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Transient analysis of OSU-MASLWR with RELAP5

Martina Molinari, Vincenzo Narcisi*, Cristiano Ciurluini, Fabio Giannetti

DIAEE - Nuclear Section, "Sapienza" University of Rome, Corso Vittorio Emanuele II, 244, 00186, Rome, Italy

* Corresponding author: vincenzo.narcisi@uniroma1.it

Abstract. The present paper deals with the assessment of the original and a modified version of RELAP5/MOD3.3 against the OSU Multi Application Small Light Water Reactor (OSU-MASLWR). The new implemented features regard suitable correlations for the heat transfer coefficient evaluation in helical geometry. Furthermore, two different modelling of the Helical Coil Steam Generator (HCSG) are assessed. In the first approach, HCSG's primary and secondary sides are collapsed in a single pipe component. In the second model, three equivalent pipes are conceived for the simulation of the three ranks composing the HCSG.
Two different power manoeuvring experiments are reproduced. The simulations highlight a satisfactory agreement in both the transients. Nevertheless, the modified code shows enhanced capabilities in the prediction of the HCSG operation. This is due to the improvements adopted in the modified version of RELAP5/MOD3.3 that allows a better modelling of the dryout phenomena occurring within helical tubes, as well as a better estimation of the primary side heat transfer coefficient. The better agreement of the heat exchange is propagated to the primary system, resulting in a more accurate prediction of the inlet and outlet core temperatures, and primary flow rate.

Key Words: *helical coil steam generator, natural circulation, transient analysis, heat transfer, small modular reactor*

1. Introduction
Best estimate System Thermal-Hydraulic (STH) codes (e.g., RELAP5/MOD3.3) are extensively used for licensing of light water reactors. To broaden code applicability to the domain of advanced nuclear power plants, it is needed to verify their modelling capabilities with respect to safety relevant thermal-hydraulic phenomena occurring in such systems. Comparison between experimental data and simulation outcomes constitutes a key point of the code validation.

In this framework, aiming at studying the operation of the Multi Application Small Light Water Reactor (MASLWR), the Oregon State University (OSU) designed and constructed the OSU-MASLWR non-nuclear test facility. The MASLWR is Small Modular Reactors (SMR), relying on natural circulation of the primary coolant in both normal operations and abnormal conditions [1]. According to the conceptual design, as it can be seen in Figure 1, the Reactor Pressure Vessel (RPV – item 5 in Figure 1) is surrounded by the High Pressure Containment (HPC – item 9 in Figure 1). The latter is partially filled with water providing pressure suppression and liquid makeup capability. The first containment vessel is hosted into a water pool, named Cooling Pool Vessel (CPV – item 10 in Figure 1), acting as the ultimate heat sink. The pressure suppression is actuated by the Automatic Depressurization System (ADS).

