

Comparative Analysis of Nodalization Effects and Their Influence on the Results of ATHLET Calculations of VVER-1000 Coolant Transient Benchmark Phase 1

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Abstract. In this paper, the results of the investigations on the nodalization effects for the ATHLET code are presented and discussed in details on the basis of experimental data for the VVER-1000 Coolant Transient Benchmark with different operating modes of four main coolant pumps. ATHLET calculations with different nodalization and their impact was analyzed. The work studied the influence of annular outlet nodalization on calculation of coolant temperature. By comparing the test data versus calculated by ATHLET we showed a good agreement between the experimental data and simulation results for analyzed parameters.

Keywords: VVER-1000, coolant transient benchmark, ATHLET, nodalization

1 Introduction

The user influences on calculated results are seen in most of the International Standard Problem Exercises, where different participants using the same code version got different results. The reasons for these differences are mainly due to different nodalization of the simulated systems. According to [1] there is no an optimal approach for the nodalization scheme. Different nodalization schemes have different thermal inertia which results in significant deviations especially for the states with a high transient rate [2].

An examination on the effect of different nodalization on the accuracy in the simulation of Kozloduy NPP Unit 6 was performed. The main objective was to check the availability of different nodalization schemes. User effects are any differences in calculations that adopt the same code version and the same initial and boundary conditions for a given power plant or test facility. The main source of code user effects on the calculated results is the nodalization of the simulated system. It is liability of the user preparing an input deck to develop an adequate and correct nodalization scheme for the given nuclear plant or test facility. An adequate nodalization for a given plant or facility to be analyzed is usually unknown because no general criteria are given. Consequently, the accuracy of a calculation is related to the choices of the user who prepares the input deck.

The code user has to build-up a detailed nodalization scheme which represents the whole system to be simulated into one-dimensional thermal-hydraulic network. ATHLET provides a modular network approach for the representation of a thermal-hydraulic system of the power unit. The code offers a number of basic elements like pipes, branches, junctions, heat structures and configuration can be simulated just by connecting them in suitable way. The size of the node is important, because when large nodes

are used, the difference between the average temperature in the control volume and the temperature at the node boundary can be considerable. This nodalization error can be reduced by applying finer grids with an increased computational time, but not always smaller nodes result in better simulations. A benchmark of different nodalization schemes was performed with two post-test calculations using different nodalizations of annular outlet section of the reactor vessel (volumes between reactor vessel and core barrel): with four and six parts. The work is focused on the modelling of flow mixing in the reactor upper plenum including validation of the ATHLET model for the simulation of VVER-1000 plants. The ability to predict the overall thermo-hydraulic response of the plant is one of the most significant contributors to a good analysis.

2 VVER-1000 Nuclear Power Plant Description

The Russian abbreviation VVER (ВВЭР) stands for water-cooled water-moderated energy reactor. It is a pressurized water reactor with hexagonal fuel assemblies (due to triangular lattice of the fuel elements) and horizontal steam generators. VVER-1000 is a pressurized water reactor with thermal power of 3000 MW and electrical output of 1000 MW. The reactor core of VVER-1000 (version V320) consists of 163 fuel assemblies: thereof 61 fuel assemblies have control rods. The main parts of the reactor are reactor pressure vessel, vessel internals, upper block, control rod drives, neutron flux and temperature measurement tubes and core. Reactor pressure vessel consists of vessel and reactor cover and is designed to fix the vessel internals and control rods system. The reactor core barrel organizes the coolant flows through the reactor, protects the reactor vessel from the neutron fluence and holds the components of the core organized in 10 groups. The unit consists of two circuits: the primary and secondary circuit. The primary coolant circuit includes the reactor

vessel, four circulation loops and a pressurizer system. Four reactor main coolant pumps of type GCN-195 provide circulation of the coolant through the primary circuit. The heat generated in the reactor core is transferred through the four steam generators type PGV-1000 to the secondary side. The saturated steam generated in steam generators is passed through a single steam turbine type K-1000-60/1500. The equipment of the primary circuit is located in a hermetic containment which is a safety system. Coolant temperature at reactor inlet is 289°C and at reactor outlet is 320°C . During normal operation the primary pressure is maintained at $15.79 \pm 0.147 \text{ MPa}$ and in secondary circuit at $6.27 \pm 0.2 \text{ MPa}$.

