

Research Article

ELSMOR European Project: Experimental Results on an Innovative Decay Heat Removal System Based on a Plate-Type Heat Exchanger

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This paper summarises the results of an experimental campaign carried out at SIET on the ELSMOR facility built in 2022 to validate a decay heat removal system for the E-SMR. Based on the passive mechanisms of natural circulation, the system aims to dissipate the reactor decay heat to a water pool, using two heat exchangers: a plate-type one coupling the primary side to the secondary side, and a vertical tube one coupling the secondary side to the water pool. Such a system is considered to be the most effective passive system, capable of safely managing the SMR accident and accidental situations, and achieving long-term decay heat removal without the need for electricity or external inputs. A description of the primary and secondary loops of the plant is given, together with the installed instrumentation and data acquisition system. In addition, the paper summarises the tests performed in terms of test procedures, test type and associated objectives, test matrix, test results, achievements, and open issues.

1. Introduction

The ELSMOR (towards European Licensing of Small MODular Reactors) project aims to provide European stakeholders with methods and tools to assess and verify the safety of Light Water Small Modular Reactors (LW-SMR) to be deployed in Europe [1, 2]. The Work Package 3 of the project deals with the SMR cooling safety functions with a special focus on integral SMRs. In particular, Task 3.3 is dedicated to the demonstration of a methodology for the experimental evaluation of passive safety systems on the prototypical passive Decay Heat Removal System (DHRS) of the E-SMR reference design. It is also dedicated to the collection of experimental data for thermal-hydraulic code validation.

The activity started with the identification of a Separate Effect Test Facility (SET) as the most appropriate to investigate the E-SMR DHRS with three main objectives: (1) to show the way to carry out an experimental campaign

to the European regulatory body called to certify SMRs in Europe; (2) to test a passive decay heat removal system based on a compact plate-type heat exchanger included in a natural circulation loop that dissipates heat into a water pool; (3) to validate different codes in pre-test and post-test analyses.

The use of a plate-type heat exchanger in an integral SMR has the advantage of large power transfer in an extremely compact configuration, but as this is the first time this type of heat exchanger has been proposed as part of a civil nuclear power plant, it requires extensive experimentation prior to application for licensing.

In general, the design of an installation starts with a technical specification that indicates (1) the objective of the test; (2) the scaling factors (e.g. height, volume, power); (3) the phenomena of interest to be reproduced and studied in the facility; (4) the required characteristics of the instrumentation and data acquisition system (e.g. accuracy, sampling frequency, etc.); (5) the test matrix.

In the ELSMOR project, the requirements were provided by other partners working on the E-SMR design, which made it possible to define the scaling factors for the facility and the characteristics of the two heat exchangers to be installed [3]. A commercial plate heat exchanger was selected to meet the specified power and pressure drops, and a vertical tube heat exchanger with suitable characteristics was available at SIET from other research [4–7]. The choice of instrumentation and DAS characteristics was based on the phenomena to be detected and the required accuracy. The design of the piping and components was supported by RELAP5 calculations carried out by ENEA, which allowed the geometric layout of the loops to be finalised [8].

Once designed, the ELSMOR facility was constructed and connected to the ancillary infrastructure available at SIET to provide water and power. The plant was then commissioned with a series of tests to verify the functionality of the loops, the instrumentation, and the DAS software.

An experimental campaign was carried out to investigate the effect of various parameters on the stability of the fluid circulation and heat transfer capabilities.

The experimental results demonstrated the effectiveness of the plate heat exchanger in the removal of residual heat and identified a range of parameters characterising the most effective operating conditions of the system.

A set of qualified data was made available to the ELSMOR project partners for post-test analyses to be performed with several codes, an activity carried out within other tasks of the same project [9].

2. The ELSMOR Facility

The ELSMOR plant simulates the DHRS of the E-SMR, where a plate type HX, i.e., Safety-Compact Steam Generator (S-CSG), couples a circuit at the thermohydraulic conditions of the reactor (primary side) to a natural circulation loop (secondary side), which is sufficient to dissipate the decay heat into a water pool by means of a vertical tube HX. The power/volume scaling factor is 1 : 50, and the height factor is 1 : 1. A simplified scheme of the plant is shown in Figure 1, and a view of the circuits is shown in Figure 2 [10]. Figures 3–5 show the installed piping and components.

The ELSMOR loop is connected to existing auxiliary systems at SIET (serving the GEST plant), which are sufficient for water supply and drainage, water circulation, heating, and pressurisation of the loops.

The design conditions of the plant are:

Primary side pressure 13 MPa and temperature 330 °C
 Secondary side pressure 10 MPa and temperature 310 °C
 Power 1 MW

The primary side of the ELSMOR test facility can be operated in both single-phase and two-phase conditions. In single-phase liquid mode, water is circulated by the primary pump through the S-CSG bypass and split partly into the S-CSG and partly back to the pump by means of a suitably sized flow restrictor; in two-phase mode, the water and

steam mixture exiting the electric heater enters the steam-water separator (flow restrictor removed) and, by gravity, water returns to the pump and steam enters the S-CSG. In single phase, the pressure is controlled by a feed and bleed method which injects and extracts water from the pressuriser according to the specified test conditions; in two phase, when the specified pressure is reached per feed and bleed, saturation conditions are achieved at the outlet of the electric heater by controlling the supplied power and primary flow.

The secondary side operates in two-phase natural circulation, driven by the heat supplied by the S-CSG (primary side) and dissipated in the water tank (heat sink) containing the submerged vertical tube heat exchanger. The pressure conditions that occur in the secondary side depend on the heat transfer from the primary side and the amount of water stored in the loop (filling ratio) for the specific test.

The S-CSG is a commercial TEMPCO plate heat exchanger, model TCBC2102H*130, consisting of 130 plates with a 45° chevron angle (90° angle between channels), Figure 6.

The in-pool HX consists of five vertical tubes, 2" OD, approximately 2 m long, with cylindrical headers at the top and bottom, Figure 7.

The pool is a vertical cylinder, approximately 1 m in diameter and 5.5 m high, which houses the HX vertical tube. It is equipped with a water supply and drainage system to control the water level during transients. The basin is open to the atmosphere.

From the point of view of the ELSMOR test, the primary side pipes of interest are those between the steam-water separator and the S-CSG, identified as the primary side hot and cold legs (PS HL and PS CL), and those between the S-CSG and the in-pool HX, identified as the secondary side hot and cold legs (SS HL and SS CL), Figure 1.

All pipework and components of the plant are thermally insulated with mineral rockwool, overlaid with aluminium cladding to limit heat losses to the environment.

The plant is equipped with three main valves, sufficient to initiate natural circulation on the secondary side (V3) and to adjust the pressure drop in the loops (V1 and V2), Figure 1. Orifices are installed on both the primary and secondary cold legs to measure the flows through the S-CSG.

3. Instrumentation and Data Acquisition System

The instrumentation installed in the ELSMOR plant consists of eight relative pressure sensors, twenty-five differential pressure sensors, one hundred resistance temperature detectors (Pt100), and twenty thermocouples (TcK), together with shunts, current, and voltage meters sufficient to provide auxiliary indications of the electrical power supplied to the heater and other signals mainly dedicated to the management of the plant. All instruments are calibrated in the SIET laboratory, and calibration constants are entered into the Data Acquisition System (DAS) software to reduce measurement uncertainty.