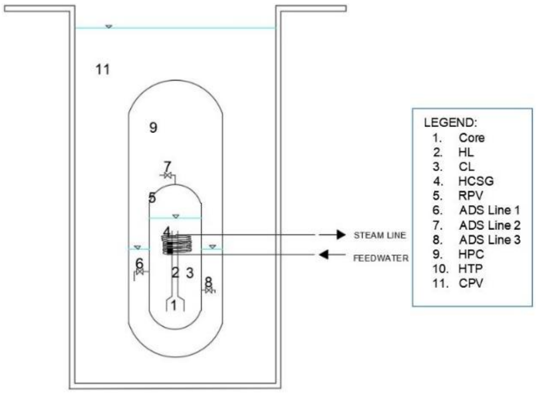


Figure 1: MASLWR conceptual design

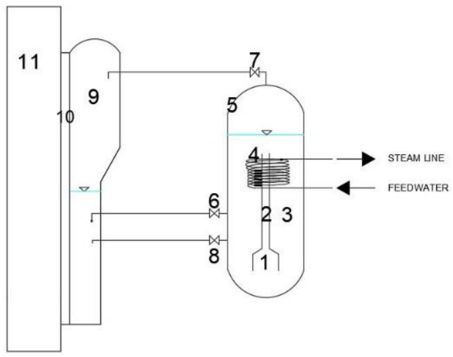


Figure 2: OSU MASLWR layout

One of the most relevant peculiarities of the MASLWR is the Helical Coil Steam Generator (HCSG – item 4 in Figure 1). The modelling of this component represents a crucial point in the safety and reliability analysis of such reactor. The aim of the present work is to assess the capabilities of RELAP5/MOD3.3, as well as of a modified version of the code, in the simulation of such component. This version has been developed at the Department of Astronautical, Electrical and Energy Engineering (DIAEE) of "Sapienza" University of Rome for advanced nuclear fission and fusion power plant applications [2], in collaboration with ENEA Brasimone Research Center. The main improvement for the present activity is to better simulate HCSG performances under different operative conditions. Some examples of the RELAP5 application for HCSG modelling were found in literature. To assess STH codes capabilities, two different validation benchmarks were carried out, using experimental data from OSU MASLWR experimental campaign. The first one was led by U.S. Department of Energy (DOE) with the OSU MASLWR 002 Test. This test has been simulated with different STH codes by several participants [3][4]. The RELAP5 models of the HCSG were developed following the modelling guidelines presented by Hoffer et al. [5]. The simulation results were in good agreement with experimental data and RELAP5/MOD3.3 had proven its capability to give a satisfactory qualitative prediction. The second benchmark, consisting in two exercises, was conducted by the International Atomic Energy Agency (IAEA): the first one regards the International Collaborative Standard Problem (ICSP) Test 1 and the ICSP Test 2, both reproduced through TRACE code [4], and the second one is related to the ICSP Test SP3 [6]. The latter was simulated by several participants, following the HCSG modelling guidelines presented by Hoffer et al. [5]. Although a general qualitative agreement with experimental data was observed, RELAP5/MOD3.3 showed some limitations in the prediction of the HCSG operation. In order to increase the simulation accuracy, the participants proposed an increase of the HCSG heat transfer area, or of the heat transfer coefficient (HTC), using a calibrated multiplicative factor greater than 1.0 [7].

To enlarge code applicability and improve its accuracy with respect to HCSG simulations, the DIAEE has developed an improved version of RELAP5/MOD3.3, that has been assessed reproducing the aforementioned tests.

2. Facility Overview

The OSU MASLWR test facility (Figure 2) reproduces the MASLWR conceptual design, presented in Figure 1, but RPV (item 5 in Figure 2), HPC (item 9 in Figure 2) and CPV (item 11 in Figure 2) are conceived as three separated vessels that accomplish the same safety operations proposed in the MASLWR design.

The facility is scaled at 1:3 length scale, 1:254 volume scale and 1:1 time scale with respect to MASLWR conceptual design [8].

The OSU MASLWR test facility consists of the RPV, the internals, and the Containment structures. The reactor core (item 1 in Figure 2) is reproduced with a Fuel Pin Simulator (FPS), consisting in 57 electrically heated cylindrical rods distributed in a 18.6 mm pitch square array with 1.33 pitch to diameter ratio. The FPS is located in the bottom region of the RPV. The HCSG (item 4 in Figure 2) is composed of vertical helical tubes and is located in the upper part. This configuration ensures the required thermal length between the power source and the heat sink, since core cooling is foreseen in natural circulation in both normal and abnormal conditions. The primary flow passes through the core and goes upstream within the Hot Leg (HL – item 2 in Figure 2) riser arriving to the Upper Plenum. Then it flows downstream through the SG and the Cold Leg (CL – item 3 in Figure 2), returning into the Lower Plenum. The secondary flow passes through HCSG, consisting of 14 helical tubes with two common headers, one for Feedwater (FW) inlet and one for the steam outlet.

Safety operations are ensured by the ADS, consisting of valves (item 6, 7, and 8 in Figure 2 and the final heat sink constituted by the HPC and the CPV, thermally coupled by a proper Heat Transfer Plate (HTP - item 10 in Figure 2).

