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Experimental and numerical investigation of molten corium behavior in lower head under external subcooling and boiling conditions

P. Pandazis [a,*], T. Hollands [a], X. Gaus-Liu [b], A. Miassoedov [b]

[a] Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Boltzmannstraße 14, 85748 Garching, Germany
[b] Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz-1, 76344, Eggenstein-Leopoldshafen, Germany

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ABSTRACT

The in-vessel melt retention by flooding the reactor vessel externally is regarded as an effective severe accident management (SAM) strategy. According to this strategy, the corium will be stabilized within the lower head, by transferring the decay heat through the wall into the containment via external cooling. One key question of this strategy is how the melt pool heat transfer reacts to different external cooling conditions. In this paper, the melt's thermal–hydraulic behavior under different external cooling conditions is studied experimentally in two LIVE tests performed in the frame of the LIVE program investigating late in-vessel melt pool behavior and calculated with the lower head module AIDA of ATHLET-CD. One LIVE test was performed under nucleate boiling condition, the other under sub-cooling condition. Melt temperature, heat flux along the curved vessel wall and the crust behavior are described in transient and steady states. The simulation results have been compared with the experimental results. The results have been demonstrated the applicability of ATHLET-CD to investigate the SAM strategy in-vessel melt retention by external cooling. Furthermore, on the basis of the experimental results the modelling of heat transfer between corium and coolant has been improved.

1. Introduction

One of the main goals of severe accident management (SAM) strategies is to avoid the release of radioactive fission products into the environment through stabilizing the degraded core within the containment. In the late phase of an in-vessel severe accident in light water reactors the molten core fuel together with the core internals (corium) are relocated in the lower plenum of the reactor pressure vessel (RPV). Without any counter measure the thermo-chemical attack of the relocated corium could lead to failure of the RPV wall. The SAM strategy of in-vessel melt retention has been developed to avoid the failure of the RPV wall and with this to avoid of radioactive fission product release into the containment. During this measurement the RPV wall has been external cooled by flooding of the reactor cavity depending on the concept, passively or actively. The decay heat of the corium can be removed through the lower head wall into the coolant and transferred to the cavity.

The success of the strategy is strongly dependent on the thermal load of the lower head characterized by the mass, the composition and the included decay heat in the corium as well as on the thermal hydraulic behavior of the melt under different cooling conditions. The relocated mass and the included decay heat are dependent on the course of the accident scenario and can be usually calculated with severe accident codes. The time of a possible lower head failure is also dependent on the cooling conditions which are characterized by complex multiphase heat transfer processes between the formed crust and the lower head wall and between the wall and the surrounding coolant. According to experimental observations there are currently three different molten pool configurations assumed in the late phase and each of these has a strong influence on the crust formation and the heat flux distribution along the lower head wall. In the simplest case a homogeneous corium pool is developed. In more complex cases the stratification of the corium pool is assumed in two or three layers due to the density difference of the non-mixable components and as a result of chemical reactions. In case of a stratified corium configuration the heat flux could focus on a smaller part of the lower head wall, resulting a high local heat load on the lower head wall. However, because of the geometry of a typical lower head, the convective processes within the corium pool and the inhomogeneous surrounding temperature and void distribution lead to an inhomogeneous heat flux distribution along the lower head wall also in the case of a homogeneous corium pool (Sehgal et al., 2013).

* Corresponding author.
E-mail address: peter.pandazis@grs.de (P. Pandazis).

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The condition of the available water in the flooded cavity has another important influence on the heat transfer. Depending on the available systems and the shape of the reactor cavity the condition of the flooded water can be sub-cooled or boiling. In case of large decay heat in the corium the heat flux values along the wall could reach the critical heat flux, boiling condition of the water changes from nucleate boiling to transition and film boiling which leads to a limitation of the heat transfer. The wall temperatures increase rapidly because of this limitation and causes a melt-through of the wall. Therefore, to determine the maximal heat flux and the departure from nucleate boiling is an important parameter of the applicability of IVR (Theofanous et al., 1996; Sehgal et al., 2013).

In the present work the transient melt behavior in the lower head has been investigated experimentally and numerically with the focus on the heat transfer and the crust formation under sub-cooling and nucleate boiling conditions in case of a homogeneous corium pool. In frame of the LIVE program performed by KIT (Gaus-Liu et al., 2016) the transient melt behavior in a large scale 3D lower head model has been experimentally investigated under different cooling conditions. The LIVE-L10 test has been dedicated to sub-cooled and the LIVE-L11 test to nucleate boiling cooling conditions for external cooling at the same corium mass and decay power. Furthermore the two experiments have been simulated with the lower head module AIDA of the severe accident code ATHLET-CD developed by GRS. The calculation results have been compared with the experiments, to investigate the capability of the implemented models in AIDA to simulate the defined key phenomena of IVR.

