V&V Status of CFD Codes Applied to BN Reactors

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Abstract. Using CFD codes for numerical simulation of thermohydraulic processes occurring in fast sodium reactors, specific character of heat transfer in liquid metals and complicity of computational model development should be taken into account due to integral layout of reactor equipment.

Application of universal non-Russian CFD codes (CFX, Star-CD, Fluent, etc.) does not enable to take into account specific character of sodium coolant because Reynolds analogy is taken as basis for parameter determination.

To solve the problem, the Russian code FlowVision implements an original model of turbulent heat transfer. Such problem is set during implementation Project "New generation codes" within which LOGOS code is developed.

One more way to solve the problem is to apply thermohydraulic codes of DNS category, and particularly CONV-3D code.

To verify CFD codes with regard to BN reactors, verification matrix is developed which includes:

- analytical tests;
- benchmarks of the basis of experimental studies;
- task on the basis of data obtained during BN-600 operation;
- tasks with regard to newly performed experimental studies.

To obtain missing data, sodium facility is designed, constructed, and commissioned at RAS UB ICMM (Perm). The following has been experimentally studied:

- convective current of sodium in pipes with various aspect relations and grade angles;
- mixing of sodium flows of different temperatures using various models.

The paper contains results of experimental studies and performed verification for coded FlowVision, CONV-3D, and LOGOS with regard to BN reactors.

Key Words: Verification and Validation, Computational Fluid Dynamics, Liquid-Metal Sodium Model

1. Introduction

Service life extension and safety improvement of operating power reactors BN-600, BN-800, and the BN-1200 reactor under development require detailed study of thermal-hydraulic processes taking place in these reactors. Studies of thermal-hydraulic processes in sodium coolant based on only experimental data does not allow obtaining necessary information on these processes to the full extent, thus, additional justification using numerical simulation of thermal-hydraulic characteristics for BN reactors should be made.

Now Computational Fluid Dynamics methods (CFD codes), capabilities of which have been enlarged by with advent of current computer technologies, could be used for these purposes.

Nevertheless, lack of turbulent heat transfer models, which consider specific character of liquid metal sodium coolant, in CFD codes requires development of special models and approaches with their further verification and validation.

This paper describes V&V status of three Russian CFD codes – LOGOS (FSUE RFNC – VNIIEF), FlowVision (JSC "TESIS") and CONV-3D (IBRAE RAN).

2. Distinctive Features of Heat Transfer in Liquid Metals

Hydrodynamics and heat exchange of sodium under the conditions, typical for BN reactor plant, have their substantial distinctive features and differences. Among the specific properties of sodium coolant, there is its high heat conductivity, which is much higher than heat conductivity of other coolants, with relatively small kinematic viscosity. It means that molecular heat transfer in liquid metal is more intensive than molecular momentum transfer. Molecular heat conductivity in sodium turbulent flow is the main contributor in transverse heat transfer not only in the wall layer but in the flow core too [1 − 3]. Thus, temperature field in liquid metal flow differs from velocity distribution and could have gradient up to the channel axis. Consequently, laws of heat transfer in sodium differ from those for non-metal liquids and gases. It is shown in Fig. 1.

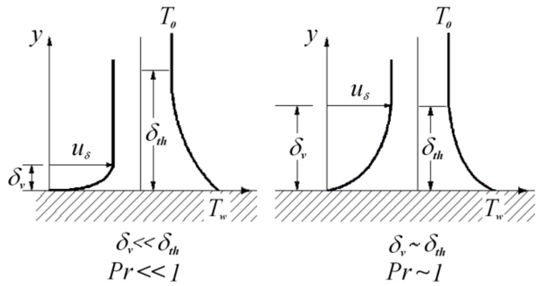


FIG. 1 – Effect of the molecular Prandtl number on relative thickness of the thermal boundary layer (u_δ, T_o – flow velocity and temperature respectively, T_w – wall temperature)