3. Models

The nodalization of OSU MASLWR can be divided in five regions: primary and secondary systems, HPC, CPV and ADS.

The model consists of hydrodynamic components, that reproduce primary and secondary loops, and heat structures, that simulate heat exchange (where expected) and structural mass inventory. The modelling is developed with the sliced approach for the entire facility [9], keeping the length ratio of adjacent nodes into the range of 1 ÷ 1.25. The primary loop is simulated with pipe components and branch components, and nodalization features are defined respecting the actual geometry of the facility. The hydrodynamic characteristics of FPS are evaluated collapsing all the 57 subchannels in a single pipe component. In the input deck, its flow area is the total FPS flow area, while the hydraulic diameter is computed considering the geometry of the single subchannel. The heat structure of the FPS is in cylindrical geometry. In order to describe the thermal power supplied, a general table of the type power-to-time is used as boundary condition. Pressure drops through the core flow plate, FPS and HCSG primary side are set as Reynolds number dependent.

The ADS has been modelled with horizontal pipes and valves. In Figure 3 Vent Lines, System Blowdown Lines and Sump Return Lines are referred to components 43 & 45, 40 & 41, and 55 & 57, respectively. Both HPC and CPV have been modelled with two vertical parallel pipes connected with cross junctions, to better simulate buoyancy and mixing within the large volumes. In Figure 3, pipe components 61 and 62 stand for the HPC, while components 65 and 66 represent the CPV. It is worth emphasizing that such systems did not operate in the considered transient tests.

Regarding the secondary loop, boundary conditions are set with time dependent volumes (feedwater inlet temperature and steam outlet pressure) and a time dependent junction (feedwater inlet flow rate).

The focal point of the present analysis is the HCSG modelling. Two different nodalization schemes are developed, investigating the dependence of the simulation outcomes on the HCSG modelling choices. In the following, the two models are referred as Model 1 and Model 2. The geometrical scheme of the primary system is the same in both the models. The HCSG shell-side consists, in both the models, of a single equivalent pipe (component 22 in Figure 3) reproducing the free space in the SG shell-side. Concerning the secondary side, Model 1 is the simplest modelling approach. As a matter of fact, the HCSG tube-side is reproduced with a single equivalent pipe (component 26 in Figure 3), collapsing all the helical tubes. Such pipe component has the average tubes length and slope evaluated as weighted average, over the number of rotations of each coil. The total flow area considers all the 14 tubes. Components 27 and 32 in Figure 3, stand for the secondary side inlet and outlet headers.

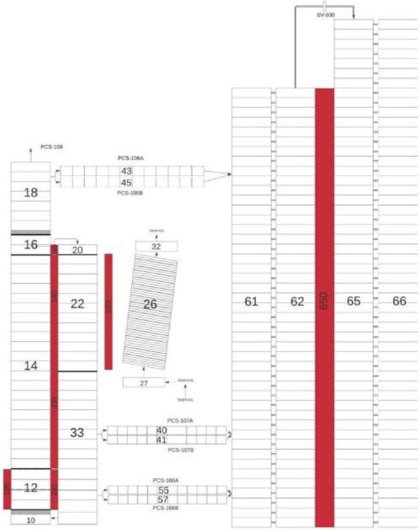


Figure 3: OSU MASLWR - RELAP5 Model 1

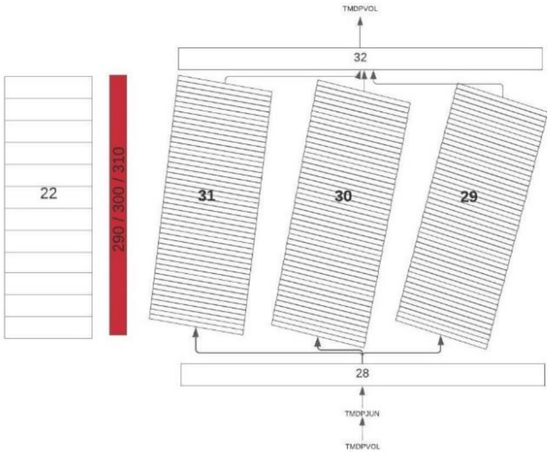


Figure 4: OSU MASLWR - RELAP5 Model 2 (zoom on HCSG)