2. LIVE test program and experiment definitions

The test vessel of LIVE 3D facility with cooling lid is shown in Fig. 1 (left). The test vessel with the inner diameter of 1 m simulates the hemispherical lower plenum of a reactor pressure vessel of a PWR in 1:5 scale. The melt surface can be either maintained as free surface by covering the test vessel with an insulation lid or cooled with a water-cooled lid. The test vessel is enclosed in a cooling vessel to enable external cooling with either water or air. Cooling water flows in at the bottom and flows out via a side outlet at the top of the cooling vessel. The decay power of the melt is simulated by 8 horizontally-oriented electrical heating coils, which can be controlled individually to realize homogenous power generation in the melt pool. The maximum homogenous heat generation is 29 kW. The liquid simulant melt is prepared in an external heating furnace, which can tilt and pour the liquid melt into the test vessel either centrally or near the vessel wall via a pouring spout. After one test the liquid melt can be extracted back to the heating furnace and the 3D post-test crust profile can be determined.

The LIVE-3D test vessel is extensively instrumented: the 3D melt temperature and 3D heat flux distributions can be determined with 80 Melt thermocouples (MT) in the bulk melt, 26 pairs of thermocouples on inner and outer surface on the vessel wall and 7 thermocouple trees (CT) mounted perpendicularly to the wall in the wall boundary area. The crust temperatures are important parameters for the determination of the boundary position of the melt/crust interface. Fig. 1 (right) shows the arrangement of thermocouples in the melt and near the wall at one azimuthal. Besides, two video cameras are installed for the observation of melt pouring process and one IR camera records the turbulent pattern on the melt surface. A more detailed description of the instrumentation is given in (Gaus-Liu et al., 2011).

Two LIVE tests with similar test conditions except the external cooling are studied: LIVE-L10 and LIVE-L11. In both tests a non-eutectic mixture of 20 mol% $NaNO_3$ – 80 mol% KNO_3 was used.

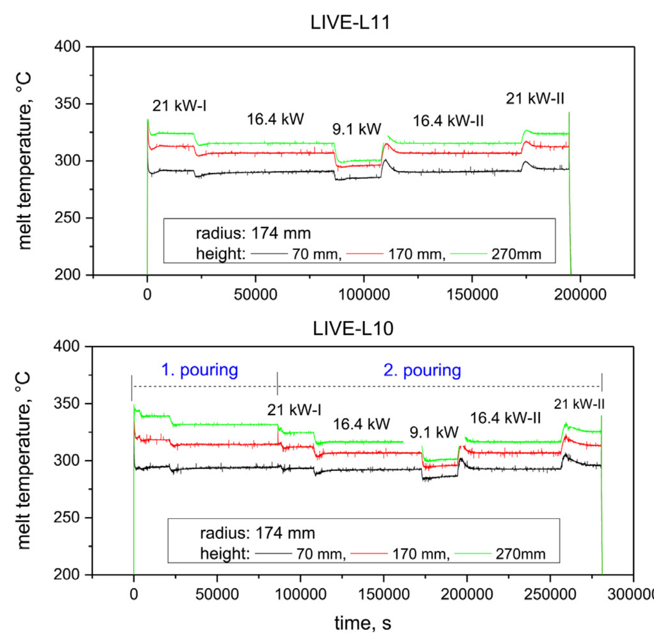

Fig. 2. Temperature progression during the test period in LIVE-L11 (top) and LIVE-L10 (bottom).

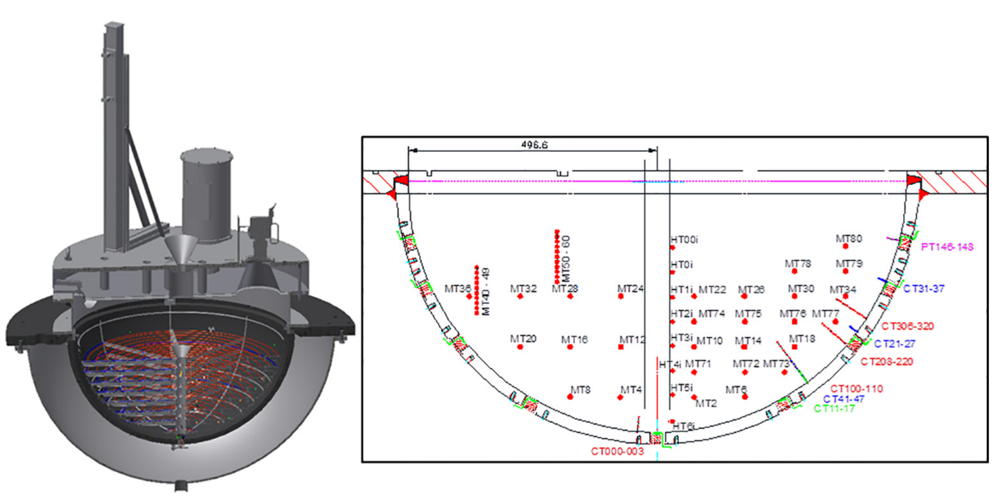

Fig. 1. LIVE vessel with top insulation (left) (Gaus-Liu et al., 2016) and instrumentation in the test vessel (right).

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