PRE-TEST COMPUTATIONAL FLUID DYNAMICS AND SYSTEM THERMAL HYDRAULICS CALCULATIONS OF THE E-SCAPE SCALED LBE POOL FACILITY

M. Greco , F. Mirelli, S. Keijers and K. Van Tichelen
SCK•CEN
Boeretang 200, 2400 Mol, Belgium
mgreco@sckcen.be; fmirelli@sckcen.be; skeijers@sckcen.be; kvtichel@sckcen.be

ABSTRACT

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) is a flexible fast-spectrum research reactor under design at SCK•CEN, the Belgian Nuclear Research Center. MYRRHA is a pool-type reactor with Lead Bismuth Eutectic (LBE) as primary coolant. The proper understanding of the thermal hydraulic phenomena occurring in the reactor pool is an important issue in the design and licensing of MYRRHA. Model experiments are necessary for understanding the physics, for validating numerical simulation tools and to qualify the design for the licensing.

The E-SCAPE (European SCAled Pool Experiment) facility at SCK•CEN is a thermal hydraulic 1/6-scale model of the MYRRHA reactor, with an electrical core simulator, cooled by LBE. It will provide experimental feedback to the designers on the forced and natural circulation flow patterns. Moreover, it enables to validate the computational methods for their use with LBE.

The paper elaborates on the pre-test analysis using Computational Fluid Dynamics and system thermal hydraulics codes. The analysis predicts the behavior of the E-SCAPE facility in the different operational conditions described in the test matrix and compares it to the anticipated MYRRHA behavior. Moreover, the paper shows and discusses the possibilities and limitations of both the CFD and the system code approaches.

KEYWORDS
E-SCAPE, MYRRHA, CFD and System Code Simulations, Liquid Metals, Decay heat removal

1. INTRODUCTION

The E-SCAPE (European SCAled Pool Experiment) facility at SCK•CEN is a thermal hydraulic 1/6-scale model of the MYRRHA reactor [1], with an electrical core simulator of 100 kW as main power source, cooled by LBE [2]. It plays an important role in the investigation of the feasibility of the passive decay heat removal after reactor shut-down and provides experimental feedback to the designers on the flow patterns in pool-type reactors. Moreover, it enables to benchmark and validate the computational methods for their use with LBE.

A set of pre-test analyses based on the as-built models of the facility has been performed using the RELAP5 system code and the Ansys CFX CFD code. The analyses cover the main steady state and transient cases as foreseen for the MYRRHA reactor and some cases specific to E-SCAPE, as the hot plug simulation. The comparison between the pre-test analyses on the E-SCAPE facility and the anticipated behavior in MYRRHA is presented and discussed.

2. FACILITY DESCRIPTION

The E-SCAPE facility is constructed at the SCK•CEN site in Mol, Belgium. The system, shown in Figure 1, consists of the main vessel, two LBE external circuits, the cooling loops, the filling & draining system and the steel structure for piping and tanks.

The main vessel and its internals are a scale reproduction of MYRRHA, except for the primary pumps and heat exchangers, which, in contrast to MYRRHA, are located in two external loops A (left in Figure 1) and B because of their large dimensions. The heat generated in the electrical core simulator in the main vessel is removed via the external heat exchangers by the cooling system using diathermic oil. Two air-coolers, positioned outside the building, dump the heat in the atmosphere.

The total volume of LBE in the main vessel and loops is 2.5 m³, the nominal temperature of the lower plenum is 200°C while the upper plenum temperature varies between 206°C (forced circulation) and 315°C (natural circulation at full core power). The flow rate varies from 2.4 kg/s (natural circulation) to 120 kg/s (forced circulation).

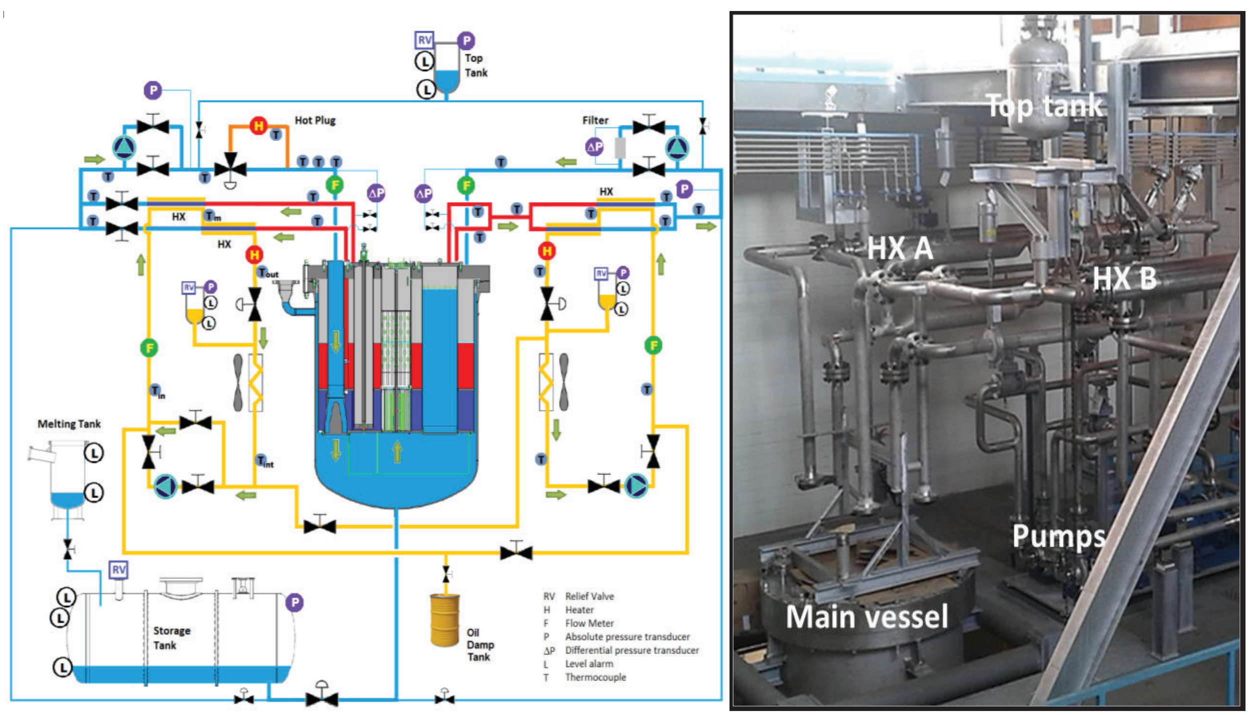

Figure 1. Overview of the E-SCAPE simplified layout and installation.