The Model 2, shown in Figure 4 limited to the HCSG scheme, presents a greater level of detail on the secondary side: three different pipe components simulate the overall number of tubes, each representative of a single tube bank. Each pipe component of the secondary side has its own thermal coupling with the primary side, provided by heat structures 290, 300 and 310. Geometrical features of each component (e.g., length, inclination, and flow area) are evaluated as the average within the proper bank. The common inlet and outlet headers are simulated with component 28 and 32 (see Figure 4). A calibration procedure is required, aiming at the distribution of the flow rate through the three pipe components. Since any information about the orifices used at the tubes' inlet is not available, concentrated pressure drop coefficients were entered in the model in order to uniform the temperature at the outlet of components 29, 30 and 31 (respectively inner coil, mid coil ad outer coil). In particular, the temperature difference was kept below the value of the thermocouples' uncertainty.

All heat losses are simulated with heat structures, with a room temperature of 295 K and environmental HTC of 6.0 W/m^{2}K.

4. RELAP5/MOD3.3 modifications

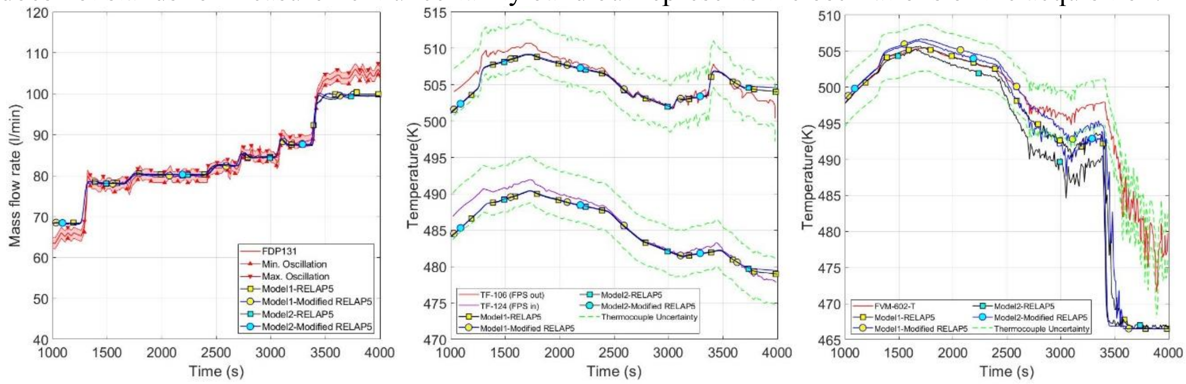
RELAP5/MOD3.3 is a STH code for the best estimate analysis of nuclear systems. It is a code for the transient analysis, developed for the U.S. Nuclear Regulatory Commission (NRC). [10].

An improvement campaign is ongoing at the DIAEE to expand the applicability of RELAP5/MOD3.3 to advanced nuclear power plant applications [2]. Aiming at improving capability of the code to simulate a HCSG, some modifications have been added in the enhanced version of the code. Modified RELAP5/MOD3.3 includes new correlations for the evaluation of the HTC in helical geometry. For the shell-side (i.e., flow rate outside the tubes) Zukauskas correlations are added for the HTC evaluation. It takes into account the annuli created between the pipe banks, considering also the eventual variable pitches. Instead, for the in-tube flow, Mori-Nakayama correlation is implemented for the HTC estimation. In addition, specific two-phase flow maps are considered for this component, which take into account tube's geometrical characteristics.

5. OSU-MASLWR 002 Test

The OSU-MASLWR 002 Test investigated the primary system flow rate, driven by natural circulation, and the steam superheating in secondary system. There are 6 power levels, from 80 kW to 165 kW. According to the experiment, the primary flow rate increases as the power supplied to the FPS rises, allowing the FPS inlet and outlet temperature difference to be kept almost constant. Boundary and operating conditions are obtained from literature [1].

