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# Experimental study of transient boiling

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**Keywords:** Transient boiling, Infra Red Thermography, nucleated boiling, film boiling

## Abstract

The clad to coolant heat transfer is a key issue in the safety evaluation of the clad failure risk during a reactivity initiated accident (RIA). It has been demonstrated that under very fast transient conditions such as those of RIA, the steady state correlations are not valid. Dedicated experiments simulating RIA conditions are required to determine the transient transfers and deeper understanding of the transient boiling phenomena is desirable. This paper presents an experimental study of the onset and development of boiling of a refrigerant flowing over a half-cylindrical wall whose heating rate is mastered. Thanks to the design of the facility, synchronized wall temperature measurement and flow visualization allow to characterize and analyse the heat transfer for the different boiling regimes. From the main results of the first tests campaigns, the impact of the wall heating rate on the boiling curve is discussed. We then draw some perspectives for further campaigns and analysis.

## Introduction

Transient boiling regimes are present in many industrial situations: cooling down of hot surfaces, chill down of pipes by cryogenic propellant before space engines re-ignition and also in accidental situations in the nuclear power plants. In this last context the reactivity initiated accident (RIA) is one of the design basis accident considered in the safety evaluation of the light water reactors. At the fuel rod level, it corresponds to a very fast power increase that induces soaring fuel and clad temperatures. Clad failure is the main risk during the accident and it is partially determined by the clad temperature transient and the ability to transfer heat toward the coolant. If boiling occurs, a vapour film can spread over the clad resulting in a deteriorated heat transfer regime. Among the several past in-pile research programs on RIA, the experiments performed on the Nuclear Safety Research Reactor (NSRR) have brought some interesting insights for the determination of a transient boiling model. They show a large impact of the heating rate on the wall to fluid heat transfer, compared to steady state case, but in thermalhydraulics conditions far from an RIA in a pressurized water reactor (Bessiron et al., 2007). The out of pile tests performed on the PATRICIA facility reproduced RIA clad heating rates on a simulated rod in those thermalhydraulics conditions. Their enlightening analysis has led to improved transient boiling curve model (Bessiron, 2007). Nevertheless, this analysis is still limited: (i) some uncertainties on measurements are related to the difficult instrumentation in such conditions but, (ii), the main limitation lies on the lack of understanding of the dependency of transfer beneath the heating rate. Therefore it is believed that deeper investigation of the process of boiling in transient conditions is required.

Most of the heat transfer models for boiling flows are established for quasi steady state conditions. Let us specify

that we consider transient boiling conditions when the time scale for the heating of the wall (over the saturation temperature of the fluid) is less than the typical period of bubble cycle in an established nucleate boiling regime. Among the few studies related to the transient boiling phenomena, some are related to explosive boiling (Glod et al., 2002), for which the time scale for heat transfer is less than the pressure relief. Those conditions do not match RIA related conditions for wall to fluid heat transfer for which the classical order of magnitude of temperature increase time is a few hundredths of second. Sakurai (2000) studied the boiling over a thin wire for a large spectrum of time scales and proposed different mechanisms of transition to film boiling according to the heating rate. Auracher and Marquardt (2002) performed boiling over a thin horizontal disk whose transient temperature is mastered and showed an increase of the heat flux during nucleate boiling and at the transition toward film boiling with an increase of the heating rate of the wall. The understanding is still missing and the conditions are far from those of RIA.

In view of the absence of analytical experiments that investigate high heating rates, with a representative geometry and accurate measurement devices, and of the lack of knowledge on rapid transient boiling the french Institut de Radioprotection et de Sûreté Nucléaire (IRSN) defined a research program to improve the knowledge of the transient boiling phenomenon. Therefore an experimental set-up has been built at the Institut de Mécanique des Fluides de Toulouse. The main objective is to study the transient boiling phenomenon over a wall simulating a fuel rod while mastering its heating rate, the bulk flow subcooling and velocity and characterizing precisely the heat transfer and the boiling incipience.

In the present paper, we introduce the main features of the facility (section 2), present the typical tests results and

their classification (section 3), provide an analysis of the observed impact of heating rate on the different heat transfer regimes (section 4), and conclude with perspectives for the next campaigns of measurements (section 5).

## Nomenclature

$h$	heat transfer coefficient ( $\text{W m}^{-2}$ )
$h_{LV}$	latent heat of vaporisation ( $\text{J.kg}^{-1}$ )
$g$	gravitational constant ( $\text{ms}^{-1}$ )
$p$	pressure ( $\text{Nm}^{-2}$ )
$T$	temperature (K)

## Greek letters

$\alpha$	thermal diffusivity ( $\text{m}^2/\text{s}$ )
$\lambda$	thermal conductivity ( $\text{W m}^{-2}/\text{K}$ )
$\phi$	heat flux ( $\text{W.m}^{-2}$ )
$\eta$	viscosity (Pas)
$\sigma$	surface tension (N/m)

