Helical Coil Steam Generator Experiments with the MOTEL SMR Test Facility in the EU-McSAFER Project

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ABSTRACT

The MOTEL (MOdular TEst Loop) test facility, designed and constructed at LUT University, Finland, is an integral test facility representing a small modular reactor (SMR) operating with natural circulation. The design of the facility resembles the NuScale SMR with a helical coil steam generator consisting of 16 steam generator tubes in four tube bundles.

A series of two steam generator experiments was performed with the MOTEL facility within the EU Horizon 2020 project McSAFER. The aim of the test series was to investigate the behavior of the helical coil steam generator and to provide data for the validation of thermal hydraulic codes. In the experiments, steady states with different heating powers were attempted. Particularly, the temperature behavior of the steam generator, both on the shell and tube sides, was studied; temperature distributions along the steam generator tubes were measured.

One of the test series focused on lower heating powers of 75 kW, 100 kW, 125 kW and 150 kW, while the other investigated steam generator behaviour at higher heating powers of 250 kW, 500 kW, 750 kW and 1 MW. Steady behaviour and production of saturated steam was observed at lower heating powers. At higher than 250 kW powers superheating started to occur but in an oscillatory manner. Also, no clear steady states could be established at higher powers as the temperatures kept increasing towards the end of each step, signifying that the steam generator was incapable of transferring all the heat produced by the core in the conditions of the high-power experiments.

KEYWORDS
small modular reactor, MOTEL facility, helical coil steam generator, natural circulation

1. INTRODUCTION

MOTEL (Modular TEst Loop) is an integral test facility recently commissioned in the nuclear safety research laboratory at LUT University. Modularity has been the guiding design philosophy behind MOTEL, as the facility consists of exchangeable main components that cab be replaced to functionally similar ones but with different designs. This way, the facility can be configured to represent various reactor designs. The current implementation of MOTEL represents a prototypical integral pressurized water small modular reactor (SMR) operating with natural circulation.

MOTEL was commissioned in 2020, and the characterizing tests were run in 2021. The results of the characterizing tests along with a more detailed presentation of the facility design philosophy and structure are presented in [1].

MOTEL has been utilized in the Euratom-funded McSAFER project to investigate SMR-specific thermal hydraulic phenomena and to provide data for the validation of safety analysis tools including thermal hydraulic system codes, subchannel codes and computational fluid dynamics (CFD) codes. This paper provides a general description of the MOTEL facility and the helical coil steam generator experiments conducted within the McSAFER project.

McSAFER is a three-year Euratom-funded project with a collaboration of 13 organizations coordinated by Karlsruhe Institute of Technology. The project aims to advance the safety research for SMRs by combining experiments and numerical simulations [2]. LUT leads the work package dedicated to thermal hydraulic experiments and code validation and performs tests with the MOTEL facility.

Two series of experiments were conducted with the MOTEL test facility within the McSAFER project in 2021-2022. The first series studied the behavior of the helical coil type steam generator of MOTEL, and the second series focused on studying core crossflows by applying asymmetrical radial core power distributions. A specific aim of the experiments was to provide measurement data for the validation of thermal hydraulic system, subchannel and CFD codes within the project. In the present paper, the MOTEL facility is presented, and the steam generator experiments, and their results are discussed.

2. MOTEL TEST FACILITY

The MOTEL facility is a model of an SMR with resemblance to the design of the NuScale type SMR [3]. The unique modularity configuration of the MOTEL facility design and construction is presented in Figure 1. The figure shows how the main part of the facility, the pressure vessel package, is constructed of the four main modules, i.e., a core, an extension piece, a steam generator, and a pressurizer module. These construction modules are stacked one above the other, mounted together with large flanges, and fastened to a support structure at the laboratory site. Together the outer walls of these modules form the outer shell of the pressure vessel of the SMR design.

The design of the core is emphasized in the MOTEL facility design. Traditionally in integral test facilities, the core with the heater rods is made long and thin to preserve the height scaling of 1:1 compared with the reference core in question. With MOTEL, this practice is not followed. Instead, the core of MOTEL has been designed wider and shorter than usual to enable studying both axial and radial flow phenomena inside the core region. The core heater rod bundle design is generic and does not directly represent the fuel design of any existing reactor type. The heater rods in the core are arranged in a rectangular grid, which is practical concerning the instrumentation and investigation of flow phenomena inside the core region. The MOTEL core is divided into twelve separately adjustable power regions as illustrated with different colors in Figure 2. This structure enables application of various core power distributions in the experiments.

