

## Experimental thermal-hydraulic study of a steam-droplets flow inside a vertical pipe during the cooling phase in LOCA conditions – effect of the steam flow rate

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### Abstract

This study concerns the cooling capacity of a high-temperature vertical pipe by a two-phase flow of superheated steam and droplets under Loss of Coolant Accident (LOCA) conditions. In order to characterize the cooling capacity, an experimental set-up was developed. The heat flux removed from the wall during the cooling phase is investigated with the use of infrared thermography (IRT) while, simultaneously, the droplet diameter and velocity are characterized by a Phase Doppler system. In parallel, measurements of Laser Induced Fluorescence (LIF) are performed to obtain the mean droplet temperature. The present paper regards the influence of the inlet steam flow rate for a representative non-deformed nuclear core geometry at sub-channel scale. In general, rewetting occurs from bottom to top in the tube, starting early with the increase in the steam flow rate. As expected, during the Leidenfrost regime, the heat transfer is enhanced when increasing the steam flow rate. Finally, smaller droplets have higher velocities and the droplets temperature does not increase significantly from up- to downstream.

### Introduction

During a Loss of Coolant Accident (LOCA) in a Pressurized Water Reactor (PWR), caused by structural failure or a leakage on the primary circuit, partial or even complete drying of the fuel assemblies may occur. In these conditions, the fuel temperature can increase up to 1200°C leading to a significant deformation and rupture of the fuel rod cladding. During the reflooding phase, water is injected through the assemblies in order to cool down and to preserve the core reactor. A two-phase flow composed by superheated steam and dispersed droplets is created because of the strong evaporation beyond the quenching front. One of the main safety issues is to estimate the capacity of the two-phase flow to cool down the fuel assemblies during the reflooding phase.

The cooling capacity during this phase depends mainly on geometrical characteristics and on the inlet thermal-hydraulic conditions (Grandjean 2007; Repetto *et al.* 2015). We can find many examples of experiments performed in the test aiming to describe the thermal-hydraulics of the cooling phase (Cho *et al.* 2011; Dunand *et al.* 2013; Jin *et al.* 2018). However, performing tests with real-like geometries and in real LOCA condition (as in-pile experiments) can be either unfeasible or dangerous. Therefore, analyses to guarantee nuclear safety during LOCA are mainly based on numerical simulation using mechanistic models. Although there are several models available in the literature (Guo and Mishima 2002; Sun *et al.* 1976), experimental data to validate them are still necessary, especially focused on the two-phase flow characteristics linked to the wall temperature decrease.

Typical characteristics of the two-phase flow in LOCA conditions are (Kim *et al.* 2017; Lee *et al.* 1984; Ruyer *et al.* 2013):

- Droplets temperature: close to saturation;

- Droplets size: 50 – 1000  $\mu\text{m}$ ;
- Volumetric fraction of liquid:  $10^{-4}$  –  $10^{-2}$   $\text{m}^3_{\text{d}}/\text{m}^3$ ;
- Steam temperature: up to 800 °C;
- Stem pressure: up to 3 bar;
- Wall temperature: 300 – 1200 °C;
- Wall emissivity: 0.5 – 0.8.

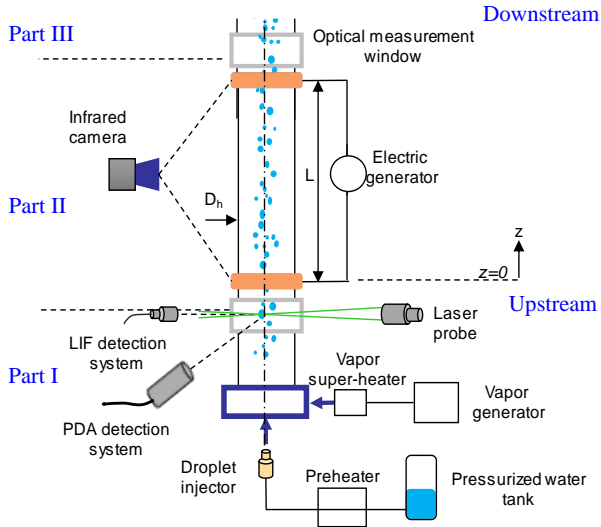
Complying these requirements, a new set-up has been built in order to estimate heat and mass transfers at a sub-channel fluid scale close to real LOCA conditions. The goal of the present paper is to investigate the cooling process of a vertical pipe with an internal two-phase dispersed flow of steam and droplets, representative of LOCA conditions at the sub-channel scale. The influence of the steam flow rate is analyzed by estimating the heat dissipated by the internal flow and by measuring the droplets characteristics.

