Simulation of PASI experiment on passive containment heat removal system with MELCOR and ATHLET

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ABSTRACT

Passive safety systems are in focus of several research projects. One of them is the EU PASTELS project, which aims at demonstration of how innovative passive safety systems can support modernisation and optimisation of the European nuclear industry. Within the project, several passive heat removal experiments are studied extensively with different computational tools, including CFD and system codes. Various numerical activities have been carried out on experiments in the PASI test facility, which simulates heat removal from containment through passive condenser connected to an external water pool. This paper summarises simulations performed with ATHLET 3.3, which is a part of the AC2 code package and severe accident code MELCOR 2.2.18019. The capabilities of the codes are discussed, highlighting the existing challenges and drawbacks of the applied approaches. A key part of the paper is a discussion on areas of future code development.

1 INTRODUCTION

Passive safety systems, such as containment heat removal systems, are in the focus of nuclear research for many years, including research projects like PASTELS. Such systems play important role mainly during severe accidents to remove energy from the containment atmosphere reducing the pressure and maintaining it on acceptable level. The PASI facility [1] is a model of the PHRS-C AES-2006 containment passive heat removal system in a reduced scale. Experiments conducted on the PASI facility focus on performance and behaviour of such system. The numerical activities related to this experiment are done both with system and CFD codes. Within this paper, recalculation of the first test PAS-01 is done both with MELCOR and ATHLET.

2 FACILITY DESCRIPTION

The reference PHRS-C AES-2006 passive cooling system for the PASI facility is composed of a set of 16 heat exchangers located inside the containment. These heat exchangers are fed by feedwater located in a tank above. The location of the pool and the heat exchanger allows development of natural circulation and consequent heat removal through the heat exchanger. When in operation, water heated in the heat exchanger flows up along the riser pipeline, through a sparger device, and enters the water tank. Steam formed in the heat exchanger is evacuated at the top of the water tank.

The PASI facility is located at the Lappeenranta-Lahti University of Technology LUT in Finland. The facility represents one passive circulation loop with piping, one heat exchanger consisting of 15 tubes, and a water pool. A cylindrical vessel simulates containment conditions around the heat exchanger. The desired pressure and temperature are maintained by steam injection. A scheme of the PASI facility is given in Figure 1.

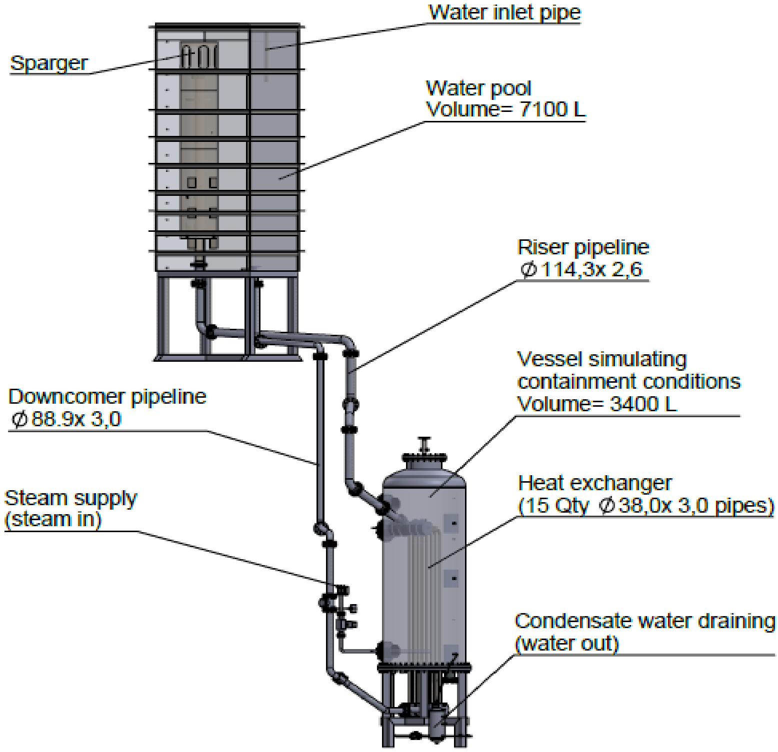

Figure 1: PASI Experimental facility [1]

2.1 Experimental scenario

Test matrix for the PASI facility in the frame of the PASTELS project was defined in [2]. This paper aims at the first test, the PAS-01, which belongs to other tests aiming at characterization of the cooling system behaviour and effect of the loop flow resistance. This test starts at atmospheric pressure and temperature. The heat exchanger, water pool and connecting pipelines were initially filled with cold water (about 11 °C). Initial water level in the water pool was 2,935 m above water pool tank bottom. The facility is then heated up by 200 kW steam injection into the vessel simulating containment. The power is then reduced to 175 kW and to 150 kW. The atmospheric part of the vessel simulating containment was closed during the test. The condensate water was periodically removed to avoid flooding of the vessel. This process led to heating up the facility and obtaining a quasi-steady state with geysering and flashing in the circuit. Then, the downcomer valve was closed in steps – from fully open to 50 % closed, 81 %, 86 %, 91 % and finally 95 %. After each increase of the flow resistance, the system found a new quasi steady state. After the last closure, the valve was opened again to 100 %.

