IN-VESSSEL MELT POOL COOLIBILITY TEST – DESCRIPTION AND RESULTS OF LIVE EXPERIMENTS

X. Gaus-Liu, A. Miassoedov, T. Cron, T. Wenz
Forschungszentrum Karlsruhe
Hermann-von-Helmholtz-Platz-1
76344 Eggenstein-Leopoldshafen, Germany
Xiaoyang.Gaus-Liu@iket.fzk.de; Alexei.Miassoedov@iket.fzk.de;
Thomas.Cron@iket.fzk.de; Thomas.Wenz@iket.fzk.de

ABSTRACT

The LIVE test program investigates in-vessel melt pool behaviour and cooling strategies for in-vessel corium retention during severe accidents in LWRs. The main part of the LIVE facility is a 1:5 scaled semi-spherical lower head of a typical pressurized water reactor. Up to now, LIVE experiments have been performed in different initial external cooling conditions, melt volumes and internal heat generations. At present the well-known simulant material KNO₃-NaNO₃ in non-eutectic composition (80 mole% KNO₃-20 mole% NaNO₃) and in eutectic composition (50 mole% KNO₃-50 mole% NaNO₃) is used. The 3D heat flux distribution through vessel wall, melt pool temperature, crust thickness and the pool melt composition can be measured or determined. Extensive results have been obtained concerning the melt pool thermal hydraulic behaviour in transient and in steady state conditions.

1 INTRODUCTION

External reactor vessel cooling (ERVC) is considered as one of the most promising severe accident management strategies for in-vessel corium retention (IVR) during a severe accident in Light Water Reactors (LWR). The success of ERVC is determined by melt pool heat transfer which is plant and sequence dependent. There is lack of knowledge about how the pool formation patterns and initial cooling conditions influence the transient state and steady state of the heat transfer behaviour in the melt pool [1]. Furthermore, not many experimental data are available for large-scale 3D geometry [2]. Based on this necessity, the experimental research program LIVE (Late In-Vessel Phase Experiments) at Forschungszentrum Karlsruhe (FZK) is being performed to investigate melt thermal behaviour and melt solidification process in the reactor vessel lower plenum under various relocation scenarios [3-6].

2 TEST PROGRAM

2.1 Test vessel description

The test facility of LIVE comprises a test vessel, a cooling vessel and a heating furnace. The test vessel is a 1:5 scaled semi-spherical lower head of a PWR, as shown in Fig. 1. The diameter of the test vessel is 1 m. The top area of the test vessel is covered with an insulated
The test vessel is enclosed in the cooling vessel to simulate the external cooling. The cooling water inlet is located at the bottom and the outlet is positioned at the top of the cooling vessel. The volumetric decay heat is simulated by means of 6 planes of heating coils in the test vessel. Each heating plane can be controlled individually to simulate homogenous heat generation in the melt pool. The maximum homogenous heating power is 18 kW. The melt is prepared in the heating furnace. The melt can be poured from the heating furnace to the test vessel either centrally or near the vessel wall. A vacuum pump extracts the residual melt back to the heating furnace at the end of test.

The test vessel has extensive instrumentation [7]. The temperatures of the wall inner surface and outer surface are measured at 5 latitudes and 4 locations at each latitude. Heat flux distribution through the vessel wall can be calculated based on these temperatures. Crust solidification processes can be monitored with thermocouple trees intruding from the wall into the melt at three locations. A precise crust detection lance can detect the crust front and measure the crust/melt boundary temperature as well as the melt pool vertical temperature profile. Two video cameras and one infrared camera are used to visualise the convection of the melt pool.

![Fig. 1. LIVE-test vessel and instrumentation](image)

### 2.2 Selection of simulant material

Important criteria for the selection of a simulant melt are that the simulant melt should be a non-eutectic mixture of several components with a distinctive solidus-liquidus range and the simulant melt should have a similar solidification and crust formation behaviour as the oxidic corium. Moreover, the simulant melt should not be toxic and aggressive against steel and vessel instrumentation and the temperature range of the simulant melt should not exceed 1000 °C because of the technical handling and the selection of the volumetric heating system and the heating furnace. Binary melts of KNO$_3$ – NaNO$_3$ are selected as simulant melts for the experiments both in non-eutectic mixture of 80 mole% KNO$_3$ - 20 mole% NaNO$_3$ and in eutectic mixture of 50 mole% KNO$_3$ – 20 mole% NaNO$_3$. The solidus temperature and the
liquidus temperature of the non-eutectic composition are about 225°C and 284°C respectively.

