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Modelling of debris bed reflooding in PEARL experimental facility with MC3D code

Janez Kokalj[a,b,*], Mitja Uršič[a], Matjaž Leskovar[a], Libuse Piar[c], Renaud Meignen[c]

[a] Jožef Stefan Institute, Jamova cesta 39, SI-1000 Ljubljana, Slovenia
[b] University of Ljubljana, Kongresni trg 12, SI-1000 Ljubljana, Slovenia
[c] IRSN (French Nuclear Safety Institute), Cadarache Nuclear Center, BP 3, 13115 Saint-Paul-lez-Durance, France

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ABSTRACT

A hypothetical severe accident in a nuclear power plant has the potential for causing severe core damage, including a meltdown. To prevent or in the case of an already formed debris bed to limit the in-vessel core degradation, the basic severe accident management strategies consider the in-vessel reflooding to ensure the debris bed coolability.

The purpose of our research was to understand the key processes and conditions related to the in-vessel debris bed coolability in the bottom reflooding conditions. Recently, experimental tests in the PEARL facility (IRSN, France) were performed to highlight the behaviour of the steam and water flow in a hot porous medium and to provide experimental data to validate 2-D and 3-D models for the debris bed reflooding. Our aim was to analyse chosen PEARL experiments performed at the atmospheric pressure. The objective was to analyse the importance of the uncertainties in the initial and boundary conditions on the simulation results and to assess the heat transfer modelling approaches. Simulations were performed using the MC3D code (IRSN, France).

In general, the performed simulations are in good agreement with the experiments. The general features, in particular the water preferential entrainment in the bypass are recovered and the analysis of calculation gives further information on the mechanisms. In particular, the mechanism of water deviation in the bypass (2-D behaviour) is described. The hypothesis of water dragged by steam coming from the debris bed region cannot be supported. However, the simulation results are indicating a noticeable impact of the actual conditions as the water temperature and the initial support bed and bypass temperature. The simulations, varying the porosity of the test section, showed that this impact affects the flow configuration and is important for cases with the 2-D configuration. The reflooding capabilities in this configuration may depend strongly on the characteristics of the debris bed. Changes in the heat transfer modelling do not have greater effect on the simulation results.

1. Introduction

During a hypothetical severe accident in a nuclear power plant a reactor core degradation might occur. A debris bed may be formed as a consequence of the core deformation or when the already melted core drops into the water (Magallon, 2006). Severe accident management strategy (SAMG) procedures have been developed to mitigate the consequences of such events. The primary aim of the SAMG procedures is to maintain the integrity of the fission product barriers. An important barrier is the reactor vessel and maintaining its integrity is possible only if the core material is coolable. Therefore, the SAMG procedures consider the in-vessel reflooding. Due to the porosity, which allows easier coolant intrusion, the debris bed provides greater chances for cooling than a pool of molten corium. In the case of not sufficient cooling, with the continuation of the accident scenario the melting of the degraded reactor core and its relocation to the lower reactor vessel plenum occurs. To prevent the ex-vessel melt release, the in-vessel melt retention strategy could be applied.

The debris bed coolability was recognized as an important nuclear safety issue in the frame of the EU SARNET-2 (Severe Accident Research NETwork of Excellence) program (Pohlner et al., 2014). In the EU SARNET-2 program the debris bed formation due to the fuel-coolant interaction and the coolability of the formed debris bed were analysed. The purpose of our research is to understand the in-vessel debris bed coolability during the bottom reflooding.

Several experiments on the debris bed coolability in the bottom reflooding conditions were performed. Tutu et al. (1984a,b) performed a bottom reflooding experiment with a preheated homogeneous test

* Corresponding author at: Jožef Stefan Institute, Jamova cesta 39, SI-1000 Ljubljana, Slovenia.
E-mail address: janez.kokalj@ijs.si (J. Kokalj).

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section containing 18 kg of debris. The purpose of the experiments was to validate the analytical models. In the performed experiments, quenching of superheated debris bed was observed and the advantage of the bottom reflooding over the top reflooding due to the increased heat flux was recognised. Next, Wang and Dhir (1988) performed an experiment with the bottom reflooding of 71 kg of debris in a homogeneous geometry, which was heated by induction. It was found that an increased pressure drop across the debris bed increases the multi-dimensional effects and reduces the quenching time. Further, in the DEBRIS experimental facility at IKE, Germany (Chikhi et al., 2014; Leininger et al., 2014; Schäfer et al., 2006; Starflinger et al., 2015), bottom and top reflooding were performed. Because of the uniform debris bed, the bottom reflooding was clearly one dimensional across the whole debris bed section. In the POMECO experimental facility at KTH, Sweden (Chikhi et al., 2014; Kazachkov and Konovalikhin, 2002; Nayak et al., 2006), the bottom reflooding was simulated with the downcomers, which significantly enhance reflooding of the debris bed compared to the only top reflooding.

