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Liquid nitrogen boiling around a temperature controlled heated wire

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1. INTRODUCTION

We present in this paper a study of pool boiling characteristics of a wire immersed in liquid nitrogen at atmospheric pressure on a 32 μm diameter heated wire. Nitrogen as a cooling fluid presents a revival of interest since the discovery in 1987 of high temperature superconductors. High temperature superconductors may have different geometries such as thin wires. Many studies have already been realized on small diameter wires [1–3]. Nevertheless, the transition region is still not well known and especially with liquid nitrogen.

We describe in the first part the experimental apparatus including the measurement cell and temperature control device. Results are then compared with available correlations.

2. EXPERIMENTAL DEVICE

2.1. *Measurement cell*

The wire is $D = 32$ μm diameter, $L = 3$ cm length copper (97.97%), tin (1.9%) and lead (0.13%) alloy. Lead makes the wire thermoresistive. Then, submitted to a current, the wire is both a heater and a thermometer. The wire calibration realized elsewhere [4] gives for temperatures higher than 50 K a linear law:

$$R = R_i + b(T - T_i) \tag{1}$$

where $b = 0.0025$ Ω K^{-1} is the wire temperature coefficient and T_i is the bath temperature (77.3 K; 1 atm). The wire is connected on four supports, two current leads and two for voltage measurement (Fig. 1). The R_i value is determined with a current intensity weak enough to limit the wire self-heating to a value less than a detectable one. The R_i value is about 0.6 Ω. These four supports are fixed on a epoxy resin plate immersed in a liquid nitrogen bath (Fig. 1). The electrical leads between supports and the outside of the cryostat are made of special cables able to transfer information with a linear bandwidth of 4 MHz.

Experiments are conducted at atmospheric pressure in a 0.15 m diameter, 0.5 m depth dewar. Liquid nitrogen height above the wire is generally between 0.1 and 0.3 m. Moreover, photographic observation has allowed a visualization of the different boiling regime structures.

2.2. *Acquisition and wire temperature control device*

A detailed description of the device is given elsewhere [5]. Voltage and current outputs are connected to an analog-digital device including power supply, signal conditioning electronic card and a real time computer whose role is state regulation, intermediate calculations, electronic card driving and data storage. *The boiling curve is obtained when the temperature wire is controlled by means of its mean electrical resistance.* The acquisition device reads voltage U and current I passing through the wire and then calculates temperature T and heat boiling flux density q with a simple algorithm based on the following relations:

$$T = T_i + \frac{1}{b}\left(\frac{U}{I} - R_i\right) \tag{2}$$

$$q = \frac{UI}{\pi DL}. \tag{3}$$

2.3. *Experimental method*

The wire is first degassed during 30 min at a temperature of about 373 K. After checking the value of R_i, the control device starts the recording of the boiling curve. Each point (q_o; ΔT_o) of this curve (which is made up of 5000 points) is obtained by the following way: a given current is applied to the wire and automatically adjusted to the U/I ratio corresponding to the chosen wire superheat. This operation is realized 1000 times for each ordered superheat ΔT_o. Then, the mean values of U and I are calculated with the 1000 samples and reported in equations (2) and (3) giving this way the point (q_o; ΔT_o).

Then a new temperature value is applied. It is also possible to choose the rate of temperature increase. Experiments reported in this work have been realized with a 1/3 K s^{-1} rate. Compared to the physical system thermal time constants and after experimental checking, this rate corresponds to a quasi-stationary regime.

When a 400 K temperature difference between wire and bath is attained, the process is reversed and the wire temperature decreases until the wire gets back to a temperature value of T_i. The uncertainty factors for q are those of current and voltage measurements (1%) and for ΔT, the same and those of the R_i (less than 0.1%) and b (3%) values deter-

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NOMENCLATURE

a	maximum amplitude of the wave [m]
b	wire temperature coefficient [Ω K^{-1}]
g	gravitational acceleration (9.81 m s^{-2})
h_{lv}	latent heat of vaporization [J kg^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
q	heat flux density [W m^{-2}]
D	wire diameter [m]
I	current [A]
L	wire length [m]
Q	heat flux [W]
R	wire electrical resistance [Ω]
T	temperature [K]
U	voltage [V].

