

SOLUTION OF THE INTERNATIONAL BENCHMARK WITH TRIP OF ONE OF FOUR REACTOR COOLANT PUMPS FOR VVER-1000 REACTOR PLANTS USING THE COMPUTER CODE PACKAGE KORSAR/GP AND COMPLEX REACTOR NODALIZATION

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Abstract

The International OECD/NEA test benchmark for the trip of one of four operating reactor coolant pumps (RCPs) was solved using thermohydraulic code package KORSAR/GP. KORSAR/GP applies 1D calculational units. This benchmark was based on experimental results obtained during commissioning of Kalinin NPP, Unit 3. During the experiments a large amount of experimental data was obtained that enabled us to supplement the validation of the computer codes and nodalizations of 1D thermohydraulic codes.

In the given transient there was a difference between coolant temperatures in different loops that resulted in the necessity of numerical simulation of the coolant mixing in the reactor plenums. To solve this problem, complex branched nodalization (i.e. the set of code calculational units) was used.

The analysis results matched closely with the experimental data. Thus it was shown that the nodalization developed with the use of KORSAR/GP and the code itself can be applied for the simulation of VVER-1000 transients with one or more RCPs in operation and sharp difference between coolant temperature in loops.

Introduction

The problem of reactor coolant mixing is under investigation worldwide. A specific experimental facility was built by the Russian Experimental and Design Organization (EDO) “Gidropress” to investigate coolant mixing [1]. Another experimental facility is situated in Forschungszentrum Dresden-Rossendorf, Germany [2].

Kalinin [3] and Kozloduy (V1000CT-2) [4] benchmarks are examples of states and transients with strongly different temperatures of coolant in the loops. The first of them is based on the transient initiated by the switch-off of one reactor coolant pump (RCP). The actual experiment was conducted and considerable of data was obtained. The second one is hypothetical that focuses on main steam line break. This work provides a description of branched thermohydraulics nodalization of a VVER-1000 that permits reliable coolant mixing calculations. The nodalization was validated by Kozloduy and Kalinin benchmarks mentioned above. Kalinin benchmark and its calculation results are presented in this paper.

Many system codes such as RELAP, ATHLET or KORSAR are used for the analysis of nuclear reactor transients. These codes include modules for modeling different physical phenomena that take place in reactor units. The thermohydraulics module is the basic one to which other modules are joined.

The reactor system is too complex to be modeled fully in 3D. Therefore system codes use 1D approximation for the analysis of the components. This approach is widely applied worldwide for reactor analyses. It applies to many reactor problems. But 1D simplification imposes some constraints for codes use. Almost every function in a reactor unit can be modeled by 1D codes but with some limitations and with some uncertainty.

The reactor vessel has a large volume that contains a number of devices, with most consisting of multiple components. If all the loops of a reactor unit are in operation and the coolant properties are the same in each loop, then only a few 1D elements are sufficient for correct reactor modeling. In other cases complex coolant mixing in reactor chambers has to be taken into account.

The actual reactor system is divided into standard elements which can be analyzed by the code. One of the basic elements is a “channel” (the name can vary for different codes). An input deck consists of the definition of various components, such as the channel element, as well as the logic of their interaction. This set of channels and other elements and their interconnections will be referred to as nodalization of the unit. Each channel consists of cells that define a calculational unit. The properties of the fluid are assumed to be constant within a cell.

Coolant mixing is highly important to correctly model in the transients mentioned. 1D codes should be tuned for modeling coolant mixing accordingly to them. The reactor chambers cannot be modeled by only one element in the cases mentioned. In this paper, the coolant flow and mixing are modeled with the use of more complex branched nodalization. Such nodalization includes a set of “channel” elements connected to each other by auxiliary elements. For example, in this paper the reactor vessel is described by about 200 “channel” elements connected to each other by about 13,000 “cross-junction” elements. This approach cannot be used for precise coolant flow modeling. It can be used for reactor behaviour modeling in a number of cases as it will be shown in the paper.

1. Calculation approach

1.1 KORSAR/GP

This paper utilizes a computer code package KORSAR [5]. This code was designed mainly in Aleksandrov Scientific Research Technological Institute. Some modules were designed in EDO “Gidropress”.

KORSAR uses a two-fluid absolutely non-equilibrium model with the same pressure for different phases in thermohydraulics. There is a possibility for using point or 3D models in neutron physics. The 3D model is built utilizing a diffusion approach. The standard model or diffusion coefficients correction model (Askew-Takeda model) can be used. Two energy groups and six groups of delayed neutrons are applied.

The neutron physics nodalization consists of channels for core and side reflector divided into layers along the height. Axial reflectors are the special layers of these channels. The number of core channels is equal to the number of assemblies. Number of layers for core is 10, 20 or 30. There are three types of mesh as an option with 1, 6 or 24 nodes per channel. The same number of nodes is in the reflector channels.

The neutron physics nodalization for the VVER-1000 reactor consists of 163 core channels (the number of fuel assemblies), 54 side reflector channels, divided into 20 layers for core and two layers for each axial reflector. Six nodes per channel were used.

