PERGAMON

International Journal of Heat and Mass Transfer 46 (2003) 355–365

International Journal of HEAT and MASS TRANSFER

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Onset of transient nucleate boiling from a thick flat sample

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Received 6 November 2001; received in revised form 26 February 2002

Abstract

Experiments of transient pool boiling from a thick copper sample having a large thermal inertia have been carried out with pentane in saturated conditions. Measurements show that the temperature at boiling incipience is strongly influenced by the transient procedure. The effects of some parameters, such as a waiting period between a preliminary procedure and the heat input or an initial subcooling of the surface, have also been investigated to understand the mechanism leading to a delay in boiling incipience under transient conditions.
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1. Introduction

Over the past years many efforts have been made to understand boiling phenomena that appear in transient processes encountered in cooling of nuclear reactor or electronic components. In these processes, with variable heat flux, an insufficient cooling can lead to the deterioration of materials. Therefore, a better knowledge of boiling mechanisms under transient conditions is of the most importance to prevent deterioration of surfaces in cooling processes. The majority of previous studies concerns transient boiling investigations from thin metal ribbon [1,2] or small diameter wires [3,4]. But, thermal properties of the experimental heater affect the transient response of the boiling heat transfer. The thinner the heater, the lower its thermal inertia favorising faster transient.

The major influence of a transient process compared to a steady-state one concerns the delay phenomenon at the onset of boiling. In 1957, from the investigation of heat transfer between a thin metal ribbon and subcooled water under transient conditions, Rosenthal [5] pointed out this phenomenon. For the experiments, heat was generated electrically in the ribbon to produce an exponentially heat generation rate. Together with visual record from a high-speed camera, temperature and heat generation of the ribbon were recorded. This investigation showed that boiling started as the ribbon temperature reached a maximum. Boiling incipience was characterised by an explosive-like formation of bubbles. Camera records showed a transition to partial film boiling before the system reached the regime of nucleate boiling. Measurements also showed that the temperature at boiling incipience increased as the heating rate and the initial subcooling were increased.

With similar heating conditions, Sakurai and Shiotsu [6] investigated the heat transfer between subcooled water and a platinum wire. Boiling incipience was detected by mean of a piezoelectric hydrophone located 40 mm away from the heater. Measurements showed that boiling started before the wire temperature reached its maximum. This phenomenon most probably relies on the fact that after boiling incipience, the wire is covered with a vapour blanket and its temperature still grows up. Experiments also showed that the faster the heating, the higher the temperature at boiling incipience.

More recently, Sakurai et al. [4] proposed a photographic study on transitions from non-boiling and nucleate boiling to film boiling due to increasing the wire heat inputs in liquid nitrogen and water. On the one hand, photographs showed that direct transitions in prepressurised liquid nitrogen and water occur due to the explosive-like heterogeneous spontaneous nucleation (HSN) in originally flooded cavities. On the other hand, photographs showed that the transition from transient

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0017-9310/03/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S0017-9310(02)00267-3

Nomenclature

$\dot{q}_{ONB}$	boiling incipience heat flux (W/cm^2)
t	time (s)
T	temperature (K)
ΔT_{ini}	initial wall subcooling, $\Delta T_{ini} = T_{ini} - T_{sat}$ (K)
ΔT_{ONB}	ONB superheat, $\Delta T_{ONB} = T_{ONB} - T_{sat}$ (K)
ΔT_{sat}	wall superheat, $\Delta T_{sat} = T_w - T_{sat}$ (K)
Greek symbol	
σ	standard deviation
Subscripts	
CHF	critical heat flux
ini	initial
ONB	onset of nucleate boiling
sat	saturation

conduction regime to film boiling due to heat inputs with short exponential periods occurs due to the HSN at around lower limit of HSN superheat, in case of experiments without pre-pressurisation.

With another heating technique, i.e. by the supply of a step heat input, Duluc et al. [3], performed transient pool boiling experiments between a bronze wire and liquid nitrogen. Measurements showed that the wire temperature rapidly increased and reached a very high value before the steady-state nucleate boiling regime established. This superheat could be higher than the homogeneous nucleation one, most probably due to the presence of vapour blankets on the wire.

Only few experiments were conducted with large thermal capacity samples under transient heating conditions. Hohl et al. [7] performed transient pool boiling experiments from a thick copper sample with FC-72 as working fluid. By mean of a controlled wall temperature system, they performed investigations of the whole boiling curve with increasing and decreasing temperature procedures. Experiments showed a hysteresis between heating and cooling transient procedures that did not exist in steady-state procedures. The effect of heating and cooling rates (heating rate up to 10 K/s) have also been investigated in all boiling regimes. Measurements showed that the higher the heating rate, the higher the wall heat flux in all boiling regimes and, in particular at critical heat flux (CHF). Inversely, the transferred heat flux at the surface decreased as the cooling rate increased. From these measurements, the effect of the transient procedure on the temperature at boiling incipience could not be investigated perhaps because the heating rates were not fast enough.

