SIMULATION OF LIVE-L4 WITH ATHLET-CD

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ABSTRACT

The test LIVE-L4 was performed at the Karlsruhe Institute of Technology (KIT) in the frame of the LIVE test series. The LIVE facility represents the lower plenum of a typical pressurized water reactor in a scale of 1:5. In order to investigate the melt behavior a substitute for corium melt is used composed of binary mixtures of sodium nitrate and potassium nitrate. The scope of the test LIVE-L4 was the investigation of the influence of external water cooling on the transient melt behavior at different power levels, while a special focus was on the examination of the crust formation and crust thickness growth.
The simulation of LIVE-L4 was performed with the current development version of the severe accident code ATHLET-CD. ATHLET-CD consists of different modules to simulate the core degradation, fission product release and transport processes as well as the late phase module AIDA for the evaluation of melt pool behavior in the lower plenum. Model improvement was necessary for the internal calculation of the heat conductivity of the vessel and for the heat transfer between melt and crust. The evaluation of the simulation results of LIVE-L4 with the improved model show that the calculated temperatures during the test and the crust thickness at the end of the experiment are in good agreement to the measured values. Furthermore, the modified version of ATHLET-CD was applied on LIVE-L1 and LIVE-L6, and the results show a better agreement to the experiment than previous calculations. In general, the results of these simulations indicate the improved capabilities of ATHLET-CD.

KEYWORDS
Melt pool, LIVE facility, severe accident, ATHLET-CD

1. INTRODUCTION

In case of severe accidents with core melt and relocation to the lower plenum the behavior of the melt in the lower plenum is still an uncertain issue and the occurring phenomena in the lower head of a pressurized water reactor (PWR) are not fully described. Several studies and test series within the last decades investigated the course of a meltdown accident, critical phases and the timing of the phenomena/processes as well as their influence on the accident progression. While the understanding of a single phase melt pool is quite well and can be modelled, the behavior of a melt pool during transient conditions is not finally investigated and understood leading to uncertainties. Especially, concerning melt behavior, formation of a melt pool in the core configuration, relocation to the lower plenum and the formation of a molten pool due to debris melting are phenomena with uncertainties. For their further investigation of these phenomena and uncertainties several test series are performed to fill the gap of knowledge. Therefore, the LIVE test series at the Karlsruhe Institute of Technology (KIT) was built and is in operation. It is a large scale facility to extend the map of experimental data for melt pool behavior in a PWR lower plenum. Different configurations of melt cooling can be considered. The experiential generated data can be used for model development e.g. for severe accident codes as well as for the validation of such code systems [1], [2].

2. TEST FACILITY AND CONDUCT OF LIVE-L4

The LIVE test facility is located at the Karlsruhe Institute of Technology (KIT) and hosts the LIVE test series. Until 2015 several tests were performed with different initial and boundary conditions. Figure 1 shows the test vessel for the LIVE experiments representing the lower plenum of a light water reactor in the scaling 1:5. The vessel is made of steel and has an inner diameter of 1 m and a wall thickness of 25 mm. The vessel is surrounded by a second vessel to allow an external vessel cooling by water, steam or air through the gap between both vessels. The inlet nozzle is located at the bottom of the outer vessel and the exit at the upper region of the vessel (cp. Figure 2) [1], [2].

Figure 1. Test vessel of the LIVE facility [2].

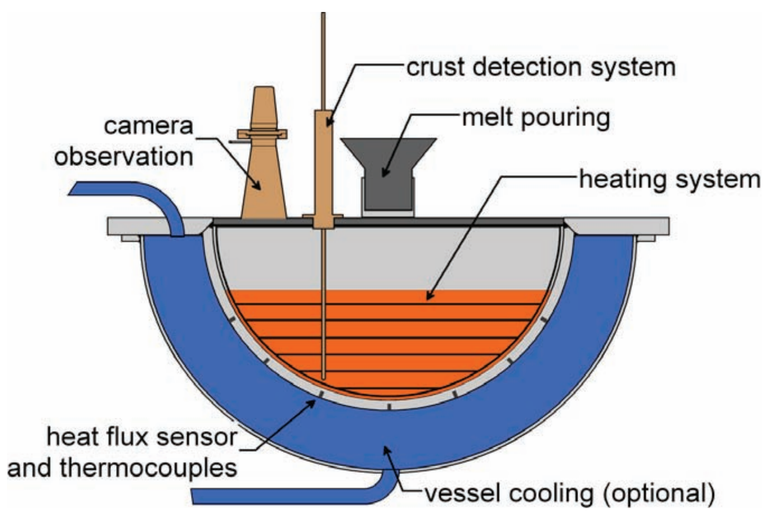

Figure 2. Scheme of the LIVE facility [2].

The heating system for the melt is shown in Figure 3. To simulate decay heat of the melt correctly a mesh with six independent planes is installed in the LIVE facility. With this volumetric heating system a homogeneous power distribution can be assured. During the test the vessel is closed by 20 mm thick steel cover plate with insulation and a second 1 mm thick steel plate. Additionally, 5 mm below the cover plate a 1 mm steel plate is located as radiation shield. The melt can be incorporated centrically or eccentrically in the vessel through two holes.

The test vessel is instrumented by a big number of measurement devices in azimuthal or polar direction. The melt is monitored via 36 thermocouples, which are located uniform in horizontal (100 mm) and vertical distance to the mesh of heating elements. To measure the crust formation a system of thermocouples was installed, which is described in detail in [2]. After the end of the test conduct the remaining melt was extracted and the final crust thicknesses were measured in different azimuthal directions depending on the polar angle.

Figure 3. Volumetric heating system of LIVE facility [2].