Neutron physics properties for these calculations were prepared with use of computer code package SAPFIR_95&RC_VVER [6].

1.2 Nodalization

Thermohydraulics nodalization is not necessarily the same as neutron physics nodalization. They are absolutely independent but joined to each other for information exchange (heat generation, water density etc.). While the neutron physics nodalization must be detailed sufficiently to describe each assembly with its own properties, thermohydraulics nodalization can be simpler. The necessary number of elements should correspond to the transient or state under investigation.

Branched nodalization was constructed for VVER-1000 transients and states with considerably different properties of coolant in loops. Main reactor components are presented in the Figure 1 [4]. The core (position 5, fig. 1) is situated in the barrel (pos. 2) and is bounded by the basket. The block of shielding tubes (pos. 1 and 3) lies on the assembly headers. The cold coolant gets from 4 loops into a reactor through 4 cold nozzles, goes down in the downcomer (pos. 4), rises in the lower plenum (pos. 7) and then is heated in the core. After that hot coolant flows through the block of shielding tubes, its sidewall perforation and barrel perforation. Then the coolant gets out of the reactor by 4 hot nozzles. The chamber above assemblies is called upper plenum.

The basis of nodalization consists of 163 identical elements “channel” (“CH” element in KORSAR) going from the bottom of the reactor to its header (Fig. 1). The number of thermohydraulic channels is the same as the number of neutron physics channels and the number of fuel assemblies so that each assembly gets its own coolant and fuel properties during the neutron physics calculation. It is important for transients with great difference of these properties in fuel assemblies. Downcomer is formed by 42 channels (the number of peripheral channels mentioned).

There are 9 horizontal channels in the upper plenum periphery. They form the volume between barrel and reactor vessel (see Fig. 2 for a scheme of the upper plenum and its nodalization). These 9 channels can be described as 2 ring channels one above another and 4 straight channels for nozzles. Lower ring consists of 4 sectors-channels divided by 4 channels for nozzles. Upper ring is whole and consists of one channel.

“Local resistance” elements (“LR” element in KORSAR) model perforated walls, bends and other obstacles that coolant flows through which cause pressure drops. These elements are spread throughout the nodalization. The values of local resistance coefficients are chosen during static calculation so that pressure drops correspond to their designed values.

There are KORSAR elements of 2 types for joining parallel channels cells: “JN” and “TM”. “JN” is cross-junction and “TM” is turbulent mixing. First one lets fluid to flow between parallel channels. But no cross flow or mixing will occur if conditions in adjoining cells are the same. In such a case “TM” element is used along with “JN”. It calculates flow mixing between cells of parallel channels in assumption (that fluid mass flowed from a cell is equal to fluid mass flowed back) (that the rate of fluid cross flow

from a cell is equal to the rate of the back one). These two elements supplement each other. “TM” element also contains models for mixing in core (in tubes bundle) when detailed nodalization is used with one or more channels per pin.