The E-SCAPE facility has been realized after performing an extensive non-dimensional analysis to preserve the overall behavior of the MYRRHA prototype plant and the major thermal hydraulic phenomena, as detailed in [3] and [4]. These phenomena deal with flow and temperature distribution, free surface oscillation, decay heat removal and residence time in the plena of the main vessel. For the pre-test calculation presented here, the Richardson scaling approach has been chosen [3][5], with the input parameters shown in Table I. With the Richardson scaling, buoyancy effects are correctly represented. This is important when studying the transition from forced to natural circulation.

The design of the E-SCAPE facility is based on the MYRRHA design as described in the "MYRRHA Technical Description" version 1.2 [6]. Although the design of MYRRHA has evolved and version 1.6 is now fully documented, system analyses have shown that E-SCAPE still properly represents the thermal hydraulic phenomena in MYRRHA. Process parameters were taken from the RELAP5 simulations of MYRRHA [7].The main characteristics of the E-SCAPE facility compared to the reference values of MYRRHA are reported in [4] and [8]. The system will work both in steady state force circulation (pumps on) and natural circulation (pumps off). The conditions reached after different events (one pump shut down, loss of heat sink) can also be simulated.

Due to the reduced dimensions of E-SCAPE, a maximum power of 100 kW is available in its core. This value allows scaling correctly the decay heat 1 s after the scram (7% of the nominal power) for the natural circulation cases. It is not feasible to properly scale the heat generated by MYRRHA in nominal operation. The maximum power is applied in all the cases, to reach the maximum temperature difference between the upper and lower plenum. The pre-test calculations demonstrate that E-SCAPE can accurately reproduce the phenomena occurring in nominal operation despite not respecting the temperature field.

Table I. Input parameters for E-SCAPE according to the Richardson scaling approach

SS case	Input	Unit	E-SCAPE	MYRRHA
Forced circulation	Power	kW	97.0	110 000
	Mass flow rate	kg/s	118.8	9 553
Natural circulation	Power	kW	97.0	7 800

3. PRE-TEST CALCULATIONS

3.1. Pre-Test Test Matrix

The pre-test calculations for the E-SCAPE facility with RELAP5 and Ansys CFX are defined on the basis of the test matrix reported in [4]. The cases are listed in Table II. All cases have been simulated with the RELAP5 system code, whereas a CFX simulation was performed only for the forced circulation and hot plug cases. The complete results are reported in [8]. In this article, cases 1+3, 4, 5 and 7 will be reported.

Table II. Test matrix for the pre-test calculations

CASE	Power	Pumps	HX	Model
1 Forced circulation	Maximum	2	4	RELAP5 + CFX
2 LOF Long term decay	Decay heat (7% to 0.5%)	C	4	RELAP5
3 LOF	Constant decay heat (7%)	C	4	RELAP5
4 Pump Failure	Constant decay heat (7%)	1	4	RELAP5
5 Partial LOHS	Constant decay heat (7%)	2	2	RELAP5
6 Partial LOHS + LOF	Constant decay heat (7%)	0	2	RELAP5
7 Hot plug	Maximum	2	4	RELAP5 + CFX

The reactor is scrammed in case 3, 4 and 5. To be conservative, the decay heat is kept constant, instead of following the decay heat curve. In forced circulation (case 1), in the hot plug transient (case 7) and at the start of each event, the power inserted in the facility is equal to the maximum power in E-SCAPE, corresponding to 7% of the scaled nominal power in MYRRHA. Thus in E-SCAPE, differently from MYRRHA, before and after an event, the power does not change for the cases analyzed here.

For comparison, RELAP5 calculations have been performed for MYRRHA using a simplified model based on the model described in [7], without the accurate simulation of the secondary and tertiary systems. In order to have a correct comparison with the E-SCAPE calculations, the analysis of MYRRHA has been carried out with powers at the start of all events of 110 MW and 7.8 MW (i.e. 7%). This will demonstrate that the power in forced circulation does not affect the mass flow rates, the velocities, the pressures or the free surface heights but only the temperature profile, thus E-SCAPE simulates correctly the hydraulic behavior of MYRRHA.

3.1.1. Case 1+3 – From forced circulation to LOF

This case combines the results of the steady state conditions in forced circulation (case 1) and natural circulation (case 3). MYRRHA and E-SCAPE work in forced circulation with both pumps running and 4 heat exchangers in action. In forced circulation, the power is 97 kW for E-SCAPE, 7.8 MW or 110 MW for MYRRHA. At 3000 s, the two primary pumps are switched off. When this event occurs, the power is set or kept at 7% of the (scaled) nominal power. In E-SCAPE the shutdown of the pumps is also associated to the closure of the two pump branches and the opening of the two natural circulation branches, whereas for MYRRHA only the pumps need to be stopped. The coast-down of the pumps is taken into account for MYRRHA and E-SCAPE. The simulation ends at 15000 s when a new steady state is reached in natural circulation. The input parameters of the secondary cooling loop remain constant.

3.1.2. Case 4 – Pump failure

Case 4 foresees the failure of one pump at 3000 s, after the steady state condition in forced circulation has been reached. The simulations end at 15000 s when a new steady state condition has been obtained. The shutdown of one pump, the power curve and the cooling system behavior remain the same as in case 3. The other pump continues running without any variation.

