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ANALYSIS OF INTEGRAL CIRCULATION AND DECAY HEAT REMOVAL EXPERIMENTS IN THE LEAD-BISMUTH CIRCE FACILITY WITH RELAP5 CODE

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Abstract

In this paper, the results of the post-test analysis of some integral circulation experiments conducted on the lead-bismuth CIRCE facility are presented in comparison with the experimental data. These experiments include the simulation of unprotected loss of flow and unprotected loss of heat sink transients in a pool-type heavy liquid metal reactor. Furthermore, the results of the pre-test analysis of a protected loss of heat sink and flow transient with decay heat removal by a heat exchanger immersed in the pool and operating in natural circulation is presented. All transient analyses have been performed with the RELAP5 thermal-hydraulic code.

Introduction

Within the THINS Project of the VII Framework EU Program on Nuclear Fission Safety, several experimental works are addressed to investigate thermal-hydraulic aspects relevant to mixed convection phenomena in heavy liquid metal (HLM) reactors cooled by lead or lead-bismuth alloy. Some experiments on the large scale facility CIRCE [1] at the ENEA/Brasimone center will be carried out to investigate the transition from forced circulation to natural circulation in a pool-type reactor in accidental conditions, with the consequent actuation of a decay heat removal (DHR) system.

In the CIRCE facility an electrically heated test section simulates the core. The forced circulation of lead-bismuth in the primary system is achieved by gas lifting in the riser and the core power is removed by a water bayonet tube heat exchanger (HX) which works under atmospheric pressure on the secondary side. The heat exchanger of the DHR system is immersed in the upper part of the cold pool and its startup and operation relies on natural circulation of lead-bismuth on the primary side, while forced circulation of air on the secondary side allows the removal of the core residual power.

A pre-test analysis has been performed with the RELAP5 Mod3.3 code [2] in order to verify the feasibility of these tests. The suitability of the RELAP5 model developed for this analysis has been first verified through the post-test analysis of integral circulation experiments carried out within the EUROTRANS Project of VI Framework EU Program.

In this paper, at first the results of the post-test analysis of some integral circulation experiments conducted on the CIRCE facility are presented in comparison with the experimental data. These experiments include the simulation of unprotected loss of flow (ULOF) and unprotected loss of heat sink (ULOH) transients. Finally, the results of the pre-test analysis of a protected loss of heat sink and flow (PLOH + LOF) transient with DHR system actuation for core residual heat removal are presented.

1. The CIRCE facility and experimental campaigns

The CIRCE facility at ENEA Brasimone research centre has a pool-type configuration and was primarily designed to model the primary system of an ADS plant cooled by molten lead-bismuth eutectic (LBE) alloy. An overview of the CIRCE facility at it was used within the EUROTRANS project is depicted in Figure 1. Forced circulation of LBE can be sustained by gas injection in the riser located above the heated section (HS) simulating the core. From the top of the riser the hot LBE circulates and cools down in the bayonet tube HX coming back to the HS inlet after mixing in the lower pool. The nominal power of the heated section is 800 kW and the LBE temperature varies between 300 – 400 °C, being the LBE mass flow rate through the primary circuit equal to 55 kg/s.

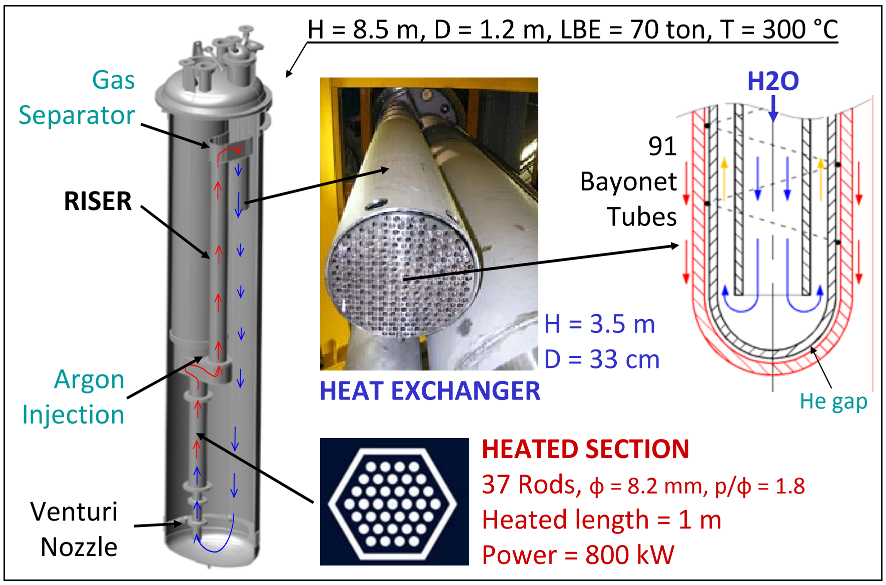


Figure 1 Overview of the CIRCE Facility

The test section representing the core is a bundle of 37 rods electrically heated arranged in a triangular lattice with a heated length of 1 m. The water HX installed and tested in the facility is a mock-up of the W-DHR Dip Cooler conceived for decay heat removal in the lead-cooled ELSY reactor [3]. The bayonet tubes of the Dip Cooler are represented in real scale, but with a slightly reduced length (3.5 m instead of 4 m of immersed tube length) due to facility geometrical constraints. A reduced number of tubes (91 instead of 397 in ELSY Dip Cooler design) are used, which should be able to remove the nominal power of CIRCE (800 kW).

During the experimental campaign conducted within the DEMETRA domain of the EUROTRAN project, several integral circulation experiments were carried out to investigate core power removal by steam generators (water HX) immersed in the LBE pool under both enhanced and natural circulation conditions in the primary circuit. Some of these tests were devoted to simulate beyond design basis accident events, namely unprotected transients, which are taken into consideration in the safety analysis of HLM reactors. Two of these transients: the ULOH and the ULOF are analyzed in this paper.