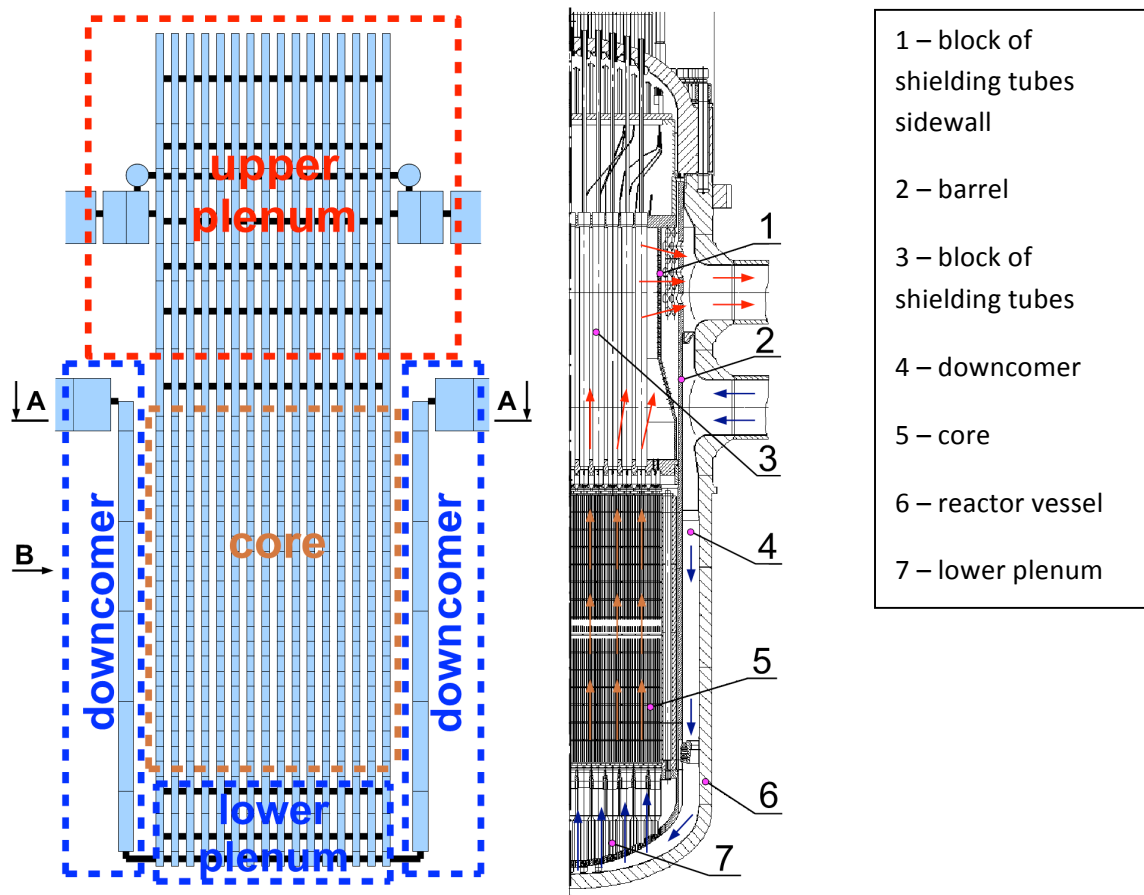


Figure 1 Reactor nodalization and layout.

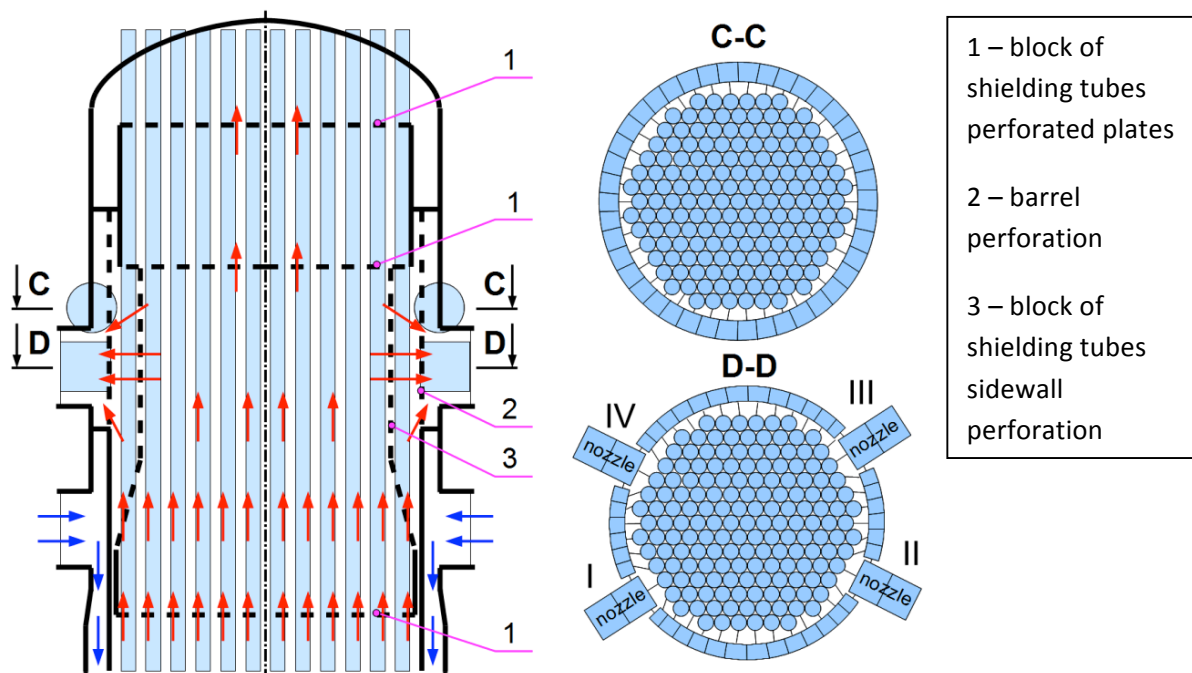


Figure 2 Upper plenum nodalization.

Every pair of adjoining cells is joined by “JN” elements in the nodalization. The cells of core and reflector are an exception as they are not connected. Cells of the downcomer are also joined by “TM” elements along with “JN”. The mixing model is very simple in this case. The cross flow value is proportionate to straight flow rates in joined channels and to mixing coefficient entered by user. The value of this coefficient is assumed to be the same for all “TM” elements in the downcomer. It is tuned in accordance with data provided by the loop mixing experiment [7]. During this experiment the coolant temperatures at the core inlet were defined. The “TM” elements were tuned to get the same temperature field in calculations. “JN” elements have also built-in hydraulic resistance tuned in accordance with design pressure drops.

Thus the nodalization observed needs auxiliary data about pressure drops and mixing intensity for construction. The data varies for different reactor designs. In case the designs differ slightly, the same nodalization can be used for all of the designs with possible corrections. There are number of VVER-1000 designs with small differences, so that the same nodalization fits all of them.

In this work the nodalization was tuned to the data provided in Kozloduy-6 benchmark specification [4]. The designs of Kalinin-3 and Kozloduy-6 reactors are the same. Thus the experimental data obtained for one of the reactors can be applied for another one.