The stepwise trend, adopted for the heat source and for the feedwater flow rate, determines the primary flow rate presented in Figure 5a. The plot compares the experimental acquisition with the results obtained with default and modified versions of the code. Each version was used twice, considering both Model 1 and Model 2. It is worth emphasizing that the facility works in natural circulation, without active system involved in the movement of the primary coolant. Moreover, due to the small flow rate, experimental measurement was affected by visible fluctuations. Thus, Figure 5a presents the experimental primary flow rate with a colored band (please refer to online version of the paper) that does not stands for measurement uncertainty band but represents the oscillations of the acquisition.



(a) *(b)* *(c)*

Figure 5: OSU MASLWR 002 - primary flow rate (5a), FPS inlet and outlet temperature (5b) and SG outlet temperature (c)

It is possible to notice that there are no appreciable differences between the trends predicted by the two code versions and between the two HCSG models. In the present test, both the codes and both the models provide a satisfactory prediction of the experimental data. In Figure 5a mainly two discrepancies can be seen: the first one at the beginning of the test and the second one in the highest power phase (after 3400 s). Regarding this latter, it must be underlined that initial conditions are poorly reported in literature [1], affecting the first phase of the simulations. In addition, there could be a certain difference between the estimated value of the pressure drops and the actual ones (no experimental data available), and these differences affect mostly the initial phase of the experiment Measurement uncertainties are not known for primary flow rate, but being flow rates very low, it is expected that uncertainties are larger than discrepancies between experiment and simulations. For this experiment, there are no considerable differences between the two code's version because the modifications do not have appreciable impact on natural circulation in that power range.

Figure 5b shows the FPS inlet and outlet temperature, respectively in purple line and red line for the experimental acquisitions. In this case the experimental data (solid lines) are reported with the error bands (dashed green lines). As for the primary flow rate, there are no appreciable disagreements between the trends predicted by the two code's versions and between the two models, all providing a satisfactory agreement with experimental data.

A slight difference between the two code versions is visible in the last phase of the experiment. As expected, with increasing HCSG power, the effects of the modification become visible. An overall good agreement between calculations and experimental data are observed. The minor discrepancy observed at the beginning of the test is mainly due to a lack of data concerning the phase preceding the experiment. The temperature difference along the FPS is kept almost constant throughout the test, confirming the good capability of the code to simulate system operation in the considered power range.

Figure 5c shows the HCSG steam outlet temperature, comparing the experimental acquisition (plus uncertainties) with computational predictions. For the whole experiment it is expected to obtain superheated steam. However, at the highest power level, the temperature tends to reduce towards the saturation temperature, while keeping superheated conditions. This phenomenon occurs because, in the final phase, the ratio between secondary mass flow rate and power to be removed is increasing, and for this reason HCSG outlet temperature is reducing. The simulations provide a satisfactory reproduction of the test, except in the final phase, where the code predicts saturated conditions at the HCSG outlet (at 3450 s, a steam void fraction of 0.8895 for RELAP5/MOD3.3 and 0.9987 for Modified RELAP5/MOD3.3). It is possible to quantify that discrepancy in 3.05 kW for RELAP5/MOD3.3, and about 1 kW for Modified RELAP5/MOD3.3 (i.e., 1.8% and 0.6% of the FPS power, respectively). One of the possible explanations for such deviation is the following. Being a one-dimensional code, RELAP5 is able to calculate only the average fluid thermodynamic properties related to a control volume. If thermocouple was installed at the tube center, it would measure the temperature of vapor phase, that in a two-phase condition here collects, and it could be slightly overheated. In this case, it would be possible that, on average, the fluid comes out from HCSG in saturated conditions, matching the code prediction.

