regimes.

- A. For an applied high voltage up to 2 kV, the liquid-vapor interface had an oscillatory motion and a dominating wavelength was clearly identifiable (fig.9).
- B. With increasing electric field, the wavelength and bubble size decreased up to a condition in which no dominating wavelength was identifiable (fig.10). The oscillatory phenomenon was likely two-dimensional in these conditions, with a circumferential oscillation superimposing to the axial one. The appearance of the boiling pattern was more similar to the nucleate boiling one. Bubbles started to detach also from the lower part of the wire and were of irregular size; lateral coalescence was observed.
- C. For high values of the wire superheat, the second film boiling regime took place (fig.11). The interface oscillated with high values of the wavelength, and bubbles were larger than in the former two regimes. The phenomenon was independent of the applied electric field in this regime.

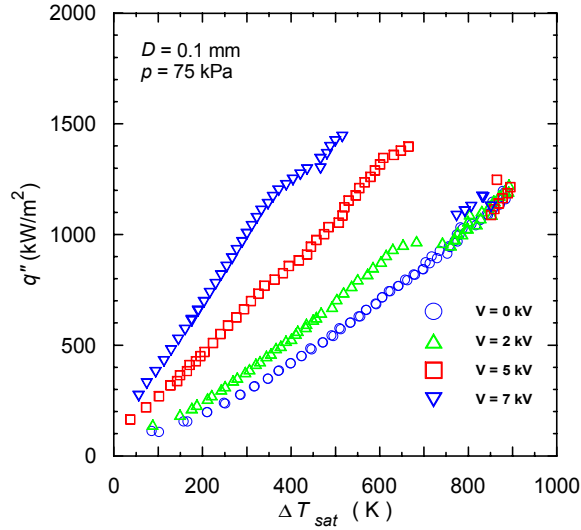


Fig. 3: Experimental data, saturated conditions.

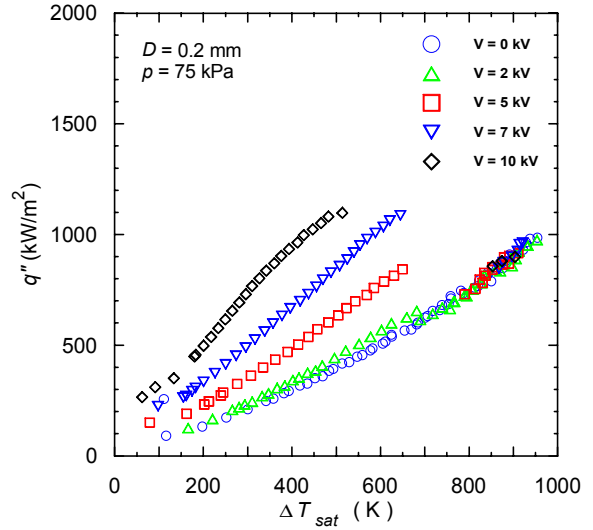


Fig. 6: Experimental data, saturated conditions.

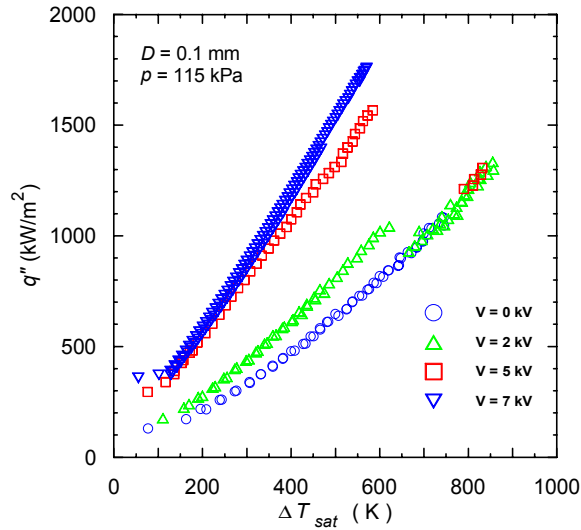


Fig. 4: Experimental data, saturated conditions.

