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ASSESSMENT OF ASTEC THERMAL-HYDRAULICS AGAINST PLATE COMPACT STEAM GENERATOR EXPERIMENTS

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Abstract. Small Modular Reactors (SMRs) are receiving important attention due to the increasing demand for clean, reliable and cost-effective energy solutions. SMR designs incorporate compact features, inherent safety through passive cooling systems and lower core inventories compared to conventional power plants. Among the different components of SMRs compact steam generators play a key role since they are devoted to the heat transfer from the primary to the secondary circuit. The use of a plate-type steam generator in an integral SMR offers the potential advantage for high-power transfer in an extremely compact configuration. While the technology of plate heat exchanger is not new, its integration within SMRs, including its coupling with a passive secondary loop and condenser to ensure reliable cooling in accidental conditions, is innovative. Therefore, careful studies and tests are necessary to meet the nuclear safety standards. Considering this, the EU-funded ELSMOR (towards European Licensing of Small Modular Reactors) project (2019-2023) aimed to improve the European capacity in evaluating and developing novel SMRs. As part of ELSMOR, an extensive experimental campaign was performed at a facility operated by SIET (Società Informazioni Esperienze Termoidrauliche, Italy) to assess the Emergency Heat Removal System of an experimental SMR. The facility consisted of a natural circulation loop connected to a primary side by a plate-type Safety-Compact Steam Generator (S-CSG), transferring heat to a water pool using a vertical tube heat exchanger. To evaluate the validity and performance of the European reference severe accident code ASTEC (Accident Source Term Evaluation Code), developed by IRSN (France), for SMRs, an ASTEC representation of the natural circulation loop and the S-CGS of the SIET facility has been developed and assessed in the framework of a KIT, IRSN, and JRC collaboration. The results of the verification phase against key and representative experiments are presented and discussed. ASTEC v3.1 results show a satisfactory agreement against the experimental data.

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1 INTRODUCTION

Small Modular Reactors (SMRs) are gaining significant attention due to the growing global demand for clean, reliable, and cost-effective energy solutions. These advanced reactor designs are smaller than traditional nuclear power plants and offer many advantages, such as enhanced safety, deployment flexibility and economy. Inherent safety in SMRs is achieved in part by passive cooling systems that operate without the need for active controls or external power sources.

Compact steam generators play a key role among the many components essential to the operation of SMRs, as they are responsible for heat transfer from the primary circuit of the reactor to the secondary circuit. The use of plate-type heat exchangers in an integrated SMR provides high power transfer capability in a compact configuration, making it ideal for the space constraints associated with these facilities. While plate heat exchanger technology is not new, its integration into SMRs, including coupling with a passive secondary loop and condenser to ensure reliable cooling under accident conditions, is innovative. This type of steam generators is expected to be included in the NUWARD SMR, which aims at further enhancing its design (Francis and Beils, 2024).

Given the critical importance of safety in nuclear technology, it is important that the design and implementation of these compact steam generators undergo careful test setups in order to evaluate their performance under several operating scenarios, including potential accident conditions. In this framework, the EU-funded project ELSMOR (towards European Licensing of Small Modular Reactors) was carried out between 2019 and 2023 with the aim of improving the European capacity for the assessment and development of innovative SMRs (European Commission, 2019). As part of this project, a facility for analyzing a passive heat removal system under natural circulation conditions was designed and built at SIET (Società Informazioni Esperienze Termoidrauliche, Piacenza, Italy). The experimental setup consisted mainly of a plate-type Safety-Compact Steam Generator (S-CSG) with its primary side being the heat source of the natural circulation loop and a vertical heat exchanger immersed in a water pool as the heat sink. An extensive experimental campaign was carried out exploring a wide range of conditions to assess the heat removal system behavior.

To evaluate the performance of the European reference severe accident code ASTEC (Accident Source Term Evaluation Code) developed by the French Institute for Radiation Protection and Nuclear Safety (IRSN), a representation of the natural circulation loop, the S-CSG and the main features of the SIET facility was developed by the Karlsruhe Institute of Technology (KIT) in collaboration with IRSN and Joint Research Center (JRC). The ASTEC model and the results of the validation phase against key representative experiments are presented below.

