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Boiling incipience in liquid nitrogen induced by a step change in heat flux

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Abstract

In the present paper are reported boiling experiments performed on a 25 μm brass wire immersed in saturated liquid nitrogen at 1 bar. A boiling curve performed under quasi-stationary heating conditions is presented. The boiling performance of the system induced by a step change in heat flux is next investigated. It is shown that a premature transition to film boiling is systematically observed when the applied heat flux is higher than 80% of the steady critical heat flux. This transition is however likely to happen as soon as the applied heat flux exceeds the steady minimum heat flux value. Boiling incipience results from the activation of pre-existing vapour embryos entrapped in the cavities of the wall. A gradual activation of the nucleation sites is observed for low values of the applied heat flux. Values higher than q''_{FDNB} (minimum heat flux for fully developed nucleate boiling measured under stationary heating conditions) lead to explosive boiling incipience in which bubble dynamics and interfacial motions are intense enough to produce an acoustic emission.
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Keywords: Boiling incipience; Stepwise heat input; Highly wetting fluids; Thin wire

1. Introduction

Liquid nitrogen is an effective coolant for various systems. In most cases exists a limited value for the operating temperature. Undesirable temperature excursions are however likely to be encountered in the normal running process due to the occurrence of fortuitous heating disturbances. High temperature overshoots may also happen during the starting up of a device as induced by a steep heating procedure. It is therefore important to gain information about boiling characteristics associated to transient heating conditions.

Due to the complexity of boiling phenomena, many studies dealing with transient heating concern pool boiling conditions. Most of them have been conducted on wires or thin films because in these cases, the wall temperature and the heat flux transferred to the fluid may be determined from analytical approximations. Investigations dedicated to massive heaters appeared with the development of inverse heat conduction methods. Their number is yet limited despite of their practical significance.

Numerous works have been developed in the last five years dealing with micro-heaters submitted to large heating rates ($>10^6$ K s^{-1}), see for instance [1–5]. These studies directed towards practical applications like thermal ink jet printers or micro-actuators deal with rapid phase change phenomena. They generally focus on boiling incipience, which happens in the form of explosive spontaneous nucleation and on the subsequent bubble dynamics. The investigated time scales are lower than one millisecond.

In a recent work, transient nucleate boiling for highly wetting fluids has been investigated considering two metallic specimen, one was a thick flat sample and the other one a thin wire [6]. The experimental procedure is similar for both samples: the heating mode is a stepwise heat generation with a prior activation of the nucleation sites. This

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Nomenclature

c_p	specific heat [J kg^{-1} K^{-1}]
D	wire diameter [m]
d	nitrogen molecule diameter [m]
F	energy factor
h_{lg}	latent heat of vaporisation [J kg^{-1}]
I	electric current [A]
J_{het}	rate of nuclei formation per unit area (heterogeneous nucleation) [m^{-2} s^{-1}]
k_B	Boltzmann constant 1.3805×10^{-23} [J K^{-1}]
Kn	Knudsen number
L	wire length [m]
m	mass of one molecule [kg]
N	number of molecules per unit volume [m^{-3}]
P	pressure [Pa]
q''	heat flux [W m^{-2}]
$\dot{Q}$	heat power [W]
R_c	mouth cavity radius [m]
r	curvature radius [m]
$\Re$	electrical resistance [Ω]
S	area [m^2]
t	time [s]
T	temperature [K]
U	voltage [V]
V	volume [m^3]
W	work of formation of the vapour embryo [J]

Greek symbols

γ	temperature coefficient [Ω K^{-1}]
δ_T	thermal diffusion length [m]
ΔT_W	wire superheat $\Delta T_W = T_W - T_{sat}$ [K]
θ	contact angle [rad]
λ_0	mean free path [m]
ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}]

Subscripts

b	brass
c	cavity
CHF	critical heat flux
e	equilibrium conditions
FDNB	fully developed nucleate boiling
g	vapour
het	heterogeneous nucleation
hom	homogeneous nucleation
J	joule
l	liquid
min	minimum heat flux
ONB	onset nucleate boiling
$\Re$	resistor
s	solid
S	wire support
sat	saturation
w	wall
W	wire

study carried out concurrently on the two specimens gives a better understanding of the effects induced by thermal inertia. Besides, conditions at boiling incipience have been highlighted for each specimen. For the thick sample, the incipient superheat is similar to the one measured under quasi-stationary heating conditions. On the opposite for the thin wire, this parameter is not constant but depends on the magnitude of the heating step.

Several boiling investigations have been reported in the literature dealing with transient heating conditions applied on thin wires. They have been performed with various heating modes and a detailed list about these works may be found for instance in [6]. Some of them have been performed with liquid nitrogen as the working fluid. As the thermal inertia of thin wires is small, boiling incipience occurs very quickly after the beginning of the heating process. A high sampling rate is therefore required for data acquisition. Most transient heating experiments performed with thin wires and reported in the literature focus on boiling incipience. The recording time period is short, typically of about a few hundreds of milliseconds. In most cases, steady-state could not be achieved. Despite of this, these various studies have brought into light some specific transient characteristics. For a stepwise heat generation Tsukamoto et al. [7] reported a premature transition to film boiling for a heat flux lower than the critical heat flux. Sinha et al. [8], then Okuyama and Iida [9] showed that the wire temperature at boiling incipience just before this transition is close to the homogeneous nucleation temperature. Sakurai and his co-workers [10–13] extensively studied boiling on a thin wire submitted to exponentially increasing heat inputs using various fluids including liquid nitrogen. They reported that the wire temperature at boiling incipience is affected by the magnitude of the heating rate. The upper limit is the homogeneous nucleation temperature observed for the highest heating rates but lower values have been measured for smaller heating rates. Similarly to Tsukamoto et al. [7], they observed a direct transition from the non-boiling regime to film boiling. As the liquid was pre-pressurized before each run, the cavities were flooded. These authors concluded that such a transition was due to heterogeneous nucleation and called the associated temperature, the “heterogeneous spontaneous nucleation (HSN) temperature”. Using a very low rampwise heating, they also observed this premature transition to non-boiling to film boiling under quasi-stationary heating conditions.

Temperature at boiling incipience was the so-called HSN temperature and its value was found to be close from the one measured at the minimum film boiling point. You et al. [14] using two highly dielectric fluids, methanol and R-113, reported a direct transition from natural convection to film boiling for small cylinders. A similar feature was observed with flat smooth surfaces by Chang et al. [15] using FC-87. In a recent work, Deev and coworkers [16] developed a model aiming to clarify the premature transition to film boiling. Considering two cryogenic fluids, nitrogen and helium, the authors showed that under stepwise heating conditions, direct transition may be explained considering heat energy stored in the superheated liquid before boiling incipience. The model also points out that boiling crisis is more likely to occur when time for boiling incipience is large in comparison with the time for the bubbles to grow until coalescence into a vapour film.

In the present paper are reported boiling experiments performed with a thin brass wire immersed in saturated liquid nitrogen at 1 bar. The transient heating investigated in the present work is a stepwise power input. An attempt will be made to answer to the following questions: what are the time scales associated to the development of the boiling pattern, i.e. the nucleate or film boiling regime? what is the transient path and the maximum superheat involved during the process? what is the nature of boiling incipience? is there a premature transition to film boiling, i.e. for $q'' < q''_{CHF}$? To this attempt, heating steps of various magnitude have been supplied to the wire. For every run, the step duration is long enough to achieve stationary boiling conditions. Obviously is required a prior and detailed knowledge of the boiling curve obtained under quasi-stationary heating conditions. It will be a reference once analysing the transients. The initial condition is controlled by the means of two parameters: the system temperature and the presence of pre-existing vapour entrapped in the cavities. The subsequent paper is organised as follows. The experimental set-up and procedures used for quasi-stationary and transient heating experiments will first be described. In the following section will be presented the boiling curve obtained under quasi-stationary conditions. Then will be examined and discussed the results obtained with applied heat fluxes of different levels.

