Verification calculations as per CFD FLOWVISION code for sodium-cooled reactor plants

S.A. Rogozhkin, S.L. Osipov, S.F. Shepelev,[a], A.A. Aksenov, M.L. Sazonova, V.V. Shmelev[b]

[a] JSC "OKBM Afrikantov", Nizhny Novgorod, Russia

[b] "TESIS Ltd.", Moscow, Russia

Abstract. The paper studies the experience in application of CFD FlowVision software for analytical validation of sodium-cooled fast reactor structure components and the results of performed verification, namely:

- development and implementation of new model of turbulent heat transfer in liquid sodium (LMS) in FlowVision software and model verification based on thermohydraulic characteristics studied by experiment at TEFLU test facility;
- simulation of flowing and mixing of coolant with different temperatures in the upper mixing chamber of fast neutron reactor through the example of BN-600 (comparison with the results obtained at the operating reactor).

Based on the analysis of the results obtained, the efficiency of CFD codes application for the considered problems is shown, and the proposals for CFD codes verification development as applied to the advanced sodium-cooled fast reactor designs are stated.

1. Introduction

JSC "OKBM Afrikantov" has been involved in development of sodium-cooled fast reactors for more than 50 years. The reactor plants that have been sequentially developed are BN-350, BN-600 (in operation), BN-800 (under construction). Currently, development of BN-1200, Generation IV reactor, is in progress. Over these years, substantial research has been done to validate thermal-hydraulic characteristics of developed reactor plants – this is mainly analytical and experimental work. Over the last years, CFD methods (CFD codes) that are based upon state-of-the-art computer technologies have been more frequently employed to validate designs.

Use of CFD codes in the nuclear power industry makes it possible to:

- substantially enhance the phenomena analyzing capabilities;
- analyze complex processes in reactor plant equipment and systems; refine their characteristics;
- abandon experimental studies or substantially simplify and reduce their scope for a number of design solutions.

The analysis of the world's scientific literature has shown that the issue with applicability of CFD software packages for analytical studies of liquid metal flows is being actively discussed by specialists in the nuclear field [1]. Validating the possibility of using CFD codes for designing, parameter optimization and safety analysis of the BN reactor plants is a topical challenge.

The main distinctive feature of CFD code application for the BN reactors is the need to take account of:

- heat transfer mechanism in liquid metals;
- integral layout of equipment in the reactor.

2. Turbulent heat transfer in liquid metals

Heat transfer in liquid metals that are characterized by low molecular Prandtl numbers [2] has a range of special features. Fig. 1 shows the effect of the molecular Prandtl number upon the ratio between the thicknesses of the dynamic and thermal boundary layers. In the turbulent thermal flow, the heat transfer is determined by both molecular and turbulent heat conduction coefficients. In conventional media, like air and water, the molecular heat conduction is important only near the wall in the viscous sub-layer. In liquid metals, the coefficient of molecular heat conduction is of the same order of magnitude as the turbulent heat conduction coefficient for the entire flow. Thus, the heat transfer mechanism in liquid metals is far different from the heat transfer mechanism in air and water.

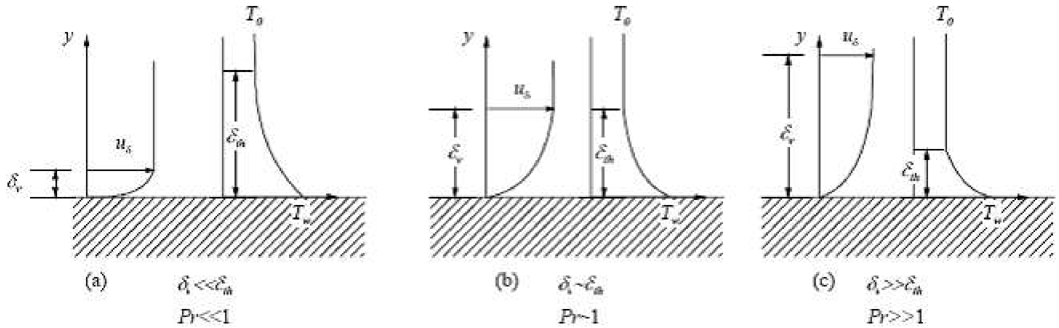


FIG. 1. Effect of the molecular Prandtl number upon the relative thickness of the thermal boundary layer.