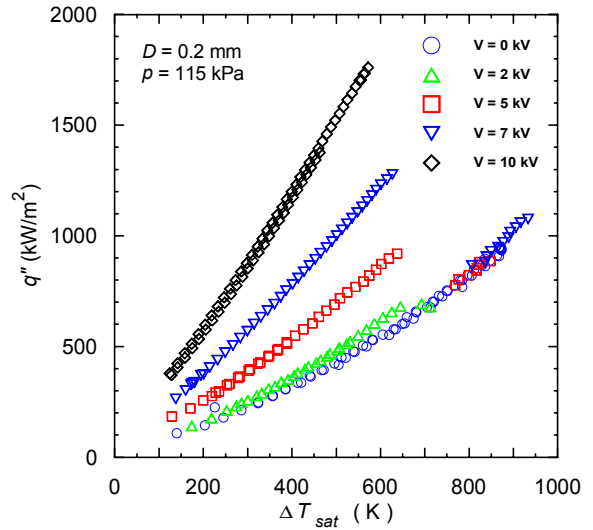


Fig. 7: Experimental data, saturated conditions.

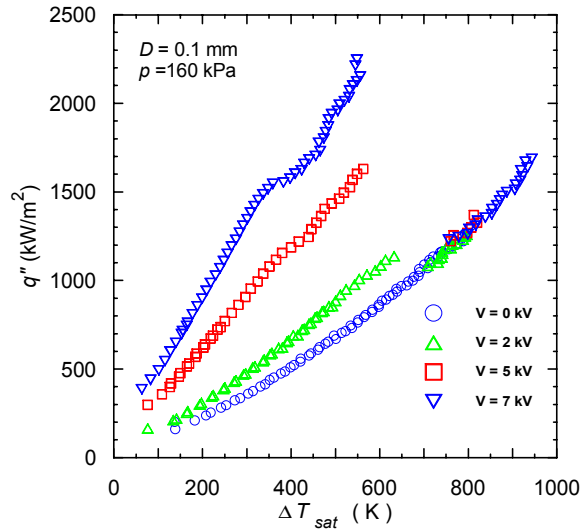


Fig. 5: Experimental data, saturated conditions.

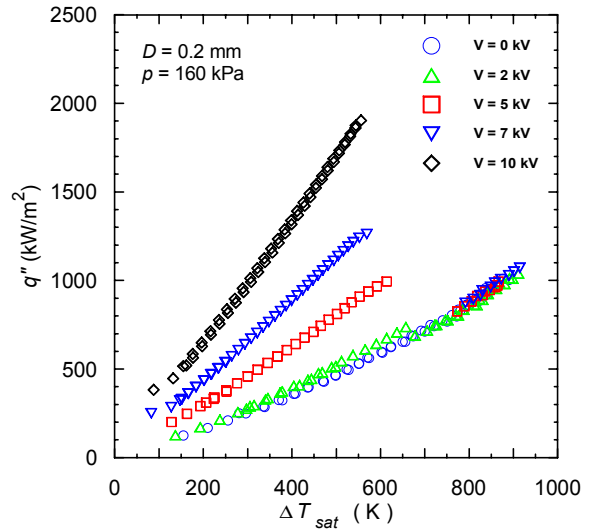


Fig. 8: Experimental data, saturated conditions.

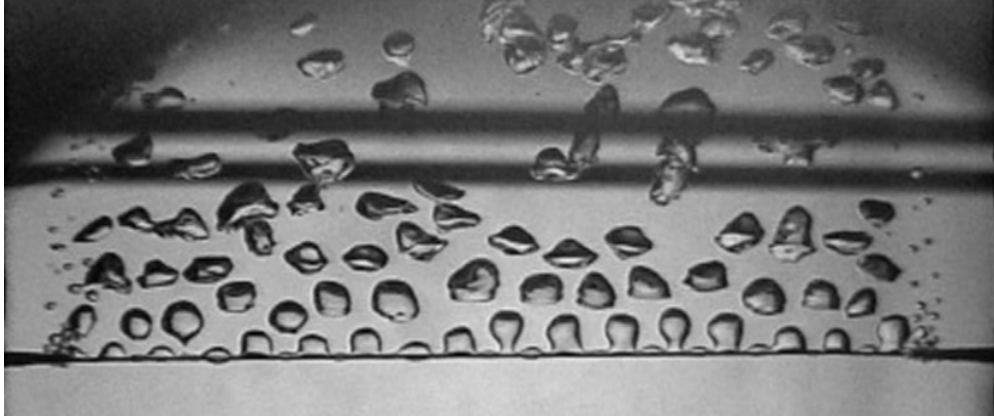


Fig. 9: First film boiling regime, monodimensional oscillatory pattern;
 $p = 115 \text{ kPa}$; $d = 0.2 \text{ mm}$; $V = 0 \text{ kV}$; $q'' = 400 \text{ kW/m}^2$; $\Delta T_{sat} = 449 \text{ K}$.

