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Group: Severe Accident Research

Analysis of Severe Accidents

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Introduction

The research activities on reactor severe accident in LWRs at the group IKET-UNA and since September 2018 named IKET-SAR from 2017 to 2018 are focused on the in- and ex-vessel core melt behavior under diverse core melt accident scenarios and reactor types. These include the melt pool formation and retention in reactor lower head, melt jet dispersion in a flooded containment cavity, and corium concrete interaction and corium coolability in a containment cavity.

Following experimental works were carried out in the two-years period:

- LIVE3D and LIVE2D: series of tests on heat transfer of homogenous and stratified melt pool
- DISCO: two Fuel Coolant Interaction (FCI) tests in reactor pit filled with water
- MOCKA: two tests on ex-vessel molten corium and Concrete Interaction (MCCI) process with basaltic concrete.

Besides the experimental activities, calculation work has been performed on the coupling of a reactor analysis code and a lower head thermal analysis solver.

Some of the important results are described in following:

Heat transfer in a stratified melt pool

General

In the course of melt pool formation in LWR lower head, the melt could be separated into several layers because of the non-miscibility of melt components. The most concerned scenario is a formation of a light metallic layer atop of an oxide pool. In this case, the decay power in the oxide pool is transferred upwards to the metallic layer. The metallic layer is then heated up and constitutes a very high thermal load on the reactor wall at this part. Unclear is how the thickness of the metallic layer influences the heat flux on the sidewall and the role of the interlayer crust on the heat transfer between the two layers. The stratified melt pool tests are high demanding on the selection of non-miscibility simulant liquids in a possible operational temperature.

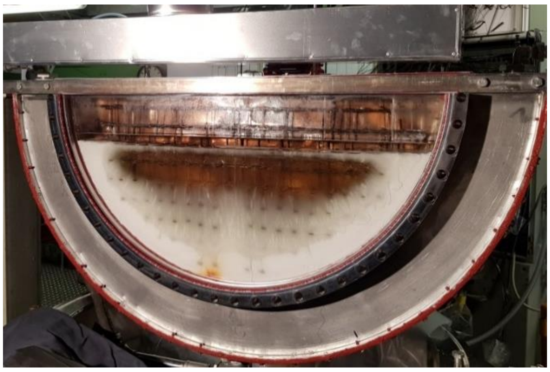
Experiment

In the frame of EU H2020 IVMR project, the LIVE2D vessel was upgraded for the conduction of the melt stratification tests. The upgrade measure includes the installation of transparent front side on the test vessel, for direct visual observation, more temperature measurements in the upper-layer region, local and environmental extraction system of possible oil vapor and automatic pool temperature control and power shutdown.

The simulant materials were determined after a series of laboratory examination. A thermal oil with high stability up to 240°C is used for the upper layer and the eutectic nitrate salt

$NaNO_3$-KNO_3 with operational liquid state temperature 224 - 350 °C simulates the oxidic layer with power dissipation.

As the first on its kind in Europe and worldwide, SAR experimental team has performed successfully a series of tests with separated melt layers and were able to demonstrate the complex interaction among the power input in the lower layer, the upper layer thickness, the boundary cooling conditions and the structure of the interlayer crust. In Figure 1 the formation of the interlayer crust at lower power input (900W) and the meltdown on the interlayer crust at higher power input of 1400W are shown



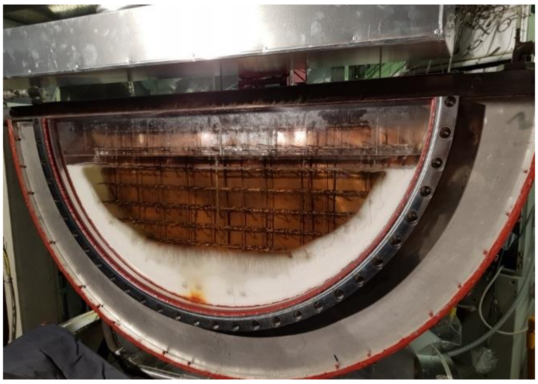


Fig. 1. Two-layer melt pool with the power input of 900W (top) and 1400W (bottom)

The movement of turbulence in the two layers can be captured with a real-time video camera; whereas the long-time process of crust formation and melt down in the whole view is recorded in time lapse. Temperature distribution in the two melt layers and on the vessel wall provide additional information of the turbulent pattern in the melt and the heat flux on the vessel wall.