Héas et al. [8,9] also performed transient pool boiling experiments with a thick copper sample and *n*-pentane at saturated conditions. The influence of several heating rates and initial conditions on the incipient boiling has been investigated. For low heating rates, the superheat at the onset of boiling (onset of nucleate boiling, ONB) was relatively small and boiling curves measured in heating and cooling procedures merged before the steady heat flux was reached. For long cooling times (in the initial procedure) or initial wall subcoolings, a large superheat at boiling incipience was reached. This investigation clearly showed that the initial procedure has a strong influence on incipient boiling conditions, and has to be controlled for measurements reproducibility.

The test conditions of the main results found in the literature are given in Table 1. For thin metal ribbons

Table 1
Test conditions of the literature data [1–8]

Authors	Heater	Fluid	Heating method
Iida et al. [1]	Horizontal Pt–Cr film heater $0.1 \times 0.25\ \text{mm}^2 \times 0.25\ \mu\text{m}$	Alcohol, toluene, water atmospheric pressure	Step heat input
Drach et al. [2]	Horizontal metal strip	LN_2 atmospheric pressure	Step heat input
Duluc et al. [3]	Horizontal bronze wire, ∅ 40 μm	LN_2 atmospheric pressure	Step heat input
Sakurai et al. [4]	Horizontal platinum wire ∅ 1.2 mm	Water, LN_2 at different pressures	Exponential heat input
Rosenthal [5]	Vertical platinum film $2.54 \times 76.2\ \text{mm}^2 \times 25.4\ \mu\text{m}$	Water atmospheric pressure	Exponential heat input
Sakurai and Shiotsu [6]	Horizontal platinum wire ∅ 1.2 mm	Water atmospheric pressure	Exponential heat input
Hohl et al. [7]	Horizontal copper block ∅ 18.2 mm, 5 mm thick	FC-72 saturated conditions $P_{sat} = 1.3$ bar	Different heating rates
Héas [8]	Horizontal copper sample ∅ 30 mm, thickness >80 mm	*n*-Pentane saturated conditions $P_{sat} = 1$ bar	Different heating rates

and small diameter wires, the Biot number is lower than 0.05, whereas, for thick flat samples, it is larger than 2.

In order to investigate the effect of a transient procedure on boiling incipience from a sample with a large thermal inertia, an apparatus has been built up. Steady-state pool boiling experiments and transient ones are compared for a better comprehension of mechanisms leading to the boiling incipience delay in transient processes. The effects of parameters such as the waiting period between the preliminary procedure and the heat input or the initial surface subcooling have also been investigated.

2. Experimental facilities

A scheme of the experimental device is shown in Fig. 1. The main part of the apparatus consists of a cylindrical glass-boiling vessel containing the heater and the fluid. This tank is a 16 cm inner diameter and 15 cm height cylinder. Two chromel–alumel thermocouples are placed in the vessel to measure liquid and vapour temperatures. Those temperatures are kept constant during heating and cooling procedures by mean of an external condenser and a heating resistance. The fluid level in the tank is kept at a constant level of 9 cm above the boiling surface for each test.

The copper block, thereafter called test heater, is cylindrical and has a height of 9 cm (Fig. 2). The 3 cm diameter boiling surface is oriented upward horizontally. The sample is electrically heated with two cartridge heaters and the lateral surface is insulated with Teflon. At the lower part of the sample, a small water heat exchanger is used to cool down the heater rapidly. Radial heat losses are small and the test heater was designed with a two-dimensional (2-D) finite element software to obtain a 1-D heat transfer within the 5 cm beneath the surface. Roughness characteristics of the heater surface are obtained with an UBM technique: $R_a = 1$ μm (arithmetical mean difference of the profile), $R_t = 15$ μm (maximal height of the profile), $S_m = 8$ μm (mean step of profile irregularities).

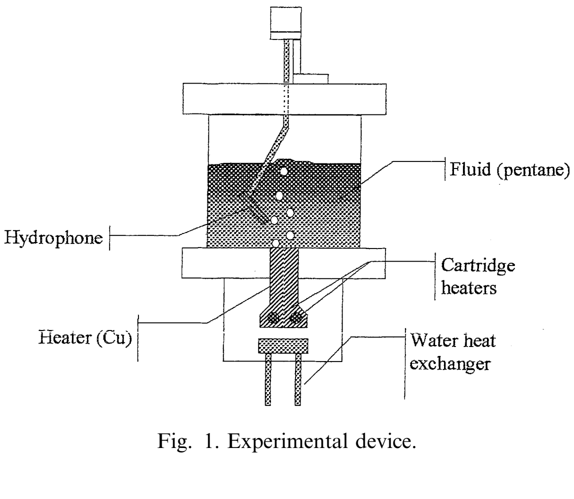

Fig. 1. Experimental device.