## Subscripts

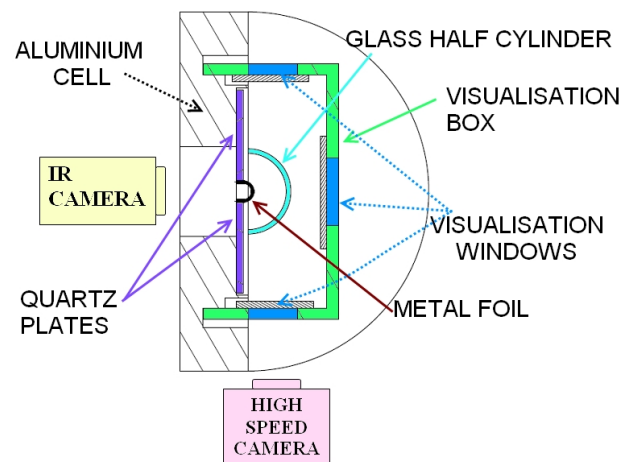
l	liquid
v	vapour
sat	saturation
w	wall

## Experimental Facility

In this section, we introduce the main features of the facility. More details can be found in Visentini *et al.* (2012) and Visentini (2012). The test section is the part of the facility where a wall is heated up by an external source. In RIA conditions, the wall is the fuel cladding of a vertical cylindrical fuel rod surrounded by upward liquid water flow. The design of the test section attempts to close up this configuration; it is the following. The total length of the test section is 20cm. The heated wall is a half cylinder metal foil supported by plane adiabatic quartz plates. The liquid is confined in a half-annulus section, *i.e.* between the external face of this half-cylinder (in dark in Figure 1), the plates (in purple) and the internal face of a larger half-cylinder made of glass (in light blue). The diameter of the heated half-cylinder is 8.4mm, which is close to a 17x17 fuel rod one. The diameter of the glass half-cylinder is 34mm. The assembly of the three components of the test section to ensure leak-tightness during heating of the wall is complex. It is surrounded by a visualisation box (in green) to reduce optical distortions.

For the heated wall, Joule effect is used and we consider the choice for a thin ( $50\mu\text{m}$ ) stainless steel foil that, due to its high resistivity ( $72\mu\Omega\text{m}$ ) allows having a high electrical resistance. It leads to a negligible time (0.6ms) for conduction between the wet outer surface and the dry (in

contact with ambient air) inner surface of the half-cylinder. As a result, it is possible to observe the thermal scene over the whole length of the test section thanks to an infra-red camera focusing on the backside of the foil (heated wall) in contact with air (inner side). The metal foil area investigated was a  $5\times 25\text{mm}^2$  rectangle with a  $240\times 320$  pixels<sup>2</sup> resolution at a 50 im/s time resolution. The transparent glass allows for direct visual observation of the boiling flow. Due to the curvature of the heated wall, one can focus on the symmetry plane of the test section and observe the wall laterally. A high-speed video camera (500im/s for a  $1024\times 1024$  pixels<sup>2</sup> window) catches therefore the incipience of vapour (bubbles or film) on the wall, the bubbles flowing toward the bulk, or the dynamic evolution of the vapour film thickness. These are key information to interpret the heat transfer variations during the transient and to suggest mechanistic models for the heat transfer coefficient or for the boiling regime transition (onset of nucleate boiling, departure from nucleate boiling or film establishment) criteria.



**Figure 1:** Test section

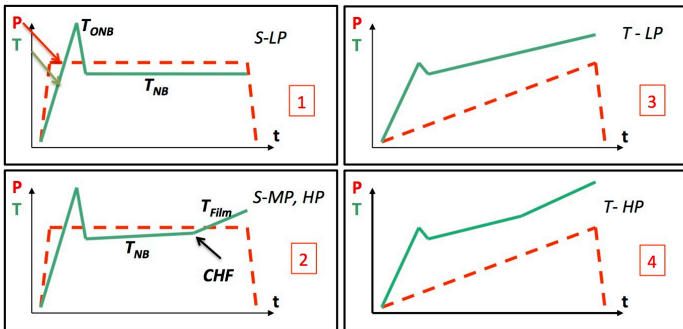
To reproduce transient boiling with relatively low power and to avoid high temperatures, the choice for an organic fluid, called HFE7000 ( $\text{C}_3\text{F}_7\text{OCH}_3$ ) has been made. Its saturation temperature at ambient pressure is  $34^\circ\text{C}$  and the corresponding latent heat of vaporization is  $132 \text{ kJ.kg}^{-1}$  (seven times less than for water). This fluid fills the test section. It can either fill the test section only, in which case the study concerns vertical pool boiling, or inserted within a loop for the study of convective boiling cases. This two-phase flow loop consisting of a gear pump, a Coriolis flow meter, a pre-heater, a 1m long channel upstream the test section to establish the flow and a condenser. Therefore, impact of flow rate and subcooling on transient boiling can be studied.