1.3 Rotation in downcomer

The nodalization provides possibility for coolant rotation in downcomer simulation. Such rotation relative to vertical axis is observed in VVER-1000 reactor units. There is no exact description of this phenomenon and its reasons. The rotation can be modeled by auxiliary “local resistance” elements that are spread in a certain way (see Fig. 3) in downcomer and by tuning parameters of these elements according to experimental data. The rotation simulation was not used in this work.

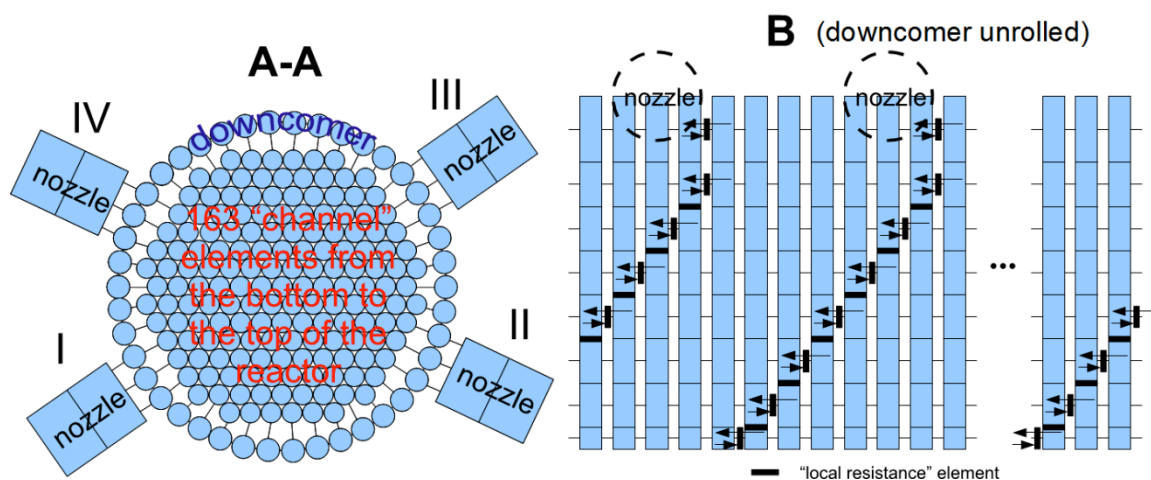


Figure 3 Downcomer nodalization (A-A and B are from figure 1).

2. Kalinin benchmark

The Kalinin benchmark was produced for codes validation. It is devoted to one of four RCPs switch-off while all other systems were in usual operation. The benchmark was provided during commissioning tests of Kalinin-3 unit. The plenty of experimental data provided by this benchmark is a sufficient advantage. Thus a number of codes models and nodalizations can be validated.

2.1 The benchmark description

The experiment was held on the 2nd of October 2005 [3]. The unit was normally operating at the initial state with its parameters equal to their nominal values. One of four operating RCPs (the 1st loop) was switched off at power level a bit less than 100 %. Automatically load-off reactor power controller began to pull down the control rods (the 10th and 9th groups of rods) decreasing the power (Fig. 4). The experimental power in the figure is provided by two measuring systems: neutron flux control system and self powered neutron detectors. The detectors of the first system are situated around the reactor vessel outside. The self powered detectors are placed in the core. The load-off reactor power controller worked until the power reached 67 %. Then automatic reactor power controller held the power near 67 % by raising the mentioned groups of control rods from time to time.

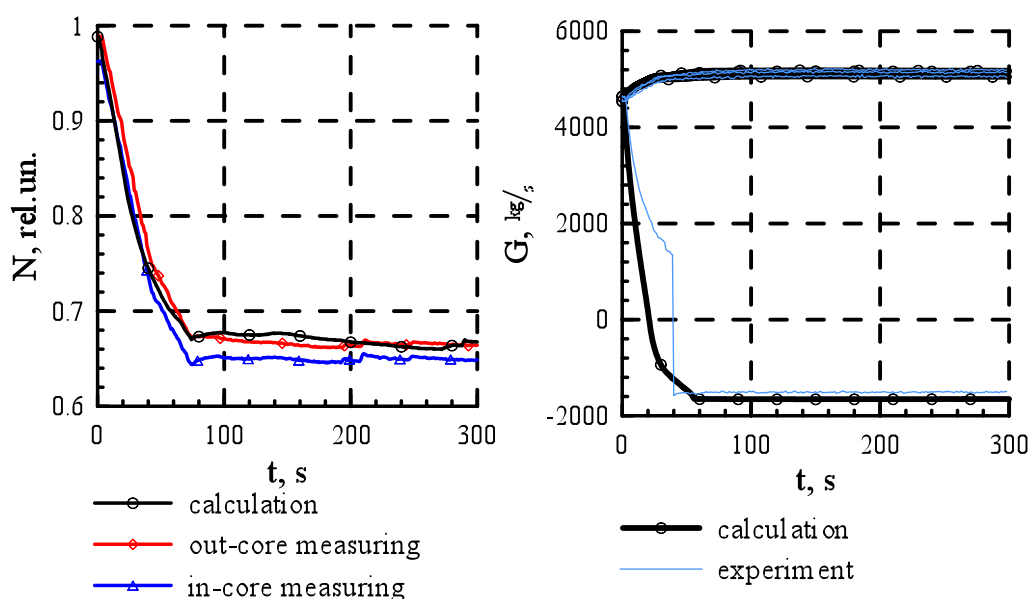


Figure 4 Reactor power and coolant flow rates in loops.