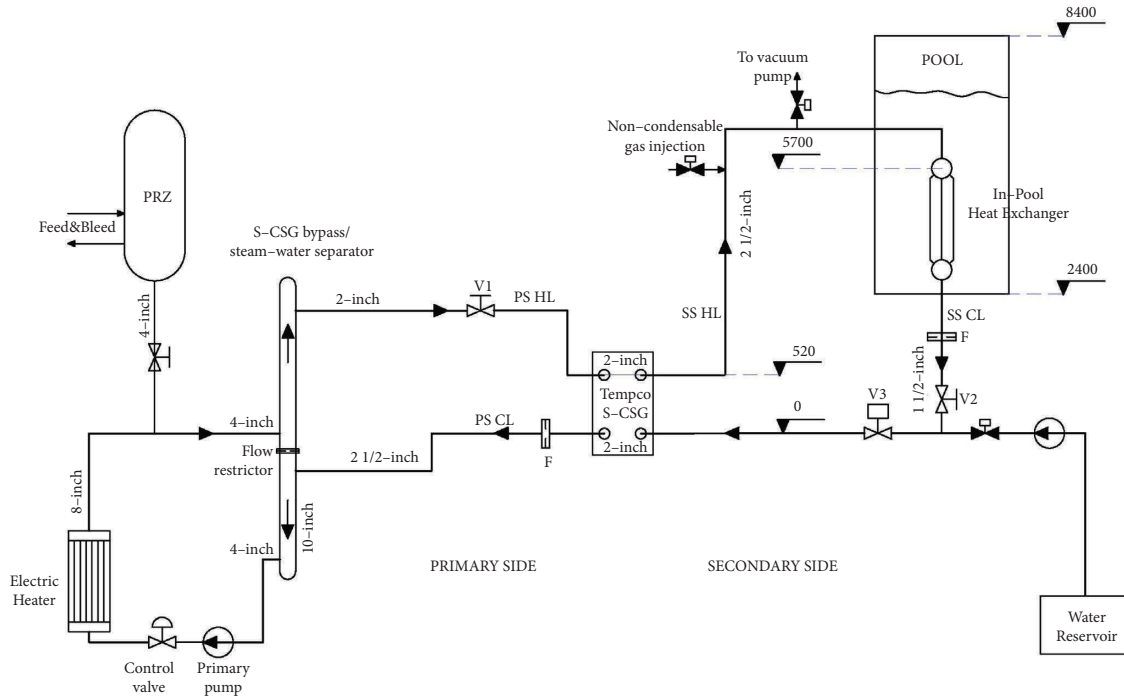


FIGURE 1: Simplified scheme of the ELSMOR facility.

Instruments are installed along the piping and on the components with particular attention to the inlet and outlet of the S-CSG, both primary and secondary.

The HX vertical tube is equipped with fluid and wall temperature sensors at various heights, as is the pool, which houses approximately 80 RTDs at various heights and radii to form a three-dimensional grid, primarily for CFD code validation. The RTDs in the pool are shown in Figure 8.

The data acquisition system consists of data acquisition cards connected directly to the cables of the instruments in the field, which, after performing the analogue-to-digital conversion, transmit the signals via Ethernet to the main DAS computer, which records the voltages and converts them into engineering (e.g., instrument pressure, differential pressure, etc.) and derived quantities (e.g., mass flow rates, enthalpies, power, etc.), Figure 9.

3.1. Estimation of the Uncertainty of Measured and Derived Quantities. An estimation of the measurement uncertainty of direct and engineering quantities is made on the basis of uncertainty propagation according to UNI CEI ENV 13005 [11] and UNI CEI 70099 [12] standards, with criteria and assumptions evaluated on a case-by-case basis. All contributions to the expanded uncertainty are taken into account, starting from the calibration uncertainty, the uncertainty of the installation position, the uncertainty of the water table, the uncertainty propagation according to the correlations that provide the derived quantities (e.g., levels, mass flows, power, etc.). A coverage factor $k=2$ is applied to the estimated uncertainty value, which represents the probability

that the set of true values of the measured quantity lies within the uncertainty range with a confidence level of 95%.

A summary of the estimated uncertainties for the main quantities is given in Table 1.

3.2. Test Matrix and Test Procedures. The test matrix performed includes seven groups of tests (A to G), each consisting of a certain number of steady states for a total of eighty-one steady state points together with transitions in between.

It includes

- (1) Tests at different primary side temperatures;
- (2) Tests at different secondary filling ratios (natural circulation loop) (the filling ratio (F.R.) is defined as the ratio between the mass present in the secondary side after mass extraction and the initial (full) mass, corresponding to 125 kg. This value includes the mass of water in the discharge line from the extraction point to the weighing system (~5 kg));
- (3) Tests with different amounts of noncondensable gas injected into the secondary side;
- (4) Tests with different pressure drops in the cold leg of the secondary side (setting of valve V2, Figure 1);
- (5) Tests with different pressure drops in the hot leg of the primary side (setting of valve V1, Figure 1);
- (6) Tests with different levels in the HX pool;
- (7) Tests with different temperatures in the HX pool;

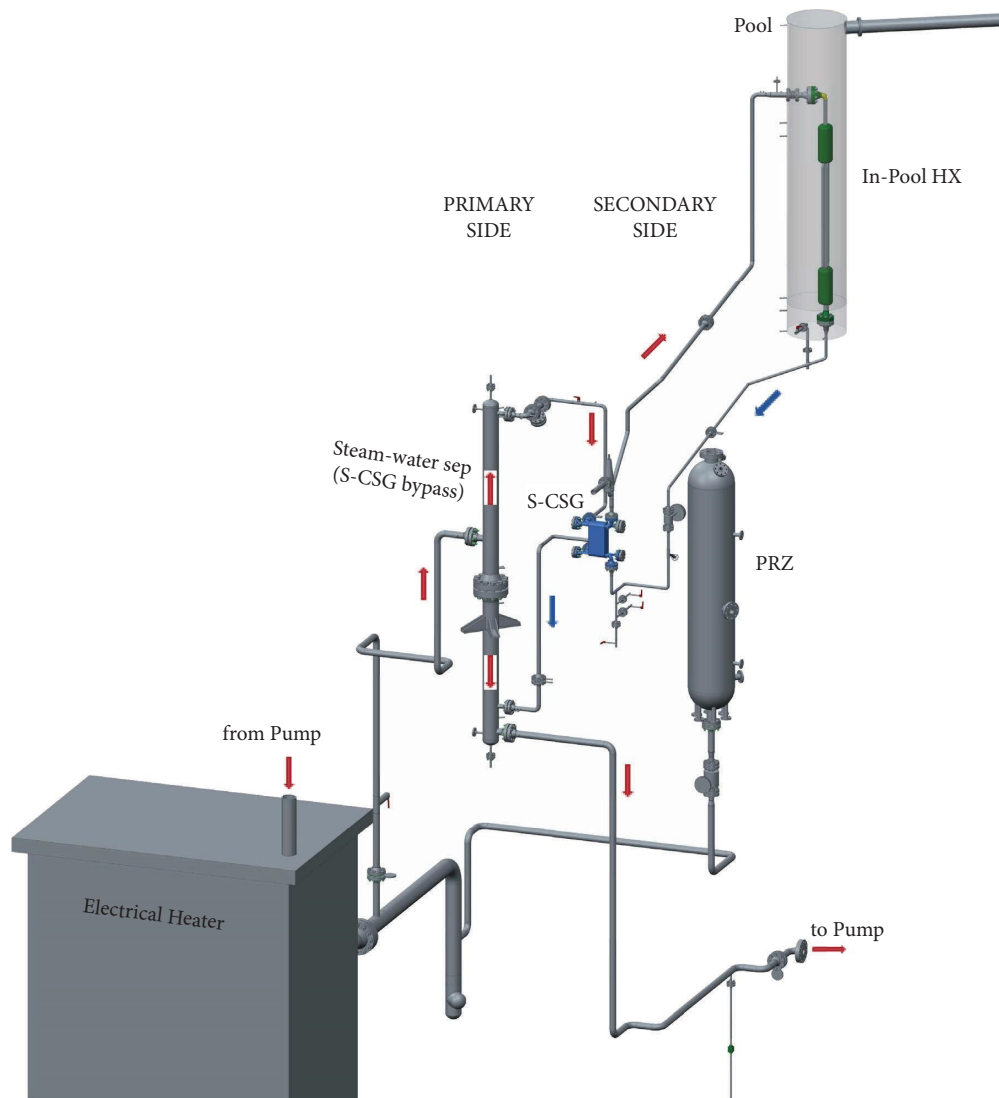


FIGURE 2: View of the main loops of the ELSMOR plant.