3.1.3. Case 5 – Partial LOHS

The partial Loss Of Heat Sink case simulates the sudden loss of two heat exchangers linked to one pump. At 3000 s, the cooling loop is deactivated for two heat exchangers and the walls of the pipes become adiabatic. The two working heat exchangers take over the heat removal for the entire system. The simulation ends at 15000 s. During the complete simulation the pumps are running. The power of the facilities varies as in case 3.

3.1.4. Case 7 – Hot plug

This transient is typical of the E-SCAPE facility. The hot plug is a small volume of hot LBE (~100°C more than nominal temperature) in a closed branch upstream the pump channel ready to be injected in the vessel. When the 3-way valve switches position, the hot volume is pushed in the lower plenum. The goal of the simulation is to determine the residence time of the fluid particles in the lower plenum and possibly in the upper plenum, by means of an elaborate net of thermocouples placed in the vessel. In the simulation the hot plug is activated at 3000 s. The calculation ends at 10000 s when a new steady state is reached. During the entire transient, the pumps are on and the 4 heat exchangers are in action.

3.2. Ansys CFX Case Setup

The model of the E-SCAPE main vessel has been realized with the CFD code Ansys CFX [9]. The mesh is an unstructured tetrahedral mesh with prismatic element in the boundary layers region. It presents 32 millions of elements. A sensitivity analysis was performed to demonstrate mesh-independence.

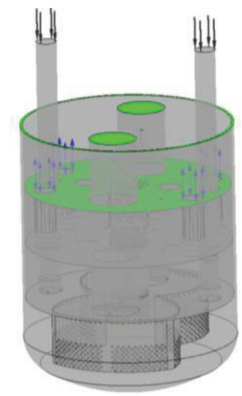

Figure 2. Boundary conditions for the Ansys CFX simulation of the main vessel of E-SCAPE.

The external circuits are not simulated with CFD: the model presents an inlet and outlet where boundary conditions are applied (see Figure 2). The inlets are the two pumps channels, highlighted by black arrows, in which a constant mass flow rate of 59.4 kg/s per pipe is applied. The inlet temperature is 200 °C. The outlet is made of the four heat exchanger channels, highlighted by blue arrows: a 0 bar reference pressure is set here. The free surface is obtained by a free-slip boundary condition and involves the top part of the upper plenum and of the external gap (the green regions). A no-slip boundary condition is applied to the walls. A uniform heat source of 97 kW is applied to the core.

The k-ε turbulence model has been used and a scalable wall function is applied. The numerical schemes used are high resolution as advection scheme and first order for turbulence. A constant turbulent Prandtl number is assumed. There's no conjugate heat transfer and the simulation is a steady state.

3.3. RELAP5 Case Setup

The thermal-hydraulic analysis has been performed using the system code RELAP5/mod.3.3, modified at the University of Pisa and ENEA to allow for LBE as cooling fluid [10]. An extended use of cross-flow junctions has been made, in order to attempt a more realistic simulation of the three-dimensional velocity and temperature fields in lower and upper plenum [8].

In contrast to the CFD simulations, the external coolant loops have been modeled including pumps, heat exchangers and the hot plug section. The input parameters for the secondary system have been analytically calculated, since E-SCAPE will use oil in the cooling loop, whereas for the RELAP5 simulations water in change of phase was used, with the values reported in Table III.

Table III. Input parameters for the E-SCAPE cooling system

Mass flow rate	kg/s	0.06
Temperature	°C	178
Pressure	bar	10

3.4. Simulation Results

In all graphs, the values of flow rate, pressure and free surface height for MYRRHA have been scaled according to the Richardson scaling laws described in [4] to be able to compare to the E-SCAPE ones.

3.4.1. From forced circulation to LOF (case 1+3)

3.4.1.1. Mass flow rate in the system code simulation (RELAP5)

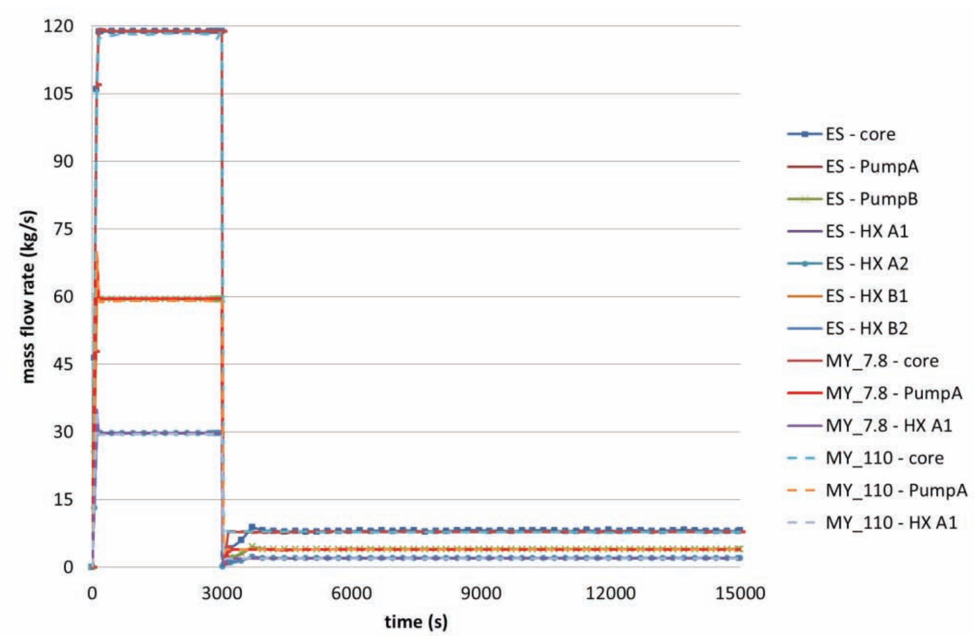

Figure 4. Mass flow rates for E-SCAPE and MYRRHA for case 1+3.