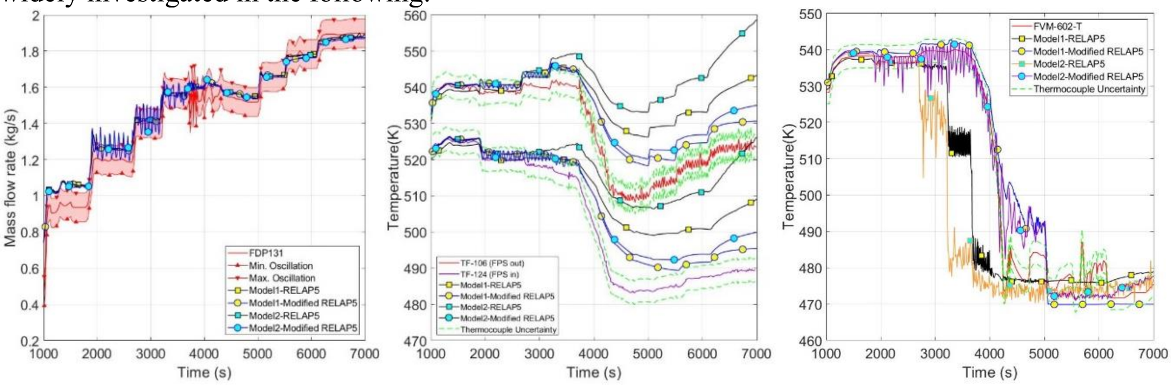
Although the increasing of the ratio between secondary mass flow rate and power to be removed is well simulated, Figure 5c shows a sharper drop of the steam outlet temperature at the end of the test. It can be caused lack of information about feedwater inlet temperature throughout the test. Considering Model 1, the two versions of the code predict the dryout at the same level. On the other hand, adopting Model 2 a slight reduction of the dryout level is predicted by the modified code, even if irrelevant. This suggests that Model 2 is more affected by the improvement added in the modified RELAP5/MOD3.3, due to the diversification of heat exchange areas with the three pipe components.

One of the main outcomes of the present test is the overall agreement between the two versions of the code, caused by the low power levels assumed in this test. Thus, a similar experiment but with a most extended range of FPS power supplied is simulated (see section 6). Furthermore, both Model 1 and Model 2 proved capable of simulating the transient test performed on the facility. The difference between the two models is only quantitative. It can therefore be said that since the two models have the same boundary conditions, the second model is more affected by possible variations in secondary mass flow rate.

6. ICSP Test SP3

The ICSP Test SP3 [7] foresees seven power steps during the experiment in the range of 80 kW ÷ 320 kW. Boundary conditions for primary and secondary system are derived from [7], where a detailed description of the test is presented.

Figure 6a shows the primary flow rate, comparing the experimental acquisition of the natural circulation and the computational results. Experimental data are provided with a colored band (refer to online version of the paper) that accounts for the oscillations observed in the measurements (it is not representative of the measurement error band; information about uncertainties on the flow rate acquisition is not available in literature). An overall good agreement is observed over the whole test, although a slight overprediction is highlighted in the first phase of the test. The only difference between the two models, are the presence of fluctuations on Model 2. These fluctuations are caused by the secondary system and propagate to primary flow rate and FPS inlet and outlet temperatures. Such is widely investigated in the following.



(a) *(b)* *(c)*

Figure 6: ICSP Test SP3 - primary flow rate (6a), FPS inlet and outlet temperature (6b) and SG outlet temperature (6c)

The FPS inlet and outlet temperatures are presented in Figure 6b, respectively in purple line and red line. Unlike the previous analysis, in the present test differences between the two versions of RELAP5/MOD3.3 are visible as the power increases above 200 kW (after 3500 s). The results of the Modified RELAP5/MOD3.3 are quantitatively closer to the experimental data for the whole experiment, especially at high power levels. These better results are due to improved prediction of HCSG heat exchange, improving cooling capabilities of the HCSG modelling. Following the satisfactory prediction of primary flow rate, the FPS inlet and outlet temperature difference is satisfactorily simulated by the modified code, for both Model 1 and Model 2.