3. Simulation of Turbulent Heat Transfer in Liquid Metals in CFD Codes

The turbulence models, implemented in a majority of CFD codes (CFX, Fluent and others), determine heat transfer parameters based on the Reynolds analogy. Its subject matter is that intensity of momentum transfer and heat transfer in turbulent flow are supposed to be equal, i.e. coefficients of turbulent exchange of momentum transfer (ν_t) and heat transfer (a_t) are considered to be equal in any flow point [4]. The Reynolds analogy allows obtaining satisfactory results for water or gas used as a coolant, but does not allow considering distinctive features of heat transfer in liquid metals, resulting in divergence of calculation and experimental results [5].

To solve this problem the unique model of turbulent heat transfer for Liquid-Metal Sodium coolant (LMS) is implemented to the FlowVision CFD code [5]. The LMS model is compatible with all k-ε turbulence models and could be used for sodium flow analysis both with high Reynolds numbers (with wall functions), and with low Reynolds number (without wall functions).

A similar task was set in frame of the "Codes of New Generation" project, in which the RANS and LES CFD-code LOGOS is developed. The code should provide simulation of thermal-hydraulic processes in fast-neutron reactor plants with liquid-metal coolants (sodium, lead, lead-bismuth) in order to justify design characteristics of the reactor plant in operation modes and reactor plant safety in accidents (except severe accidents resulting in melting and boiling of components).

One more method of problem solution is application of CFD codes based on DNS approach, in particular, the CONV-3D code [6], which could be used for precision calculations of elements of reactor plants with liquid-metal coolants to confirm their design-and-engineering characteristics and to obtain required model parameters for RANS analysis.

4. V&V Matrix of CFD Codes Applied to BN Reactors

4.1 Filling of V&V Matrix

In compliance with regulatory documents, which are valid in the industry, the possibility to use CFD codes for simulation and study of thermal-hydraulic processes in BN reactor plants should be justified by V&V results. To develop the V&V matrix for CFD codes applied to BN reactors a list of key processes and phenomena, which take place in reactor plant operation modes, simulated by CFD code, was developed, available Russian and foreign experimental data, obtained using reactor and beyond-reactor experimental basis were analyzed. In particular, the following was included in the list of key processes and phenomena: friction pressure drop in channels of simple and complex shapes, free and forced convection in large volumes, mixing of sodium coolant flows with different temperatures, etc. The following conclusions were made based on the analysis of available experimental data:

- in majority of available experimental data there is no complete information on model geometry and errors of used measuring instrumentation;
- considering specific character of sodium coolant heat transfer, lacking experimental data should be obtained at sodium test facilities;
- reactor test results should be used to justify the methodological approach applied for practical problem solution.

The experimental data on mixing of coolant flows with different temperatures, which are the most representative from the viewpoint of validation of CFD codes, were obtained at sodium test facilities [7, 8]. Data on mixing of sodium flows with different temperatures in the upper chamber of the BN-600 reactor [9] and benchmark on study of coolant flow in the upper chamber of the MONJU reactor [10] could be used as reactor test results.

The developed list of V&V problems for CFD codes applied to the BN reactor plant is given in Table I (the list includes studies described in the scope sufficient enough to make validation).

TABLE I: THE LIST OF V&V PROBLEMS.

Type of study	Problem description
Analytical tests	Turbulent flow-around of thin plate
	Laminar /turbulent flow in round tube
	Turn (turbulent flow)
	Sodium flow in tube being cooled
Foreign experimental studies of separate effects	Mixing of sodium flows with different temperatures at the TEFLU test facility (Germany)
	Mixing of three sodium streams with different temperatures at the PLAJEST test facility (Japan)

Foreign experimental reactor tests	Convectional flow of sodium in the MONJU upper chamber
Operation data	Mixing of sodium flows with different temperatures in the BN-600 upper chamber

Based on the information from Table I, the conclusion could be made that available data are very limited and do not allow covering and detailed study of the entire list of processes, which are important for simulation. Therefore, in 2013–2016, in Russia, within the Federal Target Program “Nuclear power technologies of a new generation for 2010 - 2015 and for the future till 2020” additional experimental studies were performed, which not only allow enlarging the area of justified application of CFD codes, but give unique data from viewpoint of understanding of physical processes taking place in sodium coolant (see Table II below).