3 SIMULATION AND RESULTS

The simulation was done both with ATHLET 3.3 and MELCOR 2.2.18019. For both codes, a nodalisation of the PASI facility was developed considering the capabilities and limitations of each code. Both models were used in previous steps, which included pre-test simulations as well as fine tuning of the pressure losses with forced flow through the loop. Initial and boundary conditions of both simulations are in consonance with the measured results of the PAS-01 test [3] as described in chapter 2.1.

3.1 ATHLET

The ATHLET nodalisation includes all parts of the PASI facility. Large volumes such as containment vessel and the pool take advantage of 2D modelling by two parallel pipes and a cross connection object providing horizontal flow between them. Except the cold and hot collector, which are modelled as branch objects, the remaining piping is defined by standard pipes. Boundary conditions are maintained by fill objects and time dependent volumes. An overview of the nodalisation is presented in Figure 2.

The evaluation aims at few examples of pressure differences and temperatures in some sections of the facility. A more detailed evaluation is out of scope of this paper and will be presented in PASTELS project reports. Even though the pressure losses were set previously with nearly perfect agreement for different flows, the results of the two-phase flow exhibit underestimation of most of the measured points. Figure 3 left shows the pressure losses in the downcomer section (D5006). This discrepancy leads to the overestimation of the mass flow through the circuit, cf. Figure 3 right. As in the experiment, some oscillations can be observed in the calculation as well, but the scatter is significantly lower.