3. Developing and testing the LMS turbulent heat transfer model

The turbulent heat conduction is frequently modeled in CFD codes as part of the Reynolds analogy that enables obtaining good results with gas and water used as coolants. For gas and water, the Prandtl number is taken constant and equal to ~ 1. However, because heat conduction in liquid metals is high and viscosity is low, the properties of velocity fields and temperature fields are considerably different. In this connection, the turbulent Prandtl number is not constant. The variable turbulent Prandtl number, when calculated, enables refining the contribution of turbulence to the effective (full) heat conduction coefficient.

The LMS (Liquid Metals Sodium) model [3] was developed based upon the analysis of the existing models of turbulent heat transfer. Turbulent heat conductivity λ_t in model is determined by the following relationship:

$$\frac{\lambda_t}{\rho C_p} \equiv \frac{\nu_t}{Pr_t} \equiv \alpha_t = C_\lambda f_\lambda \frac{k^2}{\varepsilon} \sqrt{\frac{2\sqrt{R\,Pr}}{0.5+R}} .$$

Correspondingly, the correlation for the turbulent Prandtl number Pr_t is

$$Pr_t = \frac{C_\mu f_\mu}{C_\lambda f_\lambda} \sqrt{\frac{0.5+R}{2\sqrt{R\,Pr}}}$$

Here $R = \dfrac{k_\theta / \varepsilon_\theta}{k/\varepsilon}$ - time scale ratio. Function f_μ is determined by the used k-ε turbulence model for turbulent kinetic energy and its dissipation rate.

Equations for variables k_θ and ε_θ:

$$\frac{\partial(\rho k_\theta)}{\partial t} + \vec{\nabla}(\rho \mathbf{V} k_\theta) = \vec{\nabla}\left(\rho\left(\alpha + \frac{\alpha_t}{\sigma_{k\theta}}\right)\nabla k_\theta\right) + \rho\alpha_t\left(\vec{\nabla}T\right)^2 - \rho\varepsilon_\theta$$

$$\frac{\partial(\rho \varepsilon_\theta)}{\partial t} + \vec{\nabla}(\rho \mathbf{V} \varepsilon_\theta) = \vec{\nabla}\left(\rho\left(\alpha + \frac{\alpha_t}{\sigma_{\varepsilon\theta}}\right)\nabla \varepsilon_\theta\right) + C_{P1}\frac{\varepsilon_\theta}{2k_\theta}\rho\alpha_t\left(\nabla T\right)^2 + C_{P2}\frac{\varepsilon_\theta}{k}\mu_t P_k -$$

$$-\rho C_{D1}\frac{\varepsilon_\theta^{\,2}}{2k_\theta} - \rho C_{D2}\frac{\varepsilon\varepsilon_\theta}{k} + \rho\xi_{\varepsilon\theta}$$

$$P_k = \nu_t\left(\frac{\partial V_i}{\partial x_j} + \frac{\partial V_j}{\partial x_i}\right)\frac{\partial V_j}{\partial x_i}, \; \nu_t = C_\mu f_\mu \frac{k^2}{\varepsilon}$$

Correction function (for low-Reynolds regimes):

$$\xi_{\varepsilon\theta} = f_{w,\varepsilon\theta}\left[(C_{D1}-4)\frac{\varepsilon_\theta^2}{2k_\theta} + C_{D2}\frac{\varepsilon\varepsilon_\theta}{k} - \frac{(\varepsilon_\theta - \alpha 2k_\theta / y^2)^2}{2k_\theta} + (2 - C_{P1})\frac{\varepsilon_\theta}{2k_\theta}\alpha_t\left(\nabla_x T\right)^2\right]$$

Damping functions:

$$f_\lambda = f_{w,\varepsilon\theta}\frac{C_{1\lambda}}{Re_t^{\;1/4}} + \left[1 - \exp\left(\frac{y^+}{A^+}\right)\right]^2, \; f_{w,\varepsilon\theta} = \exp\left[-\left(\frac{Re_t}{80}\right)^2\right]$$

Turbulent Reynolds number:

$$Re_t = \frac{k^2}{\nu\varepsilon}$$

Dimensionless distance to the nearest wall:

$$y^+ = \frac{C_\mu^{1/4} k^{1/2} y}{\nu}$$

Constants:

$C_\lambda = 0.11 \quad \sigma_{k\theta} = 1.227 \quad \sigma_{\varepsilon\theta} = 1.227$

$C_{P1} = 1.8 \quad C_{P2} = 0.72 \quad C_{D1} = 2.2 \quad C_{D2} = 0.8$

$C_{1\lambda} = 0.1 \quad A^+ = 30$.