The main differences between VVER-1000 and western pressurized water reactors are horizontal steam generators and hexagonal fuel assemblies.

3 ATHLET-2.1A Model of VVER-1000/V320

For the purpose of the research it has been used ATHLET-2.1A computer code [3]. The thermal-hydraulic system code ATHLET (Analysis of THERmal-hydraulics of LEaks and Transients) is being developed by scientific organization GRS (Gesellschaft für Anlagen- und Reaktorsicherheit) for the analysis of the whole spectrum of leaks and transients in pressurized water reactors and boiling water reactors. The code is workable for western reactor designs

as well as for Russian reactors of types VVER and RBMK/MKER.

The basic input deck for VVER-1000/V320 was developed by Technical University of Sofia [3]. ATHLET model provides a full four-loop representation of the primary and secondary sides. Each loop consists of the hot leg, the horizontal steam generator and the cold leg with the main coolant pump. The pressurizer is connected to the loop 4. Figure 1 gives an overview on the nodalization scheme of the reactor vessel and the primary loops. The main difference between the used two models is in modelling of the annular outlet section. Better prediction of hot leg temperatures requires an adequate modeling of upper plenum of the reactor.

In the ATHLET model the flow through the reactor pressure vessel is described by four parallel downcomers, a lower plenum, a core region with 163 thermal-hydraulic channels and a parallel bypass channel, the upper plenum and the reactor head. The core is modeled by 1 hot core channel and 162 average core channels. The downcomer is represented by 4 parallel fluid channels (one channel per loop) connected to each other by cross-flow junctions. The assumption of ideal coolant mixing is made for the lower plenum of the reactor, in which the coolant coming through the four downcomers gets mixed. The core channels and the bypass channel are divided into 17 axial nodes.