Experiments from Table II are described below in more detail.

TABLE II: THE LIST OF ADDITIONAL VALIDATION PROBLEMS.

Experimental studies made in Russia in 2013 – 2016	Mixing of sodium flows with different temperatures in T-tube
	Mixing of sodium flows with different temperatures downstream baffle in channel
	Mixing of sodium flows with different temperatures in mixer
	Convective flow of sodium in tube (*l/d*=5)
	Convective flow of sodium in tube (*l/d*=20)

4.2. Additional Experimental Studies to Fill the V&V Matrix

Special experiments were arranged to study free convection of sodium in a cylindrical cavity with end supply and discharge of heat in tubes with a tube inclination angle to the vertical of 0, 45^o, 90^o and aspect ratios *l/d=5* [11, 12] and *l/d=20* [13], and detailed analysis of heat flow dependence on an inclination angle in the entire range from 0 to 90^o for the cylinder with aspect ratio *l/d=20* [14]. Schemes of experimental models for free convection studies are given in Fig. 2. The both of them show location of thermal couples.

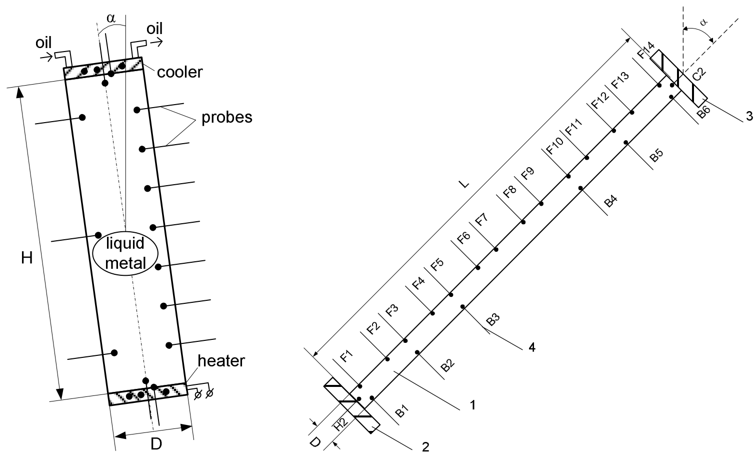
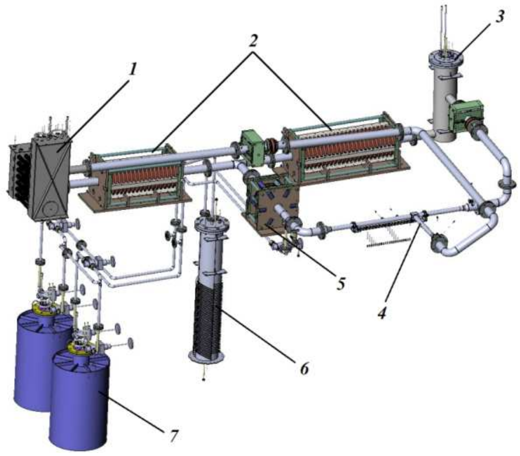


FIG. 2 – Schemes of experimental models to study free turbulent convection with aspect ratios l/d=5 (left) and l/d=20 (right)

The temperature in the model was measured using standard Chromel-Alumel thermal couples with an insulated junction, with this junction diameter of 1 mm. Values of sodium average velocity were estimated based on results of cross-correlation analysis of signals from neighboring thermal couples.

