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# LIVE2D Experiments on Thermohydraulics of Stratified Melt Pool in LWR Lower Plenum

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## Abstract

In-vessel melt retention (IVMR) as a promising strategy in Severe Accident Management for Light Water Reactors is adopted in VVER 440 or AP600 reactors as well as in higher power reactors around 1000 MWe, like AP1000 and Chinese CPR 1000. There is still a large uncertainty of the in-vessel melt retention by external cooling at power higher than 1000 MWe, and especially where a thin metallic layer appears on the top of a heat-generating oxide layer. Less knowledge based on large-scale experiments is available until now of the interactive physical, chemical and thermohydraulic processes between the oxide layer and the metallic layer. Experiments with naturally separated two liquid layers were conducted in the upgraded LIVE2D test facility in Karlsruhe Institute of Technology, using a nitrate salt mixture as lower (oxide) layer simulant and high-temperature oil as upper (metal) layer simulant. The transparent front wall of the test vessel enables direct observation of global convection patterns of the melts and the response of crust at the layer interface. Two series of experiments with three upper layer thicknesses and different surface boundary conditions were carried out. The experiments reveal major thermohydraulic characteristics of the simulated metallic layer during the transient and steady states and show a strong dependence of the heat flux focusing effect on the upper boundary cooling condition and the upper layer thicknesses.

## Introduction

In order to prevent vessel failure by a corium pool with decay heat in the lower plenum of a water-cooled reactor, a potential solution is flooding the reactor cavity with water and thus establishing sustained heat removal by external cooling water in natural convection. Henry [1] and Theofanous [2] proved that the external cooling strategy could protect the vessel integrity for a reactor up to 1000 WMe during a steady-state configuration of a homogenous oxide corium pool. However, the PIRT analysis [3] within the European H2020 IVMR project reveals that the uncertainty for the success of IVMR increases substantially during a transient state when molten metal accumulates on top of the oxidic corium in the lower head during the course of melt down of core steel structures and ablation of pressure vessel material. The thermohydraulics of a stratified melt pool is very complex since it is a dynamic process with the heat transfer and material interaction between the two layers with the involvement of an interlayer crust. If the stratified metallic upper layer is small and the upper surface heat transfer is limited, the vessel wall could receive a very high heat flux ("focusing effect").

The intensity of this heat flux focusing effect is strongly influenced by the upper surface cooling condition, the upper layer thickness, the behaviour of the interlayer crust and when there is no interlayer crust on the metallic layer reversing and the turbulence between the layers. In the upgraded LIVE2D facility, pioneering experiments with naturally separated simulant melts under large geometry und varying upper layer thicknesses and upper boundary conditions are therefore performed to improve the understanding of the heat transfer of a stratified melt pool.

## LIVE2D Test Facility and Performance

The LIVE2D test vessel in semicircular slice geometry simulates the RPV lower head (Figure 1) in 1:5 linear scale. The inner diameter is 1 m and the width is 12 cm. The vessel material is stainless steel and the wall thickness is approx. 24 mm. The curved surface of the vessel is enclosed in a curved cooling vessel and the top area can be covered either with a metal plate or a water-cooled steel lid. The vertical backside of the test vessel is isolated and the front side was upgraded with quartz plates, which enable the direct visualization of the melt pool. The decay heat is simulated with nine planes of independently controlled electrical resistance heating wires. LIVE2D shares the melt preparation system and infrastructure with the LIVE3D facility [4].

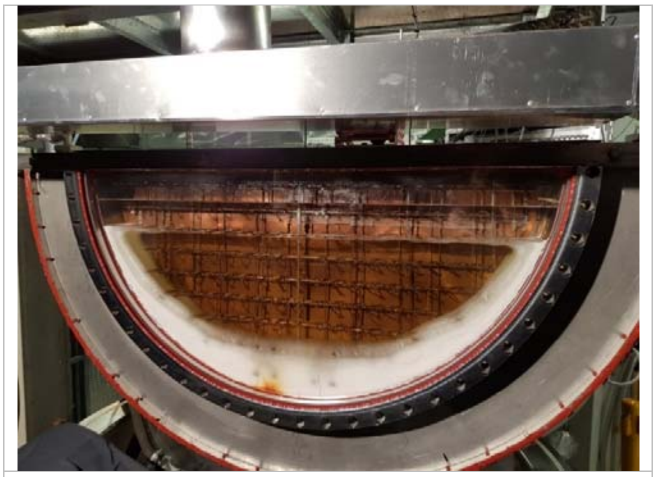

Figure 1: LIVE2D experimental setup.