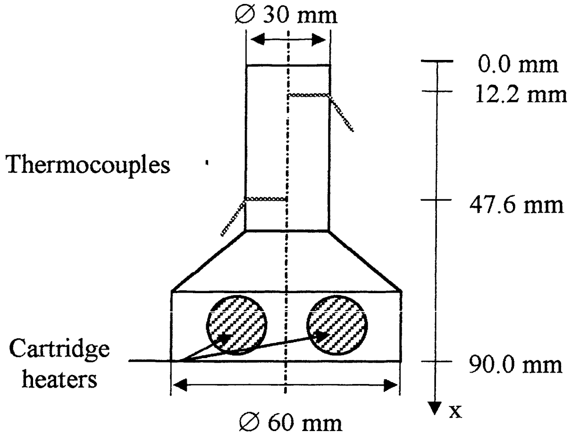

Fig. 2. Test heater.

Heat flux and superheat at the surface are computed by mean of an inverse heat conduction calculation [10], using two temperature measurements at 12.2 and 47.6 mm beneath the surface. Thermocouple positions were fixed in order to obtain the best results regarding the inverse method stability and the result precision. The data acquisition rate is 1 Hz, thus the surface heat flux and surface temperature are calculated every 1 s. The uncertainties on thermocouple locations, copper thermal properties and thermocouple calibrations lead to ±0.2 K accuracy on the surface superheat. The accuracy in calculated surface heat flux is about ±0.2 W/cm^2 for low heat flux and ±0.5 W/cm^2 for high heat flux.

Investigations are carried out with a 99.9% pure *n*-pentane in saturated conditions at $P_{sat} = 1$ bar ($T_{sat} = 36$ °C). Prior to each boiling test, the fluid is degassed allowing venting non-condensable gases.

As investigated in this work, onset of boiling is very sensitive to initial conditions. In order to have identical initial conditions for each test, allowing good experiment reproducibility, a preliminary working procedure is applied (Fig. 3). This procedure begins with the supply of a heat flux ramp from 0% up to 20% of CHF (27 W/cm^2) during the first 3000 s. Thus the nucleate boiling regime is obtained without risk of surface damage after 2300 s of heating. Afterwards, during the next 600 s, a ramp from 20% up to 90% of CHF is supplied to the cartridge heater. This is done in nucleate boiling regime. Then, the heat input corresponding to 90% of CHF is maintained during 30 min. This procedure permits the activation of many nucleation sites. Afterwards, the sample is rapidly cooled down until the surface temperature reaches the desired value, e.g. the equilibrium temperature of saturated conditions. This is done by the use of a water heat exchanger placed at the bottom of

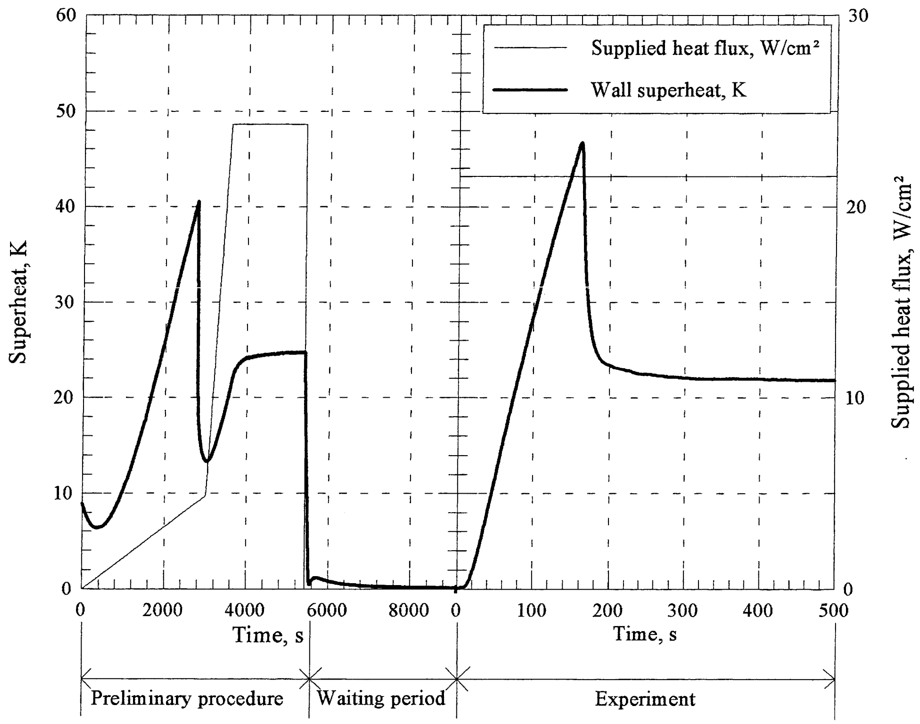

Fig. 3. Superheat and heat flux versus time during the preliminary procedure, the waiting period and an experiment.

the copper sample. After the preliminary procedure, a certain period with no heat input can be maintained. This period, called the waiting period (Fig. 3), can influence the conditions of boiling incipience, as described in Section 3.4. After that, the experiment is started by supplying the desired power to the cartridge heaters resulting in a wall temperature increase (Fig. 3). The data acquisition program and the inverse method computation are started when the heater is turned on. For each studied configuration, due to results dispersion, about ten tests are carried out allowing the determination of mean values and their standard deviations.