Greek symbols

λ_d	most dangerous Taylor wavelength, $\lambda_d = 2\pi\sqrt{\left[\frac{3\sigma}{g(\rho_l-\rho_v)}\right]}$ [m]
ρ	density [kg m^{-3}]
σ	surface tension between the liquid and its vapor [N m^{-1}]
$\Delta T = T - T_i$	temperature difference between wire and liquid bath [K].

Subscripts

c	conductive
i	related to the initial value (conditions of saturation)
l	related to the liquid
Max	related to the peak heat flux
o	related to an ordered value
v	related to the vapor.

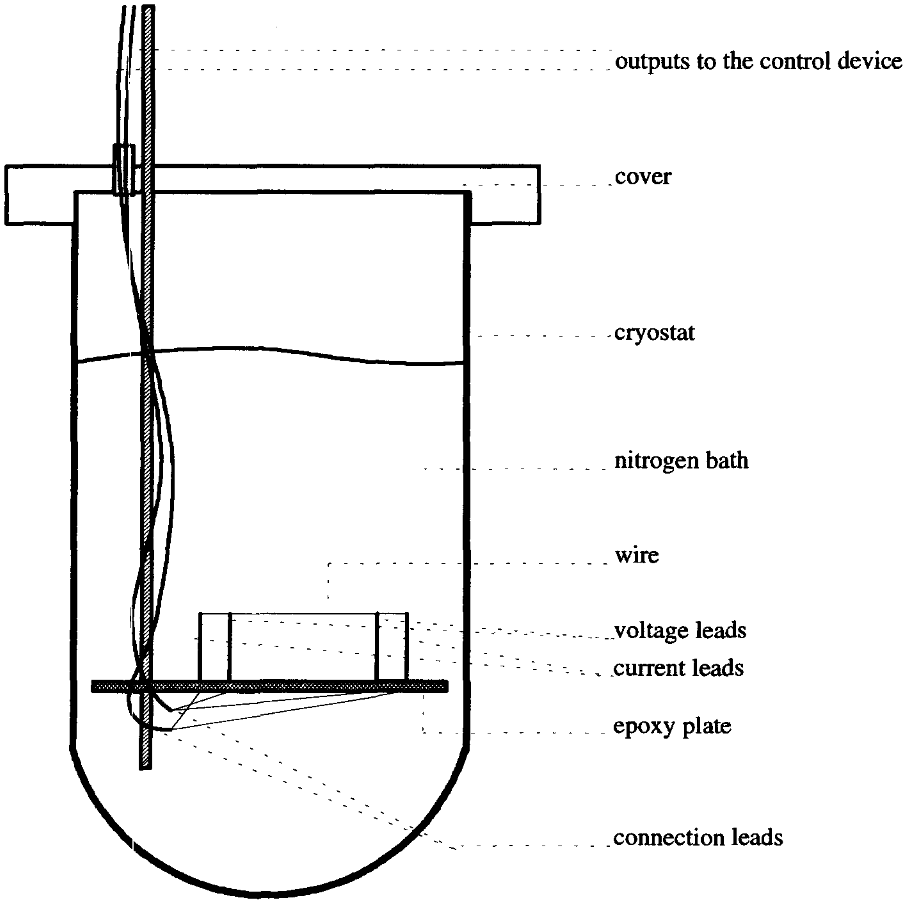

Fig. 1. Experimental apparatus.

mination. This leads to an error in the mean temperature difference ranging from 3 to 6%.

3. EXPERIMENTAL RESULTS

We present here a boiling curve (Fig. 2) obtained with this control device, which has been realized with a liquid nitrogen height above the wire equal to 0.26 m.

We globally obtain the various expected regimes and in particular the hysteresis cycle.

For increasing temperature, the heat transfer process leads to the path ABCDE: the various corresponding regimes are natural convection (AB), transition boiling (BCD) and film boiling (DE). For decreasing temperature, the path is then EmFCGMA, which corresponds first to the film boiling regime (EDm), then to the transition regime (FCGM) and finally to the nucleate boiling regime (MA).