Although KNO$_3$-NaNO$_3$ mixtures are widely used as simulation materials of corium in the nuclear safety research and as thermal storage mediums, the phase diagram of this system is still under discussion [8]. Therefore FZK has measured the liquidus temperature from 100 mole% KNO$_3$ to 50 mole% KNO$_3$ - 50 mole% NaNO$_3$ with both a slow heating and a slow freezing. The results from these methods differ by a maximum of 4 °C. Fig. 2 shows the calibrated liquidus temperature of KNO$_3$-NaNO$_3$ system with the heating up method.

![Liquidus line of KNO$_3$-NaNO$_3$ measured at FZK.](image)

**Fig. 2. Liquidus line of KNO$_3$-NaNO$_3$ measured at FZK.**

### 2.3 Test matrix

Eight tests have been performed up to now in different conditions. The test conditions of these tests are given in Table 1. The main features of the tests are:

- mass of melt: either 120 l of melt in tests L1, L2, L3 and L3A or 210 l in tests L4, L5L, L9 and L9A were used. Scaled to the reactor case, the mass of melt corresponds to 70% and 100% of the total core inventory respectively.
- initial cooling condition: for the tests applying 120 l melt, initial external air cooling and then water flooding after 2 hours was performed in L1 and L3 test; whereas initial external water cooling was performed in all other tests.
- melt pouring position: the melt was poured near the wall at 157.5° azimuth angle in the tests L3, L3A and the second pouring of L5L, in other tests the melt was poured centrally.
- simulant melt composition: eutectic melt of 50 mole% KNO$_3$ - 50 mole% NaNO$_3$ with a melting temperature of 224°C was applied in L9 and L9A, whereas a non-eutectic melt of 80 mole% KNO$_3$ - 20 mole% NaNO$_3$ with melting temperature range of 284°C-224°C was applied in other tests.
- initial melt temperature: in the tests with non-eutectic melts the initial melt temperature was 66°C above melting temperature, whereas in the tests with eutectic melts, the initial melt temperature was either 125°C above melting temperature (L9) or 75°C above melting temperature (L9A).
- heating power: in most tests more than one heating plateau was applied. Each heating period lasted several hours so that the thermal-hydraulic steady state in the vessel was assumed to be achieved. For the mass amount of 120 l, 10 kW and then 7 kW were
applied, whereas for the mass amount of 210 l, five heating plateaux of the order of 18 kW, 10 kW, 5 kW, 10 kW, 18 kW (15 kW in L4) were applied.

Table 1: Test conditions of the preformed LIVE 3D experiments

<table>
<thead>
<tr>
<th></th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
<th>L3A</th>
<th>L4</th>
<th>L5L</th>
<th>L9</th>
<th>L9A</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial cooling</td>
<td>air</td>
<td>water</td>
<td>air</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
</tr>
<tr>
<td>pouring position</td>
<td>center</td>
<td>center</td>
<td>lateral</td>
<td>lateral</td>
<td>center</td>
<td>center-\rightarrow</td>
<td>lateral</td>
<td>center</td>
</tr>
<tr>
<td>pouring numbers</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>amount of melt, liter</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>210</td>
<td>120 + 90</td>
<td>210</td>
<td>210</td>
</tr>
<tr>
<td>power plateaux</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>simulant material</td>
<td>non-eutectic</td>
<td>non-eutectic</td>
<td>non-eutectic</td>
<td>non-eutectic</td>
<td>non-eutectic</td>
<td>non-eutectic</td>
<td>eutectic</td>
<td>eutectic</td>
</tr>
<tr>
<td>cooling water flow rate</td>
<td>45 g/s</td>
<td>45 g/s</td>
<td>45 g/s</td>
<td>45 g/s</td>
<td>1.3 kg/s</td>
<td>1.3 kg/s</td>
<td>1.3 kg/s</td>
<td>1.3 kg/s</td>
</tr>
</tbody>
</table>

3 RESULTS

3.1 Influence of heat generation

The influence of different heat generations on melt temperature, heat flux distribution in thermal hydraulic steady state of LIVE cases is investigated. Other test conditions are identical and are referred to as standard test conditions in this study which means the special influence of the initial cooling condition and melt pouring position is not considered. The standard test conditions are:

- initial external water cooling;
- central melt pouring;
- non-eutectic melt;
- initial melt temperature /maximum temperature above $T_{\text{liq}}$: 350°C/66°C.

