Nucleate Pool Boiling of Liquid Nitrogen on a Brass Ribbon with Different Positions

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Abstract— The nucleate boiling is a phenomenon of heat transfer which occupies an important place in the industrial sector particularly in the areas of electric power generation and refrigeration, because it enables to reach high flux densities with relatively low temperatures differences. To quantify the thermal exchanges in pool boiling, an experiment of steady and transient nucleate boiling is carried out on liquid nitrogen from a brass ribbon fixed in the two vertical and horizontal positions and subjected to different heat flux densities. The initial conditions for the nucleation sites activation are carried out with a heat flux corresponding to 90% of the critical flux. In addition, the wall superheat variation was recorded and controlled. Moreover, the influence of different ribbon positions on the boiling triggering time, superheat of triggering and critical flux density has been investigated.

Index Term— Experimental study, Pool boiling, Liquid nitrogen, Superheat on triggering, Critical flux density.

I. INTRODUCTION

Nucleate pool boiling heat transfer study is of great interest either for the understanding of basic physical mechanisms or for the many industrial applications such as the cooling of electronic equipment. This process is the subject of a large number of studies at steady and transient state regimes for different geometric surface (wires, ribbons, massive samples) which are made of various materials and have been investigated over a wide range of boiling conditions [1-7]. The study on massive samples generally concerned the case where the temperature or heat flux are imposed [6-10].

In steady-state regime, Nukiyama [1] was the first who investigated the heat transfer between sub-cooled water and an horizontal platinum wire heated by Joule effect. This investigation showed that heat transfer can be carried out in first instance on pure conduction and then possibly by convection until the liquid reaches the superheating conditions required for the onset boiling. Similarly, Duluc et al. [11] have carried out studies on cooper wires in liquid nitrogen at saturation. The authors tried to study the transition region observed between nucleate boiling and film boiling regimes. Moreover, many authors have worked on pool boiling in transient regime because transient phenomena are commonly encountered in practical applications. Indeed, heat transfer has to be controlled at the beginning of boiling phenomenon in order to avoid any undesirable superheat during the transient process that could deteriorate heat transfer or damage the system. Rosenthal and Miller [12] were the first who investigated this transient phenomenon with a ribbon submerged in stagnant water. The authors observed the overshoot temperature and delay time occurring in the process of incipient boiling when the ribbon is rapidly heated. They also studied the effects of the heating exponential period and the sub-cooling upon the transient characteristics of boiling phenomenon.

Furthermore, the activation of nucleation sites has an influence on the boiling, as wall superheat or heat flux is increased, the number density of sites that become active increases. Gaertner and Westwater,[13] presented a new technique with nickel and water, the result obtained show that the number density of active nucleation sites is related to the flux density. Heas et al. [14,6] also investigated the influence of several heating rates and initial conditions on the incipient boiling. The experiment was carried with a thick copper sample and n-pentane at saturated conditions, experiment showed that for low heating rates, the superheat at the onset of boiling (ONB) was relatively small and boiling curves measured in heating and cooling procedures merged before the steady heat flux was attained. And for long cooling times or initial wall sub-coolings, a large superheat at boiling incipience was attained. This study clearly showed that the initial procedure has a strong influence on incipient boiling conditions, and has to be controlled for measurements reproducibility. As the flow density increases the vapor reaches the upper surface of the pool, it condensates and cools.

The cooling is then ensured by the liquid which falls toward the heating element. If the flux density increased the productions of vapor becomes too intense and go up to surface in columns. The quantity of the vapor in the columns reaches a value such as the fluid is stopped in its descent to the heating element. We then come to a boiling crisis that corresponds to the disappearance of any contact between the liquid and the heated element, this phenomenon occurs when the critical heat flux (CHF) is reached. Haramura and Katto [15] proposed a correlation to calculate the critical heat flux density in the case of a ribbon. Mudawar and Howard [16] presented another quantitative expression of the critical heat flux density depending on the ribbon orientation angle.

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The purpose of the present paper is to investigate transient nucleate boiling under stepwise heat generation for brass ribbon and highly wetting fluids (liquid nitrogen). Boiling time transition, superheat which corresponds to boiling triggering and also critical flux are investigated, using two different position of ribbon. The influence of number density of sites is also examined. In both cases, the initial condition is controlled by the means of two parameters: the system temperature and the presence of pre-existing vapor within cavities. The second condition is achieved by a preliminary heating procedure, implemented systematically before each run. The experimental device will first be described for both positions of ribbon as well as the primary procedure. The steady boiling curves obtained for both positions of ribbon will be presented and their own characteristics highlighted. Moreover, the transient results will then be examined. Finally, a comparative analysis of transient feature for both positions will be outlined in the last section.