The electrical power is provided by a power supply SORENSEN SGA. It covers the 0-40V voltage range and the 0-250A current range. A special attention is paid to the electrical connections, as the contact resistance must be reduced. The electrical power that is dissipated in the foil is in average 85% of that dissipated through the whole system, including electrical connections and connection cables. The power supply is driven by an arbitrary

generator where all kind of curves can be programmed, more specifically peaks or gradual power ramps. The power supply can provide a current increase up to 45A/s. Thermal losses on the backside of the foil have been estimated to be less than 1% of the heat flux transmitted. Lateral conduction inside the foil has been numerically simulated and is found to be negligible. The analysis supports that the power generated in the wetted part of the foil is directly transferred toward the fluid (and not through the plates). The heat flux transmitted to the fluid per unit surface area,  $\phi$ , can be deduced from the known electrical power generated into the wetted part of the foil,  $q_{gen}$ , and its energy variation deduced from IR measurements,  $\rho e c_p dT/dt$ , from a thermal balance:  $q_{gen} = \rho e c_p dT/dt + \phi$ , where  $e$  is the foil thickness. The accuracy has been estimated around 20%, mainly due to uncertainties on the foil's geometry.

### Experimental parameters and results

The main data concern the temperature evolution of the foil. A spatial average temperature is deduced from IR measurements that can be plotted against time. As far as relatively long transients are concerned (total power supply time between 1 and 10s), the results can be gathered in four main categories, as illustrated in Figure 2.

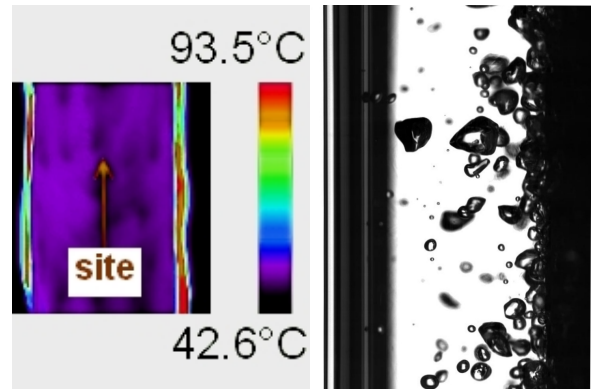


**Figure 2:** Typical shapes of power input (in red) and temperature measurements (in green)

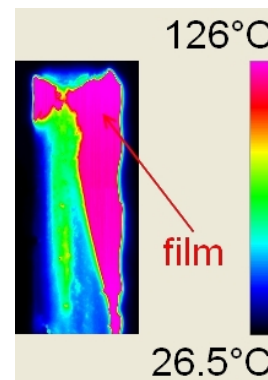
In the first case ("1" in Figure 2), the power  $P$  (red curve) is a step function of time which level is lower than a threshold of 300W. In this case, the temperature (green curve in Figure 2) of the wall first increases till a peak value, and then decreases till a constant value. The peak value actually corresponds to the onset of boiling ( $T_{ONB}$ ). The plateau value for larger times means that a stable nucleate boiling regime ( $T_{NB}$ ) has been reached for the imposed power level. In the second case ("2" in Figure 2), the power is still a step function of time but for power higher than 300W. Then no stable nucleate boiling regime can be reached, and, after the peak corresponding to the onset, the temperature of the wall increases continuously. The increase rate (slope of the curve) is first constant but suddenly shifts to another larger constant for larger times. This slope change is the signal of transition toward the establishment of a vapour film along the wall and a subsequent decrease of the heat transfer. In the third and fourth cases ("3" and "4" in Figure 2), the power is a ramp function of time. Therefore no steady state boiling regime can be achieved. The wall temperature evolution still exhibits a peak corresponding to the onset of boiling. For

case "3", the power never exceeds a 800W value and the temperature time evolution after the peak has a constant slope; the system stays in a nucleate boiling regime. In the case "4", the power is higher and there is a time for slope change in the temperature curve, corresponding to the onset of vapour film spreading along the wall. In the following, tests of type 1 and 3 will also be referred as being low power (LP) ones, while tests of type 2 or 4 as being for medium or high power (MP or HP).

The onset of nucleate boiling can be clearly characterized from the measurements. It actually coincides with the visual observation of first bubbles on the wall thanks to the high-speed camera. The vapour film onset is also clearly distinguishable. Let us note that before the onset of vapour film, the temperature of the wall is almost uniform. Local variations of small magnitude can be observed and correspond to the regions underneath bubbles in the nucleate boiling regime (see Figure 3). When vapour begins to cover the wall, the temperature over the wall is highly non uniform with rather high values increasing steeply under the spreading vapour layer (see Figure 4). Therefore, for these conditions, the average wall temperature is no more usable to derive a heat transfer coefficient.



**Figure 3:** Left hand side: snapshot of IR camera wall temperature measurements in the nucleate boiling regime. On its right, corresponding high-speed camera image with the heated foil on the right and the glass wall on the left. Local wall cooling associated to nucleation site can be seen on IR picture.

