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Numerical and experimental investigation of 3D coolant temperature distribution in the hot legs of primary circuit of reactor plant with WWER-1000

Nowadays the demands for accuracy of determining the weighted mean reactor power significantly increases due to implementing programs aimed at increasing installed power at nuclear power plants with WWER-1000 reactors. This accuracy strongly depends on the coolant temperature stratification in the primary circuit pipes, especially in the hot legs. Thus, the acute problem is to investigate the phenomenon on the basis of the full-scale tests experimental data and the calculated data of computational fluid dynamics simulations.

The paper presents the full-scale experimental data on the coolant temperature distribution in the hot legs obtained via I&C systems, primarily via in-core monitoring system. These data were obtained at the pilot operation stage of Unit 4 Kalinin nuclear power plant in a stationary mode at nominal power level. To present the results of calculating simulation for the same mode CFD codes are used.

German title of publication

German version of abstract

1 Introduction

In recent years the measures are being taken to increase the installed capacity at the power units with WWER-1000 reactors in Russia and abroad [1, 2]. This causes corresponding changes to margin error requirements in operative definition of the basic operational parameters by means of I&C systems. Therefore, the research aimed at finding and eliminating the causes of higher errors and uncertainties of main controlled parameters is an urgent task.

The experience of commissioning and operation WWER-1000 reactors proves [3, 4] coolant temperature stratification in the hot legs of primary circuit. This phenomenon has a significant effect on the readings of coolant temperature monitoring channels. The difference in the readings of monitoring channels of the same parameter reaches from 3 K to 10 K at nominal power level, depending on the composition of the fuel loading and the particular operating condition. It is obvious that such readings should not be taken into account for operational decision-making, or in further calculations in the in-core monitoring system (ICMS) without appropriate adjustments. However, the problem is that despite long-term experience in operating different WWER-1000 power units, systemic research into the temperature stratification phenomenon with reference to the given power units has not been carried out. Therefore, the readings adjustments of the coolant temperature monitoring channels done today, have no sufficient theoretical and methodological foundation.

The phenomenon of the coolant temperature stratification in hot legs and relevant operational problems has also been long observed at PWR units [5]. In countries where PWR units are operated a certain attention to studies of temperature stratification in the primary circulation pipes (PCP) is paid [6, 7]. However, these studies have unfinished character due to complexity and significant amount of work required, as well as insufficient use of full-scale experimental data, which reduces their value and applicability for operational tasks. According to this problem the important coolant mixing experiments in the upper plenum were performed at the ROCOM test facility [13]. It was demonstrated that the mixing is incomplete and the tendency was found.

The present paper summarizes the first attempt of association effort of two teams to conduct more extensive and systematic study of the designated problem. These teams earlier presented the results of their studies of the given problem [3, 8], which were obtained on the basis of different methodologies in according with their specialization and possibilities.

This paper presents the full-scale experimental data on the coolant temperature distribution in the hot legs of PCP received via I&C system during Unit 4 Kalinin nuclear power plant (NPP) commissioning in a steady state at a nominal power level. For the same condition the results of modelling calculation obtained by one of the computational fluid dynamics (CFD) code are presented. On the basis of a comparative analysis of experimental and calculated data the possible technical solutions and the scope of further research are suggested.

2 Experimental data

The experimental data were obtained at a stage of power ascension tests of the Unit 4 Kalinin NPP with WWER- 1000 (reactor plant project V-320). These data represent, first of all, readings of ICMS channels that perform coolant temperature monitoring in hot legs. Besides that, readings of similar monitoring channels from the other I&C systems were taken to increase representativity of the comparative analysis. The location of the used temperature detectors of the coolant temperature monitoring channels at loop 1 and loop 2 hot legs is shown on Fig. 1. Their location at loop 3 is similar to the one at loop 1, and at loop 4 it is similar to the one at loop 2. At NPP Kalinin Unit 3 and Unit 4 in each hot and cold leg are used 7 temperature detectors (6 thermocouples and 1 resistance thermometer) for ICMS. Thus, the ICMS loop coolant temperature monitoring at the investigated power unit provides representative information.

According to the design requirements, ICMS channels of temperature monitoring have essentially smaller accuracy error in comparison with similar channels in other I&C systems. Besides that, according to safety regulations, calibration should be done to eliminate possible systematic errors for ICMS temperature monitoring channels at hot stage during start-up procedures. The specified circumstances have defined the choice of the power unit and measuring system for obtaining the experimental data.