Figure 6c presents the HCSG steam outlet temperature. An overall agreement between the two codes and the experimental data is observed up to 3000 s. After that, large qualitative and quantitative differences between the two versions of the code are observed. As power increases above 200 kW, the default version of the code shows limited capabilities to reproduce the experimental acquisition, determining a quick temperature drop at around 3000 s. This sharp temperature drop probably takes place because the dryout occurs very close to the HCSG outlet. According to RELAP5/MOD3.3 there is no dryout as opposed to Modified RELAP5/MOD3.3 which estimates the dryout in the last control volume of the component, and therefore there is a low overheating of the steam.

As already discussed for OSU-MASLWR 002 test, the default code is not able to simulate the correct heat exchange between primary and secondary system at high power levels. Modified RELAP5/MOD3.3, however, moves away from the trend of the default code not only maintaining the qualitative trend of the experimental data, but falling within the temperature uncertainty band.

Despite the overprediction between 4100 and 5000 s, the improvements introduced in the modified version of the code are evident. As expected, in the calculations performed with Modified RELAP5/MOD3.3, the height where the liquid water disappears is reduced. The differences between the two code versions are evaluated considering the control volumes where the single-phase steam occurs in HCSG secondary side. The major difference between the two versions occurs at high power levels and it is higher before 4000 s. Another effect of Modified RELAP5/MOD3.3 concerns the HTC: analyzing where saturated nucleate boiling occurs, as expected, there is an increasing number of control volumes where it shows up. This effect takes place because saturated nucleate boiling areas are the most affected by code modifications.

A substantial difference between the two models is the presence of fluctuations on the SG outlet temperature. Oscillations propagate from secondary side to primary side and are visible in both FPS inlet and outlet temperatures (Figure 6b) and primary flow rate (Figure 6a). Indeed, when HCSG secondary side parameters fluctuate, also the heat transfer within the steam generator is unstable. This results in oscillations in the primary side temperatures. Once the thermal field in the primary system is altered, also the natural circulation, whose driving force is the density difference between hot and cold leg water columns, starts to oscillate. In order to exclude the possibility that such fluctuations depend on the time step adopted for the simulation, a time step sensitivity has been carried out varying this parameter from $5 \cdot 10^{-4}$ s to $5 \cdot 10^{-3}$ s. Computational outcomes proved to be independent from the time step used for simulation purposes. Another explanation of this behavior could be the establishment of instabilities on the secondary system, typical of parallel channels connected to the boundaries via headers. Such fluctuations could appear for two-phase flow instabilities and/or for different distribution of the flow rate. It is worth noticing that experimental data on feedwater distribution through the parallel tubes are not available. A preliminary calibration of the pressure drops through the parallel channels has been carried out in Model 2, to obtain the same HCSG outlet temperature between pipe components. But there is no evidence that such control was performed in the experiment. Finally, it is not possible to exclude computational instabilities among the causes of the observed fluctuations.

Despite the presence of fluctuations, also in Model 2 the height where the single-phase steam appears with Modified RELAP5/MOD3.3 is reduced, and the number of control volumes where saturated nucleate boiling occurs is increased.

7. Conclusions

Both RELAP5/MOD3.3 and Modified RELAP5/MOD3.3 gave an overall satisfactory result at low power levels, showing the main differences at high power. At low power levels the modifications do not provide appreciable improvements. In fact, the default code is already able to predict the experimental data with satisfactory accuracy. It is essential that the modified code continues to predict in the same way what happens at low powers, because there must be no variations where the default version is already able to work. On the other hand, at high power the default code highlighted limits that were partially, but satisfactory, overcome by the modified version of the code which, therefore, proved to be more able to simulate the system operation in a wider operational range with respect to the default version.

From the point of view of the comparison between the two models, it must be taken into account that a more detailed model, based on parallel pipe components, may encounter instabilities beyond a certain power threshold. These instabilities of Model 2 can turn out to be more dampened in the case of using the Modified RELAP5/MOD3.3 and consequently the impact on the primary system is less important. With the same code version used, the two models have results that are consistent with each other. This evaluation is important from the point of view of the modification made to the code because it implies that it is probably not affected by the nodalization performed.

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