Table 1: Material properties.

| **Properties** | **Lower layer simulant:**<br>**50% $KNO_3$-50% $NaNO_3$** | | **Upper layer simulant:**<br>**Thermal oil** | |
|---|---|---|---|---|
| | at 224 °C | at 260 °C | at 140 °C | at 220 °C |
| Liquid temperature range, °C | 224-400 | | 0-240 | |
| Density (kg/m³) | 1964 | 1937 | 755 | 540 |
| Kinematic viscosity (mm²/s) | 2.76 | 2.23 | 11 | 9 |
| thermal conductivity (W/mK) | 0.48 | 0.47 | 0.15 | 0.15 |
| thermal capacity J/(gK) | 1.29 | 1.31 | 1.7 | 1.83 |
| Pr | 14.5 | 12.0 | 94 | 59 |
| Ra | $10^{12}$ - $10^{13}$ | | $10^{8}$ - $10^{9}$ | |

The eutectic binary nitrate salt 50% $KNO_3$ - 50% $NaNO_3$ as the lower layer simulant and a thermal oil as upper layer material were selected. A comparison of main thermohydraulic properties of the two simulants are given in Table 1. Melt temperature distribution, boundary-near temperatures and wall temperatures were measured. The heat flux determination at the vessel wall is based on the inner and outer wall temperatures. IR videos, real time videos and time-lapse videos were recorded.

The first test series (LIVE-2L-SO1) was performed with a 2-layer melt pool and a hot upper atmosphere. Three upper layer thicknesses in the subsequence of 35 mm, 75 mm, 110 mm and 75 mm were realized with a total test duration of about 100 hours. The lower layer thickness was kept at the height of 340 mm during the whole test. There was only volumetric heating in the lower layer, simulating the prototypical case of decay heat release in the lower oxide layer. The vessel wall was externally cooled with water and the upper surface of the vessel was covered with a thin metal plate. In the second test series (LIVE-2L-SOTC), the total melt pool height was kept at 452 mm, the varying upper layer thickness was realized by shifting the interlayer positions. In contrary to SO1, the melt pool was covered with a water-cooled steel lid. In Table 2 the main features of the two test series are given.

Table 2: Main features of the test series.

| Test | Simulant material | | Height of layer, mm | | Heating phase, W | Boundary conditions | |
|---|---|---|---|---|---|---|---|
| | Upper layer | Lower layer | Upper layer | Lower layer | heating only in lower layer | Top surface | Vessel wall |
| SO1 | Thermal oil | eutectic $NaKNO_3$ | 35 | 340 | 1300 – 940 – 1040 – 1310 – 1400 – 900 | Hot air (metal plate covers the vessel) | Water cooled |
| | | | 75 | 340 | 1300 – 1800- 1150 | | |
| | | | 110 | 340 | 2200 – 1800 – 1400 – 1600 | | |
| | | | 75 | 340 | 1600 | | |
| SOTC | Thermal oil | eutectic $NaKNO_3$ | 110 | 340 | 3000 – 3600 - 4250 | Rigid cooling (Water cooled lid) | Water cooled |
| | | | 75 | 375 | 4230 – 3000 - 3600 | | |
| | | | 35 | 415 | 3600 – 3000 – 4300 – 3400 –2400 – 1800 | | |

## Results of Melt Transients

Several phenomena of the transients of the interlayer heat transfer can be observed thanks to the large-scale character and the optic observation possibility of the test setup. Firstly, the interlayer crust melts down or builds up depending on the interlayer temperature, which is a process parameter of the two-layer heat transfer. Figure 2 shows the melt pool with or without a compact interlayer crust. Secondly, the interlayer crust thickness is not uniform, and it changes non-synchronically from the central to the peripheral region. The interlayer crust is always thinner in the axial center than at the cold region near the wall, and the crust stabilization period is longer than the temperature stabilization in the lower layer. Since the upper layer transient couples with the crust change period, it was correspondingly longer than that in the lower layer, as shown in Figure 3.