### Experimental set-up

Figure 1 presents a schematic diagram of the experimental set-up COLIBRI (COoLing of Blockage Region Inside a PWR Reactor) which consists of a test section, a droplet liquid supply system and a superheated steam supply system. This apparatus is the same as used in previous work (Peña Carrillo *et al.* 2018).

The test section is made of Inconel-625 and divided into three parts: Parts I and III are fixed tubes with a thickness of 0.57 mm and internal diameter  $D_i$  of 11.78 mm, which corresponds, respectively to a typical rod clad thickness and to a hydraulic diameter of a non-deformed PWR sub-channel. Part II has an axial length  $L$  of 170 mm and the thickness and the internal diameter are the same as Parts III and I for the present study. A dispersed two-phase flow of water steam and water droplets is supplied upstream Part I of the test section. A steam generator and a super-heater (AURA ®) provide the water vapor at temperatures up to 200°C and a maximum flow

rate of 10 kg/h. Meanwhile, a piezoelectric injector (FMP Technology ®) produces the droplets of the dispersed flow with sizes up to 500 µm and a maximum flow rate of 2 kg/h.



**Figure 1:** Schematic diagram of COLIBRI experimental set-up

Optical measurements accesses are placed upstream and downstream Part II to measure the droplet characteristics. Their diameter and axial velocity are measured using a Phase Doppler Analyzer (PDA, Dantec Dymanics®), including a PDA reception optics and a P80 signal processor. An LDA transmitter probe (Dantec-Dynamics Fiber Flow®) generates the laser excitation volume with the green line (wavelength of 514.5 nm) of an argon-ion laser. The structure of the PDA-system used in the present work allows us to measure droplets diameters up to 300 µm with an uncertainty of 10%. The uncertainty of the droplets axial velocity is 5%.

Meanwhile, the droplets mean temperature is measured with Three-color Laser Induced Fluorescence (3cLIF) thermometry, which works due to the dependence on temperature of a fluorescent dye dissolved in water. The concentration of this dye is  $5 \cdot 10^{-6}$  mol/l, hence it has little influence on water properties. One great advantage of using 3cLIF in the present work is the possibility to measure the droplets temperature considering the effect of the droplets diameter by the use of fluorescence ratios (Labergue *et al.* 2010, Labergue *et al.* 2012). The uncertainty of the 3cLIF technique is not evident, depending on the uncertainties of the fluorescence ratios, but also on calibration parameters and on the number of collected droplets. In the present work, the statistical error of the fluorescence ratios is 1%, which leads to a droplet temperature uncertainty of  $\pm 5$  °C.

Infrared thermography (IRT, IR camera CEDIP ®) is performed in order to measure the wall temperature at the outer surface of Part II. Although the tube is 170 mm long, only the central 100 mm length were considered to eliminate the effect of the copper electrical contacts, which act as heat sinks. Since the tube is thermally thin ( $Bi \ll 1$  for all the test cases), we can consider the tube temperature  $T_w$  as uniform in the radial direction. Performing an energy balance on an axial element of the tube at a position  $z$  and time  $t$ , we can estimate the heat flux dissipated by the steam-droplets flow during the cooling phase

$\varphi_{int}$ :

$$\varphi_{int}(z, t) = - \left( \frac{S_t \rho_w c_{p,w}}{\pi D_{int}} \right) \frac{dT_w(z, t)}{dt} - \left( \frac{D_{ext}}{D_{int}} \right) \varphi_l(z, t) \quad (1)$$

where  $S_t$  is the tube cross-sectional area,  $\rho_w$  and  $c_{p,w}$  are, respectively, the density and the specific heat of the tube material,  $D_{int}$  and  $D_{ext}$  are the tube internal and external diameter, and  $\varphi_l$  is the heat loss to the environment by radiation and natural convection. The uncertainty of the temperature measurement is  $\pm 5$  °C, and of the estimated internal heat flux is  $\pm 10\%$

Part II is heated by Joule effect with the use of a 3,3 kW DC power source (TDK lambda ®) until an initial temperature of about 600°C. Once this temperature is reached, the power source is turned off and the cooling phase starts and the tube temperature and the droplets size and velocity are measured simultaneously with IRT and PDA, respectively. The droplets mean temperature up- and downstream is measured by 3cLIF thermometry before the cooling phase only.