2. Experimental apparatus and procedures

2.1. Experimental setup

The test cell is immersed in a Dewar vessel, 150 mm in diameter (Fig. 1). Experiments have been performed with liquid nitrogen under atmospheric pressure and saturated conditions (1 bar; 77 K). Temperature of liquid nitrogen being lower than ambient temperature, the saturation value is therefore controlled by pressure. Temperature in the liquid bath is affected by hydrostatic overpressure. During the experiments, the liquid height above the wire was about 0.4 m leading to a hydrostatic overpressure nearly equal to 3% of the atmospheric pressure. Temperature of the liquid in direct contact with the wire was therefore slightly modified (<0.3 K). The critical pressure and temperature of liquid nitrogen have small values, 33.6 bar and 126 K, respectively. Liquid nitrogen does not contain dissolved gases except maybe some traces of helium, hydrogen or neon. It is a highly wetting fluid and has a low surface tension. The critical heat flux is moderate, of about 10–20 W cm^{-2}. Lastly, the temperature for homogeneous nucleation is low (~100 K at atmospheric pressure). As a consequence the limiting value for the liquid superheat is small (~32 K at atmospheric pressure).

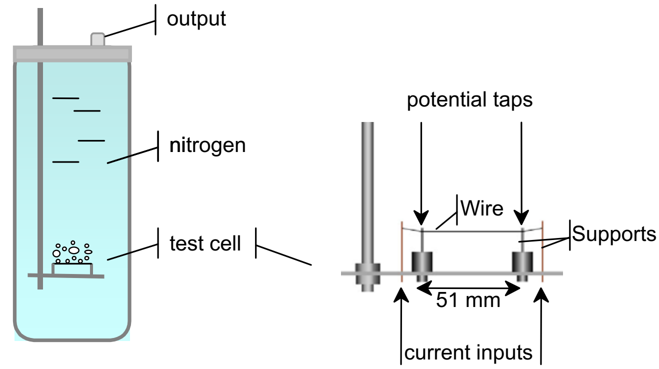


Fig. 1. Schematic of the test apparatus.

A photographic system consisting in a Nikon D70 6.1 Megapixels SLR digital camera was used. Images have been recorded with a resolution of 3008 × 2000 pixels.

The wire is made of brass, 25 μm in diameter and 51 mm in length. Due to its mechanical fragility, neither polishing nor surface finish have been realized. Even though the wire surface appears as a smooth one to the naked eye, a visualisation performed with an electronic scanning microscope revealed that many grooves were present on the wire surface, likely to be due to the manufacturing process (Fig. 2).

As the wire diameter is small, temperature can be considered as uniform in the radial direction. The thermoresistive nature of the wire makes it both a heater and a temperature sensor. The heat flux generated by Joule effect

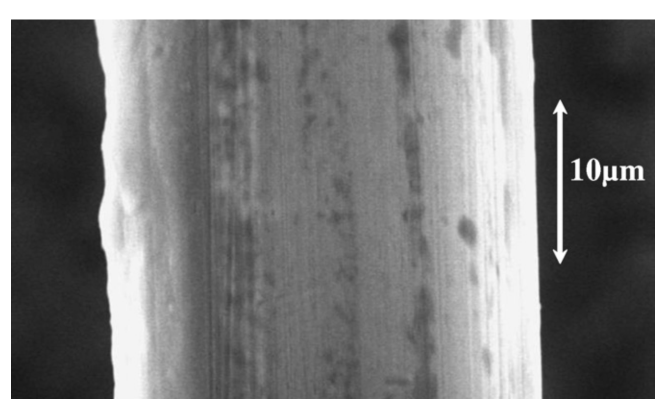


Fig. 2. Surface micro-geometry of a 25 μm brass wire observed with a scanning electron microscope.

q''_J and the average superheat of the wire ΔT_W are calculated as follows:

$$q''_J = \frac{U_W I}{\pi D L} \quad (1)$$

$$\Delta T_w = \Delta T_W = T_W - T_{sat} = \left(\frac{U_W}{I} - \Re_{W,T_{sat}}\right)\frac{1}{\gamma} \quad (2)$$

$\Re_{W,T_{sat}}$ is the electrical resistance of the wire at the temperature T_{sat} and is close to 5.5 Ω. The temperature coefficient of the wire remains equal to $\gamma = 0.01055\ \Omega\ K^{-1}$ in the investigated temperature range. In order to measure the current intensity $I(t)$ and the voltage $U(t)$, the wire is connected on four supports (Fig. 1). It is soldered on two external pins for current supply and held with silver paste on two internal contacts for voltage measurement. Heat loss by the supports could be estimated, under steady state conditions, as less than 3% of the total heating power in the nucleate boiling regime and lesser than 10% in the film boiling regime [17].

The heating step is achieved by the means of a voltage step. A schematic view of the electrical circuit is shown in Fig. 3. It includes a power supply, a relay, a resistor $\Re_\Re$ and the wire itself $\Re_W$. The resistor used for the intensity measurement has a value which remains equal to $1 \pm 0.0005\ \Omega$ provided that heat dissipation remains lower than 8 W. This condition is achieved during experiments as the electrical current in the circuit never reaches 1 A. The heating step is delivered in the circuit once the relay has been switched on. The relay, a mercury type one, leads to closing time constants, whose value remains lower than 50 μs and excludes any overshoot phenomenon. Both voltages $U_\Re$ and U_W connected to the high impedance input of two analogical differential amplifiers specifically designed for this experiment are recorded and stored in a computer.

The average superheat of the wire is determined using Eq. (2). The heat flux released in the fluid q'' is obtained from a heat balance:

$$q'' = q''_J - \rho_b c_{p,b} \frac{D}{4}\frac{\partial T_W}{\partial t} - \frac{\dot{Q}_S}{\pi D L} \quad (3)$$

where ρ_b and $c_{p,b}$ are the density and the specific heat of brass and $\dot{Q}_S$ is the heat power conducted through the wire supports.

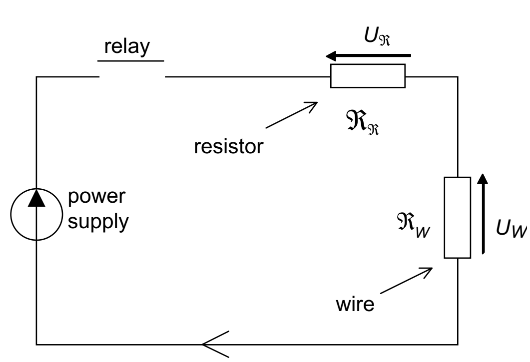


Fig. 3. Schematic of the electric circuit.

As the wire diameter is small, the second term in the right hand side of Eq. (3) can generally be neglected. This approximation is however no longer correct during early stages as the wire temperature rises sharply. The last term in the right hand side may also be neglected as the conductive heat flux $\dot{Q}_S$ varies with the square of the diameter. This assumption is not relevant during partial film boiling as large temperature gradients are generated along the wire [18]. The whole experimental procedure leads to an uncertainty in the heat flux of about $\pm 0.2\ W\ cm^{-2}$ and of about ±1 K in the temperature measurement.