3.1. *Natural convection* (*AB*)

If the characteristic length is taken as the heating element diameter (32 μm), this yields to a very low value 0.5 of the Rayleigh number. It is then possible to maintain a laminar natural convection regime for high temperature differences between wire and fluid (15–25 K) as shown on part AB.

This regime can be characterized by a relation between heat flux density and temperature difference such as:

$$q \propto \Delta T^{m} \tag{4}$$

with an experimental m value of about 1.2.

3.2. *Nucleate boiling* (*MA*)

The photographic pictures show isolated bubbles for low wire temperatures. With increasing temperature, these bubbles become more and more numerous and the departure frequency gets higher but the columns boiling regime reported by authors like Moissis and Berenson [6], for high wall overheatings, does not appear in our experiments.

Visual observation gives some bubble diameters between 250 and 600 μm. For the nucleate boiling regime the experimental m value [equation (4)] is between 2.5 and 3.5.

These values are in good agreement with the ones of Stephan and Abdelsalam [7], who reported experimental results in nucleate boiling for various fluids. For cryogens, they give for the m coefficient a value of 2.66.

The discrepancy around this value is probably due to the surface finish whose role has been reported by many authors.

3.3. *Film boiling* (*mDE*)

Film boiling appears when the heating element surface temperature (imposed by the control device) is high enough to generate a permanent vapor sheath around the surface. The light vapor laying under the heavier liquid leads to an unstable pattern whose characteristic space parameter is the so-called Taylor wavelength.

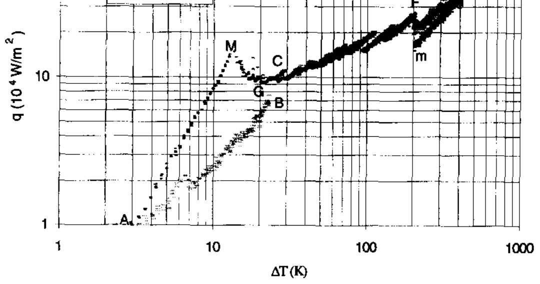

Fig. 2. Boiling curve obtained in liquid nitrogen with a temperature controlled heated wire (32 μm diameter).

For small diameter cylinders, the surface tension effect in the direction perpendicular to the wire axis, must be taken in account, as suggested, in 1964, by Liehnard and Wong [8]. The Taylor wavelength is then shortened with respect to the plate case

$$\lambda_{\mathrm{d}} = 2\pi\sqrt{3}\Big/\sqrt{\left[\frac{g(\rho_{\mathrm{l}}-\rho_{\mathrm{v}})}{\sigma}+\frac{2}{D(D+2a)}\right]} \tag{5}$$

where "a" is the maximum amplitude that the wave would have if it were a sinusoid.

Using both this approximation and experimentally measured values of λ_{d} (between 0.001 and 0.0015 m), the maximum amplitude "a" may be calculated. Its value is between 15 and 40 times the wire radius. This result shows that "a" cannot be neglected when calculating the value of the Taylor wavelength.

As shown in Fig. 3, in the case of small cylinders, the liquid vapor interface cannot be thought as a sinusoidal one. (Besides, the vapor sheath is almost invisible.) The same observations have already been made by authors like Liehnard and Wong [8] (25 μm diameter wire in isopropanol) or by Tsukamoto and Uyemura [3] (50 μm diameter wire in liquid nitrogen).

The $\{q\,;\Delta T\}$ values obtained in the film boiling regime are usually compared with the Breen and Westwater correlation [9] established for cylinder diameters between 5 μm and 50 mm. This correlation takes in account the wire diameter, the Taylor wavelength and various properties of the liquid such as surface tension, latent heat, liquid density, or of the vapor such as thermal conductivity, specific heat, dynamic viscosity or density.