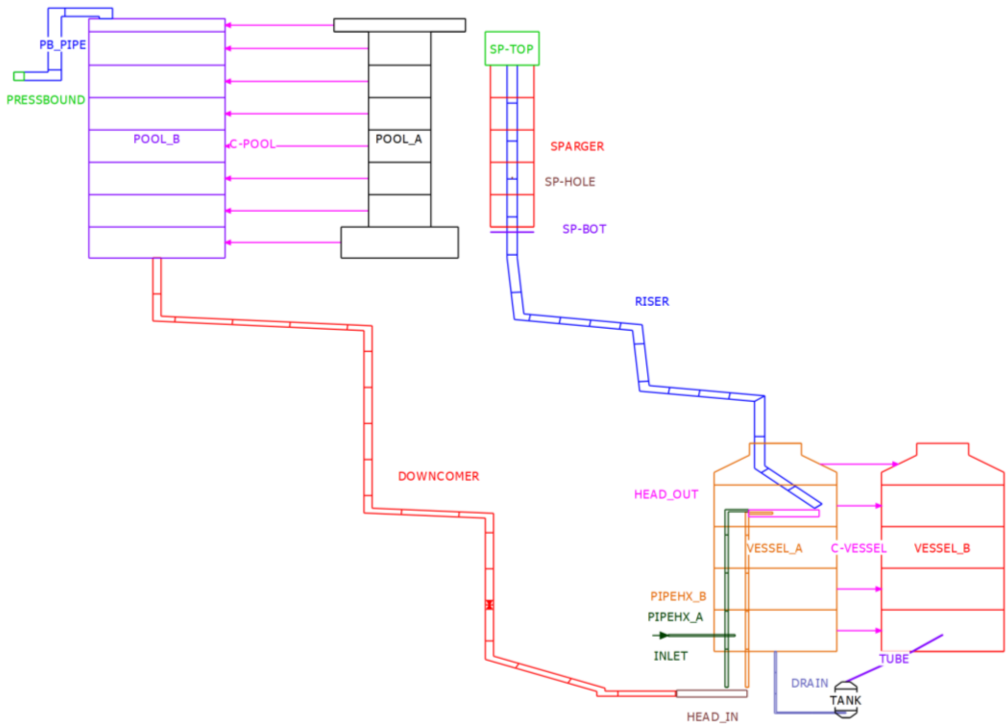

Figure 2: ATHLET nodalisation of the PASI test facility

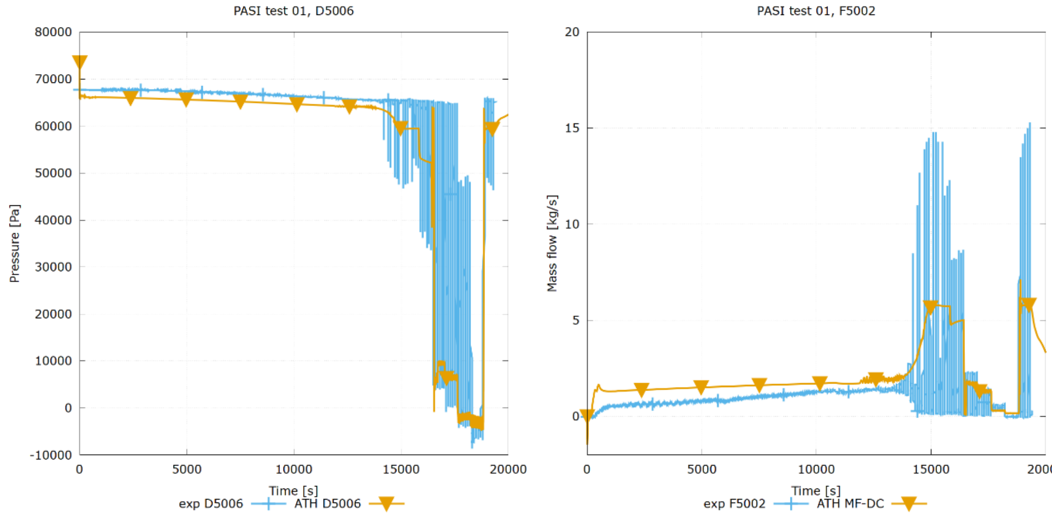

Figure 3: ATHLET results of the PAS-01 (left – pressure difference across the downcomer, right – mass flow in the downcomer)

To illustrate the calculated temperatures, two positions in the circuit are evaluated. The temperature in the riser pipeline close to the heat exchanger (Figure 4 left) is underestimated until 7500 s approximately. This is caused by generally higher mass flow in the circuit due to underestimated pressure losses and an unexpected flow oscillation in the first seconds of the process. In the later phase, the calculated temperature is higher compared to the experiment. The temperature in the pool lower section (Figure 4 right) is overestimated significantly. This effect is caused by the adopted 2D approach, which provides very good mixing with reduced stratification. As for the pressure differences, the calculation exhibits more stable flow with less oscillations when compared to the experiment.

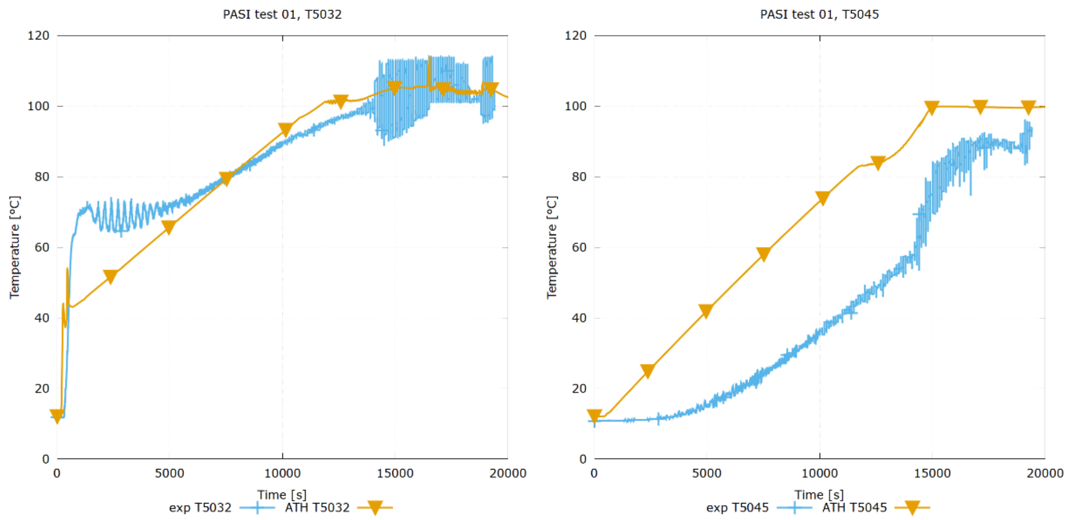

Figure 4: ATHLET results of the PAS-01 (left – temperature in the riser, right – temperature in the pool)