The impacts of heating power are investigated in the L4 test. Four heat generation levels in the sequence of 18kW, 15 kW, 10 kW and 5kW for heating of 210 l melt were applied. The height of melt pool was 425 mm, and Ra number during 18 kW heating period was assumed to be $4.46 \times 10^{13}$ and Ra number during 5 kW heating period was assumed to be $1.21 \times 10^{13}$. In Table 2 the determined heat density in the melt and the ratio of the heat removed through the vessel sideline are given.

Table 2: Heat density and the fraction of heat removed through vessel wall

<table>
<thead>
<tr>
<th>Heating power</th>
<th>18kW</th>
<th>15kW</th>
<th>10kW</th>
<th>5kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>heat density [kW/m³]</td>
<td>81</td>
<td>67</td>
<td>45</td>
<td>22</td>
</tr>
<tr>
<td>$Q_{\text{wall}} / Q_{\text{heating}} [%]$</td>
<td>80.2</td>
<td>79.1</td>
<td>74.3</td>
<td>55.7</td>
</tr>
</tbody>
</table>

Fig. 3 shows the melt temperature at different vessel heights during different heat generations. The temperature points in Fig. 3 (a) were measured by thermal couples located at...
74 mm from the axis in L4 test; the temperature profiles shown in Fig. 3 (b) were obtained by a crust detecting lance during the L5 test which intruded into the melt at the position of 365 mm from the axis. Fig. 3 (a) shows that increasing heating power led to increase of overall melt temperature in the melt pool. Increasing the heating power also resulted in the tapering of the melt temperature upwards to the melt surface. Fig. 3 (b) reveals the detailed melt temperature distributions during different heating powers. There is a temperature boundary layer of ~4 mm adjacent to the crust/melt interface. The temperature gradient within the boundary layer during 18 kW heating power was about 9°C/mm. Adjoining this boundary layer a region with violently fluctuating temperature was measured. The fluctuation of the melt temperature is supposed to be a result from downward flow of cooled-down melt. Upon this region there was a stagnant zone with increasing temperature upwards and a turbulent zone with nearly homogeneous melt temperature.

![Graph showing melt temperature dependence on vessel height in the L4 test](image1)

![Graph showing melt temperature vertical profile in the L5L test](image2)

Fig. 3: (a) Melt temperature dependence on vessel height in the L4 test, 74 mm from axis; (b) melt temperature vertical profile in the L5L test, 365 mm from axis.

![Graph showing heat flux distribution along vessel height](image3)

Fig. 4. Heat flux distribution along vessel height under different heat generation levels.
The vertical distribution of heat flux through the vessel sidewall is shown in Fig. 4. Up from 10 kW, the heat flux increased significantly from 60° polar angle to the melt surface with increasing heating power. The highest heat flux was just below the melt surface. At the lower part of the melt pool, which is located below 30° polar angle, the heat fluxes were low and remained almost unchanged during different heat generation levels. No notable dependency of heat flux on heating power can be observed at the lower part of the melt pool.

### 3.2 Influence of initial cooling condition

Two initial cooling conditions are compared in this study. One is the initial water cooling, which means water is injected into the cooling vessel and a certain flow rate of cooling water is adjusted at the beginning of melt pouring. The other one is the delayed water cooling, which means the vessel is air cooled during the first two hours after melt pouring, and then the test vessel was externally water flooded. In the case of the delayed water cooling (L1 and L3 tests), the cooling effect was so low during the air cooling period that the melt temperature increased continuously and the upper part of the crust formed at the vessel inner wall surface was molten. After water flooding, a new crust layer was built up under low cooling rate. The different cooling condition resulted in different crust growth rates and crust thermal conductivity. The crust growth rates under different initial cooling conditions are compared during the 10kW heating power period. Fig. 5 shows the crust growth rate at the polar angle 52.9° under the delayed water cooling (L1 and L3) and under the initial water cooling (L2) conditions. The melt solidified significantly faster under the initial water cooling condition than that under delayed water flooding.