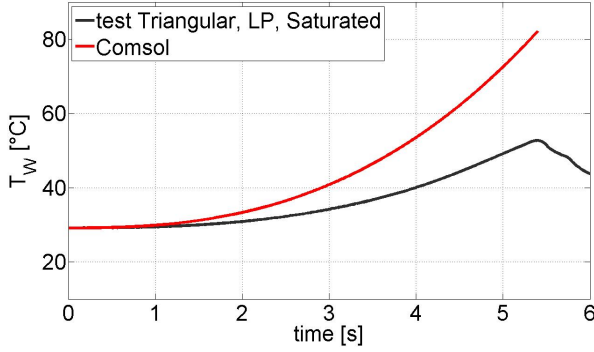


**Figure 4:** Wall temperature for a case "2" test. The development of the vapour film is visible from the top right of the IR picture.

## Data Analysis

### Single-phase heat transfer

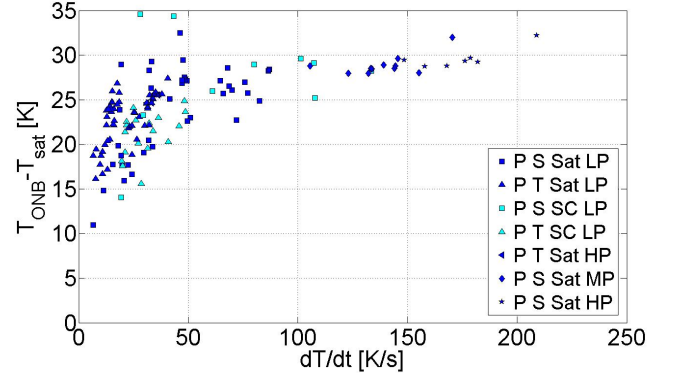
In the first stage of the tests, heat is only transferred to the liquid. The mean wall temperature as a function of time has been compared to numerical simulations of one-dimensional transient conduction throughout the liquid, the Joule effect power being imposed inside the foil. The simulations have been performed using the software COMSOL multiphysics. Such comparison is illustrated in Figure 5. The experimental temperature is always less than the computed one. Since the heat transfer coefficient deduced from experiments is also larger than for classical convection values, both transient conduction and convection should contribute to this heat transfer. A better understanding of the heat transfer could be achieved by analysing the flow pattern over the foil in the half-annulus geometry of the test section. Particle image velocimetry has been used to improve its knowledge but further ongoing work is needed.



**Figure 5:** Wall temperature time evolution in the single-phase stage (till the first maximum). Red curve: computed transient conduction. Black curve: IR average measurements of foil temperature.

### Onset of nucleate boiling

The time for onset of nucleate boiling is clearly deduced from IR temperature measurements. Let us consider the difference between the corresponding peak temperature  $T_{ONB}$  and the saturation temperature  $T_{sat}$ . This value varies a lot according to the test, as it can be seen in Figure 6, where it has been plotted against the wall temperature increase rate  $dT/dt$  just before the onset for a large set of tests in the pool boiling configuration of the test section. We can see that  $(T_{ONB} - T_{sat})$  increases with  $dT/dt$ . For  $dT/dt$  greater than  $50\text{Ks}^{-1}$  it reaches an asymptotic value close to  $30^\circ\text{C}$ .



**Figure 6:** Onset of nucleate boiling temperature as a function of wall temperature increase rate. P reads for pool boiling, S for step power signals (case 1 and 2 in Figure 2), T for ramp power signals (case 3 and 4 in Figure 2), Sat for saturated liquid, SC for subcooled one, LP, MP and HP for low, medium and high power resp.

To interpret this variation, the Hsu criterion (1962), is used to evaluate the corresponding size of active nucleation sites. Their range  $[r_{c\ min}; r_{c\ max}]$  reads:

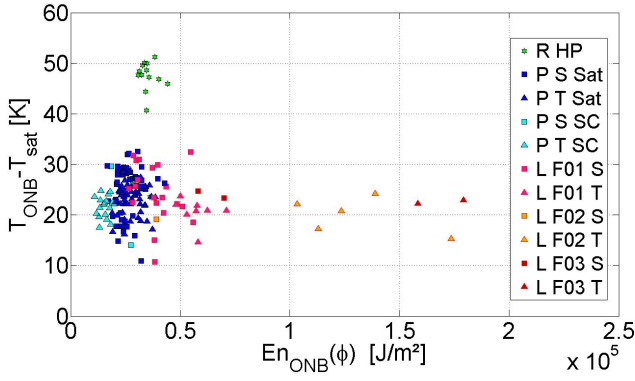
$$\left\{ \begin{array}{l} r_{c\ min} \\ r_{c\ max} \end{array} \right\} = \frac{\delta_i}{4} \left[ 1 - \frac{T_{sat} - T_L}{T_w - T_L} \mp \sqrt{\left( \frac{T_w - T_{sat}}{T_w - T_L} \right)^2 - \frac{12.8 \sigma T_{sat}(p_L)}{\rho_V h_{LV} \delta_i (T_w - T_L)}} \right]$$