A new experimental campaign is under preparation within the ongoing activities of the THINS project of VII Framework EU Program. Some tests will be conducted in CIRCE to investigate the decay heat removal in HLM reactors by a heat exchanger immersed in the primary pool and working under natural circulation condition on primary side. Particular emphasis will be devoted to investigate and monitor: (1) mixed and natural convection and stratification phenomena in the LBE pool, (2) the transition from forced to natural circulation in the primary system, (3) the startup and stabilization of natural circulation of LBE through the heat exchanger, and (4) the capability of the DHR system to remove the core residual power.

The installation of the DHR system in the CIRCE facility is schematized in Figure 2. The DHR heat exchanger is made of one bayonet tube and the decay power is removed by forced circulation of air on the secondary side. The outer shell of the bayonet tube is insulated by a thin air gap in order to limit the heat loss to the surrounding pool. Further upgrading of the CIRCE facility includes the insulation of the riser wall, with the aim to reduce the large heat loss observed during previous tests, and the implementation of a large number of new measurement points (mainly thermocouples) to monitor the evolution of interesting phenomena including temperature stratifications in the pool.

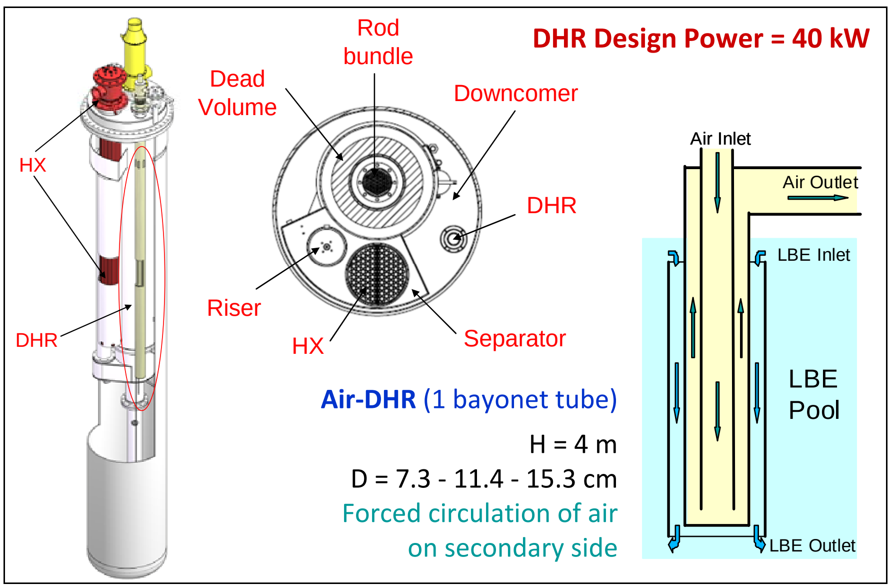


Figure 2 DHR heat exchanger arrangement in the CIRCE facility

The test matrix for THINS foresees the execution of various DHR tests at different core power levels and with the primary system operating under both forced and natural circulation conditions. The pre-test analysis presented in this paper concerns the PLOH + LOF transient, with transition from enhanced to natural circulation in the primary system at transient initiation.

2. RELAP5 modelling of the CIRCE facility

The RELAP5 code has been developed to simulate accidental thermal-hydraulic transients in LWR reactors. The code has been implemented with lead alloy thermo-physical properties by ENEA and Ansaldo for lead- and LBE-cooled fast reactor applications. The modified RELAP5 code has been validated on a number of experiments under both natural and forced convection conditions [4, 5] and used in the safety analysis of accelerator driven systems (e.g. the LBE-cooled XT-ADS and lead-cooled EFIT reactors [6]) and critical systems (e.g. the lead-cooled ELSY reactor).

The RELAP5 nodalization scheme used in the analysis of CIRCE experiments is depicted in Figure 3. The heated section is simulated by only one RELAP5 heat structure representing the 37 electrically heated rods. Pressure losses through the Venturi nozzle (calibrated and positioned in the inlet pipe to measure the LBE mass flow rate in the primary circuit) and the spacer grids are taken into account by calibrated singular pressure loss coefficients. The injection of argon at the riser bottom is modelled to reproduce the enhanced circulation in the primary system. Gas separation and release to the cover gas is taken into account at the riser exit, while the hot LBE is forced downwards through the HX tube bundle. The three different sectors of the HX tube bundle (7, 54, and 30 tube regions) with independent water feeding on the secondary side are simulated. Cross-flow junctions are used to try to take into account LBE mixing among the three different zones on the primary side. The bayonet tube of the DHR heat exchanger immersed in the upper part of the cold pool is also simulated and the air mass flow rate is imposed at the inlet as a boundary condition.

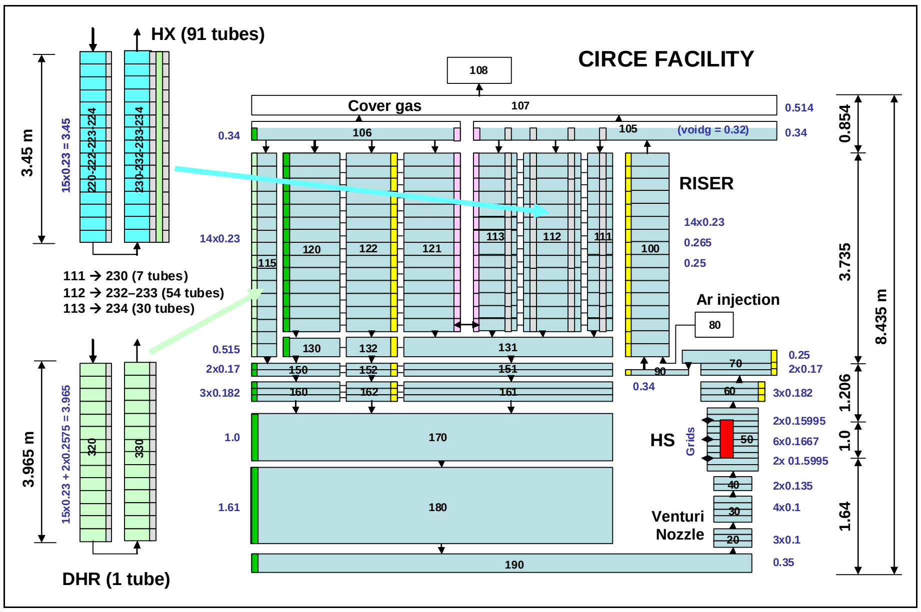


Figure 3 RELAP5 nodalization scheme of the CIRCE facility

Heat losses towards the LBE cold pool from non insulated hot components are taken into account in the RELAP5 modelling. In particular, the heat loss from the hot leg and the riser wall has a very significant impact on the HX inlet temperature, as demonstrated by the analysis of DEMETRA tests. The upper volume of the LBE pool, where the heat exchangers are located, is discretized in three regions and the sub-volumes are connected by cross-flow junctions. This is done to tentatively take into account natural convective phenomena induced by wall heat losses in the LBE pool. For the pre-test analysis of DHR experiment, the insulation by a thin air gap of the DHR external tube and the riser wall, introduced in the upgraded CIRCE facility to limit the heat losses towards the cold pool, has been then modelled.

