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Experimental investigation of heat transfer in transient boiling

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ABSTRACT

During an hypothetical reactivity initiated accident in the core of a nuclear reactor, a power excursion occurs on some fuel rods. The consequent rapid boiling is a matter of study for the nuclear power plants safety evaluation, because of the risk for rod-clad failure. In order to better understand the influence of power excursions and to characterize the phases of the rapid boiling phenomenon, an experimental set-up has been built at the Institut de Mécanique des Fluides de Toulouse (IMFT). The test section is a semi annulus. The inner half cylinder is made of a stainless steel foil, heated by Joule effect. Thanks to the design of the facility, synchronized wall temperature measurement and flow visualization allow to characterize and analyze the heat transfer for the different boiling regimes: nucleate boiling, critical heat flux and film boiling. From the main results, the impact of the wall heating rate on the boiling curve is discussed. The more the heating rate increases, the higher the heat flux is.

1. Introduction

Transient boiling regimes are present in many industrial situations: cooling down of hot surfaces [1], chill down of pipes by cryogenic propellant before space engines re-ignition [2,3] 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 vapor film can spread over the clad resulting in a deteriorated heat transfer regime. Among the several past research programs on RIA performed on research reactors, the experiments conducted on the Nuclear Safety Research Reactor (NSRR) have brought some interesting insights for the determination of a transient boiling model, [4]. They show a large impact of the heating rate on the wall to fluid heat transfer, compared to steady state case, but in thermal-hydraulics conditions far from an RIA in a pressurized water reactor. The tests performed on the PATRICIA facility [5], reproduced RIA clad heating rates on a simulated rod in those thermalhydraulics conditions. Their enlightening analysis has led to improved transient boiling curve model. Nevertheless, this analysis is still limited: (i) some uncertainties on measurements are related to the difficult instrumentation in such conditions but and (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 [6]. Among the few studies related to the transient boiling phenomena, some are related to explosive boiling, e.g. [7], 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 [8] 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 Marquadt [9] 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 separate effect experiments that investigate high heating rates, with a representative geometry

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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 this article, the experimental apparatus and the measurement techniques are first described. Then, the evolution of the wall temperature is plotted, for the tests where the nucleate boiling regime was established and for those where the film boiling was reached. The trends of the boiling onset temperature, T_{ONB}, the mean nucleate boiling-regime temperature T_{NB} and the film boiling thermal evolution are shown. For each regime the effect of the transient heating is pointed out.

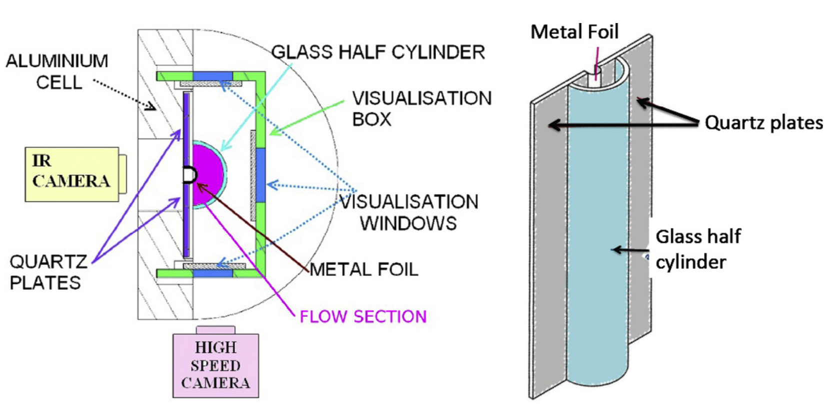
2. Experimental set-up and measurement techniques

In this section, we introduce the main features of the facility. More details can be found in [10]. The experimental set-up consists of a metal half-cylinder heated by Joule effect, placed in a half-annulus section. The inner half cylinder is made of a 50 μm thick stainless steel foil. Its diameter is 8.4 mm, and its length 200 mm. The outer part consists of a 34 mm internal diameter glass half cylinder (Fig. 1). The semi-annular section is filled with a coolant 1-methoxyheptafluoropropane (C3F7OCH3), which will be referred as HFE7000 (3 M). This fluid has been chosen because of its low saturation temperature (34 °C at atmospheric pressure), its latent heat of vaporization (ten times smaller than the water one), and the reduction in the critical heat flux that it induces (for atmospheric pressure, the critical heat flux given by Zuber's correlation is 1.11 MW/m^2 for water and 0.17 MW/m^2 for HFE7000). It allows to reduce the required power to reach the transient boiling conditions. The main physical properties of HFE7000 at saturation temperature and atmospheric pressure are given in the table below, where ρ, c_p, λ, ν, σ, h_{LV} are the density, heat capacity, thermal conductivity, kinematic viscosity, surface tension, latent heat of vaporization, respectively. L and V are the subscripts for liquid and vapor.

ρ_L (kg/m^3)	c_{pL} (J/(kg K))	λ_L (W/(m K))	ν_L (m^2/s)	σ (mN/m)
1385.8	1300	0.075	$0.32 \cdot 10^{-6}$	11.451
ρ_V (kg/m^3)	c_{pV} (W/(m K))	λ_V (W/(m K))	ν_V (m^2/s)	h_{LV} (kJ/kg)
8.26	975	0.0135	$0.293 \cdot 10^{-6}$	132

Stainless steel has been chosen for the foil because of its high resistivity (72 μΩm). The resistivity and the reduced foil thickness allow to have a high electrical resistance and thus an elevated Joule power. The thickness homogeneity was verified by checking the uniformity of the heated foil temperature by means of an infrared camera. The thermal gradient across the foil thickness is expected to be negligible, since the Biot number Bi characterizing the thermal resistance of the foil by comparison to the thermal resistance of the flow is very small. For a high heat transfer coefficient $h = 6000$ W/m^2/K, $Bi = he_w/\lambda_w = 0.018$, e_w being the foil thickness. The thermal gradient across the metal foil has also been calculated by one-dimensional transient conduction equation using the software *COMSOL Multiphysics*. The results show that the temperature difference is less than 0.05 K. In the following the wall temperature measured by the Infrared camera at the backside of the metal foil will be considered equal to the temperature of the wall in contact with the fluid. Moreover, the foil-thickness diffusion time, 0.6 ms, is actually small enough to assume that there is no time lag between the thermal evolution of the outer and inner wall. Thus, it is possible to measure the temperature of the wall that is in contact with the air, in order to know the temperature of the wall that is wetted. The metal half-cylinder is glued to two lateral quartz glass plates (3 mm thickness, 42 mm width, 200 mm length). The plates, together with the foil, are placed in an aluminum cell. In this cell, a visualization box is created in order to reduce optical distortions. This box is also filled with HFE7000. There are windows on the back of the aluminum cell; they allow the electrical connections and the visual access to the metal foil from the backside. A special attention is paid to the electrical connections, as the contact resistance must be minimized.

The electrical power that is dissipated in the foil is in average 85% of that of the whole system, including also electrical connections and connection cables. The electrical power is provided by a power supply *SORENSEN SGA*. It covers the 0–40 V voltage range and the 0-250 A current range. It can be used even at very low power, since it can supply even tension and current close to zero. The power supply is driven by an arbitrary generator where all



(a) *cross section* (b) *side view of the metal foil and glass tube*

Fig. 1. Test section.