To study processes of mixing of flows with different temperatures the sodium test facility, which general view is shown in Fig. 3, was developed, manufactured and put into operation in Institute of Continuous Media Mechanics of the Ural Branch of Russian Academy of Science (ICMM UB RAS) [15].



1 – sodium-air heat exchanger; 2 – electromagnetic pumps; 3 – heater; 4 – experimental model; 5 – electromagnetic pump-throttle; 6 – cold trap; 7 – sodium storage tanks
FIG. 3 – The general view of sodium test facility

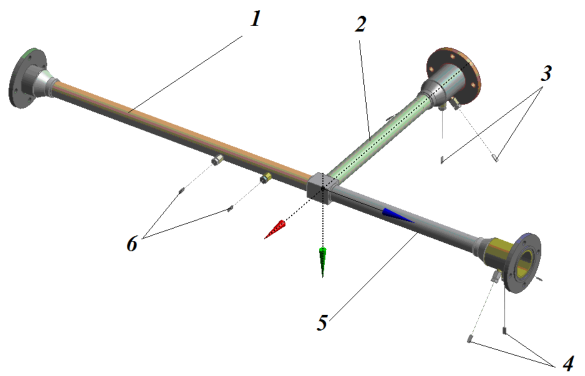
The test facility consists of "cold" and "hot" branches and a test section. Each branch includes a sodium-air heat exchanger or a heater and an electromagnetic pump and measuring instrumentation for coolant flow and temperature. Basic parameters of sodium test facility are given in Table III.

TABLE III: PARAMETERS OF SODIUM TEST FACILITY.

Parameter	Value
Electric heater power, not less than, kW	20
Heat exchanger power, not less than, kW	20
Maximum flow rate of "hot" sodium through the experimental model, l/s	1.0
Maximum flow rate of "cold" sodium through the experimental model, l/s	0.5
Sodium temperature in the test section, not more than, °C	250

Experimental studies on mixing of sodium flows with different temperatures were made at test facility on various models: a T-tube, a baffle in the channel, and a mixer.

Let us consider experimental studies on the T-tube model in more detail (see Fig. 4). The T-tube is a T-shaped connection of straight stainless steel tubes of 40 mm inner diameter, tube wall thickness is 1.5 mm. In the T-tube the "hot" sodium circulates in the through mode, and "cold" sodium circulates via the side supply. "Hot" and "cold" sodium enters the T-tube via honeycombs. The selected thickness of the T-tube model wall ensures low heat retention, which allows measuring temperature pulsation at the external surface of the circuit using an infra-red imager. Low-inertia micro thermal couples were used to measure temperature in sodium flow.



1 – mixing portion; 2 – "cold" sodium inlet portion; 3 – thermal couples at the "cold" branch inlet; 4 – thermal couples at the "hot" branch inlet; 5 - "hot" sodium inlet portion; 6 – thermal couples in flow
FIG. 4 – The T-tube model

Experimental studies were performed for three modes which differ in ratios of flow rates and temperatures between "hot" and "cold" coolant, coming to the inlet portions of the T-tube model (see Table IV below).

The following designations are accepted in Table IV:
- Q_h –coolant volume flow rate in the hot branch, ml/s;
- Q_c – coolant volume flow rate in the cold branch, ml/s;
- T_h – sodium temperature at the hot branch inlet, °C;
- T_c – sodium temperature at the cold branch inlet, °C.

TABLE IV: BASIC CHARACTERISTICS OF EXPERIMENTAL MODES

Mode number	Q_h, ml/s	Q_c, ml/s	T_h, °C	T_c, °C
1	1040	490	207	153.4
2	556	231	222.1	126.3
3	915	830	184.9	140.8

Experimental studies allow obtaining data on temperature pulsation in sodium flow and on the external surface of the T-tube.