The mass flow rates passing through the core, the pumps and heat exchangers of E-SCAPE and MYRRHA in both configurations (7.8 MW and 110 MW before the scram) are shown in Figure 4. Only one pump and one heat exchanger of the two MYRRHA configurations are presented. In all the cases, the two pumps deliver exactly the same mass flow, which is equally distributed into the four heat exchangers. In forced circulation, steady state is reached in less than 200 s and the trends are perfectly overlapping. When the pumps switch off, the mass flow rate reaches the minimum but then increases again to a steady state value in natural circulation, exactly 7% of the forced circulation value. The mass flow is created by difference of temperature between the thermal center of the core and the heat exchangers, corrected by the control valves in E-SCAPE to match the scaling requirements. The comparison between the E-SCAPE values and the MYRRHA ones shows that the profiles are exactly the same, except a deviation right after the shutdown of the pumps due to the different switching procedure.

The comparison with both the models for MYRRHA demonstrates that the mass flow rates are not affected by the power inserted in the core for the steady state conditions in forced and natural circulation.

3.4.1.2. Mass flow rate in the CFD simulation (CFX)

In order to evaluate the ability of RELAP5 to simulate the correct mass flow rate in complex 3-D geometries through the use of cross-flow junctions, the flow exiting the holes of the barrel (see Figure 2) from the CFD simulation with Ansys CFX has been compared to the results obtained by RELAP5 in forced circulation. The comparison is shown in Figure 5. The results obtained by the CFD model have been used to tune the pressure drops (K-factors) of the RELAP5 model. Perfect agreement is obtained.

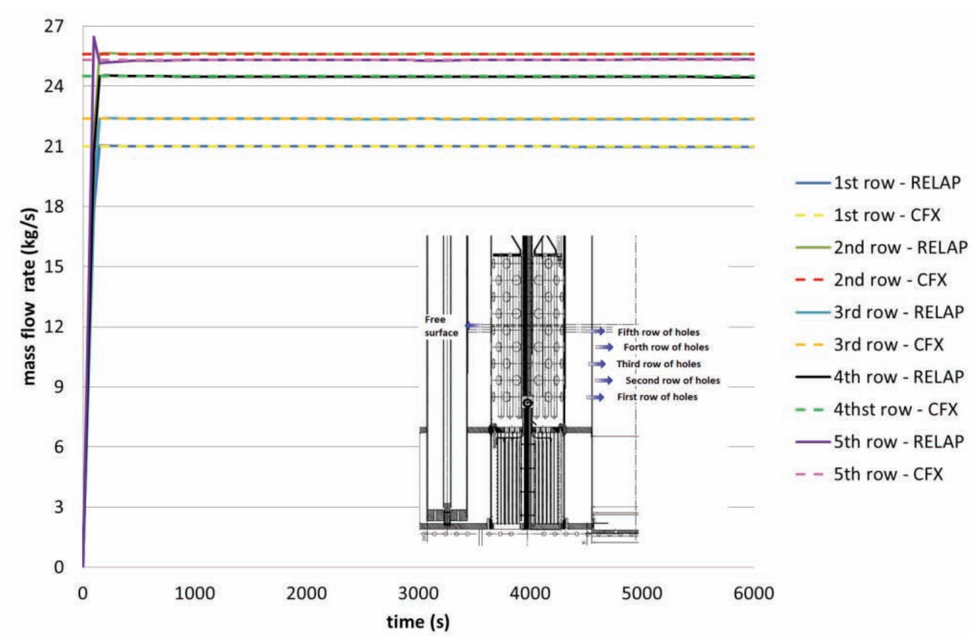

Figure 5. Mass flow exiting the first 5 rows of holes in the E-SCAPE barrel in steady state – Comparison CFX/ RELAP5

3.4.1.3. Pressure differences in the system code simulation (RELAP5)

The pressure differences for core, ACS and plena in E-SCAPE and MYRRHA are shown in Figure 6. DP_core represents the pressure drop due to the lower and upper grid of the core and the core itself, DP_ACS represents the pressure drop due to the ACS and the holes in the barrel and the DP_plena represents the pressure difference between the upper and lower plenum.

The profiles are perfectly overlapping in forced circulation. One more time it is evident that the different core power does not influence the hydraulic performance of the scaled model of the MYRRHA reactor. After the shutdown of the two pumps, the pressure difference in natural circulation decreases to few hundreds of Pa. Profiles are overlapping. The oscillatory behavior is due to the low values of the pressure.

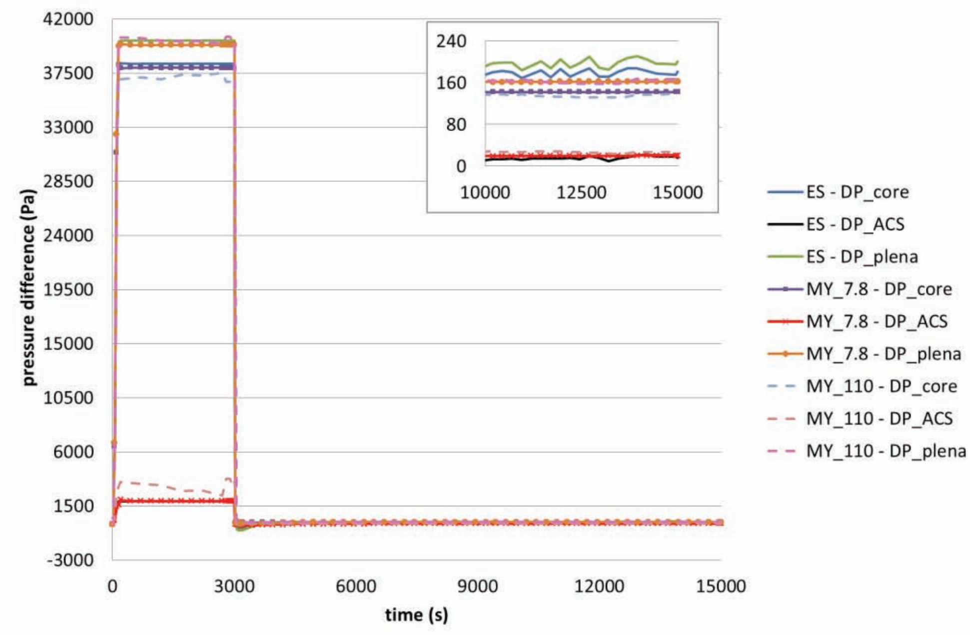

Figure 6. Pressure differences for E-SCAPE and MYRRHA in case 1+3.