The experimental data have been received in a steady stationary mode with a complete set of working reactor coolant pumps (RCP) at nominal power level with the first fuel loading and 108 effective days burn up. The stationary mode steadiness was confirmed by achievement of ^{135}Xe stationary poisoning, absence of automatic power controller trips and thermal balance performance check according to primary and secondary circuits parameters. Obviously, it was supposed that the major factor of temperature stratification character is non-uniformity of power release in the core. For the chosen mode it is reflected in Fig. 2 as a map of fuel assemblies (FA) relative powers.

On this map we can see that the core power release had good symmetry. This fact plays a significant part in estimating the reliability of ICMS information regarding the core power release monitoring, in interpreting the results of the executed analysis, and also in further analyses of stratification in modes with essential asymmetry of power release. Other obvious factors affecting the character of stratification are design features of reactor internals on a coolant path in reactor vessel from the core exit to hot legs nozzles in various reactor plants projects. The corresponding schemes and drawings are not presented in this work, because they have no basic differences from serial V-320 project. The key reactor parameters necessary for modelling calculation are presented in Table 1.

3 Modelling calculation methodology and results

For calculations of temperature distribution in PCP SolidWorks Flow Simulation computer code was applied, which is a universal analysing tool used in hydraulic gas dynamics and a heat transfer [11]. The code has been applied earlier for the same mixing problems [8]. This code represents a multipurpose program with possibility of both stationary and non-stationary thermo-hydraulic processes analysis. Flow Simulation is the module for analysing hydraulic gas dynamics in the environment of SolidWorks. The basis of the code's mathematical method is finite element modelling of system components with geometrical form of any complexity.

For calculating the coolant stream temperature distribution and it's mixing in PCP "hot" path the boundary conditions are common circuit characteristics of the reactor plant. The flow rate and coolant temperature at FA outlet are calculated by a code START [9] on the basis of current power release distribution in FA (Fig. 2).

The reactor plant elements modelling was done under following conditions:

1. To reduce the computional costs and consumption time only the hot part of primary circuit was considered on the segment from the FA outlet to the pipeline turn to the steam generator;

2. Heat conduction in solids (vessel and core internals) was considered for calculation of the coolant temperature distribution;

3. All outer boundaries are considered adiabatic;

4. Standard k-ε model was used for a turbulence modelling;

5. Due to little distinction in loops coolant temperatures at the reactor inlet (Table 1), the azimuthal rotation of loops flows in the reactor vessel downcomer was not considered. The average loops coolant temperature was used at the core inlet;

6. Boundary conditions at the inlet into the system are the flow rate and coolant temperature at each FA outlet;

7. The distribution of the coolant flow rate and temperature at FA outlet was led to symmetry of 60 degrees;

8. Boundary conditions at the outlet are the flow rates for 1, 2, 3 loops when the loop 4 is pressure open;

9. As convergence criteria the values of loops outlet flow temperatures and velocities were checked.

Due to above mentioned simplifications all geometrical structures in considered part of the reactor model are geometrically resolved by the grid total of 7.9 million cells (4.8 fluid cells, 1.1 solid cells and 2.0 partial cells), that is less detailed compared to previous analysis performed [12].

The temperature distribution in the block of guide tubes (BGT) of the reactor vessel is presented in Fig. 3. The obtained coolant temperature distributions directly at the reactor exit and in cross-sections with temperature detectors located in hot legs of loop 1 and loop 2 are shown on Fig. 4. The distributions in loop 3 are similar to the ones in loop 1, and in the loop 4 they are similar to the one in loop 2. Bold isotherms show the area of cross-section having mean mass temperature of the coolant in a hot leg. Arrows show the projection of the coolant movement direction vector. In each cross-section the coolant temperature non-uniformity on 100 mm depth from the pipeline internal surface of (on the depth of temperature detectors sleeves immersion) is defined.

The comparison of the obtained coolant temperature distributions with similar calculations [6] shows the presence of common formation mechanism of the stratified flows in the reactor vessel at hot legs inlets. The warmer coolant flows and the ones with average temperature from the central core part pass the BGT without considerable mixing up to BGT perforation wall and are localized in the top parts of outlet pipelines. The coldest coolant flows from peripheral FA, as well as the cold flows of baffle and spacer ring leakings are localized in the bottom part of pipelines without much mixing. We can also see that in this type of reactor the character of localization at loops with even and odd numbers is different.