2 OVERVIEW OF THE ELSMOR FACILITY

The ELSMOR facility mainly consists of two loops, thermally coupled together by means of the plate-type S-CSG. The Primary Side (PS) is operated in a single-phase liquid mode with forced water circulation. Additionally, double-phase conditions can also be met in the PS. The Secondary Side (SS) is operated in a two-phase mode with natural circulation conditions driven by the heat provided in the S-CSG and dissipated in the water pool. For the ELSMOR facility, the power/volume scaling factor is 1:50 and the height factor is 1:1 (Ferri et al., 2023a).

In Fig. 1, the main characteristics of the plant are presented. The S-CSG is a commercial TEMPCO plate-type heat exchanger, model TCBC2102H*130, with 130 rectangular plates. The in-pool heat exchanger (HX) consists of five 2-meter-long vertical tubes with cylindrical headers at the top and bottom. For nomenclature purposes, the pipe lines between the S-CSG and HX are identified as the secondary side hot and cold legs (HLSS and CLSS). Similarly, for the pipe lines between the S-CSG and the S-CSG bypass, there is the primary hot and cold legs (PS HL and PS CL).

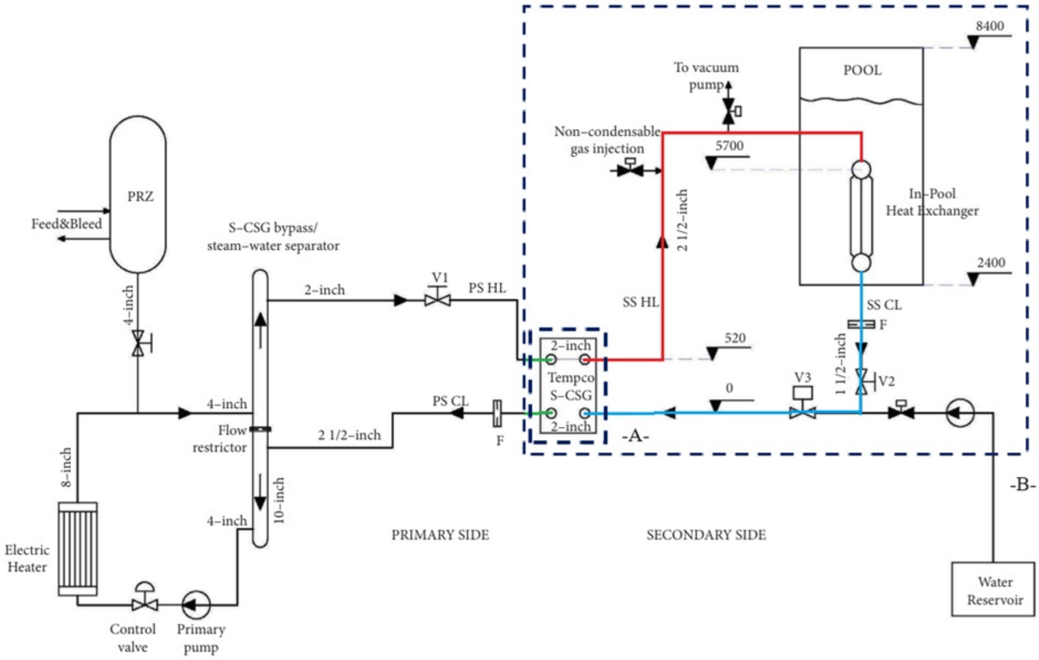

Figure 1: Simplified diagram of the ELSMOR Facility. Adapted from Ferri et al. (2023a)

All the pipelines are made of stainless-steel pipes with a thermal insulation of mineral rock-wool and covered with aluminum cladding to reduce the heat losses to the environment. In addition, the system is equipped with different sensors to measure pressure, pressure losses and temperature at strategic points of the PS and SS circuits.

A schematic representation and geometric specifications of the plate exchanger are given in Fig. 2 and Table 1, respectively.

Parameter	Value
L_1 / L_2 [m]	0.62 / 0.52
W_1 / W_2 [m]	0.19 / 0.09
H [m]	0.294
Exchange area per plate [m^2]	0.095
a - Distance between plates [mm]	2.15
t - plate thickness [mm]	0.5
N° of plates	130
D_p - Inlet/Outlet connections diameter [mm]	50.8

Table 1: Condition number for the Stekhlov operator.

For the modelling, the following considerations are taken:

- The number of fluid channels is 129, of which arbitrarily 65 are considered for the PS of the S-CSG and 64 for the SS.