- (8) Tests with two-phase conditions in the primary side (steam to S-CSG inlet after mixture separation in the steam-water separator).

3.3. *Test Procedure for Single-Phase Tests.* The two types of tests, single-phase and two-phase primary flow, are carried out according to the corresponding test procedures, which are summarised as follows and are useful for steady state and transient analysis.

With reference to Figure 1:

- (1) Fill the primary and secondary sides with cold water and vent air from the loops;
- (2) Fill the instrument pressure lines with cold water and check the P and DP instruments for hydro-zero;
- (3) Close the secondary side valve V3;
- (4) Set the specified secondary side fill ratio by taking water and weighing it;

- (5) Adjust the primary pressure drop by setting valve V1 on the HL to the specified opening turns;
- (6) Adjust the secondary pressure drop by setting valve V2 on the CL to the specified opening turns;
- (7) Start primary side circulation using the primary pump;
- (8) Heat the primary side by the electric heater to less than 2.5°C/min;
- (9) Control the primary side pressure in automatic mode based on the PRZ pressure signal (feed and bleed method);
- (10) When the specified primary side temperature is reached, vacuum the secondary side using the vacuum pump. Achieve a vacuum of approx. 0.05 MPa;
- (11) Adjust the primary flow rate to match the specified flow through the S-CSG;
- (12) Start the test by opening the valve V3;



FIGURE 3: View of primary side of ELSMOR plant and S-CSG.

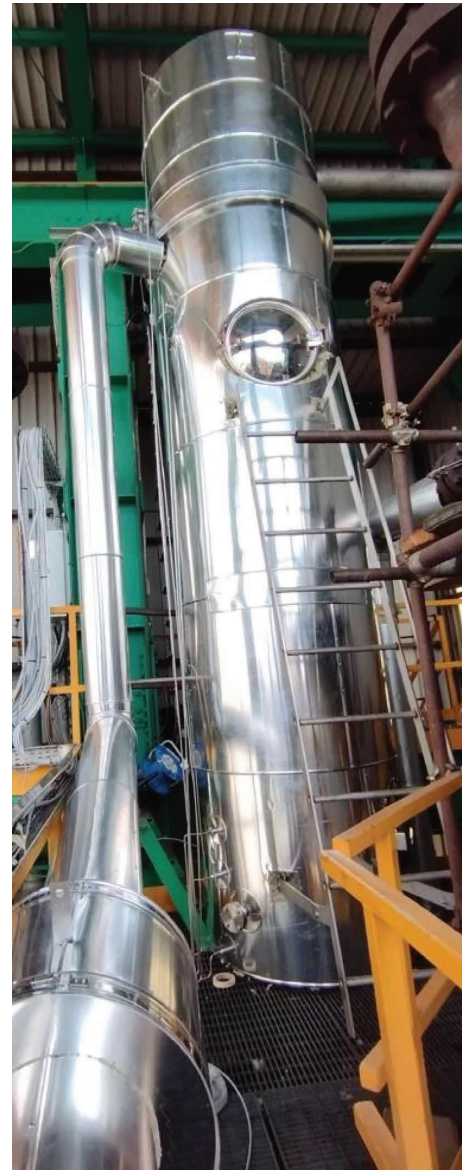


FIGURE 5: Pool.



FIGURE 4: View of secondary side of ELSMOR plant and S-CSG.

- (13) Wait for natural circulation to begin;
- (14) Wait for steady-state conditions to be reached and maintain parameter constants for approximately 300 s. The average values over this time period represent the conditions for the steady-state points of the test matrix;

- (15) Change the required parameters (e.g., primary side temperature) and wait for new steady-state conditions;
- (16) Change another parameter (e.g., filling ratio or noncondensable gas injection) and wait for new steady-state conditions;
- (17) When all specified parameters have been explored, stop the test: switch off power to the electric heater, stop the primary pump, and stop the primary feed pump and all auxiliary systems.

3.4. *Test Procedure for Two-Phase Tests.* With reference to Figure 1, for tests on the primary side in two-phase conditions: remove the flow restrictor in the steam-water separator; set V1 (primary side HL) and V2 (secondary side CL) fully open.

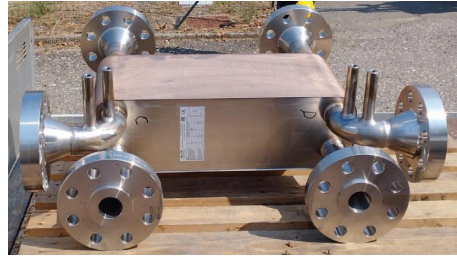


FIGURE 6: S-CSG before installation.

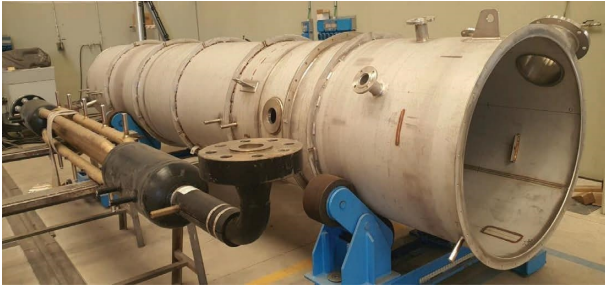


FIGURE 7: Pool and in-pool HX before installation.

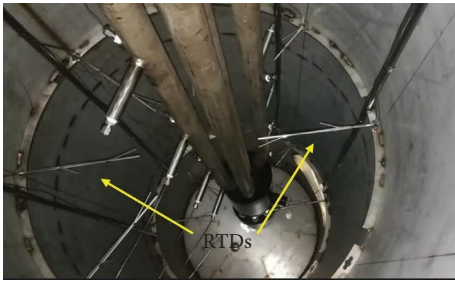


FIGURE 8: Pool temperature sensors.

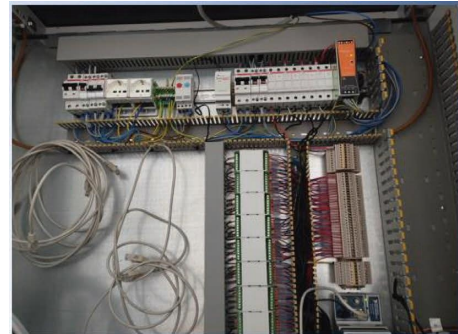


FIGURE 9: Card cabling in the DAS frame.

Proceed as for single-phase tests until the system has warmed up with primary side flow higher than specified;

- (i) Control the primary side pressure in manual mode from the PRZ pressure signal (feed and bleed method);
- (ii) Maintain the primary side temperature at the specified value by controlling the power supplied to the electric heater;
- (iii) When the specified primary side temperature is reached, vacuum the secondary side using the vacuum pump. A vacuum of about 0.05 MPa should be achieved;
- (iv) When saturation conditions are reached at the primary side, reduce the flow rate to get two-phase conditions at the outlet of the electric heater and reduce the water level in the steam-water separator;
- (v) Reduce the water level in the steam-water separator by controlling the PRZ bleed;

- (vi) Control and maintain the separator level so that the primary side of the S-CSG is empty of water and full of steam;
- (vii) When conditions are stable, start the test by opening the trigger valve V3;
- (viii) Wait for natural circulation to start;
- (ix) As the separator level rises, reduce the primary flow rate until the S-CSG is uncovered;
- (x) Wait for steady-state conditions to be reached and maintain parameter constants for approximately 300 s. The average values over this time period represent the steady-state points of the test matrix;
- (xi) Change the secondary side filling ratio and wait for new steady conditions;
- (xii) When all specified filling ratios have been explored, stop the test: switch off the power to the electric heater, stop the primary pump, and stop the primary feed pump and all auxiliary systems.