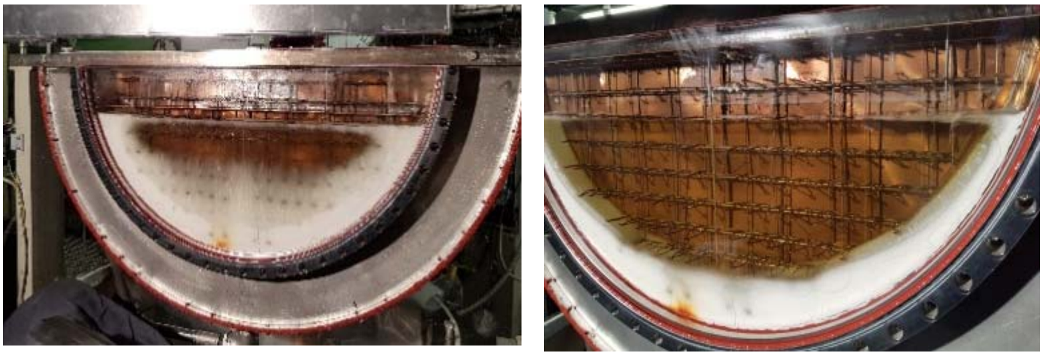

Figure 2: Interlayer crust during SO1 test: left: with crust, right: almost without crust.

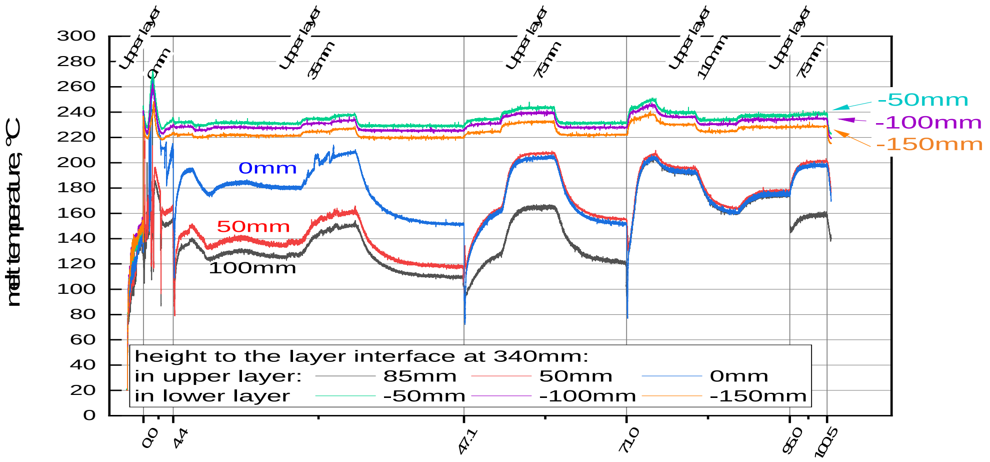

Figure 3: Transient melt temperature in SO1 test. Reference height °0” is at layer interface

Several other interesting crust behaviours have been observed: a) the shrinkage of the crust at the wall in the oxide layer enables a gap at the crust / vessel wall interface, this enables the upper layer material flowing into the gap; b) the interlayer position underwent slight shift after a power change due to the thermal expansion of the lower layer simulants.

## Results during the Melt Steady-State

### - *Melt flow pattern in the upper layer*

During the SO1 test where a hot atmosphere existed on top of the upper layer surface, global circulation of melt flow in the upper layer was observed. The melt in the axial central zone was heated up and flowed upwards to the upper surface, then it drifted horizontally outwards to the cooled wall region, there the melt was cooled and flowed downwards to the layer bottom and thereafter it directed back to the central region along the bottom. The global circulation resulted in different vertical temperature profiles at different radial positions. The upper layer melt flow during the SOTC test where the upper surface was rigidly cooled shows a very different flow pattern. It was similar to the Rayleigh-Bernard convection with several strong convection cells.

### - *Heat flux focusing effect in the upper layer*

Figure 4 shows the heat flux in the two tests at different heating powers. Strong heat flux focusing effect was observed during SO1 test, where the upper boundary cooling was poor. In contrary, during the SOTC test heat fluxes in the upper layer were general lower than the maximum heat fluxes in the lower layer except at low power input. In addition, the upper layer can withstand higher power input in the lower layer if it is cooled at the top. Increasing the upper layer thickness can mitigate slightly the heat flux, however it is far less effective than the upper surface cooling.