5. V&V Status of CFD Codes LOGOS, FlowVision and CONV-3D Applied to Sodium Coolant

V&V of CFD codes LOGOS, FlowVision and CONV-3D was completed on all data, given in Tables I and II by the end of 2016. Calculation errors for some of the parameters were determined based on the validation results. In particular, calculation errors for pressure drop, temperature (from the maximum value) and flow velocity do not exceed 15%. Some results of validation are given below in more detail.

5.1. Validation Results on the Problem of Mixing of Sodium Flows with Different Temperatures in the T-tube

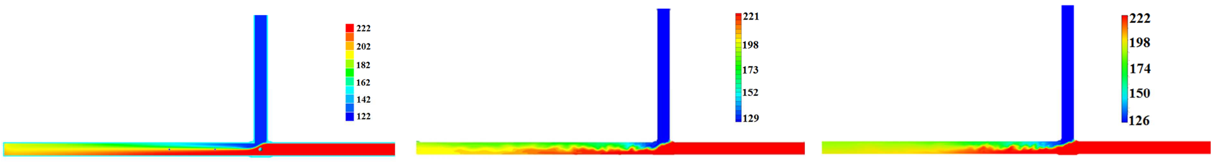
The model for numerical simulation of the process of mixing of sodium flows with different temperatures in the T-tube includes honeycombs and diffusers on inlet portions in addition to the T-tube.

The assigned boundary conditions correspond completely to the conditions under which the experimental studies were performed.

As a result of numerical simulation the following was obtained:

- fields of velocity and temperature in the symmetry plane of the structure for three modes;
- graphs of temperature variations depending on time in control points.

Computation results for mode 2 in compliance with Table IV are given in Fig. 5.



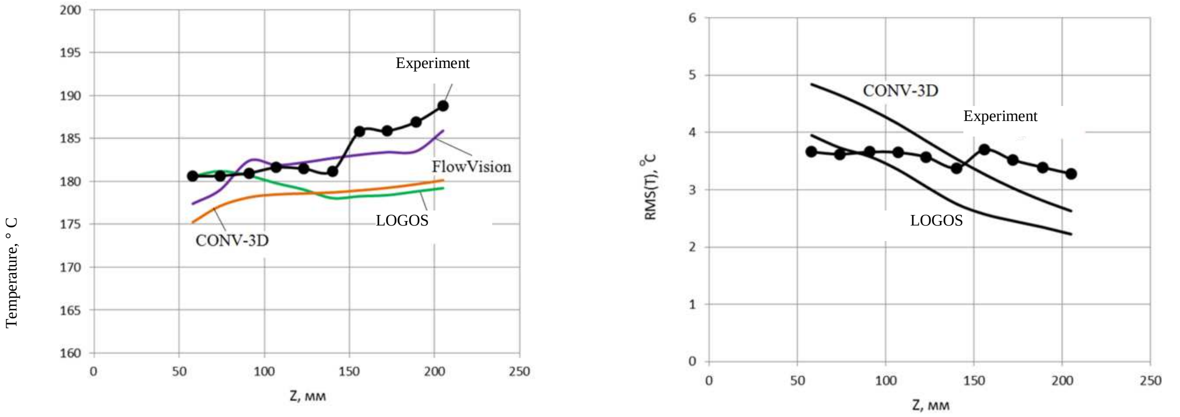
a) *b)* *c)*

FIG. 5 – Coolant temperature distribution (°C): a) FlowVision, b) CONV-3D, c) LOGOS

Calculation results and experimental data were compared by the following parameters:

- average temperature in control points;
- root-mean-square deviation of temperature pulsations in control points;
- spectral characteristics of temperature pulsations.