2.2. Experimental procedures

2.2.1. Quasi-stationary heating experiments

The quasi-stationary boiling curves have been performed using four different brass wires. The wire is heated with small increasing or decreasing increments using a computer-controlled power supply, operating under voltage mode. Thus, reproducible heating conditions from one run to another have been achieved. The heating rate has been selected sufficiently low to observe quasi-stationary boiling curves.

2.2.2. Transient heating experiments

Transient heating experiments have been realised using a systematic prior heating procedure. This procedure consists to gradually bear the wire into a nucleate boiling state. The associated heat flux is about $23\ W\ cm^{-2}$ and corresponds to fully developed nucleate boiling. The wire is maintained in this vigorous boiling regime during 30 s in order to ensure that most nucleation sites have been activated. Afterwards, the power is switched off and the wire recovers very quickly its initial temperature equal to the saturated bath temperature. In order to avoid any residual motion of the bath, a time delay of about 5 min is considered before the beginning of the transient heating step. Using this short time delay between the preliminary heating procedure and the transient heating run, one can expect numerous vapour embryos to be present within the cavities.

3. Boiling incipience during quasi-stationary heating experiments

3.1. Quasi-stationary boiling curve

A typical boiling curve obtained under quasi-stationary heating conditions is presented in Fig. 4. One observes the classical convective regime until boiling onset (q''_{ONB}). Discrete bubbles appear on the wire and then become more numerous as the heat flux is increased (Fig. 5a and b). The wire is entirely covered with bubbles for a heat flux value equal to q''_{FDNB}. Nucleate boiling develops (Fig. 5c) until the critical heat flux q''_{CHF} is achieved. At that point a direct transition to partial film boiling occurs: the wire is partially covered by a vapour film while nucleate boiling

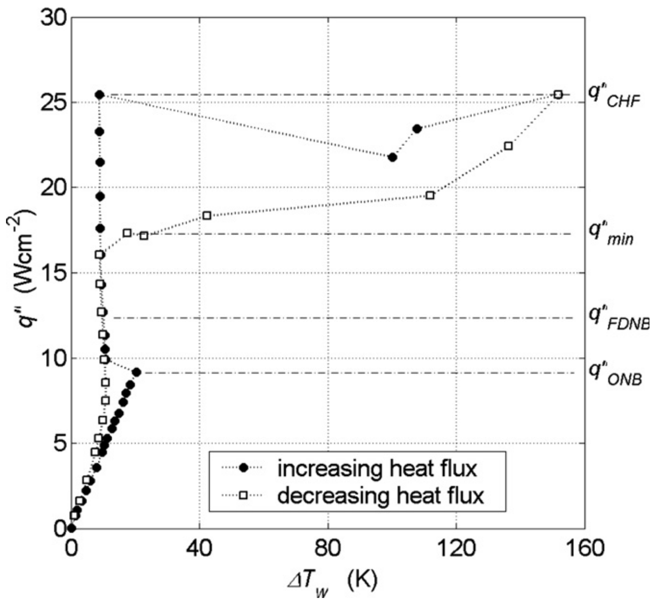


Fig. 4. Quasi-stationary boiling curve realised with a 25 μm brass wire immersed in liquid nitrogen ($P = 1$ bar).

is observed on the other part [18]. This feature is specific to thin wires. Despite of large temperature gradients generated along the wire by the two boiling regimes, the small value of the wire diameter leads to a small conductive heat flux inside the solid. Any further increase of heat flux leads to an extension of the wire area covered by film boiling while the part covered by nucleate boiling recedes (Fig. 5d). Reciprocally any decrease of heat flux below q''_{CHF} leads to a reduction of the wire area covered with film boiling while the part of the wire covered by nucleate boiling increases. This situation lasts until a minimum limit of the heat flux q''_{min} is attained for which another direct transition happens leading the wire back to nucleate boiling. This feature is connected to the existence of a minimum heat flux q''_{min} for film boiling which is the so-called minimum heat flux required to sustain the vapour sheath.

3.2. Boiling incipience

The aforementioned boiling regimes have been observed with all tested wires and for the 16 runs being performed. The boiling curves however exhibit differences at boiling inception (ONB). Two main kinds of boiling incipience have been identified from these various tests. In the first one, boiling onset occurs at a high wire superheat of about 20 K ($\Delta T_{\mathrm{ONB}} \approx 20.4 \pm 2.1$ K). The corresponding heat flux, close to 9 W cm^{-2}, is important as heat transfer coefficients associated to natural convection on small cylinders are high ($h \propto D^{-1/4}$). A sharp noise, sounding like a click, is heard at boiling incipience. The wire superheat is instantaneously reduced of about 10 K (Fig. 4). This kind of boiling incipience was observed for 10 of the 16 runs. For the six others, departure from single-phase heat transfer occurs earlier ($\Delta T_{\mathrm{ONB}} \approx 11.8 \pm 1.2$ K), the heat flux being about 6 W cm^{-2} and no significant reduction of the wire temperature was induced by boiling onset. No sound could be heard. Considering now the whole 16 runs, it seems *a priori* very difficult to identify a consistent trend in the incipience behaviour from one run to the next. Similar features were observed by You et al. [19] using saturated R-113 at 1 atm and chromel wires 130 μm in diameter. The authors recommended the use of statistical or probabilistic means to display boiling incipience. Thus in the present case, the probability that boiling incipience has already happened when the wire superheat reaches 22 K is close to one.

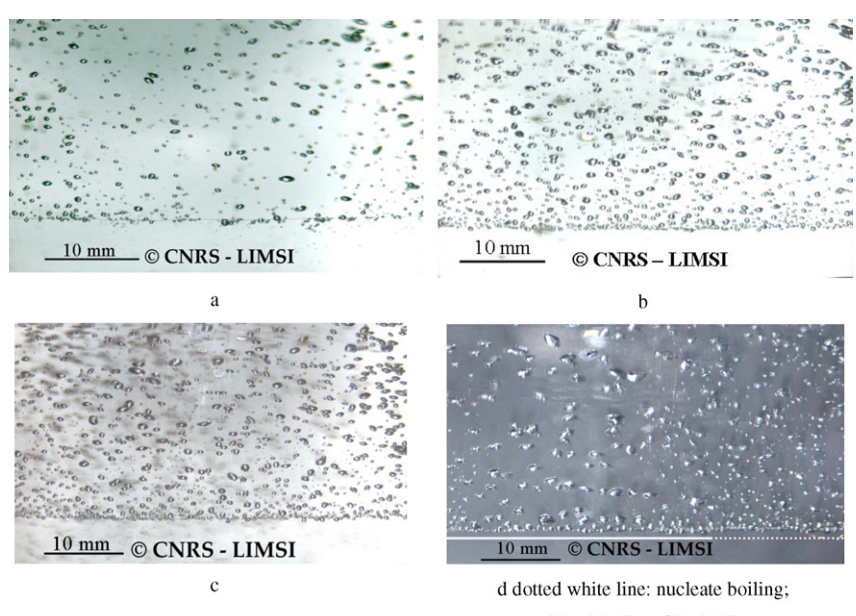


Fig. 5. Various boiling patterns on a 25 μm brass wire immersed in saturated liquid nitrogen at 1 bar.

Comparing these two kinds of boiling incipience, it may be inferred that the second one is associated to a gradual activation of the nucleation sites while the first one corresponds to a rapid triggering of numerous nucleation sites. In the following, a distinction will be made between "progressive boiling incipience" and "simultaneous boiling incipience". Since all quasi-stationary boiling curves have been realised using the same computer controlled heating procedure, differences observed at boiling incipience are mainly due to the change in the cavity contents from one run to another. The conditions required for a nucleation site to become active will be briefly recalled in the next sections. First, vapour has to be trapped in the cavity and to remain stable (no collapse must occurs). Then the liquid superheat has to be high enough to allow bubble growth.