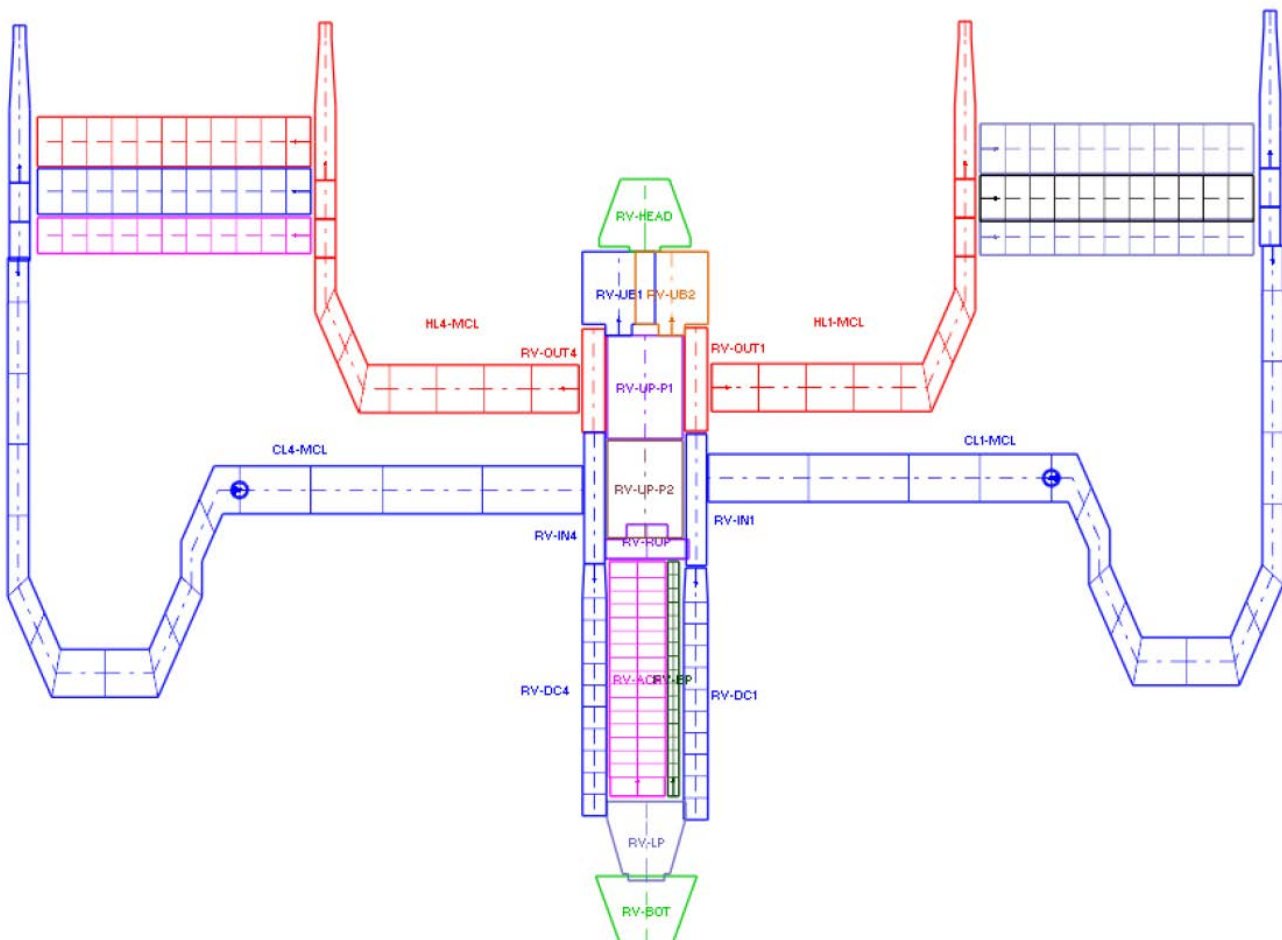


Figure 1. Nodalization of the reactor vessel and the primary loops in ATHLET model.

The upper plenum of the reactor is divided into two major radial parts – the inner and outer ring. The inner ring simulates the part above the reactor core with the block of shielding tubes and the space till the perforated core barrel. The outer ring includes the volume between the core barrel and the outlet nozzles. The core outlet coolant flow is collected with the bypass flow in the volume above the core assuming full coolant mixing above the fuel assemblies. The inner zone of the upper plenum is modeled by a five control volumes and one volume for reactor head.

For the reactor outlet annular section (volumes between reactor vessel and core barrel) are used 4 branch components to present outlet ring in relation to the associated hot legs and 4 single junction pipes for a cross flow between them because in ATHLET two branches can not be directly linked as they have no junctions. The inner and outer rings are connected with radial junctions simulating radial coolant flow.

To simulate correctly the asymmetrical processes in the outer circular ring between reactor vessel and perforated core barrel is needed more sophisticated model of outlet section. In case with switched off main coolant pump, flow rate reverses in corresponding leg and the reversed coolant flow coming from hot leg is redistributed mixing with flow entering other three outlet nozzles. Mixing of the coolant is performed in the zones between the reactor vessel and perforation at the upper part of the core barrel, due to high hydraulic resistance caused by double perforated ring between the inner and outer part of the upper plenum, which resistance prevents coolant from reversed leg to enter into block of shielding tubes. Pressure losses in the perforation of the core barrel are about 0.01 MPa. Further outer circular ring in ATHLET model was divided into 6 sections with six thermal-hydraulic channels with cross-flows between them. Four of them are connected directly with the four hot legs and the remaining two sections simulate the volumes between the first and second legs and between the third and fourth ones. This type of arrangement of the outlet annular section follows the asymmetrical cold legs' nozzle locations on the reactor vessel periphery for VVER-1000. The angle between the second and third nozzles and