3.4.1.4. Pressure differences in the CFD simulations (CFX)

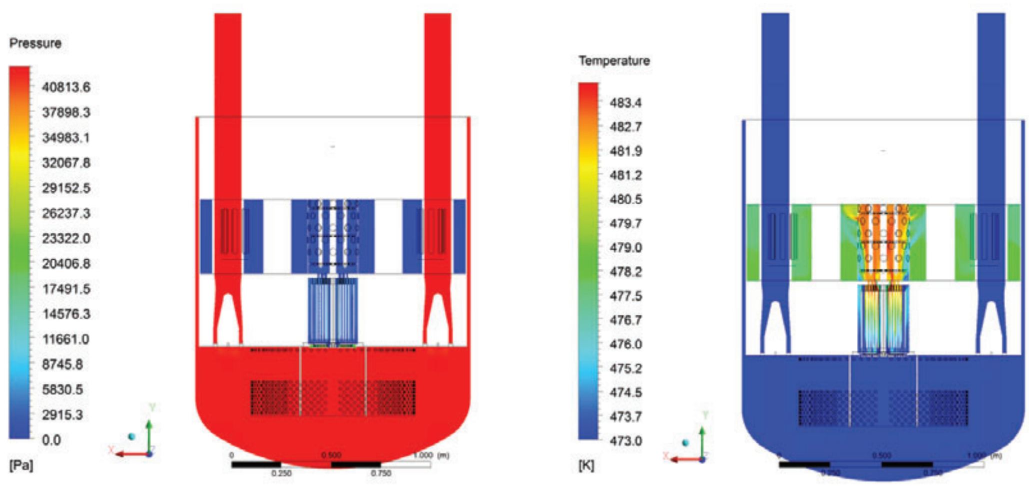

Figure 7. Pressure field (left) and temperature field (right) in the pump plane for the E-SCAPE facility obtained by a Ansys CFX simulation for the steady state case

Figure 7 shows the relative pressure field in the E-SCAPE facility in the pump plane in forced circulation. The pressure drop between the upper and the lower plenum is around 40 kPa, in agreement with Figure 6. The biggest contribution to the pressure drop is given by the lower grid, as detailed in [8]. The comparison confirms that RELAP5 is able to predict the correct pressure distribution in complex 3D geometries.

3.4.1.5. Temperature differences in the system code simulation (RELAP5)

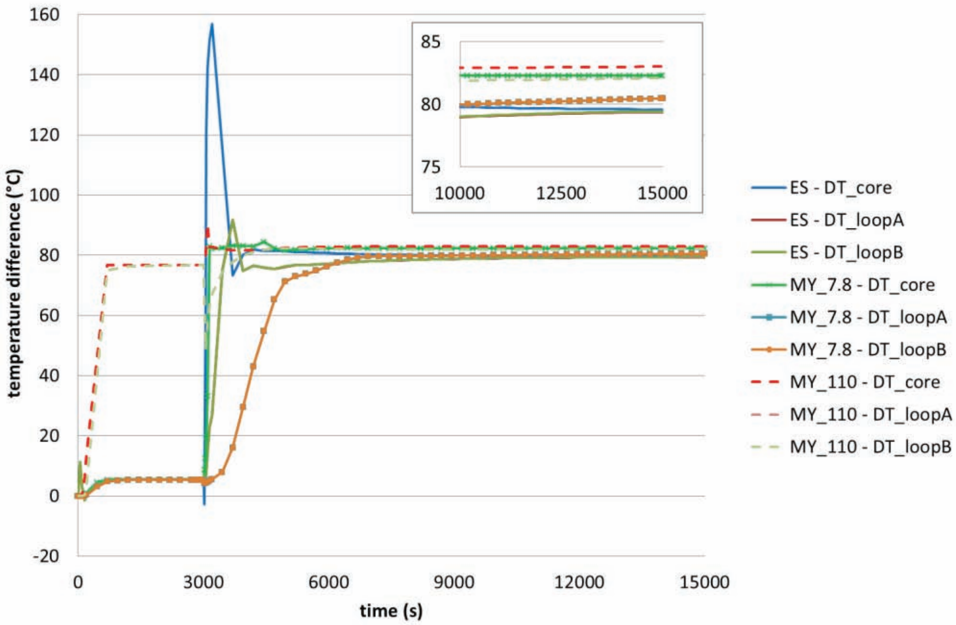

Figure 8. Temperature difference for E-SCAPE and MYRRHA for case 1+3.

The temperature differences in the core, in the loop A and in the loop B of E-SCAPE and MYRRHA are shown in Figure 8. DT_core represents the temperature difference between the outlet and the inlet of the core, DT_loopA and DT_loopB represent the temperature difference between inlet and outlet of each couple of heat exchangers.

In forced circulation, the profiles of core and heat exchangers are perfectly overlapping demonstrating that all the power inserted is extracted by the cooling loops. The temperature difference of the MYRRHA case at 110 MW is around 77°C, as indicated in [6] and [7], whereas for MYRRHA at 7.8 MW and E-SCAPE the temperature difference is around 5.5°C.

Right after the shutdown of the pumps, the temperature in the core of E-SCAPE presents a peak of 155°C, due to the simulation of the valves and pump behavior with RELAP5, whereas the picks are smaller for MYRRHA. The switching procedure and in particular the timing of the valves has to be optimized making use of the experimental results in order to reproduce the correct response with the system codes. Once the steady state has been reached, the trends of E-SCAPE are very similar to the ones of MYRRHA at 7.8 MW. MYRRHA at 110 MW is slightly higher. Again the natural circulation is not affected by the initial power of the core.