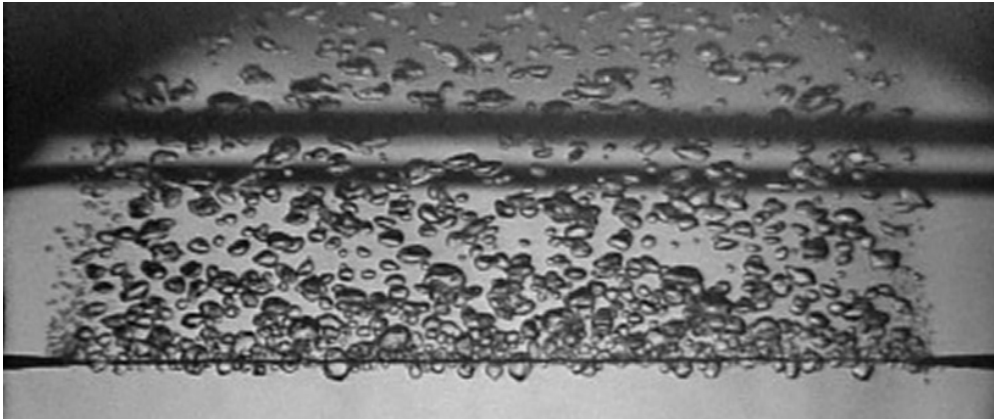


Fig. 10: EHD enhanced film boiling regime, multidimensional oscillatory pattern;
 $p = 115 \text{ kPa}$; $d = 0.2 \text{ mm}$; $V = 7 \text{ kV}$; $q'' = 400 \text{ kW/m}^2$; $\Delta T_{sat} = 201 \text{ K}$.

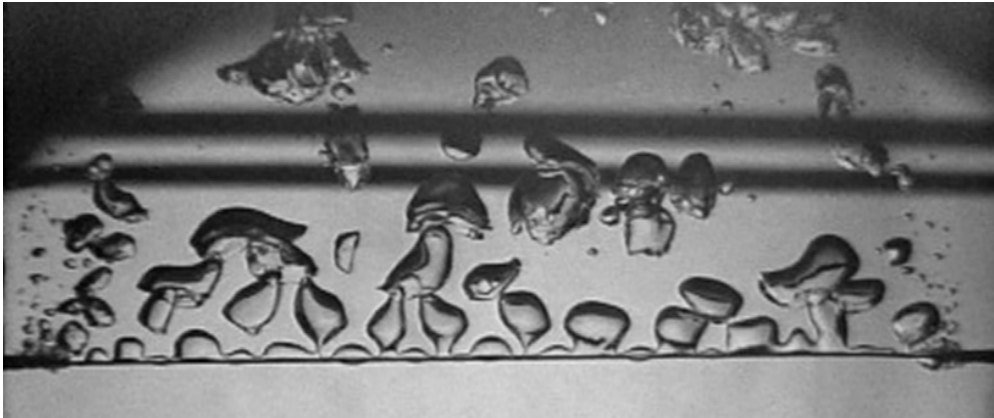


Fig. 11: Second film boiling regime, independent of applied voltage;
 monodimensional oscillatory pattern; $p = 115 \text{ kPa}$; $d = 0.2 \text{ mm}$;
 $V = 7 \text{ kV}$; $q'' = 850 \text{ kW/m}^2$; $\Delta T_{sat} = 781 \text{ K}$.

Measurement of the oscillation wavelength

The oscillation wavelength was measured by digital processing of the video images. The error on this measurement was estimated to be about 15 % (Cipriani, 1999). Only the cases with no applied electric field will be discussed in the following: in fact, it was impossible to measure a dominating wavelength for applied voltage higher than 2 kV. The wavelength was found to be almost constant with increasing wire superheat. The measured value was compared with the predictions available in literature, i.e. the theoretical one by Lienhard and Wong (1964)

$$\lambda_{d,cyl} = \frac{2\pi\sqrt{3}l_L}{\sqrt{1+2/R'}} \quad (3)$$

and the empirical one by Sakurai *et al.* (1984)

$$\lambda_{d,cyl} = 2\pi\sqrt{3}l_L \left(\frac{2R'}{2R'+0.85} \right) \quad (4)$$