The unit was at power level of 67 % with 3 RCPs in operation after the transient. In this state cold coolant from three operating loops comes to the 1st loop through the downcomer. Further cold coolant goes to steam generator and is overcooled there. After steam generator it goes to the reactor outlet chamber. It mixes there with the main flow of coolant and gets to 3 operating loops in different proportions. The modeling of coolant mixing and getting these proportions correct is the outstanding problem for 1D codes. In this case the reactor upper plenum cannot be modeled in a simple way with one modeling element only. That is why more complex nodalization was applied to calculate the benchmark.

After the RCP was switched off the flow rate began to fall in the corresponding loop (fig. 4). The flow rate in the loop was positive during approximately 25 sec. as the fly wheel in the RCP did not let it stop immediately. The flow-measuring device indication was not reliable at the beginning of the process (about 70 sec.) because it is not applicable for evaluating flow rate during RCP trip period. It should be also mentioned that the uncertainty of flow rate indication is very high in the case of reverse flow (more than 200 kg/s). Lack of indication made uncertain instant of time when the flow stopped. The curve of flow rate was not defined too.

Temperature of coolant in cold and hot legs is presented at fig. 5 and 6. Experimental curves represent thermocouples indications. There are 6 thermocouples for each point of indication.

As the flow rate in the 1st loop fell the overall flow rate through the core fell too. This process was faster than the unit unload. That is why the coolant temperature in 2nd, 3rd and 4th loops rose firstly (Fig. 5). However the temperature in the cold leg of the 1st loop dropped. The drop of temperature was caused by the flow rate descent. Descending flow rate resulted in water overcooling in the steam generator. After flow stopped the reverse movement began. Firstly, the point of temperature indication was flowed by the coolant moving in a normal way. Secondly, it was flowed by the same coolant returning back on the reverse way. At the instant of stop this coolant was situated between the point of indication and the reactor vessel. The indicated temperature rose as this coolant had not been so overcooled. After that the coolant began to come to the point of indication from other three loops. Due to the reasons mentioned above this coolant was hotter than stopped coolant of the 1st loop cold leg. That is why the temperature indication boosted and reached a peak. This peak was related to all cold loops and was of the same instant of time. From the peak moment the temperature of the primary circuit coolant began to go down smoothly to its stationary value. Similarly the coolant temperature went down in all loops. At the end of the transient the temperature edged up following the saturation temperature in the steam generators.

The hot legs coolant temperature is presented in Fig. 6. Until 30 sec. from the beginning of the process the temperature in 1st and 4th loops remained stable and in 2nd and 3rd loops increased. Probably the plateau of 1st and 4th loops temperature stemmed from the descent of temperature in the cold leg of the 1st loop. This cold coolant got to the core and rose to the upper plenum being not mixed enough. At the same time temperature of the main flow went up. The coolant with lower temperature from the 1st loop mixed with the coolant with higher temperature from other loops and entered hot legs of 1st and 4th loops (nozzle of the 4th loop is closer to the 1st loop than others). Thus the temperature stayed the same during 30 sec. After that the temperature in the 1st loop plummeted for the reverse flow began and the coolant from steam generator poured to the hot leg. Temperatures in other loops also decreased as the overall primary circuit coolant became colder.