At hot legs inlet the coolant has the maximum temperature non-uniformity. It also has two areas of flow vortex in different directions in the bottom and in the top part of the pipeline. For loops with odd numbers the vortex is clockwise in top part and counter clockwise in the bottom part. The vortex direction in the top and bottom part of the loops with even numbers is opposite compared to the vortex directions in the odd number loops. There is flow rotation while passing through the pipeline which facilitates mixing and reduces non-uniformity. However, it seems that measurement plausible non-uniformity occurs far from the temperature detectors locations in hot legs [8].

4 Comparison of calculated and experimental data

The calculated and measured temperatures at loop 1 and loop 2 hot legs are shown in Fig. 5. These data at loop 3 are similar to the ones at loop 1, and at loop 4 they are similar to the ones at loop 2. They are given in cross-sections with temperature detectors on depth of 100 mm from an internal surface of the pipeline. The grid here corresponds to the one in A-A cross-section for loop 1 in Fig. 1. In each cross-section there is defined a root-mean-square deviation (RMSD) of the calculated values of coolant temperature from the measured ICMS values. In all cross-sections, except one, RSMD did not exceed the measuring error for the ICMS temperature monitoring channels with temperature detectors having the individual calibration equal ±1 K. At the same time RSMD at all cross-sections for all loops was 0.9 K.

The above mentioned results allow speaking about satisfactory correspondence between obtained experimental and calculated data. It is also proved by the fact that the difference between the calculated mean weighted temperature in hot legs and the temperature values obtained from thermal balance tests does not exceed 0.5 K.

At the same time the character of calculated and experimental temperature distributions testifies that the model used does not fully correspond to real processes and design features. In particular, it is possible to assume, that there is some underestimation of the influence of asymmetry in BGT wall perforation in the region of Emergency Core Cooling System (ECCS) nozzles by using CFD code calculation. Besides that, it is possible that the simplification about the absence of the azimuthal rotation of loop flows in the downcomer influences the calculation result. Such assumption is brought about by the results of coolant temperature field definition tests at core inlet, executed on different WWER-1000 units [10]. These results have shown that the greatest angle of loop flows rotation in the reactor vessel occurred at Kalinin NPP Unit 4 among all observed units and, accordingly, the most intensive mixing between loops flows was marked at this unit. Earlier the azimuthal rotation of loops flows in the reactor vessel was also shown by the results of the other coolant mixing start-up tests, for example, during the commissioning of the Kozloduy NPP Unit 6. The V1000CT-2 thermalhydraulics benchmark is based on the measurements at these tests and many works have been performed in the framework of this benchmark [14].

5 Conclusions

Design and operational limits connected with coolant temperature in hot legs should be established and reconsidered according to the results of both full-scale tests and calculations of 3D coolant temperature distributions of in hot legs by means of CFD codes.

ICMS operating algorithms should provide the possibility of including in mean weighted temperatures calculations the information from all I&C temperature monitoring channels and the calculated results obtained by means of CFD codes.

It is necessary to locate the temperature detectors in hot legs at the farthest possible distance from the reactor vessel. The detector locations in a one cross-section must be distributed at regular intervals all along the perimeter of the pipeline cross-section.

More definite conclusions can be obtained providing that research is continued following the comparative analysis of experimental and calculated data in different operational modes. The set of such modes should include the ones which will allow to define the effect of a reactor power level, fuel burn up, offset, power release asymmetry, etc. A test facility is able to provide some corresponding data [13]. It was shown that it is sufficient to obtain the mixing coefficients between each fuel assembly outlet and positions within the hot leg. On that basis temperature field reconstruction in the hot leg can be done using as input data from neutron kinetic codes [13]. The approach can be check by few full-scale experiments as proposed. For WWER reactors the Gidropress V1000 test facility should be adequate for this purpose [15].