It was found that both the relations largely underestimated the oscillation wavelength if R' is evaluated on the basis of the wire radius. The value of R' was thus corrected to account for the thickness of the vapor shell surrounding the wire, which in turn was evaluated by assuming a purely conductive heat transfer within it

$$R'_{corr} = \frac{R+a}{l_L}, \quad a = R \left(e^{\frac{k_v}{\alpha R}} - 1 \right) \quad (5)$$

In this way, the correlation of Sakurai, Eq.4, gave a reasonable agreement with the experimental data, especially for the 0.2 mm wire, while the one by Lienhard, Eq.5, still underestimated the measured values, see figs.12-13.

Effect of system parameters

The heat transfer coefficient increased with increasing pressure. The increase is of about 20% from 75 kPa to 160 kPa with no applied voltage, and of 30 % for an applied voltage of 7 kV. Bubble size and oscillation wavelength decreased with increasing pressure.

The effect of subcooling can be only outlined, since just one value of subcooling was tested: an increase in heat transfer coefficient in subcooled conditions was measured, and the difference was greater at lower superheats and higher applied voltages. Bubbles were smaller and progressively collapsed inside the liquid.

The heat transfer coefficient increased of about 40 % (in the absence of electric field) for the lower diameter tested (0.1 mm). In the presence of electric field, the increase was up to 70%, that is, the enhancing effect of electric field is stronger in this case. The oscillation wavelength and bubble size were found to decrease as well. A decrease of the heat transfer coefficient with increasing diameter was measured also by Carrica *et al.* (1996).

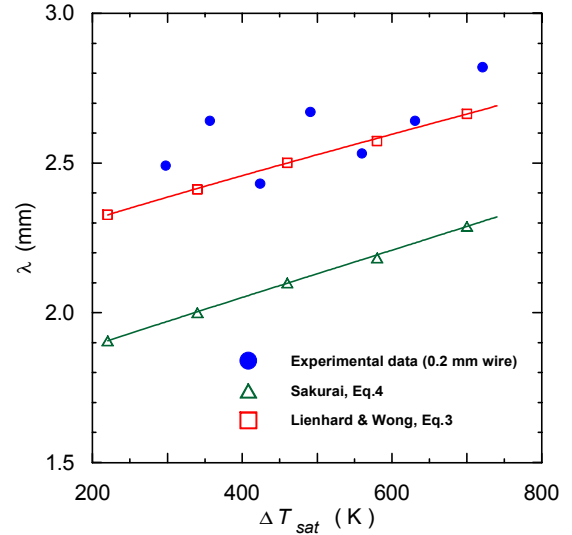


Fig. 12: Measured and calculated oscillation wavelength, 0.2 mm wire.

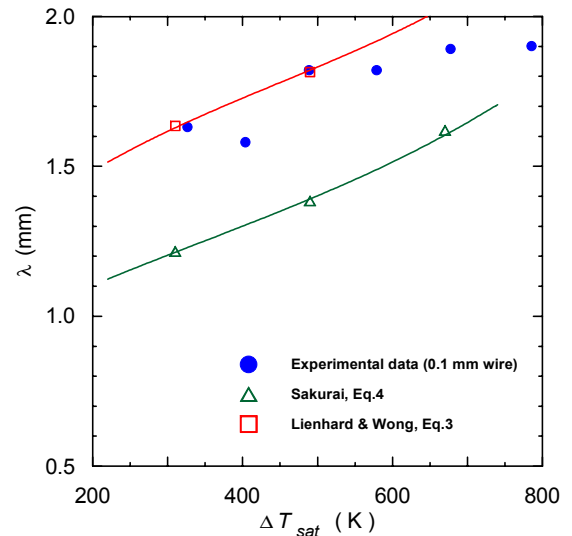


Fig. 13: Measured and calculated oscillation wavelength, 0.1 mm wire.