![Fig. 5: Crust growth rate under different initial cooling condition at the polar angle 52.9°.](image)

The thermal conductivity of crust corresponds adversely to the crust growth rate. As it is shown in Fig. 6, the crust layer formed during the initial water cooling (L3A test) has lower thermal conductivity than the one formed during delayed water cooling condition (L3 test). The difference in thermal conductivity can be traced back to the crust crystal structure and the crust porosity which are strongly dependent on the rate of solidification.

As a result of the crust thermal conductivity, the final crust layer thickness for the same local heat fluxes was different. The final crust layer formed under initial water cooling condition was thinner than that formed under delayed water cooling condition. Above results suggest the interaction among the solidification parameters: the initial cooling condition determines the solidification rate, which in turn influences the microstructure and the porosity of the crust. The microstructure of the crust exerts strong influence on the crust thermal conductivity.

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conductivity and the final crust thickness. This phenomenon observed in the simulant melt implies a general character of the solidification process of non-eutectic melts. Therefore it could also appear in corium melt.

![Graph showing crust thermal conductivity at the polar angle of 37.6°.](image)

Fig. 6. Crust thermal conductivity at the polar angle of 37.6°.

### 3.3 Influence of material properties of the melt

Results from the non-eutectic melt (L4) and from the eutectic melt (L9) have been compared. The important material properties are given in Table 3. Other test conditions are identical, which are given in Table 1.

<table>
<thead>
<tr>
<th>Material properties of eutectic melt and non-eutectic melt</th>
<th>50-50 KNO3/NaNO3</th>
<th>80-20 KNO3/NaNO3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c_{p,liq} [\text{J/kgK}])</td>
<td>1311 at 250 °C</td>
<td>1369 at 316 °C</td>
</tr>
<tr>
<td></td>
<td>1320 at 267 °C</td>
<td></td>
</tr>
<tr>
<td>(c_{p,sol} [\text{J/kgK}])</td>
<td>1183 at 100 °C</td>
<td>1140 at 100 °C</td>
</tr>
<tr>
<td></td>
<td>1236 at 206 °C</td>
<td>1328 at 210 °C</td>
</tr>
<tr>
<td>(h_{fus} [\text{J/kg}])</td>
<td>100.200</td>
<td>58.730</td>
</tr>
<tr>
<td>(h_{poly} [\text{J/kg}])</td>
<td>27.760</td>
<td>42.270</td>
</tr>
<tr>
<td>(T_{solidus} [°C])</td>
<td>224</td>
<td>224</td>
</tr>
<tr>
<td>(T_{liquidus} [°C])</td>
<td>224</td>
<td>284</td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td>1967 at 224°C</td>
<td>1914 at 284°C</td>
</tr>
<tr>
<td>Viscosity [pasx10³]</td>
<td>4.64 at 250°C</td>
<td>3.32 at 300°C</td>
</tr>
<tr>
<td>Heat conductivity [W/(mK)]</td>
<td>0.474 at 250°C</td>
<td>0.439 at 300°C</td>
</tr>
</tbody>
</table>

Besides the difference in melting temperature, the differences in the solidification process and in the crust microstructure are well known: during the solidification of non-eutectic melt, the crust/melt interface temperature is lower than the bulk melt liquidus temperature, a mushy zone exists and the microstructure of the solid shows cellular or dendrite structure; whereas during the solidification of the eutectic melt, the crust/melt interface temperature remains constant at the melting temperature, a planar front exists, the solid presents fine grains and there is no macro-segregation of melt components [9-10].