3. Post-test analysis of DEMETRA experiments

The post-test analysis of some DEMETRA experiments has been performed in order to verify the suitability of the RELAP5 model to simulate CIRCE experiments under various transient conditions. The DEMETRA tests n. 1 (steady-state at nominal power), the test n. 3 (ULOH transient), and the test n. 5 (ULOF transient) have been calculated with RELAP5 and the code results have been compared with experimental data.

3.1 Steady-state at nominal power (test n. 1)

This experiment was mainly devoted to demonstrate the good performance of the water HX for core power removal and the stable operation of the system under enhanced circulation in the primary circuit. The Figure 4 shows the boundary conditions of the test and how they are reproduced in the RELAP5 calculation.

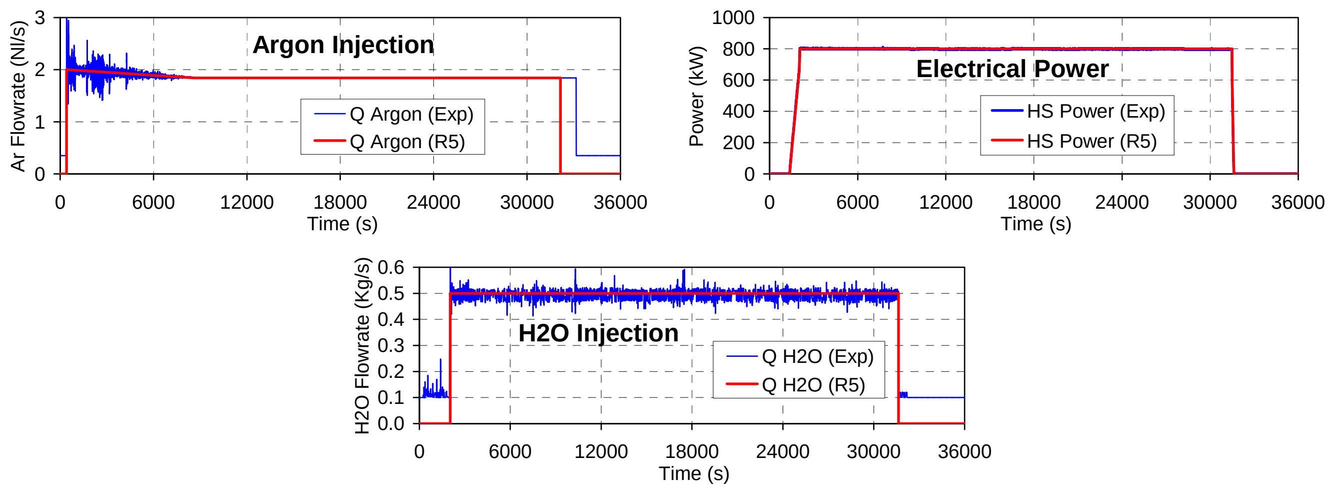
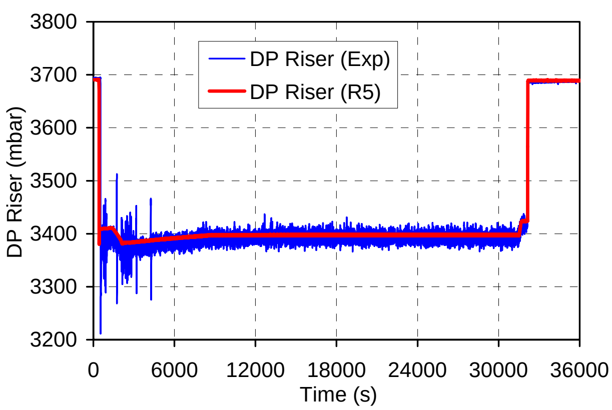


Figure 4 Boundary conditions of the test n. 1

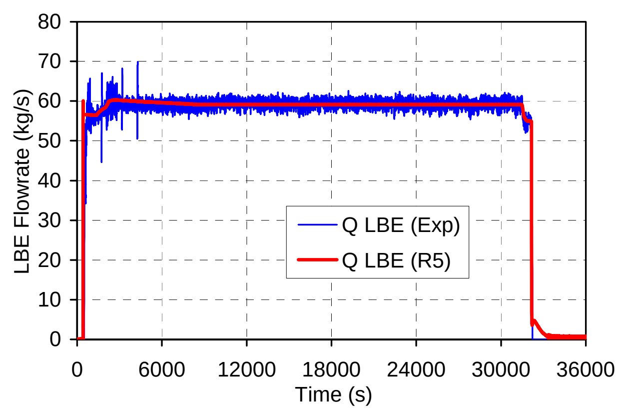
The experiment is initiated by argon injection in the riser (argon mass flowrate = 2 Nl/s) at t = 415 s to start the enhanced circulation in isothermal conditions at 300 °C. At t = 1360 s the power ramp is initiated reaching the nominal power of 800 kW at t = 2060 s. As soon as the power ramp is completed, the water injection in the HX is started at a constant mass flow rate of 0.5 kg/s, which is sufficient to remove the HS power (only partial evaporation of water is possible within the HX, because of his operation under atmospheric pressure on water side). Steady-state conditions are maintained for more than eight hours. Finally, the test is terminated at t = 31630 s by contemporary stop of electrical power supply and water and gas injections.