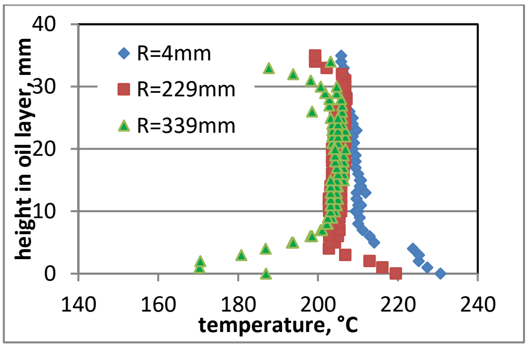


Fig. 2. Melt temperature distribution at three radial positions in a 35mm upper layer

Ex-vessel fuel coolant interaction (Ex-FCI) experiment in the DISCO test facility

Tests performed in DISCO facility investigate the phenomena during an ex-vessel FCI. A high-temperature iron–alumina melt is ejected under high pressure from RPV bottom to reactor cavity of a certain reactor design.

The major objective of these experiments was to determine the shape and size of the melt jet/steam in a transparent cavity. The influence of the geometry of the cavity and the openings to the containment sub-containments and dome on the pressure escalation and particle distribution in reactor is another objective of the study.

The test data include (i) high-speed video data to visualize the melt jet and water interaction, (ii) melt/steam volume in interaction zone, (iii) pressure evolution in reactor cavity and other parts of a containment, (iv) temperatures in RPV/RCS vessel, cavity and containment vessel, (v) characterization of melt debris, (vii) break opening characteristics and dispersal of water and melt at the end of interaction.

The experiments were carried out in the DISCO-H facility which was used before for Direct Containment Heating (DCH) experiments and the FCI experiments mentioned above. In Figure 3 at the left, the DISCO-H facility and at the right, the transparent cavity are shown.

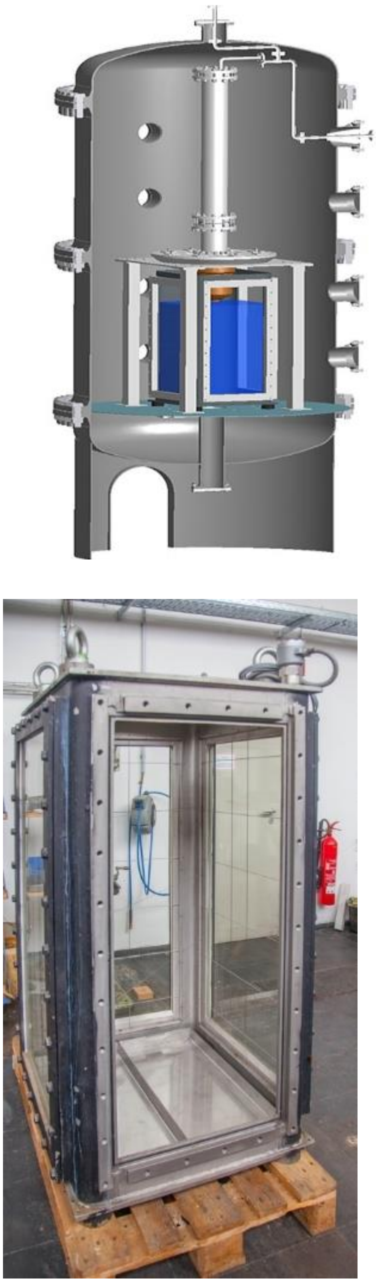


Fig. 3: Left: containment pressure vessel and internal structures of RPV/RCS and cavity. right: the cavity (water pool), a cuboid vessel with glass windows at three sides

Fig. 4 Vizualisazion of the interaction zone by means of a high-speed video recording. Top: t=26ms, bottom: t=295ms

After ignition of the thermite the break of the wire installed close to the brass plug was detected about 10 s later. This time is defined as t = 0 s. The 2200°C hot melt was ejected by nitrogen at 1.0 MPa into water at 50°C. The maximum pressure in the water vessel was 0.32 MPa after 0.6 seconds. The pressure in the containment increased from 0.1 MPa to 0.17 MPa, Figure 5. No steam explosion occurred. Most of the melt debris was found in the water vessel and had a median diameter of 2 mm, Figure 6.