where  $\sigma$  is the interfacial tension coefficient,  $\rho$  the density,  $h_{LV}$  the latent heat,  $p$  the pressure, the subscripts  $L$  and  $V$  for liquid and vapour and  $\delta_i$  is the thermal boundary layer thickness, which can be estimated as  $\lambda_L/h$ ,  $h$  being the heat transfer coefficient  $h = \varphi/(T_w - T_L)$ . For the lowest power levels  $T_{ONB} - T_{sat}$  is close to  $20^\circ\text{C}$ , the heat transfer coefficient  $h$  about  $1000\text{Wm}^{-2}\text{K}^{-1}$  and the size of the active nucleation sites between  $r_{c\ min} = 0.3\mu\text{m}$  and  $r_{c\ max} = 33\mu\text{m}$ . For the highest power levels  $T_{ONB} - T_{sat} = 30^\circ\text{C}$ , the heat transfer coefficient  $h$  can reach  $4000\text{Wm}^{-2}\text{K}^{-1}$  and the size of the active nucleation sites is between  $r_{c\ min} = 0.17\mu\text{m}$  and  $r_{c\ max} = 9.2\mu\text{m}$ . The rather small values found for  $r_{c\ min}$  can be explained by the smooth surface of the metal foil. Moreover, HFE7000 is highly wetting on this surface, and therefore tends to fill the wall cavities. Then the size of initial vapour nucleus may be smaller than the cavity size.

The time to reach the  $T_{ONB}$  value has been analyzed and is never lower than 0.1s. Actually, to set the nucleation conditions, a minimum amount of energy is required to over-heat a liquid layer. The energy  $E_{ONB}$  released between the beginning of the heating ( $t=0$ ) and the onset of nucleate boiling ( $t=t_{ONB}$ ) has been experimentally estimated from the heat flux  $\varphi$  time evolution:

$$E_{ONB} = \int_0^{t_{ONB}} \varphi(t) dt$$

The criterion for onset ( $T_{ONB} - T_{sat}$ ) has been plotted against  $E_{ONB}$  for the whole set of tests performed in Figure 7.



**Figure 7:** Onset of nucleate boiling temperature as a function of released energy. L stands for convective conditions (Loop) and the flow rate FOX corresponds to 0.Xl/s. R HP stands for rapid tests at high power.

It shows that a minimum of around  $10^4 \text{Jm}^{-2}$  is required to set the nucleation and that  $E_{ONB}$  ranges between  $10^4 \text{Jm}^{-2}$  and  $4 \cdot 10^4 \text{Jm}^{-2}$  for all the pool boiling tests. This range is quite narrow regarding the various experimental conditions: square or triangular signal, low, medium or high power.  $E_{ONB}$  can be larger in flow boiling (“L” tests) since one part of this energy is evacuated by forced convection.

### Nucleate boiling

Let us first consider the tests for which a *steady state nucleate boiling regime* can be reached (tests of type 1 in Figure 2). Let us note that, to our knowledge, no correlation has been validated in the literature for HFE7000 boiling. Among the correlations we considered, the Forster and Zuber one (1955) shows the most interesting trend. It is based on the model for micro convection in the liquid layer at the wall induced by the bubble formation and reads

$$\phi_{NB} = B \left[ \frac{\rho_L c_{PL} (T_W - T_{sat})}{\rho_V h_{LV}} \right]^{5/4} \left[ \frac{\mu_L c_{PL}}{\lambda_L} \right]^{-7/24} \left[ \frac{\rho_L r_b^3}{2\sigma \alpha_L^2 \sqrt{\pi}} \right]^{-1/4} \rho_V h_{LV}$$

where  $r_b$  is the radius of a bubble at equilibrium over an overheated wall at  $T_W$  temperature:

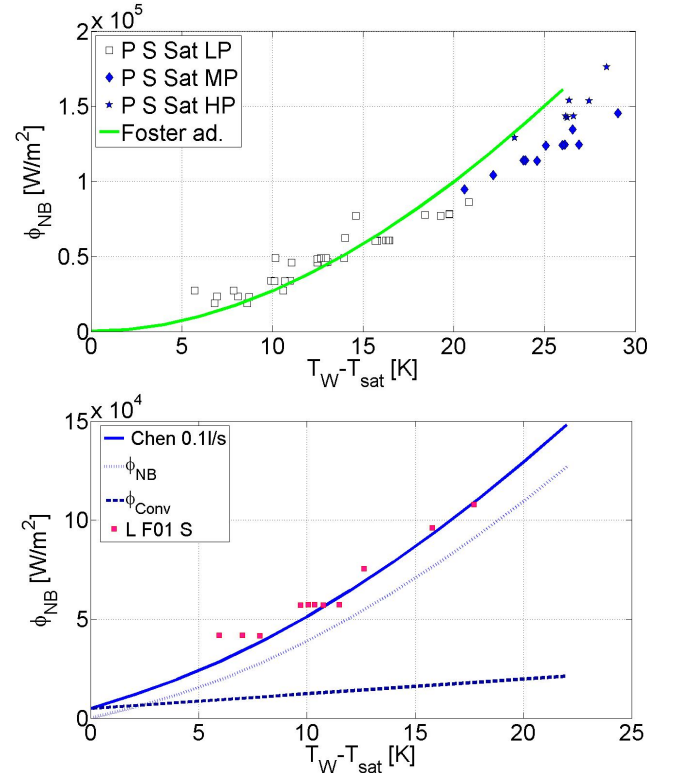
$$r_b = \frac{2\sigma}{h_{LV} (T_W - T_{sat})} \frac{T_{sat}}{\rho_V}$$