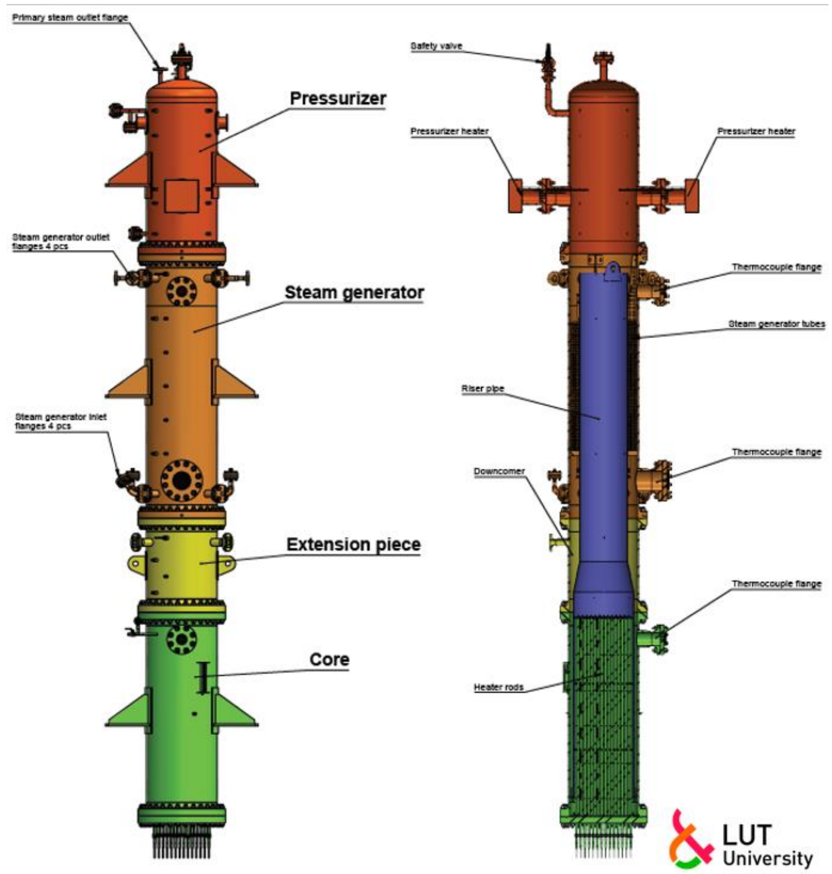

Figure 1. Modules comprising the pressure vessel (left) and insight on the SMR design (right) of the MOTEL test facility.

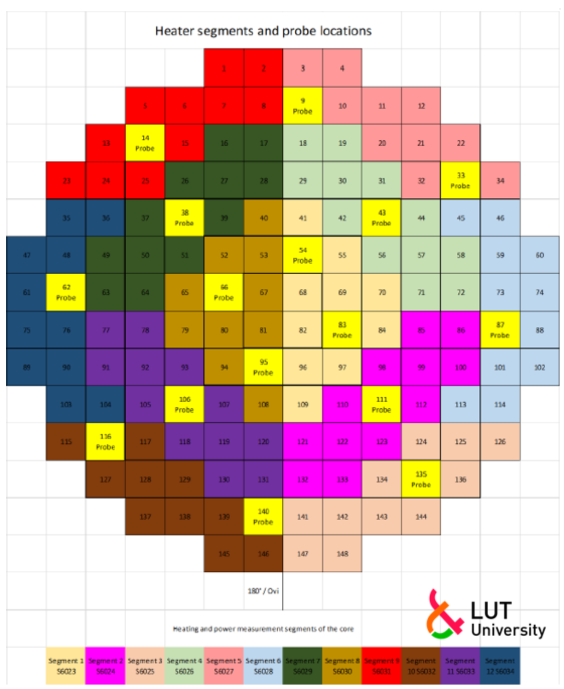

Figure 2. Radial power segments of the MOTEL core. Each square represents one heater rod, except the yellow measurement rods. Different colors represent the adjustable heating segments.

An essential feature in the MOTEL design is the helical coil steam generator construction. The behavior of such a steam generator type is one of the key interests in the research activities with MOTEL. A specific characteristic of this type of steam generator is that the secondary side flow and boiling takes place inside the steam generator tubes, whereas the primary side water flows outside the tubes, through the shell side of the steam generator tube bundles. The steam generator is presented in Figure 3. The steam generator is located inside the steam generator module, i.e., at the top part of the annular downcomer space inside the pressure vessel of MOTEL. The steam generator consists of 16 steam generator tubes connected to four cold collectors on the bottom and four hot collectors on the top.

The outer diameter of a single steam generator tube is 15 mm, and there are four different lengths of tubes. The lengths of the single steam generator tubes vary from 20.0 m to 25.1 m. The heat transfer area of a single tube varies from 0.942 m^2 to 1.183 m^2, the total heat transfer area of the steam generator being 17.0 m^2. Construction-wise, half of the tubes are coiled clockwise and half counterclockwise. A set of four different length tubes form a tube bundle with its own cold and hot collector. Figure 4 presents a cross-section of the four different size tube loop set-ups. Due to the coiling and length differences of the steam generator tubes, the tubes intertwine and form loops with different diameters. Each of the loops comprise four steam generator tubes on four different layers intertwined. Diameters of the four loops vary from 515 mm to 650 mm.

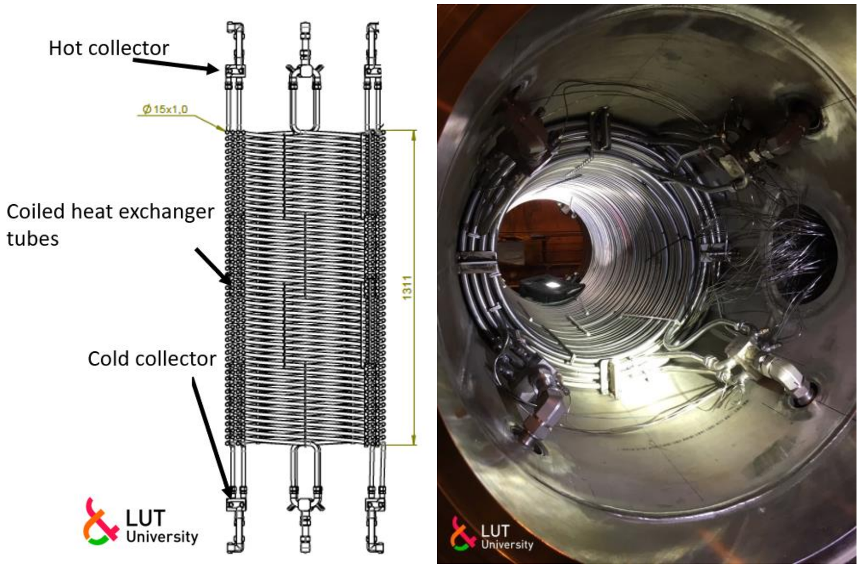

Figure 3. MOTEL steam generator.