The main outcomes of the test n. 1 are compared with the RELAP5 results in Figure 5. After start of gas injection, the differential pressure in the riser (Figure 5.a), which depends on the weight of LBE column, reduces according with the void fraction which establishes along the riser. A further slight diminution of in the riser ΔP is consequent to the LBE heatup and due to density change versus temperature. The reduction in riser ΔP represents the driving force by gas lifting and buoyancy which must counterbalance the pressure losses in the primary circuit, mainly through the HS. Therefore, the LBE mass flow rate in the primary circuit (Figure 5.b) clearly increases as soon as the riser DP reduces. The LBE mass flow rate evolution, measured by a calibrated Venturi nozzle positioned in the inlet pipe, is very well reproduced by the code, as well as the riser ΔP. This means that the total pressure loss in the circuit is very well predicted too.

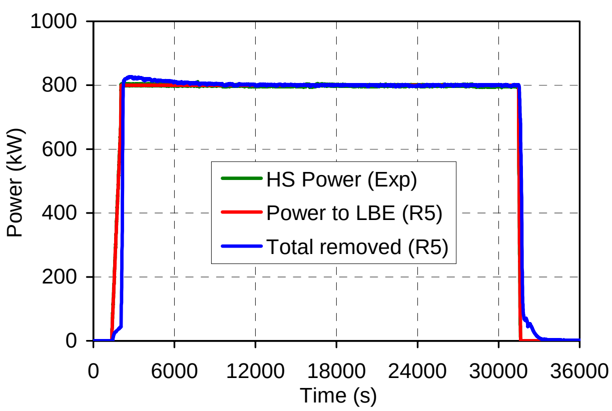
Steady-state conditions are attained soon in the system after the onset of water injection in the HX, as indicated by the power balance in Figure 5.c and the primary temperature evolution in Figure 5.d. Since the external vessel wall heaters were switched-off during the test, the heat loss from the vessel wall (approximately 50 kW) contributed to remove the HS power and, therefore, the effective power removed by the HX is about 750 kW. After a small temperature peak, the LBE temperature at the HS inlet stabilizes at 303 °C (Figure 5.d). The average ΔT through the HS is about 93 °C, as a result of the thermal balance through the HS calculated by RELAP5. Different temperatures are measured at the HS outlet depending on the location of thermocouples in the bundle sub-channels. As expected, the highest temperature is measured in central sub-channels and the lowest one at the bundle periphery, which is expected to be more representative of the average value. The thermal-hydraulic behaviour of the system and power removal by the HX is quite well simulated by RELAP5. The primary temperature overestimation at the beginning of the transient (see Figure 5.d) is likely due to limitation of the 1-D model in representing temperature stratifications in the cold pool, which might delay the transit time back to the HS of hot LBE flowing out from the HX, before water injection start-up. Another important outcome of the test is the large heat loss observed from the hot leg and the riser walls towards the surrounding cold pool, leading to important temperature reduction at the HX inlet. This very high power loss, estimated to be approximately 260 kW, cannot be calculated with standard 1-D heat transfer models and, therefore, it has been tentatively reproduced with RELAP5 using calibrated convective heat transfer coefficients on the hot leg and riser walls.



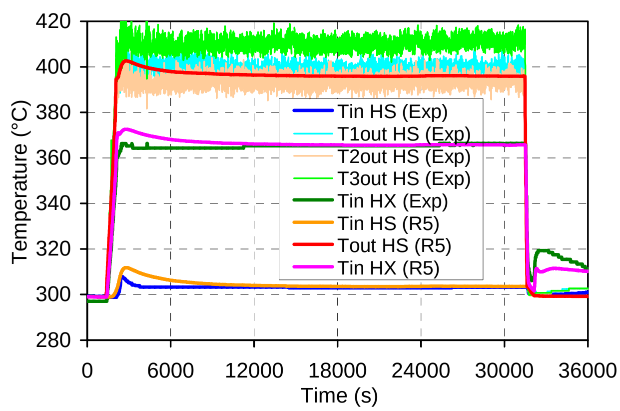
a) ΔP in the riser



b) LBE mass flow rate in primary circuit



c) HS power and HX removed power



d) LBE temperature through HS and at HX inlet

Figure 5 Main outcomes of the test n. 1 and comparison with RELAP5 results

3.2 ULOH transient (test n. 3)

This experiment was devoted to simulate an ULOH accidental transient in a HLM reactor, consisting in the total loss heat removal by the secondary circuits with failure of the reactor scram by the protection system. The Figure 6 shows the boundary conditions of the test and how they are reproduced in the RELAP5 calculation. The first part of the test was devoted to attain a steady-state conditions as discussed for the previous test n. 1. Then the ULOH transient was started at t = 9820 s by stopping the water injection in the HS, while the electrical power supply was maintained at the nominal level of 800 kW. The transient duration was limited to about half an hour, in order to avoid excessive temperatures in the system, in particular to limit the clad peak temperature at the HS outlet. The transient was then terminated at t = 11650 s by switching off the electrical power supply along with the gas injection.