Under the PROGRES research program experiments are being performed at the PRELUDE and PEARL facilities at IRSN, France (Bachrata et al., 2013; Chikhi et al., 2014; Chikhi and Fichot, 2017; Fichot et al., 2012; Pohlner et al., 2014; Repetto et al., 2013). The PROGRES experimental program was launched to highlight the behaviour of a steam and water flow in a hot porous medium and to provide experimental data to validate the 2-D and 3-D models for the debris bed reflooding (IRSN Research programs, 2016). The PROGRES experimental program is used to investigate the phenomena and consequences of the water reflooding of simulated damaged reactor core, when most of it had been collapsed and had formed a debris bed. The PEARL facility is with 500 kg of debris devoted to the bottom and top debris bed reflooding on a large scale. In contrast to the most of the earlier experiments where the test sections were homogenous, the PEARL test section consists of different zones, allowing investigating the effect of differences in geometry. Chikhi and Fichot (2017) presented the main results of some of the PEARL reflooding experiments and developed an analytical model, which takes into account the deviation of water from central debris bed into the bypass. The effect of the bypass and two-dimensional reflooding in the PEARL experiments were also analysed with numerical simulations using the ICARE-CATHARE code (Chikhi et al., 2017).

To describe the general features of the debris bed reflooding phenomena computer codes were developed, including MEWA from IKE, DECOSIM from KTH, CORIUM-2D from RSE, Italy, and PORFLO from VTT, Finland (Parozzi et al., 2010; Pohlner et al., 2014). Recently, the MC3D code from IRSN was upgraded to enable the debris bed coolability modelling (Raverdy et al., 2017). The MC3D code is devoted to the multiphase flow simulations in thermal-hydraulics and nuclear safety studies (Meignen et al., 2014). Its major use is in the fuel-coolant interaction phenomena evaluation. The applicability of the MC3D code to simulate the cooling of a debris bed was already demonstrated with some first simulations of the PEARL experiments (Raverdy et al., 2017). The analysis of performed simulations have shown an important role of the bypass at high injection velocity and high initial bed temperature on the water and steam flow path and reflooding time. Some general trends of validation of the MC3D code may also be found in Mutelle et al. (2017). Although there are various uncertainties for modelling, namely the role of interfacial frictions between water and steam, and the precise heat and mass transfer mechanisms, the results obtained are considered as sufficient, first, for explaining the general features of the flow, second, in regards of the general high uncertainties during a severe accident and debris bed formation.

The purpose of the paper is to analyse with the MC3D code the debris bed bottom reflooding experiments at atmospheric pressure performed in the PEARL facility. Our aim is to analyse the flow in the 2-D porous debris bed with bypass. Further, our aim is to perform a complementary validation of the MC3D code, to give insights into the effect of different experimental conditions on the results and to analyse the effect of potential uncertainties of the experimental conditions on the simulation results.

2. PEARL experiment

In the PEARL experiments performed in frame of the PROGRES campaign n°1, the effects of initial debris bed temperature, inflow water velocity and pressure were investigated (Chikhi and Fichot, 2017). In this paper, the focus is only on the experiments performed at the atmospheric pressure.

In this section, the experimental setup and the experimental findings are briefly reminded.

2.1. Experimental setup

In the PEARL experiments, the test section consisted of a vertical tube with internal diameter 540 mm and length of 2.6 m (Chikhi and Fichot, 2017). As sketched in Fig. 1, the debris bed with diameter of 450 mm and height of 500 mm consisted of stainless steel balls with diameter of 4 mm. Quartz balls with diameter of 8 mm supported the steel debris bed. Below as well as above the debris bed was a layer of quartz balls of 100 mm and 50 mm, respectively. The steel debris bed was enclosed with a 45 mm layer of quartz balls, simulating the less degraded core parts.

In the PEARL experiments, first, the test section was preheated with a steam flow to the saturation temperature. In the second phase, an induction technic was used to heat the steel debris bed to the desired temperature. After that, the heating was stopped and the water injection started from the bottom. When the water level reached the debris bed, the heating of the steel debris bed was started again to simulate the decay heat. The experiments stopped when the entire temperature of the debris bed was below the saturation temperature. It was noticed that, due to the heat conduction, the quartz balls in the bypass were also initially heated. The actual mean temperature of the bypass is not known with precision in the presented experiments, but the energy contained in the bypass could be estimated to be up to nearly 30% of the total energy to be extracted (neglecting the energy of the quartz

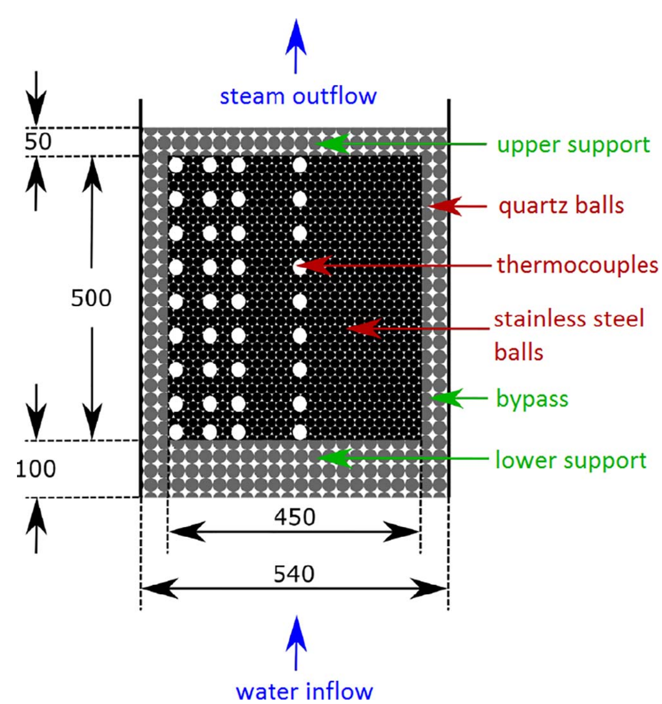

Fig. 1. Schematic presentation of test section of PEARL experiment (PROGRES campaign n°1) with measures in mm.