The first ratio is a Jacob number,  $Ja$ , and the second one a Prandtl number,  $Pr$ . The constant  $B$  is taken equal to 0.0015 for water at atmospheric pressure to 50 bar, for n-butyl alcohol at 3.4 bar and for mercury between 1 and 3 bar. For experimental data in saturated boiling the constant  $B$  has been taken equal to 0.0021. For sub cooled boiling, the correlation of Forster and Zuber has to be modified for a best prediction of the experimental data: the  $Ja$  number is based on the temperature difference ( $T_W - T_L$ ), with  $T_L = 23^\circ\text{C}$  in the experiments and the constant  $B$  is multiplied by a suppression factor  $S = 0.75$ . For the convective cases

(in the presence of the loop), we use the Chen’s correlation (1966). In this correlation the heat flux is divided into two contributions, one due to the convection  $\phi_{conv} = h(T_W - T_L)$  and one due to the nucleation  $\phi_{NB}$  for which we used the Forster and Zuber’s correlation (based on  $T_W - T_L$  and with a suppression factor issued from Collier (1981)  $S = [1 + 2.53 \cdot 10^{-6} \text{Re}^{1.17}]^{-1}$ ). The heat transfer coefficient  $h$  is corrected for refrigerants as suggested by Bennett and Chen (1980):

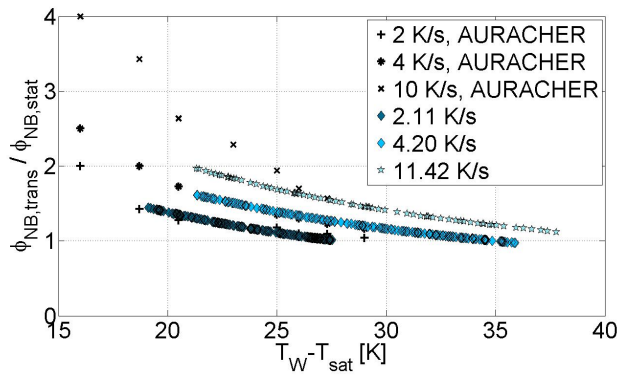
$$\frac{hD}{\lambda_L} = 0.023 \text{Re}^{0.8} \text{Pr}^{0.696}$$

In Figure 8, we compare our data to those correlations. The curves show a good agreement between the correlations and the experimental data. It can be seen that the nucleate boiling contribution is dominant and tends to decrease as the liquid flow rate increases.



**Figure 8:** Nucleate boiling flux has a function of wall temperature, experiments (symbols) vs correlations (lines). Top figure: saturated pool conditions. Bottom figure: loop conditions.

(4) In transient regimes, the heat transfer toward fluid is too low to prevent the wall temperature rise. As  $dT/dt$  increases, the ratio between the actual heat flux  $\phi$  and the steady state value of nucleate boiling at the corresponding wall temperature  $\phi_{NB}$  increases like  $\phi/\phi_{NB} = 0.04 dT/dt$ . The results are compared to the experiments of Auracher and Marquardt (2002) obtained in transient boiling of FC72 on a small horizontal disk. For the same range of  $dT/dt$  values a good agreement between the two sets of experiments is found as it can be seen in Figure 9. However, in these experiments, the wall temperature was controlled whereas in our experiment, we impose the electrical power, then the condition is closer to an imposed value of the heat flux.



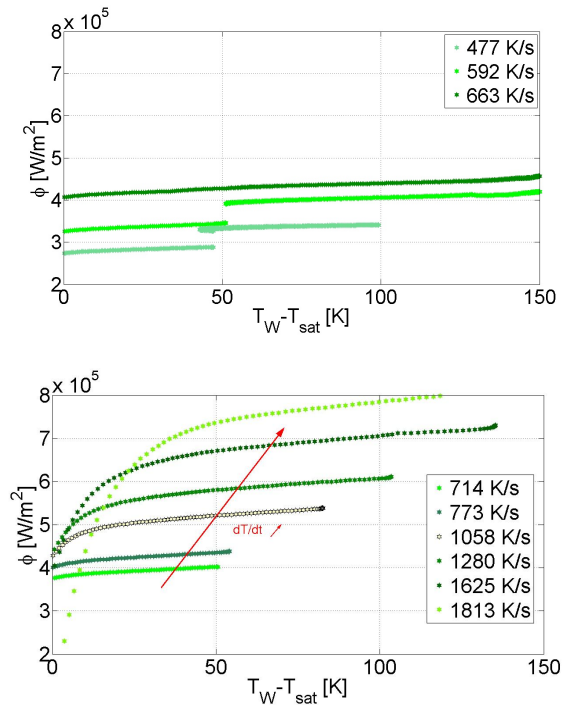
**Figure 9:** Ratio between transient and nucleate boiling heat flux as a function of wall temperature for various rates of increase: comparison between HFE7000 data of the present work and Auracher and Marquardt's results (2002)

