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EXPERIMENTAL STUDY OF THE INTENSIFICATION OF HEAT TRANSFER BY POOL BOILING LN2: APPLICATION TO COOLING OF A BRASS RIBBON IN HORIZONTAL POSITION

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ABSTRACT

Boiling heat transfer process is important because it is a way to increase the flux density transmitted at low temperature differences. To quantify the thermal exchanges, we performed an experimental study of the nitrogen pool boiling, in transient conditions, on a horizontal brass ribbon for a fixed flux density. The results show that there is no break between the monophasic convection zone and the nucleated boiling region. In the nucleated boiling zone, the temperature variations are very small. We also note that the overheating required to trigger boiling increases with the time delay after the activation of nucleation sites.

Keywords: *Phase change; Pool boiling; Nitrogen; thermal inertia; Overheated.*

1. INTRODUCTION

The aim of research on the pool boiling is to characterize steady-state and dynamic conditions of the cryogenic fluid boiling (LN2) on massive metallic materials, wire and ribbons. By boiling heat transfer process is very important industrially because it is a way to increase the flux density transmitted at relatively low temperature differences (many research focuses on the intensification of heat transfer techniques). Although in the majority of industrial applications, boiling takes place during the flow of the dysphasic fluid. The pool boiling has been the subject of a large number of studies because it is the basis for the understanding of heat transfer in boiling systems.

In most cases, the dimensioning of cooling system is made from steady-state studies. They started for more than a century, but considering the complexity of the phenomenon, the acquired knowledge does not allow to properly quantify the heat exchange without an experimental study. Several correlations are generally developed according to specific constants of the liquid-wall couple. The experiments performed in steady state allow the determination of these constants. However, during the starting phase or during sudden variations of the flux in the cooling systems, the flux densities or wall temperatures can significantly differ from those determined in the steady state. A good knowledge of boiling transient requires a thorough experimental approach. In addition, boiling transient reveals some peculiarities whose understanding will expand fundamental knowledge on the phenomenon of boiling.

More precisely, the objective of this work is to improve knowledge of the free boiling phenomenon of liquid nitrogen on a brass ribbon horizontally positioned and to determine the operating limits associated to this phenomenon in both, steady and transient regimes. As for the steady regime, the purpose of the study is to determine the boiling trigger point and the critical flux which represent an important issue for the security of systems. For the Transient regime, it is about the determination of the temperature of the onset of boiling and its maximum value and the establishment of a parametric study showing the influence of the imposed flux level and waiting time between preliminary process and the imposed flux echelon.

Studies of boiling at transient regime began in the late 50s (Cole, 1957; Rosenthal, 1957; Johnson et al., 1961) with the aim to simulate the rapid temperature increase during accidents that may occur in a nuclear reactor. These studies involved the exponential heating of metal films in water at atmospheric pressure. Kawamura et al. (1970), Sakurai et al. (1970), Sakurai et al. (1992) extended these studies to other heating methods (especially flux ramps). However, most of these recent studies on the boiling transient were performed on metallic wires, metallic ribbon and bulk samples, on which flux echelons are imposed (Iida et al., 1994; Drach and Fricke; 1996; Sakurai et al., 1996; Duluc et al., 1999; Héas et al., 1998; Héas et al., 2003). Studies on bulk samples were performed by imposing either a flux or a temperature imposed and comparing the results (Héas et al., 1998; Héas et al., 2003; Hohl et al., 1996; Hohl et al., 1998; Hohl et al., 2001; Owens and Florshuetz, 1972; Peyayopanakul and Westwater, 1978; Westwater et al., 1986; Casadessus, 1997).

On one hand, Sakurai et al. (1970, 1992) have extended the studies related to metal films heating on which are imposed flux ramps in water at atmospheric pressure. They have shown that the temperature of the metal film continues to increase after the onset of boiling, and the onset temperature corresponds to the value for which the experimental points deviate from the values of the conduction regime.

On the other hand, Drach et al. (1996) have showed that during heat with an echelon flux of a nickel film immersed in LN2 at atmospheric pressure, the onset of boiling occurs before the establishment of the convection regime, and before the temperature reaches its maximum

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value. They also demonstrate that for a smooth (roughness less than 0.1µm), the maximal overheating value increases with the imposed flux. At a duty point in nucleated boiling, when we increase progressively the heat flux density, increasingly vapor appears on the heating element in the form of columns of steam.