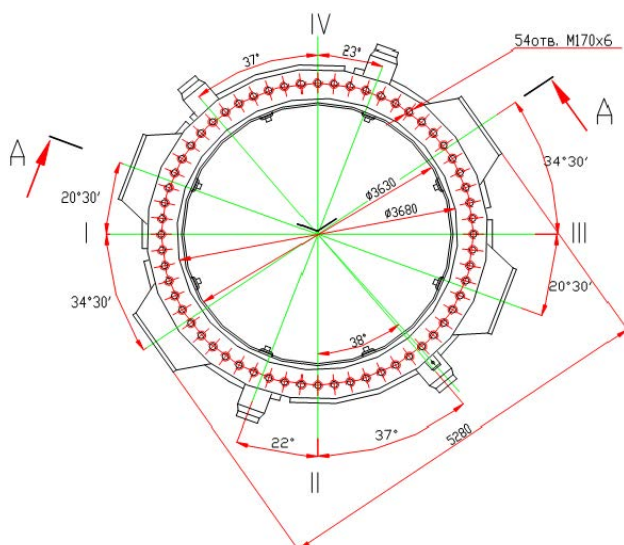


Figure 2. Cross sections of the nozzles ring.

between the fourth and first nozzles is 55° , while the angle between the first and second nozzles and between the third and fourth nozzles is about twice bigger 125° (Figure 2).

The secondary side is modelled with four loops. Each one of them includes a horizontal steam generator, a main steam line and main steam header.

The primary circuit make-up and let-down systems are not modeled, therefore this system does not influence the simulations.

The model of VVER-1000 of the Kozloduy NPP built by computer code ATHLET is described in details in [3].

4 Description of V1000CT-1 Test

During the plant-commissioning phase at the Kozloduy NPP Unit 6 several start-up tests had been made [4,5]. One of them was main coolant pump switching on at reduced power while three other pumps are in operation [6]. This event is characterised by a rapid increase in coolant flow through the core resulting in a coolant temperature decrease. Due to feedback it causes to insertion of positive reactivity and reactor power increases from 883.5 MW to 894 MW.

Before the start of experiment there are three coolant pumps in operation – first, second and fourth with total coolant mass flow through the core 13.611 kg/s and the reactor power is 29.45% of the nominal level. After switching on the third main coolant pump mass flow through the core increases which causes increment of reactor power to 29.8% of nominal.

V1000CT-1 benchmark was developed to provide a validation basis for the computer codes used for simulation of nuclear reactors. Three benchmark exercises were defined as the aim of Exercise-1 is to examine the primary and secondary system model responses using a neutron point kinetics simulation.

5 Results

Two calculations are performed with ATHLET using different nodalization: with 4 outlet annular sections as case # 1 and with 6 outlet annular sections as case # 2. The two input decks were derived from a general ATHLET model for reactor type VVER-1000 V-320. A power plant steady state before the start of the transient calculation was first achieved. The initial conditions of the plant before beginning of the experiment and the results from calculations with ATHLET are listed in Table 1. The steady state results of the calculations approximate within the specified uncertainty of measured plant data with exception for temperature in second hot leg for case # 1. From the steady-state results it is seen that there are better agreement for the cold leg coolant temperatures compared to the hot leg coolant temperatures. The reason is the complicated mixing of the coolant flow in the upper part of the reactor vessel at the initial steady state.

The results from ATHLET are compared with experimental data from the plant and are shown in Figures 3–13. The simulations with ATHLET were made up to 130.0 s. As it is

Table 1. Initial conditions of the transient

Parameter	Test	Accuracy	Case # 1	Case # 2
Core power, MW	883.50	±60	875.17	875.72
Primary side pressure, MPa	15.60	±0.3	15.61	15.60
First cold leg temperature, °C	282.55	±2.0	282.25	282.34
Second cold leg temperature, °C	281.55	±2.0	281.83	281.29
Third cold leg temperature, °C	281.35	±2.0	281.78	281.65
Fourth cold leg temperature, °C	282.25	±2.0	281.77	282.09
First hot leg temperature, °C	294.05	±2.0	293.9	294.39
Second hot leg temperature, °C	289.85	±2.0	292.17	290.6
Third hot leg temperature, °C	277.75	±2.0	276.89	276.84
Fourth hot leg temperature, °C	293.15	±2.0	292.19	293.06
Core flow rate, kg/s	13611	±800.0	13219.13	13234.95
First loop flow rate, kg/s	5031	±200.0	4907.62	4905.48
Second loop flow rate, kg/s	5069	±200.0	4918.49	4932.79
Third loop flow rate, kg/s	-1544	±200.0	-1525.56	-1518.77
Fourth loop flow rate, kg/s	5075	±200.0	4918.58	4915.45
Pressuriser level, m	7.44	±0.15	7.44	7.44