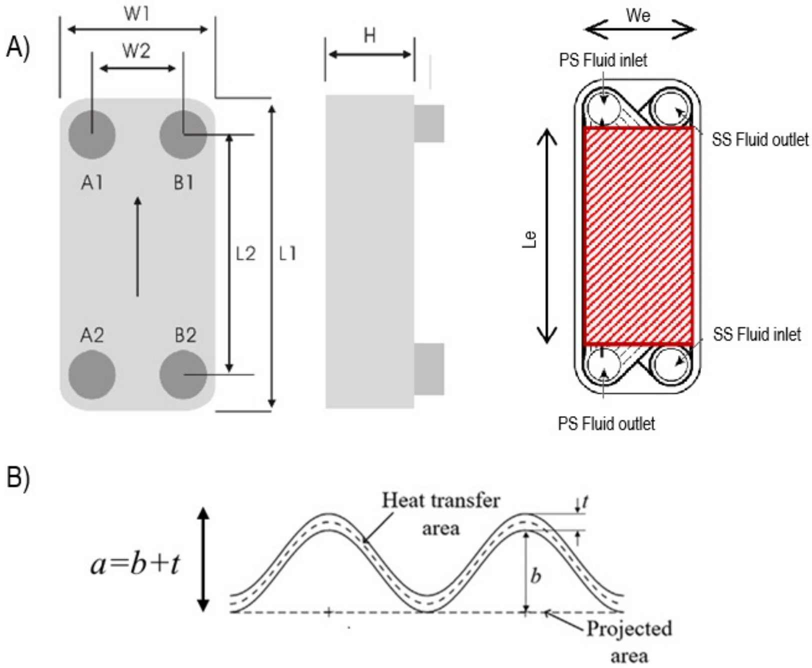

Figure 2: A) S-CSG geometry (adapted from TEMPCO - Solid Temperature (2024); Congiu et al. (2022)). B) Geometrical detail of the corrugated plate (Taken from Kang et al. (2022))

- The distance between the plates (a) consists of the plate thickness (t) and the width of the fluid channel (b). See Fig. 2 B).
- The plate thickness (t) is assumed to be 0.5 [mm].
- According to Ola (2011), the exchange area in a plate should be limited by the region marked in red in Fig. 2 A), with a projected area of $L_e \times W_e$, with $L_e = L_1 - D_p$ and $W_e = W_1 + D_p$

3 MODELLING APPROACHES WITH THE CODE ASTEC

Within ASTEC, the CESAR module simulates the 1D two-phase thermohydraulic in a defined domain. The two-phase model is a two-fluid model in which both gas and liquid phases are taken into account and up to five non-condensable gases can be included in the simulations (Chatelard et al., 2016). In this work, the code version V3.1.1 was used. Two approaches were considered. On the one hand, an ASTEC representation of the S-CSG was used, with inlet and outlet boundary conditions for the PS and SS (region -A- in Fig. 1). On the other hand, this representation was incorporated into the secondary loop domain, including the pool and the in-pool heat exchanger (In-Pool HX) (region -B- in Fig. 1).

3.1 S-CSG representation

The S-CSG domain consisted of two pipes exchanging heat through a wall, as it can be seen in Fig. 3. Each pipe is divided into 14 elements. The first and last volumes correspond to the inlet and outlet regions of the steam generator on each side, respectively, while the 12 inner volumes are responsible for the real heat exchange through a wall that is also discretized into 12 volumes.

The temperature, pressure, and mass flow were set for the inlet of each pipe, and the pressure was specified for the outlets using the experimental data (Bersano et al., 2023).

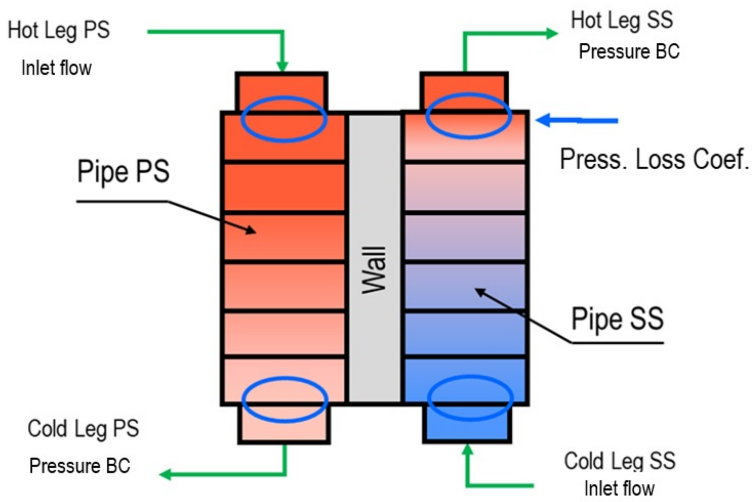

Figure 3: Generic representation with the ASTEC code of the S-CSG domain (number of volumes shown is simply illustrative).