3.5. Test Performed. Seven sets of tests are carried out to investigate the effect of different parameters on natural circulation and heat transfer.

TABLE 1: Estimated measurement uncertainties for the main ELSMOR data.

Quantity	Variable	Units	Measure	Expanded uncertainty	U (%)
Primary side pressure	P_001	MPa	11.92	0.01	0.1
Secondary side pressure	P_003	MPa	6.45	0.01	0.2
S-CSG primary side differential pressure	DP_021	kPa	22.26	0.03	0.1
S-CSG secondary side differential pressure	DP_020	kPa	6.21	0.04	0.6
S-CSG primary side inlet temperature	TF_074	°C	310.9	0.15	0.0
S-CSG primary side outlet temperature	TF_075	°C	281.7	0.15	0.1
S-CSG secondary side inlet temperature	TF_070	°C	266.3	0.15	0.1
S-CSG secondary side outlet temperature	TF_071	°C	280.3	0.15	0.1
Vertical tube HX inlet temperature	TF_072	°C	280.3	0.15	0.1
Vertical tube HX outlet temperature	TF_068	°C	70.2	0.12	0.2
Pool water level	L_001	m	4.01	0.06	1.4
Pool water mass	M_001	kg	3008	39	1.3
Pool water average temperature	T_ave	°C	99.6	2.8	2.8
S-CSG primary side flowrate	F_011	kg/s	3.576	0.171	4.8
S-CSG secondary side flowrate	F_007	kg/s	0.555	0.007	1.3
PS S-CSG power	W_CSG	kW	575	30	5.2

3.5.1. Group G Tests. The tests of group G (first in order of execution) provide information on the behaviour of the system without non-condensable gas on the secondary side, with decreasing F.R. (32.08 to 21.07%), with different primary side temperatures (250 to 310 °C), and with reduced level in the pool.

3.5.2. Group A Tests. The Group A tests provide information on the behaviour of the system in the presence of a fixed quantity of non-condensable gas on the secondary side since the start of the transient (288.13 Nl of air), at constant F.R. (20%), at different primary side temperatures (260 to 320 °C), and at a reduced level in the pool.

3.5.3. Group B Tests. The Group B tests provide information on the behaviour of the system without non-condensable gas on the secondary side, with decreasing F.R. (15.2 to 11.9%) until destabilisation of the circuit, with increasing F.R. (15.9 to 16.32%) until restabilisation, with decreasing F.R. (16.32 to 14.39%) until destabilisation at constant primary side temperature (320 °C), at a high level in the pool.

3.5.4. Group C Tests. The Group C tests provide information on the behaviour of the system with the V1 valve on the primary side partialised with an increasing quantity of non-condensable gas on the secondary side (0 to 1402.21 Nl of N₂) at constant F.R. (31.20%) and constant primary side temperature (320 °C). Once the maximum quantity of noncondensable gas injected has been reached, it is tested at decreasing F.R. (31.20 to 20.40%).

3.5.5. Group D Tests. The Group D tests provide information on the system behaviour with valve V1 partialised on the primary side, without non-condensable gas on the secondary side, with decreasing F.R. (60.16 to 14.08%) up to the destabilisation of the circuit, with increasing F.R. (14.08 to 18.16%) up to the restabilisation at a constant high primary side temperature (310 °C).

Once the cycle is restabilised and the F.R. is increased to 30%, the system behaviour is explored by decreasing F.R. (30 to 15.44%) until cycle destabilisation, with increasing F.R. (15.44 to 16.91%) until restabilisation at constant low primary side temperature (260 °C).

3.5.6. Group E Tests. The Group E tests provide information on the behaviour of the system with valve V1 on the primary side and valve V2 on the secondary side partialised (the secondary side V2 valve is 10/12 turns open corresponding to CV ~5.7 over a full opening CV of 47.1), without non-condensable gas on the secondary side, with decreasing F.R. (30.64 to 14.34%) until the system is destabilised, with increasing F.R. (14.34 to 16.17%) until restabilisation at constant primary side temperature (310 °C).

Once the system has been stabilised and the F.R. has been increased to 30.65%, the system behaviour is studied by increasing the closure of valve V2 (10/12 turns open to full closure) and returning to the initial position (10/12 turns open) with destabilisation and circulation stopping followed by system restabilisation at a constant F.R. (30.65%) and at a constant primary temperature (310 °C).

3.5.7. Group F Tests. The Group F tests provide information on the behaviour of the system with the primary side in two-phase conditions, i.e., with low level in the steam-water separator and steam in condensation in the S-CSG primary side, without non-condensable gas in the secondary circuit, with decreasing F.R. (39.2 to 20%) and at constant primary side temperature (310 °C).

3.6. Description of the Results of a Test. The test described has been chosen because it is one of the most representative for demonstrating the functionality of the system and because it highlights the main phenomena occurring in the loop for the majority of the tests carried out. It consists of a sequence of two consecutive and contiguous tests named ELSMOR_00099 and 00100 (details of all the test results are

given in [10]). Each test is carried out after the primary side has been heated to the specified conditions, and the filling ratio and vacuum have been achieved in the secondary side. The opening of trigger valve V3 starts the natural circulation and heat transfer from the primary to the secondary circuit. The sequence of events is shown in Table 2, while the values of the main parameters in steady state are summarised in Table 3.

Figures 10(a), 10(b), 11(a), and 11(b) show the evolution of the pressure and flow rate of the natural circulation loop. At the start of the system, both increase and then decrease slightly with each withdrawal of water from the loop to reduce the filling ratio. The sudden drop in pressure and the interruption of the circulation show the destabilisation of the system at F.R. $\sim 15\%$, followed by a strongly oscillating flow rate until the circulation is stabilised again after several water injections up to F.R. $\sim 18\%$.

Figures 12(a), 12(b), 13(a), and 13(b) show the evolution of the water level in the pool and the power transmitted by the S-CSG (power is estimated by an enthalpy balance between the inlet and outlet of the primary side of the S-CSG, at the measured pressure, temperature, and flowrate). The decrease in the level is due to the boiling of the pool water for heat rejection through the vertical tube heat exchanger. The increase in the level is due to water make-up to avoid uncovering the heat exchanger. The exchanged power increases as the F.R. decreases to reach a stable value around 600 kW at F.R. $\sim 35\%$. The power drops when the system destabilises, but despite the instability, ~ 200 kW continues to be rejected to the pool.

Figure 14 shows the evolution of the secondary side flow vs. F.R. around the instability zone. Two curves are shown: the blue one is the flow rate at decreasing F.R. and the yellow one is at increasing F.R. The destabilisation of the system occurs with a strong reduction of the secondary side pressure and strong oscillations of the flow rate at F.R. around 15%, while at increasing F.R., it restabilises around 18%, showing a hysteresis in the process.

4. Summary of Results

The results of the tests carried out on the ELSMOR plant have made it possible to verify the effectiveness of the innovative E-SMR passive heat removal system with a plate HX in a reduced-height loop under different operating conditions and to explore the range of parameters that make the circulation stable or unstable. In general, the operation of the system is stable and effective, and when an unstable circulation occurs at very low F.R. ($<15\%$), a certain amount of heat removal is still guaranteed.

The functional characteristics of the system are described as follows based on the influence of various parameters.