For a metallic film heated with a ramp flux, Sakurai et al. (1970, 1992) have demonstrated that the time of onset of boiling decreases as the flux increases. In the case of an echelon flux heating for different surfaces submerged horizontally in liquid nitrogen, Drach et al. (1996) have shown that during transient regime, overheating reaches its steady state value without exceeding it for low fluxes, and exceeds it then stabilizes at different steady state values for strong flux imposed between 10 and 20 W.cm^{-2}.

One of the important results of the study of boiling transient on the ribbons is the possibility of a direct passage from the conduction system to a film boiling system.

According to Iida et al. (1994), for a high flux, a vapor layer grows along the wire and the transition boiling occurs when this vapor layer completely covers the wire.

2. EXPERIMENTAL PROCEDURE AND SET-UP

The experimental apparatus includes a support formed of studs for maintaining and electrical supply for the ribbon (length = 10^{-1} m, width = 4.10^{-3} m, thickness = 25.10^{-6} m) exposed to flux echelons generated by a power supply. This support is constantly immersed in a Dewar container filled with LN2. A platinum probe, an assembly comprising an endoscope, a camera for observation, an acquisition chain and a program that can acquire a large number of points on the requested frequency (105 Hz) due to an acquisition card controlled by LabView (fig. 1).

In the horizontal position (fig. 2), the ribbon is attached to a Bakelite support using an adhesive ECCOBAND 286 manufactured by Emerson & Cuming. The Bakelite and glue are insulating. The flux meter is positioned beneath the glue in order to measure the heat flux density which passes through the insulating adhesive. This allows estimating the losses at the imposed flux density and to ensure that it is predominantly released in the contact surface between the ribbon and liquid nitrogen. The flux meters used include sensors that are calibrated to set the proportionality factor (also known as sensitivity factor) which binds sensors signals to exchanged flux density.

The choice of the ribbon is conditioned by two main characteristics of materials: the importance of the electric resistivity at the temperature of liquid nitrogen and the thermoelectric sensitivity. The geometric factor also plays an important role; in fact, the electrical resistance of the ribbon must be important, so that dissipation by Joule effect is sufficient without exceeding the melting temperature.

The values of electrical resistivity of ribbon at 0°C (ρ_0) and the Brass temperature coefficient (σ_0) are calculated in the calibration phase. This allows to calculate the electrical resistivity ρ (Eq. 1) and to deduce the overheating ΔT (Eq. 2). The flux density is given by equation 3.

$$\rho(T) = \frac{R\,S_t}{L} = \frac{U\,S_t}{I\,L} = \rho_0\,(1+\sigma_0\,T) \quad (1)$$

$$\Delta T = T - T_{\mathrm{LN2}} \quad (2)$$

$$\dot{q} = \frac{U\,I}{S_e} \quad (3)$$

Activation of nucleation sites is performed by maintaining the heating power at 90% of the critical flux for 5 minutes. After the return to the equilibrium temperature, the sample kept at a dozen of centimeters of the liquid free surface and supplied by constant flux density echelons. Its resistance value is regularly saved by instrumentation acquisition.

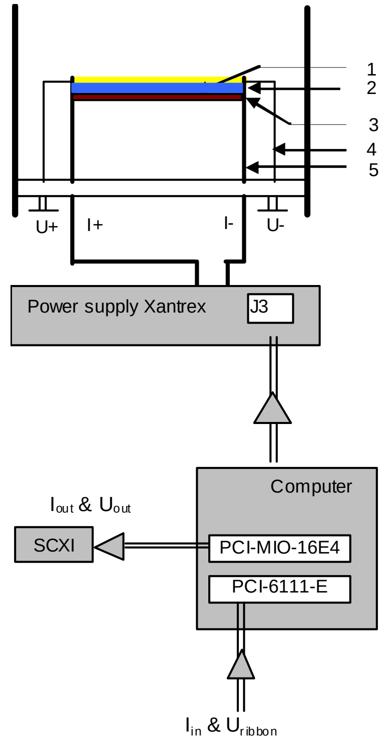

Fig. 1 Experimental Set-up Basic.