In the experiment LIVE-L4 the corium melt was substituted by a composition of sodium nitrate $NaNO_3$ and potassium nitrate KNO_3 like in other LIVE tests before. The mixture allows a safe technical handling, because as a substitute for the oxidic part of corium of the mixture shows comparable physical properties as well as thermodynamic and thermal hydraulic behavior at melt temperatures in the range of 300 °C. The mixture consists of 20 mol% KNO_3 and 80 mol% $NaNO_3$ and has a maximum temperature difference between solidus and liquidus of app. 60 °C. This melt composition can be used in the range of 284 °C (liquidus temperature) and 370 °C (chemical dissociation).

In an external apparatus the mixture of 68 kg $NaNO_3$ and 324 kg KNO_3, leading to 210 l of the needed melt composition, were heated up to 350 °C. The experiment started with the pouring of the melt into the vessel through the central hole, which took about 100 s and 207 l melt entered the vessel [2]. The overall time of the experiment was app. 54 hrs. During this test period five different power levels were established to investigate the transient behavior of the melt as well as the crust formation. Therefore, each phase took so long until a stationary state was established by a homogeneous power generation (except the last phase). The five phases are characterized as follows representing a stepwise decrease of the power followed by a stepwise increase foreseen at same power levels:

- 18 kW-I
- 10 kW-I
- 5 kW
- 10 kW-II
- 18 kW-II

Due to the failure of heating plane 4 in the last phase the maximum of 18 kW occurred only for a short peak and led to a total power of 15 kW afterwards. The test conduct of LIVE-L4 is given in Figure 4 and detailed in [2].

The gap between both vessels was filled with water. From 4 minutes before the initiation of the test until the end water flew constantly through the gap with 1.3 kg/s. The inlet temperature was 15.5 °C and led to an outlet temperature between 16 and 19 °C. Due to this external cooling a crust formation just from the beginning of the experiment was possible.

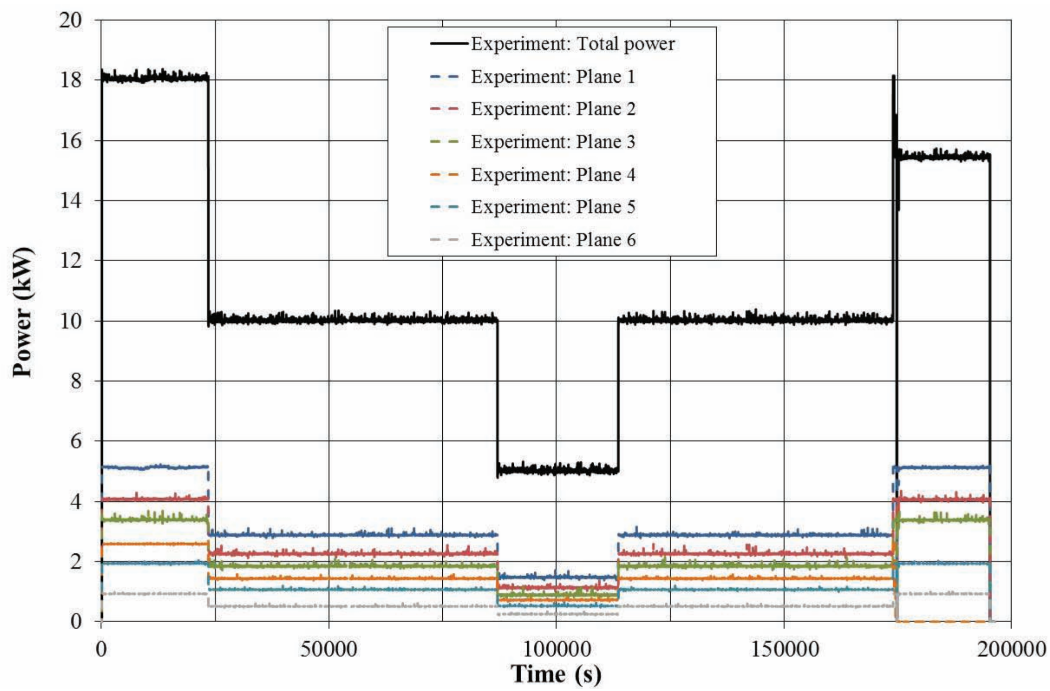

Figure 4. LIVE-L4 test conduct.

3. NUMERICAL MODELING

The following subchapters describe the used severe accident code ATHLET-CD (Analysis of THermal-hydraulics of LEaks and Transients – Core Degradation), as well as the necessary improvement for the lower plenum model AIDA in ATHLET-CD.

3.1. ATHLET-CD code description

The ATHLET-CD code has been developed and validated for severe accident applications. The development and integration of models in ATHLET-CD is done by the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH in close co-operation with the Institut für Kernenergetik und

Energiesysteme (IKE), University of Stuttgart. ATHLET-CD includes also the aerosol and fission product transport module SOPHAEROS, which is being developed by the French Institut de Radioprotection et de Sûreté Nucléaire (IRSN). With the models for the formation and movement of metallic and ceramic melts in the core area and the thermal behavior of particle beds, as well as for the release of fission products and aerosols in the core area and their transport and deposition in the cooling circuit, the application range of the computer code has been extended significantly in the recent years. For the simulation of debris beds a specific model MEWA was developed with its own thermal-hydraulic equation system, coupled to the ATHLET-thermo-fluid-dynamics at the outer boundaries of the debris bed. The transition of the simulation of the core zones from ECORE to MEWA depends on the degree of degradation in the zone. The current code version comprises also late phase models for core slumping, melt pool behavior within the vessel lower head (new module AIDA) and vessel failure. This is demonstrated by successful post-test calculations of bundle and integral experiments or the simulation of the TMI-2 accident and the incident at Paks-2 [3]. Full plant simulations can be performed by coupling ATHLET-CD with the containment code COCOSYS. The ATHLET-CD structure is modular, both to provide a variety of models for the simulation and to provide an optimum basis for further development (Figure 5). For a comprehensive simulation of the thermal-fluid dynamics in the nuclear steam supply system, the ATHLET system code has been fully integrated in ATHLET-CD [4], [5].