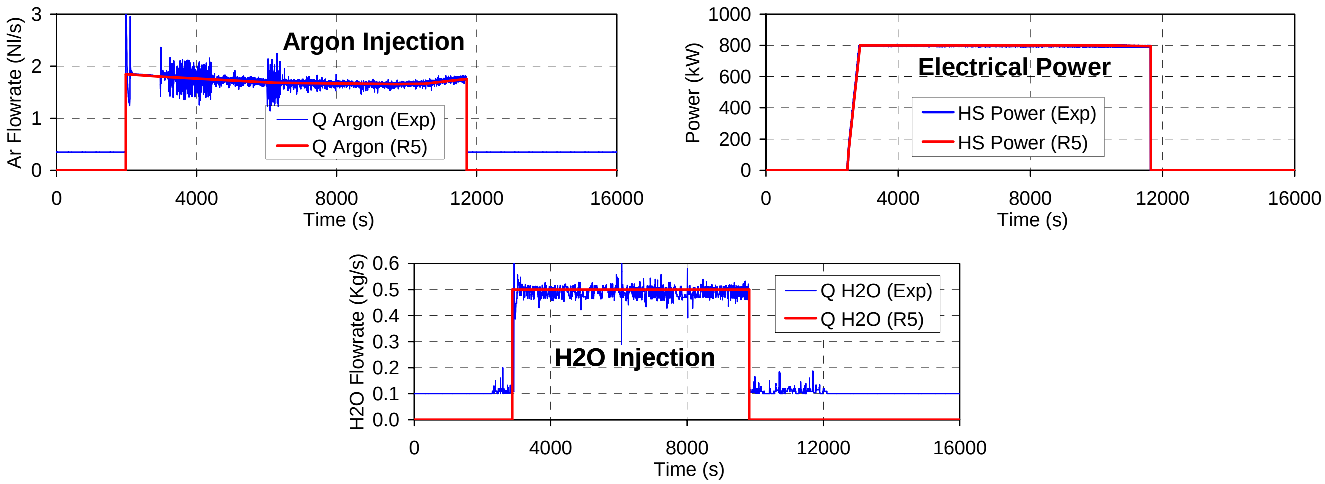
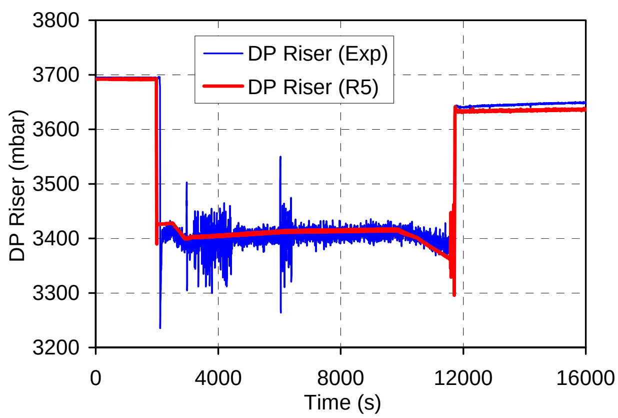
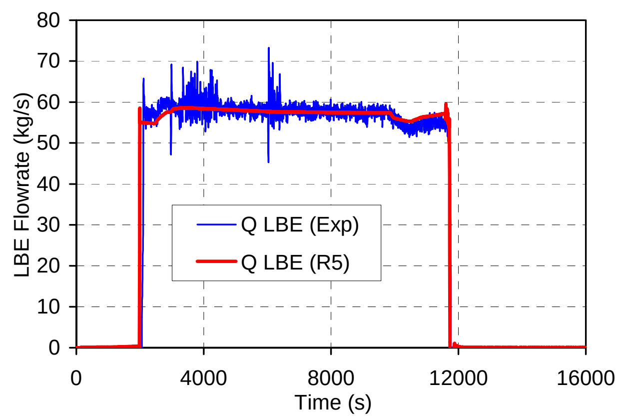


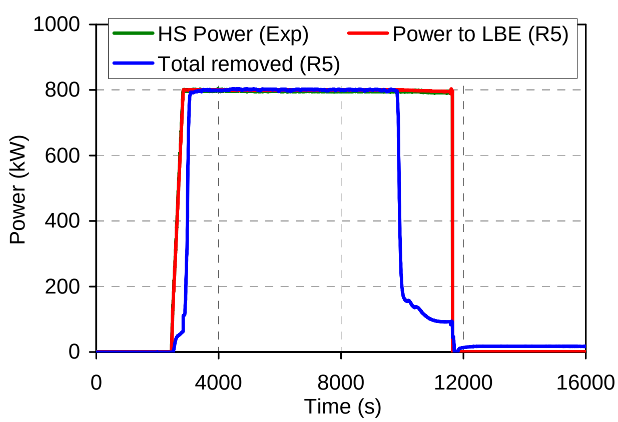
Figure 6 Boundary conditions of the test n. 3



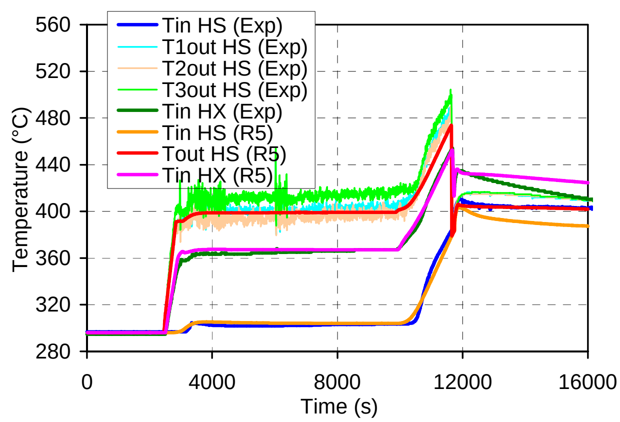
a) ΔP in the riser



b) LBE mass flow rate in primary circuit



c) HS power and HX removed power



d) LBE temperature through HS and at HX inlet

Figure 7 Main outcomes of the test n. 3 and comparison with RELAP5 results

The main outcomes of the test n. 3 are compared with the RELAP5 results in Figure 7. The steady-state operation before the ULOH transient initiation is very similar to the previous one (test n. 1). Therefore, the riser ΔP (Figure 7.a) and the LBE mass flow rate evolution (Figure 7.b) are very well simulated by RELAP5, as well as the HS power removal by the HX plus vessel heat loss (Figure 7.c) and the LBE temperature stabilization in the primary system (Figure 7.d). In this test, the shorter duration of the power ramp and the prompt actuation of the HX water injection limit the overheating calculated by RELAP5 at the beginning of the stabilization phase.

As soon as the water injection is stopped at transient initiation, the total power removed drops down to about 150 kW and then progressively reduces up to 90 kW at the end of the transient phase (see Figure 5.c). Such a residual power removal includes both vessel heat losses and the thermal inertia of HX structures. The onset of HS heatup (Figure 5.d) is calculated a little bit earlier than in the test, likely due to hot LBE temperature stratification effect in the cold pool. However, the thermal inertia of the whole system and then the HS heatup at the end of the transient are quite well reproduced by the code.