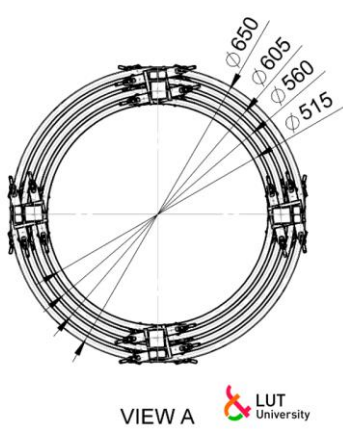

Figure 4. Loops formed by the MOTEL steam generator tubes.

The pressurizer of MOTEL is located at the top part of the pressure vessel. The pressurizer has two heating elements to adjust the primary pressure inside the test facility. During normal operation, the primary side is filled with water up to a chosen set elevation at the level of the pressurizer. The main relief valve (safety valve) of the facility is located at the top of the pressurizer.

MOTEL represents an integral SMR where the whole primary circuit is inside the reactor pressure vessel. The primary system of MOTEL operates passively by natural circulation, and thus no primary pumps are needed to circulate the primary side water. The water heats up in the core region, flows upwards at the center of the vessel via the hot riser space above the core element. Above the top of the riser, water turns and flows downwards along the edge of the vessel in the annular downcomer space. At the top part of the annular downcomer, the hot primary water flows across the shell side of the steam generator tubes. There, the heat from the primary side is transferred to the secondary side, to the tube side of the steam generator. Below the steam generator region, the cooled primary water flows down via the lower annular downcomer space to the bottom of the pressure vessel. Finally, there, via an annular flow-through opening below the inner shell of the pressure vessel, water flows to the core section and the circulation continues.

The secondary side is actively operated, as the feedwater from the water reservoir is pumped through a water manifold to four cold collectors. The water flows through the cold collectors into the steam generator tubes. From each cold collector, secondary water flows through four steam generator tubes. Due to the heat received from the primary side, the water starts to boil inside the tubes. The generated steam is directed from the tubes to four hot collectors, and out from the pressure vessel via pipelines to one steam manifold, and out from the system.

The total height and outside diameter of the MOTEL pressure vessel are approximately 7.4 m and 711 mm, respectively. The maximum heating power of the core is approximately 1 MW. For both primary and secondary sides, the design pressure and temperature are 40 bar and 250 °C, respectively. Table 1 summarizes the main characteristics of the facility. Table 2 summarizes the characteristics of the MOTEL steam generator.

Table I. Main characteristics of the MOTEL test facility

Characteristic	MOTEL
Total height [m]	7.4
Outside diameter of main vessel [mm]	711
Maximum primary/secondary pressure [bar]	40
Maximum primary/secondary temperature [ºC]	250
Number of helical coil steam generator tubes	16
Maximum core heating power [kW]	990
Number of heater rods	132
Heated length of heater rods [mm]	1830
Diameter of heater and measurement rods [mm]	19.05
Number of measurement rods	16
Number of dummy rods	145
Diameter of dummy rods [mm]	18
Main material of the components	Stainless steel
Insulation material / thickness [mm]	Mineral wool / 120, aluminum cover

Table II. Characteristics of the steam generator

Characteristic	MOTEL
Number of tubes / tube bundles	16 / 4
Tube outer diameter / wall thickness [mm]	15 / 1.0
Tube lengths [m]	20.0 / 21.7 / 23.4 / 25.1
Helical coil loop diameters [mm]	515 / 560 / 605 / 650
Total heat transfer area [m^2]	17.0

3. STEAM GENERATOR EXPERIMENTS

The steam generator experiments within the McSAFER project consisted of two experiments, which were performed in the autumn of 2021. Steady states with different uniform core heating power levels up to the maximum power of the facility were attempted with MOTEL. The experiments were conducted in two separate runs with four power steps in each. The run testing the behavior of the steam generator at lower core powers consisted of power steps of 75 kW, 100 kW, 125 kW and 150 kW, while the other run was conducted with power steps of 250 kW, 500 kW, 750 kW and 1 MW. The primary and secondary pressures during the experiments were 35 bar and 10 bar, respectively. Each power step was run for 3600 seconds. Before the initiation of each experiment, the facility was heated up and pressurized to the desired pressure level, and temperatures in the facility were let to stabilize.

Particularly, the temperature behavior of the steam generator, both on the shell and tube sides, was studied. Temperature distributions along the steam generator tubes were measured. In addition, in the experiment with lower core powers, the steam generator’s capability to superheat steam was tested at the end of the experiment by means of running the facility with 150 kW and 100 kW core power but with smaller secondary feedwater flow rates.

Figure 5 shows the secondary side temperature measurements of the steam generator. There are 79 thermocouples in the secondary side inside the steam generator tubes. Each of the 16 steam generator tubes includes five temperature measurements, of which two are at both ends of the tube near the cold and hot collectors and three are at three elevations (bottom, middle, top) along the spiral section of the steam generator tube as presented in Figure 5.