Comparison of the film boiling regime data (points located between E and m in Fig. 2) with both the Breen and Westwater correlation adapted to our experimental conditions (liquid nitrogen, wire diameter of 32 μm, most dangerous Taylor wavelength between 0.001 m and 0.0015 m) and Frederking's experimental results [2] (31.2 μm diameter wire in saturated nitrogen bath) is plotted in Fig. 4. Our experimental values are lower than Frederking's ones of about 40% but are in very good agreement with the Breen and Westwater correlation including an experimental Taylor wavelength of 0.0015 m.

3.4. *Peak heat flux* (*M*)

The mean value obtained in our experiments for the peak heat flux is 14.2 10^4 W m^2. This value must be compared with the empirical correlation proposed by Kutateladze and Borishanskii [10] established from cylinders of various diameters:

$$q_{\mathrm{Max}} = Ah_{\mathrm{lv}}\rho_{\mathrm{v}}^{1/2}[g\sigma(\rho_{\mathrm{l}}-\rho_{\mathrm{v}})]^{1/4}. \tag{6}$$

The A constant experimentally determined is function of fluid, heater geometry and fluid-heating surface interaction. If the heated body is a cylinder, A is, besides, a function of the heating element diameter. Kutateladze *et al.* [11], from experimental results, have plotted the A value vs a dimensionless diameter D^* given by:

$$D^* = \frac{D}{\left[\dfrac{\sigma}{g(\rho_{\mathrm{l}}-\rho_{\mathrm{v}})}\right]^{1/2}}. \tag{7}$$

For liquid nitrogen, the $\sigma/g(\rho_{\mathrm{l}}-\rho_{\mathrm{v}})$ term which represents the ratio of surface tension force to the buoyancy force is equal to 10^{-6} m. With a heating element of 32 μm in diameter, D^* is equal to 0.03, which yields an A constant value of about 0.11 (in order for comparison this value is 0.16 for a horizontal plate). Finally the value of the critical flux

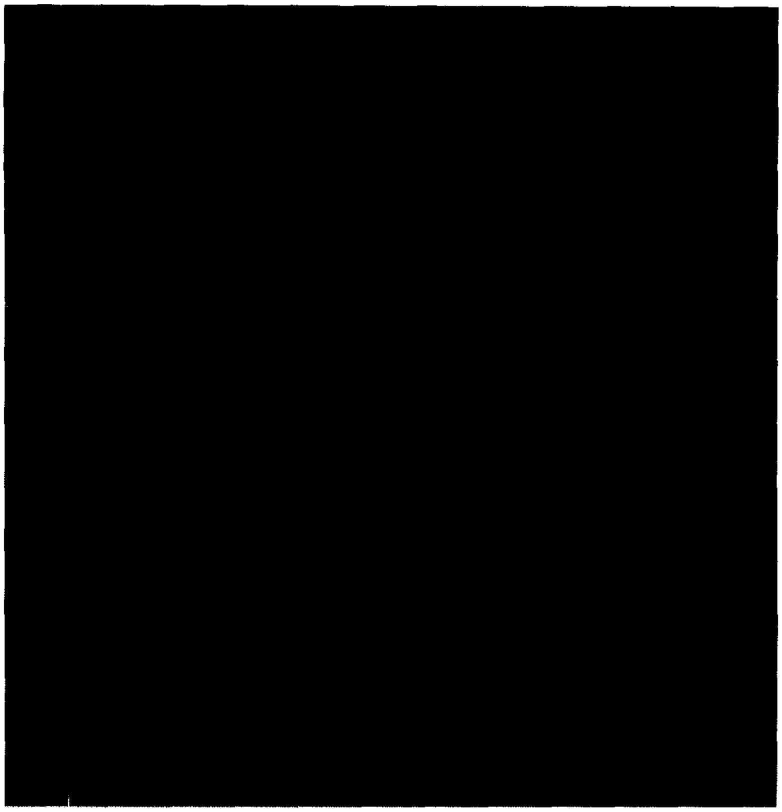

Fig. 3. Photographic observation of film boiling regime.

obtained with the Kutateladze and Borishanskii correlation is:

$$q_{\mathrm{Max}} = 13.7 \times 10^4 \mathrm{~W~m^{-2}}$$

which confirms both our results and the Kutatelateladze and Borishanskii correlation.