3.3 ULOF transient (test n. 5)

This experiment was devoted to simulate an ULOF accidental transient in a HLM reactor, consisting in the loss of all primary pumps with failure of the reactor scram. The aim of this test was to investigate the transition from forced to natural convection and the stabilization of natural circulation in the primary system. The Figure 8 shows the boundary conditions of the test and how they are reproduced in the RELAP5 calculation. In this test, the initial stabilization phase is attained at a reduced HS power level (710 kW) than the nominal one, and by augmenting the gas injection flowrate up to 3 Nl/s, in order to increase the LBE flowrate in the primary system, thus reducing the HS ΔT. This test procedure was chosen to avoid excessive clad peak temperatures at the HS outlet during the transient phase.

The ULOH transient was started at t = 10730 s by stopping the gas injection in the riser, while the electrical power supply was maintained at a constant level of about 720 kW. The transient phase lasting more than one hour was terminated by switching off the electrical power supply at t = 15010 s, followed by stop of water injection in the HX at t = 15260 s.

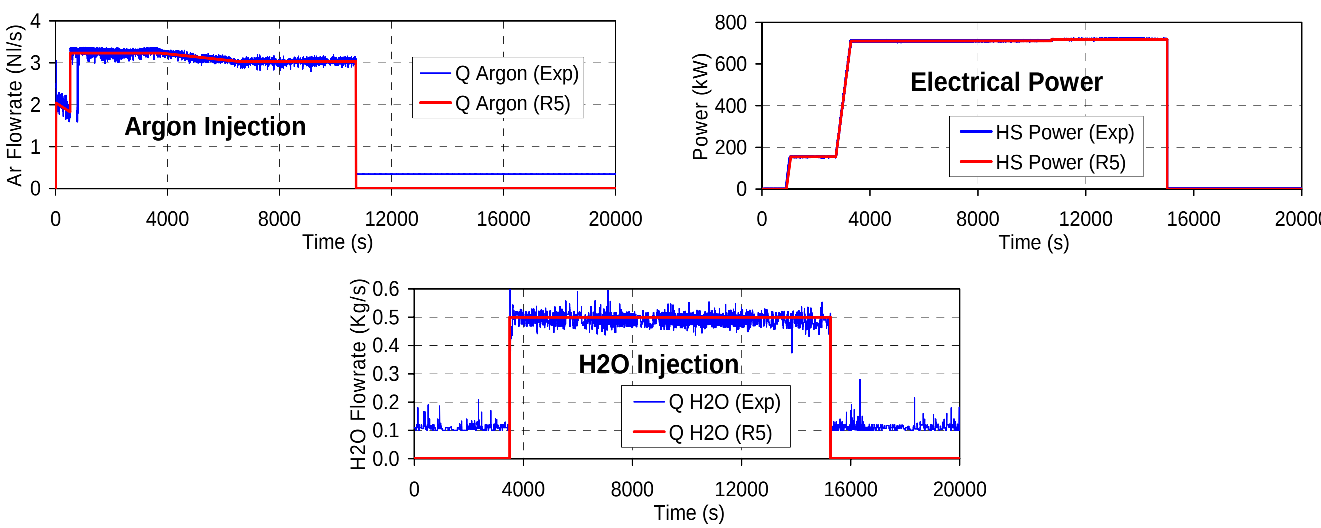
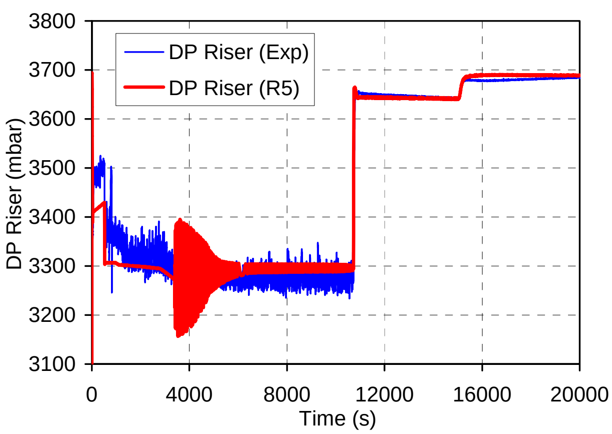
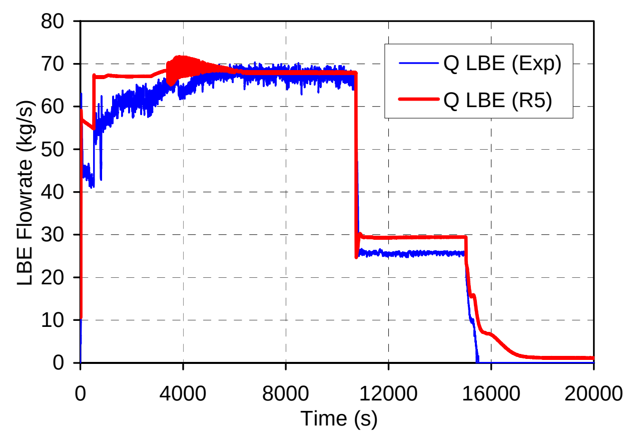


Figure 8 Boundary conditions of the test n. 5

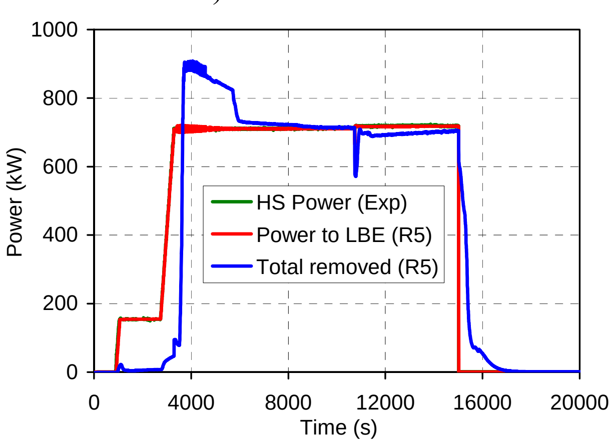
The main outcomes of the test n. 5 are compared with the RELAP5 results in Figure 9. The attainment of the initial stabilization phase was more problematic in this test, since the selected operating condition was not the nominal one, as in the previous tests. The larger gas injection, with increased void fraction in the riser, likely resulted in bubble coalescence phenomena This led to reduce the gas lifting effect, as indicated by lower values of ΔP riser (Figure 9.a) and LBE mass flowrate measurements (Figure 9.b), before to achieve a stable behaviour at about t = 5000 s. This effect cannot be captured by RELAP5. However, strong oscillations of riser ΔP are calculated in the time period t = 3000 – 6000 s, but they are not explained. Some delay in start-up of water injection after reaching full power and some unbalance between HS power and HX removed power (Figure 9.c) resulted in initial overheating of the system in the time period t = 3000 – 6000 s (see Figure 9.d). After reducing the HX power removal by stopping the water injection in the external zone of the tube bundle at t = 5700 s, stabilized conditions have been attained in the system until the initiation of the transient phase. As illustrated in Figure 9, the steady-state conditions of the system just before the ULOF transient phase are well reproduced by RELAP5.