A proposed preliminary model to explain the second boiling transition

The visual observation of the transition indicated that at its occurrence the oscillatory regime of the interface reverted from a two-dimensional pattern to a monodimensional one. On this basis, it is supposed that the transition takes place when multiple values of the oscillation wavelength cannot be accommodated along the circumference of the interface, i.e. when

$$\lambda_{dE} > \pi(R+a) \quad (6)$$

The electric field at the liquid-vapor interface (on the vapor side) is evaluated as the one in a cylindrical condenser with two concentric layers of materials (liquid and vapor) of different electric permittivities:

$$E_{0v} = \frac{V_2}{R+a} \left(\ln \frac{R+a}{R} + \frac{\epsilon_v}{\epsilon_l} \ln \frac{R_2}{R+a} \right)^{-1} \quad (7)$$

The effect of the electric field on the oscillation wavelength is given by (Di Marco and Grassi, 1993)

$$\lambda_{dE} = \lambda_{d0} \frac{\sqrt{3}}{El^* + \sqrt{El^{*2} + 3}} = 2\pi \sqrt{3} l_L \frac{\sqrt{3}}{El^* + \sqrt{El^{*2} + 3}} \quad (8)$$

where the electric influence number El^* is given by

$$El^* = \frac{\epsilon_{eq} \cdot E_{0v}^2 \cdot l_L}{\sigma} = \frac{\epsilon_{eq} \cdot E_{0v}^2}{\sqrt{(\rho_l - \rho_v) \sigma g}} \quad (9)$$

Strictly speaking, the above relationships are valid only for a plane interface and they will be retained herein for simplicity. The equivalent permittivity for two dielectric materials, assuming that the liquid layer has a thickness far larger than the one of the vapor, a , has the form (Di Marco and Grassi, 1994)

$$\epsilon_{eq} = \frac{\epsilon_0 \epsilon_l (\epsilon_l - \epsilon_v)^2}{\epsilon_v [\epsilon_l \text{th}(ka) + \epsilon_v]} \quad (10)$$

Finally, if the critical conditions given by Eq.6 holds, the wave number k can be expressed as

$$ka = \frac{2\pi}{\lambda} a = \frac{2}{R+a} a \quad (11)$$

In fig.14, the value of the ratio $C_\lambda = \lambda_{dE} / \pi(R+a)$ is reported vs. a . The two dimensional enhanced film boiling regime is possible only if $C_\lambda < 1$. It can be seen from fig.14 that for the 0.2 mm wire the enhanced regime is never possible for low values of the applied voltage ($V \leq 2$ kV), as verified experimentally. For higher values of V , the two-dimensional regime is possible only if a is lower than a critical value which increases with V .

The proposed model suffers for two main limitations: a) the electric field is evaluated for a solid outer electrode (and not for a squirrel cage as in the actual configuration), b) the oscillation wavelength and effect of the electric field on it are modeled as on a plane interface. Nonetheless, it is able to explain the observed phenomena at least on a qualitative basis.

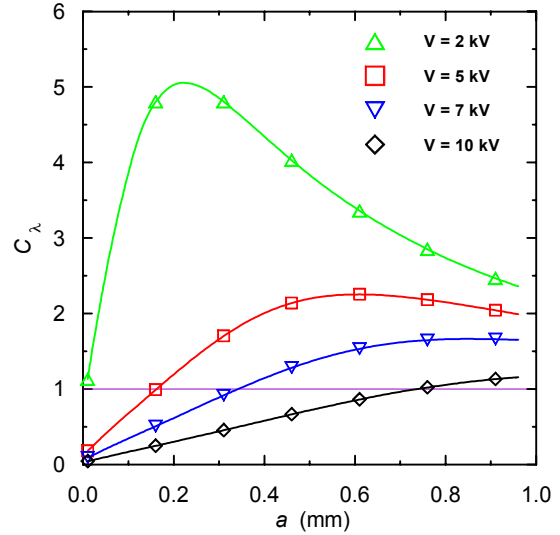


Fig. 14: Measured and calculated oscillation wavelength, 0.2 mm wire.

CONCLUSIONS

Experiments were carried out on saturated pool boiling of FC-72 on platinum wires in the presence of an externally imposed d.c. electrostatic field of cylindrical geometry. The results showed that in this case two different film boiling regimes are present. They are separated by a second regime transition, similar to the one separating nucleate boiling from film boiling. The second regime, at larger wire superheat, is quite independent of the presence of the electric field. Conversely, in the first film boiling regime, at lower wire superheat, a significant improvement of heat transfer performance can be gained, if a voltage beyond a certain threshold is applied. This may have significant applications in enhanced boiling heat transfer, where generally film boiling was not formerly considered due to its very poor efficiency. By EHD enhancement, heat transfer coefficients closer to nucleate boiling ones can be obtained.