To detect inception of boiling, a piezoelectric hydrophone located 35 mm upper the boiling surface is used. Amplification of the output signal delivered by the hydrophone allows obtaining a precise and reliable detection of the time corresponding to the onset of boiling (ONB).

3. Results and discussion

3.1. Test description and determination of ONB

Fig. 4 shows the surface superheat and heat flux evolutions calculated by the inverse method during a typical experiment. The heat flux dissipated in the cartridge heaters corresponds to 80% of CHF and the initial surface superheat is set to 0 K ($T_p = T_{sat} = 36$ °C $\pm$ 0.1 K). This experiment was performed directly after the preliminary procedure, i.e. without waiting period.

After the preliminary procedure, just before the heat flux input, temperatures in the sample decrease as the distance from the boiling surface increases. When the heat flux is applied, a certain time lag is needed for the temperature gradient in the sample to be inverted. This is the reason why the surface heat flux and superheat calculated by the inverse method first slightly decrease. Moreover, at the beginning of the test, the temperature difference between both thermocouples is of the order of magnitude of the uncertainties. At the beginning, the surface temperature and heat flux are almost constant and increase slowly. This is typical of conduction during a period close to 80 s.

As the surface temperature increases, convective heat transfer regime establishes and convective cell movements can be observed in the fluid upon the heating surface. Superheat and heat flux vary quasi-linearly in this regime.

With these test conditions, boiling suddenly starts, in a quasi-explosive manner, when the superheat is around 54 K. It seems that boiling first starts from a certain wall point and spreads out very rapidly to the whole surface. The boiling regime that characterises the beginning of boiling seems to be a transition boiling one (or partial film boiling). Indeed, the surface is only partially wetted.

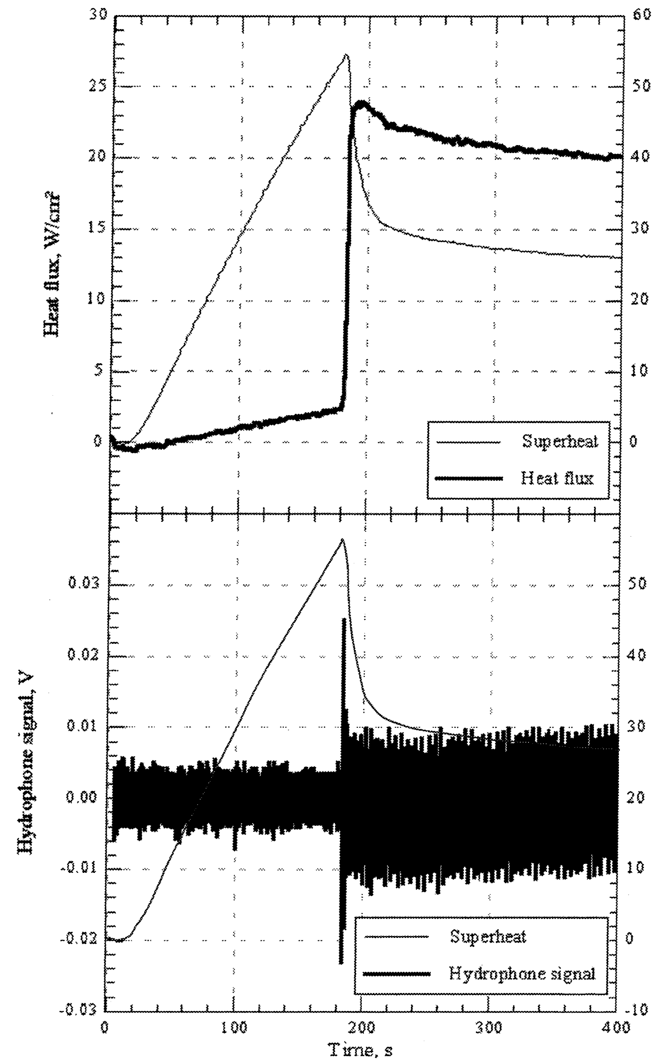

Fig. 4. Superheat, heat flux and hydrophone signal evolutions during an experiment.

Then, boiling phenomenon at the surface becomes "calmer" and nucleate boiling regime settles.

With the hydrophone, the determination of the time corresponding to boiling incipience is very precise and in good agreement with the one given by the inverse heat conduction method. As shown by Fig. 4, boiling starts when the surface temperature reaches its maximum. As boiling takes place, the surface temperature decreases very rapidly and tends to a limit corresponding to steady-state nucleate boiling. The maximum surface heat flux, which is of the order of CHF, is reached when the wall temperature begins to decrease. Afterwards, the surface heat flux decreases and tends to a limit corresponding to steady-state nucleate boiling.