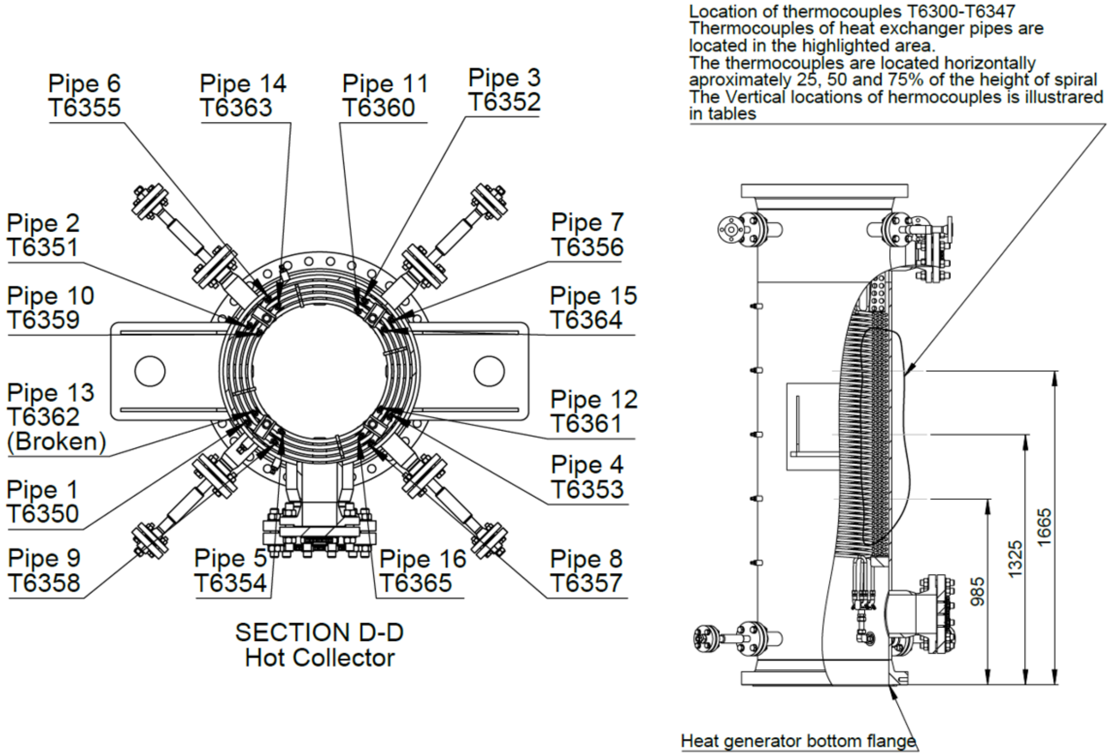

Figure 5. MOTEL steam generator secondary side temperature measurement locations.

4. RESULTS

4.1 Low power levels

The overall behavior of the facility during the experiment with lower core powers is presented in Figure 6. There was slight fluctuation of the primary mass flow rate. The secondary pressure stayed quite stable during this experiment.

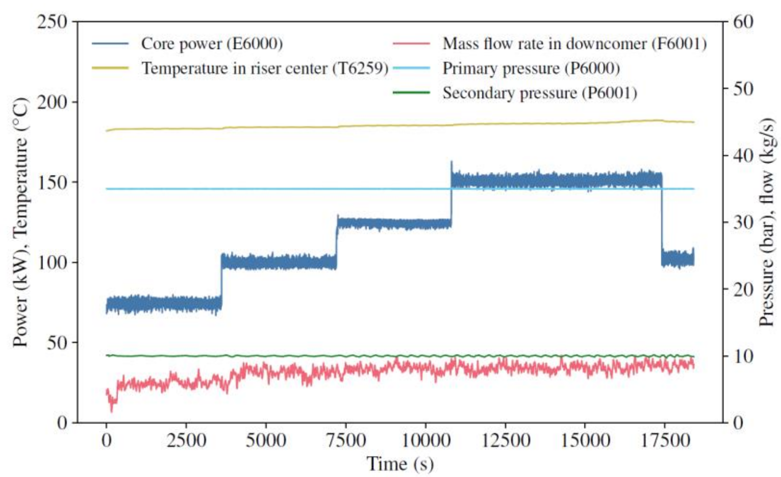

Figure 6. General behavior of the MOTEL facility during the steam generator experiment with power levels of 75 kW, 100 kW, 125 kW and 150 kW.

The primary side temperatures were measured at five different elevations in the steam generator region. Figure 7 shows the primary temperatures at the highest and lowest measurement elevations. On both elevations, the data of two temperature measurements located on different sides of the facility (difference 140°) are presented, as well as an average of these two measurements. In addition, an estimated steady-state temperature is presented with a red line, calculated as an average of the latter 1/3 (i.e., 20-minute time window) of each power step.

Due to the low core power levels, the primary temperatures were quite stable during the different power steps. A clearly increasing trend of temperatures can only be seen when the different secondary feedwater flow rates were tested after the actual core power level steps.

On the top of the steam generator, the temperature distribution inside the steam generator shell side was quite uniform, both measurements measuring practically identical temperature values (Figure 7, left). The difference between the measurements increased when the primary water flowed down inside the downcomer and more heat was transferred to the secondary side. The thermocouples measured clearly different temperatures on the lower part of the steam generator (Figure 7, right). Also, the fluctuation of the temperatures increased as the heat transfer and the pressure/temperature fluctuation on the secondary side started to affect the primary temperatures.

