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Experimental and numerical thermal-hydraulics study of a steam-droplets flow in a venturi-type vertical tube with flow deviation - application to LOCA in PWR reactor

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Abstract

During reflooding after a hypothetical loss of coolant accident (LOCA) in a pressurized water reactor (PWR), a flow of steam and dispersed droplets forms and propagates in the assemblies. During the accident, rods can be deformed and ballooned, thus reducing the hydraulic diameter of some sub-channels. In this scenario, the rods' cooling may be affected since the steam will be diverted to less blocked sub-channels. For security reasons, the characterization of heat transfers in these areas is important to know in order to well evaluate the consequences of such an accident (meltdown of the core). This study is dedicated to the estimation of heat and mass transfers in these blocked zones

Introduction

After a LOCA, water is injected into the reactor plenum to limit the accident consequences. During the core reflooding, a dispersed flow film boiling (DFFB) regime forms downstream of the quenching front due to the contact of cold water with the rods at high temperatures. This DFFB flow serves to cool the rods that are not yet in direct contact with the water. However, this DFFB flow is well known, the characterization of heat and mass transfers is complex, due to various phenomena such as droplets fragmentation, coalescence and evaporation, poly-disperse droplet distribution, droplets impact, turbulence, non-thermodynamic equilibrium between phases, and radiation (Jin et al. 2018). Also, depending on the severity of the accident, the nuclear rods can deform, blocking some sub-channels, i.e. reducing the passage area of the refrigerant fluid. In these cases, the steam formed in the quenching front will be diverted to less blocked areas, decreasing the steam/wall convection in blocked sub-channels. Oliveira et al. (2020) found that the blockage ratio is the predominant parameter in the fluid deviation in a bundle with blocked sub-channels, being proportional to the blockage ratio. This blockage ratio (τ_b) is a parameter used to characterize the reduction in the cross-section due to the deformation of the cladding in a LOCA; defined as the ratio of the sub-channel area lost after deformation to the area of an intact sub-channel.

To characterize all heat and mass transfers phenomenon, an experimental bench, called COLIBRI, was built. COLIBRI allows to determine the heat flux released by a steam/droplets flow on the scale of an intact or partially

blocked sub-channel ($\tau_b=61\%$ and 90% , with and without steam deviation) under typical thermal-hydraulic conditions of a LOCA (Peña Carrillo et al. 2019). On the other hand, a code named NECTAR was developed with the aim of calculating heat and mass transfer phenomena from a mechanistic point of view, as well as the dynamics of droplets considering a polydispersed flow.

The purpose of this work is to compare the experimental heat flux extracted by the steam flow with dispersed droplets in a representative partially blocked sub-channel ($\tau_b=61\%$ and 90%) with steam deviation and an undamaged representative sub-channel COLIBRI bench. Moreover, the contribution of each phenomena is determined using models available in the literature and used in the DRACCAR code. At the end, the accuracy of DRACCAR code will be evaluated, especially the heat fluxes due to droplets' impact. Indeed, the droplets' model impacts work well for an intact sub-channel at a very low concentration of droplets but it has to be validated for higher concentrations.

Experimental Facility

The COLIBRI test section (Fig. 1) is divided into three parts: 1) the superheated steam and droplet injector followed by a stainless steel section (up to the first optical window) with a steam bypass, 2) a removable Inconel 625 tube that allows testing two values of blockage ratios ($\tau_b= 0, 61\%$ and 90%). This part is heated by Joule effect and its external wall temperature is measured by an infrared camera. These tubes have the same hydraulic diameter of zones of interest (intact or blocked) and a steam deviation system located upstream

Table 1

T_v (°C)	\dot{m}_v (kg/h)	\bar{u}_d (m/s)	d_{10} (μm)	τ_b
460	3.54	11.5	195	0%
469.5	3.95	13.2	219	61%

of them governs the steam flow which is supposed to enter the zones as in a real situation.

