Modelling of Debris Bed Collability in Bottom Reflooding Conditions with MC3D Code

Janez Kokalj
Jožef Stefan Institute
Jamova cesta 39
SI-1000 Ljubljana, Slovenia
janez.kokalj@ijs.si

Mitja Uršič, Matjaž Leskovar
Jožef Stefan Institute
Jamova cesta 39
SI-1000 Ljubljana, Slovenia
mitja.ursic@ijs.si, matjaz.leskovar@ijs.si

ABSTRACT

A hypothetical severe accident in a nuclear power plant has the potential for causing severe core damage, including meltdown. To prevent or in the case of 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. Due to the debris bed porosity, which allows easier coolant intrusion, the debris bed provides greater chances for cooling than a pool of molten corium. When the cooling is not sufficient, with the continuation of the scenario the degraded reactor core is melted and relocated to the lower reactor vessel plenum. To prevent the ex-vessel melt release the in-vessel melt retention strategy could be applied.

The purpose of our research was to understand the key processes related to the in-vessel debris coolability in the bottom reflooding conditions. First, the recently performed tests in the PEARL facility under the PROGRES experimental program (IRSN, France) are reminded. The PROGRES experimental program was launched to provide experimental data to validate 2-D and 3-D models for the debris bed bottom reflooding. Next, the modelling and analysis of some of the PEARL experiments using the MC3D code (IRSN, France) are described. The aim of the performed work was to analyse the uncertainties in the initial and boundary experimental conditions and to assess the hydrodynamic behaviour and heat transfer modelling approach in the MC3D code.

1 INTRODUCTION

During the course of a hypothetical severe accident in a nuclear power plant the reactor core degradation occurs and the debris bed is formed. The debris bed is less coolable than the intact reactor core. 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) programme [1]. In the EU SARNET-2 programme the ex-vessel debris bed formation due to the fuel-coolant interaction and the coolability of the formed debris bed were analysed. Currently, the in-vessel debris bed reflooding is also under investigation at international level in the IVMR (In-Vessel Melt Retention Severe Accident Management Strategy for Existing and Future NPPs) project in the frame of the EC Horizon 2020 [2].
The purpose of our research is to understand the in-vessel debris bed coolability in the bottom reflooding conditions. Several tests were performed, including experiments by Tutu et al. (BNL, USA) [3], in the PRELUDE and PEARL facilities (IRSN, France) under the PROGRES research program [1], [4], [5]. To describe the general features of the phenomena computer codes were developed, including MEWA (IKE, Germany), DECOSIM (KTH, Sweden), CORIUM-2D (RSE, Italy), PORFLO (VTT, Finland) and MC3D (IRSN, France) [1]. The MC3D code [6] was used to simulate the coolability of the formed debris bed in our work. The MC3D code was already validated on the PRELUDE, PEARL and Tutu et al. experiments [7], [8].

In the article the performed complementary analysis of the experiments from the PEARL facility is presented. The first objective is to analyse the PEARL experiments and describe their features. The second objective is to compare the PEARL experiments to determine the effect of the temperature of the debris bed on the reflooding. Besides the MC3D modelling of the PEARL experiments also the performed sensitivity study on the initial and boundary conditions and parameters of the physical modelling of heat transfer is presented.

2 PEARL EXPERIMENTS

The PROGRES experimental program was launched by IRSN, France, to provide experimental data for validation of 2-D and 3-D models of debris bed bottom reflooding [9]. It is used to investigate the phenomena and consequences of the water reflooding of damaged reactor core, when most of it had been collapsed and had formed a debris bed.

The test section consisted of a vertical tube with internal diameter 540 mm and length of 2.6 m. The debris bed with diameter of 450 mm and height of 500 mm consisted of stainless steel balls with diameter of 4 mm. The debris bed was supported by quartz balls with diameter of 8 mm. There were layers of 100 mm of quartz balls below the debris bed, 45 mm at the side of the debris bed and around 50 mm above the debris bed (Figure 1).