4.1. Filling Ratio Impact. The filling ratio of the secondary side is a fundamental parameter that greatly influences the natural circulation and heat transfer from the primary side.

Filling ratios ranging from 60 to 14% have been studied, and the following conclusions have been drawn:

High filling ratios lead to high pressure conditions on the secondary side, which can be dangerous for the integrity of the system and must be avoided (F.R. $\sim 50 \div 60\%$).

The system shows a stable circulation with an intermediate filling ratio ($40 \div 20\%$).

The circulation becomes unstable at low F.R. levels ($14 \div 15\%$).

The circulation shows hysteresis, i.e., if the F.R. is reduced, the circulation becomes unstable, and if the F.R. is increased from unstable conditions, it becomes stable at an F.R. value higher than the destabilisation value.

4.2. Primary Side Temperature Impact. The primary side temperature affects the heat transfer rate between the primary and secondary sides.

PS temperatures ranging from 260 to 320 °C have been investigated, representative of the different reactor primary side conditions, e.g., during a LOCA.

In general, the system has shown stable operation at the different primary side temperatures tested.

4.3. Primary Side Pressure Impact. For single-phase primary side tests, the primary side pressure has a negligible effect on the system behaviour and is set to values sufficient to fix the specified temperature.

For tests in two-phase conditions on the primary side, the pressure is strictly related to the temperature, which drives the heat transfer.

4.4. Primary Side Flow Rate Impact. In single-phase tests, the primary flow rate through the S-CSG is determined by balancing the pressure drop between the hot leg (through valve V1) and the steam-water separator tank through the flow restrictor.

Primary side flow rates in the range of 3 to 4 kg/s have been investigated. The heat transfer increases as the flow rate increases, but so does the pressure drop. Considering that there is natural circulation in the reactor, both on the primary and secondary sides of the S-CSG, tests were carried out around the flow rate specified for the mock-up of 3.4 kg/s.

4.5. Pool Temperature Impact. The water temperature in the pool affects the condensation rate in the vertical tube heat exchanger: the lower the temperature, the greater the heat transfer.

Pool temperatures ranging from 10 to 100 °C have been studied.

In most tests, water stratification was observed, with colder water at the bottom and hotter water at the top. One of the factors that increases stratification in these tests is the replenishment of the pool with cold water from the bottom to keep the level sufficiently high as mass is lost to evaporation at the top. Details of the temperature stratification are not highlighted in this paper as they are beyond the scope of demonstrating the functionality of the system.

TABLE 2: List of events for tests ELSMOR_00099 and 00100.

Time (s)	Event	Notes
<i>Test ELSMOR_00099_C</i>		
73	Initial filling ratio of the secondary side: 60.16% vacuum in the secondary side (SS) 0.5bar	Valve V1 on the PS HL is 7 turns open out of 9.5 turns (fully open)
74–299	Triggering valve V3 opened	Start-up (triggering valve opening). Vacuum conditions in the SS
360–660	Natural circulation start-up and stabilisation	
700–1140	Steady state at primary side (PS) T (TF_082) 309.6°C; FR 60.16%	
978–1060	PS temperature stabilisation around 310°C	
1140–1440	6.5kg mass extracted from the SS; F.R. 55.04%	
1550–1625	Steady state at PS T 310.8°C; FR 55.04%	
1900–2300	6.28kg mass extracted from the SS; F.R. 50.00%	
2860–2930	Steady state at PS T 310.0°C; FR 50.00%	
3070–3600	6.22kg mass extracted from the SS; F.R. 45.04%	
3615–3708	Steady state at PS T 309.8 °C; FR 45.04%	
3890–4350	6.30kg mass extracted from the SS; F.R. 40.00%	
4390–4470	Steady state at PS T 309.7°C; FR 40.00%	
4500–4900	6.35kg mass extracted from the SS; F.R. 34.92%	
5349–5502	Steady state at PS T 310.0°C; FR 34.92%	
5630–6400	6.05kg mass extracted from the SS; F.R. 30.08%	
6506–6600	Steady state at PS T 309.9°C; FR 30.08%	
6700–7000	6.4kg mass extracted from the SS; F.R. 24.96%	
7075	Steady state at PS T 309.9°C; FR 24.96%	
6275–7353	Refilling of HX-Pool through V009 by opening FCV07	
<i>Test ELSMOR_00100_C</i>		
95	6.3 kg mass extracted from the SS; F.R. 19.92%	
Refilling stop of HX-Pool through V009 by closing FCV07		
200–470	Steady state at PS T 309.6°C; FR 19.92%	
480–515	3.1 kg mass extracted from the SS; F.R. 17.44%	
700–1100	Steady state at PS T 309.7°C; FR 17.44%	
1184–1220	3.1 kg mass extracted from the SS; F.R. 14.96%	
1740–2100	Steady state at PS T 310.5°C; FR 14.96%	
2140–2150	0.55 kg mass extracted from the SS; F.R. 14.52%	
2225–2600	Steady state at PS T 310.1°C; FR 14.52%	
2622–2632	0.55 kg mass extracted from the SS; F.R. 14.08%	
2790–3100	Steady state at PS T 310.0°C; FR 14.08%	
3150–3210	0.46 kg injected into the SS; F.R. 14.45%	
3300–3600	Steady state at PS T 310.1°C; FR 14.45%	
3680–3740	0.46 kg injected into the SS; F.R. 14.82%	
3890–4240	Steady state at PS T 309.9°C; FR 14.82%	
4250–4310	0.46 kg injected into the SS; F.R. 15.19%	
4420–4480	0.46 kg injected into the SS; F.R. 15.56%	
4678–4738	0.46 kg injected into the SS; F.R. 15.94%	
4896–4956	0.46 kg injected into the SS; F.R. 16.31%	
5150–5210	0.46 kg injected into the SS; F.R. 16.68%	
5348–5408	0.46 kg injected into the SS; F.R. 17.05%	
5523–5583	0.46 kg injected into the SS; F.R. 17.42%	
5681–5741	0.46 kg injected into the SS; F.R. 17.79%	
5896–5956	0.46 kg injected into the SS; F.R. 18.16%	
6550–6900	Steady state at PS T 309.9°C; FR 18.16%	
7340	PS temperature reduction started to 260°C	
Strong reduction of SS flowrate and circulation destabilisation		
	Unstable	
	Unstable	
	Unstable	
	Unstable	
	Unstable	
	Unstable	
	Unstable	
	Unstable	
	Unstable	
	Unstable	
	Unstable	
	Re-stabilised	

Bold characters put in evidence the time intervals that identify the steady-state.

TABLE 3: Summary of steady conditions ELSMOR_00099 and 00100.