In addition to the applied boundary conditions, the prescription of singular pressure loss coefficients is an important step to be performed. In this case, coefficients were set at the junctions between the first and second volume and between the second-to-last and last volume in each pipe. A single steady state experiment was selected to fit these coefficients.

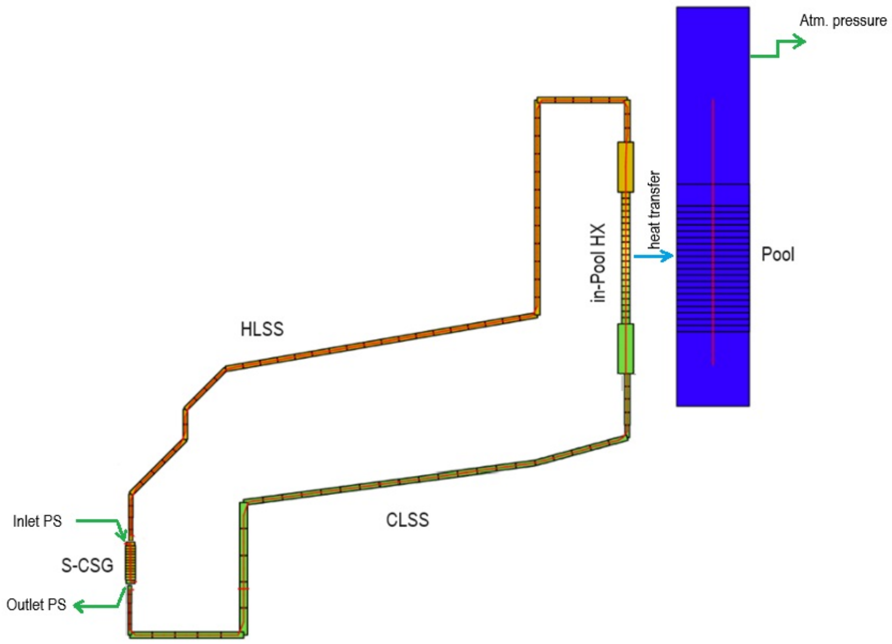

Figure 4: ASTEC representation for the Secondary Side of the ELSMOR facility (number of volumes shown is simply illustrative).

3.2 Secondary loop representation

The secondary closed loop of the facility was also modeled incorporating the S-CSG, previously described, and the HX and the piping connections. In Fig. 4, the ASTEC representation of the SS is presented.

The same nodalization was mantained for the S-CSG. The Cold Leg (CLSS) and Hot Leg (HLSS) were modeled using 40 and 53 volumes, respectively. In both cases, the geometries and arrangements along the entire length of the piping were kept as close as possible to the plant specifications. In order to capture the heat losses along the pipes, a heat transfer coefficient of 36.0 [W/m^{2}K] was imposed along with the corresponding external temperature, according to the information delivered in the experiment reports (Ferri et al., 2023b). The HX was modeled using two volumes for the upper and lower zones and 21 inner volumes accounting for the effect of the 5 tubes of the exchanger. The pool itself was discretized similarly to the HX in order to be able to analyze the stratification of the pool. However, this specific study will be the subject of future analysis.

Boundary conditions were defined as mass flow, temperature and pressure at the inlet of the PS of the S-CSG, and pressure at the outlet. In addition, an atmospheric pressure boundary condition was specified at the top of the pool.

Due to the large number of accessories such as flanges, elbows, vales, reducer and expanders, singular pressure loss coefficients were defined along the pipelines using one single steady-state experiment as a reference.

4 RESULTS

The results obtained with the ASTEC code using two different datasets developed by KIT are presented below. Each dataset corresponds to the simplified S-CSG and the secondary loop models.