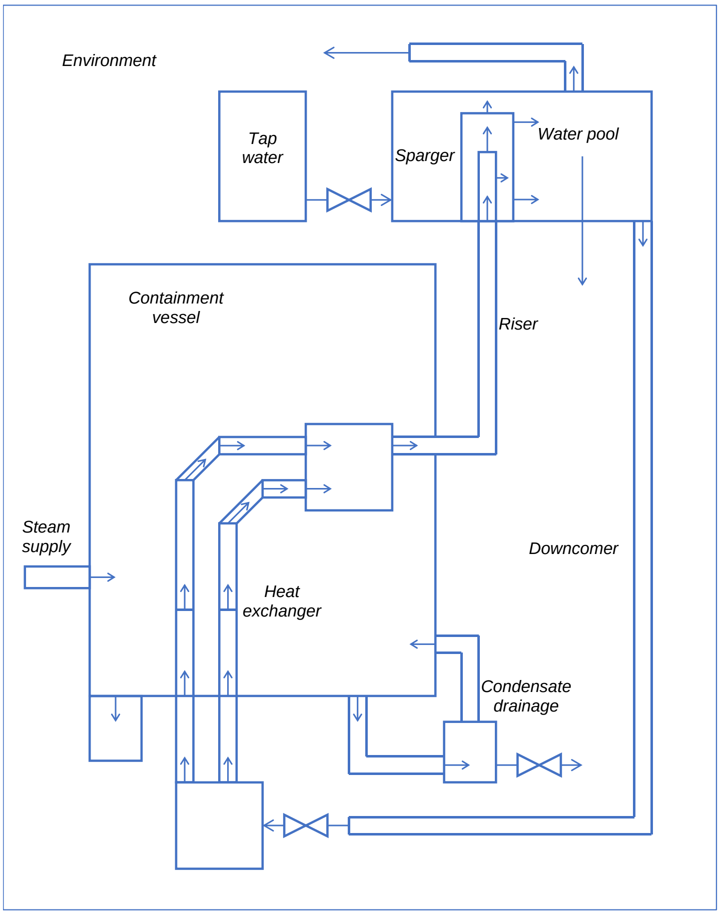

Figure 5: MELCOR nodalisation of the PASI test facility

3.2 MELCOR

Model for MELCOR is intentionally simple compared to the ATHLET model. MELCOR is mostly used for long term integral calculations of whole nuclear power plants. Fine detailed nodalisations of real plant parts with many nodes could be overly demanding from the computation time point of view. Therefore, models of auxiliary plant systems are built rather simply. Experiments used for validation should be modelled with comparable level of details. The scope of this work is to investigate if reasonable results can be obtained with simple model and if not, what level of details is required. In any case, more detailed nodalisation of PASI is also planned.

The current model consists of 26 control volumes, 32 flow paths and 51 heat structures. Overall nodalisation (without heat structures) is shown in the figure above. Model was developed according to available data, e.g. [1]. Pressure loss coefficient as a function of the downcomer shutoff valve opening is taken from [4]. The model allows simulation of cold tap water supply into water pool, but it was kept closed in the experiment PAS-01.

As in the previous case, the evaluation aims at pressure differences and temperatures. The coarse nodalisation approach used in MELCOR does not allow precise estimation of all measured pressure loses in the circuit. The pressure loss in the downcomer is in good agreement when the valve is fully opened. After closing the valve, the pressure difference is overestimated significantly, cf. Figure 6 left. Even though some local quantities may not be estimated correctly, the general behaviour, i.e. the mass flow in the circuit is in very good agreement with the experiment, except earlier development of oscillations at 12500 s approximately, cf. Figure 6 right.