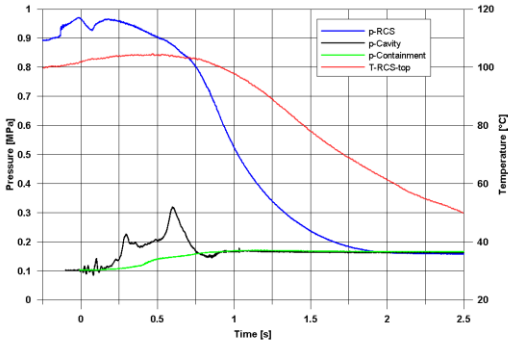


Fig. 5: Pressure in reactor cooling system, cavity and containment

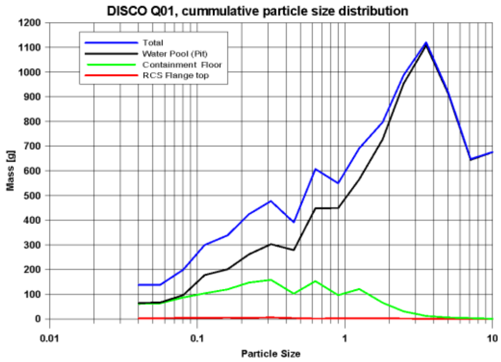


Fig. 6: Mass distribution of the collected debris

MOCKA-SSM experiments on basaltic concrete with and without rebars

The large-scale MOCKA (Metal Oxide Concrete Interaction in KArlsruhe) experiments at KIT investigated the interaction of a simulant oxide (Al_2O_3, ZrO_2, CaO) and metal melt (Fe) in a stratified configuration with different types of concrete. The program was focused on assessing the influence of a typical 12 wt% reinforcement in the concrete on the erosion behavior. The developed method of using the heat of chemical reactions to simulate the decay heat allows to obtain a rather prototypic heating of both melt phases and to study the interaction of the melt with a reinforced concrete.

A series of large-scale MOCKA experiments studied the interaction of the melt with siliceous and LCS concrete. Different erosion behaviour between siliceous and limestone concrete were found in several 2D MOCKA experiments. A highly pronounced lateral ablation was observed in all MOCKA tests using LCS concrete with and without rebars. The corresponding lateral/axial ratios of the ablation depth are approximately 3 In the MOCKA experiments with siliceous concrete, the overall downward erosion by the metal melt was of the same order as the sideward one. In addition, the lateral erosion in the overlaid oxide melt region was about the same as in the metal melt region. Fig 7 shows MOCKA experiment performance.

Fig. 7: MOCKA test facility.

To study the erosion behaviour of basaltic concrete, typical for Swedish BWRs, two experiments have been performed in the MOCKA test facility within the EU project of FP7 SAF-EST. MOCKA-SSM1 with and MOCKA-SSM2 without reinforcement in the basaltic concrete, Figure 8.. For both MOCKA-SSM tests, concrete crucibles with an inner diameter of 250 mm are used. Both the sidewall and basement are instrumented with Type K thermocouple assemblies to approximately determine the position of the progressing melt front into the concrete as well as tungsten-rhenium thermocouples for measuring the melt temperatures. A total of 51 thermocouples are implemented.

The basaltic concrete does not contain a concrete plasticizer, consequently, the fluidity of the concrete was considerably reduced. This in turn led to difficulties in distributing the concrete within the rebar structure. Therefore, some cavities were formed in the concrete.

The preparation of the crucible without rebars was completely unproblematic.