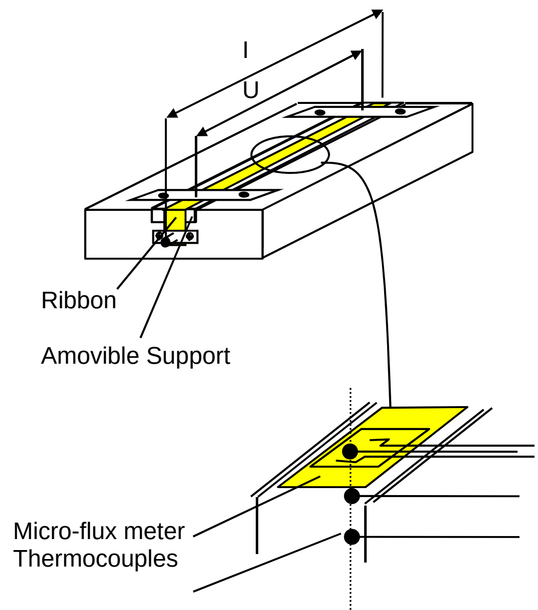

Fig. 2 Experimental Set-up for a ribbon horizontally positioned.

3. EXPERIMENTAL RESULTS AND ANALYSIS

In this part, we present the experimental results obtained from the study of free boiling of liquid nitrogen in stationary and transient regime on brass ribbons. We will focus on the influence of different parameters on the heat exchange during boiling in transient regime and, in particular, the influence of the time delay on the triggering of boiling, and the heating rate. The time delay is the time between the preliminary procedure and the echelon flux imposed to the ribbon. Different heating rates are obtained by varying the level of the echelon flux imposed. The accuracy in the determination of the temperature and the surface flux is respectively ± 0.3 K and ± 0.1 W.cm^{-2}.

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3.1 Boiling curve during steady regime with an increased flux

We present below some results obtained during steady regime with a ribbon mounted in horizontal position. After the conventional procedure of sites activation, we start recording temperature variation values of the ribbon as a function of different flux echelons.

Figure 3 shows that bubbles begin to appear for an average flux of 0.47 $W.cm^{-2}$ and overheating of 8 K. Critical flux or maximum flux is approached to an average flux density of 13 $W.cm^{-2}$ and a overheating of 6.6 K. In fact, this critical flux corresponds to the limit value of the flux density that can be exchanged without inducing a sudden rise of the ribbon temperature and damage risk.

The coefficient of heat exchange h is considerably higher in nucleated boiling than in natural convection. For a horizontally fixed ribbon, the trigger point of boiling corresponds to an overheating of the wall less than the overheating characterizes the boiling trigger for a vertically fixed ribbon (Agounoun et al., 2007). Indeed, to an horizontally fixed ribbon, thermal exchange occurs at one side. The number of nucleation sites is lower than that on a vertically fixed ribbon, where the exchange occurs on both sides. For the same reason, there is an improvement of heat exchange when the ribbon is in the horizontal position.

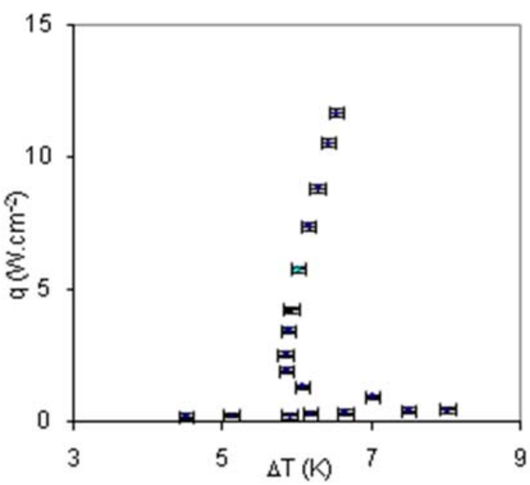

Fig. 3 Boiling curve of liquid Nitrogen in steady regime with an increased flux in contact with a ribbon mounted in horizontal position at saturation under a pressure of 1 atm.

3.2 Boiling curve during steady regime with a decreased flux

The boiling curve of descending flux is obtained after the curve with increased flux. We decrease the values of flux with an amplitude of 1.5 W/cm^2 up to a flux density of 2.5 W/cm^2, and 0.2 W/cm^2 up to a flux density of 0.3 W/cm2 (fig. 4).