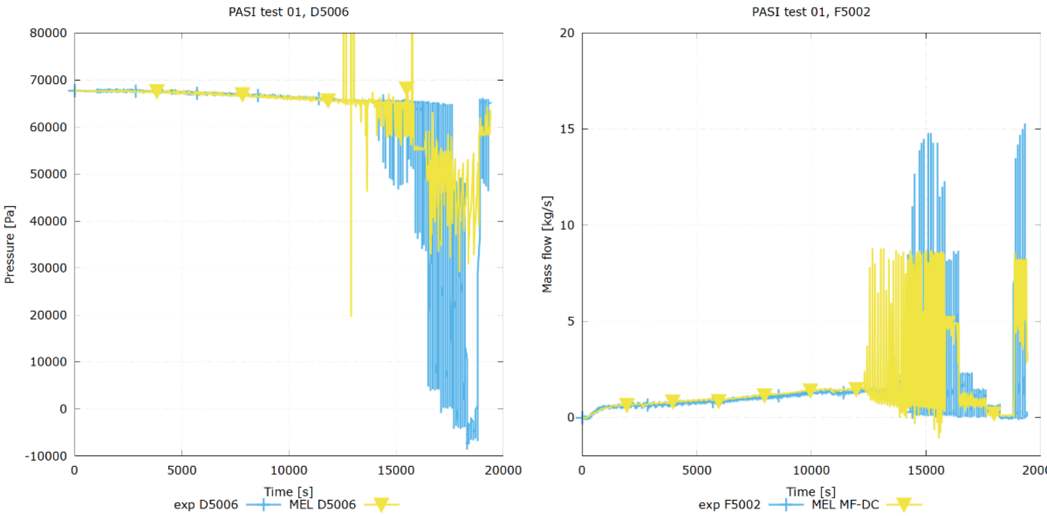

Figure 6: MELCOR results of the PAS-01 (left – pressure difference across the downcomer, right – mass flow in the downcomer)

The temperature in the riser close to the pressure vessel is in good agreement. The simulation provides generally slightly higher values and shows earlier development of oscillations, cf. Figure 7 left. The temperature in the pool lower section is overestimated, cf. Figure 7 right. This effect is caused by the 0D approach, which assumes immediate mixing of the content and average temperature of the volume, i.e. the stratification cannot be achieved in this case.

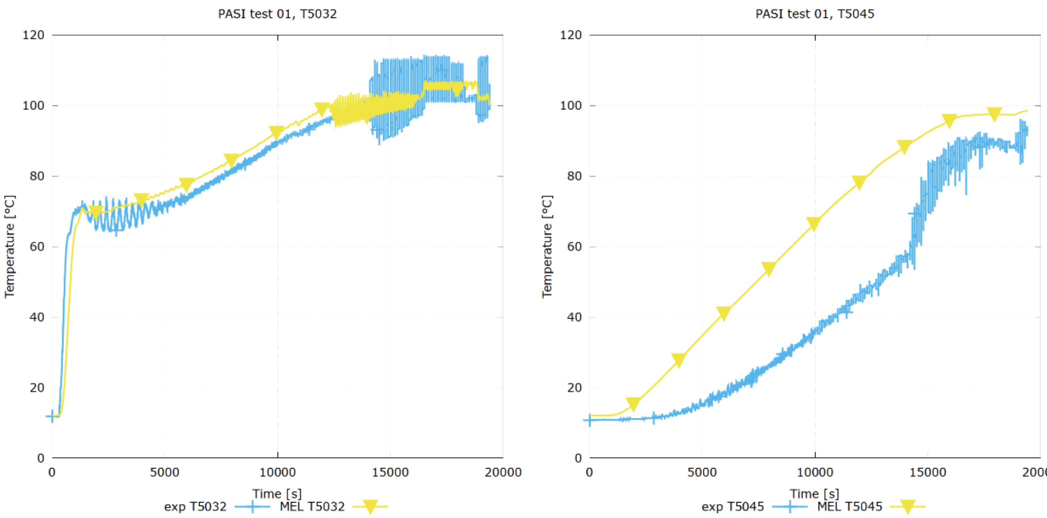

Figure 7: MELCOR results of the PAS-01 (left – temperature in the riser, right – temperature in the pool)

4 SUMMARY

Both codes proved to be applicable for evaluation of the PASI experiment with some remarks. The simulation conducted with ATHLET exhibits slightly lower pressure losses, even though the pressure losses were set up previously on forced flow tests. Furthermore, in early phase of the calculation some unexpected flow oscillations leading to increase of the mass flow were observed. This problem will be studied in following simulations. Regarding the temperatures, the discrepancy observed for the riser temperature is tied with the flow oscillations in the early phase. The pool temperatures are generally close to the average pool temperature, even though the pool adopted 2D modelling approach. To get the stratification correctly, the nodalisation would have to be refined.

MELCOR simulations exhibit very good agreement for the mass flow and for the temperature in the riser tube. The calculated mass flow rate, however, is much less oscillating compared to experiment when downcomer shutoff valve is partly closed. The calculated pool temperature is close to the average pool temperature. Temperature stratification cannot be observed due to 0D modelling approach. Creating finer nodalisation could bring more detailed results, e.g. stratification.

ACKNOWLEDGMENTS

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The PASTELS project idea has also obtained the NUGENIA label on 23/09/2019 (Certificate number: 2019NUG0076) prior to the submission of the project to the European Commission.

ACRONYMS

AC2	ATHLET – COCOSYS
AES-2006	Атомная электростанция (Nuclear Power Plant), Russian design
CFD	Computational Fluid Dynamics
EU	European Union
PASI	Passiivinen lämmönsiirtojärjestelmä (Passive heat removal system)
PASTELS	Passive systems: Simulating the thermal-hydraulics with experimental studies
PHRS-C	Passive Containment Heat Removal System

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