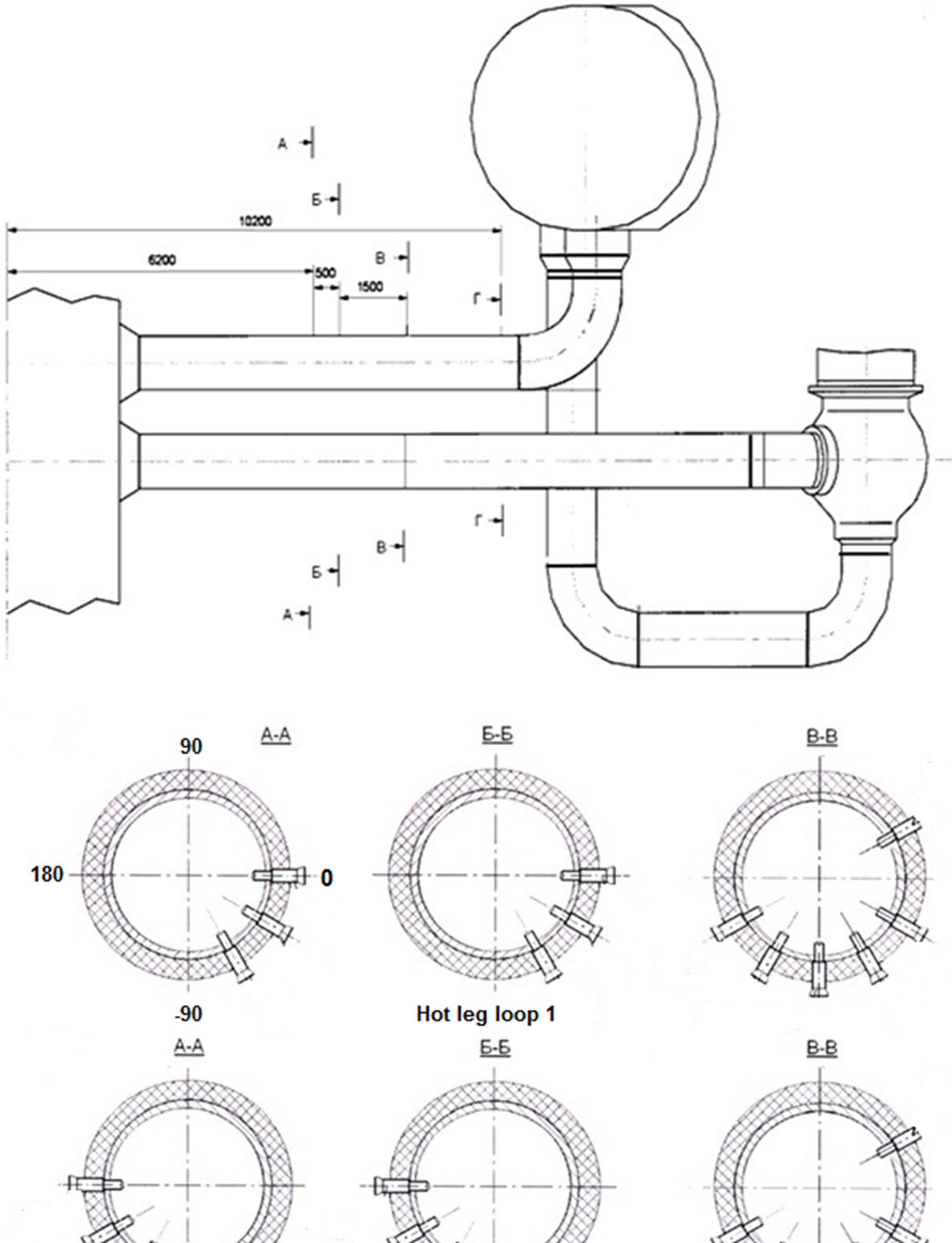


Fig. 1. Location of temperature detectors at loop 1 and loop 2 hot legs