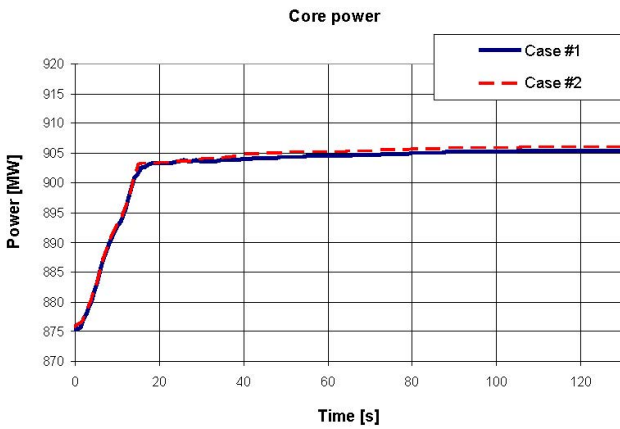


Figure 3. Comparison of reactor power.

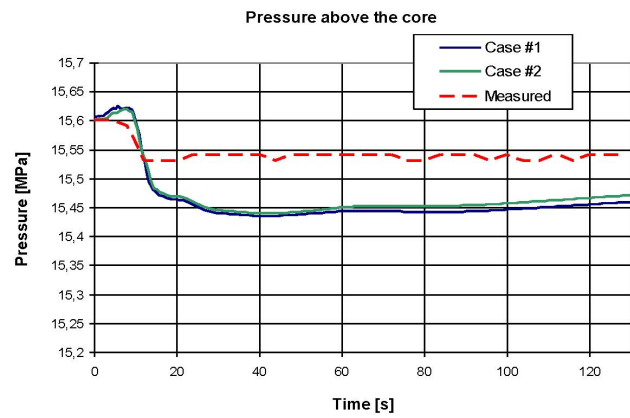


Figure 5. Comparison of primary side pressure.

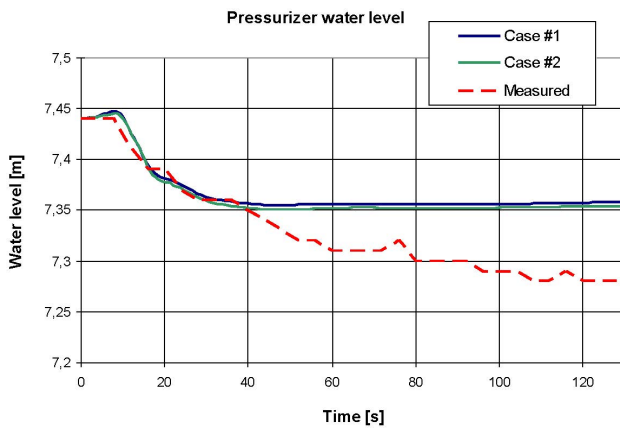


Figure 4. Comparison of pressurizer water level.

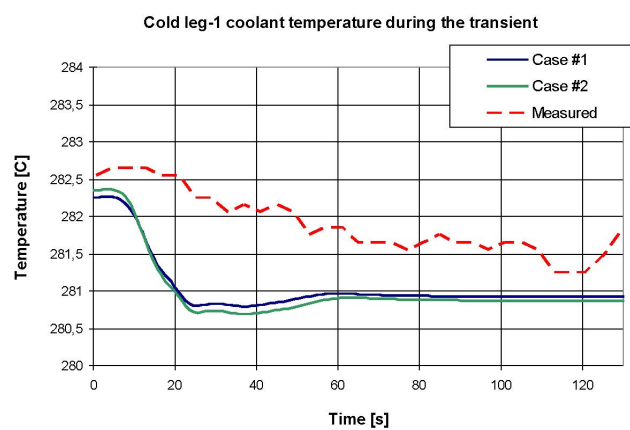


Figure 6. Comparison of cold leg-1 temperature.

seen from the results ATHLET predicts correctly the processes in the power plant.