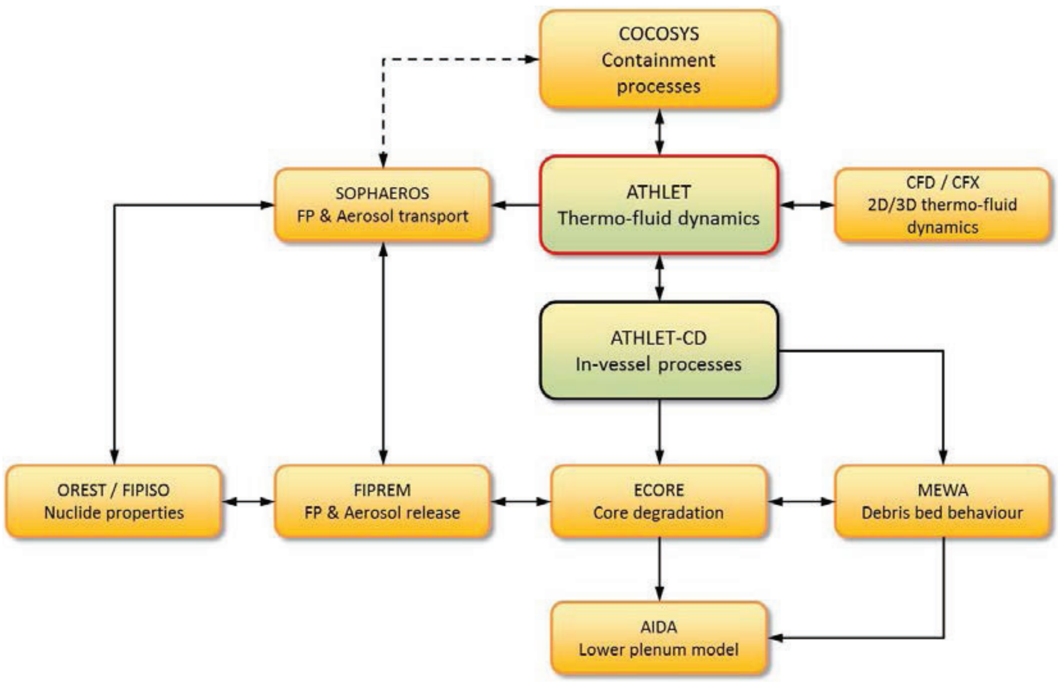

Figure 5. Modular structure of ATHLET-CD.

3.2. Model Improvement

Due to some discrepancies between experiment and first simulations of LIVE-L4 the necessity for model improvements was identified concerning heat conductivity in the vessel wall, code internal prediction of the Nusselt number and heat flux between melt and crust. Therefore, the following model improvements were done to predict the physical behavior more precise.

In the current version of ATHLET-CD two different types of steel are implemented (SA 533 B1 and MnMoNi 5 5) and their material properties like density, heat capacity and heat conductivity are used. The comparison of the properties of the implemented steel types and the used steel in the LIVE facility shows that the heat conductivity is app. four times higher in the currently implemented steel types (cp. [1], [2]). As a consequence the source code was modified to use the steel of the LIVE facility for the simulation including a temperature depending formula for the prediction of the heat conductivity through the vessel wall as given in [2].
The original version of the late phase model AIDA allows to choose one of four correlations (Figure 6, left) for the heat transfer from the melt to an upper crust and to choose one of seven correlations (Figure 6, right) for the prediction of the heat transfer from the melt to a lower crust. The results of the simulation show that the recommended option (correlation 4: upwards, correlation 7: downwards, cp. Figure 6) for the prediction of the Nusselt number as well as some other combinations of the available options led to a too high heat transfer especially from the melt to the upper crust. The Nusselt number is overestimated in comparison to the experimental observations, where the Nusselt number is predicted to 100-200 for Rayleigh numbers in the range between $1.0 \cdot 10^{13}$ and $4.3 \cdot 10^{13}$ [2]. To improve the model basis the possibility to use the same correlation (Reineke: 5) for the heat transfer to the upper and lower crust was implemented (cp. Figure 5). With this modification the heat transfer to the crust can be predicted much closer to the experiment. As a consequence this model option was evaluated by the application on two other LIVE experiments and the results could be improved as well. So, this model option is recommended for LIVE tests.