Corresponding to the liquidus temperature of the eutectic melt, the melt temperature in the test of eutectic material (L9) was generally ~ 60°C lower than the one of non-eutectic test. However, the heat flux distributions through the vessel sidewall of the two tests are comparable. In Fig. 7 the heat fluxes along the vessel height during 18 kW heating period are shown. It is also notable that the final crust thickness profiles of the two tests were similar, but the crust thermal conductivities were quite different. The crust heat conductivity shown in
Fig. 8 implies that the heat conductivity of the eutectic crust is considerably higher than the one of the non-eutectic crust. The post-test porosity analysis reveals that the mean porosity of the eutectic crust is 2.6 %, whereas the mean porosity of the non-eutectic crust is about 4.8 %. This implies the compact microstructure of the eutectic crust is one of the causes for the high thermal conductivity of the eutectic solid material.

![Graph showing heat flux through vessel sidewall from L9 and L4.](image1)

Fig. 7: Heat flux through vessel sidewall from L9 and L4.

![Graph showing crust thermal conductivity from L4 and L9 test at polar angle of 37.6°.](image2)

Fig. 8: Crust thermal conductivity from L4 and L9 test at polar angle of 37.6°.

### 3.4 Influence of initial melt temperature

The impact of the initial melt temperature on the thermal hydraulic transient state and steady state is investigated with the eutectic melt in L9 and L9A. The thermal hydraulic transient state is defined that in this period the crust growth rate is greater than zero, whereas the thermal hydraulic steady state is defined that the crust growth rate is zero. Therefore there is no mass transfer between crust and liquid melt in the steady state. The initial melt temperature of L9 and L9A were 350°C and 300°C respectively. Only 18 kW and 10 kW heating periods were performed in L9A test. Other test conditions of the two tests are identical (Table 1).

During the steady state of the two tests, the melt temperature and the heat flux distribution through the vessel sidewall compared very well with each other. The crust thicknesses during the same heating power were also comparable. But some difference of the...
melt pool behaviour during the transient state period can be observed. In the case of higher initial melt temperature (L9), the transient heat flux was higher and correspondingly more heat was removed through the vessel wall at the beginning period of the test. Fig. 9 demonstrates the total heat removed through the vessel wall at the beginning of the test. The main portion of the excessive heat in L9 was transferred through the wall during the first hour after melt pouring.

![Graph showing heat removed through the vessel wall during the initial period of test.](image)

Fig. 9. Heat removed through the vessel wall during the initial period of test.

High initial melt temperature led also to a longer thermal hydraulic transient state period. Fig. 4 compares the time periods of crust growth at different vessel heights in the two tests. The crust growth periods of L9 were about twice as long as those in L9A test. In all tests, also with non-eutectic composition, the crust growth period in the lower part of the vessel is longer than in the upper part.

<table>
<thead>
<tr>
<th>polar angle</th>
<th>L9-350°C</th>
<th>L9A-300°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>[°C]</td>
<td>[sec]</td>
<td>[min]</td>
</tr>
<tr>
<td>37.6°</td>
<td>13000</td>
<td>217</td>
</tr>
<tr>
<td>52.9°</td>
<td>8500</td>
<td>142</td>
</tr>
<tr>
<td>66.9°</td>
<td>5000</td>
<td>83</td>
</tr>
</tbody>
</table>

### 4 CONCLUSIONS

Eight LIVE tests have been performed to investigate the melt pool transient and steady-state behaviour under different heating and cooling condition. Comprehensive experimental results have been obtained regarding the melt pool temperature, heat flux distribution through the vessel sidewall, the crust thickness profiles and crust properties. Furthermore, the influences of initial cooling conditions and initial melt temperature on the transient and steady state melt pool behaviour are studied. Both non-eutectic and eutectic melts were used and their solidification character and the behaviour of the melt pool are presented. In detail, following conclusions can be drawn:

- increasing heating power in the melt leads to tapering of melt temperature and heat flux upwards to the melt surface;
- initial water cooling conditions leads to high crust growth rates, low crust thermal conductivities and thinner crust layers;
- low melting temperature of the eutectic melt leads to low melt pool temperature for the same heating power and melt mass. However, the heat flux distribution through the vessel wall for eutectic melt is comparable to that for non-eutectic melt. The final crust thicknesses are similar for both compositions, but the thermal conductivity of the eutectic crust is considerable higher than the one of the non-eutectic crust;
- high initial melt temperature influences crust growth period and the transient state heat flux, but has only a small influence on the steady state melt pool behaviour.

REFERENCES