II. EXPERIMENTAL DEVICE

Pool boiling experiments are carried out on a brass ribbon for two different position (length=10^{-1} m, width = 2.10^{-3} m, thickness = 50.10^{-6} m) which is subjected to stepwise flux generated by a power supply system. The cell is immersed permanently in a Dewar tank filled with LN2 whose temperature is followed by a platinum probe (see fig.1, 2). The experiments are performed using nitrogen under atmospheric pressure (1atm, 77K). Furthermore, a package consisting of an endoscope, a camera for the observation, and a data acquisition system that allows acquiring a large number of points at the requested frequency (10^3Hz), as well as an acquisition card controlled by LabView, complete the experimental device.

A. Vertical position

In this position, the ribbon is suspended with two copper holding pads and completely immersed in the liquid nitrogen, the heat exchanges are carried through both sides of the ribbon.

B. Horizontal position

In this one, the ribbon is fixed horizontally on a support in Bakelite using glue ECCOBAND 286 manufactured by Emerson & Cuming [17]. The surface contact (bakelite and glue) with the ribbon is insulating. The flux meter is placed below the glue in order to measure the density of heat flux passing across the insulating glue. This allows estimating the losses of the imposed flux density and to ensure that this latter is mostly released in the contact surface between the ribbon and the liquid nitrogen. The flux meters used include sensors that are calibrated in order to set the sensitivity factor which links their signals to the exchanged flux density.

In the case of fine ribbons with more or less small widths such as ours, we assume that the surface temperature is uniform over the ribbon’s entire length. We estimate its value through the resistivity \( \rho \) [18], the linear approximation describing \( \rho \) as a function of the temperature is sufficient, which will be confirmed later by a calibration of a brass ribbon.

III. PRELIMINARY PROCEDURE

In transient-state regime, the first tests carried out showed a considerable influence of the initial conditions on the triggering of boiling. Héas et al. [19] as well as Anderson and Mudawar [20] showed that time, temperature and pressure prior to transient boiling experiments greatly influence the onset of boiling and the temperature overshoot. In order to improve the reproducibility of the tests and to better control initial conditions and to allow comparison of transient boiling results obtained from the two positions of the heating sample, a preliminary procedure was performed for each test:

1. The ribbon resistance is measured at ambient temperature and then in Dewar tank of liquid nitrogen, we deduce the value of \( \rho_0 \) from the relation:

   \[
   \rho(T) = \rho_0 (1 + \sigma_o T)
   \]

2. Nucleation sites are activated by applying to ribbon a flux density equal to 90% of critical flux. This phase must last 5 minutes.

3. After the return to the equilibrium temperature (that the ribbon temperature equal to the liquid nitrogen saturation temperature), the sample is powered by step-wise flux density in order to reach nucleate boiling state without risk of surface damage.

4. Also, the acquisition program is started, this acquisition permits measurement the voltage at the ribbon terminals.
with a sampling frequency of 10^5 HZ. The values recorded of this voltage represent an average more than five hundred measurement points. This makes it possible to calculate the ribbon superheat corresponding to each voltage measurement and thus establish the superheat variation curves as a function of time.

5. Finally, the ribbon resistance value is measured after handling to ensure that ribbon resistivity has not changed during handling.

IV. CALIBRATING THE RIBBON

The ribbon calibration was done in two parts. Firstly, we have immersed the sample in a bath of oil thermostat at high temperatures varying from +20°C to +90°C. Secondly, the sample was immersed in a mixture of ethanol and liquid nitrogen at low temperatures varying from -100°C to +20°C. The values of the resistivity \( \rho(T) \) have been determined on basis of the average temperature of the three temperature sensors immersed in the bath (see fig.3). The polynomial approximation of the second order of \( \rho(T) \) is the following:

\[
\rho(T) = 5.10^{-6} T^2 + 0.0097 T + 7.3842
\]

V. STEADY BOILING CURVE

We present below in steady state regime some results obtained for a ribbon for both positions. After the conventional procedure of sites activation, we raised the variation of the ribbon’s temperature with different stepwise heating.

A. Vertical position

Fig.1 present the result of boiling obtained in steady-state regime for the brass ribbon in vertical position. The boiling curve shows that the heat flux density increases with a step about 0.44W.cm\(^{-2}\) in natural convection area (AB). In this area, the classical correlations are used to predict the average heat transfer coefficient \( h \) [21]. At point B, the flux density imposed becomes important and allows the activation of the first nucleation sites. Small bubbles begin to appear on the heated surface for a mean flux density of 0.44W.cm\(^{-2}\) and a superheat of 12.2W.cm\(^{-2}\). This causes a decrease of wall temperature until 4.77K. At point C, the activation of the nucleation sites becomes important and the bubbles number increase. This feature can be explained considering the distribution of nucleation sites over both surfaces: any increase of the wall superheat leads to the activation of smaller cavities and thus to a regular increase of the nucleation sites density. Furthermore, the critical flux density measured for this ribbon position is equal to 3.92W.cm\(^{-2}\).