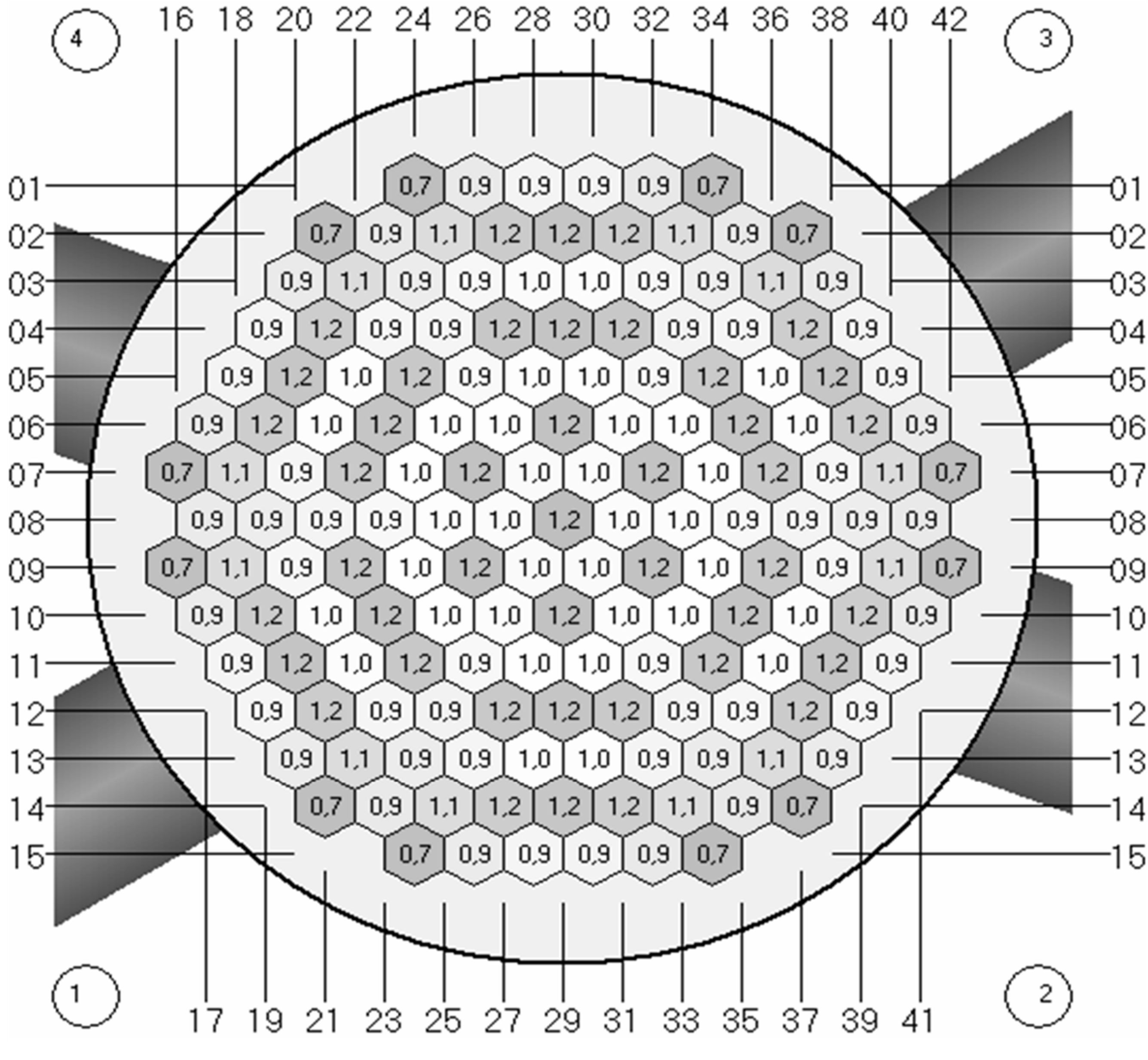


Fig. 2. Map of FA relative powers