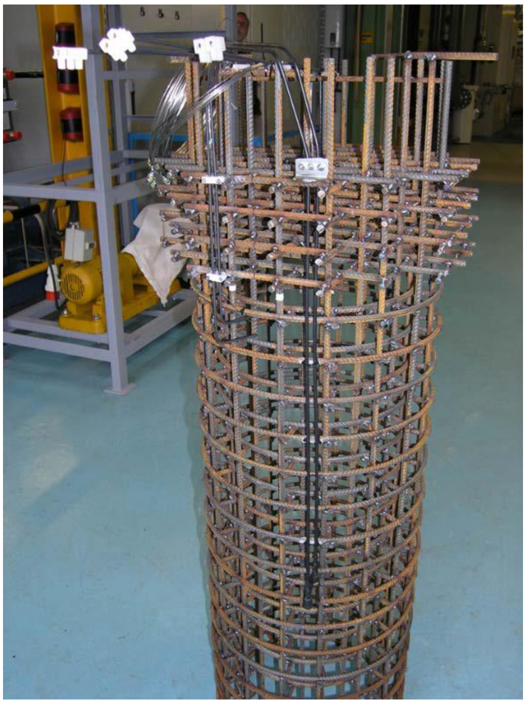


Fig. 8: MOCKA-SSM1 rebar structure

The melt is directly generated in the test crucible by a thermite reaction of 80 kg thermite powder and 30 kg CaO. The resulting melt consists of 42 kg Fe, overlaid by 68 kg oxide melt (initially 56 wt.% Al2O3, 44 wt.% CaO). The collapsed height of the metal melt is about 13 cm and that of the oxide melt 50 cm. The initial melt temperature at start of interaction is approximately 1800 °C. The CaO admixture lowers the solidus temperature and the viscosity of the melt. The resulting solidus temperature of approx. 1360 °C is sufficiently low to prevent a formation of an initial crust at the oxide/concrete interface.

After the completion of the thermite burn thermite and Zr was added to the melt within approximately 40 minutes in the experiments under consideration. The heat generated by the thermite reaction and the exothermal oxidation reaction of Zr is mainly deposited in the oxide phase. Due to density-driven phase segregation the metal melt at the bottom of the crucible is fed by the enthalpy of the steel which is generated in the oxide phase by the thermite reaction of the added thermite. Taking the added Zr and thermite into account, approximately 75 % of the heating power is deposited in the oxide phase and 25 % in the metal melt.

A highly irregular final shape of the ablation was observed in the MOCKA-SSM2 without reinforcement, Figure 9. This irregular shape was caused by a strong concrete spallation process, which resulted in simultaneous splash out of a substantial amount of oxide melt. The post-test cavity erosion profile of MOCKA-SSM1 with reinforced concrete showed a more regular shape of the erosion front, because the reinforcement seems to stabilize the concrete against the spallation process. In the tests with siliceous and LCS concrete such a behaviour during MCCI was not observed. However, more MCCI experiments on basaltic concrete are needed to confirm the observed phenomena. If the strong spallation is an inherent property of the basaltic concrete, then it must be considered as an issue for nuclear safety assessment.

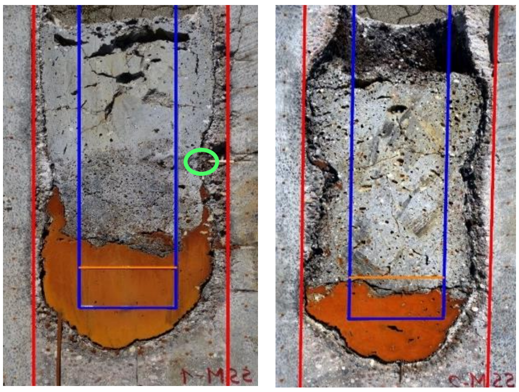


Fig. 9: Section of the MOCKA-SSM1 (left) and MOCKA-SSM2 (right) concrete crucible with an indication of the initial size of the crucible cavity (blue line). The orange line indicates the initial height (13 cm) of the metal melt and the red line marks the outer surface of the basaltic cylindrical crucible.

Coupling of a reactor analysis code and a lower head thermal analysis solver

Due to the recent high interest on IVR, development of de-tailed thermal and structural analysis tool, which can be used in a core-melt severe accident, is inevitable. Although RELAP/SCDAPSIM is a reactor analysis code, originally developed for US NRC, which is still widely used for severe accident analysis, the modeling of the lower head is rather simple, considering only a homogeneous pool. PECM/S, a thermal structural analysis solver for the RPV lower head, has a capability of predicting molten pool heat transfer as well as detailed mechanical behavior including creep, plasticity and material damage. The boundary condition, however, needs to be given manually and thus the application of the stand-alone PECM/S to reactor analyses is limited. By coupling these codes, the strength of both codes can be fully utilized. Coupled analysis is realized through a message passing interface, OpenMPI. The validation simulations have been performed using LIVE test series and the calculation results are compared not only with the measured values but also with the results of stand-alone RELAP/SCDAPSIM simulations

Analysis method

- RELAP/SCDAPSIM

The RELAP/SCDAPSIM code, designed to predict the behavior of reactor systems during normal and accident conditions, is being developed as part of the international SCDAP Development and Training Program (SDTP). RELAP/SCDAPSIM consists of three separate modules: RELAP5 calculates thermal hydraulics, SCDAP calculates core heat-up, oxidation and degradation, and COUPLE is used to calculate the heat-up of reactor core material that slumps into the lower head of the RPV and is subsequently represented as debris.