Measurements show that, in transient conditions, incipience boiling superheat is larger than the CHF superheat. Thus, boiling starts in the transition-boiling regime. Since a large heat flux is transferred to the liquid, the surface temperature decreases until it reaches a stable value. It is important to note that, in our test conditions, incipience superheat is smaller than the Leidenfrost temperature ($\Delta T_{\mathrm{Leidenfrost}} = 132$ K) [11]. This is most probably the reason why there was no transition to film boiling that could damage the surface.

3.2. Test analysis

Fig. 5 shows the evolutions of energies supplied to the cartridge heaters, transferred to the fluid, stored in the copper block and lost by its lateral surface during the experiment previously described in Fig. 4. These results are obtained from a model solved with the Microfield

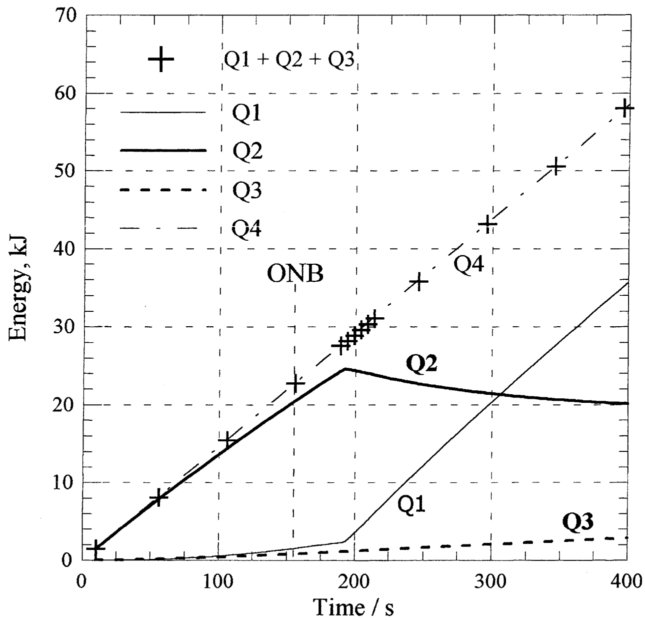

Fig. 5. Evolution of various energies along an experiment: (Q1) energy transferred to the fluid; (Q2) energy stored in the test heater; (Q3) energy lost at lateral surfaces and at the base of the heater and (Q4) energy supplied to the cartridge heater.

finite element software. Contrarily to the inverse method which only concerns the upper part of the copper block (1-D heat conduction), this direct analysis of the whole test heater includes the cartridge heaters. The delivered energy is calculated from the heat input and modelised as an internal source in the lower part of the test heater. The transferred energy to the fluid is calculated from measurements of the heat transfer coefficient at the surface versus time. For the calculation of the thermal losses, the overall heat transfer coefficients at lateral surface and heater bottom are assumed constant. As a consequence of insulation and temperature levels, the thermal conductance at the base of the heater is set to 20 $W/m^2 K$, around the lower cylindrical part to 14 $W/m^2 K$, along the conical part to 5.5 $W/m^2 K$ and around the upper cylindrical part to 6.2 $W/m^2 K$ during the whole experiment. These two last values were calculated with a classical external free convection correlation, and the others were obtained by means of temperature measurements during one experiment.

As boiling starts, the excess of energy stored in the sample is released, and the heat flux transferred to the liquid increases abruptly. The excess of stored energy in the heater, e.g. the difference between the internal energy of the heater at boiling incipience and its energy in steady-state nucleate boiling is close to 2 kJ (10% of the heater internal energy). If the heater had not stored energy in excess, boiling would have started at a time of 155 s. The energy transferred to the fluid increases slightly in convective regime and more rapidly in nucleate boiling due to the high heat transfer coefficient. The so-called lost energy increases regularly with time, due to constant heat transfer coefficient.

The sum of the transferred, stored and lost energies is also shown in Fig. 5 and is equal to the amount of energy supplied to the heater. This is a good validation of the heat transfer coefficient values along lateral surfaces and at the base of the heater.

Fig. 6 compares the temperature variations measured at 12.2 mm and 47.6 mm with the ones calculated at the same locations. In conduction and convection regimes, e.g. until boiling incipience, the agreement is good for both depths. After beginning of boiling, corresponding to the maximum in Fig. 6, measured temperatures are slightly smaller than calculated ones, for both positions. This may be due to an inaccuracy in heater thermal properties used for the direct simulation. The comparison between measured and calculated temperatures at both thermocouple depths validates the modelisation of temperature distribution and heat transfer in the heater during an experiment.