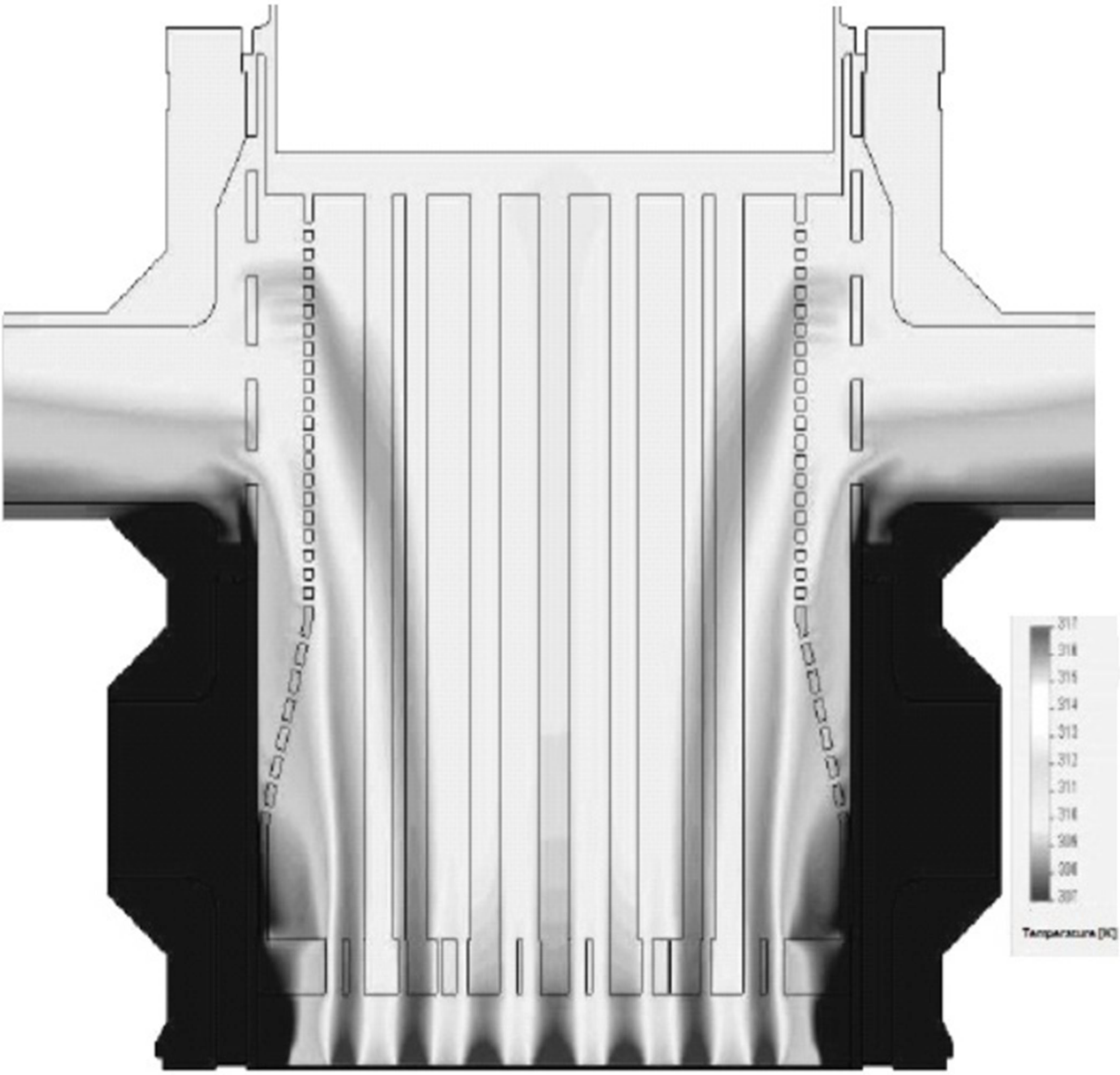


Fig. 3. The calculated temperature distribution in BGT

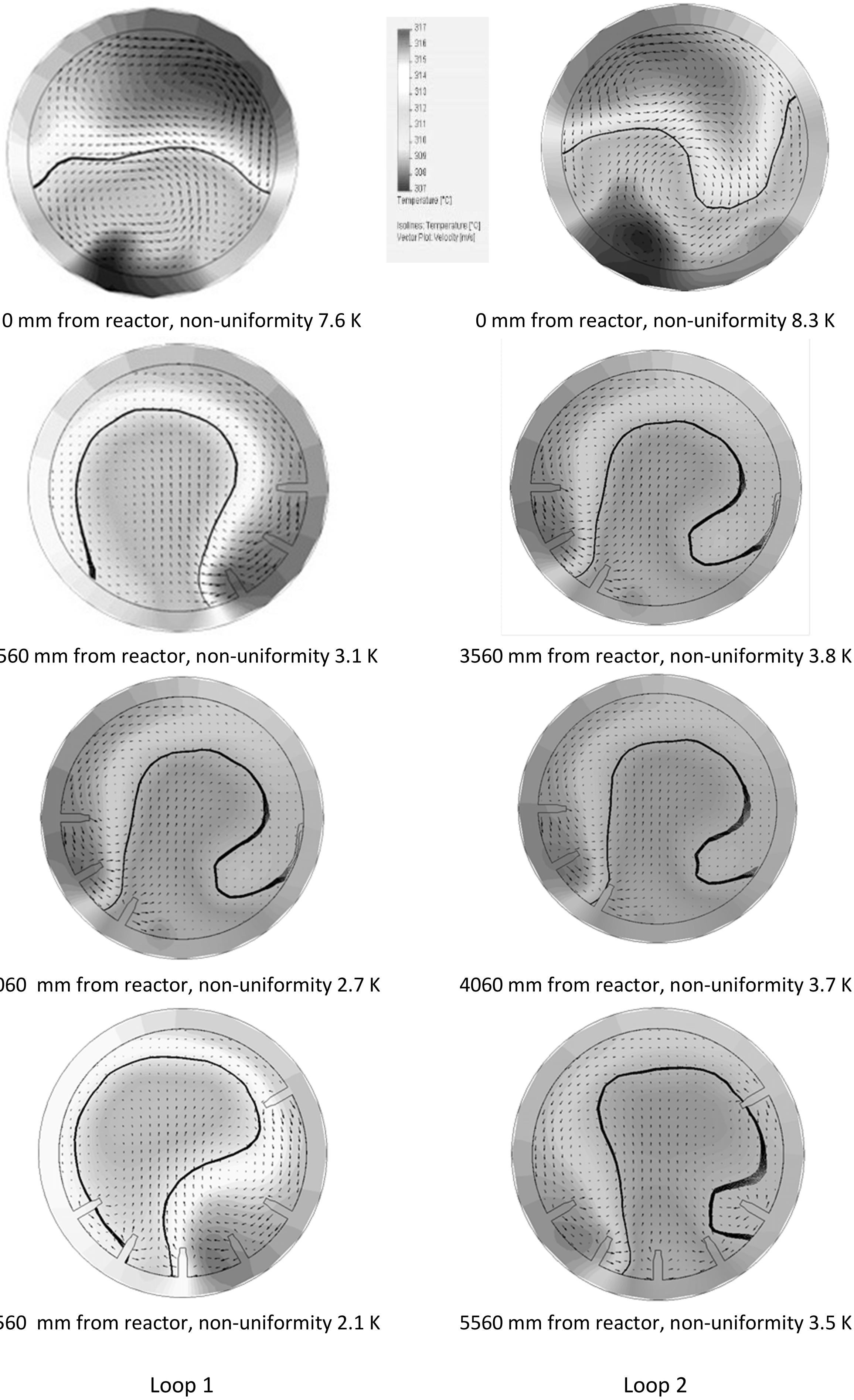