Figure 1: Schematic presentation of test section of PEARL experiment with measures in mm (left) and computational geometry with $23 \times 62$ cells (right).
In experiments, first, the test section was preheated with the steam flow to the saturation temperature. In the second phase induction was used to heat the debris bed to the desired temperature. After reaching the desired temperature, heating was stopped and water injection started from the bottom. When the water level reached the debris bed, heating of the 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.

During the experiments the temperature and pressure were measured at different positions. The rapid change of temperature measurements was used to determine the quenching front velocity in the debris bed and in the bypass. The steam flow was measured at the top of the test section. The initial and boundary conditions and the main results of experiments reported in [4] are summarized in Table 1.

Table 1: Initial and boundary conditions and main results of some PEARL experiments [4].

<table>
<thead>
<tr>
<th>initial and boundary conditions</th>
<th>PA_0</th>
<th>PA_1</th>
<th>PA_2</th>
<th>PA_4</th>
<th>PA_5</th>
</tr>
</thead>
<tbody>
<tr>
<td>debris bed temperature [K]</td>
<td>423</td>
<td>673</td>
<td>973</td>
<td>673</td>
<td>673</td>
</tr>
<tr>
<td>water velocity [m/h]</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>induction power [W/kg]</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>pressure [bar]</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>results</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>reflooding time [s]</td>
<td>108</td>
<td>240</td>
<td>490</td>
<td>440</td>
<td>185</td>
</tr>
<tr>
<td>steam production [kg]</td>
<td>11.2</td>
<td>30.7</td>
<td>59</td>
<td>44</td>
<td>27.6</td>
</tr>
</tbody>
</table>

3 SIMULATION WITH MC3D

Simulations of the experiments were performed with the MC3D version 3.8 code, which is devoted to the multiphase thermal-hydraulic flow studies and evaluations in the field of nuclear safety [6]. Its major use is in the evaluation of fuel-coolant interaction phenomena.

3.1 MC3D code

The MC3D code is an Eulerian code. For each component mass, momentum and energy equations are solved. Velocities are attributed to the cell boundaries and other variables to the cell centre.

The heat exchange models are based on the heat transfer models for a single drop. The heat transfer modelling also depends on a flow map, which is based on the relative volume fraction of gas and liquid. At low relative fraction (standard value 0.3) of gas the flow is considered as bubbly and the melt particles are in a direct contact with water or through the vapour film. At high relative fraction of gas (standard value 0.7), the flow is considered as gas with some liquid droplets and melt particles are in contact with the gas. In between is the transition flow.

Recently the MC3D code was upgraded to enable the debris bed coolability modelling. The debris bed is considered as a porous media. Several classical skin friction laws for porous media are available and where tested by IRSN. Those optimizing the results in the range of conditions expected in severe accident context were selected as the default laws. It was concluded that some parameters needed to be adjusted for debris bed. This concerns mainly the flow configuration and the bubble maximum size. As a consequence, a "debris zone" operator is introduced, used to define by the user the extent of the debris bed. With the “debris” zone operator, the bubbly and gas flow phases are limited with fixed relative fraction of gas of 0.1 and 0.9, respectively [8].
3.2 Simulation