The comparison of the calculation results is shown in Fig. 6. The best accuracy for average temperature was obtained by the FlowVision code with the LMS model; pulsations were not simulated because the URANS approach was used. To simulate pulsations LES and quasi DNS approaches were used (computations were made by LOGOS and CONV-3D codes).Good agreement between experimental and calculation data was obtained using both codes.



a) *b)*

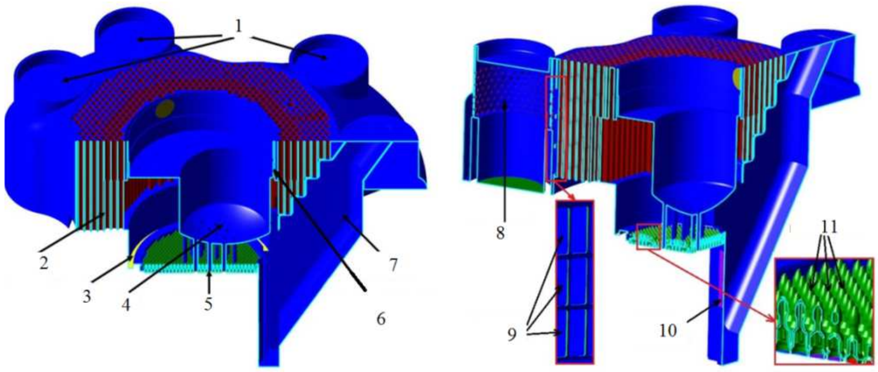
FIG. 6 – Comparison of the calculated results: a) average temperature dependence on coordinate Z; b) root-mean-square deviation dependence on coordinate Z

Analysis of calculation results obtained using FlowVision, CONV-3D and LOGOS codes for three experimental modes show that the URANS approach could be used for average temperature estimation with a reasonable accuracy, because the best accuracy was obtained for the FlowVision code. To estimate temperature pulsations quasi DNS approach can be used because the best accuracy was obtained for CONV-3D code. Nevertheless, it should be noted that using of quasi DNS approach requires considerable computational time and resources compared to the URANS approach.

5.2. Validation Results on the Problem of Mixing of Sodium Flows with Different Temperatures in the Upper Chamber of the BN-600 Reactor

The problem of mixing of sodium flows with different temperatures in the upper chamber of the BN-600 reactor was considered.

The calculation model of the flow path of the reactor upper chamber (RUC) was developed including top nozzles of core fuel assemblies, in-vessel shielding tubes, an elevator baffle and a heat exchanger support (see Fig. 7). Heat exchanger was simulated using porous body model.



1 – intermediate heat exchanger; 2 – safety rods; 3 – annular gap around the support; 4 – central rotating column; 5 – core; 6 – gap between reactor neck shell and sheets of large rotating plug; 7 – elevator baffle; 8 – support of intermediate heat exchanger; 9 – entrance gates of intermediate heat exchanger; 10 – slot in support; 11– fuel assembly top nozzle

FIG. 7 – The calculation model of the BN-600 reactor upper chamber

Sodium mass flow rate and temperature were set as boundary conditions at the top of all fuel assemblies. The same conditions were determined on boundaries corresponding to the overflow windows of the rotary plug, the annular gap around the support, the slot in the support and bypass flowmeter. Problem formulation is given in detail in [9].

Simulation results for the BN-600 reactor upper chamber are shown in Fig. 8. The behavior of sodium flowing from the core to the intermediate heat exchanger is similar for three codes. The difference is in the direction of flow after flow-around the bottom of the central rotating column. FlowVision and LOGOS calculations show practically vertical flow of sodium from fuel assemblies of the main array along the central rotating column, and CONV-3D calculations show the flow inclined to the intermediate heat exchanger. Vortex areas are observed in the results of calculations for all three codes.