3.2.1. Vapour trapping

Liquid nitrogen is a highly-wetting fluid, whose static contact angle is small, less than 10° [20]. It has therefore a good ability to seep into the natural cavities created by surface irregularities. Depending on the shape of the cavity and on the dynamics of the liquid vapour interface, vapour may be trapped or not. The criterion developed by Bankoff [21] is that vapour will be trapped provided that the static contact angle of the liquid on the solid surface is larger than the cone angle of the cavity. Extending Bankoff's criterion to the dynamic contact angle, You et al. [19], Tong et al. [22] developed a model aiming at describing vapour entrapment in conical cavities. It was shown that for a highly wetting liquid, the activation of the vapour embryos will occur within conical cavities provided that the dynamic contact angle encountered during the former boiling process has been large enough to entrap vapour. The advancing contact angle is known to be higher than the static contact angle, its magnitude being increased by the interfacial velocity. For instance, vapour may be trapped during the detachment process of the former bubbles. From their analysis, Tong et al. [22] concluded that boiling incipience for highly wetting fluids was a random process.

3.2.2. Stability of the vapour embryos

Once trapped within a cavity, a vapour embryo is stable if the conditions of thermodynamic equilibrium are achieved, i.e. mechanical, thermal and chemical equilibria. For a spherical vapour embryo, these conditions are well known [23]. However in most cases, vapour embryos are influenced by the shape and the size of the cavities in which they are trapped and are therefore no more spherical. Their stability needs the junction of the interfacial meniscus on the wall of the cavity to be consistent with the static contact angle between the fluid and the wall. Thus for a highly wetting fluid re-entrant cavities are likely the only ones to include stable vapour embryos.

3.2.3. Size of the active cavities

The incipient superheat may be connected to the mouth radius R_c of the active cavities using the classical criterion developed by Griffith and Wallis [24]. As the saturation temperature of liquid nitrogen is low, no residual gas is entrapped within the cavities of the wall except vapour nitrogen and maybe some traces of non-condensable He, H_2 or Ne. Thus, the relation proposed by Griffith and Wallis writes:

$$\Delta T_{\mathrm{ONB}} = T_{\mathrm{W}} - T_{\mathrm{sat}}(P_{\mathrm{l}}) \approx \Delta P \left(\frac{\mathrm{d}T}{\mathrm{d}P}\right)_{\mathrm{sat}} = \frac{2\sigma}{R_{\mathrm{c}}} \frac{T_{\mathrm{sat}}}{h_{\mathrm{lg}}\rho_{\mathrm{g}}} \tag{4}$$

For large incipient superheats, as suggested by You et al. [19], a corrected form taking into account the non-linearity of the saturation curve should however be preferred:

$$\Delta T_{\mathrm{ONB}} = T_{\mathrm{W}} - T_{\mathrm{sat}}(P_{\mathrm{l}}) \approx T_{\mathrm{sat}}\left(P_{\mathrm{l}} + \frac{2\sigma(T_{\mathrm{w}})}{R_{\mathrm{c}}}\right) - T_{\mathrm{sat}}(P_{\mathrm{l}}) \tag{5}$$

$T_{\mathrm{sat}}\left(P_{\mathrm{l}} + \frac{2\sigma(T_{\mathrm{w}})}{R_{\mathrm{c}}}\right)$ is the saturation temperature at the pressure inside the cavities, $\sigma(T_{\mathrm{W}})$ is the surface tension at the wire temperature.

Using Eqs. (4) and (5) and the properties of liquid nitrogen listed in Jensen et al. [25], the mouth radius of the active sites is evaluated and reported in Table 1. It shows significant differences between results given by Eqs. (4) and (5). The more accurate equation, i.e. Eq. (5), has therefore to be employed. In the present experiments, bubbles are emitted from sites whose mouth radius has a very small value, especially at high superheats. Considering the tiny values indicated in Table 1, the question arises about the validity of a macroscopic description for the interfacial region. The mean free path λ_0 of vapour nitrogen within the sites can be estimated using the classical kinetic theory of gases:

$$\lambda_0 = \frac{k_{\mathrm{B}}T}{\sqrt{2}P\pi d^2} \tag{6}$$

where k_{B} and d are the Boltzmann constant and the diameter of the nitrogen molecule, respectively. Under initial conditions, λ_0 is close to 0.013 μm and has the same order of magnitude than the mouth radius of the active sites. Flows within the cavities are therefore slightly rarefied and as the Knudsen's number $Kn = \lambda_0/2R_{\mathrm{c}}$ is greater than 0.01, continuum formulations are no more valid to describe them. Particle methods such as molecular dynamics, particle-in-cell and the direct Monte Carlo simulation are

Table 1
Boiling incipience under quasi-stationary heating conditions

Boiling incipience	Simultaneous boiling onset	Progressive boiling onset
Number of occurrence (16 runs)	62.5%	37.5%
ΔT_{ONB} (K)	16.3–22.5	10–13
Mean value of ΔT_{ONB} (K)	20.4 ± 2.1	11.8 ± 1.2
R_{c} (μm) calculated from Eq. (4)	0.066–0.09	0.115–0.15
R_{c} (μm) calculated from Eq. (5)	0.012–0.027	0.044–0.072

attractive tools to study the early stages of the bubble growth.

Lastly is briefly reminded that conditions like smooth surface with only small cavities, highly wetting liquids or high wall superheats are known to promote a very rapid, inertia controlled growth of the vapour bubble [23]. Besides, Carey [23] reported that for liquid metals of low contact angles, “at high superheat, the bubbles grow almost explosively, generating a shock wave in the liquid that makes an audible sound”. All the aforementioned characteristics provide a suitable explanation for the “simultaneous boiling onset”. Conversely, when vapour embryos of larger size are entrapped in some cavities of the wall, boiling incipience is more likely to occur at lower superheats leading to a slower, thermally controlled bubble growth.

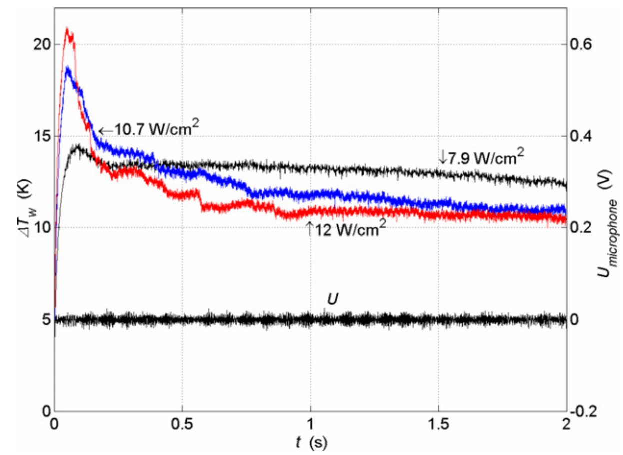


Fig. 6. Time evolution of the wire superheat for a low nucleate boiling heat flux.