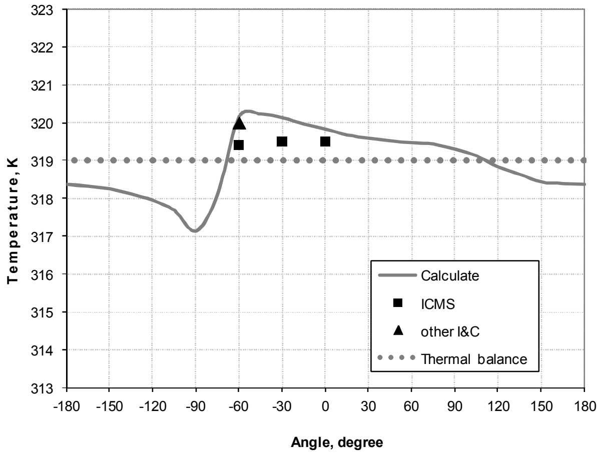
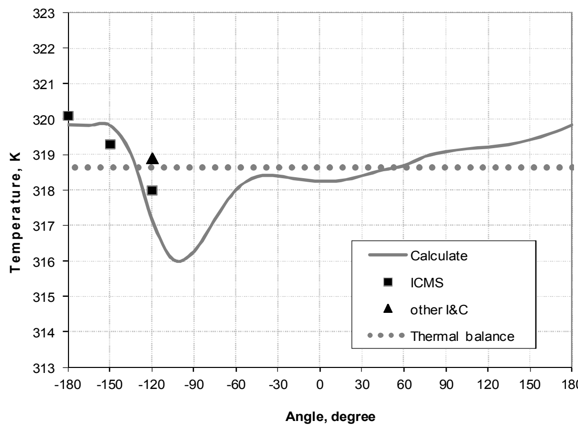