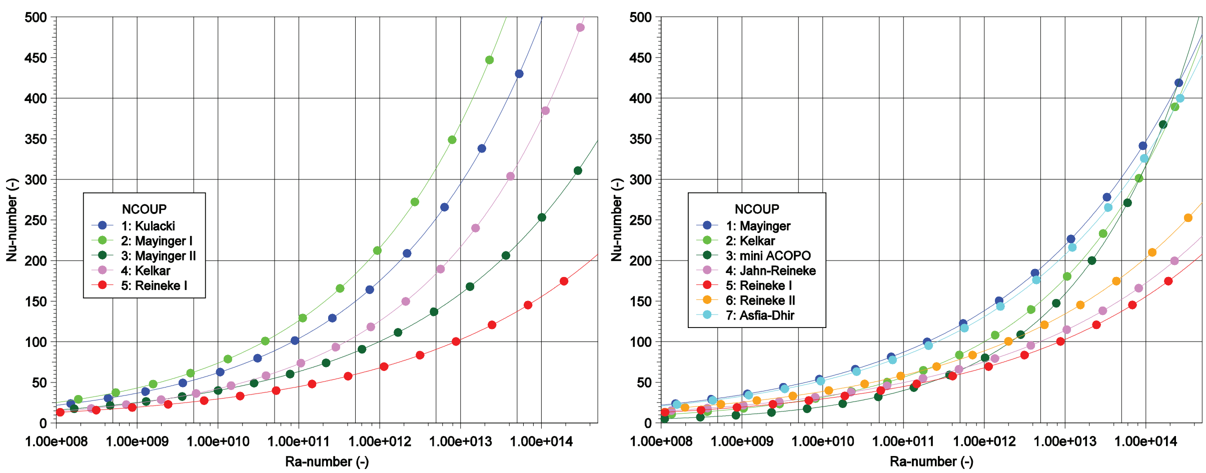

Figure 6. Correlations for the prediction of the Nusselt number for the upper (left) and lower (right) crust.

The heat flux from the melt to the crust is calculated by the Nusselt number and the temperature difference between melt temperature (T_{melt}) and interface temperature (T_{int}). As shown in Figure 7 the interface temperature has to be chosen in the region of the phase change $T_{sol} < T_{int} < T_{liq}$.

To consider the difference between configurations with and without external cooling, which is not covered by this method yet, the heat flux to the phase boundary between melt and crust was calculated based on the film temperature which is assumed in a first approach to be $T_{film} = 0.5 \cdot (T_{int} - T_{sol})$ instead of T_{int}. In general, this assumption overpredicts the heat flux, which leads to an overestimation of the cooling of the melt in case of cooled cases (crust formation).

In the modified development version of ATHLET-CD the interface temperature for the phase boundary is used in case of a formed crust by external cooling like in the original version of AIDA. In cases without external cooling (no crust at the vessel wall) the temperature difference is calculated considering the liquid phase of the phase boundary temperature ($T_{int} = T_{liq}$), which led also to an improvement of the simulation results of the experiment LIVE-L1.

The module AIDA including the heat transfer models in different directions (upwards/downwards), which consider existing and approved correlations, were validated by the application on LIVE-L1, L4 and L6. Furthermore, the module AIDA was applied for simulations of TMI-2.

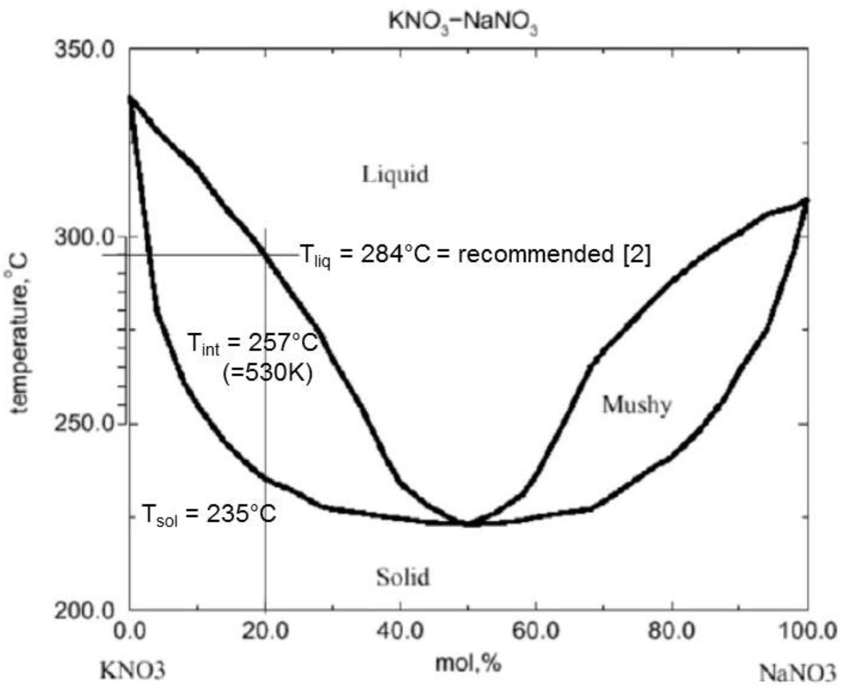

Figure 7. Phase diagram KNO_3-$NaNO_3$ [1].

4. SIMULATION RESULTS

At the beginning of this chapter a short description of the implemented initial and boundary conditions as well as some assumptions for the simulation are given.

The experimental initial and boundary conditions of the test LIVE-L4 were taken from [2] and implemented in the “stand alone” version of AIDA in the frame of ATHLET-CD. That means that the initial and boundary conditions of the test are directly implemented as an input and not part of a full sequence simulation leading to a melt formation in the lower plenum. This includes also geometrical data and material properties of the melt and crust which are not taken from the ATHLET-CD package. Only the material data of the steel are directly implemented in the source code as discussed in chapter 3.2.
Due to the failure of the heating plane 4 in the fifth phase of the experiment, the expected heating power for the melt of 18 kW is captured only for a very short peak, which led to a total power of only 15 kW in this phase (see Figure 4).

Due to the fact that the pouring of the melt cannot be simulated by ATHLET-CD, the height of 0.43 m is used as initial condition and the power of 18 kW starts at the point 0 s instead of 83 s in the experiment.