3.3. Comparison between steady-state and transient measurements

Fig. 7 compares boiling curves obtained in transient heating and in steady-state heating or cooling procedures. The transient boiling curve is obtained with a heat input corresponding to 80% of CHF, imposed to the cartridge heaters directly after the preliminary procedure. The initial subcooling of the boiling surface is equal to zero ($T_{ini} = T_{sat}$). For steady-state procedures,

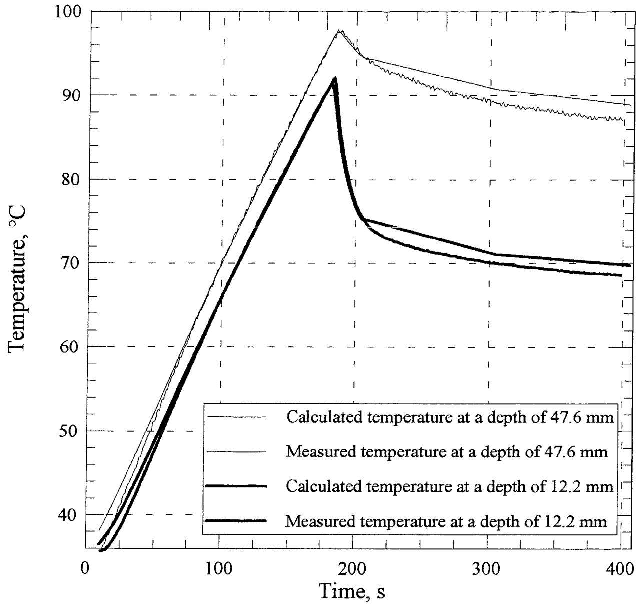

Fig. 6. Comparison between calculated and measured temperatures.

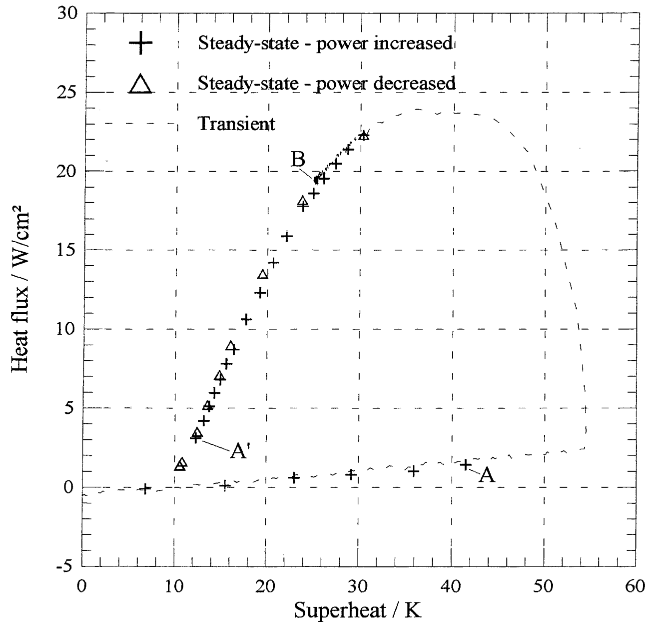

Fig. 7. Comparison between steady-state and transient boiling curves.

heat flux is stepwise increased, respectively decreased, with little steps of about 0.5 W/cm^2 in convective regime and 2 W/cm^2 in nucleate boiling. It should be noted that, because of the large thermal inertia of the test heater, in steady-state conditions, the time required between two steps to obtain a steady-state regime is of the order of an hour in convective regime.

At low superheats, in convection regime, no significant difference on the boiling curves appears between both procedures. It seems that the convective heat transfer coefficient at the surface does not strongly depend on the procedure. In steady-state condition, surface superheat at boiling incipience can not be precisely determinated because boiling starts between two steps.

However, Fig. 7 shows that this temperature is smaller in steady-state condition than in transient one. This result confirms the tendency obtained with low thermal inertia heaters, e.g. by Duluc et al. [3].

However, it should be noted that in steady-state conditions, due to the procedure, boiling starts about 5–6 h after the test beginning whereas boiling starts after 3 min in the transient procedure. This large convective heating period difference between both procedures leads to large difference in the level of energy transferred to the fluid. Thus, the thermal boundary layer temperature and thickness are larger in steady-state than in transient conditions. This phenomenon may explain the difference in boiling incipient temperature between both procedures. But, as discussed in Section 3.4, a waiting period between the end of the preliminary procedure and the onset of boiling can also lead to higher ONB superheats.

In transient condition, as boiling starts, the temperature decreases and tends to a limit corresponding to steady-state nucleate boiling, point B in Fig. 7. The shape of the boiling curve calculated by the inverse method is explained in Sections 3.1 and 3.2. In steady-state condition, the point A is the last point in free convection regime. As boiling begins, the wall superheat highly decreases and tends to a limit corresponding to steady-state nucleate boiling, point A' in Fig. 7. In this condition, a certain amount of excess energy stored in the test heater is also released, leading to a difference between the imposed heat flux and the wall heat flux.