### Departure from nucleate boiling

Establishment of a vapour film from nucleate boiling is only achieved for few high power tests for steps and ramps power signals. Due to the non-uniformity of wall temperature during transition toward film boiling (Figure 4), this corresponds to a moderate slope change in the average wall temperature time evolution. As the wall becomes covered by the vapour film, its temperature reaches very high values. In the context of this first tests campaign, the power signal is then shut down to avoid any damage of the test section. For the available data for heating rate between 5K/s and 11K/s, the range of values of the heat flux at the beginning of the transition is 0.1-0.3MWm<sup>-2</sup>. This is in the order of magnitude or twice the value of the critical heat flux for HFE7000 that can be evaluated thanks to classical correlations (Zuber, 1959). Further analysis including more local estimation of heat transfer and spreading dynamics would deserve further analysis. The same is true for film boiling regime analysis in these rather long transient tests where nucleate boiling has not time to establish but still to initiate.

### Film boiling

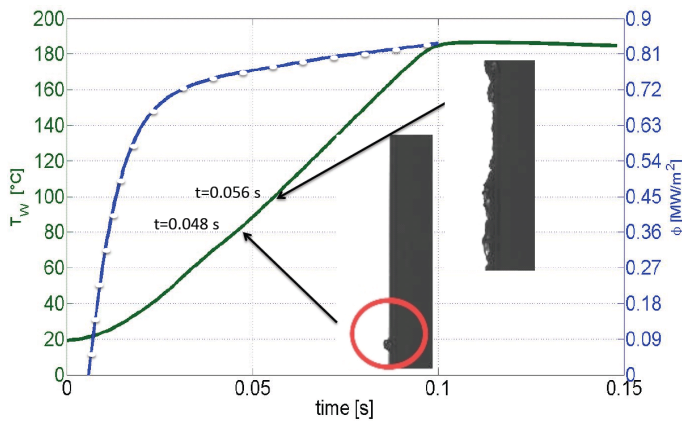
Only for very rapid transient tests of duration less than 0.5s at very high power a vapour film is established over all the metal foil. In Figure 10, heat flux in film boiling is reported for rapid transient tests at high power for a duration of 0.5s (Figure 10 Top) and 0.1s (Figure 10 Bottom). The heating rates have been estimated before the onset of nucleate boiling. For 0.5s and the two lowest heating rates 477 K/s and 592 K/s an increase in the heat flux is observed at 0.2s for a wall superheat of  $T_W - T_{sat} = 50^\circ\text{C}$ . This discontinuity corresponds to the onset of nucleate boiling. For the highest heating rate 663K/s, this discontinuity disappears and boiling starts at 0.1s. For shorter heating time of 0.1s and higher heating rates (Fig. 10 Bottom), the nucleation on the wall is followed a few milliseconds later by an explosive boiling leading to the formation of the vapour film (for the two lowest heating rates 714 K/s and 773 K/s the duration of the test is too short to reach the onset of boiling).



**Figure 10:** Wall heat flux as a function of mean wall temperature for a large set of wall temperature increase rates.

An example is shown in figure 11 where the temperature and power time-evolutions are plotted for the heating rate around 1800K/s. From the images of the high-speed camera it is possible to observe the bubble nucleation and the formation of the vapour film. At time  $t=0.048\text{s}$  a first bubble appears on the heated surface. The wall temperature is  $80^\circ\text{C}$  which correspond to a superheat of  $46^\circ\text{C}$ . At  $t = 0.052\text{s}$  nucleation is observed everywhere on the surface and at  $t = 0.056\text{s}$ , the wall is completely covered by a vapour film. The wall temperature reaches  $100^\circ\text{C}$  at this time. It is interesting to notice that at atmospheric pressure the spinodal limit deduced from the Van der Waals isotherms is reached for a liquid temperature equal to  $98.5^\circ\text{C}$ . This value explains the vapour explosion occurring on the wall. A large amount of energy is quickly transferred. The heat flux gradually increases from single-phase flow heat transfer to film boiling heat transfer. For  $T_W - T_{sat} = 100^\circ\text{C}$ , the heat transfer coefficients range between 3000 and 8000  $\text{Wm}^{-2}\text{K}^{-1}$ , which is one order or two orders of magnitude larger than the predictions based on an integral boundary layer approach of the laminar vapour film (Bromley, 1950) or on correlation for turbulent film boiling in steady regime (Hsu and Westwater, 1958).





**Figure 11:** Wall temperature (green curve) and heat flux (blue dotted curve) during a very rapid transient; snapshots of high-speed camera at onset of nucleation and film establishment.