Test file	SS time (s)		P_003 (MPa)	P_001 (MPa)	DP_020 (kPa)	DP_021 (kPa)	TF_074 (°C)	TF_075 (°C)	TF_071 (°C)	TF_072 (°C)	TF_068 (°C)	TF_070 (°C)	L_001 (m)	M_001 (kg)	F_011 (kg/s)	F_007 (kg/s)	W_CSG-PS (kW)	T_ave (°C)
	f1	f2																
ELSMOR_00099	360	660	9.33	11.71	4.91	22.62	310.6	289.4	305.7	305.6	191.2	187.0	4.91	3838	3.491	0.717	415	19.1
	1140	1440	9.15	11.93	5.10	22.29	311.8	289.4	304.4	304.3	202.8	200.4	4.90	3807	3.475	0.742	437	39.4
	1900	2300	8.51	11.93	5.34	21.96	310.9	286.9	299.3	299.2	217.3	214.4	4.89	3754	3.466	0.750	465	62.3
	3070	3600	7.82	11.94	5.61	21.82	310.8	284.4	293.4	293.3	230.6	227.7	4.60	3504	3.452	0.722	507	76.8
	3890	4350	7.15	11.93	5.88	22.06	310.7	281.9	287.2	287.2	245.3	241.5	4.43	3371	3.545	0.659	563	80.3
	4500	4900	6.62	11.92	6.16	21.86	311.1	281.3	282.0	282.0	263.0	258.5	4.32	3270	3.533	0.590	582	88.3
	5630	6400	6.45	11.92	6.21	22.26	310.9	281.7	280.3	280.3	270.2	266.3	4.01	3008	3.576	0.555	575	99.6
	6700	7000	6.39	11.91	6.10	21.81	310.9	282.1	279.6	279.6	273.3	269.6	3.82	2867	3.565	0.525	568	99.4
	200	470	5.99	11.91	6.19	21.93	310.6	282.0	275.5	275.5	273.5	272.6	4.65	3544	3.594	0.449	569	76.6
	700	1100	5.83	11.92	6.03	22.58	310.7	283.3	273.7	293.2	273.5	272.7	4.55	3457	3.609	0.375	549	80.9
ELSMOR_00100	1740	2100	1.10	11.79	14.92	22.13	311.5	300.0	310.7	302.4	182.6	185.0	4.45	3375	3.512	0.232	234	85.4
	2225	2600	0.99	11.81	14.10	22.15	311.1	300.3	310.4	301.8	177.7	180.3	4.44	3361	3.484	0.282	218	86.5
	2790	3100	0.88	11.81	12.24	21.78	311.1	300.8	310.2	301.2	173.0	175.3	4.43	3352	3.481	0.343	207	87.5
	3300	3600	0.92	11.80	13.24	21.81	311.1	300.6	309.9	300.0	173.9	176.6	4.42	3340	3.396	0.216	208	88.3
	3890	4240	0.93	11.80	13.25	22.33	310.9	300.4	309.6	299.8	174.1	177.1	4.41	3329	3.475	0.167	211	89.3
	6550	6900	5.83	11.83	5.97	22.08	310.9	283.2	273.7	296.6	273.4	271.6	4.25	3184	3.479	0.377	535	99.6

See note (list of variables as in Table 1).

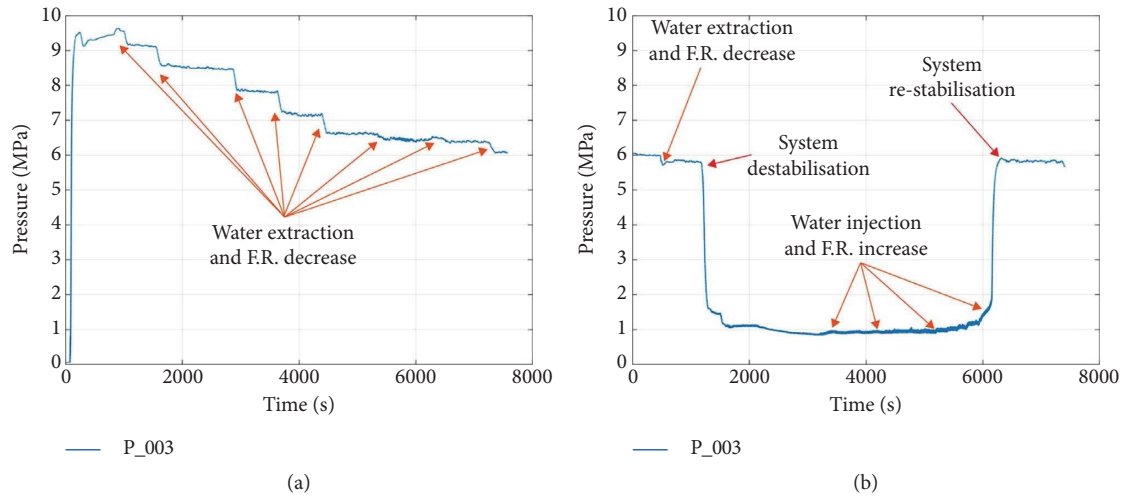


FIGURE 10: (a, b) Secondary side pressure.

4.6. Pool Level Impact. The water level in the pool affects the condensation rate in the vertical tube heat exchanger: the lower the level, the lower the heat transfer.

Pool levels ranging from 4.5 to 2 m have been studied, but many tests have been carried out at high levels, i.e., with the HX fully covered.

4.7. Secondary Side Cold Leg Pressure Drop Impact. The pressure drops on the secondary cold leg (between the in-pool HX outlet and the S-CSG inlet) affect the natural circulation in the loop. The pressure drops can be adjusted by gradually closing the manual valve V2. Most tests have been carried out with the valve fully open, while some tests have been carried out with the valve only 10/12 turns open. At such a position, a minimum effect on the natural circulation and heat transfer rate is observed. At a constant valve position, the greatest influence on the circulation is given by the filling ratio.

Subsequent valve positions were tested from 10/12 turns open to fully closed and back to 10/12 turns open. A destabilisation of the circulation was only observed at the minimum valve opening (1/12 turn open), with a rapid re-stabilisation on reopening the valve.

4.8. Secondary Side Non-condensable Gas Impact. The presence of non-condensable gas (air or nitrogen) on the secondary side only affects the natural circulation and heat transfer at high injection rates (~1000 NI) until the secondary F.R. remains above 20%. The non-condensable gas accumulates in the lower header of the in-pool HX until it accumulates in the tubes. The more gas present, the lower the outlet temperature of the in-pool HX and the lower the quality at the outlet of the S-CSG. The effect on heat transfer is small until the filling ratio is high enough to prevent gas from reaching the S-CSG.

Non-condensable quantities from 0 to 1400 NI have been tested.

4.9. Primary Side Two-Phase Conditions' Impact. The ability of the system to operate with steam on the primary side of the S-CSG (representative of reactor conditions in an advanced phase of a LOCA transient, with primary mass lost to uncover the S-CSG) has been verified by maintaining the steam-water separator level below the lowest connection of the S-CSG. This mode of operation is representative of a natural circulation of steam in the primary side of the S-CSG, which sucks in as much steam as it can condense, cooled by water circulating in the secondary side. An estimate of the transferred power with two-phase conditions on both the primary and secondary sides can be made by assuming that dry saturated steam enters the primary side of the S-CSG (while the quality at the secondary side S-CSG outlet is unknown). A similar estimate can be obtained by an energy balance at the pool (water temperature increase and level decrease for evaporation). In any case, the relatively high power transferred confirms the good performance of the system.

4.10. Aggregated Data. The steady-state data, as averages of parameters at steady time intervals, have been collected and observed in an aggregated manner in order to provide some general indications of the behaviour of the S-CSG with variation of specific parameters.

Figure 15 shows that the secondary side pressure increases with increasing F.R. and with increasing primary side temperature.

Figure 16 shows that the degree of subcooling at the secondary side S-CSG inlet increases with increasing F.R., but it is slightly affected by increasing primary side temperature.

Figure 17 shows that the secondary side flow rate increases with increasing F.R., but it is slightly affected by increasing primary side temperature.

Figure 18 shows that the secondary flow rate decreases with increasing amount of noncondensable gas in the SS, but the decrease is noticeable at large amounts.