The experiments selected give information about the system behavior with a two-phase water flow in the secondary side. The F.R.[1] is decreased from 60.16% to 14.96%, in a sequence of steady-state conditions, until destabilization is reached and then it is increased up to 18.16%, in different steps, until restabilization is reached. The PS inlet temperature was set to approximately 310°C (583.15 K) and a pressure of $\approx$ 12 [MPa]. Once the flow is restabilized, a series of tests were conducted with a PS inlet temperature of 260°C (533.15 K), pressure of $\approx$ 10 [MPa] and a F.R. in the SS from 30% to 15.44%. The mass flow rate in the PS was $\approx$3.5 [kg/s] and for the SS ranged between 0.17 to 0.75 [kg/s]. A total of 23 steady-state experiments were achieved with the conditions mentioned above. The detailed experimental matrix can be found in Bersano et al. (2023).

4.1 S-CSG without complete secondary loop modeling

To analyze the simplified case of the S-CSG, where the complete secondary loop is not included, flow conditions are imposed on both the primary and secondary sides according to the experimental data.

Fig. 5 A) shows a comparison between the calculated and experimental values for the power exchanged in the S-CSG. Each point corresponds to a steady-state condition with specific combination of FR, pressure and Temperature. The 45° solid line indicates perfect agreement, while the ±10% and ±15% deviation limits are also marked. It can be noted that the simulations show

[1]The filling ratio (F.R.) is defined as the ratio between the current mass in the loop and the initial mass.

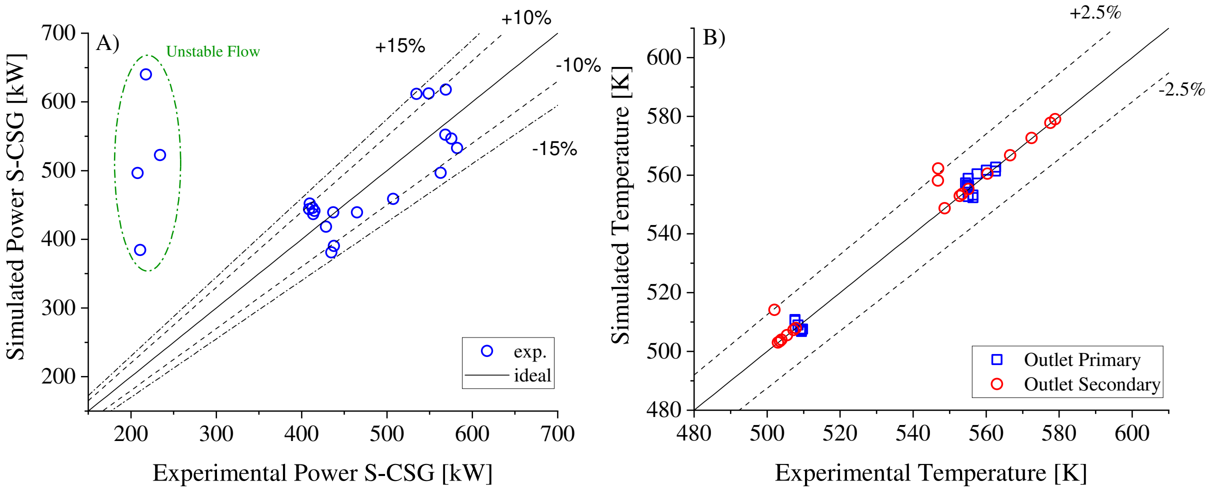

Figure 5: A) S-CSG power exchange and B) Outlet temperature comparison between the experimental and simulated values (Bersano et al., 2023).

a general good agreement with the measurements, with deviations of less than 15%. Of these, 70% exhibit deviations of less than 10%. The largest outliers correspond to cases with FR<15%, which experienced unstable flow conditions. These unstable conditions correspond to the interruption of the natural circulation, which ASTEC could not simulate under the conditions used.

Similarly, Fig. 5 B) shows the comparison between the calculated and measured temperatures at the outlet of the PS and SS of the S-CSG. The results presented for the SS outlet correspond to both saturation and superheated steam conditions when they are reached. As can be seen, the results exhibit very good agreement, with almost all the cases analyzed showing deviations of less than ±2.5%. The "unstable flow" cases with FR<15% were not plotted and analyzed, and they will not be included in further analyses in this work.