Based on the experimental conditions the configuration A2 in the module AIDA is used representing an oxydic melt pool without water in the lower plenum. Furthermore, the original nodalisation of the vessel with 40 zones and 10 layers was reduced to 5 layers showing approximately the same results. Additionally, the time steps in the simulation could be increased to 1 s without a loss of accuracy.

In the following the results for temperatures, heat balance, heat flux and crust thickness of the simulation are evaluated in comparison to experimental data.

4.1. Temperatures

Figure 8 shows different experimental melt temperatures at three elevations and the average melt temperature in the test in comparison to the only melt temperature calculated by AIDA in ATHLET-CD, (AIDA is a point model for the melt phase, which predicts only one melt zone leading to one temperature). The axial temperature profile in the experiment due to the external cooling (higher temperature in the upper melt region) cannot be simulated due to this assumption in the model. The comparison of the average melt temperature in the test and the predicted temperature in AIDA shows a good agreement except a small overprediction in the first phase.

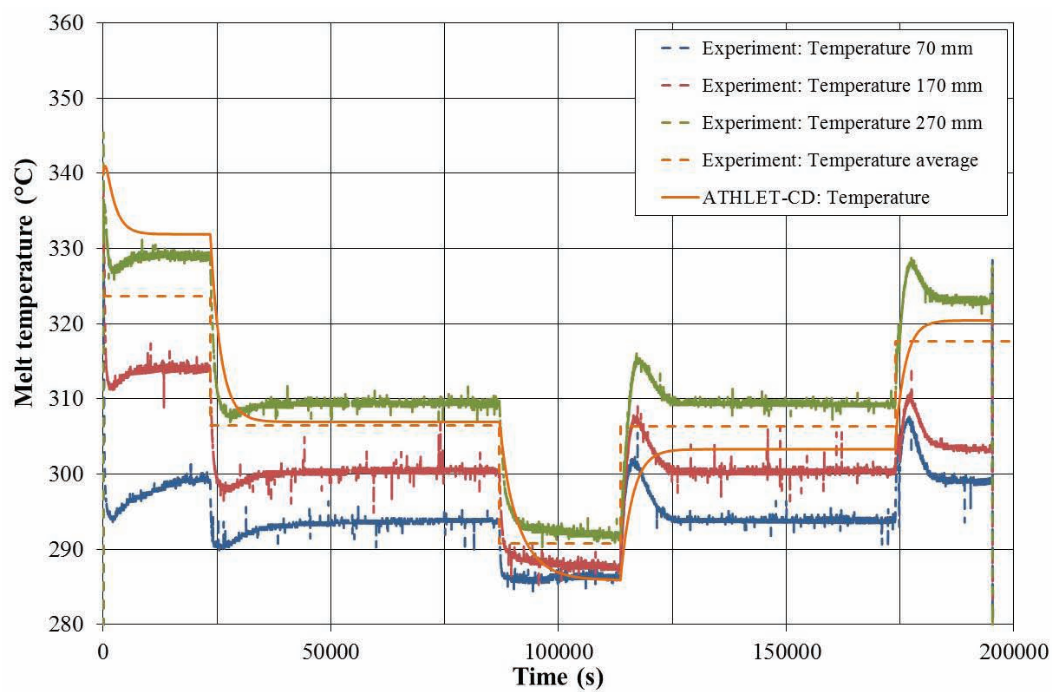

Figure 8. Experimental and simulated melt temperatures.

The measured and predicted inner and outer wall temperatures are given in Figure 9 and Figure 10. The comparison is based on the measurement devices given in [2]. In the case of the external vessel cooling with a constant heat transfer coefficient of 600 W/m²K (input parameter) and a constant water flow rate of 1.3 kg/s the inner and outer wall temperatures in the upper vessel region are calculated in good agreement to the experiment using the modified code version. At the bottom of the vessel (0 °) as well as in the lower region of the wall the experimental temperatures are overestimated by ATHLET-CD. This can be explained by the assumption of only one melt pool and one melt temperature, which does not predict the axial temperature profile of the experiment and captures the measured data at the top of the melt better because of the predicted position of the center of gravity in the upper melt region.

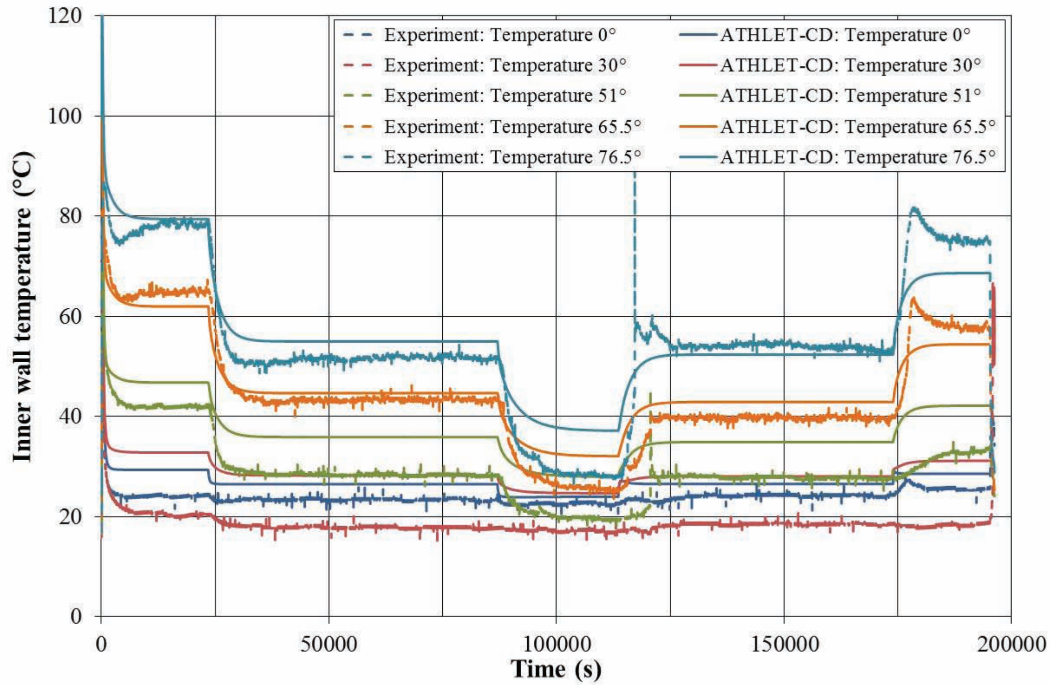

Figure 9. Experimental and simulated inner wall temperatures.