The reactor power increase during the transient calculated by ATHLET for the two cases is shown in Figure 3. There are no available measured plant data for the reactor power during the experiment. The reactor power predicted by two nodalization schemes has the same initial value and trend during transient. At the end of the simulation the core power in case # 2 (906.005 MW) is slightly greater with

0.693 MW compared with case # 1 (905.312 MW), which corresponds to the difference in the initial power of the both cases (Table 1).

The comparison of measured and calculated water levels in the pressurizer is presented in Figure 4. During the first 38 s of the simulations the calculated values of the pressurizer levels resemble the measured value. After that ATHLET predicted for both cases pressurizer levels significantly higher compared to the measured value, while the

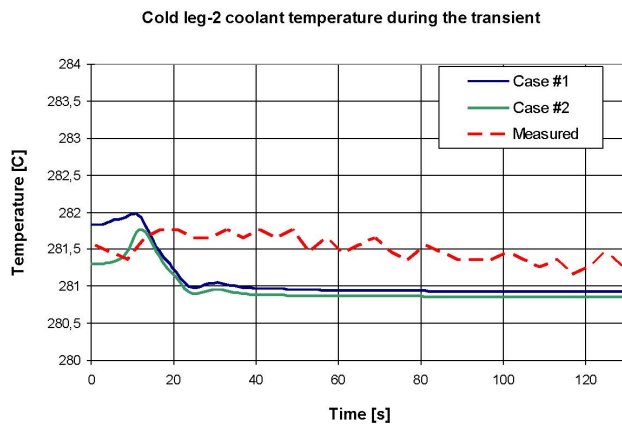


Figure 7. Comparison of cold leg-2 temperature.

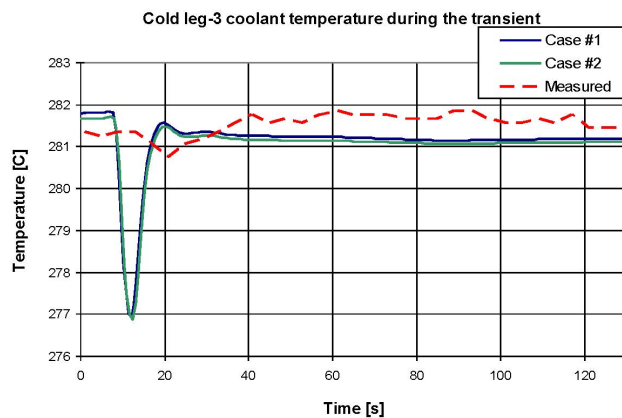


Figure 8. Comparison of cold leg-3 temperature.

difference between the two ATHLET runs is negligible.

The calculated pressures in primary circuit in both cases are identical with negligible differences while there is a significant deviation with measured data. Lower pressure calculated by two ATHLET runs is caused because the make-up and the let-down system are not modeled in input files.

Comparison of the cold and hot leg coolant temperatures is presented in Figures 6–13. From the results it can be seen that the ATHLET-2.1A code calculates similar temperatures for the both nodalization schemes, as there are several differences.

The temperature in cold leg-2 is depicted in Figure 7. In case # 1 at the beginning of the transient the temperature of the coolant is higher than measured one and the temperature in case # 2. This is due to asymmetrical processes in the outer circular ring between reactor vessel and perforated core barrel described in detail in the explanation of hot-2 leg temperature. In calculation with 4 outlet annular sections the temperature drop in cold leg-2 is more than two times larger than simulation with 6 outlet annular sections.

The largest deviation was observed in cold leg-3 in the interval from 8 to 17 s during the start-up of third main coolant pump. ATHLET shows drop of the coolant temperature by 5°C, while such a drop of the temperature was not measured in the plant data. The observed discrepancy could be explained considering the flow direction. Before

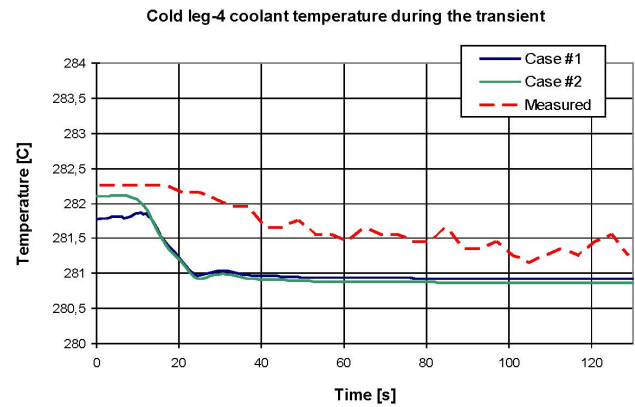


Figure 9. Comparison of cold leg-4 temperature.