The model is implemented in the Russian software package FlowVision [4], [5]. FlowVision simulates complex 3D laminar and turbulent gas and liquid flows inside/around different natural and technical objects. It has a wide spectrum of modeling capabilities implemented in different models and modules: conjugate heat transfer, combustion, radiation, moving bodies, free-surface flows. FlowVision is based on the finite-volume method and rectangular adaptive mesh with local refinement. Grid generation is fully automated. FlowVision uses a subgrid geometry resolution to approximate the curvilinear shape of a computational domain with high accuracy. The efficient parallel algebraic solver provides highly scalable calculations essentially speeding up the most complex simulations.

The LMS model is verified by simulation of mixing processes with two sodium coolant flows having different temperatures. The said processes have been experimentally studied in the TEFLU facility [6].

The TEFLU sodium facility (Fig. 2) consists of a vertical tube 110 mm ID and an axially moving grid. The main flow of cold sodium circulating in the tube, while passing through the grid, is mixed with a jet of hot sodium that is coming from the central hole. In the course of the experiment, three flow modes were investigated, namely, forced convection mode, transient mode and free convection mode. The temperature and velocity of sodium were measured in the radial and axial directions.

In the analysis performed by FlowVision, the input velocity and temperature of the hot jet and main flow were assigned constant according to the conditions of the experiment.

Results obtained by FlowVision with the classic *k-ε* model at Pr_t=1 and with the developed LMS model are compared in Fig. 3 to experimental data for the forced convection mode.

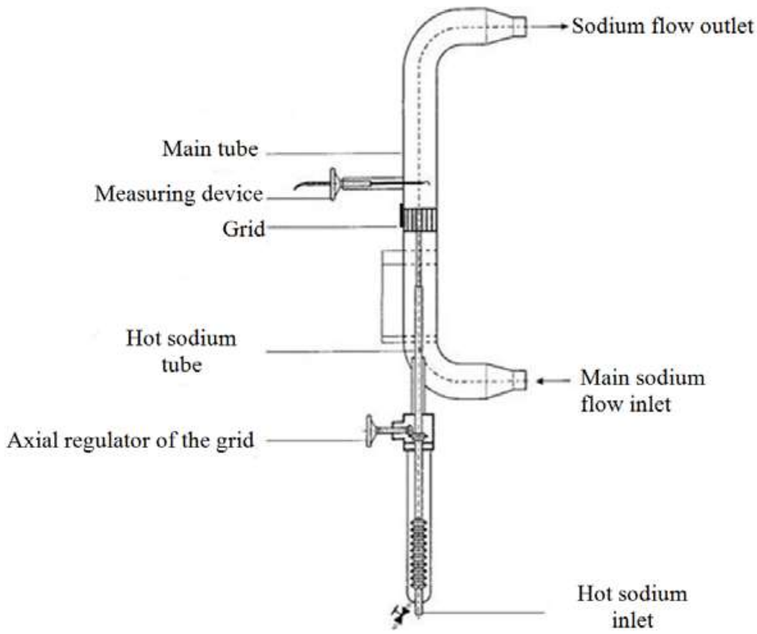


FIG. 2. Test facility model design.