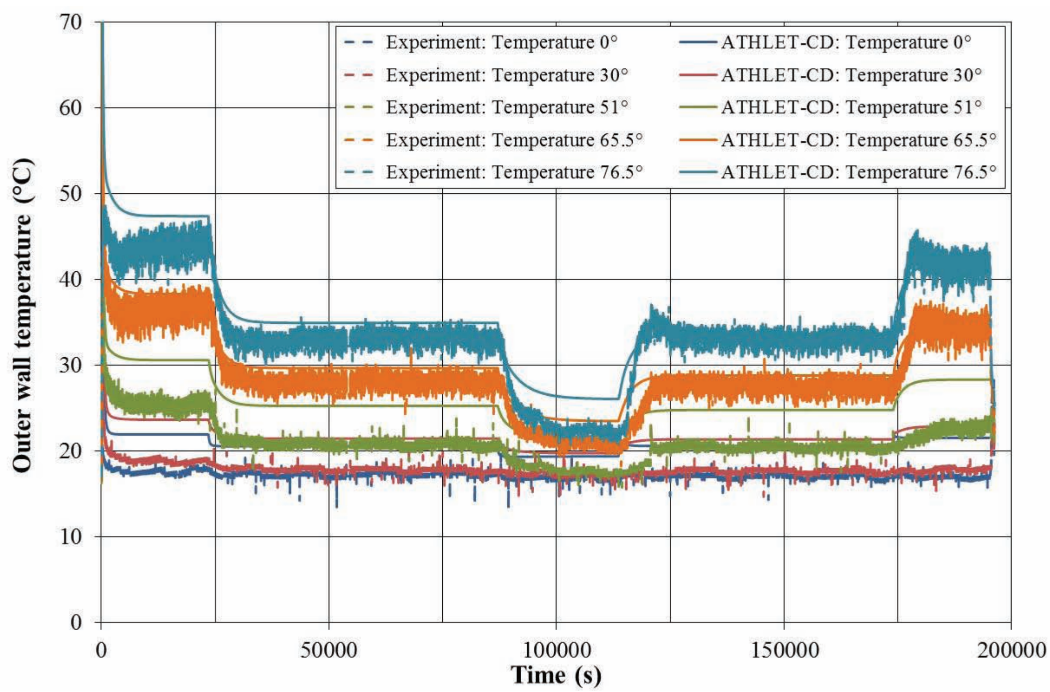

Figure 10. Experimental and simulated outer wall temperatures.

Figure 11 shows the measured and calculated temperatures of the crust. The comparison of the experimental data and the results of the simulation with ATHLET-CD shows some discrepancies. Due to the fact that the measured temperatures vary strongly depending on the position of the measurement device in the crust (0 mm – 10 mm) including times where the melt temperature is monitored, the comparison is done for devices close to the wall in phases with long stationary conditions (10 kW). It can be seen that AIDA predicts the temperatures in the upper region close to the measured data in this phase, but overpredicts the experiment in nearly all other phases and positions due to the uncertainties in the experiment and the assumptions of the melt as discussed above. Furthermore, the gap thickness between the crust and the wall is uncertain and has a big influence on the results.

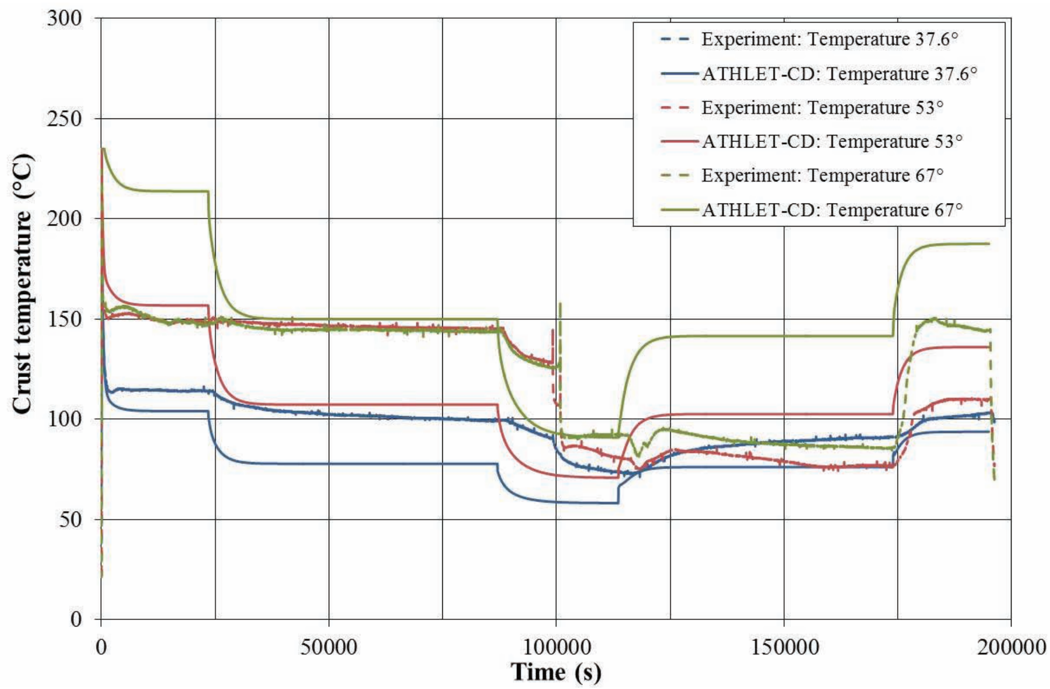

Figure 11. Measured and simulated crust temperatures.