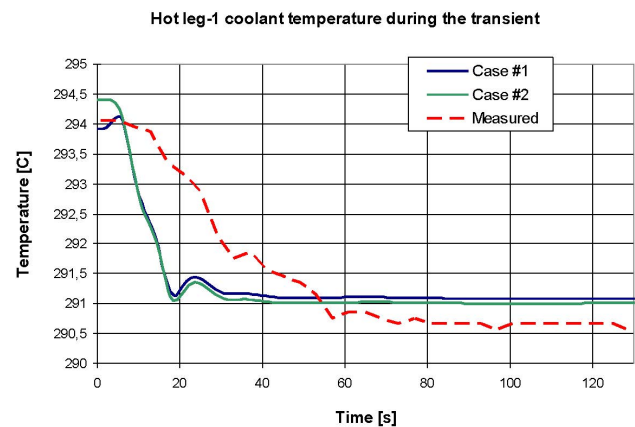


Figure 10. Comparison of hot leg-1 temperature.

start-up of third main coolant pump flow in this loop is reversed. Due to switching on the pump-3 the water which is in hot leg that once has passed through the steam generator is forced back and goes two times through the third steam generator heat-exchange tube bundle, because flow rate reverses back to normal stream, decreasing the temperature of coolant additionally with 5°C.

Figure 10 shows variations in the hot leg-1 coolant temperature during the transient for the two cases. In case # 2 the initial temperature is slightly higher compare to case # 1. The explanation for this is that in case # 2 it was considered the fact that this circuit is the least affected by the reverse flow with the lower temperature in leg-3. It is seen also for temperatures in fourth leg (Figure 13). In case # 1 initial temperature is lower than measured one with 0.97°C while in case # 2 calculated temperature at the beginning of the transient is lower only with 0.09°C, which is ten times more precision.

The largest difference between calculated and measured data in hot legs is observed in loop 2 in the interval from 0 to 18 s (Figure 11). The code predictions showed a peak of the temperature, while such a peak was not observed in the plant data. Before switching on the third main coolant pump the temperature of the coolant in hot leg-2 is lower than that in hot legs-1 and -4 because it is most affected by the coolant with low temperature coming from loop-3 with the reversed flow, because it is nearest to leg-3. The temperature in hot leg-1 is highest because it is outermost from leg-3, therefore first leg is least affected by the

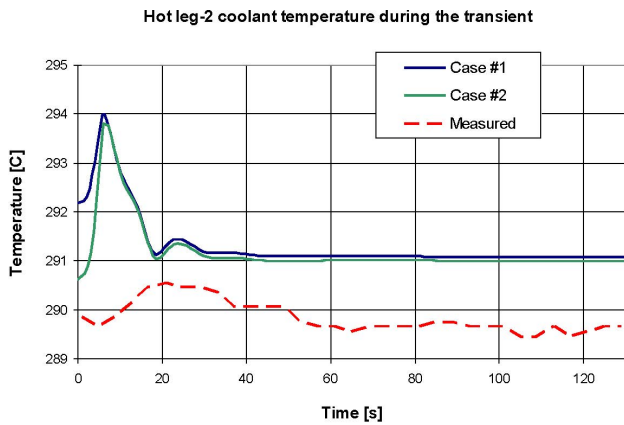


Figure 11. Comparison of hot leg-2 temperature.