4. Transient heating experiments

In this section, the boiling performance of the system induced by a step change in heat flux is investigated. Various levels of heat flux have been applied to the wire in order to examine the onset and development of all boiling regimes. Results will be presented in the following sections considering time evolution of the wire superheat induced by the step change in heat flux. It appears that this evolution may be split in two successive stages. The first one ($0 \leqslant t \leqslant t_1$) is characterized by a rapid temperature increase induced by single-phase heat transfer. Time t_1 corresponds on the curve to the deviation from single-phase heat transfer [17]. At that time, the change in the heat transfer conditions induced by boiling onset is perceptible on the wire superheat. The second stage starting at boiling onset (t_1) ends at steady-state (t_2). It represents the time period required for the development of the stationary boiling pattern, i.e. nucleate or (partial) film boiling.

4.1. Nucleate boiling: low heat flux $q'' < q''_{\mathrm{FDNB}}$

For an applied heat flux varying from 7 to 12.5 W cm^{-2}, steady-state finally achieved corresponds to a wire superheat ranging between 10 and 12.5 K. Referring to the quasi-stationary boiling curve plotted in Fig. 4, it can be seen that these values are associated to low nucleate boiling: discrete bubbles are emitted from several nucleation sites as illustrated by Fig. 5a. Time evolution of the wire superheat is plotted in Fig. 6 for three different heating rates. For these runs, data acquisition has been performed with a sampling rate ranging between 800 and 2000 Hz. Time evolution of the wire superheat is characterized by a rapid increase at early stages until a maximum value is obtained then by a gradual decrease towards steady-state. Due to the small size of the wire, thermal inertia induces only slight effects and in a first approximation, the electrical power supplied to the wire may be considered at any time as almost integrally released in the fluid. As reported in a former study [17], the rapid increase of the wire superheat results from convection heat transfer. During the second stage ($t_1 \leqslant t \leqslant t_2$) a gradual decrease of the wire temperature is observed. It is induced by the emission and the subsequent growth of vapour bubbles at some locations along the wire, the nucleation sites being activated successively. For these low heating rates, a waiting period as long as a few seconds between the activation of two consecutive nucleation sites is likely to be observed. Even though nucleation sites appear to be activated randomly, it seems however possible to distinguish among these results the following trend: the higher the heating rate, the higher the incipient superheat. The nucleation sites activated at a high superheat are in turn more numerous and their triggering occurs in a narrow lapse of time. As a consequence a faster decrease of the wire temperature is observed. Thus, time required for the activation of all vapour embryos ($\Delta t_2 = t_2 - t_1$) appears to be relatively long compared to time needed for boiling inception (t_1): Δt_2 may be as long as several seconds while t_1 is only of a few hundreds of milliseconds. Some of the characteristics listed above, like boiling onset and the development of the boiling pattern appear very similar to the ones observed under quasi-stationary heating conditions during the so-called progressive boiling incipience.

4.2. Fully developed nucleate boiling for medium heat flux conditions: $q''_{\mathrm{FDNB}} < q'' < q''_{\min}$

For an applied heat flux ranging between 13 and nearly 17 W cm^{-2}, data acquisition has been performed with a sampling frequency of 4000 Hz. Time evolution of the wire superheat is plotted for three different levels of heat flux (Fig. 7). Significant differences are observed with the curves displayed in Fig. 6. At early stages, the temperature rise induced by single-phase heat transfer is faster due to the higher heating rates. In contrast with the results presented in Fig. 6, the value of the incipient superheat is similar for the three heating rates, ranging between 21.5 and

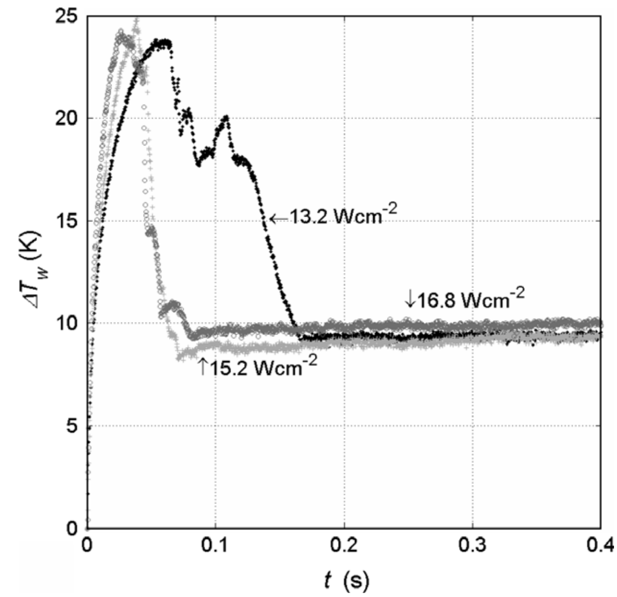


Fig. 7. Time evolution of the wire superheat for an intermediate nucleate boiling heat flux.

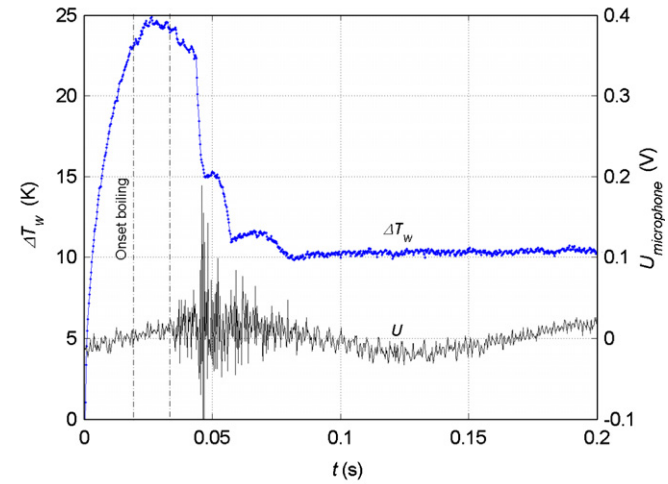


Fig. 8. Signal recorded by the microphone superimposed with the wire superheat $q'' = 16.8\ \mathrm{W\ cm^{-2}}$.

23.5 K. The major difference with the curves plotted in Fig. 6 concerns time elapsed from boiling onset to steady-state (Δt_2), whose magnitude is now similar to the time required for boiling inception (t_1). Unlike transient curves associated with the development of low nucleate boiling for which a gradual decrease of the wire temperature is observed (Fig. 6), the three curves plotted in Fig. 7 present a large temperature drop of about several kelvins in a few milliseconds. Such a drastic change results from the vaporisation of the microlayer [26]. This feature usually associated to hemispherical bubble growth is more likely to be observed with a high heat flux. Besides, this temperature drop reveals the simultaneous occurrence along the wire of numerous bubbles. The wire superheat is indeed a spatial average computed from the electrical resistance of the wire; an event as visible as a temperature change of several kelvins in a few milliseconds represents therefore the contribution of the whole wire. For an applied heat flux ranging between 13 and 17 W cm^{-2}, steady-state finally achieved corresponds to fully developed nucleate boiling; this is consistent with the quasi-stationary boiling curve presented in Fig. 4. Numerous nucleation sites are active, emitting bubbles with high frequencies as shown in Fig. 5b. At steady-state, fluctuations of the wire temperature are then characterised by small amplitudes and high frequencies (Fig. 7). Lastly, for these levels of heat flux, an audible click was systematically heard a short while after the heat switching, the sound intensity increasing with the magnitude of the applied heat flux. A microphone has been inserted at the top of the Dewar vessel in order to connect the recorded sound with time evolution of the wire superheat. A typical example of the obtained results is presented in Fig. 8 for the heat flux equal to 16.8 W cm^{-2}. The microphone was separated from the wire by a liquid column of about 400 mm in height topped by a layer of vapour nitrogen of about 20 mm. Sound velocity in nitrogen is about 850 m s^{-1} in the liquid phase (1 bar, 77 K) and 200 m s^{-1} in the saturated vapour phase. Thus a pressure event occurring in the vicinity of the wire should be detected by the microphone with a time lag no longer than 0.001 s. As it can be seen in Fig. 8, the voltage delivered by the microphone is temporarily modified by an acoustic pressure wave while no change could be detected for a heat flux lower than 13 W cm^{-2} (a typical example of the microphone signal is presented in Fig. 6). Time at the beginning of the acoustic wave and time corresponding to the deviation from single-phase heat transfer are slightly delayed (about 0.015 s). The acoustic emission vanishes as steady-state is achieved. This audible feature appears to be associated with the development of the first bubbles, the maximum acoustic emission being observed during the microlayer vaporisation. Even though a detailed analysis of this complex phenomenon necessitates a high speed camera, a link can be made with a recent study. Using an ultrathin Pt-wire, Glod et al. [4] investigated the explosive vaporisation of water close to its superheat limit. Using a pressure transducer, they recorded the acoustic pressure induced by this boiling process and simultaneously performed a visualisation. The generation and expansion of a vapour microlayer explosion is shown to cause a positive pressure pulse. The acoustic pressure signal presents some negative or positive values depending on acceleration ($\mathrm{d}^2V/\mathrm{d}t^2 > 0$) or deceleration ($\mathrm{d}^2V/\mathrm{d}t^2 < 0$) of the vapour volume growth. To sum up, the results presented in this section show that an applied heat flux higher than 13 W cm^{-2} leads to the occurrence of numerous bubbles along the wire. Boiling incipience appears to be of "explosive nature" in so far as it happens a very short while after heat switching and leads to an acoustic emission. These characteristics appear very similar to the ones associated with the so-called simultaneous boiling incipience observed under quasi-stationary heating conditions and described in Section 3.2.