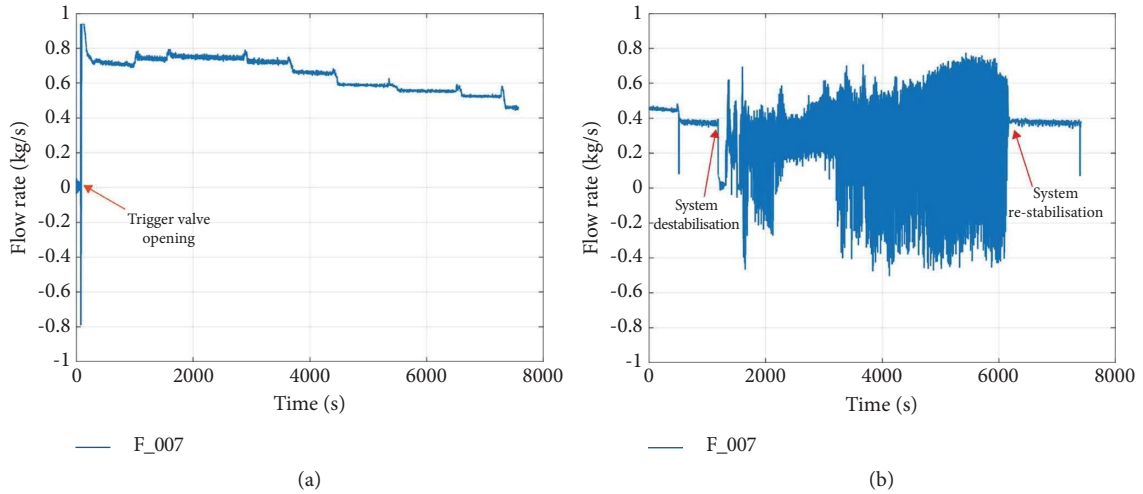


FIGURE 11: (a, b) Secondary side flow rate.

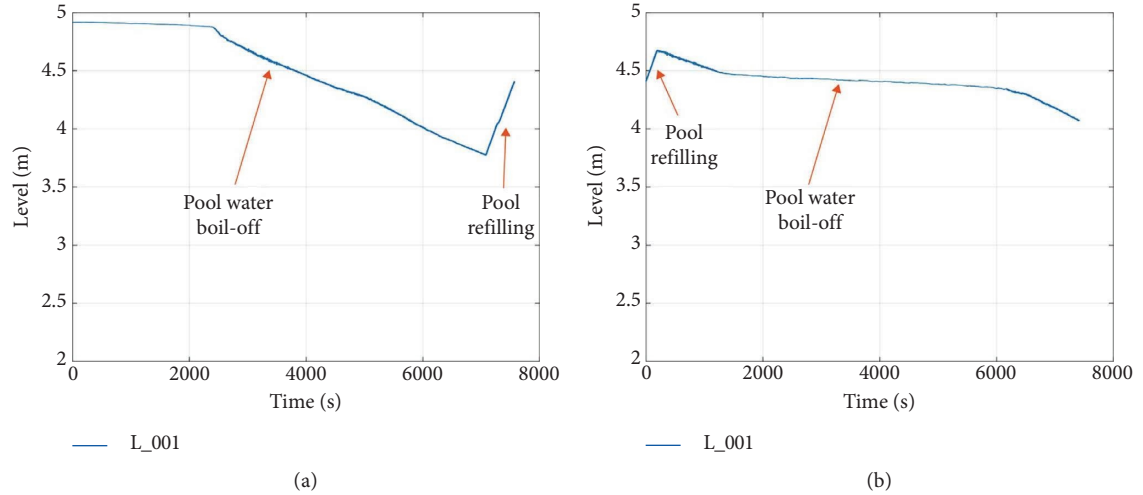


FIGURE 12: (a, b) Pool level.

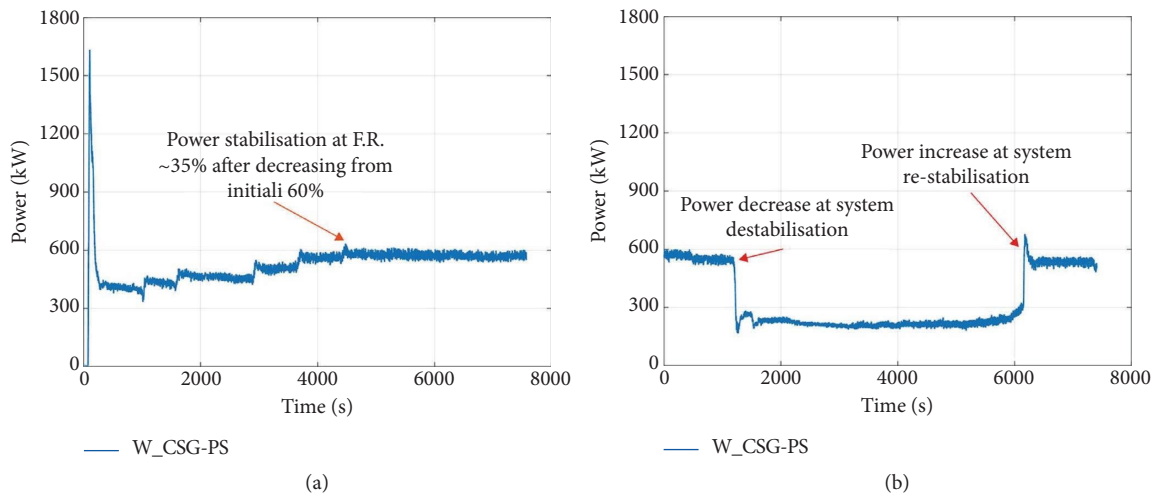


FIGURE 13: (a, b) S-CSG power.

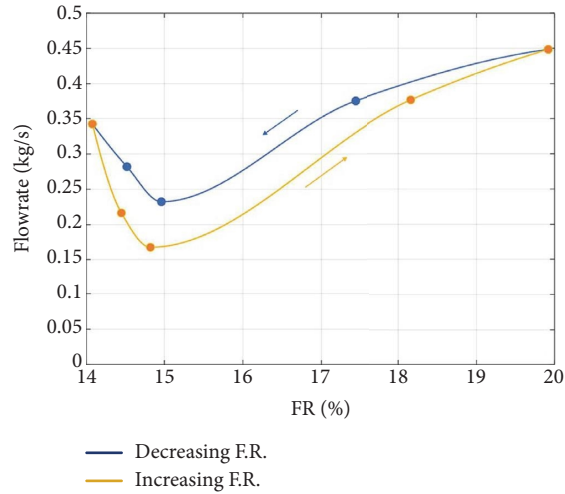


FIGURE 14: Secondary side flow rate versus filling ratio at the instability zone.

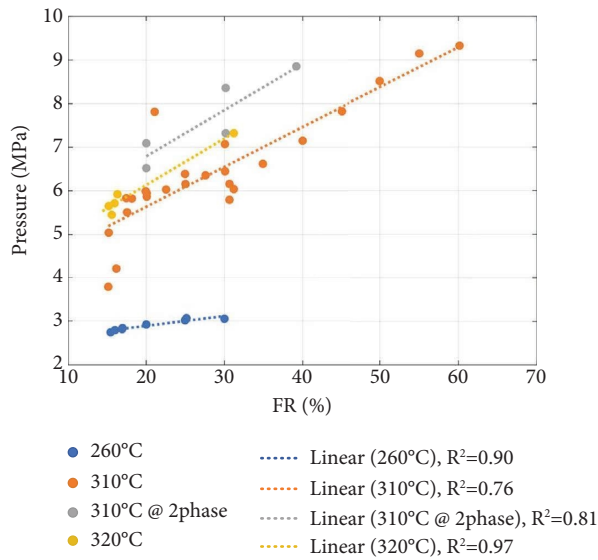


FIGURE 15: Secondary side pressure vs. F.R. at different primary side temperatures.