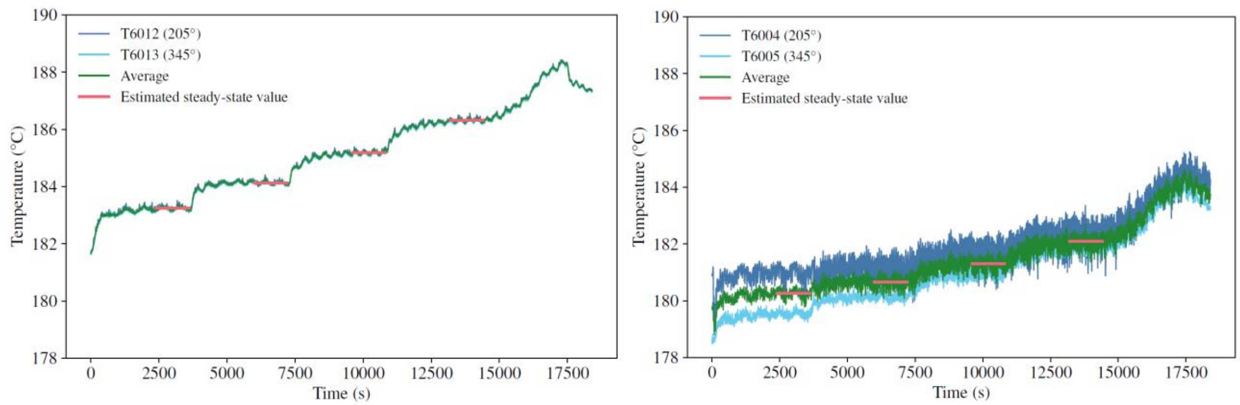

Figure 7. Steam generator primary side temperatures on the highest (left) and lowest (right) elevations during the steam generator experiment with power levels of 75 kW, 100 kW, 125 kW and 150 kW.

On the secondary side, temperature distributions inside each steam generator tube were measured with five thermocouple measurements in each tube at different elevations. Figure 8 presents the steam generator secondary side temperature behavior during the experiment at the bottom and top locations. The figure includes the data of all 16 temperature measurements (blue curve) and their average (green curve) at the elevation in question. Also, the steady-state value of each core power step was estimated (red line).

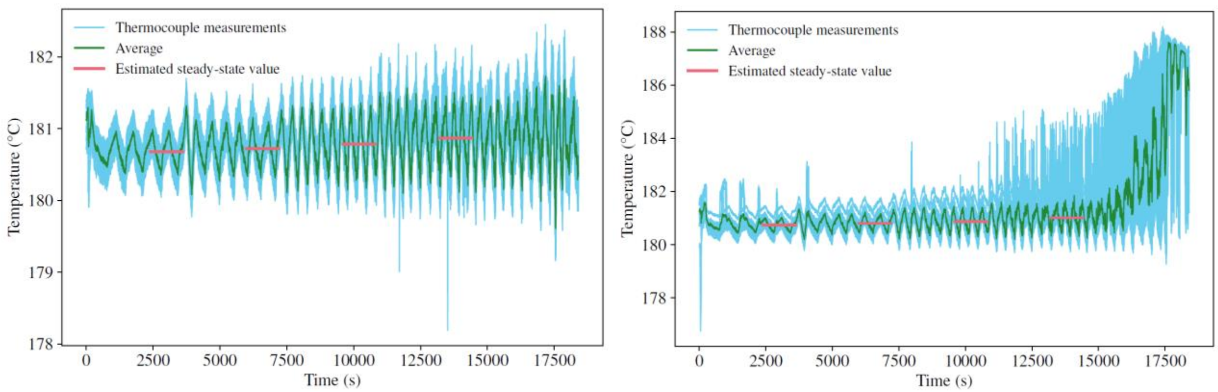

Figure 8. Steam generator secondary side bottom (left) and top (right) location temperatures during the steam generator experiment with power levels of 75 kW, 100 kW, 125 kW and 150 kW.

Figure 8 shows temperature fluctuation on the steam generator tube side due to the secondary side pressure control. The pressure is controlled with a valve. Due to the design of the valve, very rapid movements of the regulating element are not possible. Augmented by the small steam volume in the secondary side, the pressure control is somewhat coarse, leading into the fluctuation of the temperatures. During the last power step of 150 kW, another type of fluctuation becomes visible in the blue curves as some tubes start to superheat steam and this happens in an oscillatory manner. On average, however, in all power levels, the saturation temperature was reached in the bottom region of the steam generator and the secondary temperatures stayed practically the same along the whole length of the steam generator. No significant superheating of steam happened during the applied core power levels. At the end of the experiment, when different feedwater flow rates were tested, an increasing temperature trend and a stronger fluctuation can be seen, which indicates that steam was superheated during that testing.

Figure 9 (left) presents the primary side axial temperature distribution during each core power step. The data consists of the averaged values of each power step on all five measurement levels (the red line values in Figure 7). The figure clearly shows the primary temperature differences between the different power steps.

Figure 9 (right) also presents the averaged secondary side axial temperature profiles of all 16 steam generator tubes with the different core power levels used. In the lowest measurement point near the cold collectors there were differences in the temperatures, but in the steam generator region the saturation temperature (180 °C, the water saturation temperature at the used 10 bar pressure) was reached in the lower part of the steam generator, and the temperatures stayed at that level on the whole length of the steam generator. Thus, on average, no superheating of steam happened during the experiment.