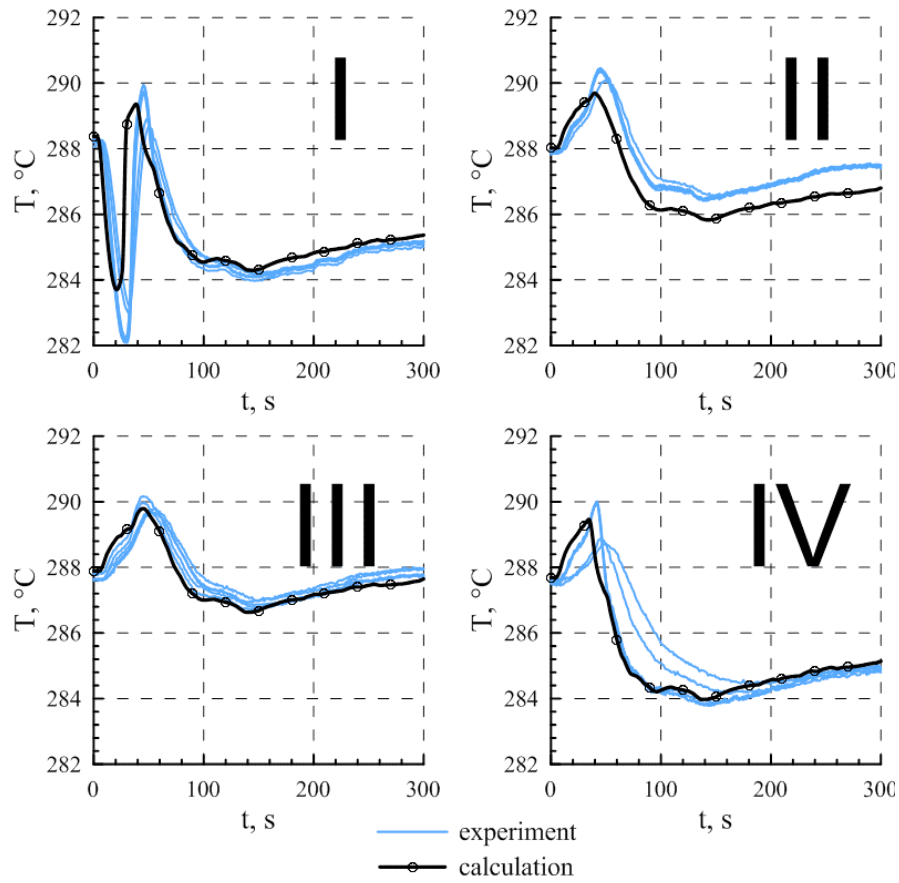


Figure 5 Coolant temperature in cold legs.

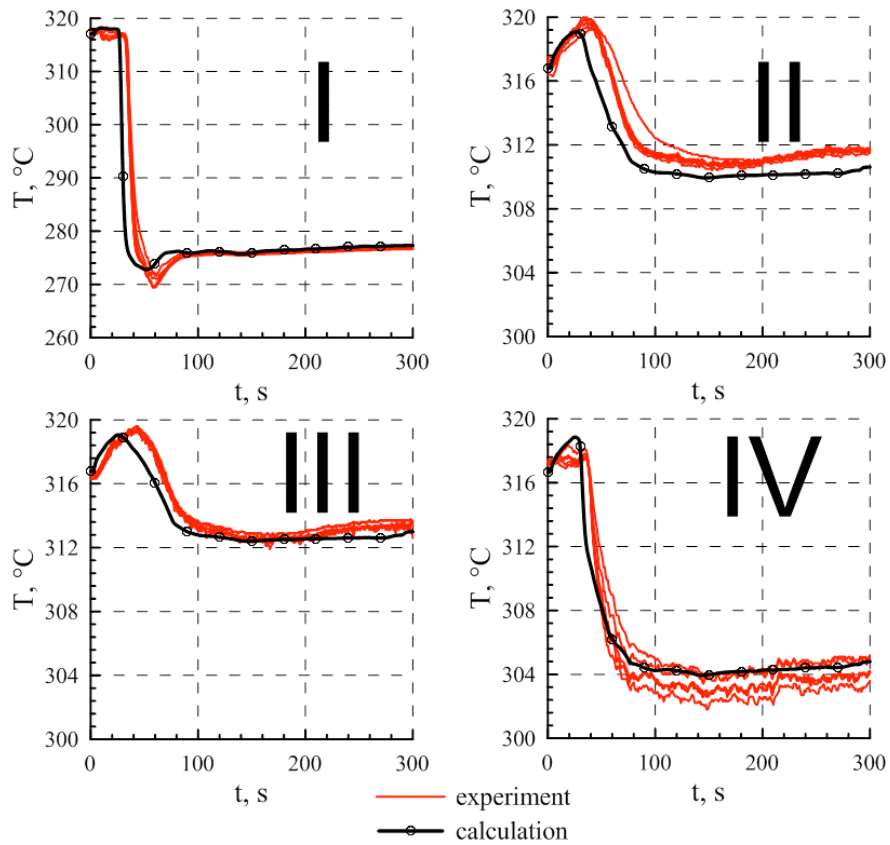


Figure 6. Coolant temperature in hot legs.

2.2 Assumptions

The calculated initial state (statics) was tuned to experimental data. Boundary conditions listed below were accepted from experimental data:

- pressure in main steam header;
- steam generators feed water temperature;
- steam generators level (through feed water flow rate tuning).

The nodalization included the primary circuit and a part of the secondary circuit. Primary circuit consisted of reactor vessel with its equipment, main circulation pipes, steam generators and pressurizer with surge line and injection line. Blow and make-up system was not included into the nodalization as well as emergency systems because they had no influence.

Table 1 demonstrates the number of nodalization cells for different equipment. The length of main circulation pipe cells is slightly more than 0.5 m. Such detailed modeling describes coolant flow in the 1st loop when its temperature varied along the pipe.

Table 1 Number of cells for equipment.

Name of the equipment	Number of cells
Hot leg	20
Cold leg	64
Steam generator tubes	5 channels with 25 cells each
Pressurizer	9 for surge line 12 for pressurizer vessel

Secondary circuit nodalization included steam generators, steam lines and main steam header. “Local resistance” elements were also spread in the circuits where they were required (pipe bends, valves etc.). The secondary circuit part of the steam generators was modeled with use of a simple non-dimensional approach.

2.3 Results

The results of calculation along with experimental data are presented in Fig. 4-7 above and Fig. 8-10 below. The calculated values agree with experimental data. They differ mostly not more than measurement uncertainty (table 2).