The figure 4 shows that the hysteresis phenomenon occurs when the heat flux is applied progressively from a zero value up to high values. Boiling begins when a relatively large overheating is reached. The surface is then subject throughout to the nucleated boiling regime with a sudden decrease in the difference ΔT of temperature between the ribbon and liquid nitrogen. This boiling retardation occurs when the nucleation sites are embedded. It is then necessary to evaporate the liquid trapped to activate sites. It is possible to eliminate this effect by initially applying a high heat flux to the walls in order to ensure nucleation cavities. During the descending phase, there is no delay because the nucleation sites are already activated.

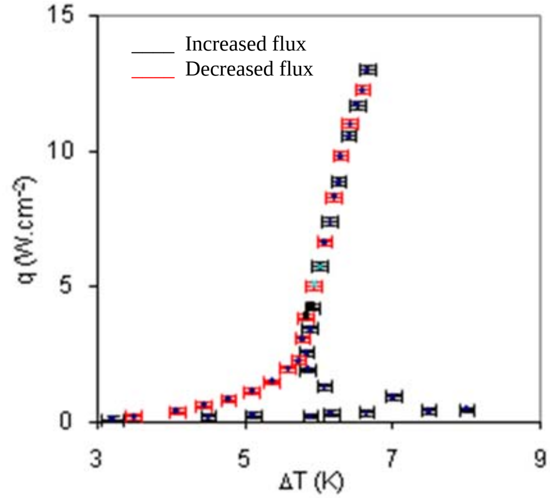

Fig. 4 Comparison of experimental boiling curves of liquid Nitrogen during steady regime for an increased and a decreased flux in contact with a horizontally fixed ribbon at saturation under a pressure of 1atm.

3.3 Boiling curves during transient regime

A ribbon degassing procedure is systematically carried out before each recording in order to ensure a reproducible initial state. It consists on applying to the ribbon a flux equal to 90% of the critical flux during a period of 5 min, which allows the activation of all the nucleation sites. Flux values corresponding to different regimes of the stationary boiling curve (natural convection, nucleated boiling) were applied.

Imposed flux values less than 0.21 $W.cm^{-2}$ lead to stationary states of natural convection with a transitional regime duration of approximately two seconds (Fig. 5).

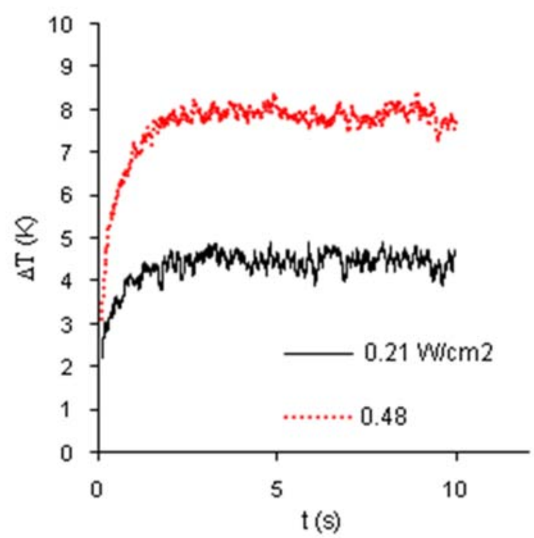

Fig. 5 Overheating as a function of time in the convection zone.

For imposed flux values between 1.32 $W.cm^{-2}$ and 1.9 $W.cm^{-2}$, the maximum overheating obtained is 13.4 K over a period of about 0.43 seconds. The increase in heat transfer due to the LN2 stirring near the wall decrease the temperature of the ribbon of about 6 K (fig. 6).

For flux densities between 2.58 $W.cm^{-2}$ and 6.4 $W.cm^{-2}$, the overheating during transient regime can reach a value of 17.6 K in a time of 0.075 second (fig. 7). Figure 7 qualitatively shows that the results obtained with an horizontally fixed ribbon are similar to those obtained with a vertically

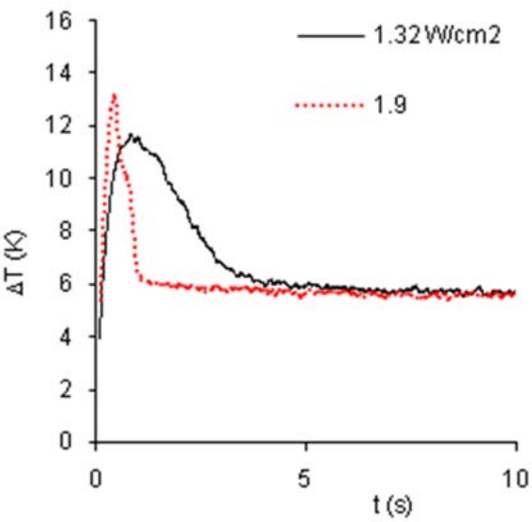

Fig. 6 Evolution of overheating in the small zone of nucleated boiling.

fixed ribbon (Agounoun et al., 2007). In the horizontal case, it is also observed that the heating rate has a greater influence on the maximum temperature. Indeed, the maximum overheating increases with the imposed flux density.