The obtained data are qualitatively in agreement with the ones previously obtained for R-113 in both steady-state and transient tests on wires of different diameters (Carrica *et al.*, 1996). In the case of no applied electric field, a satisfactory agreement with available correlations in literature for oscillation wavelength was obtained, if the reference length is evaluated on the basis of the radius of the vapor layer, rather than of radius of the wire.

Visual observation of the occurring phenomena led to conclude that the existence of the enhanced film boiling regime looks linked to the possibility to have a multi-dimensional oscillation pattern on the vapor-liquid interface. This inspired a simple model to qualitatively explain the transition, which can be improved in the future.

NOMENCLATURE

a	vapor blanket thickness	(m)	γ	platinum temperature coefficient	(K ⁻²)
A_h	heater area	(m ²)	ΔT_{sat}	wire superheat	(K)
C_λ	$= \lambda_{dE} / \pi(R+a)$		ΔV	voltage drop across the wire	(V)
El^*	electrical influence number		ϵ	relative dielectric permittivity	
g	gravity acceleration	(m/s ²)	ϵ_0	vacuum dielectric permittivity	(F/m)
I	current intensity	(A)	λ_d	oscillation wavelength	(kg/m ³)
k	wave number	(m ⁻¹)	ρ	density	(kg/m ³)
l_L	Laplace length	(m)	σ	surface tension	(N/m)
p	pressure	(Pa)	Suffixes		
p_r	reduced pressure $= p/p_{crit}$		0	in the absence of the electric field	
q''	heat flux	(W/m ²)	$corr$	corrected	
R	radius of the wire	(m)	cyl	cylinder	
R_E	resistance of the wire	(Ω)	E	in the presence of the electric field	
R_0	resistance of the wire at 0 °C	(Ω)	l	liquid	
R'	dimensionless radius, R/l_L		sat	saturated	
T	temperature	(K)	v	vapor	
V	applied high voltage	(V)	w	heated wall	
α	heat transfer coefficient	(W/m ² K)			
β	platinum temperature coefficient	(K ⁻¹)			

ACKNOWLEDGMENTS

The apparatus was designed and assembled in the laboratories of the University of Pisa, with the assistance of Kayser Italia. Mr. R. Manetti designed and realized the electronics. Dr. G. Memoli gave his assistance for statistical data treatment.

This work was funded by ASI (Italian Space Agency) under grant ASI-94-RS-122 and by ESA (European Space Agency).