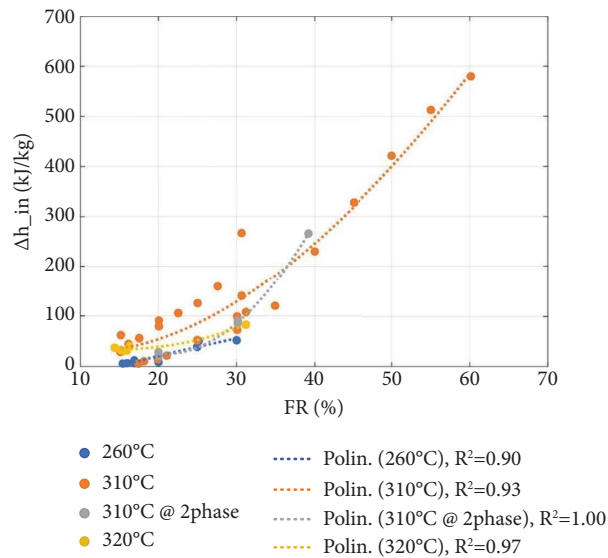


FIGURE 16: Secondary side subcooling at S-CGS inlet vs. F.R. at different primary side temperatures.

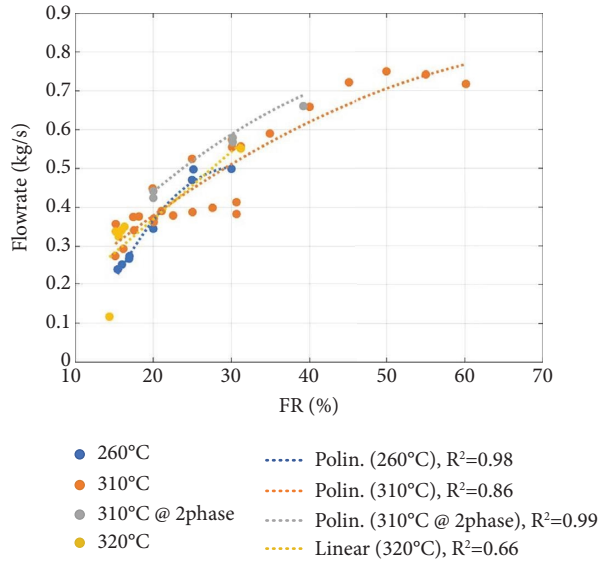


FIGURE 17: Secondary side flow rate vs. F.R. at different primary side temperatures.

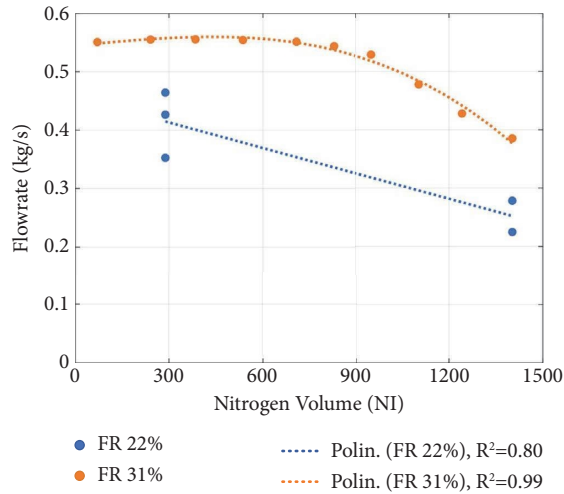


FIGURE 18: Secondary side flow rate versus noncondensable gas injected at different F.R.

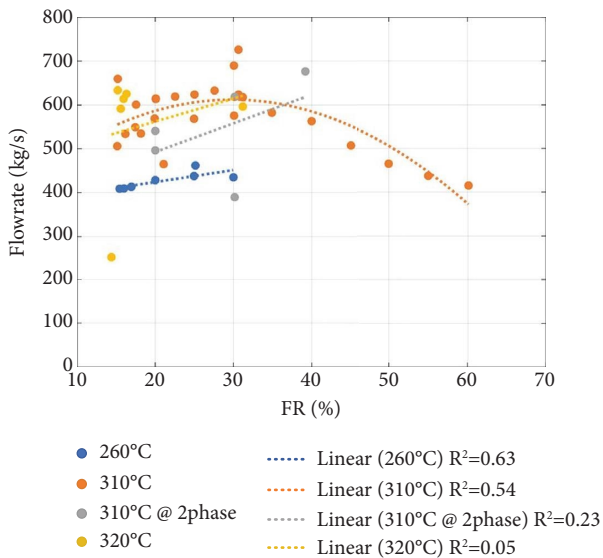


FIGURE 19: S-CSG power versus F.R. at different primary side temperatures.

Figure 19 shows that the power transferred by the S-CSG increases with increasing F.R. and with increasing primary side temperature (at least for F.R. between 15 and 30%) and decreases for higher F.R. (tests performed at a single temperature).

4.11. Criticality and Open Items. The results of the ELSMOR experimental campaign, apart from demonstrating the effectiveness of the investigated innovative DHRS, show that further points should be investigated to provide a more complete set of information for both system design and code validation. In particular,

- (i) Circulation instabilities and how they are affected by different parameters such as the water level in the cold leg of the secondary side in correspondence of the vertical tube at the HX outlet, injected or residual noncondensable gas, etc.;
- (ii) Heat transfer from the primary side in two-phase conditions at the S-CSG inlet. A limited number of tests were carried out in this campaign, and an extension of the database is planned;
- (iii) Heat transfer degradation and clogging with non-condensable gas injected into the primary side to investigate conditions representative of the reactor primary side;
- (iv) Heat transfer between the vertical tube HX and the pool, mainly for code validation and estimation of heat transfer coefficients;
- (v) Different steam generator designs to be installed in place of the S-CSG with possible loop piping upgrades for database and code validation.

5. Conclusions

With regard to the E-SMR, the experimental campaign at the ELSMOR facility at the SIET Laboratories in Piacenza, Italy, was successfully completed to verify the effectiveness of an innovative passive heat removal system based on a natural circulation loop that includes a plate heat exchanger and a vertical tube heat exchanger that dissipates the decay heat to a water pool.

Eighty-one steady-state test points were acquired, together with transient conditions essential for characterising the system and validating the thermal-hydraulic computer codes in different tasks of the ELSMOR project. In particular, tests were carried out on the primary side in single-phase and two-phase conditions.

The results showed that the system is effective and stable in its operation, except for very low filling ratios on the secondary side, which lead to unstable conditions and a sharp reduction in heat removal. A range of intermediate filling ratio values (20 ÷ 40%) was identified for the stable operation of the system.

The small effect of the non-condensable gas in the secondary on the system operation was demonstrated, as well as the small effect of the increased pressure drop in the secondary cold leg.

A set of experimental data will be made available to the ELSMOR project partners for post-test analysis and code validation.

The European stakeholders have a demonstration that the experimental activity is a fundamental means to assess and verify the innovative safety systems of SMRs to be certified and built in Europe.

Nomenclature

CFD:	Computational fluid dynamics
DAS:	Data acquisition system
DHRS:	Decay heat removal system
ELSMOR:	Toward European licensing of small modular reactors
E-SMR:	European small modular reactor
F.R.:	Filling ratio
HX:	Heat exchanger
OD:	Outer diameter
PS:	Primary side
PS CL:	Primary side cold leg
PS HL:	Primary side hot leg
PRZ:	Pressuriser
RTD:	Resistance temperature detector
SMR:	Small modular reactor
SS:	Secondary side
SS CL:	Secondary side cold leg
SS HL:	Secondary side hot leg
TcK:	Thermocouple K-type
WP:	Work package.

Data Availability

All the test data are restricted to the partners of the ELSMOR consortium. The data of the tests described in this paper are made public and can be accessed at <https://sietpc.sharepoint.com/:f:/s/ELSMOR/EptQjz2p1GrpUocuKFndBsBmr4NXWW5gjSgRya74DqWAQ?e=b8nGdr>. Note: the public excel file has big dimensions. Please download the file before opening it. For more information on the ELSMOR project, please visit <https://cordis.europa.eu/project/id/847553>.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper, as it is part of the “Dissemination” section of the ELSMOR project.

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