A. Horizontal position

In the same way, fig.5 clearly shows that the boiling curve begins by a natural convection area for low flux density (AB). In this area, vapor has not occurred on the surface. From point B, some nucleate sites comes active with an increase in the heat flux density, then small bubbles begin to appear on horizontal ribbon surface for a surface superheat (\( \Delta T_{OB} \)) of about 11.3K and heat flux density close to 1.2W.cm\(^{-2}\). This causes a decrease of wall temperature until 4.77K. At point C, the activation of the nucleation sites becomes important and the bubbles number increase with the heat flux density. This process continues until reaching a critical flux value approached at a mean density of 16.6 W.cm\(^{-2}\) and a parietal superheat of 11.2 K.
VI. TRANSIENT BOILING CURVE
In this part, transient nucleate boiling results for both positions are exposed and discussed.

A. Transient boiling curves for ribbon’s vertical position
For this position, superheat variation as a function of time is presented for three regimes of boiling curve (natural convection, nucleate boiling, and film boiling).

Natural convection zone
This zone corresponds that which is before the boiling triggering in the boiling curve, it appears that there is a first phase of exchange where the heat transfer coefficient depends only on liquid. On transient regime, fig.6 shows that for low flux density (0.19-0.43W.cm⁻²), the heat generated by Joule effect is dissipated by natural convection around the ribbon. The surface superheat increases for 1.5 seconds. As the surface superheat increases, the heat transfer by convection establishes and convective cell movements can be observed in the fluid upon the heating surface. Then for a certain limited value, the surface superheat stabilizes with only convective wall-liquid exchanges.

Nucleate boiling zone
As investigated in this work, onset of boiling is very sensitive to initial conditions, i.e., the preliminary procedure permits the activation of many nucleation sites. Fig.7 exposes the superheat ΔT evolution for different flux densities imposed. It clearly shows that boiling suddenly starts, when the superheat is around 17.5 K and 1.72W.cm⁻² for heat flux density imposed. We note that the nucleate boiling starts when the surfaces superheat reaches its maximum. First of all, boiling starts from a certain ribbon’s point and spreads out very rapidly to the whole both surface of ribbon. As boiling takes place, the surface superheat decreases very rapidly and tends to a limit corresponding to steady-state nucleate boiling, i.e. that the nucleate sites becomes fully active.

Time evolution of the surface superheat is plotted in Fig.8 for other heat flux density imposed. It shows that in the transient-state regime, the heating rate has a considerable influence on the superheat required to trigger the boiling. Indeed, the increase in the heating rate generates the activation of all nucleation sites, therefore, a large number of small bubbles spread on both surfaces of ribbon. Moreover, when the heat flux density increases the superheat increases up to 24K in 0.05 to 0.15 seconds of transient regime, afterwards, it decreases and stabilizes in time less than 0.25 seconds.

Fig. 4. Steady-state boiling curve of the vertical position

Fig. 5. Steady-state boiling curve of the horizontal position

Fig. 6. Transient superheat ΔT versus time for different step-wise heat generations in the natural convection area.

Fig. 7. Transient superheat ΔT versus time for different step-wise heat generations in the low nucleate boiling area.
**Film boiling zone**

Fig. 9 shows that for a certain heat flux density around 5.78 W cm\(^{-2}\), a sheath of vapor grows along the ribbon and the boiling film occurs when the bubbles cover the whole ribbon’s both surface.

Furthermore, the critical flux appears quite instantly after the nucleation appearance. In this point, the surface superheat corresponding to the critical flux is about 26.5 K. Then the transition to stable film boiling is carried with heat flux density equal to 5.78 W cm\(^{-2}\). In this point it is also possible to have a direct transition between the conduction and film boiling regimes without nucleated boiling phase.

**B. Transient boiling curves for ribbon’s horizontal position**

In this part the transient result qualitatively shows that the results obtained with a horizontally fixed ribbon are similar to those obtained with a vertically fixed one.

**Natural convection zone**

Similarly with vertical position, fig. 10 shows that for a low heat flux density imposed lower than 1.17 W cm\(^{-2}\) the surface superheat increases during the first two seconds. Afterwards, stabilizes and tends to a limit corresponding to steady-state of natural convection. The values \(\Delta T\) obtained in permanent regime are in good agreement with those reached in transient regime.