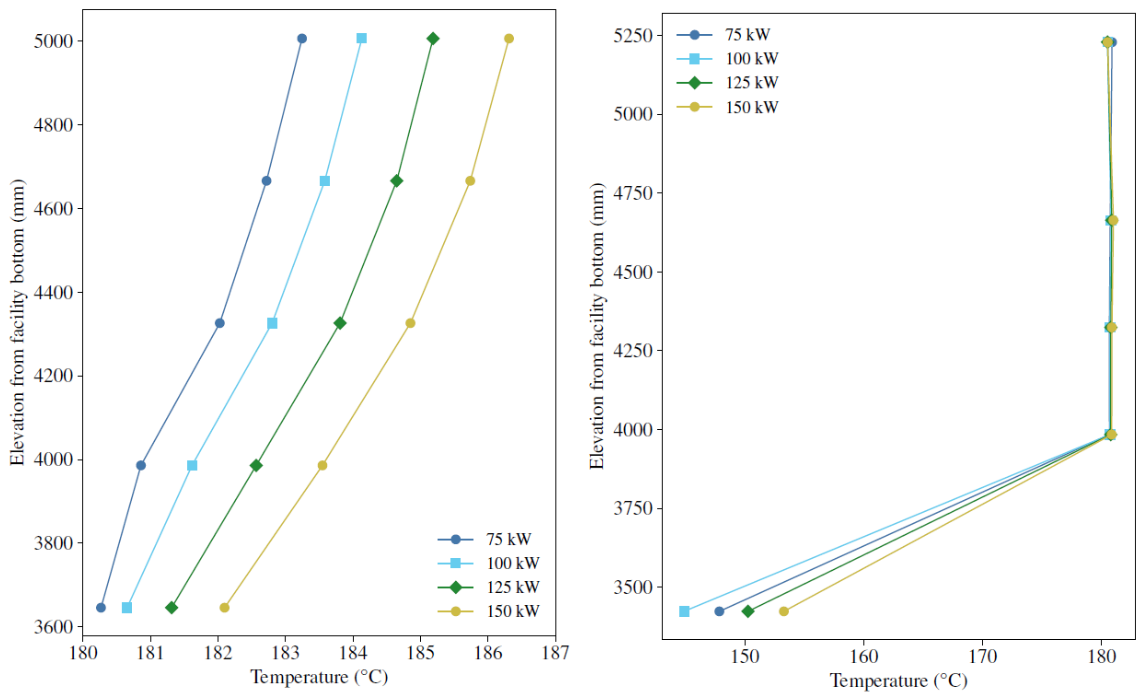

Figure 9. Steam generator primary side axial temperature profiles (left) and averaged secondary side axial temperature profiles of all steam generator tubes (right) during the steam generator experiment with power levels of 75 kW, 100 kW, 125 kW and 150 kW. Note: flow direction on the primary side is from top to bottom, and on the secondary side from bottom to top.

4.2 High power levels

The overall behavior of the facility during the experiment with higher core powers is presented in Figure 10. The two last power steps were conducted as separate runs, which can be seen as discontinuous data in the figure. There was some fluctuation in the secondary pressure and the primary mass flow rate, which had a slightly rising trend during the power steps especially with the larger core powers.

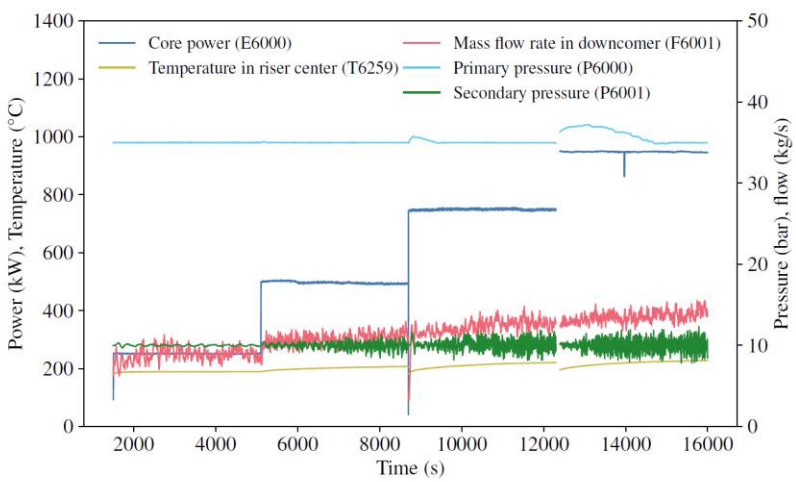

Figure 10. General behavior of the MOTEL facility during the steam generator experiment with power steps of 250 kW, 500 kW, 750 kW and 1 MW.

On the primary side, temperatures were measured at five different elevations in the steam generator region. Figure 11 shows as an example the evolution of the primary temperatures at the highest and lowest measurement elevations. On both elevations, the data of two temperature measurements located on different sides of the facility (difference 140°) are presented, as well as an average of these two measurements. In addition, an estimated steady-state temperature is presented for each power step.

During the first power step (250 kW), the primary temperatures were very stable, but from the second step (500 kW) onwards, an increasing trend in the primary temperatures remained and an equilibrium could not be reached in the timeframe of the experiments. Although no steady temperature level was reached for these steps (500 kW, 750 kW, 1 MW), a 20-minute average was still extracted from the end of the steps to represent a quasi-steady-state value for the purpose of plotting axial temperature profiles. On the top of the steam generator, the temperature distribution inside the steam generator shell side was quite uniform, as both measurements measured practically identical temperature values, see Figure 11 (left). The difference between the measurements increased when the primary water flowed downwards inside the downcomer and more heat was transferred to the secondary side. The thermocouples measured clearly different temperatures on the lower parts of the steam generator, as presented in Figure 11 (right). Also, the fluctuation of the temperatures increased on the lower parts of the steam generator as the heat transfer and the pressure/temperature fluctuation on the secondary side started to affect the primary temperatures.