The onset temperature was determined by the deviation of the evolution in temperature obtained experimentally from that of the analytical solution during the pure conduction regime.

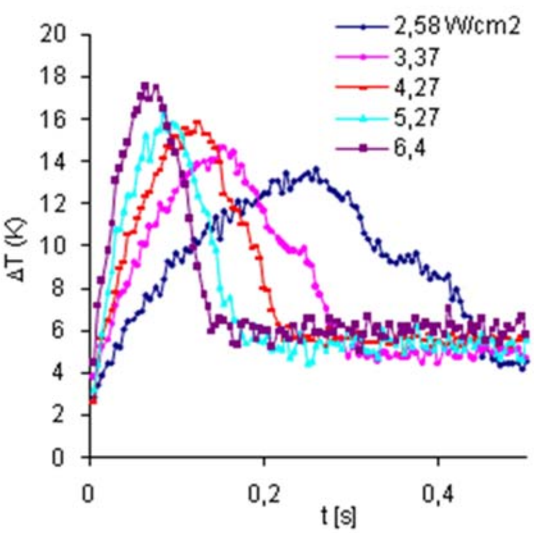

Fig. 7 Overheating in the nucleated boiling zone fully developed**.**

For a flux of about 13.6 W.cm^{-2}, we observe that the duration of the nucleated boiling regime decreases (figures 8, 9). For a high flux, a vapor envelope grows along the ribbon and the boiling film occurs when the vapor envelope completely covers the ribbon. When the heating rate is extremely high, a large number of small bubbles appear at the onset of boiling. Boiling film occurs when the bubbles cover the entire surface of the ribbon and the overheating of the ribbon is then close to that corresponding to homogeneous boiling theory. The ribbon is broken after reaching a overheating temperature of almost 700 K for about 16 seconds.

On figure 10, we note that overheating required to trigger boiling increases with the time-delay to a time limit of 1hr 40mins. Beyond this value, time-delay parameter has no more influence. So when the time-delay is zero, the standard deviation of the parietal overheating is low, it increases rapidly with the time-delay and stabilizes when this time increases.

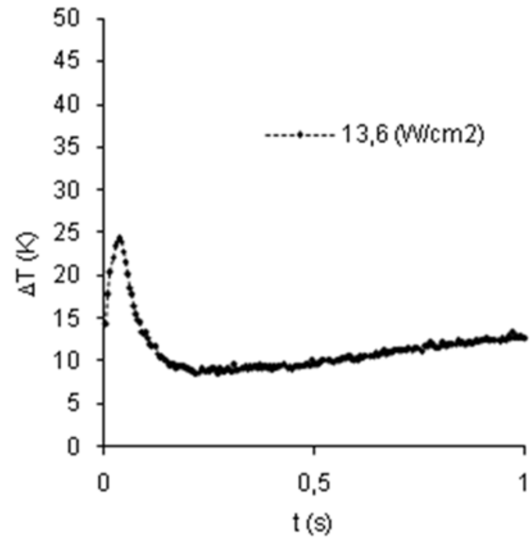

Fig. 8 Temporal evolution of overheating. The flow pulse begins at t = 0 and lasts at 1sec**.**

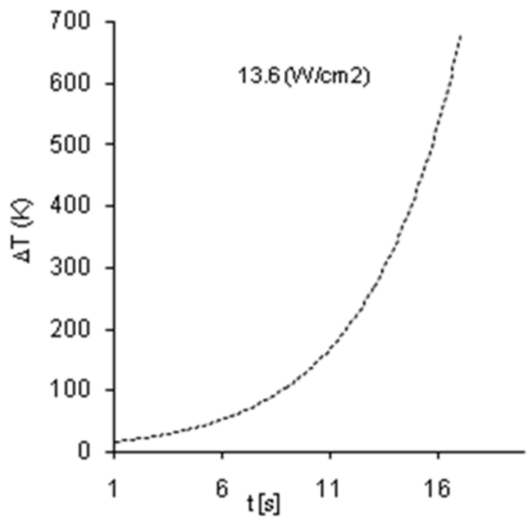

Fig. 9 Temporal Evolution of overheating. The flow pulse begins at t = 1sec and lasts at 20 sec.