3.4.1.6. Temperature differences in the CFD simulations (CFX)

Figure 7 shows the temperature field in the E-SCAPE facility. In the lower plenum the LBE is at 200°C. When the fluid flows through the core the temperature increases. The average difference of temperature between upper and lower plenum is around 6 °C, in agreement with Figure 8.

CFD is capable of predicting local temperatures, allowing to detect zones with excessive heating. The pictures demonstrate that the average temperature given by the system code RELAP5 in the volumes is in full agreement with the temperature difference detected by the Ansys CFX code.

3.4.1.7. Free surface heights in the system code simulation (RELAP5)

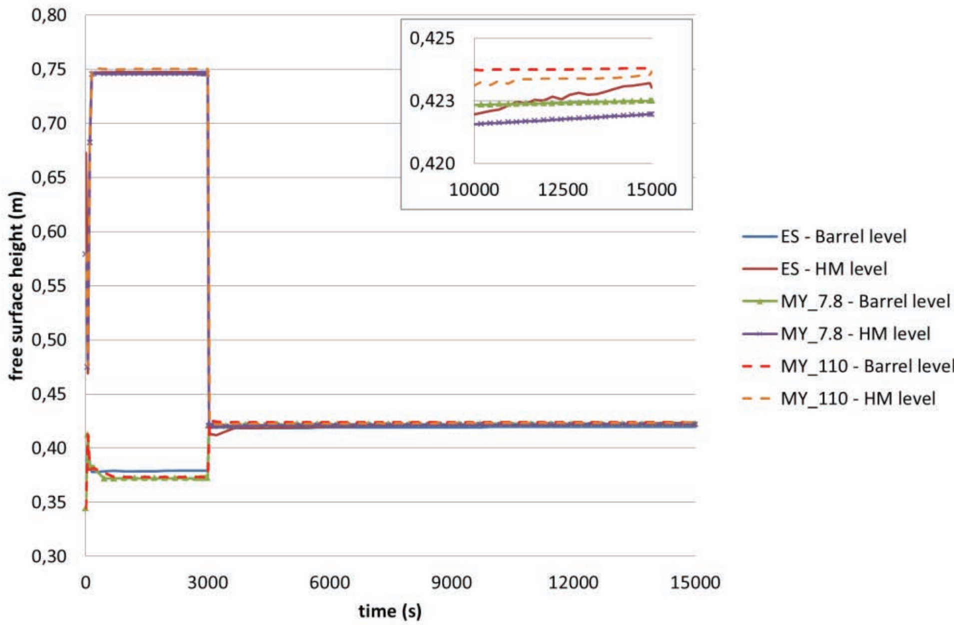

Figure 9. Free surface heights for E-SCAPE and MYRRHA in case 1+3.

The free surface levels in the barrel and in handler machine of E-SCAPE and MYRRHA are shown in Figure 9. The difference between the two free surfaces is due to the pressure drops of the core, the upper and lower grid and the ACS. After the pumps shutdown, the distance between the free surfaces reduces strongly because of the large reduction in flow rates and pressure drops. All the profiles are perfectly overlapping, demonstrating that E-SCAPE can properly simulate the behavior of MYRRHA.

3.4.2. Pump failure (case 4)

3.4.2.1. Mass flow rate in the system code simulation (RELAP5)

The mass flow rates passing through the core and the two pumps of E-SCAPE and MYRRHA are shown in Figure 10. E-SCAPE responds to the shutdown of the pump in the B-loop in a similar way to MYRRHA: the pump in the A-loop delivers more mass flow, due to the changed characteristic of the system and a reverse flow occurring in the B-pump, when the coastdown is finished. In the B-loop, natural circulation does not occur since it is overcome by the action of the working pump. The mass flow rate values of the reactor and its model are different due to the loop configuration of E-SCAPE and the characteristics of the pumps, which are different from the MYRRHA pump.

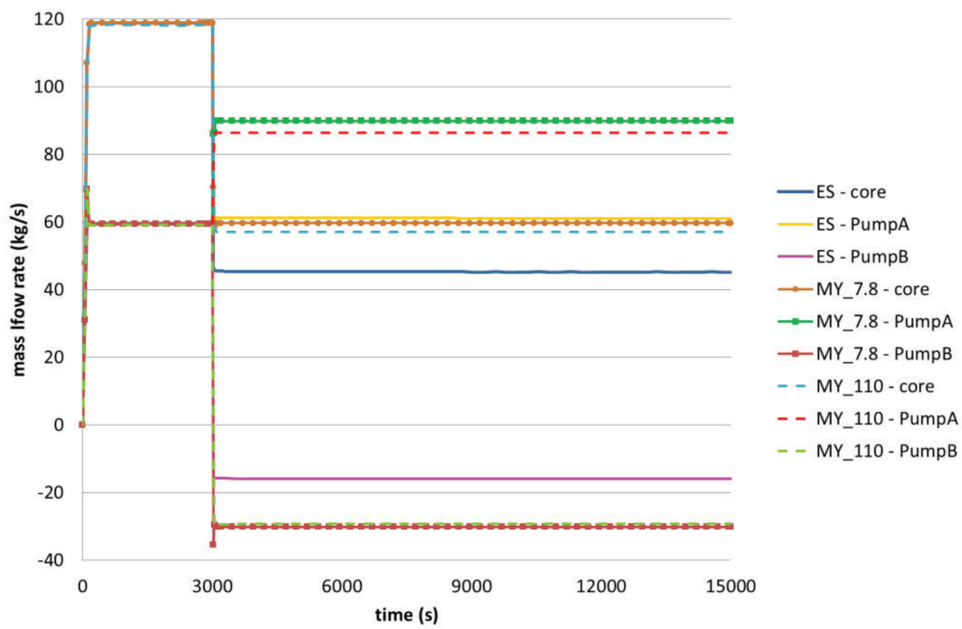

Figure 10. Mass flow rates for E-SCAPE and MYRRHA for case 4.

3.4.2.2. Temperature differences in the system code simulation (RELAP5)

The temperature differences in the core, in the loop A and in the loop B of E-SCAPE and MYRRHA are shown in Figure 11. The temperatures in the B-loop are negative because the flow is going in the opposite direction, from the pump inlet to the heat exchangers outlets. The values are different for E-SCAPE and MYRRHA due to the different mass flow rates, but the response to the event is the same.