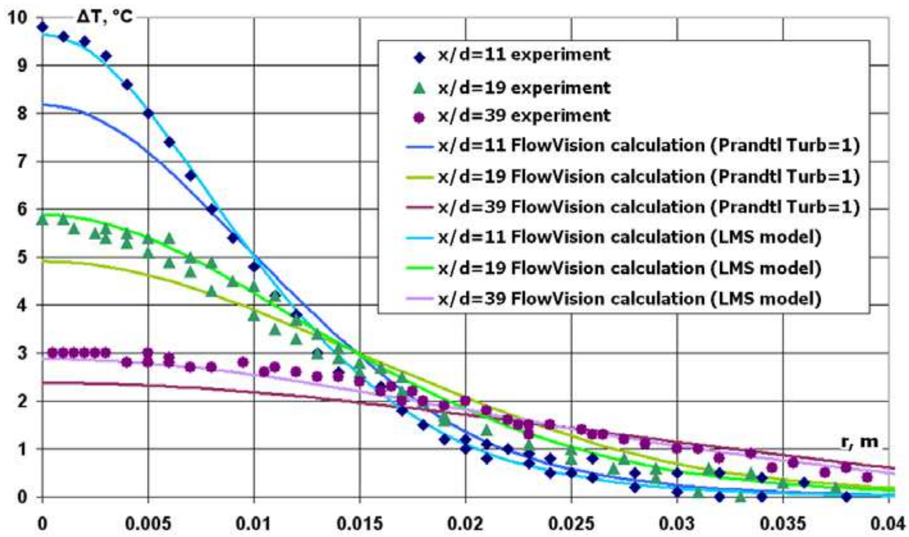


FIG. 3. Radial profiles of temperature; forced convection mode

x – coordinate of the calculational cross section; d – hot sodium tube diameter.

The LMS model testing showed very good convergence of calculated results and experimental data. At the same time, the maximum error in the temperature calculation for the free and forced convection modes does not exceed 2%; for the transient mode, 6%.

4. Modeling the flowing and mixing processes for coolant flows with different temperatures at the upper mixing chamber in the BN-600 reactor

One of the distinctive features of using CFD codes with the BN reactors is the integral layout of equipment, which means that all the primary equipment is placed inside the reactor vessel.

In order to verify the methodical approach employed to model physical processes in the reactor with the integral layout of equipment and to validate the new LMS model of turbulent heat transfer in the sodium coolant, the streaming and mixing of coolant flows with different temperatures was numerically modeled in the BN-600 reactor upper mixing chamber. FlowVision was verified through comparing the calculated temperatures with the temperatures measured by tank thermocouples and IHX inlet thermocouples.

The computer model of the reactor upper mixing chamber took account of the FA nozzles in the core, in-vessel protection tubes, elevator wall and intermediate heat exchanger (IHX) support (Fig. 4, 5). A porous body model was used to simulate the heat exchanger.

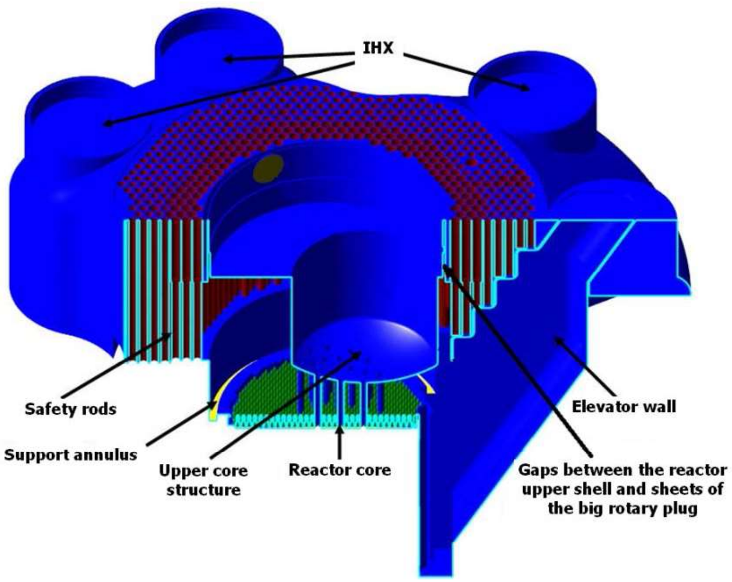


FIG. 4. Computer model of the BN-600 reactor upper mixing chamber.