In steady-state condition, as the heat flux is increased further, superheat grows up and the nucleate boiling curve can be described, going from point A' to point B in Fig. 7. Fig. 7 clearly shows, that the stabilised point (superheat and heat flux) corresponding to the transient procedure belongs to the same boiling curve than the one measured with the steady-state procedure.

Fig. 7 also compares boiling curves measured under steady-state heating and cooling conditions. A first hysteresis is observed at the ONB between both procedures. This phenomenon, already mentioned by many authors such as Shi et al. [12], is due to the mechanism of first nucleation site activation. Moreover, in the partially developed nucleate boiling regime, no second hysteresis, due to vapour propagation to neighbouring cavities, is observed between steady-state heating and cooling. This result confirms the measurements of Blum et al. [13], who showed a similar tendency from the investigation of pool boiling of FC-72 from a thick copper sample under steady-state conditions.

3.4. Effect of a waiting period on ONB

Fig. 8 shows the effect of a waiting period (defined in Fig. 3) on the temperature at boiling incipience. Measurements were carried out with a heat input corresponding to 80% of CHF and no initial wall subcooling.

Measurements show that boiling incipience superheat increases as the waiting period grows up, until a waiting period of about 2 h. Afterwards, this parameter does not seem to have any influence on the boiling incipience superheat. This tendency is most likely the result of a deactivation of nucleation sites with time. Indeed, real

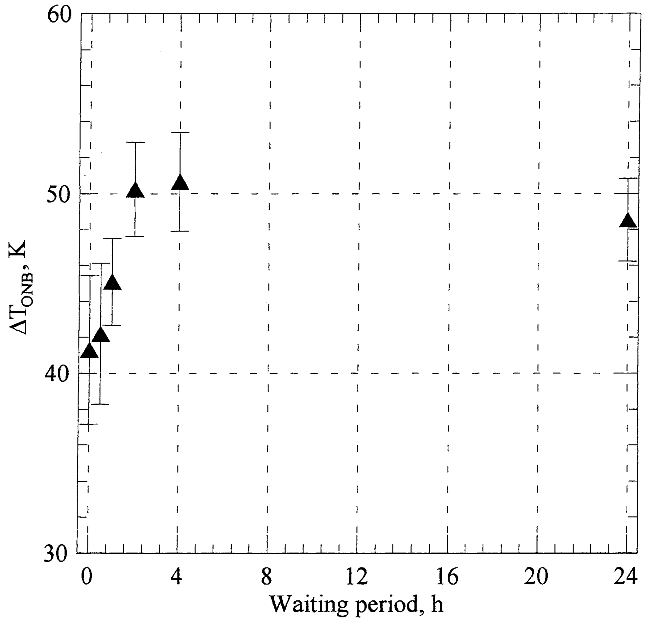

Fig. 8. Effect of the waiting period on the ONB superheat.

surfaces are characterised by very small cavities containing entrapped gas. Boiling starts because the gas contained in those cavities expands, enabling the first bubble to grow. During the preliminary procedure, nucleation sites are activated during 30 min. If the surface is heated directly after the preliminary procedure, cavities still contain a certain amount of gas and boiling can start sooner. On the contrary, if the surface is not immediately heated, the gas contained in the cavities tends to diffuse. Because of the structure of the surface, a certain amount of gas cannot flow away. This residual amount of gas that stays in the cavities will enhance boiling phenomena. It seems, from our measurements, that after a 2 h period, the nucleation sites are deactivated, and the activation effect due to the preliminary procedure has no more influence.

The incipient boiling conditions (superheat, heat flux and time) as well as their standard deviations are given in Table 2. Since the heat transfer coefficient stays almost constant during the convective regime, heat flux and time corresponding to ONB are directly proportional to the boiling incipience superheat.

3.5. Effect of an initial wall subcooling on ONB

Fig. 9 presents the effect of an initial wall subcooling on the temperature at boiling incipience. Measurements were carried out with a heat input corresponding to 80% of CHF, immediately after the preliminary procedure, without any waiting period.

Two areas can be seen in Fig. 9:

- If the initial wall superheat is higher than 3 K, the boiling incipience superheat is around 8 K. In this case, when the heat flux is supplied, some nucleation sites are still activated on the surface. Boiling incipience is realised by propagation from activated sites to others. When boiling starts, the nucleate boiling

Table 2
Effect of the waiting period on incipient boiling conditions

Waiting period (h)	ΔT_{ONB} (K)	$\sigma\Delta T_{\mathrm{ONB}}$ (K)	$\dot{q}_{\mathrm{ONB}}$ (W/cm^2)	$\sigma\dot{q}_{\mathrm{ONB}}$ (W/cm^2)	t_{ONB} (s)	σt_{ONB} (s)
0	41.3	4.1	2.39	0.35	140	13
0.5	42.2	3.9	2.66	0.32	146	14
1	45.1	2.4	2.62	0.17	156	8
2	50.2	2.6	3.01	0.22	175	10
4	50.6	2.7	3.41	0.35	178	10
24	48.5	2.3	3.53	0.27	172	9