As seen in Figure 1, simplified 2-D geometry was applied. The mesh was axial symmetrical and cylindrical coordinates were used. The radius of the mesh was 0.27 m and the height was 2 m to ensure that only steam is exiting the test section. The mesh size was 23×62 cells. A convergence analysis was previously conducted in [10]. The test section was divided into several zones. From height 0.1 m to 0.6 m and from radius 0 m to 0.225 m the debris bed zone was defined. In the debris bed zone the porosity was set to 0.4 and the balls with diameter of 4 mm were used. Additionally, the volumetric power was applied in the debris bed zone. At the same height at the outside of the debris bed zone the bypass zone was defined between radius 0.225 m and 0.27 m. In the bypass zone, the porosity was set to 0.4 and the balls with diameter of 8 mm were used. Below and 50 mm above the debris bed and bypass zones also support zones with porosity set to 0.4 and the balls with diameter of 8 mm were defined. Only steam was set above the height of 0.65 mm. Water with the temperature of 343 K was injected through the bottom boundary of the test section and the pressure was set at the top boundary. All the zones with balls were modelled by the “debris zone” operator, which is dedicated to the porous media. The stainless steel properties were used for the stainless steel balls in the debris bed and also for the quartz balls surrounding the debris bed. Namely, only one material can be modelled in the current version of the code. The initial and boundary conditions were the same as in the experiment (see Table 1). In the debris bed zone the initial temperature was set lower than in the experiment to consider the temperature increase due to the volumetric power. In the experiment the induction heating was turned on at the moment, when water reached the debris bed. But, in the MC3D simulation the volumetric power was used already at the beginning of the calculation. In the MC3D simulations, the quenching front propagation and the steam outflow were monitored up to the time when the debris bed zone was cooled down below 10 K above the saturation temperature. With reflooding, the temperature of the stainless steel balls falls rapidly to few degrees above the saturation temperature. The temperature of the balls in the bypass, upper and lower support zone was set to the value at which the available internal energy is the same as for the quartz balls at the saturation temperature (considering the specific heat).

3.3 Results for PA_1 experiment and discussion

The PA_1 experiment was chosen as the basic one because the temperature of the debris bed was between the bounding values (PA_0 and PA_2) and the water inflow velocity was between the PA_4 and PA_5 experiments. First, the main features of the PA_1 experiment were investigated.

In Figure 2 the reflooding of the test section is shown. In the simulation it takes 28 seconds for the water to reach the debris bed. At that moment, the lower support zone is not completely cooled down to the temperature of the incoming water. After reaching the debris bed the water starts to evaporate (in Figure 2 that can be seen as a section with lower liquid fraction). Hot steam also heats the upper support zone (in Figure 2 for time step at 100 s the debris bed is not enclosed with the green line – isotherm at 400 K, which indicates that the upper support zone has a temperature above 400 K). In the lower support zone, the water level rises evenly through the whole section. As the water reaches the hot balls in the debris bed zone, the produced steam and the difference in the hydraulic resistance push the water in the bypass. In the bypass, the balls have a lower temperature and their diameter is twice of the diameter of the balls in the debris zone. The bypass is the preferential path for both water and steam. At the end, it can be observed that the preferential path for steam (red arrows in Figure 2) is changed, because the path directly upward is significantly shorter than the path through
the bypass [4]. Although the water floods the bypass faster than the debris bed zone and some water flows through the bypass above the upper support zone, no reflooding of the debris bed zone from the top can be observed.

Figure 2: Time sections of reflooding simulation for PA_1 case.
3.4 Analysis of initial and boundary conditions and modelling approaches

Because of the uncertainty of exact initial and boundary conditions (temperature gradient in the bypass and temperature of the incoming water at the debris bed entrance) an sensitivity analysis of initial and boundary conditions was made for the PA_1 case. The considered cases are shown in Table 2. In the “T quartz +” case the temperature of the balls in the bypass zone and in the lower and upper support zones was raised. In the experiment, the zones were heated with steam, but some additional heat transfer from the balls in the debris bed zone with conduction might have occurred. The temperature of the quartz balls was specified as the average between the temperature of the balls in the debris bed and the saturation temperature. The temperature of the stainless steel balls in the bypass zone and in the lower and upper support zones was set according to the available internal energy. In the “T water +” and “T water -” cases the temperature of the incoming water was raised or lowered for 30 K respectively.

In the MC3D code the physical models for heat transfer for a single droplet is used. In porous media, such as the simulated one, the heat transfer might be different. Therefore the “h -” case with the halved and the “h +” case with the doubled heat transfer coefficients for convection and conduction between the melt droplet and surrounding were performed (Table 3).

Table 2: Table of initial and boundary conditions for sensitivity analysis.