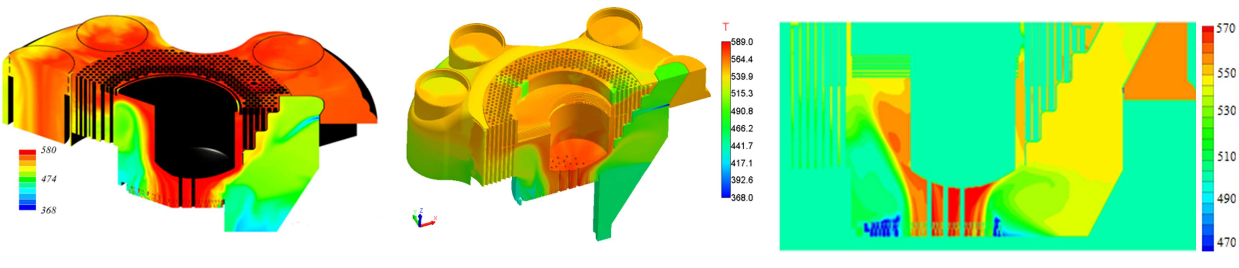
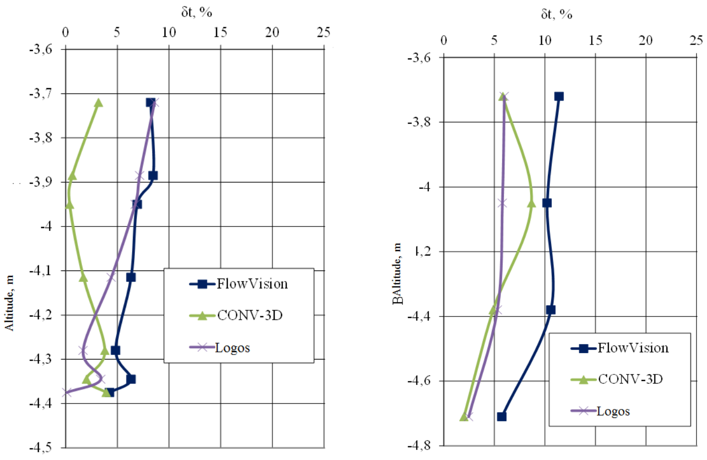


FIG. 8 – Results of simulation of the BN-600 reactor upper chamber. Temperature distribution (°C): a) FlowVision, b) LOGOS, c) CONV-3D

Validation was made by comparison of calculation results obtained for temperature distribution with those measured by tank thermal couples, and by thermal couples placed at the intermediate heat exchanger inlet. Fig. 9 shows the results of the comparative analysis.



a) *b)*

FIG. 9 – The relative deviation of calculated temperature values from measured values along the height of intermediate heat exchanger (IHX): a) 5 IHX-A, b) 4 IHX-B

Comparison of the relative deviations for three codes shows that the best coincidence ~ 4 % was obtained by the CONV-3D code, in this case very fine grid (~540 mln of cells) was required. The average relative deviation ~ 5 % was obtained for the LOGOS code, in this case computation was performed using computational grid of ~ 60 mln of cells. The average relative deviation for the FlowVision code is~ 8 %, in this case the most coarse computation grid was used ~ 56 mln of cells.

Thus, all CFD codes, intended to simulate heat and mass transfer processes in liquid metal coolants, showed satisfactory results at which the relative deviation of temperature does not exceed 10 %. The above mentioned comparative analyses show that spent time and computation resources increase as computation accuracy increases.

6. Conclusion

Available Russian and foreign experimental data, obtained using reactor and beyond-reactor experimental basis for sodium coolant, were analyzed. The V&V matrix for CFD codes applied to BN reactors was formed on the basis of the analysis performed.

To obtain lacking data for codes validation the sodium test facility was developed, manufactured and put into operation in Russia. Experimental studies were performed.

Large-scope work was performed on V&V of FlowVision code and codes, developed within the framework of the “Codes of New Generation” subproject of Proryv” (or “BREAKTHROUGH”) project, LOGOS and CONV-3D, on all experimental data from the V&V matrix developed.

At the end of 2016 results of LOGOS and CONV-3D codes V&V were submitted to Rostechnadzor for independent review. The results of this review should confirm the justification of application of these codes with estimated accuracy in the range of non-dimensional parameters claimed by developers.

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