4.3. Fully developed nucleate boiling for high heat flux conditions $q''_{min} < q'' < 0.8q''_{\mathrm{CHF}}$

For an applied heat flux ranging between 17 and 20 W cm^{-2}, two kinds of boiling performance are likely to be observed for the same heat flux value. A typical example is presented in Fig. 9, the applied heat flux being 19.9 W cm^{-2}. A first run leads to the development of steady nucleate boiling, the wire superheat being stabilized to about 13 K. On the other hand, a second run induces the development of partial film boiling, the wire superheat being stabilized to nearly 60 K. This feature is nevertheless not really surprising referring to the quasi-stationary boiling curve presented in Fig. 4 and to the associated photographs in Fig. 5c and d. This curve shows that for a heat flux ranging between q''_{min} and the critical heat flux q''_{CHF}, at least two steady states are available depending on the boiling pattern established on the wire. Under quasi-stationary heating conditions, the nature of this boiling pattern is governed by the heating procedure: nucleate boiling is first observed as the heat flux is increased. Beyond the critical heat flux, partial film boiling is established on the wire. Nucleate boiling may again be observed on the whole wire length provided that the heat flux is lowered below the minimum heat flux (q''_{min}). These operating conditions are well known and reproducible. Unlike quasi-stationary heating conditions, it seems however very difficult to predict the boiling pattern to be established on the wire when the magnitude of the applied heat flux is comprised between q''_{min} and q''_{CHF}. Both runs presented in Fig. 9 correspond to a same power value applied on the wire. At early stages, heat transfer is performed in the liquid phase and time evolution of the wire superheat is therefore reproducible. As the wire superheat reaches a value close to 22 K, both curves start to diverge. One of the curves starts to rise sharply until the superheat reaches a limit value close to 60 K. This transient path reveals that boiling crisis has happened leading the wire to partial film boiling. On the other hand, the second curve presents a rapid decrease until a superheat of about 12 K is achieved. This second transient path is very similar to the ones previously described in Section 4.2. It corresponds to the development of nucleate boiling associated with a simultaneous boiling onset. Hence, the divergence observed between the two curves is due to vapour dynamics succeeding boiling incipience. In both cases, i.e. the development of nucleate or partial film boiling are involved with similar time scales. For this reason, the conditions for the development of nucleate or film boiling may under certain circumstances be very close.

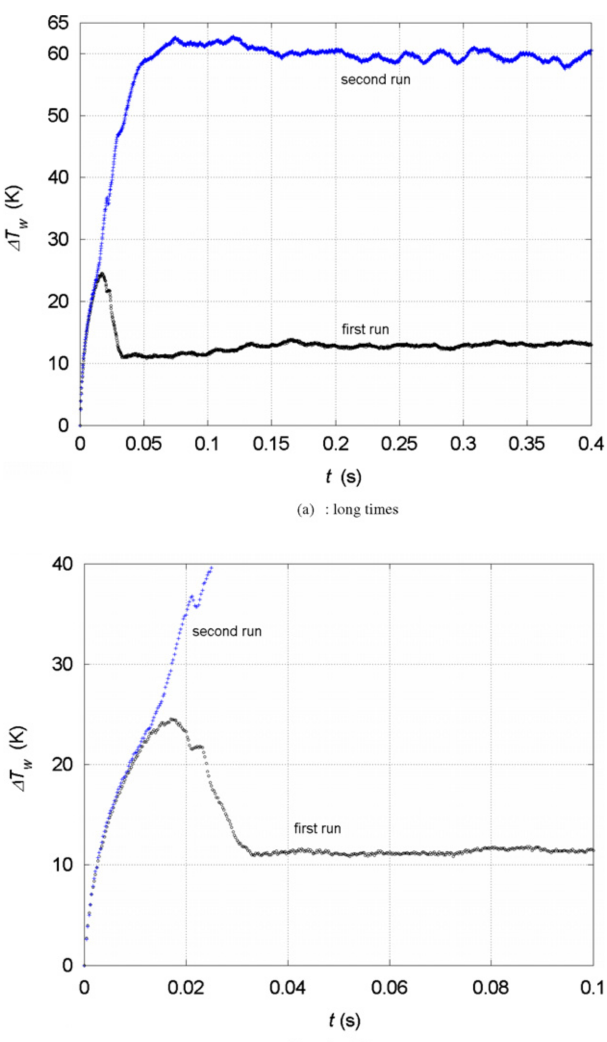


Fig. 9. Time evolution of the wire superheat for two runs carried out with a high nucleate boiling heat flux $q'' = 19.9$ W cm^{-2}.

The above results confirm that a direct transition towards partial film boiling is likely to happen as soon as the applied heat flux exceeds the threshold value of q''_{min} given by the quasi-stationary boiling curve. This is indeed a premature transition inasmuch as it happens for a heat flux lower than the steady critical heat flux. This feature is consistent with the analysis developed by Deev et al. [16]. However, these results highlight that a premature transition does not systematically happen as soon as the heat flux exceeds the q''_{min} value. Bubble dynamics succeeding boiling incipience is very likely to play an important role. Lastly, these results show that the incipient superheat associated to a premature transition is always higher than 22 K and increases with the applied heat flux. The highest value, close to 26 K, has been obtained for a heat flux of 26.2 W cm^{-2}. A direct transition to film boiling was formerly observed in liquid nitrogen and reported into different papers in particular by Shiotsu, Sakurai and their co-workers [10–13]. According to these authors, the direct transition to film boiling is due to heterogeneous nucleation in the flooded cavities of the wall [10]. In their experiments, the corresponding superheat of liquid nitrogen has been measured to range between 22 and 32 K depending on the heating rate. In the present study, the incipient boiling superheat measured during direct transition to partial film boiling appears to be very similar even though the wire is different both in nature (brass vs. platinum) and in diameter (0.025 vs. 1 mm). One may expect a thick wire to have cavities with larger size than a thin wire. Nevertheless, liquid nitrogen is a highly wetting fluid: large cavities are flooded and only the very small re-entrant cavities of the wall act as potential nucleation sites. As mentioned in Section 3.2.3, the size of the active nucleation sites may be estimated considering the incipient superheat measured under quasi-stationary heating conditions. Sakurai and his co-workers reported some quasi-stationary boiling curves obtained at one bar and saturated conditions. The transition from natural convection to nucleate boiling was measured in one case for a surface superheat close to 10 K [13] and in the other close to 20 K [10]. These values are similar to the ones measured in the present study and indicated in Table 1. As far as the size of active nucleation sites are concerned, both studies are therefore comparable.