## Results and Discussion

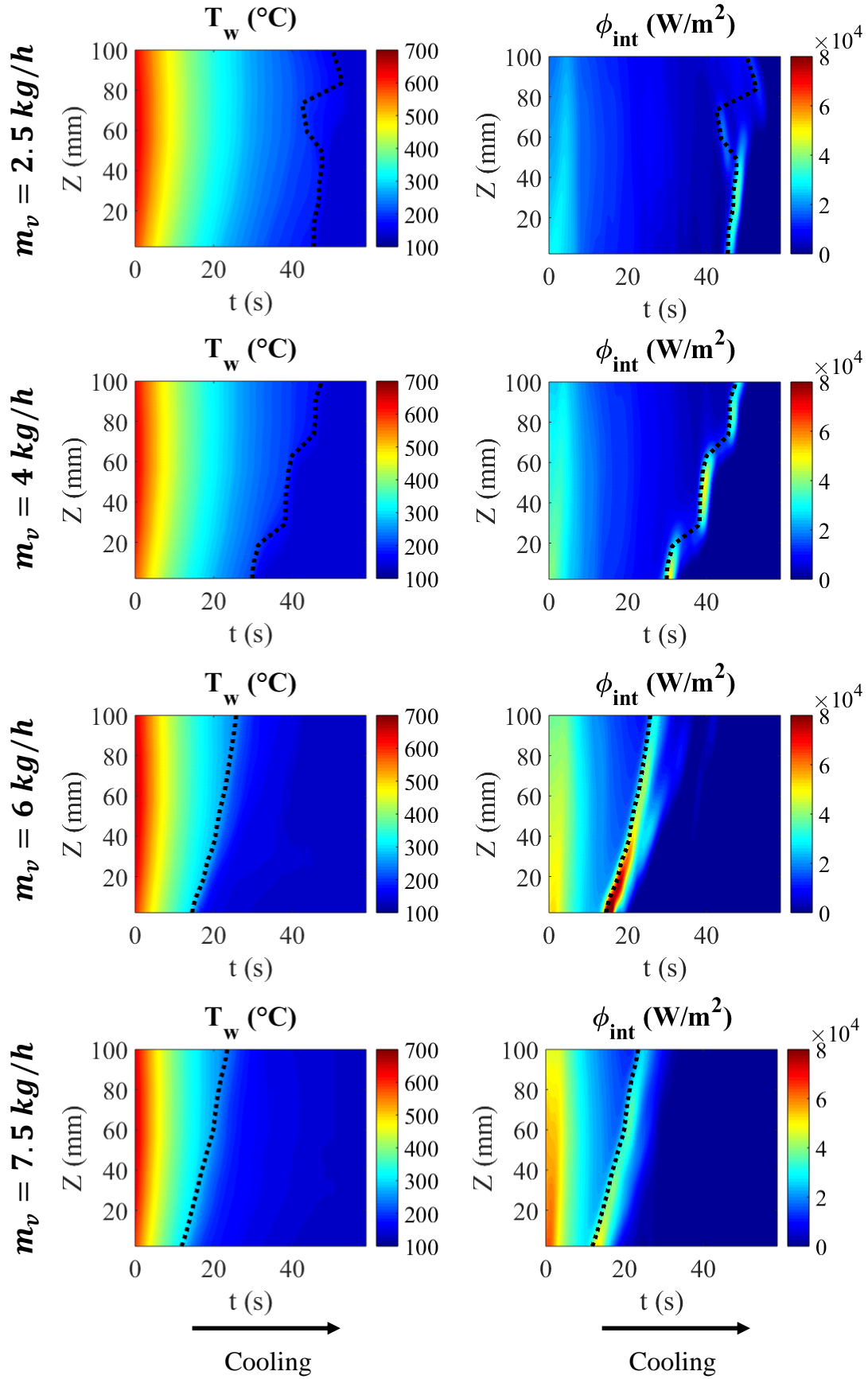
Table 1 shows the tested configurations upstream part I for a droplet flow rate of 0.8 kg/h and a droplet temperature of 62°C at the injection. Mean droplet measurements upstream of Part II using PDA are also presented.

**Table 1:** Configurations tested in the present study and droplets characteristics upstream of Part II.

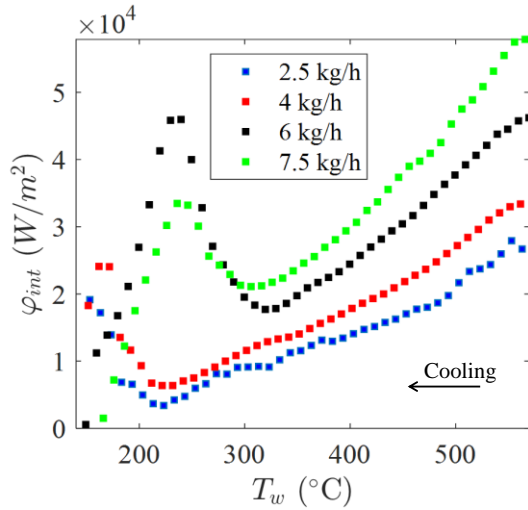
Steam flow rate (kg/h)	Steam temperature (°C)	Mean droplet velocity (m/s)	Mean droplet size, $d_{10}$ (µm)
2.5	155	11.5	84
4	165	14.5	109
6	190	23	98
7.5	195	30	100

Figure 2 presents spatiotemporal maps of the tube temperature and the heat flux dissipated by the internal two-phase flow by the use of Equation 1. The dashed line on the maps indicates the position of the rewetting front, where the droplets impinge onto the wall and wet it, increasing the heat transfer and sharply reducing the wall temperature. We can see that rewetting occurs generally from bottom to top. With the steam flow rate of 2.5 kg/h, rewetting began almost instantaneously at the bottom and in the middle of the tube, rapidly spreading to all over the length. Furthermore, we can see rewetting occurs earlier with higher steam flow rates.