<table>
<thead>
<tr>
<th>case</th>
<th>T bypass [K]</th>
<th>T water [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>basic</td>
<td>359</td>
<td>343</td>
</tr>
<tr>
<td>T quartz +</td>
<td>440</td>
<td>343</td>
</tr>
<tr>
<td>T water +</td>
<td>359</td>
<td>373</td>
</tr>
<tr>
<td>T water -</td>
<td>359</td>
<td>313</td>
</tr>
</tbody>
</table>

Table 3: Table of parameters in physical models of heat transfer.

<table>
<thead>
<tr>
<th>case</th>
<th>heat transfer coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>basic</td>
<td>1</td>
</tr>
<tr>
<td>h -</td>
<td>0.5</td>
</tr>
<tr>
<td>h +</td>
<td>2</td>
</tr>
</tbody>
</table>

In Figure 3 the steam flow rate and the integral mass of steam for the simulation of the PA_1 experiment are shown. To compare the integral mass of steam, the end of the simulation in the experiment was determined from the graphs as the point where the steam flow rate falls drastically and the graph of the integral mass of steam breaks. The case “basic” is compared with the cases of the analysis of the initial and boundary conditions and the analysis of the physical modelling. The changed initial and boundary conditions have a larger effect on the results than the varied parameter in the physical models.

As seen in Figure 3, increased water temperature (“T water +”) or temperature of balls in the bypass (“T quartz +”) increase the steam flow rate and extend the reflooding time (steam flow rate decreases about 20 s later than in the “basic” case). Extended time of reflooding occurs due to the increased evaporation of water. Because more water evaporates, it takes longer for the water to fill the test section. The increased steam flow rate for the “T quartz +” case can be explained with the higher internal energy of the bypass zone. As seen in the first half of the simulation, when the bypass zone is being reflooded, the steam flow rate is more significant for the “T quartz +” case than for the “basic” case. In the “T water +” case the increase in the steam flow rate is due to the higher internal energy of the incoming water and consequently less energy is needed to evaporate (because the incoming water in the “T water +” case is at the saturation temperature, no energy is needed for heating). In the “T water -” case the results are the opposite as in the “T water +” case. The steam flow rate is reduced and the time of reflooding is shortened. Both can be explained with the lower internal energy of water. The initial temperature of water in the “T water -” case is
60 K below the saturation temperature. Consequently more energy than in the “basic” case is used for heating the water to the saturation conditions, before it can evaporate.

As seen in Figure 3, the analysis of the parameters in the physical models of heat transfer shows smaller dependency of the steam flow rate on the heat transfer coefficient. In the “h -” case the heat transfer coefficient is halved and the transients in the steam flow rate are smoother. At the end of the simulation the steam flow rate declines slower comparing to the “basic” case. The smoothing of the transients was expected because the heat transfer rate from the balls is smaller. On the opposite, the “h +” case with the doubled heat transfer coefficient shows faster transients of the steam flow rate. The steam flow rate maximum at the end of the simulation is higher than in the “basic” case and the decline is faster.

The comparison of the reflooding time in the simulation with the experimental one (Table 4) shows a good matching between them. The integral mass of steam in Figure 3 indicates higher initial energy of the system as it is in the “basic” case, either because of the higher temperature of the bypass zone (“T quartz +”) or because of the higher temperature of the incoming water (“T water +”).

Figure 3: On the left are graphs of the steam flow rate, on the right are graphs of the integral mass of produced steam. Top two graphs are the analysis of initial and boundary conditions and comparison with the experiment (PA_1), lower two represent the analysis of the parameters of physical models and comparison with the experiment. Experimental results are extracted from [4].
Table 4: Comparison of experimental and simulation’s reflooding time.