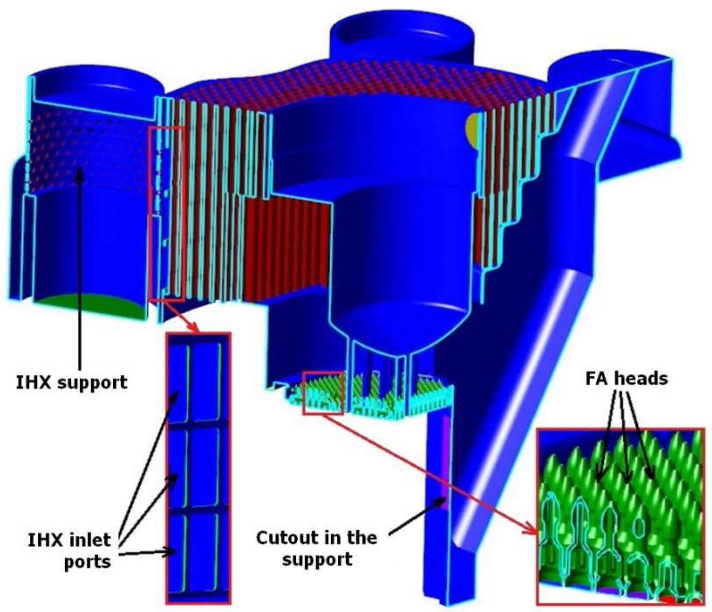


FIG. 5. Fragment of the computer model of the BN-600 reactor upper mixing chamber.

In order to correctly simulate the coolant flow in the reactor upper mixing chamber, all main design elements had to be taken into account, in particular, FA nozzles in the core and in-vessel protection tubes. The characteristic dimensions of these elements are far less than the main part of the construction. Hence, the resolution of flows in the respective channels required lessening the dimension of calculational cells (the dimensions of the calculational cells in the model are from 0.3 to 5 cm). It resulted in that the calculational mesh was substantially increased and the need arose to use high-performance computers. Fragments of the calculational mesh are shown in Fig. 6. The number of calculational cells in the solved task is 53 million.

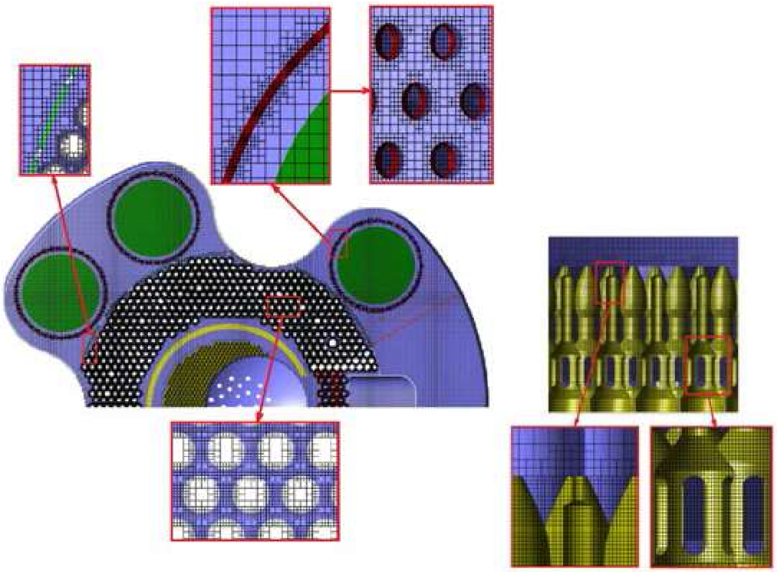


FIG. 6. Fragment of the calculational mesh.

Sodium coolant flow velocity, sodium temperature, flow turbulization ratio and turbulence scale were assigned as the input boundary conditions at the ends of all FAs. The same conditions were determined at the boundaries corresponding to the cross-flow ports in the rotary plug, support annulus, cutout in the support and bypass flow meter outlet (Fig. 7).