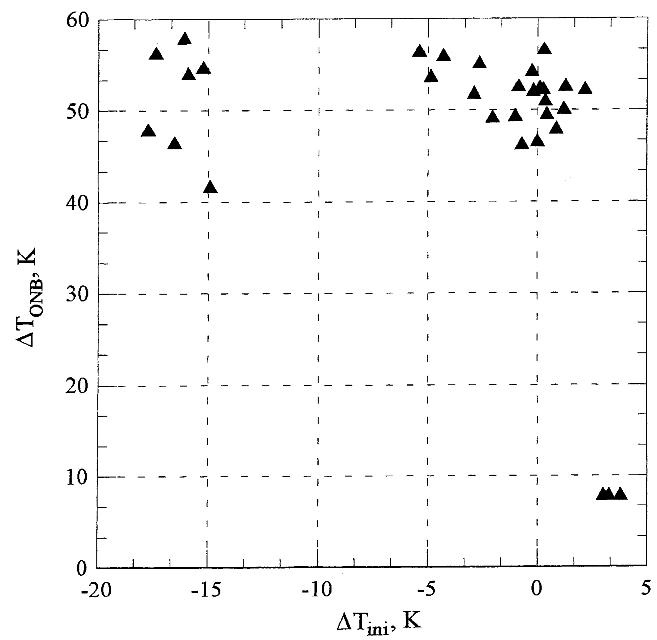

Fig. 9. Effect of an initial wall subcooling on the ONB superheat.

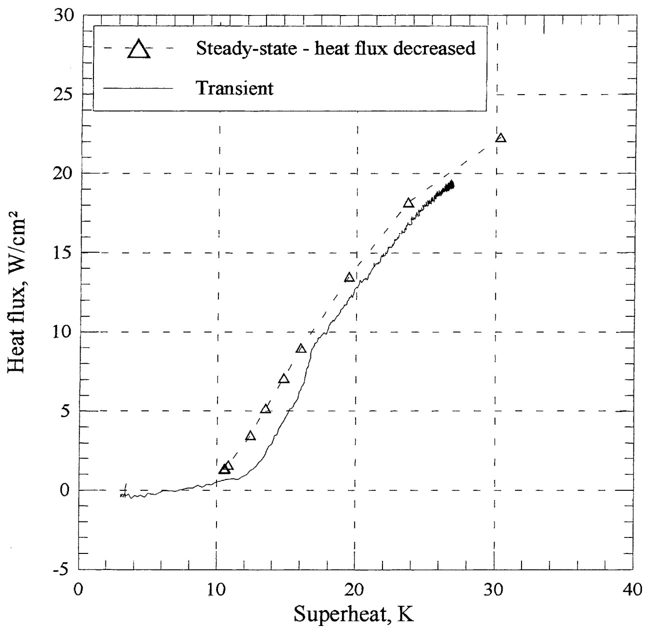

Fig. 10. Transient boiling curve with an initially superheated surface.

regime settles at the surface and the transient boiling curve joins the one of steady-state pool boiling obtained for decreasing heat flux for which it remains active nucleation sites. Such a boiling curve is shown in Fig. 10.

- If the initial wall superheat is smaller than 3 K, the incipience boiling superheat is around 50 K. This value is almost constant (it varies within the uncertainties area), whatever the value of the initial surface superheat. In this case, when the heat flux is dissipated, the surface has no activated sites, as described in Section 3.3. Thus boiling incipience appears in a quasi-explosive manner and spreads out very rapidly on the whole surface. Boiling curves such as the one shown in Fig. 7 are obtained. The first boiling regime that appears at the surface is the partial film boiling one, before it becomes stable in the nucleate boiling regime as described previously.

It seems that an initial subcooling of the boiling surface leads to a rapid deactivation of the nucleation sites.

4. Conclusion

This study confirms experimental results on boiling incipience obtained on wires and ribbons for thick samples having a large thermal inertia. The temperature at boiling incipience strongly depends on the heating procedure. Under transient conditions, boiling starts with a certain delay leading to much higher boiling incipience superheat. Onset of boiling is very abrupt and before boiling phenomenon stabilises at the surface, a transition to partial film boiling has been observed.

Measurements showed that nucleation sites can be deactivated if a certain period is waited between the preliminary procedure and the heat input. This phenomenon leads to larger boiling incipience surface superheat.

This study also shows that boiling incipience superheat strongly depends on the initial surface temperature. In order to have incipience at low temperature and thus to decrease risks of surface deterioration due to late boiling incipience, a sufficient initial superheat should be kept at the surface.

The very important phenomena that have been investigated in this study are directly applicable to the two-phase cooling of electrical components. Hence, to enhance their reliability and their lifetime, the temperatures should always be beyond a limit. Thus, it is recommended to always dissipate a low heat flux in order to keep an initial wall superheat and maintain some nucleation sites activated.

Acknowledgements

This work was supported by the CNRS in the frame of the AMETH laboratories group.

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