An important step was to analyze the pressure losses achieved across the plates, since some

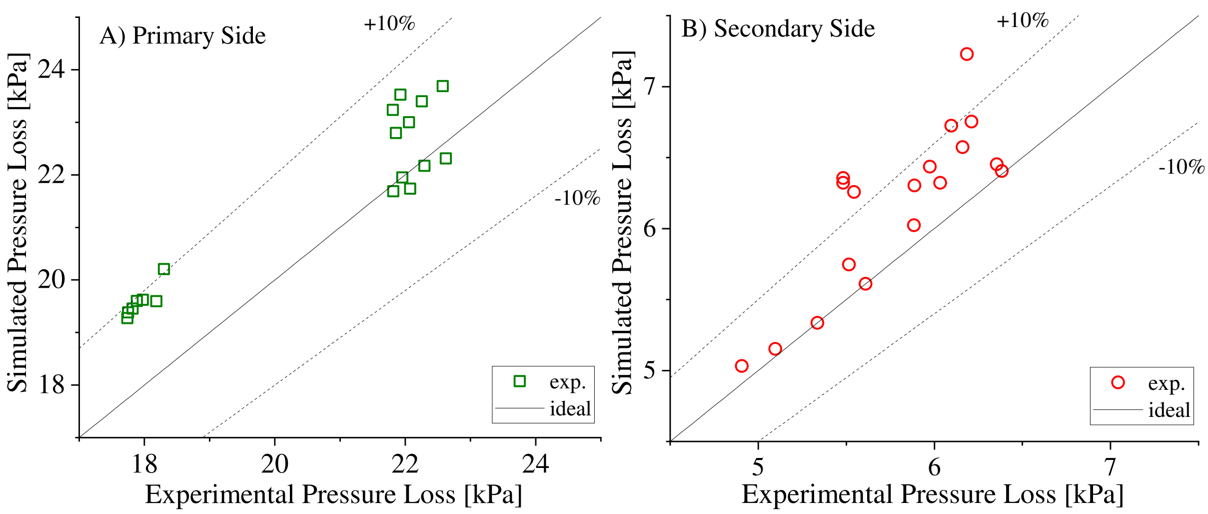

Figure 6: Comparison of the pressure difference at the plates between experimental and simulated valued (Bersano et al., 2023).

parameters were fitted using a single steady-state case. To do this, the primary and secondary pressure losses of the plate heat exchanger are presented in Fig. 6 A) and B), respectively. In most cases, the observed deviations are less than 10% when comparing the simulation results with the average experimental values during the steady-state conditions. The most significant deviations in both cases correspond to cases where the inlet temperature was of 260°C in the PS. It is important to note that the simulation parameters were fitted using a case with a FR = 50% in the SS and inlet temperatures of ≈311°C in the PS, corresponding to the case with the highest mass flow rate in the SS. Considering that the analyzed cases covered a wide range of conditions, a good agreement was obtained.

As can be seen from the comparisons made, despite the observed deviations, the representation used to model the S-CSG with the ASTEC code produces reasonable results.

4.2 S-CSG with secondary loop modeling

In the second dataset, only the primary flow conditions are input parameters because the secondary loop and pool are included and simulated. The experiments selected for the following analyses are the same as in Section 4.1.