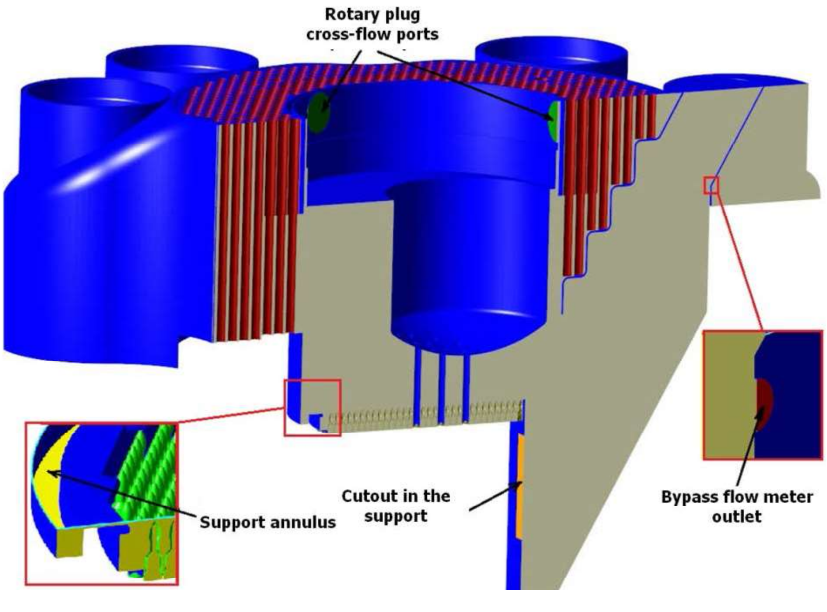
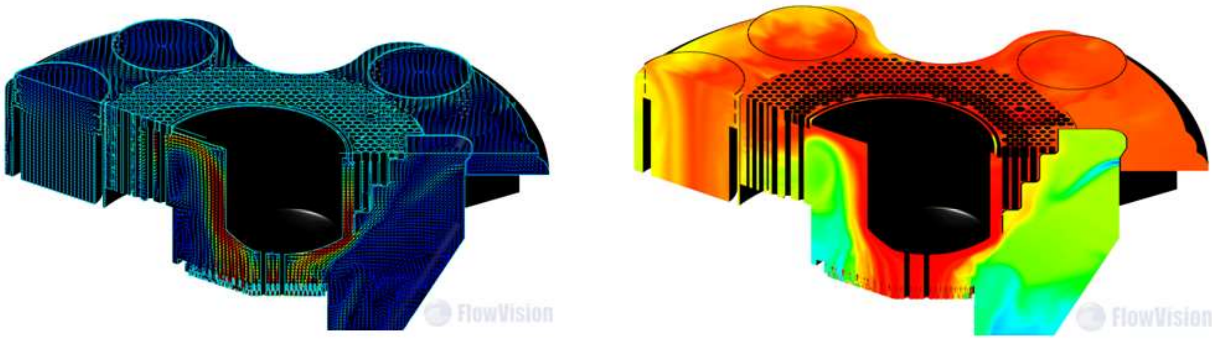


FIG. 7. Boundary conditions.

The streaming and mixing of coolant flows with different temperatures in the BN-600 reactor upper chamber were numerically modeled with the use of 128 processors with 4 cores per processor. In FlowVision, all calculational steps are parallelized, namely, calculational domain decomposition, discretization, iterative solving of algebraic equations, as well as processing and visualization of calculated results. The calculational time was ~ 3 weeks.

As a result of modeling, coolant velocity fields and temperature fields were obtained on the flow path of the reactor upper mixing chamber (Fig. 8).



a) Velocity distribution *b) Temperature distribution*

FIG. 8. Numerical modeling results.

The error of the numerically modeled results compared to the results measured in the operating BN-600 reactor does not exceed 11% (Fig. 9, 10).

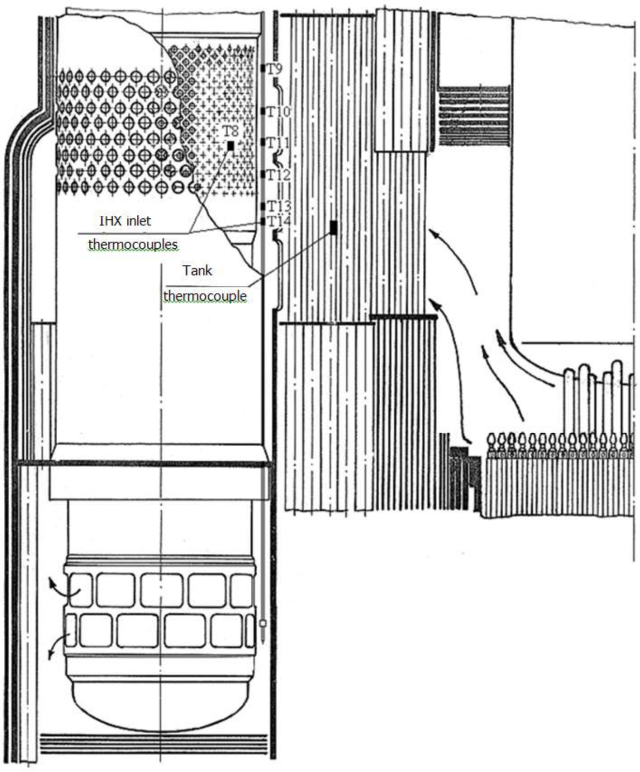


FIG. 9. Thermocouple location diagram.