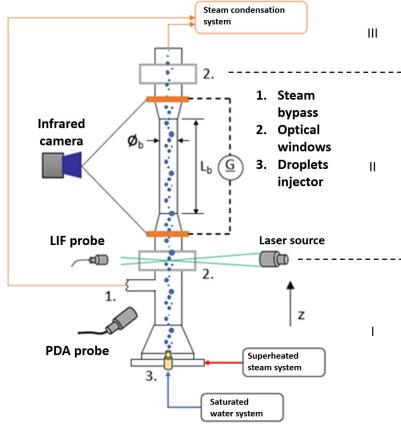


Figure 1: Schematic design of COLBRI experimental bench.

Borosilicate optical windows upstream and downstream of the test section allow the use of optical techniques. The droplets' diameter and velocity are measured by Phase Doppler Analysis (PDA) and their average temperature by laser-induced fluorescence (LIF) (Peña Carrillo et al. 2019).

Results and Discussion

Table 1 shows two tested configurations upstream part I for a droplet flow rate of 7.5 kg/h at saturation temperature. Inlet mean droplet measurements using PDA are also presented, but other results will be presented at the conference.

The heat flux released from the wall by the internal flow is calculated from a heat balance based on the spatial-temporal decrease of the tube temperature, measured with the infrared camera and deducting the estimated losses with the environment. Fig. 2 shows the heat flux found experimentally for the intact sub-channel ($\tau_b=0\%$) without deviation and a for the partially blocked sub-channel ($\tau_b=61\%$) with a deviation of 69% of the steam (only 31% of the initial steam flow enters the tube). Only the film boiling zone is represented as it is the most critical phase during the rods cooling.

From the results it can be seen that the steam bypass generated a decrease in heat transfer, however this decrease is not proportional to the steam flow deviation. A more in depth analysis will be presented in the final article, where the total internal heat dissipation and the contribution of the different heat transfer mechanisms are analyzed with the aim of a mechanistic model. In particular, the simulation with NECTAR code shows that the droplet impacts on the wall contribute more to the total heat transfer than the steam convection and the wall when the steam is deviated (Fig. 3).

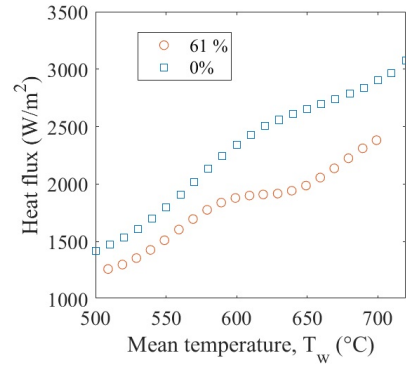


Figure 2: Heat flux as a function of the wall temperature.

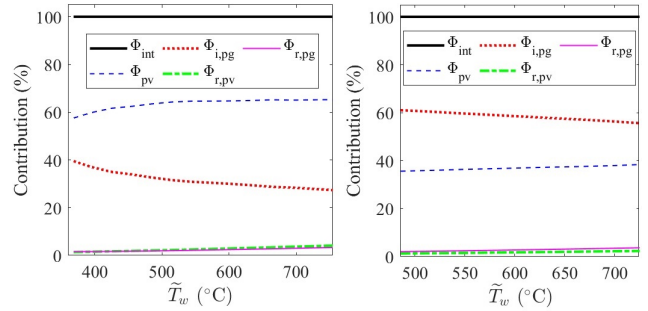


Figure 3: Contribution of each heat transfer mechanism (Φ_i : droplets impact, Φ_{pv} : wall/steam convection).

Conclusion

In this work, a comparison between the experimental results of the COLBRI experimental bench on the heat transfers in a DFFB regime that takes place in a representative partially blocked and intact tube of a PWR subchannel was carried out. This comparison shows a decrease in the heat extracted when the steam is diverted in a partially blocked sub-channel. In the same way, the droplets' importance in the cooling of the partially blocked sub-channels was evidenced, partially compensating for the decrease in the heat extracted by the steam after having been deviated. However, there are phenomena that have not yet been integrated into the numerical code which are important to take into account, and they are mainly the coalescence of droplets and the possible change in flow regime when the steam deviation is considerable.

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