The calculated coolant temperature changed faster than measured one during the transient (before 100 s). However they differ not more than 2 K (measurement uncertainty) when new stationary state is reached (after 100 s).

Table 2 Measurement uncertainties.

Parameter	Uncertainty
Neutron power	2 % (relative to nominal power)
Flow rate in primary circuit loop	200 kg/s for straight flow and more than 200 kg/s for reverse one
Temperature in primary circuit loops	2 K
Pressure above core	0.13 MPa

Unfortunately calculated curve of flow rate in the 1st loop cannot be checked with experimental data by the reasons mentioned above. The temperature curves analyses show that calculated RCP trip was faster than the actual one. Most likely it was attributable to understated RCP moment of inertia. It did not include the moment of inertia of the rotor. Enlarged RCP moment of inertia should extend the trip by some seconds.

Excess pressure above the core is presented at the Fig. 7. The pressure fell during 90 sec. due to the coolant temperature decrease. Calculated pressure drops faster and calculated pressure trough is deeper. They are a little lower than measurement uncertainty range during this period. It could arise from an uncertainty of the steam generator model.

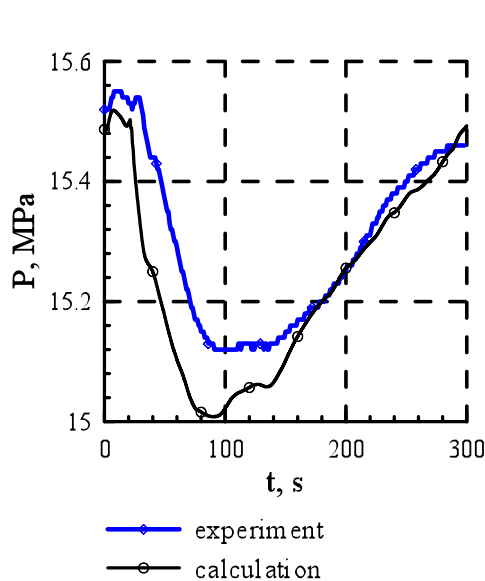


Figure 7 Pressure above the core.

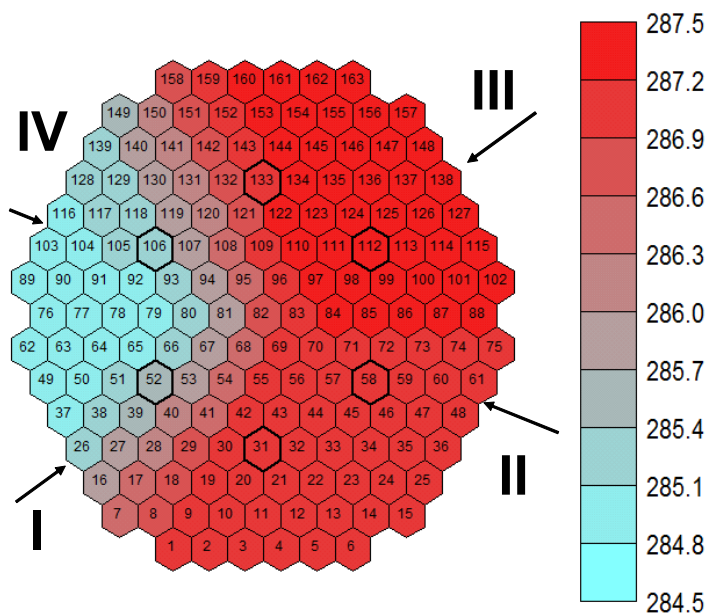


Figure 8 Coolant temperature at the core inlet at the end of the transient (°C).

Fig. 8 shows the coolant temperature at the core inlet. The 4th loop coolant enters the core being not wholly mixed. This figure demonstrates why complex nodalization should be used. Full mixing models are not acceptable here since they give coolant temperature the same for whole core inlet. Unfortunately the coolant temperature at the core inlet was not measured during the experiment and no comparison can be made.

Temperatures at the core inlet differ not more than 4 K. The same time temperatures in upper plenum differ at 30-35 K. It means that cooling mixing in upper plenum is more

important for calculation than in lower plenum. Upper plenum process has more influence on the temperature distribution.

Fig. 9 presents relative power distribution. Experimental and calculated powers in assembly No. 97 (left picture) differ considerably. The 97th assembly was changed out of turn during operation. It was not taken into account during neutron physics properties preparation. Probably it slightly influenced other parameters.

During the transient the neutron field was pressed out to the core periphery by the control rods. It became also asymmetric following the coolant temperature field at the core inlet. The neutron field rose at the coolant cold sector (see Fig. 8).