4.2. Heat balance

The induced power by the heating elements is given in Figure 12 in comparison to the heat transferred from the melt to the upper and lower crust. Due to the fact that an upper crust is only formed in the time period with 5 kW, power upwards can be assumed as heat transferred to the upper boundary of the crust and is lower than the power downwards. The sum of power upwards and downwards in each stationary phase is equal to the induced power. The calculated heat transfer to the lower crust and subsequently to the bottom of the vessel is in good agreement to the experimental observations (cp. [2]).

The calculated and experimental predicted distributions of the heat fluxes for the five phases of the test are given in Figure 13 as function of the polar angle along the vessel wall (0°: bottom of the vessel). As described in [2] the measured data between 0° and 30° are quite uncertain and show a wide band of values. This leads to a minimum at 30° which cannot be assured. So, the shown overestimation by the code at the experimental minimum position is uncertain and not sure. In regions of higher angles (> 50°) the calculated heat flux distribution is in good agreement to the experiment.

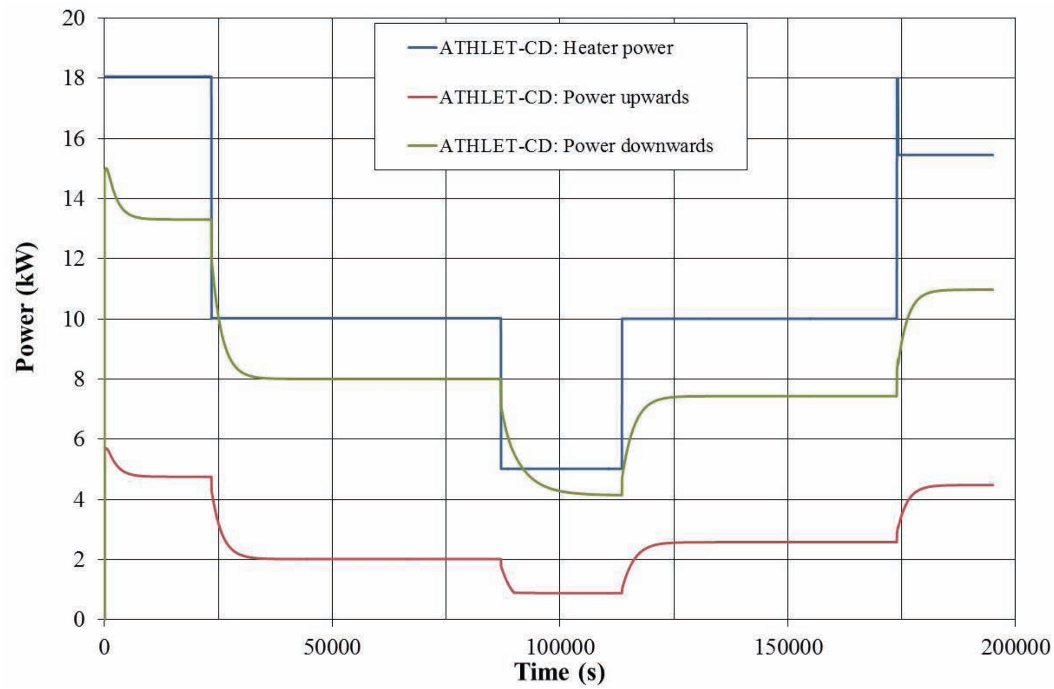

Figure 12. Heat balance in the simulation.