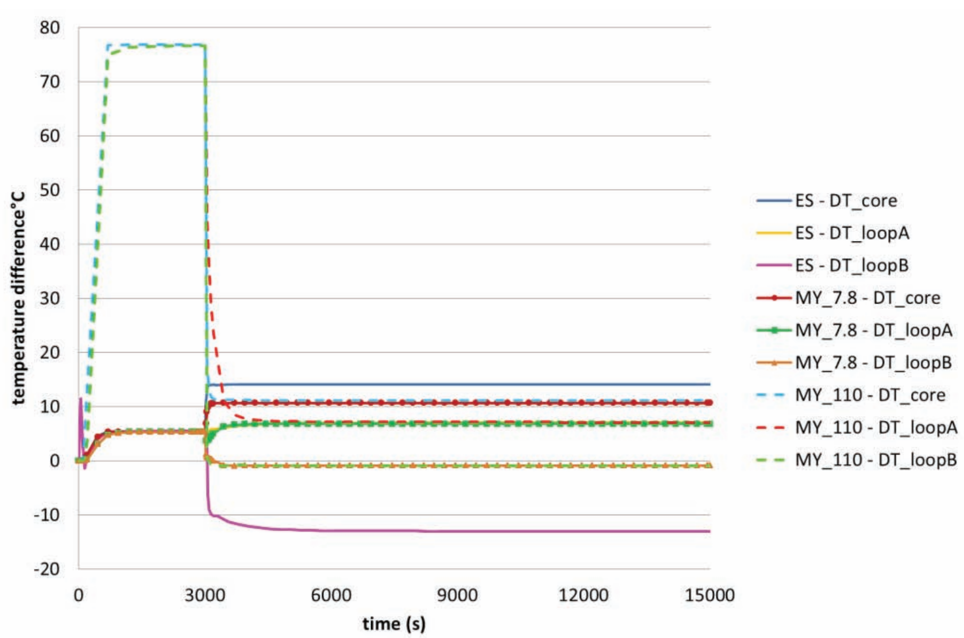

Figure 11. Temperature differences for E-SCAPE and MYRRHA in case 4.

3.4.3. Partial LOHS (case 5)

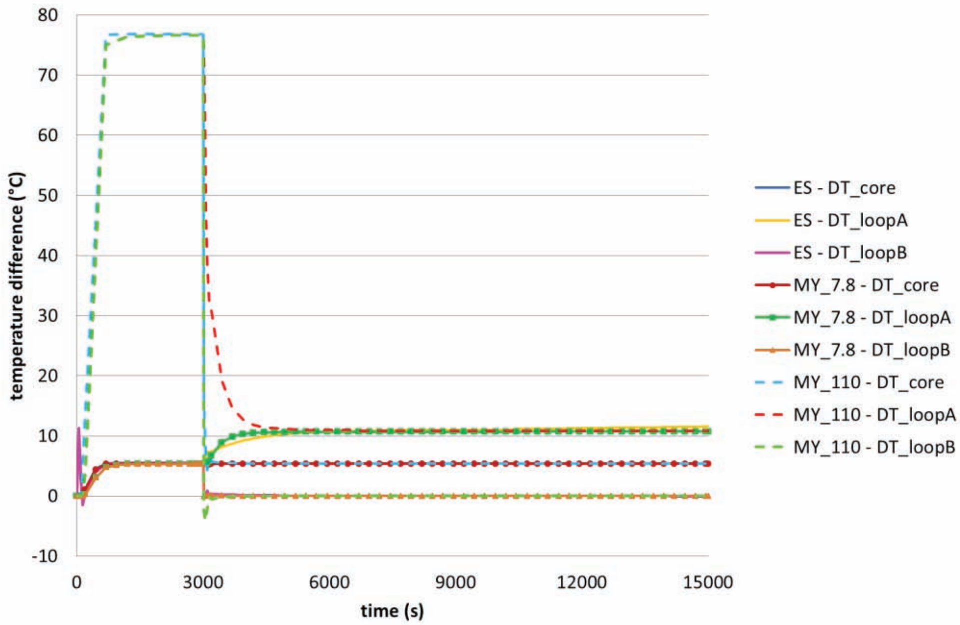

Figure 12. Temperature difference for E-SCAPE and MYRRHA in case 5.

The temperature differences in the core, in the loop A and in the loop B of E-SCAPE and MYRRHA are shown in Figure 12. Since at 3000 s the heat exchange between the water of the secondary system and the LBE of the primary system for the B-loop is reset to zero, the temperature difference in this side becomes null. The temperature difference in the core remains the same as in forced circulation (6°C), because the mass flow rate and the power do not change. All the heat inserted by the core has to be removed from the working heat exchangers in the A-loop, which double their temperature delta (12°C). The trends are perfectly overlapping, after the event, for the three models, demonstrating that E-SCAPE follows the same behavior of the prototype reactor.

3.4.4. Hot Plug transient (case 7)

The temperature profiles for the lower plenum and core obtained with the RELAP5 simulation during the hot plug case are compared with the results from the CFD simulation [11] and presented in Figure 13.
The graphs have the same trend and the hot plug passage is detected in the lower plenum after 5 s and in the core after 10 s, both for the RELAP5 and CFD calculations. The temperatures calculated by RELAP5 are around double of the temperatures given by the CFD simulation and the duration of the phenomenon is longer. RELAP5 averages the values on the entire volume, whereas CFX returns a local measurement. Also the flow direction is forced in the 1-D configuration, whereas in the 3D model there is more mixing.