Many tests were realized for each time-delay in order to provide an average value of overheating obtained values and the corresponding standard deviations (Table 1).

Table 1 Time-delay influence on the trigger boiling conditions

Test	*1*	*2*	*3*	*4*	*5*
Time-delay (min)	0	60	90	100	110
Overheating (K)	13.8	15	16	17	17
Standard deviations (K)	0.5	0.7	1	1.5	1.5

In transient condition, the boiling depends considerably on the time elapsed between the preliminary procedure and the test. This time, called the time-delay, influences the overheating of the boiling trigger. This is due to the deactivation of the nucleation sites over time. Indeed, the actual surfaces are rough and can trap gas inside small cavities. The vapor embryos formed in these cavities favor the initiation of the boiling.

During the preliminary procedure, about 5 minutes, there is an activation of the nucleation sites of the surface. After this, if the surface is heated immediately, a certain amount of gas still exists in the cavities and accelerates the initiation of the boiling. On the other hand, if a time is allowed to elapse before the surface is heated, the gas trapped in the cavities tends to diffuse into the liquid near the wall. In this case, the overheat required to trigger the boiling become higher.

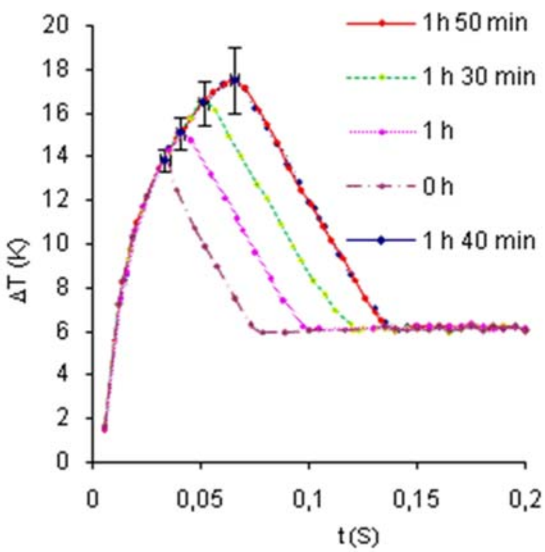

Fig. 10 Temporal evolution of overheating for different time-delays for a horizontally fixed ribbon.

4. CONCLUSIONS

The results show that the temperature at the onset of boiling, is strongly linked to the speed and the heating mode. During transient regime, boiling begins with a delay which creates significant overheating. The boiling triggering is abrupt and, before the boiling stabilizes on the surface, a transition to the film boiling regime may be observed. The measurements also show that the nucleation sites can be disabled if a certain time-delay is observed between the preliminary process and the echelon of imposed flux to ribbon. Overheating needed to trigger boiling is higher for long time-delays. This study led to results that can be applied to electrical components cooling in order to increase their efficiency and life-time. In order to avoid a strong overheating trigger boiling, it is possible to always maintain a surface temperature above certain limit. It can thus be recommended to always dissipate low flux to be sure that the surface temperature is sufficient to facilitate the activation of nucleation sites. This study was performed with one type of sample and fluid. It is necessary to diversify the nature of the fluid-sample combinations to test their influence on heat exchange during boiling transient. It is also necessary to vary the size of the sample and to lead a comparative study with wires or massive to assess the influence of the sample inertia.

NOMENCLATURE

I	*Intensity of electric current (A)*
L	*Length of ribbon (m)*
l	*Width of ribbon (m)*
$\dot{q}$	*Heat flow density (W.m^{-2})*
Se	*Emissive surface (m^2)*
T	*Temperature of ribbon (K)*
T_{LN2}	*Temperature of liquid nitrogen (°C);*
T	*Temperature of ribbon (°C);*
ΔT	*Overheating (K)*
U	*Electrical tension (V)*
ρ	*Electrical resistivity (Ω.m)*
St	*Cross-section (m^2);*
ρ_0	*Electrical resistivity at 0°C (Ω.m);*
σ_0	*Superficial tension at 0°C (N.m);*

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