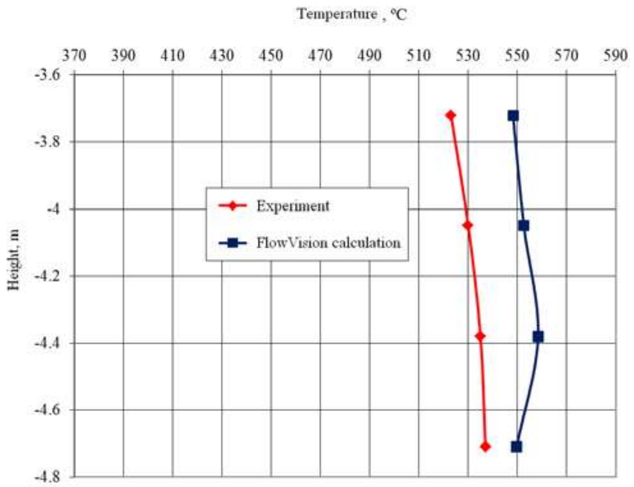
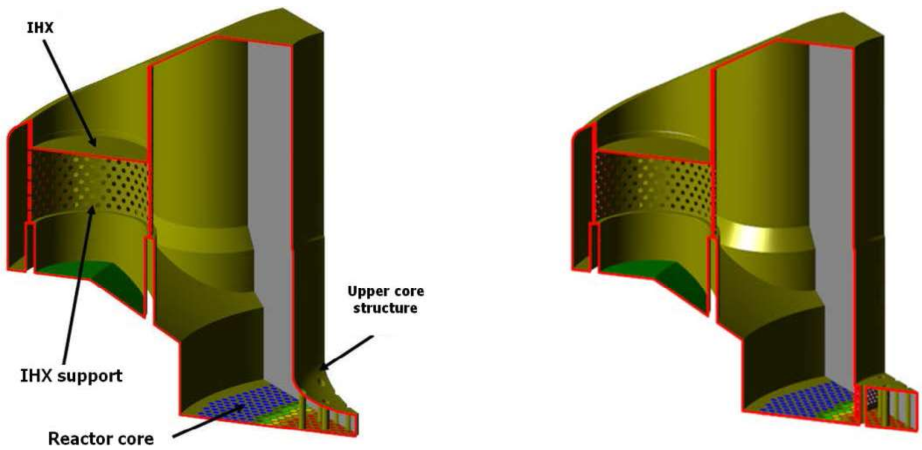


FIG. 10. Numerically modelled results compared to the results measured in the operating BN-600

5. Numerical modeling used for validation of design solutions on BN-1200 central rotary column

The performed verification enabled using FlowVision to model coolant flow in the BN-1200 reactor upper mixing chamber in order to select the shape of the bottom part in the upper core structure (spherical or flat bottom). The shape of the bottom part in the upper core structure determines mixing efficiency of coolant flows with different temperatures and a possibility of gas entrainment at the argon-sodium interface.

In addition to the physical model from the previous task, the numerical modeling of coolant flow in the BN-1200 reactor upper mixing chamber utilized the free surface/interface transfer model VOF (Volume Of Fluid). It is used to model the motion of the sodium layer in the reactor tank. Fig. 10 shows geometrical models used in the calculations.