### - *Upper layer heat transfer correlation*

The Ra and Nu numbers of the upper layer heat transfer from the experimental results are presented in Figure 5 in comparison with Churchill & Chu correlations. Film temperature is used as reference temperature for the material properties, and the height of the upper layer is the characteristic length. The experimental results obtained a considerably lower Nu number in comparison with Churchill & Chu correlations [5]. This arise the question on the application limitation of the Churchill & Chu correlations, which were obtained from the condition of a heated sidewall bound to an infinitive large cavity and without the influence of bottom and surface condition.

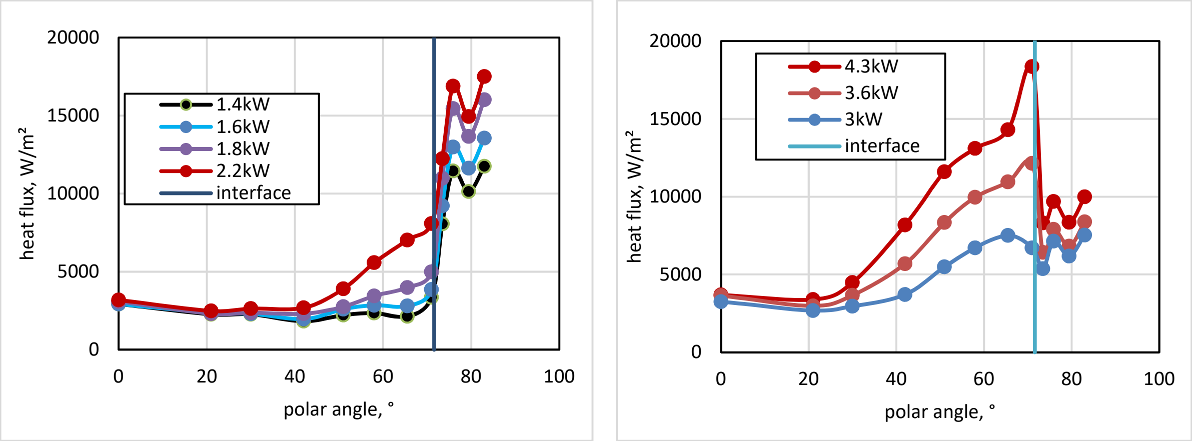

Figure 4: Heat flux at the vessel wall with 110 mm upper layer. Left: during SO1 test; right: during SOTC test.

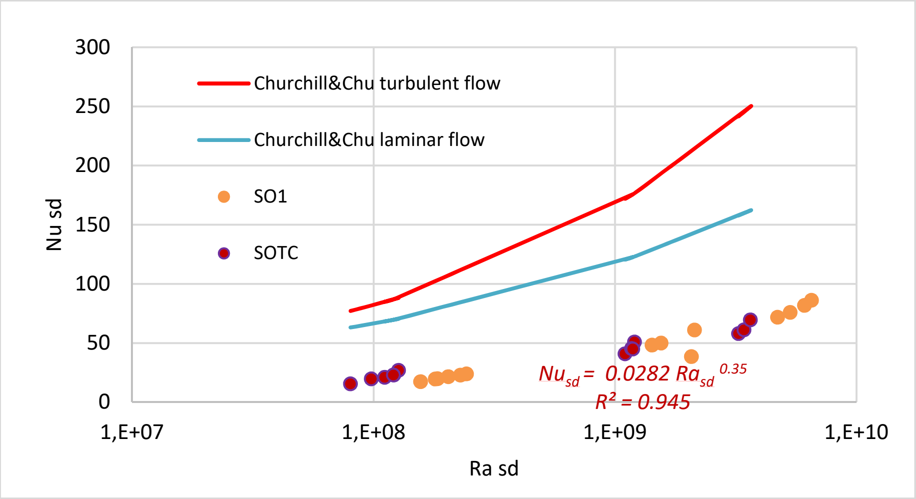

Figure 5: Comparison of Nu with the heat transfer at the upper layer sidewall.

## Conclusions

Large-scale two-layer melt tests were successfully performed in the LIVE2D test facility by varying the upper layer thickness and the upper boundary cooling condition. Different transient behaviour of the upper melt layer was observed which is related to the behavior of the interlayer crust and the thermal expansion of the lower layer. Strong heat flux focusing effect can be identified when the upper surface cooling is poor. The experimental results indicate massive overestimation of the traditional Churchill and Chu heat transfers correlations.

## Literatures

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