**Nucleate boiling zone**

The transient superheat evolutions for high heat flux density imposed with ribbon’s horizontal position are presented in fig. 11 and 12. This shows that the nucleate boiling begins when the superheat reaches a maximum. In this point the activation nucleate sites permit to boiling suddenly starts, in a quasi explosive manner. Similarly with vertical position, after the triggering of the boiling, the surface superheat decreases rapidly until reaching values corresponding to those of steady-state regime of the nucleate boiling. The maximum surface heat flux, which is of the order of CHF, is reached when the surface superheat begins to decrease. On the other hand, we note that the bubbles begin to appear on the ribbon’s surface for a superheat of about 15.7 K and in a time of 0.3 s with value of heat flux density imposed equal 3.46 W cm\(^{-2}\) and about 14 K for the heat flux density imposed equal 2.40 W cm\(^{-2}\) (see fig. 11). Furthermore, in fig. 12 curves show that the heat flux density increases when the time corresponding to boiling triggering decreases. Indeed, when the heat flux density increases, the superheat rapidly increases to maximum value. Due to heat transfer enhancement associated with boiling occurrence, wall temperature starts to decrease whereas heat flux at the wall increases.
Film boiling zone

The total vaporization of the liquid around the ribbon is realized when the surface superheat is greater than 35 K for heat flux density imposed about 16.2 W/cm² (see fig. 13), this leads to the formation of a vapor film over the heated surface.

It is found that the lifetime of the nucleated boiling decreases. Similarly, the surface superheat increases continuously for higher heat fluxes and the transition to stable film boiling occurs. Moreover, we note that the critical heat flux, which characterizes the transition to film boiling, is surpassed. Stationary values of film boiling would be obtained in steady-state regime (fig. 5).

VII. RIBBON POSITION INFLUENCE ON THE SUPERHEAT EVALUATION

The comparison of wall superheat variation with time for both positions is showed in fig. 14. Superheat chart appear for ribbon’s horizontal position, at first glance, to be less evolved than the one obtained with vertical position: In the early stages of heating, the superheat increase with time is noted for both positions. Indeed, heat is released by conduction then natural convection in the liquid phase. The low efficiency of these heat transfer mechanisms leads to a rapid increase of the wall superheat. This sharp rise is stopped by the vapor onset.

Moreover, the maximum superheat that corresponding to boiling triggering depends on the surface position, in this case we note that the maximum superheat corresponding to the vertical position is higher than that of the horizontal position, this is caused by the quantity of heat transmitted to the liquid. Indeed, the quantity of heat released from a sample surface to boiling liquid increases as the superheat ΔT is increased, this is confirmed by the study of Nukiyama [1] with a metal surface and water as a cooling liquid. In the case of nucleate boiling of liquid nitrogen, curves (fig.14) show that the quantity transmitted from the ribbon on vertical position to the liquid nitrogen is more important as compared with that transmitted from ribbon on horizontal position.

Furthermore, we note that the bubbles begin to appear on the ribbon’s surface in vertical position for a superheat of about 23.17K and in a time of 0.07s, while for horizontal position, the bubbles begin to appear on the surface for a superheat of about 15.24K and a time of 0.15s. On the other hand, the maximum superheat of boiling triggering is about 50% higher for vertical position than for horizontal position. After the boiling triggering, the wall superheat decreases rapidly to the steady-state regime of the nucleate boiling due to activation of all nucleate sites.
boiling have shown that, for very fast heating conditions, the beginning temperature of boiling may be higher than that in stationary conditions, in spite of the existence of the vapor trapped in the nucleation sites. This shows that the existence of vapor-liquid inside the cavities plays a key role in the boiling process.

**Nomenclature**

\( h \) heat transfer coefficient, Wm\(^{-2}\)K\(^{-1}\)  
\( i \) electric current, A  
\( L \) ribbon length, m  
\( l \) ribbon width, m  
\( q \) heat flux, Wm\(^{-2}\)  
\( S_t \) ribbon transverse surface  
\( S_e \) emissive surface, m\(^2\)  
\( t \) time, s  
\( T \) temperature, K  
\( U \) voltage, V  

Greek symbols  
\( \rho \) electrical resistivity, \( \Omega \)m  
\( \lambda \) thermal conductivity, Wm\(^{-1}\)K\(^{-1}\)  
\( \rho_0 \) electrical resistivity of the ribbon at 0°C, \( \Omega \)m  
\( \sigma_0 \) temperature coefficient

**Subscripts**  
CHF critical heat flux  
OB onset boiling

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