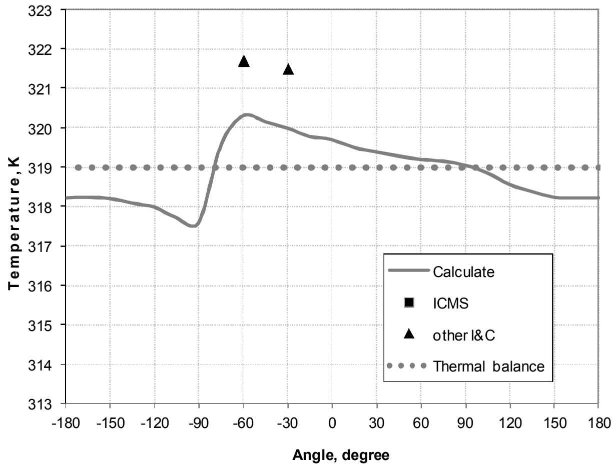
Fig. 4. The calculated coolant temperature distributions at loop 1 and loop 2 hot legs



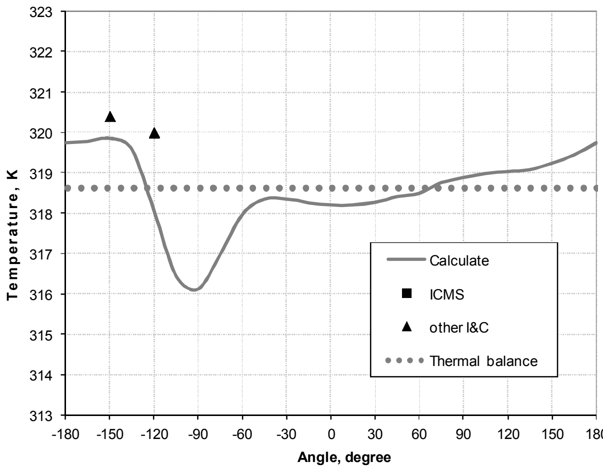
Cross section A-A, RMSD from ICMS 0.6 K



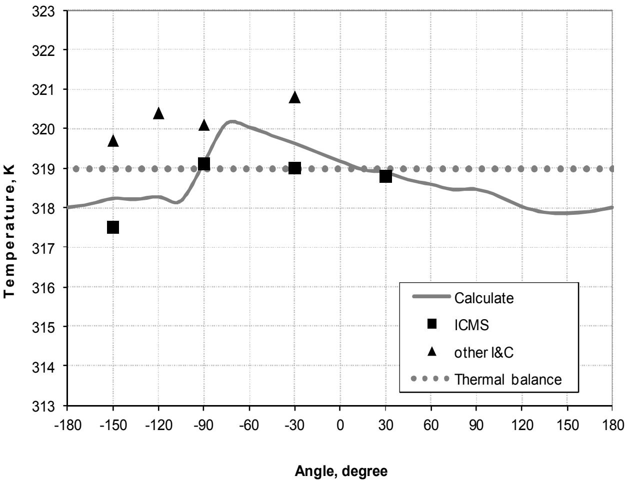
Cross section A-A, RMSD from ICMS 0.6 K



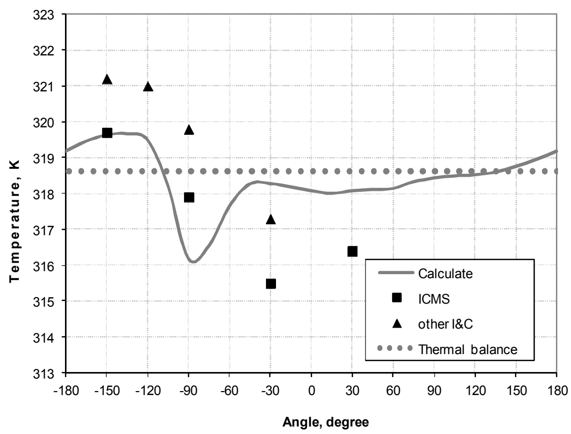
Cross section Б-Б



Cross section Б-Б



Cross section B-B, RMSD from ICMS 0.5 K



Cross section B-D, RMSD from ICMS 1.2 K

Loop 1

Loop 2

Fig. 5. The calculated and measured temperatures at loop 1 and loop 2 hot leg.

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