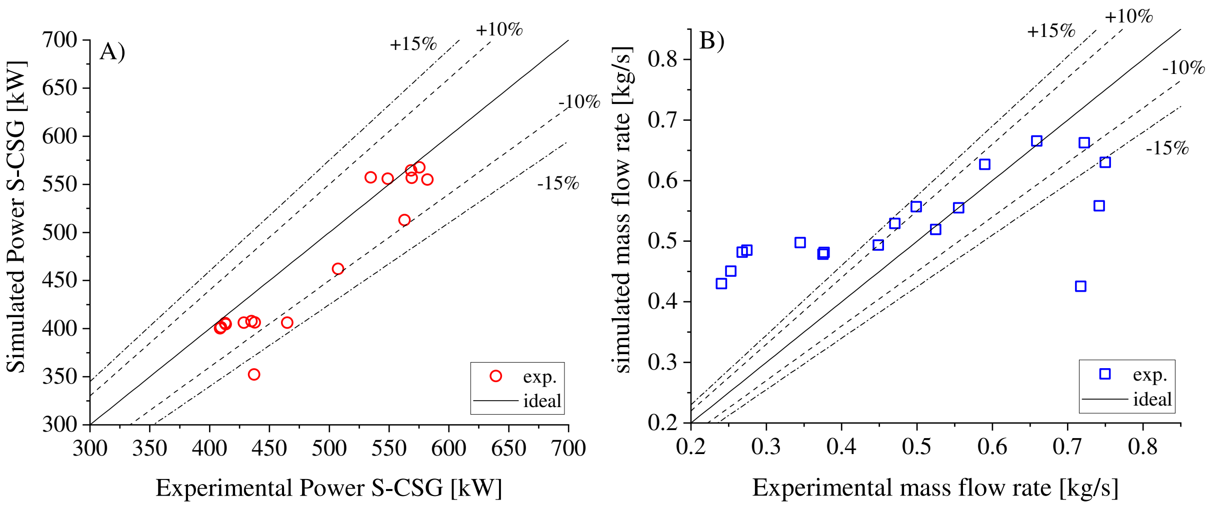

Figure 7: A) S-CSG power exchange and B) mass flow rate comparison between the experimental and simulated values for the secondary loop model in ASTEC (Bersano et al., 2023).

In Fig. 7 A), a comparison of calculated and experimentally obtained S-CSG Power is presented for the selected experiments with stable flows. Similarly, in Fig. 7 B), a comparison of mass flow rates is shown. In A), it can be seen that, in general, there is a tendency to obtain slightly lower results compared to Fig. 5 A), where the S-CSG is analyzed without the SS loop. However, it has been observed that approximately 90% of the calculated cases the deviations are within ±10%, obtaining a good agreement between the calculation and the experimental measurements. On the contrary, significant deviations are observed in B) for 45% of the cases. These deviations correspond to cases where the FR deviates from 30%. The adjustment of the pressure loss coefficients in the secondary loop were performed using a steady-state experiment with a 30% FR to model the effect of the fittings and accessories in the facility. The results show that these fitted values cannot be applied for different two-phase conditions in the loop. The further the studied condition is from FR=30%, the greater the deviations. Similar to the

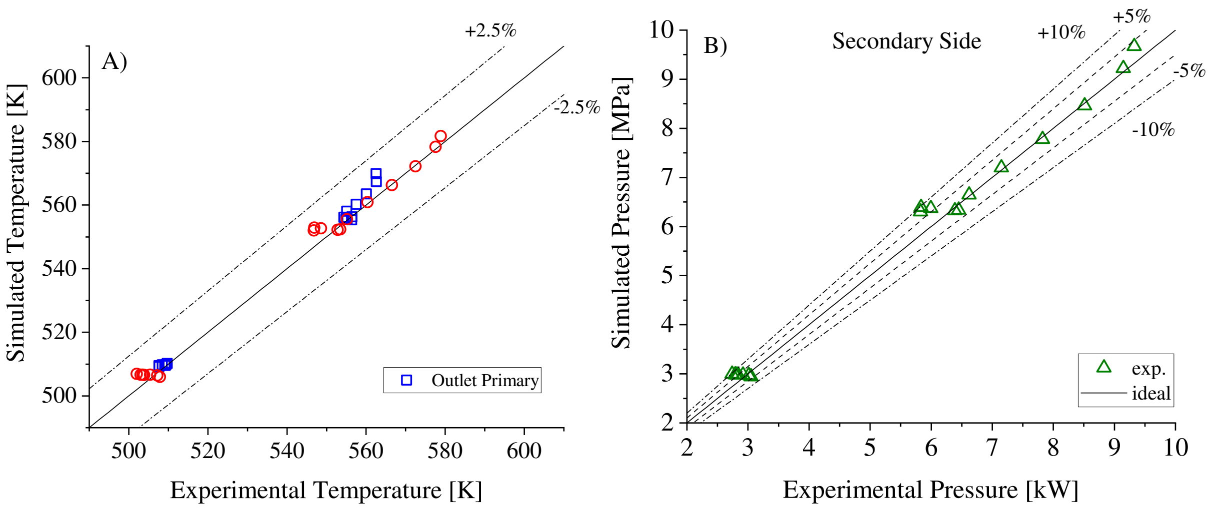

Figure 8: Comparison of the pressure difference at the plates between experimental and simulated values for the secondary loop model in ASTEC (Bersano et al., 2023).

simplified S-CSG model, the cases with unstable flows (FR<15%) could not be captured by the model, so these data were not included in the figures.