- Lower head molten pool thermal analysis solver

Since it is computationally expensive to simulate this complex behavior by solving a set of Navier-Stokes equations, a number of models using lumped parameter methods and distributed parameter methods were developed to construct a computationally effective and sufficiently accurate simulation platform. PECM is used in the present study to predict the thermal behavior of the molten pool.

- Coupling method

A coupling interface, OpenMPI is used in this study due to its advantage of development cost and the calculation time. OpenMPI is a Message Passing Interface (MPI) library, which can be used for parallel calculation and coupling of solvers. In order to utilize the parallel run and information exhange through OpenMPI, several MPI functions are needed to be used in the codes for initialization, finalization of the calculation, and sending and receiving message (Fig. 10)

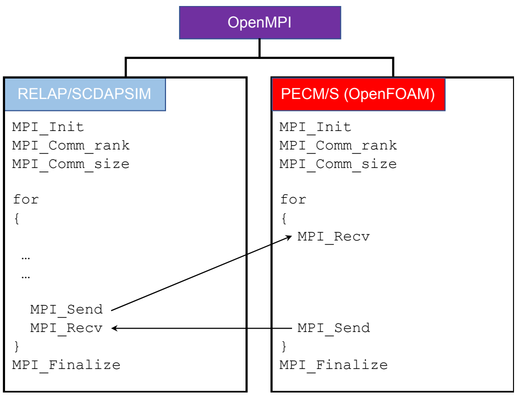


Fig. 10 Coupling of RELAP/SCDAPSIM with PECM/S.

The schematic image of the nodalization for the coupled analysis is displayed in Figure 11. The external cooling vessel is realized by pipe/annulus components (components 200 and 201) of RELAP5 and the vessel wall is assumed to be vertically connected on the side of the volumes. Heat structure components are used to represent the outer wall of the cooling vessel. A single volume (component 101), considering the amount of the molten pool, is used for the lower plenum and two volumes are attached to it for the water/air inlet and outlet, respectively. The heat transfer of molten pool and the vessel wall is calculated by PECM/S. The heat transfer coefficients at the melt surface, the external wall and the inner wall above the melt surface are calculated by the heat structure package of RELAP5.

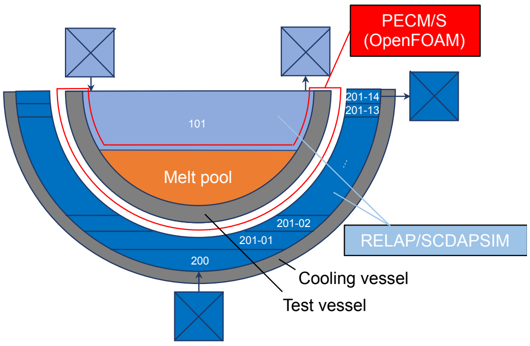


Fig. 11 Nodalization of the coupled analysis of a LIVE test

The validation has been conducted using LIVE-L1, L7V and L6 tests, which have different cooling conditions and melt pool formation. The heat flux, wall temperature and crust thickness of the coupled analysis is the steady-states were compared with the experiment and with the RELAP/SCDAPSIM stand-alone calculation. A better agreement with the experimental values was obtained with the coupled analysis. For example in Figure 12, the heat flux I calculated by R/S-PECM/S was smaller than that of R/S in the lower vessel region and closer to the experimental data. The location and the value of maximum heat flux was also well predicted.

In summary, as shown by the validation analyses, the coupled approach significantly improved the prediction of the lower head thermal behavior in comparison to the RELAP/SCDAPSIM standalone calculation. Since PECM/S includes the mechanical analysis models, the mechanical behavior of the vessel can also be calculated in future applications to a real-scale severe accident analyses.

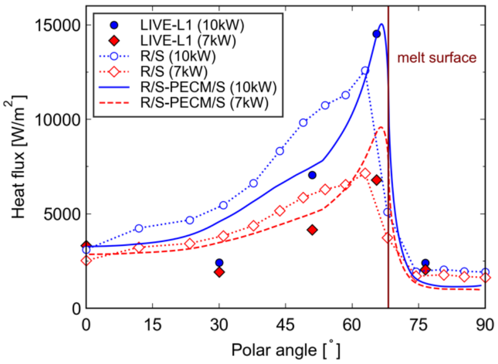


Fig. 12 LIVE-L1 heat flux profiles

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