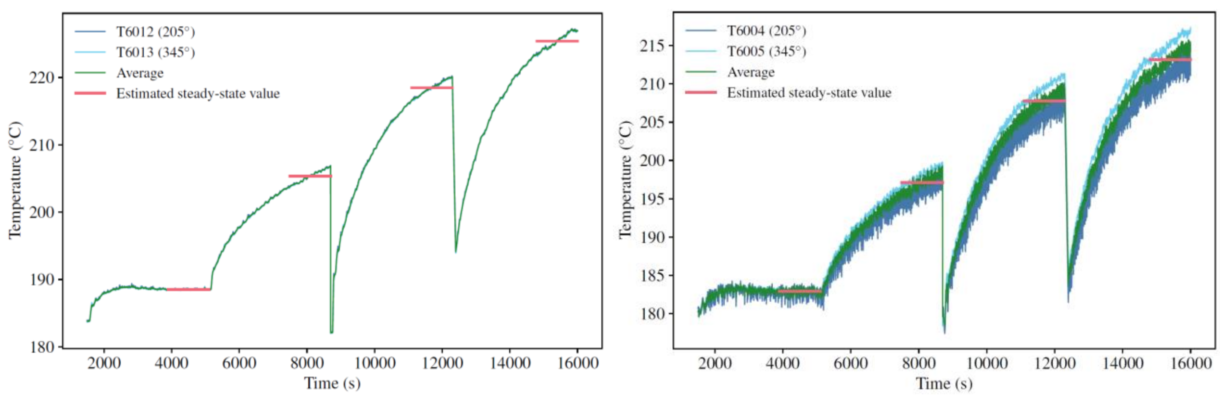

Figure 11. Steam generator primary side temperatures on the highest (left) and lowest (right) elevations during the steam generator experiment with power levels of 250 kW, 500 kW, 750 kW and 1000 kW.

On the secondary side, temperature distributions inside each steam generator tube were measured with five thermocouple measurements in each tube at different elevations as shown in Figure 5. Figure 12 presents the steam generator secondary side temperature behavior during the experiment at the bottom and top locations. The figure includes the data of all 16 temperature measurements (blue curves) and their average (green curve) at the elevation in question. Also, a steady-state value of each core power step was estimated (red lines).

Figure 12 shows strong temperature fluctuation on the steam generator tube side. Also, apart from the 250-kW step, an increasing temperature trend is visible during the steps, similar to the primary side data in Figure 11. During the 250 kW-step, there was also less fluctuation of the temperatures. During the 250-kW step, the temperatures stayed approximately on the same level on each elevation of the steam generator (approximately 180 °C). This indicates that very little superheating of steam took place with this core power level and the used secondary feedwater flow.

The increasing fluctuations in the secondary side temperatures, especially in the higher power levels can be attributed to the increase in the primary side temperatures (i.e., increased superheating temperatures) and nonuniform, fluctuating pressures between the tube bundles. The check valves in the feedwater lines prevent water from flowing backwards from one collector to another. When pressure rises in a certain tube bundle, the feedwater flow to that collector stops, and then the remaining water vaporizes and superheats even in the lower part of the steam generator. When the pressure in the tube bundle decreases, the check valve opens, and relatively cold water flows into the tube bundle. This can be seen in Figure 12 as an increase in the temperature fluctuations especially in the higher power levels. The time-averaged temperatures are not indicative of the energy transfer of the system, even though they give insight to the general behavior of the steam generator.

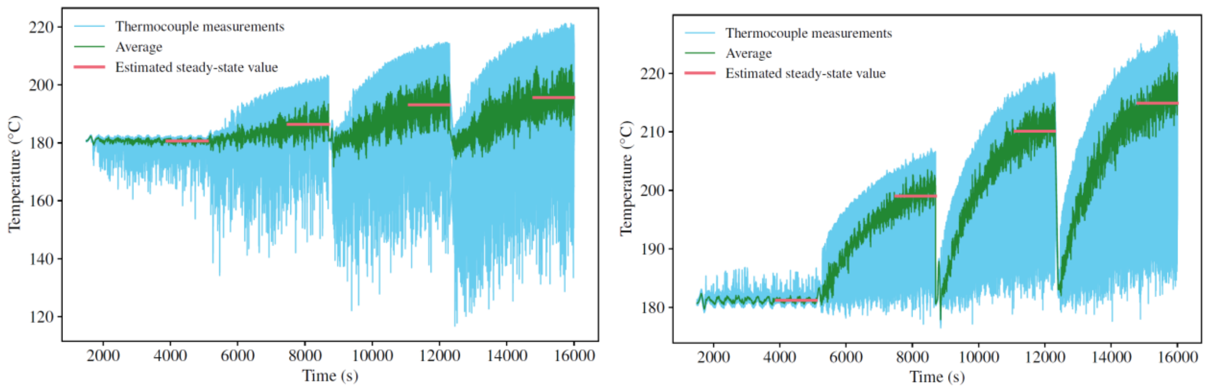

Figure 12. Steam generator secondary side bottom (left) and top (right) location temperatures during the steam generator experiment with power levels of 250 kW, 500 kW, 750 kW and 1000 kW.