The superheat limit in liquid nitrogen leading to homogeneous nucleation is close to 32 K [8]. Under certain circumstances, the presence of a solid wall may reduce the work required to form a vapour embryo of critical radius and then reduce the incipient superheat. To our opinion, it cannot be certified *a priori* that a liquid superheat as low as 22 K is induced by heterogeneous nucleation. This statement needs at least to be discussed. An attempt to clarify this point is developed in the following section.

The rate of formation of vapour embryos due to heterogeneous nucleation writes [23]:

$$J_{\mathrm{het}} = N^{2/3}(T)\left(\frac{1+\cos(\theta)}{2}\right)\sqrt{\frac{3\sigma(T)}{\pi mF}}\exp\left[-\frac{W_{\mathrm{hom}}(T)F}{k_{\mathrm{B}}T}\right] \quad (7)$$

where F, the energy factor defined by the ratio $W_{\mathrm{het}}/W_{\mathrm{hom}}$, is a geometric parameter that also writes [27]:

$$F = 3(c_2 + c_3\cos(\theta)) - 2c_1 \quad (8)$$

here θ is the contact angle and the coefficients c_1, c_2, c_3 are defined as

$$c_1 = V/\frac{4}{3}\pi r_{\mathrm{e}}^3 \quad c_2 = S_{\mathrm{g}}/4\pi r_{\mathrm{e}}^2 \quad c_3 = S_{\mathrm{sg}}/4\pi r_{\mathrm{e}}^2 \quad (9)$$

with V the volume of the vapour embryo and r_{e} its equilibrium radius. S_{lg} and S_{sg} are the respective area of the liquid–vapour and solid–vapour interfaces.

For a smooth surface F is expressed as

$$F = \frac{2 + 3\cos\theta - \cos^3\theta}{4} \quad (10)$$

and decreases with the contact angle. Using Eqs. (7) and (10), the heterogeneous nucleation rate J_{het} for a smooth surface is plotted in Fig. 10 as a function of the contact angle for various superheats of liquid nitrogen. Considering

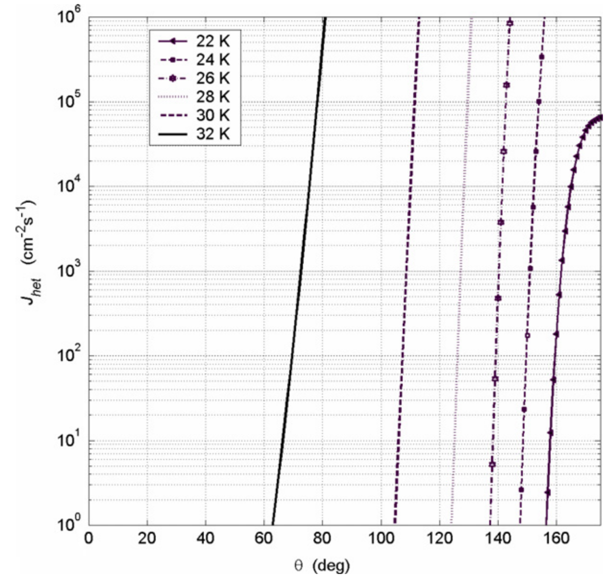
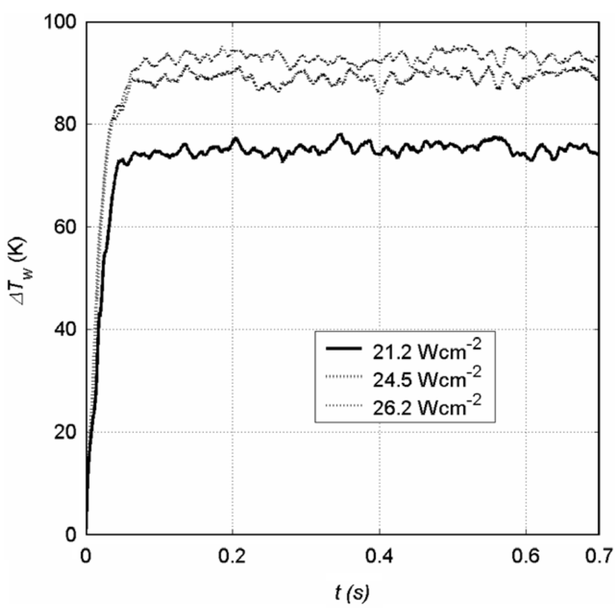


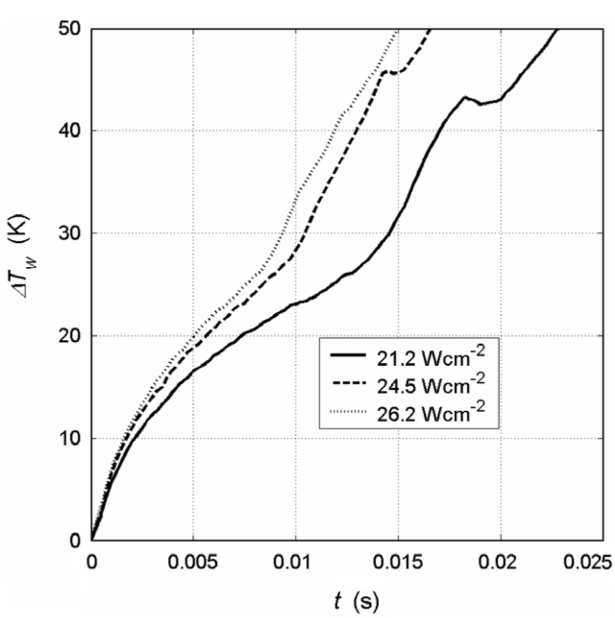
Fig. 10. Heterogeneous nucleation rate in liquid nitrogen for a smooth surface and various liquid superheats vs. contact angle.

the heating area of the wire ($S_{\mathrm{W}} \approx 4\times10^{-6}$ m^2) and the temperature rise (typically 1 K in 10^{-3} s for $\Delta T_{\mathrm{W}} = 20$ K), the rate of formation of embryos usually employed in the literature, i.e. 10^6 cm^{-2} s^{-1}, is suitable in the present experiment to evaluate the superheat of heterogeneous nucleation. Besides, Fig. 10 shows that heterogeneous nucleation in liquid nitrogen on a smooth surface could be at the origin of the boiling onset provided that the static contact angle between the fluid and the solid wall is higher than 60–70°. This high value seems however very unlikely to be observed with a high surface energy like a smooth metallic wall and what is more with a highly wetting fluid like nitrogen. As a conclusion, the theory for heterogeneous nucleation on a smooth surface does not provide a suitable explanation for the superheats measured during the premature transition to film boiling. The small value of the static contact angle appears to be the limiting parameter. Heterogeneous nucleation remains however a possibility considering that the wire surface may locally be covered with impurities up to increasing the value of the static contact angle. For instance, some residues of grease resulting from the manufacturing process may be present on the wire. They represent a low energy surface leading to a significant alteration of the static contact angle.