3.5. *Minimum film boiling flux* (*m*)

The experience gives a value of 9×10^4 W m^{-2} which may be compared with semi-empirical correlations established for small diameter cylinders by authors like Liehnard and Wong [8] or Liehnard and Dhir [12]. These two correlations applied to our case for a 32 μm diameter cylinder immersed in a liquid nitrogen bath give values equal to 7.33×10^4 W m^{-2} and 4.5×10^4 W m^{-2}, respectively.

In our experience with wire temperature controlled, a premature transition from the film boiling regime to a mixed boiling regime described below, takes place without obtaining the minimum film boiling flux.

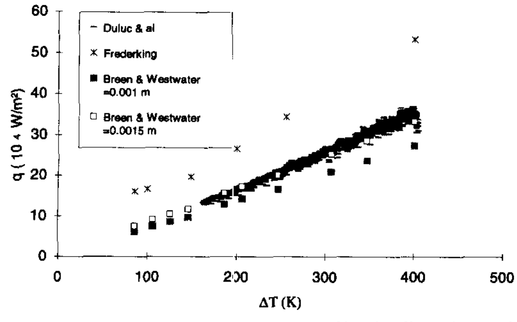

Fig. 4. Comparison of experimental film boiling data with the Breen and Westwater correlation (see text for details).

3.6. *Transition*

To avoid any confusion, we call transition the intermediate region located between the fully developed film boiling regime (Em in Fig. 2) and the peak heat flux (M Fig. 2). This region displays two distinct zones, a first one located between M and G with a negative slope and a second one located between points G and D with a positive slope.

3.6.1. *Negative slope zone* (*MG*). This zone, which for our experimental conditions, is of very small width (less than 3 K) has been very difficult to stabilize by the temperature control device [13]. It has been observed previously by various authors and notably by Sakurai and Shiotsu [14].

3.6.2. *Mixed boiling* (*GD*). This zone has a width of about 300 K and corresponds, for a given ΔT_{o}, to a stationary coexistence on the wire of both nucleate and film boiling regimes. At point G, the nucleate boiling area is much greater than the film boiling one. Beyond point G, the film boiling regime advances along the wire until point D (where the wire is totally covered with film boiling). This stationary coexistence of both boiling regimes has previously been observed, notably by Zhukov and Barelko [15].

Again, this coexistence of zones of different temperatures is controlled in terms of an imposed resistance. Moreover, this is only possible provided that the conductive heat flux along the wire is not too high. It is possible to show [16] that this flux is mainly a function of heating element thermal conductivity and diameter

$$Q_{\mathrm{c}} \propto k^{1/2} D^{3/2}. \tag{8}$$

With our geometrical configuration, this conductive heat flux has been estimated [13] to be about 0.01 W, which remains low in comparison with boiling heat fluxes, which have magnitudes of about 0.3 W.

Even though the wire used in our experiments is a very good thermal conductor (alloy where copper is in majority), its low diameter is in favor of the coexistence on the wire of zones whose temperatures are different and furthermore whose boiling modes are different.

4. CONCLUSION

Boiling curves presented in this work have been realized in liquid nitrogen with a 32 μm diameter heating wire by *controlling the mean temperature of the heating element* in stationary conditions. These curves do confirm some expected results, in particular for nucleate boiling and film boiling, and bring into light the following points:

(1) It is possible to maintain a laminar natural convection for high temperature differences because of the small heating element diameter.

(2) For film boiling, the Breen and Westwater correlation can be used provided that the wavelength λ_d value that takes in account the wire radius and the wave amplitude is used (i.e. the experimental one).

(3) Transition zone located between the peak heat flux and the minimal film boiling heat flux may be decomposed in two regions: a first one with a negative slope where some nucleate boiling zones and some vapor zones coexist in an unstable way; a second one of positive slope called mixed boiling region where nucleate and film boiling regimes coexist in a stable way. Work is in progress to provide more information on this region.

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