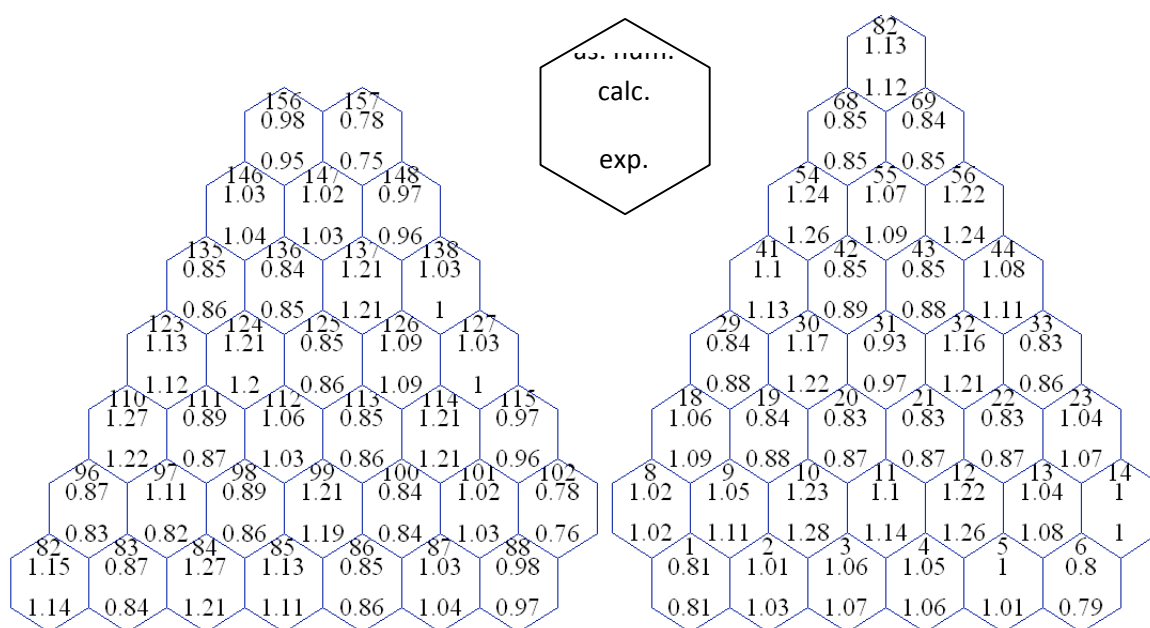


Figure 9 Relative assemblies power (K_q) at beginning (left) and end (right) of the transient for 1/6 parts of core.

Fig. 10 demonstrates axial profiles of power for assembly No. 65. Calculated curves correspond well to experimental data.

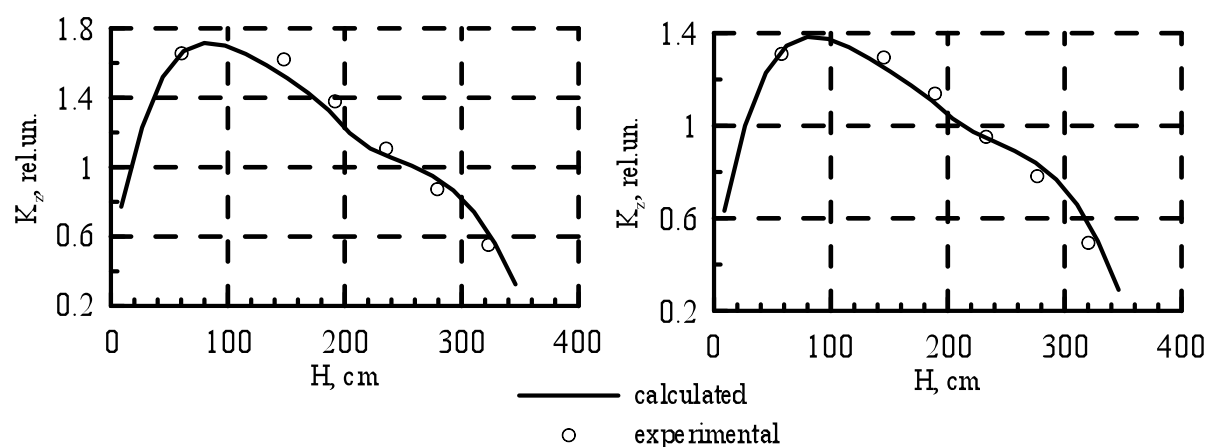


Figure 10 Axial power profiles for assembly No. 65 (left) and for core (right) at the end of the process (1300 sec.). The profiles are normalized to 1.

3. Conclusion

The work presented complex branched nodalization of VVER-1000 reactor for system 1D code KORSAR. As demonstrated this nodalization is able to model coolant mixing in the reactor chambers.

Primary and secondary circuits were included to the nodalization and Kalinin benchmark was solved with use of it. The results of calculation correspond closely with the experimental data. Some differences probably stem from reactor coolant pump (RCP) trip modelling. It may have an uncertainty due to understated RCP moment of inertia.

The nodalization needs new tests for validation. The field of application is to be determined. The test observed makes it reliable to claim that the nodalization is acceptable to calculate transients with 4 or 3 RCPs in operation. Most likely it is also good for 1 and 2 RCPs in operation cases. The case of natural circulation should be examined properly.

The influence of mesh should be clarified too. It means that several nodalizations with different number of cells and channels should be constructed for calculation of the same transient.

At present complex nodalization is applied to safety assurance calculations. New validation tests are planned.

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