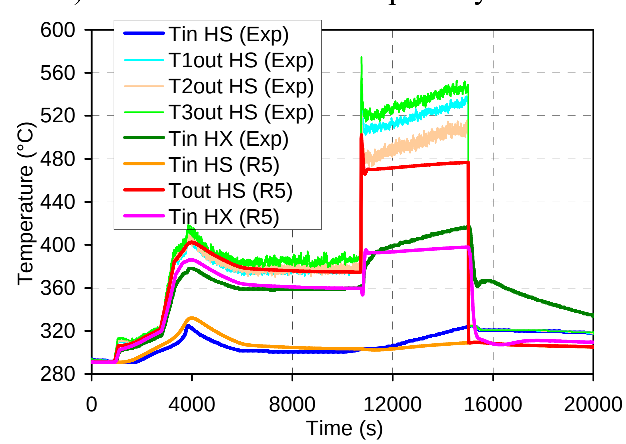
a) ΔP in the riser



b) LBE mass flow rate in primary circuit



c) HS power and HX removed power



d) LBE temperature through HS and at HX inlet

Figure 9 Main outcomes of the test n. 5 and comparison with RELAP5 results

When the argon injection was stopped at t = 10730 s, the driving force by gas lifting was quickly lost, as indicated by sudden ΔP riser increase in Figure 9.a, leading to transition from forced to natural circulation in the primary circuit. Natural circulation quickly stabilized in the primary system at approximately 38% of the initial value. Stable natural circulation is also predicted by RELAP5, but the calculated value is about 15% higher than the one measured in the test (Figure 9.b). Because of the

LBE mass flow rate overestimation, the temperature increase at the HS outlet is under predicted by the same order of magnitude (Figure 9.d). Furthermore, almost certainly the larger mass flow rate through the HX leads to overestimate the convective heat exchange, thus reducing the unbalance between HS and removed power. As a consequence, the progressive increase of primary temperature observed in the test during the transient phase is not reproduced by the code.

4. Pre-test analysis of the DHR experiment

The main purpose of the DHR experiment is to investigate decay heat removal by heat exchangers immersed in the pool working in natural circulation on the primary side. This experiment is devoted to simulate a PLOH + LOF accidental transient in HLM reactors, consisting in the contemporary loss of all primary pumps and secondary circuits, with consequent reactor scram and decay heat removal by natural circulation by emergency systems.

The boundary conditions applied in the RELAP5 pre-test calculation are illustrated in Figure 10. The experiment begins with the injection of gas (approximately 1.7 Nl/s of argon) in the riser to promote the enhanced circulation of LBE in the primary system and get the nominal flowrate of about 55 kg/s. Once the forced circulation is stabilized in the primary circuit, the HS power ramp is initiated at t = 750 s and the nominal power of 800 kW is reached at t = 1000 s. As soon as the power is at its nominal value, the water injection in the HX is started, in order to remove the power and stabilize the temperatures in the primary system with a ΔT of about 100 °C through the HS and the HX.

As in previous tests, the normal operation of the facility is maintained for about 2 – 3 hours in order to attain well stabilized conditions in the primary system, before to start the transient phase. At t = 10000 s, the PLOF + LOF transient is initiated by switching off the gas injection. At the same time the electrical power supply is quickly reduced down to 5% of nominal value (40 kW) to reproduce a decay power level, the water injection in the HX is stopped and the forced circulation of air (0.3 kg/s) is started in the secondary side of the DHR heat exchanger to remove the decay power. After more than three hours from the beginning of the transient, the experiment is ended by switching off the electrical power supply and the air injection at t = 22000 s.

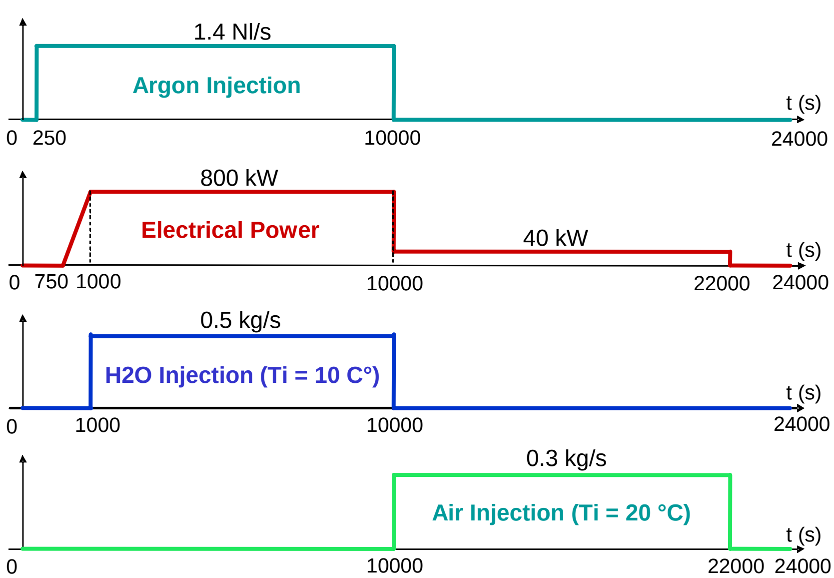
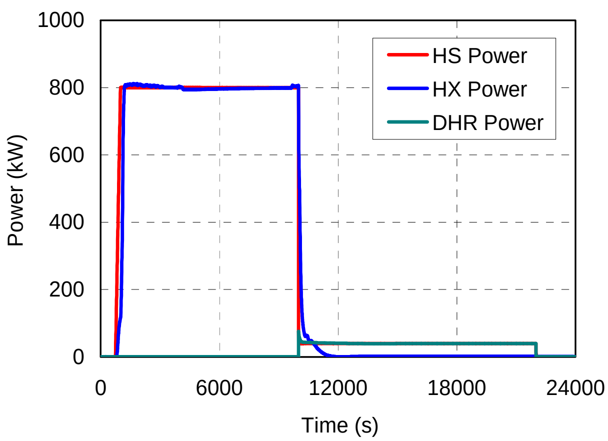