### Conclusion and perspectives

Clad to coolant heat transfer during transient boiling, such as during a reactivity initiated accident, is still insufficiently understood. The “Institut de Sûreté et de Radioprotection Nucléaire” in collaboration with the “Institut de Mécanique des Fluides de Toulouse” investigates the phenomenon thanks to a dedicated experiment. The facility can simulate rapid and mastered heating of a wall in contact with a refrigerant fluid. A large range of wall heating rates can be achieved from a few K/s till 2000K/s. Space and time evolutions of the wall temperature, wall heat flux and visual observation of boiling are recorded. It allows to catch boiling regime transition (onset of nucleate boiling or vapour film establishment) and to deduce the quantitative effect of wall heating rate on the heat flux over the whole range of heat transfer regimes. From the analysis of the first campaign tests, the following conclusions can be drawn. The single-phase heat transfer stage is a mix of transient conduction and convection. For transient cases, the onset of nucleate boiling is mainly characterized by a threshold of energy transferred to the fluid rather than a wall temperature criterion. For very rapid transient, the spinodal limit is reached after a few milliseconds. Steady nucleate boiling regime of HFE7000 is well described by Forster and Zuber’s correlation for saturated or subcooled pool boiling or by Chen’s correlation for convective case. Transient conditions heat flux increases linearly with wall heating rate in a consistent way with the results obtained by Auracher and Marquardt. The heat flux at departure from nucleate boiling is close to the Zuber’s correlation and increases with wall heating rates, in agreement with results obtained by Auracher and Marquardt. For very rapid transient tests, the vapour film covers instantaneously the heated wall and heat transfer is one or two orders of magnitude larger than the correlation prediction for the same wall temperature and steady state conditions.

These results show the ability of the facility to investigate transient boiling phenomenon. Further work is still required to refine the analysis and to provide models for the wall heating rate impact on heat transfer. Next campaigns would, more specifically, focus on the film

boiling regime. More local analyses are required as well as the determination of steady state film boiling regimes.

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### References

- Auracher, H., and Marquardt, W., Experimental studies of boiling mechanisms in all boiling regimes under steady-state and transient conditions. *International Journal of Thermal Sciences*, Vol. 41, pp. 586-598, 2002.
- Bennett, D. L., and Chen, J.C., Forced convective boiling in vertical tubes for saturated pure components and binary mixtures. *AIChE J.*, Vol.26, pp.454-461, 1980.
- Bessiron, V., Modelling of clad-to-coolant heat transfer for RIA applications. *Journal of Nuclear Science and Technology* Vol. 44 No 2, pp 211-221, 2007.
- Bessiron, V., Sugiyama T., and Fuketa, T., Clad-to-coolant heat transfer in NSRR experiments. *Journal of nuclear science and technology*, Vol. 44, No. 5, pp. 723-732, 2007.
- Bromley, J. A., Heat transfer in stable film boiling. *Chemical Engineering Progress*, Vol. 46, No. 5, pp. 221-227, 1950.
- Chen, J. C., Correlation for boiling heat transfer to saturated fluids in convective flow. *Ind. Eng. Chem. Proc. Design and Dev.*, Vol. 5, No. 3, pp. 322-339, 1966.
- Collier, J. G., Forced convective boiling. in *Two-phase flow and heat transfer in the power and process industries*, A. E Bergles, J. G. Collier, J. M. Delhay, G. H. Hewitt and F. Mayinger, Eds., Hemisphere, New-York, 1981.
- Forster, H. K. and Zuber, N., Bubble dynamics and boiling heat transfer. *AIChE J.*, Vol. 1, pp. 532, 1955.
- Glod, S., Poulikakos, D., Zhao, Z., and Yadigaroglu, G., An investigation of microscale explosive vaporization of water on an ultrathin Pt wire. *International Journal of Heat and Mass Transfer*, No.45/2, pp. 367-379, 2002.
- Hsu, Y. Y. and Westwater, J. W., Film boiling from vertical surfaces, *AIChE J.*, Vol. 4, pp. 58, 1958.
- Hsu, Y. Y., On the size range of active nucleation cavities on a heating surface. *Journal of Heat Transfer*, pp. 207-212, 1962.
- Katto, Y., and Ohno, H., An improved version of the generalized correlation of critical heat flux for the forced convective boiling in uniformly heated vertical tubes. *International Journal of Heat Mass Transfer*, Vol. 27, No. 164, pp. 1-1648, 1984.
- Sakurai, A., Mechanisms of transitions to film boiling at CHF in subcooled and pressurized liquids due to steady

and increasing heat inputs. Nuclear Eng. Design, Vol 197, pp 301–356, 2000.

Visentini, R., Colin, C., and Ruyer, P., Experimental investigations on heat transfer in transient boiling. Proceedings of ASME 2012 Summer Heat Transfer Conference HT2012, July 8-July 12, 2012, Puerto Rico, USA HT2012-58245, 2012.

Visentini, R., Étude expérimentale des transferts thermiques en ébullition transitoire. PhD thesis, University of Toulouse, France, 2012.

Zuber, N., Hydrodynamic aspects of boiling heat transfer. Atomic Energy Commission Report AECU 4439, 1959.