Figure 13 (left) presents the primary side axial temperature distribution during each power step. The data consists of the averaged values of each power step on all five measurement levels (the red line values in Figure 11). The figure clearly shows the primary temperature differences between the different power levels.

Figure 13 (right) also presents the averaged axial temperature profiles of all 16 steam generator tubes with the different core power levels used. In the lowest measurement point near the cold collectors there are arbitrary differences in the temperatures, but in the steam generator region, the differences are according to the used core power levels. The figure clearly shows that during the 250-kW power step, the saturation temperature is reached already at the bottom measurement point, which is located on the lower part of the steam generator, and on average no superheating takes place during this step. During the higher-power steps (500 kW, 750 kW, 1 MW), the saturation temperature is reached already at a lower elevation. The axial temperature trend is slightly increasing along the whole length of the steam generator during these steps.

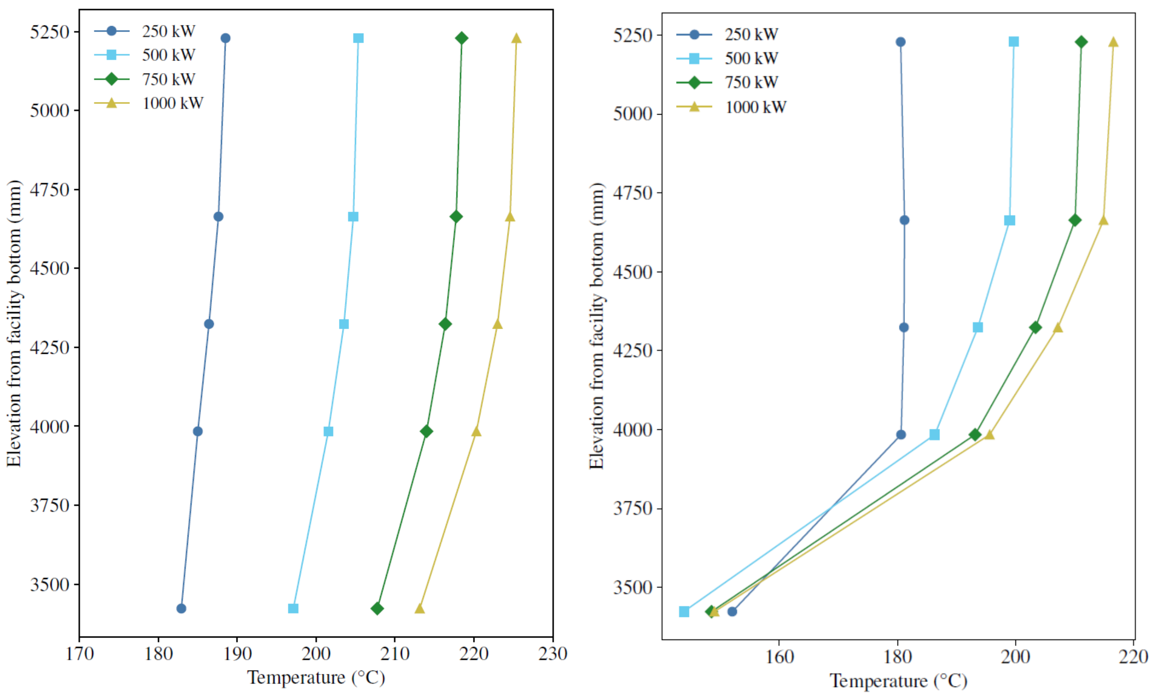

Figure 13. Steam generator primary side axial temperature profiles (left) and averaged secondary side axial temperature profiles of all steam generator tubes (right) during the steam generator experiment with power levels of 250 kW, 500 kW, 750 kW and 1000 kW. Note: flow direction on the primary side is from top to bottom, and on the secondary side from bottom to top.

5. CONCLUSIONS

The modular test facility MOTEL, currently representing an integral pressurized water SMR, was commissioned at LUT University in Lappeenranta, Finland in 2020 and is currently utilized in experiments within the Euratom-funded research project McSAFER to provide data for code validation and insight to the behaviour of a prototypic SMR operating at natural circulation. MOTEL features a helical coil steam generator, whose behaviour was specifically investigated within McSAFER. Two steam generator experiments were conducted in 2021. In the experiments, steady states with different uniform core heating power levels were attempted. The experiments were conducted in two sets of experiments, one focusing on lower power levels of 75 kW, 100 kW, 125 kW and 150 kW, and another one on higher power levels of 250 kW, 500 kW, 750 kW and 1 MW.

The power levels up to 250 kW resulted in stable behavior with the primary side temperatures reaching an equilibrium level. Some coarse fluctuations due to the secondary side pressure control could be seen in the temperatures. On the secondary side, the temperatures reached the saturation temperature already at the lower part of the steam generator and on average remained at saturation the whole extent of the steam generator, although slight superheating was observed in some individual tubes especially with the power levels of 150 kW and 250 kW.

At the higher power levels of 500 kW, 750 kW and 1 MW the facility started to clearly superheat steam. However, the superheating happened in very unstable manner observed as strongly fluctuating secondary side temperatures. Also, at these power levels the steam generator was incapable of transferring all heat generated in the core as no equilibrium in the temperatures could be reached at least in the timeframe of the experiments.

The steam generator experiments provided first insight to the behavior of the MOTEL facility and particularly the helical coil steam generator. The unstable superheating behavior observed at higher heating powers warrants further investigations to determine the operating parameter boundaries for stable behaviour. Yet, the experiments have already provided useful data for the validation of thermal hydraulic system and CFD analysis codes.

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