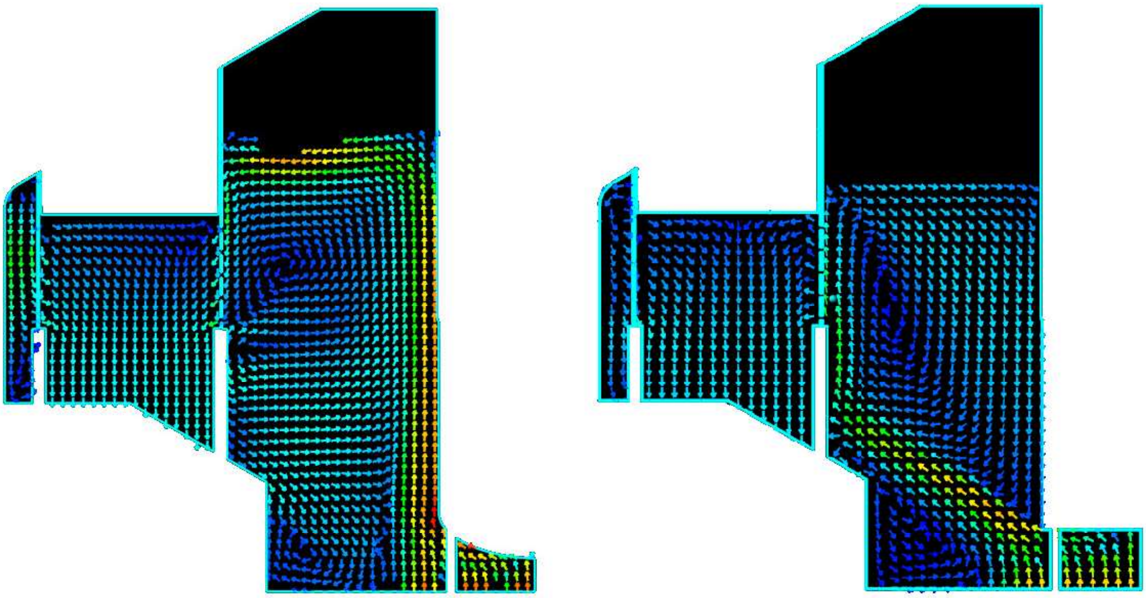


a) Upper core structure with the spherical bottom *b) Upper core structure with the flat bottom*

FIG. 11. Computer models of the BN-1200 reactor upper mixing chamber.

Results shown in Fig. 11a that are calculated for the upper core structure option with the spherical bottom illustrate sodium streaming when it flows from the upper core plane. One can see that the main flow is concentrated near the walls of the upper core structure . A vortex zone is formed near the IHX, as well as waves are formed at the sodium-argon interface, which may result in a gas entrainment and transport in the circulation circuit.

The streaming pattern in the upper core structure with the flat bottom (Fig. 11b) is very much different from that in the upper core structure option with the spherical bottom. The main flow goes from the foundation of the upper core structure to the IHX. The flow is streaming along the heat exchanger walls. In the area upstream of the IHX, a vortex zone is formed but the vortex rotation direction is opposite to that in the option with the spherical bottom. No waves are on the sodium surface and eventually there is no argon entrainment. This testifies to the advantage of this design.



a) Velocity distribution; upper core structure with the spherical bottom

b) Velocity distribution; upper core structure with the flat bottom

FIG. 12. Computer models of the BN-1200 reactor upper mixing chamber.

Based on the comparative analysis of results calculated for two options of the upper core structure design to be used in the BN-1200 reactor upper mixing chamber, recommendations were prepared to optimize the design in order to enhance the mixing efficiency of coolant flows with different temperatures and to prevent the gas entrainment at the sodium-argon interface.

6. Suggestions for verifying CFD codes with respect to the BN reactors

In the course of developing the CFD code verification plan with respect to the BN reactors, the existing Russian and non-Russian experimental data were analyzed that had been obtained in in-pile and out-of-pile experimental facilities. The following can be concluded based on the performed analysis:

- In most available experimental data, there is no comprehensive (in terms of CFD code verification) information about the model geometry and errors of used measurement equipment.
- Given the specificity of heat transfer in the sodium coolant, correct experimental data should be obtained in sodium test facilities. Experimental results from the water test facilities can be used to verify fluid dynamics tasks and the methodical approach employed in CFD codes for solving.
- In-pile studies are the main source of data for the integrated verification of CFD codes.

Currently, available and trustworthy experimental data for verification of CFD codes have been obtained in the BN-600, Monju and Phénix reactors and in the TEFLU sodium facility. In the future, data will be used that are planned to be obtained at the sodium facilities in SCC RF Institute of Physics and Power Engineering and RAS UB Institute of Continuous Media Mechanics as part of work on the BN-1200 reactor plant and preoperational adjustment work on the BN-800 reactor.

It is planned to complete CFD verification work with respect to the BN reactors in 2016.

7. Conclusion

The experience of CFD FlowVision code application using LMS model of turbulent heat transfer in the sodium coolant and specially developed methodical approach aimed at analysing reactors with equipment integral layout shows efficient numerical modeling of thermal-hydraulic processes in BN reactor upper mixing chamber.

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