Despite the discrepancies observed for the mass flow rate in Fig. 7 B), very satisfactory results were obtained for the temperature at the outlet of both sides of the S-CSG and for the pressure in the loop taken at the outlet of the mentioned plate heat exchanger. These results are presented in Fig. 8 A) and B) for the temperature and the pressure, respectively. It can be observed that about 90% of the simulated cases have errors of less than ±2.5% and ±10%, respectively. This indicates that the code, despite certain simplifications, is able to reproduce the experimental results with good agreement.

5 CONCLUSIONS

As part of a collaboration with IRSN and JRC, KIT participated in the study of the experiments performed in the ELSMOR project and in the evaluation of the ASTEC code capabilities for modeling the facility, including a plate-type Steam Generator representative of the NUWARD reactor design.

In this framework, two ASTEC input decks were developed at the KIT: a simple model of the S-CSG and a model of the secondary circuit of the ELSMOR plant, which also includes the In-pool HX-pool system. The simple model for the S-CSG showed good agreement when compared with selected experimental data, conducted under a wide range of conditions including pressure, temperature, secondary mass flow and filling ratio (FR). In general, the model presented a good behavior, achieving good results for key variables such as temperature at the outlet of PS and SS, plate pressure differences, and exchanged power. The largest deviations occurred in cases where the FR was less than 15%, where a destabilization of the natural convection in the secondary loop was experimentally observed.

The model for the secondary loop of the ELSMOR plant showed promising results when comparing the code's results with the experiments. The most significant departures from the ideal behavior were observed in cases where the FR deviated from 30%, which was the case value used to fit the singular pressure loss coefficients throughout the pipeline. This suggests that a tailored set of coefficients for each condition is necessary to accurately reproduce the system. During the analysis, the secondary flow instability or loss of natural convection could not be reproduced, even at low FR values. Further investigations are required related on this topic.

However, despite the geometric simplifications made in both the secondary loop and the S-CSG model itself, and the deviations observed, the CESAR module of ASTEC v3.1.1 can still reproduce the proposed system global behavior.

REFERENCES

Bersano A., Lombardo C., Alblouwy F., Karppinen I., Silde A., Nikitin K., Grosjean B., Morin F., Martin J., and Weyermann F. ELSMOR D3.6: Code Benchmark on natural circulation with prototypical heat exchanger submerfed in pool. Technical Report, 2023.

Chatelard P., Belon S., Bosland L., Carénini L., Coindreau O., Cousin F., Marchetto C., Nowack H., Piar L., and Chailan L. Main modelling features of the astec v2.1 major version. *Annals of Nuclear Energy*, 93:83–93, 2016. doi:10.1016/j.anucene.2015.12.026.

Congiu C., Ferri R., and Achilli A. ELSMOR - Plate-type Heat Exchanger S-CSG. 2022.

European Commission. Towards European Licencing of Small Modular Reactors - ELSMOR Project. 2019. https://cordis.europa.eu/project/id/847553.

Ferri R., Achilli A., Congiu C., Marcianò S., Gandolfi S., Marengoni M., Bersani A., and Passerin D'Entreves A. Elsmor european project: Experimental results on an innovative decay heat removal system based on a plate-type heat exchanger. *Science and Technology of Nuclear Installations*, 2023:6672504, 2023a. doi:10.1155/2023/6672504.

Ferri R., Congiu C., Achilli A., Gandolfi S., Marcianò S., Marengoni M., and Bersani A. Test report for natural circulation with prototypical heat exchanger. Technical Report, 2023b.

Francis D. and Beils S. NUWARD SMR safety approach and licensing objectives for international deployment. *Nuclear Engineering and Technology*, 56:1029–1036, 2024. doi: 10.1016/j.net.2023.12.045.

Kang J., Bak J.Y., Lee B.J., Chung C.K., and Yun B. Numerical investigation of a plate-type steam generator for a small modular nuclear reactor. *Nuclear Engineering and Technology*, 54:3140–3153, 2022. doi:10.1016/j.net.2022.02.020.

Ola U.E. *Plate Heat Exchanger Design Methodology*. Bachelor's thesis, Central Ostrobothna University of Applied Sciences, 2011.

TEMPCO - Solid Temperature. T plate b c - c series-super high pressure brazed plate heat exchanger. Technical Report, 2024.