REFERENCES

- Baboi N.F., Bologa M.K. and Klyukanov A.A., 1968, Some Features of Ebullition in an Electric Field, *Appl. Electr. Phenom.*, 2 (20), pp.57-70.
- Baumeister K.J. and Hamill T.D., 1967a, Film Boiling from a Thin Wire as an Optimal Boundary-Value Process, *ASME Paper 67-HT-62*.
- Baumeister K.J. and Hamill T.D., 1967b, Laminar Flow Analysis of Film Boiling from a Horizontal Wire, *NASA TN D-4035*.
- Berghmans J., 1978, Prediction of the Effect of Electric Field on the Most Unstable Wavelength During Film Boiling on Small Wires, *J. of Electrostatics*, Vol.5, pp.265-272.
- Bonjour E., Verdier J. and Weil L., 1962, Improvement of Heat Exchanges in Boiling Liquids under the Influence of an Electric Field, *Proc. AIChE-ASME 5th Nat. Conference*, Houston (USA).
- Bromley L. A., 1950, Heat Transfer in Stable Film Boiling, *Chem. Eng. Prog.*, 58, pp.67-72.
- Bromley A. L., 1952, Effect of Capacity of Condensate, *Ind. Eng. Chem.*, vol.44, p. 2966.
- Carrica P., Di Marco P., Grassi W., 1996, Electric Field Effects on Film Boiling on a Wire, *Experimental Heat Transfer*, vol.9, pp.11-27.
- Choi L., 1962, Electrohydrodynamic Boiling Heat Transfer, Ph.D. Thesis, MIT, Cambridge.
- Cipriani M., 1999, *Experimental Study on the Influence of the Electric and Gravitational Fields on Pool Film Boiling (in Italian)*, Degree Thesis, University of Pisa.
- Di Marco P. and Grassi W., 1993, Saturated Pool Boiling Enhancement by means of an Electric Field, *Enhanced Heat Transfer*, vol.1, n.1, pp.99-114.
- Di Marco P. and Grassi W., 1994, W. Gas-Liquid Interface Stability in Presence of an Imposed Electric Field, *Proc. 12th UIT National Conference*, L'Aquila (I), pp.299-310.
- Di Marco P., Grassi W., 1995, Influence of Local Phenomena in Pool Boiling Experiments of R113 on a Wire, *Proc. 13th UIT National Conference*, Bologna, pp.307-318.
- Di Marco P., Grassi W., 1996, Nucleate Pool Boiling in the Presence of an Electric Field and in a Variable Gravity Field: Results of Experiments in Parabolic Flight, *Proc. of Eurotherm Seminar n.48*, ed. by D. Gorenflo, D. Kenning, C. Marvillet, Paderborn, D, pp.255-264.
- Di Marco P., Grassi W., Iakovlev I., 1997, Single and Two-Phase EHD Enhanced Heat Transfer - A Review of Experimental Results, *48th International Astronautical Conference*, Torino (I), paper IAF-97-J.1.04.
- Jones T. B., 1978, Electrodynamically Enhanced Heat Transfer in Liquids – A Review, *Advances in Heat Transfer*, vol.14, pp. 107–148.
- Jones T.B. and Hallock K.R., 1978, Surface Wave Model of Electrohydrodynamically Coupled Minimum Film Boiling, *J. of Electrostatics*, vol.5, pp.273-284.
- Jones T.B. and Schaeffer R.C., 1976, Electrohydrodynamically Coupled Minimum Film Boiling in Dielectric Liquids, *AIAA J.*, vol.14, pp.1759-1765.
- Lienhard J.H. and Wong P.T.Y., 1964, The Dominant Unstable Wavelength and Minimum Heat Flux during Film Boiling on an Horizontal Cylinder, *J. Heat Transfer, Trans. ASME*, Vol.86, pp.220-226.
- Markels M. and Durfee R.L., 1964, The Effect of Applied Voltage on Boiling Heat Transfer, *AIChE J.*, vol.10, pp.106-110.
- Markels M. and Durfee R.L., 1965, Studies of Boiling Heat Transfer with Electrical Fields, *AIChE J.*, vol.11, pp.716-721.
- Nishikawa K., Ito T. and Kuroki T., 1972, Pool Boiling Heat Transfer from a Horizontal Cylinder to Saturated Liquids, *Int. J. Heat Transfer*, vol.15, pp. 853-862.

- Pomerantz M.L., 1964, Film Boiling on Horizontal Tube in Increased Gravity Fields, *J. Heat Transfer, Trans ASME*, vol. 86C(2), pp. 213-219.
- Sakurai A., Shiotsu M. and Hata K., 1988, Effect of System Pressure on Film Boiling Heat Transfer, Minimum Heat Flux and Minimum Temperature, *Nuc. Sci. Eng.*, 88, pp. 321-330.
- Sakurai A., Shiotsu M. and Hata K., 1990a, A General Correlation for Film Boiling Heat Transfer from Horizontal Cylinder to Subcooled Liquid: Part 1 – A Theoretical Pool Film Boiling Heat Transfer Model Including Radiation Contribution and its Analytical Solution, *J. Heat Transfer, Trans ASME*, vol.112, pp. 430-440.
- Sakurai A., Shiotsu M. and Hata K., 1990b, A General Correlation for Film Boiling Heat Transfer from Horizontal Cylinder to Subcooled Liquid: Part 2 – Experimental Data for Various Liquids and its Correlation, *J. Heat Transfer, Trans ASME*, vol.112, pp. 441-450.
- Sakurai A., Film Boiling Heat Transfer, 1990, *Proc. 9th Int. Heat Transfer Conf.*, Jerusalem, Israel, vol.1, KN-10, pp.157-186.
- Siviour J.B. and Ede A.J., 1970, Heat Transfer in Subcooled Pool Film Boiling, *Proc. 4th Int. Heat Transfer Conf., Amsterdam*, vol. 5, B3.12.
- Verplaetsen, F.M.; Berghmans, J.A., 1999, Film Boiling of an Electrically Insulating Fluid in the Presence of an Electric Field, *Heat and Mass Transfer/Waerme- und Stoffuebertragung* vol. 35, n. 3, pp. 235-241.
- Westwater J.W. and Breen B.P., 1962, Effect of Diameter of Horizontal Tubes on Film Boiling Heat Transfer, *Chem. Eng. Progr.*, vol.58, pp. 67-72.