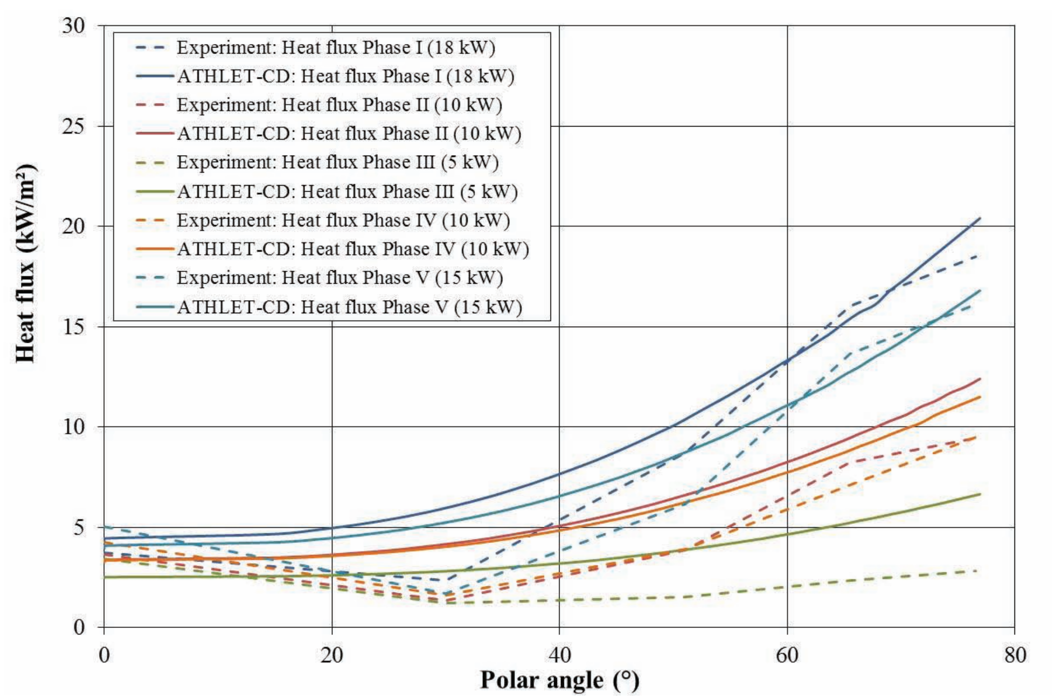

Figure 13. Estimated and calculated heat flux along the vessel.

4.3. Crust thickness

In general, the simulation underpredicts the measured data in time behavior and in contrast to the experimental observations the crust thickness development is simulated identically in both 10 kW phases and does not show different behavior as measured in the test. But, the experimental data are estimated depending on the measured crust temperatures, which lead to some uncertainties [2].

The deviations in the experimental data can be seen in Figure 14, where the minimum and maximum of the post-test evaluated crust thicknesses are given in comparison to the calculated values by AIDA. The crust thickness is underpredicted along the vessel from the bottom to the top. The calculated maximum is in the range of the experiment, but it is predicted at the bottom compared to a polar angle of 20° in the experiment. Reasons for that could be the uncertainties in the measurement in this region as well as the assumption made in AIDA.

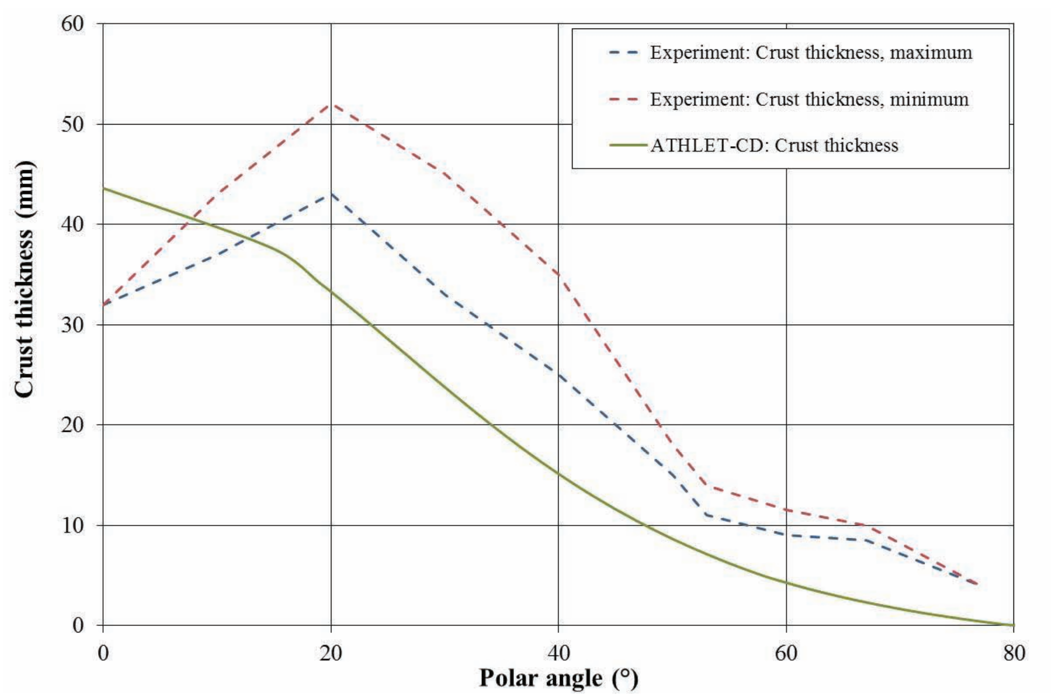

Figure 14. Estimated and calculated crust thickness.

5. CONCLUSIONS

The experiment LIVE-L4 performed in the frame of the LIVE test series at KIT delivers data of the thermal behavior in case of a melt relocation into the lower plenum as a possible consequence of a severe accident in light water reactors. The LIVE facility represents the lower plenum of a typical light water reactor in a scaling of 1:5. In the test LIVE-L4 the influence of the external water cooling on the transient melt behavior is investigated. Therefore, different power levels are induced into the melt, while a special focus was on the crust formation in the melt pool.

The simulation was performed with the current development version ATHLET-CD 3.0B and the late phase model AIDA was used. The simulation was done with the so called “stand alone” version of AIDA. That means the initial and boundary conditions are directly implemented in the input deck and mainly not taken from the ATHELT-CD code package. For the simulation model improvement was necessary for the internal calculation of the heat conductivity of the steel vessel as well as for the heat transfer between melt and crust.

The simulation was evaluated by comparison of different temperatures (melt, crust, wall), heat balance and crust thickness with experimental data. The results of the simulation of LIVE-L4 with the improved model show that the calculated temperatures during the test and the crust thickness at the end of the experiment are in good agreement to the measured values.

Furthermore, ATHLET-CD including the improved model base was applied on LIVE-L1 and LIVE-L6, which were simulated with previous code versions, and the results of these simulations show a better agreement in comparison to the corresponding experimental data. In general, the results of these tests indicate the improved capabilities of the late phase model AIDA within ATHLET-CD.

ACKNOWLEDGMENTS

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