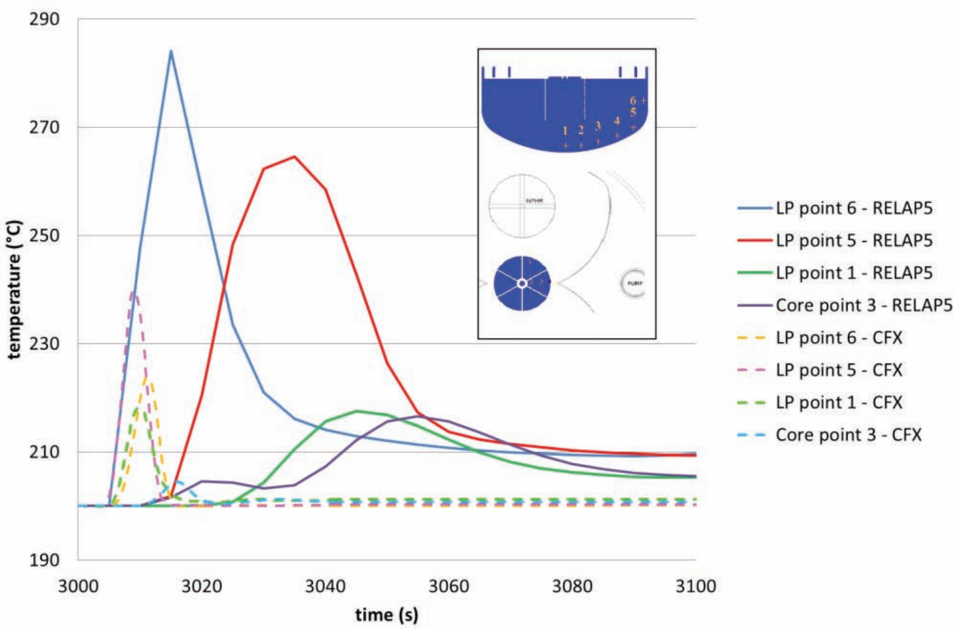

Figure 13. Temperature profiles for the Lower Plenum and the core of E-SCAPE calculated by RELAP5 and CFX during the hot plug case.

4. CONCLUSIONS

The E-SCAPE (European SCAled Pool Experiment) facility at SCK•CEN is a thermal hydraulic 1/6 scale model of the MYRRHA reactor, with an electrical core simulator of 100 kW as main power source, cooled by LBE.

A set of pre-test analyses based on the as-built models of the facility has been performed using the RELAP5 system code and the Ansys CFX computational fluid dynamic code.

The comparison between the pre-test analysis on the E-SCAPE facility and the anticipated behavior in MYRRHA shows that E-SCAPE is capable of simulating the steady state conditions of MYRRHA both in forced circulation and in natural circulation consequent to an event. The transient behavior of E-SCAPE is different from the one of MYRRHA, due to the presence of the two external loops and the actuation of the valves to pass from forced to natural circulation.

In forced circulation and for the hot plug case, the results obtained by the RELAP5 calculation have been compared to the outcome of a CFD analysis performed with CFX. The comparison confirms that RELAP5, despite its 1-D characteristic, can simulate complex 3-D phenomena, however after proper tuning of the models based on the input of the 3-D models. No information on local data can be retrieved.

The results of the pre-test analyses will be used later for the comparison with the experimental results.

NOMENCLATURE

ACS	Above Core Structure
C	Coastdown
CFD	Computational Fluid Dynamics
E-SCAPE	European SCAled Pool Experiment
ES	E-SCAPE
MY_X	MYRRHA at X MW
HX	Heat Exchanger
LBE	Lead-Bismuth Eutectic
LOF	Loss Of Flow
LOHS	Loss Of Heat Sink
MYRRHA	Multi-purpose Hybrid Research Reactor for High-tech Application
SS	Steady-State
THINS	Thermal Hydraulics of Innovative Nuclear Systems

REFERENCES

1. De Bruyn D. et al., April 2014, The MYRRHA ADS project in Belgium enters the Front End Engineering Phase. 2014, Proceedings of the 2014 International Congress on Advances in Nuclear Power Plants. Charlotte, NC, United States, American Nuclear Society, pp.646-654.
2. Fazio C., Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials, Compatibility, Thermal-hydraulics and Technologies. s.l. : OECD/NEA, 2007. 6195.
3. Greco M., Mirelli F., Van Tichelen K., 2013, Report on the design of the HLM pool mock-up and experiments. Deliverable 2.1.04, FP7 Collaborative Project THINS N° 249337, EURATOM.
4. Van Tichelen K., Greco M., Mirelli F., Viviani G., E-SCAPE: a scale facility for liquid-metal, pool-type reactor thermal hydraulic investigations. THINS 2014, Nuclear Engineering and Design, NED-S-14-00985.
5. Van Tichelen K., Vanderhaegen M., Jajarayu S., Keijers S., Roelofs F., 2011a, Scaling analysis for the European heavy liquid metal scaled pool facility E-SCAPE. International Topical Meeting on Nuclear Reactor Thermal Hydraulics 14 (NURETH-14), Toronto, Canada, Canadian Nuclear Society.
6. Ait Abderrahim H., et al., October 2011, MYRRHA Technical Description. SCK-CEN/593205/42.
7. Bubelis E., Schikorr M., February 2012, FASTEF safety analysis – critical mode. Deliverable D2.3, FP7 Collaborative Project CDT N° 232527, EURATOM.
8. Greco M., Mirelli F., Van Tichelen K., Eckert S., 2015, Report on the HLM pool experiments: facility description and pre-test analysis. Deliverable 2.1.08, FP7 Collaborative Project THINS N° 249337, EURATOM.
9. ANSYS, Inc. ANSYS CFX, 2012, Solver Modeling Guide. Canonsburg: s.n.
10. Coccoluto G., Gaggini P., Labanti V., Tarantino M., Ambrosini W., Forgione N., Napoli A., Oriolo F., May 2011, Heavy liquid metal natural circulation in a one-dimensional loop. Nuclear Engineering and Design, 241, 1301-1309.
11. Viviani G., Forgione N., Ambrosini W., Van Tichelen K., Castellitti D., 2014, Optimization of the RELAP model for the E-SCAPE pool facility based on CFD analysis, Master Thesis, Ingegneria Energetica, Pisa.