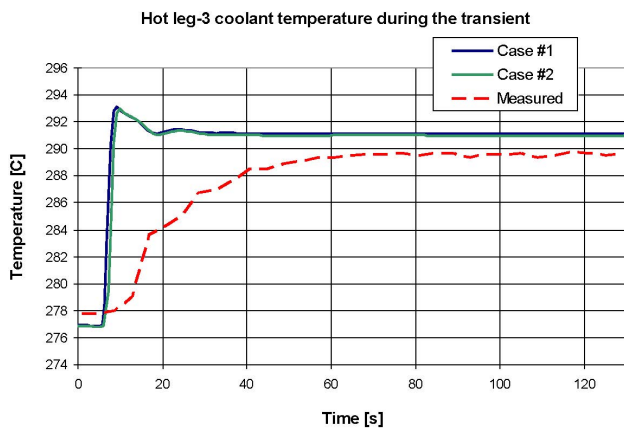


Figure 12. Comparison of hot leg-3 temperature.

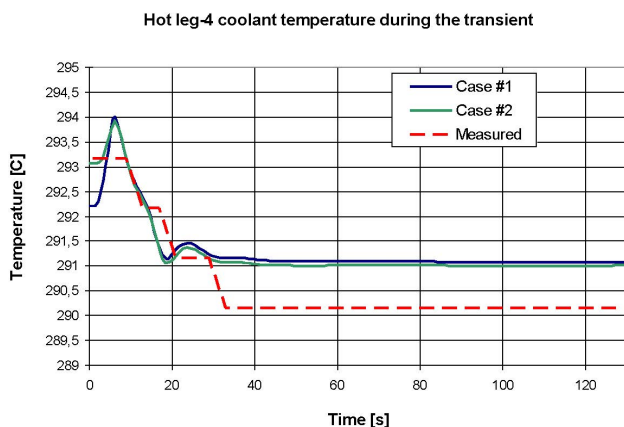


Figure 13. Comparison of hot leg-4 temperature.

reversed flow in loop-3. At the beginning of the transient, the flow in loop 3 reverses back and coolant with a higher temperature from loops 1 and 4 enters loop-2, which together with disappearance of coolant with low temperature coming from loop-3 causes the peak of the temperature in the hot leg-2. Later into the transient, the coolant temperature in hot legs 1, 2 and 4 decreases due to the increasing coolant flow through the reactor core.

The most likely reason for the differences between ATHLET runs and measured value in hot leg-3 temperatures in the first 40 seconds of the transient is the thermal inertia of the measurement devices. The time delays of the

measurement systems were not incorporated into ATHLET results.

At the end of the simulation the outlet temperature for the four legs is established at around 291°C while the measured data is different for the four legs. This difference is most likely due to core radial non-symmetry power distribution. Switching on the main coolant pump-3 results in changing spatial distribution of reactivity feedback during the transient as the core cooling is redistributed and subsequently changing spatial power distribution. In ATHLET with the point kinetics model radial and axial power distribution is kept constant during whole simulation as local reactivity effects cannot be taken into account.

The temperatures for both calculations at the end of the transient have a good match with plant data with maximum deviation of about 1.3°C. As it is seen from the comparison the calculated coolant temperatures in cold and hot legs in case # 2 have better similarity with measured data at the beginning of the experiment. In the first 10 s of the transient temperatures in case # 1 for hot leg-1 and hot leg-3 are lower compared to case # 2 and measured values while in hot leg-2 are significantly higher. At the end of the calculations the temperatures in case # 2 are stabilized at about 0.07°C higher than temperatures in case # 1. It is interesting to be noticed, that the temperature of the coolant in hot leg-2 (Figure 11) after first 20 seconds of the transient in case # 2 is stabilized at a higher value compared to initial temperature while in case # 1 the temperature is lower than initial value.

6 Conclusions

Simulation outcomes confirm the dependence of the results of the used nodalization. While core power, pressurizer level and pressure are practically the same in the both cases, significant deviations are observed in the temperature of the coolant in the four coolant loops. The calculations reveal that the different nodalization schemes in the upper plenum have a strong effect on the flow mixing in the early phase of the transient of about 25 s due to asymmetrical flow in the outlet circular ring and distribution of the reverse flow, and a remaining effect in the later phase. Dividing outer circular ring in ATHLET model into 6 sections improved the simulation at the beginning of the transient.

Acknowledgments

The model of VVER-1000 for ATHLET was developed by Yoto Georgiev during his PhD thesis. The research presented in the current paper has been supported by Technical University of Sofia's research subsidy.

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