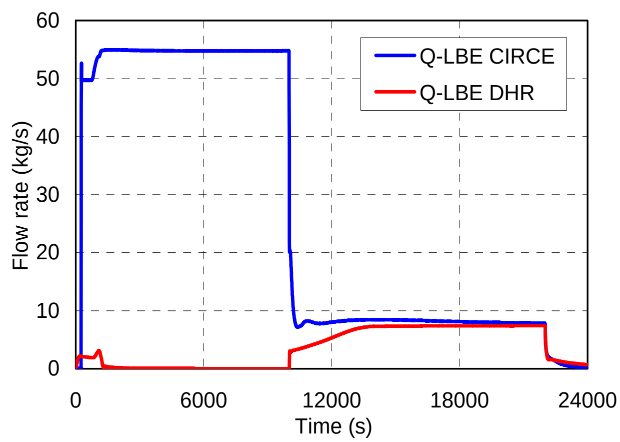
Figure 10 Boundary conditions for the DHR experiment

The main results of the pre-test analysis of the DHR experiment are illustrated in Figure 11. The RELA5 calculation shows that the expected stabilized conditions are attained in the primary system at t = 10000 s. Thanks to the riser wall insulation, the total heat loss in the hot leg is reduced by more than 50% (112 kW instead of 260 kW without riser insulation). The consequent temperature increase at HX inlet (Figure 11.c), with corresponding increase in LBE–water ΔT between primary and secondary sides, leads to improve the performance of the HX, which is now able to remove the nominal HS power of 800 kW (Figure 11.a). In fact, the vessel wall heaters are maintained in operation during the test, so that the total electrical power supply must be entirely removed through the HX. During the stabilization phase, the temperature at the DHR heat exchanger inlet progressively increases reaching 370 °C at t = 10000 s (Figure 11.d), due to residual heat losses from the hot leg and through the external HX shell towards the upper part of the cold pool where the DHR heat exchanger inlet is located.

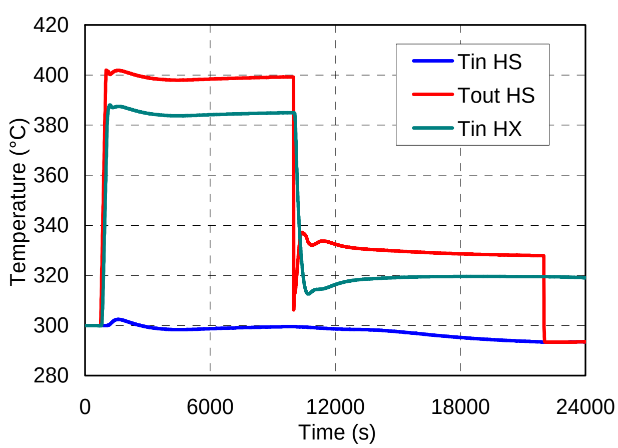
As soon as the PLOH + LOF transient is initiated at 10000 s, stable natural circulation in the primary circuit is predicted by the code (Figure 11.b) with a mass flow rate around 8 kg/s (about 15% of the initial value). Quick start-up of natural circulation is also predicted through the DHR system, with prompt removal of the decay power (Figure 11.a). The mass flow rate through the DHR system progressively increases and stabilizes at 7.4 kg/s after t = 14000 s, close to the primary flowrate value. The ΔT through the HS and the DHR heat exchanger stabilize around 35 °C during the transient phase.



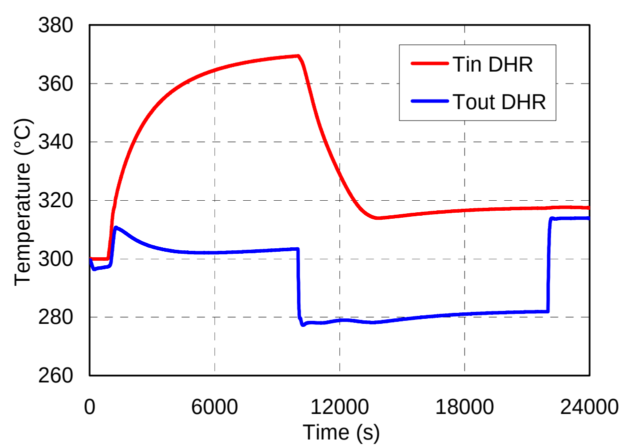
a) HS, HX and DHR powers



b) CIRCE and DHR LBE mass flow rates



c) LBE temperature in the primary circuit



d) LBE temperature at DHR inlet/outlet

Figure 11 Main results of the pre-test analysis of the DHR experiment

5. Conclusions

The experiments conducted on the CIRCE facility within the EUROTRANS project have provided a valuable data base for system code validation purposes. The post-test analysis of the DEMETRA tests has demonstrated the suitability of the RELAP5 model to simulate CIRCE experiments under various transient conditions including the transition from forced to natural circulation in the primary circuit. In particular, the right operation of the water HX for power removal and the attainment of stabilized conditions in the primary system are well reproduced by RELAP5. Some uncertainties remain in the simulation of transient conditions, likely connected with 3-D effects in the LBE pool, namely buoyancy, mixing and temperature stratification, since these phenomena cannot be addressed with the 1-D model of RELAP5.

The DHR experiments to be conducted on the upgraded CIRCE facility within the THINS project will provide further valuable and consistent data for both 1-D system codes and more detailed 3-D CFD models validation. The pre-test analysis of the DHR experiment with RELAP5 has confirmed the suitability of the DHR system design. The transition from forced to stable natural circulation in the primary circuit is also confirmed, as well as the prompt start-up of the DHR heat exchanger for decay heat removal by natural circulation on the primary side.

Acknowledgments

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