<table>
<thead>
<tr>
<th>case</th>
<th>experimental reflooding time [s]</th>
<th>MC3D simulation’s reflooding time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA_0</td>
<td>108</td>
<td>148</td>
</tr>
<tr>
<td>PA_1</td>
<td>240</td>
<td>263</td>
</tr>
<tr>
<td>PA_2</td>
<td>490</td>
<td>462</td>
</tr>
</tbody>
</table>

3.5 Comparison with PA_0 and PA_2 experiments

In the PA_0 and PA_2 experiments, the temperature of the balls in the debris bed zone was changed. In the PA_0 experiment, the temperature was set to 423 K whereas in the PA_2 experiment it was set to 973 K, which is closer to what is expected in the case of debris bed in a reactor core. For both experiments, similar as for the PA_1 experiment, an analysis of the initial and boundary conditions and parameters in the physical models for the heat transfer was done. The initial and boundary conditions are as shown in the Table 1, the parameters for the analysis were the same as for the PA_1 experiment (Table 2 and Table 3). The only differences are for the “T quartz +” case where the temperature of the balls in the bypass zone and in the lower and upper support zones was calculated according to the temperature of the balls in the debris bed zone.

In the simulation of the PA_0 experiment (lower temperature of balls in debris bed zone), the reflooding time is in all cases longer than in the experiment (Table 4). The steam flow rate is lower than in the experiment (Figure 4), but because of the longer reflooding time the integral mass of steam compared to the experimental one at the reflooding time is slightly higher. The difference can be explained with the additional heating time, providing more

![Figure 4: Steam flow rate and integral mass of steam for experiment PA_0.](image-url)
internal energy in the system. At the beginning of the “T quartz +” case, a peak in the steam flow rate can be observed. When the water level reaches the debris bed zone, the lower support zone is not completely cooled down yet. The water flowing in the debris bed zone has therefore a higher temperature than at the inlet and thus less energy is needed for the water heating and evaporation. In the “T water +” case the steam flow rate through the whole simulation is larger than in the case “basic” which could be expected because of the higher internal energy of the water. The changed heat transfer coefficient (“h +”, “h -”) affects the pace of transients but the integral mass of steam is almost the same.

In the simulation of the PA_2 experiment (higher temperature of balls in debris bed zone), the reflooding time in the “basic” case is about 6 % shorter than in the experiment. The steam flow rate in the simulation is slightly above the experimental values (Figure 5), but the

![Figure 5: Steam flow rate and integral mass of steam for experiment PA_2.](image-url)

two peaks measured in the experiment are not reproduced (in the “basic” case). At the beginning of the “T water +” case one maximum in the steam flow rate can be observed, similar to the one in the experiment. The reason might be that water at saturation conditions reaches the hot balls. In the “T quartz +” case two peaks in the steam flow rate are present at the beginning. In this case also the temperature of the balls in the bypass zone and in the the lower and upper support zones is high (520 K). Another peak might have appeared because of the fast reflooding of the support zones and the bypass zone. In the second half of the simulation in the “T water -” case the steam flow rate is lower than in the “basic” case. In this case also the integral mass of steam is lower (because of lower internal energy of water). The integral mass of steam for the “T water +” and “T quartz +” cases matches with the experimental value. In the case with the higher heat transfer coefficient (“h +”) the steam flow rate is lower than in the “basic” case, but the reflooding time is extended. The physical
properties of the heat transfer according to the flow diagram might be the reason for that phenomenon.

4 CONCLUSION

The PEARL experiments were simulated with the MC3D code and the calculation results were compared to the experimental measurements. In general, the MC3D code was capable to cover the experimental dynamics and that might be sufficient for nuclear applications. Nevertheless, additional investigations are necessary. First, the range of conditions covered by the simulated tests must be extended. The observed differences in the reflooding time due to the flow through the bypass zone also suggest additional investigation of the modelling approaches. The simulation results should be improved by enabling the modelling of the differences in the material properties between the debris bed and the bypass. Additionally, the importance of the uncertainties on the information about the bypass and water conditions was demonstrated. It seems that the “basic” case with the bypass zone and the support zones at saturation temperature has a lower internal energy than it was in the experiment and that the simulation cases with the higher internal energy (“T quartz +” and “T water +”) more accurately describe the experiment.

ACKNOWLEDGMENTS

The authors acknowledge the financial support of the Slovenian Research Agency within the research program P2-0026. Renaud Meigned, Stephane Picchi and Libuse Piar from IRSN are thanked for valuable discussions.

REFERENCES