By taking temperature points in the map in Figure 2 and finding their correlated internal heat flux, we can plot a mean boiling curve for each steam flow rate, as presented in Figure 3. For all the cases, the cooling starts in the Leidenfrost regime and finishes in the nucleate boiling regime and conjugated convection. We can observe that the heat flux increases with the increase in the steam flow rate during the Leidenfrost regime. The Leidenfrost temperature, the minimal point where rewetting occurs, increases with the higher steam flow rates. This behavior could be related to the fact that the kinetic energy of droplets impinging the wall increases with the higher steam velocity and, consequently, the Leidenfrost temperature increases (Dunand *et al.* 2013).

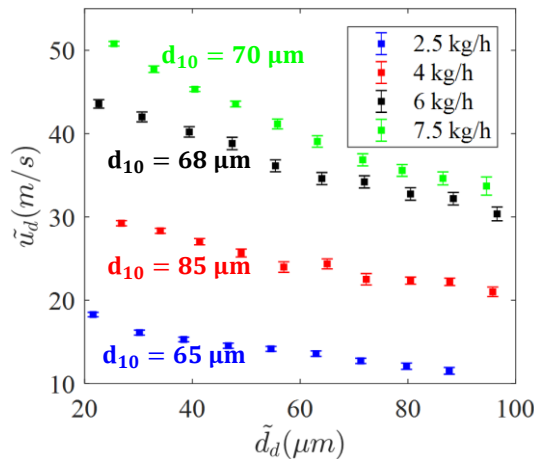


**Figure 2:** Spatiotemporal maps of temperature and heat flux dissipated by the internal two-phase flow for each steam flow rate, and the evolution of the rewetting front (dotted line)



**Figure 3:** Heat flux as a function of the wall temperature.

Figure 4 shows the mean droplet velocity downstream of Part II as a function of droplet size for the four configurations. For a better comparison, these results are for the period of time when the mean axial temperature of the wall was within the range of  $400^{\circ}\text{C} < \bar{T}_w < 500^{\circ}\text{C}$ . This correlation of droplets characteristics and wall temperature is possible due to the synchronized measurements of IRT and PDA. As expected, the droplet velocities increase with the steam flow rate. For all the cases, the velocity of smaller droplets is higher than the larger ones. Moreover, droplet velocities downstream are higher than values upstream in Table 1 due to the increase in the steam temperature along the tube, hence decreasing the steam density and producing an acceleration of the flow. Mean droplet sizes ( $d_g$ ) are between 23% and 30% smaller downstream of the tube due to evaporation.



**Figure 4:** Droplet velocity downstream as a function of the droplet size for the wall temperature range of  $400^{\circ}\text{C} < \bar{T}_w < 500^{\circ}\text{C}$ .

As mentioned before, 3cLIF measurements were performed before starting the cooling phase up- and downstream Part II. Although the results show slight heating of droplets about  $3^{\circ}\text{C}$  (Table 2), this difference is still within the uncertainty of the technique. The mean droplets temperature seems to not change significantly with the steam flow rate.

**Table 2:** Mean droplet temperature upstream and downstream part II using LIF technique.

Steam flow rate (kg/h)	Mean droplet temperature upstream ( $^{\circ}\text{C}$ )	Mean droplet temperature downstream ( $^{\circ}\text{C}$ )
2.5	81	84
4	79	82
6	80	85
7.5	82	85

## Conclusions

A new experimental set-up was built focused on the characterization of two-phase flows at a sub-channel scale to study a LOCA. Using specific optical techniques such as LIF, PDA and infrared thermography, it is possible to characterize wall-to-fluid heat flux, as well as droplet characteristics during the cooling transient phase. These experimental data are useful for further validation of mechanistic models to estimate heat transfer in the dispersed flow regime during LOCA. The main findings are:

- Wall rewetting starts from bottom to top in the tube and it occurs earlier with higher steam flow rates;
- The Leidenfrost temperature is higher for higher steam flow rates due to an increase in the droplets kinetic energy;
- The droplets diameter is reduced by 23% to 30% downstream the heating tube compared to upstream values because of evaporation;
- The droplets velocity is higher downstream the test section due to an acceleration of the steam flow;
- And the droplets mean temperature is not significantly changed from up- to downstream of the tube.

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