Let us now briefly consider heterogeneous nucleation initiated at the wall of a commercial material whose surface contains various scratches or cavities. Using analytical considerations Cole [28] and Thormählen [27] investigated heterogeneous nucleation initiated from cavities of various shapes. The work required to form a vapour nucleus within a surface cavity may be made vanishingly small by simply reducing the size of the cavity towards zero but the number of molecules likely to be involved in the formation of a cluster is in turn reduced to zero. As a consequence, the rate for embryo production has to be considerably increased in order to observe nucleation. In the present case, for a spherical cavity of 0.01 μm in diameter, the rate of formation of embryos should be multiplied by 5×10^{10}. Moreover, the formation of an embryo within a spherical cavity does not necessarily lead to bubble emission: the embryo has to become unstable. As a conclusion, for liquid nitrogen, an incipient superheat as low as 22 K may hardly be explained by heterogeneous nucleation. Boiling onset is more likely to result from the activation of pre-existing vapour embryos entrapped in the cavities.



(a) : long times



(b) : short times

Fig. 11. Time evolution of the wire superheat for a film boiling heat flux.

4.4. Film boiling: $q'' > 0.8q''_{\mathrm{CHF}}$

For an applied heat flux higher than 20 W cm^{-2}, nucleate boiling could no longer be observed. A direct transition occurs leading the wire to partial film boiling in a very short while (Fig. 11). The wire superheat reaches a high value (75–95 K) in less than 0.1 s. At early stages, one observes a very rapid temperature rise induced by single-phase heat transfer. The change of slope in the temperature curve, related to boiling incipience, occurs at about 0.010 s (0.011 s for $q'' = 21.2$ W cm^{-2} and 0.008 s for $q'' = 26.2$ W cm^{-2}). In another work dealing with transient natural convection around a line heat source [17], time for convection onset has been shown to scale as $(q'')^{-1/2}$. This time is estimated in the present case to be about 0.030 s (0.035 s for $q'' = 21.2$ W cm^{-2} and 0.030 s for $q'' = 26.2$ W cm^{-2}). Thus for high values of the applied heat flux, temperature distribution in the liquid just before boiling incipience results from heat diffusion. Considering in a first approximation that the wire is a line heat source with negligible edge effects, the problem may be reduced to a one dimensional case: isotherms in the liquid are therefore cylindrical [29]. It is then possible to estimate the distance δ_{T} beyond which the thermal perturbation is no longer perceptible, for instance using the criterion $T(\delta_{\mathrm{T}},t_1) - T_{\mathrm{sat}} = 0.01$ K. The calculation shows that δ_{T} ranges from 120 μm ($q'' = 26$ W cm^{-2}) to 170 μm ($q'' = 20$ W cm^{-2}). These small values promote the growth of hemispherical bubbles and as a consequence the formation of a vapour film due to lateral coalescence.

During the experiments, a sharp sound was heard a very short while after heat switching and was recorded by the microphone. Its intensity is higher than the one measured with lower heat fluxes and detailed in Sections 4.2 and 4.3. Furthermore, as the top of the Dewar vessel is opened with a small aperture, a vapour jet is ejected through this hole. The superimposition of the wire superheat with the

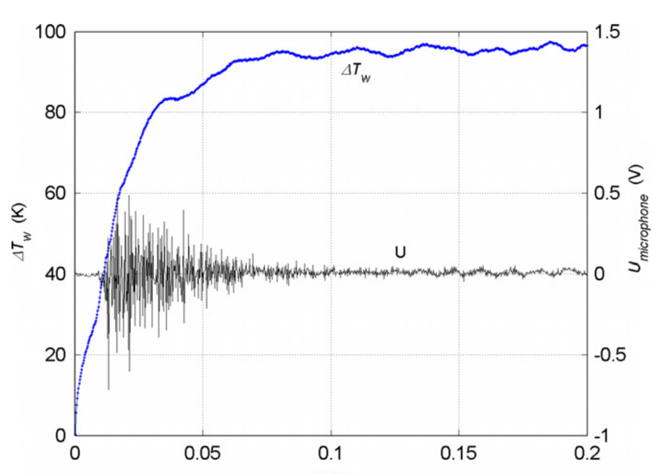


Fig. 12. Signal recorded by the microphone superimposed with the wire superheat $q'' = 26.2$ W cm^{-2}.

microphone signal is presented in Fig. 12 for a heat flux equal to 26.2 W cm^{-2}. Times corresponding to the end of single-phase heat transfer (boiling incipience) and to the beginning of the pressure wave are now in very close proximity. As observed for lower values of the applied heat flux (Sections 4.2 and 4.3), the acoustic pressure wave vanishes when steady state is achieved. Here again, the acoustic event is associated to the generation and growth of the vapour phase.

5. Summary and conclusions

In the present paper are reported boiling experiments performed on a 25 μm brass wire immersed in saturated liquid nitrogen at 1 bar. A quasi-stationary boiling curve has first been obtained. Then, heat fluxes of variable intensity have been supplied to the wire in order to investigate boiling incipience and the subsequent development of all boiling regimes. Analysing the boiling performance of the system induced by transient heating conditions in light of the stationary boiling curve, one may classify the results in four groups depending on the magnitude of the applied heat flux q'' supplied to the wire.

For $q'' < q''_{\mathrm{FDNB}}$, steady-state obtained at the end of the transient process corresponds to low nucleate boiling in which discrete vapour bubbles are emitted at some points along the wire. For $q''_{\mathrm{FDNB}} < q'' < q''_{\mathrm{min}}$, steady state finally achieved is fully developed nucleate boiling. For $q'' > 0.8q''_{\mathrm{CHF}}$, a direct transition from the non-boiling regime to partial film boiling is observed. Lastly, for $q''_{\mathrm{min}} < q'' < 0.8q''_{\mathrm{CHF}}$, steady-state may be either fully developed nucleate boiling, either partial film boiling. A premature transition to film boiling is thus likely to be observed when the applied heat flux exceeds the q''_{min} value and will indeed be observed for $q'' > 0.8q''_{\mathrm{CHF}}$.

Time scales associated with the development of these various boiling regimes are mainly governed by boiling incipience and the subsequent bubble dynamics. For low values of the applied heat flux ($q'' < q''_{\mathrm{FDNB}}$), the wire temperature increases slowly enough to allow a gradual activation of a few nucleation sites. Several seconds may be required for this process. For $q'' > q''_{\mathrm{FDNB}}$, the wire superheat increases sharply and reaches rapidly 22 K. This particular value has been measured under quasi-stationary heating conditions as the upper limit for boiling incipience. This feature takes place in the form of numerous bubbles occurring at once along the wire. The subsequent bubble dynamics and interfacial motion are intense enough to produce an acoustic emission. Just before boiling incipience, the thermal boundary layer around the wire is thin, of about a few hundreds of microns, promoting this way, for the highest heating steps ($q'' > q''_{\mathrm{min}}$), a lateral coalescence and therefore a premature transition to film boiling. Whatever the boiling regime to be developed, i.e. fully developed nucleate boiling or film boiling, the associated time scale is very short of about a few hundreds of milliseconds. Finally, it should be underlined that nucleate boiling onset induced by a stepwise heating occurs in a narrow range of wire superheats in comparison with the one measured under quasi-stationary heating conditions. This particular feature might be useful in situations for which a proper control of the boiling incipience conditions is required.

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