The Effect of Flow Swirling on the Safety and Reliability of Nuclear Power Installations of New Generation

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Abstract. Hydrodynamics and heat exchange in the elements of thermal hydraulic tracts of ship nuclear reactors of the new generation were numerically simulated in this work. Parts of the coolant circuit in the collector and piping systems with geometries that may lead to generation of stable large-scale vortexes, causing a wide range of acoustic oscillations of the coolant, were selected as modeling objects. The purpose of the research is to develop principles of physical and mathematical modeling for scientific substantiation of optimal layout solutions that ensure enhanced operational life of icebreaker’s nuclear power installations of new generation with reactors of integral type.

1. Introduction
The study of processes leading to generation of sustainable vortex structures in the channels of complex geometry, is connected with the need to exclude resonant effects from the elements of thermal hydraulic circuits of new generation in marine nuclear power units with nuclear reactor of the integral type. This is expedient in case of coincidence of frequencies of acoustic fluctuations of the coolant with natural frequencies of the elements of the nuclear reactor internals. This may cause a risk of vibration processes and regimes of thermal cycling, leading to reduction in strength characteristics of heat exchange surfaces, the interloop leakages and other negative consequences.

It is known that the main circulation pumps and non-stationary hydrodynamic processes in the coolant (acoustic waves, vortex formation, turbulence, cavitation, etc.) are the main sources of exciting oscillations in primary circuits of nuclear power installations. The vibrational properties of nuclear power installation as a hydro-mechanical system are not be reduced to simple superposition of frequency characteristics of its elements (the reactor, steam generator, pumps, pressurizer, pipelines, etc.). The possibility of arising of acoustic resonances in the mono-block design may be connected with nonlinear superposition of frequency spectra of the major fluctuations and their overtones, due to the influence of complicated turbulent internal and external flows in the tube bundles of the steam generator and the influence of the other sources of disturbances, in particular, centrifugal pumps of the primary circuit and the pipeline system of pressurizer.

The considered here several test problems correspond to the cases of flows that can occur due to loop supply of the coolant, start-up and transient operation of the reactor, the design features, resulting in the creation of torque, or the inconsistent work of the pumps.
2. Simulating vortex formations in the pressure header of a reactor unit of integral type

One of the first meaningful attempts to mathematically model complex vortex flows with large-scale circulation flow in the collectors of nuclear reactors was made by A. N. Patrashev [1]. The analysis of the current state of the problem of numerical modeling of complex turbulent flows held in the monograph [2] showed that the use of turbulence models of different classes to calculate the swirling flows is still a separate issue and should be based on a deeper understanding of the physics of swirl flows.

The appearance of spontaneous flow swirling which is not provided for nominal flow regime in the manifold system can be attributed to the effect of secondary flows. By definition, the secondary flow is a time-averaged flow developing in the plane perpendicular to the primary flow direction.

Calculations of velocity fields and pressure areas of the inlet coolant manifold and the transition from the downward annular section of the manifold to the pressure chamber in front of the entrance to the core were performed for a simplified model of the manifold using ANSYS CFX codes. The configuration of the three-dimensional computational domain is shown in figure 1 a. Four inlet pipes of the coolant supply loop are shown in the upper part of the figure.

Figure 1. Scheme of a simplified model of the manifold: a) 3D geometry of the computational model of the investigated part of the collector system; b, c) - the structure of the computational mesh: b) – in the area of the inlet pipe, c) – in the bottom part of pressure.

Non-transparent allocated volume shows the space occupied by the core. The size of cells in near-wall areas was chosen based on the specified Reynolds number, the geometrical data and thermal properties of the water coolant for the nodes of cells closest to the walls to fall in the region of the logarithmic law of flow velocity distribution and for the use of standard near-wall functions. For this calculation we have chosen the mesh that consists of 1.3 million nodes and 7.1 million elements. The number of elements and the size of cells of the computational mesh are changed depending on the complexity of geometry of various parts of the manifold. To improve the accuracy of calculations near the streamlined surfaces thickening of the computational grid was created (figure 1 b, c).

Different turbulence models were used for mathematical description. It enables the comparative analysis of results and choice of the most appropriate model on the basis of comparison with the
experiments or, in their absence, with the alternative analysis. In particular, the monograph [2] contains theoretical description of the conditions favorable for the development of secondary vorticity and the transition to helical motion with generation of large-scale vortex structures.

There were 3 series of computational experiments: 1 - without swirl flow in the input branch pipes; 2 - with flow swirling in the inlet pipes when the influence of centrifugal pumps was considered; 3 – with irregular coolant flow rate in the loop inlets. For the 3rd series of calculations, it was assumed that the difference in coolant flow, provided by the pumps in the neighboring nozzles situated at 60° or 120° from one another along the arc perimeter, was changed by 12.5%, while the total flow rate remained unchanged.

The calculations were carried out using the following turbulence models: Eddy Viscosity Transport Equation, SSG Reynolds Stress and Shear Stress Transport, as well as models of inviscid fluid No Viscosity.

According to the selected analysis algorithm and formulation of boundary and initial conditions, the process of vortex formation was considered only in the region of the downward part and in the pressure chamber of the collector system. The space of the core was represented as a porous body. The distribution of hydraulic resistance met the required predetermined pressure differential in the core. It was accepted that the transverse motion of the coolant in the core is negligible.

Computational experiments have shown that the results of calculations on different turbulence models, although being significantly different, indicate the same qualitative result: the selected scheme of coolant supplying leads to arising the large-scale vortices.

At that the frequency of rotation in these vortices and the amplitude of oscillations generated by them depend on the chosen geometry and on the coolant flow rate. On the basis of the comparative analysis of applicability of turbulence models it may be concluded that the most adequate are the results obtained with the model of Shear Stress Transport.

The illustrations presented in figures 2, 3 show that the development of large-scale vortex motion under the downward coolant motion causes the flow swirling in all area of the pressure chamber, which entails a reduction in pressure and, consequently, a decrease in the flow rate of coolant in the central part of the pressure chamber directly under the core of nuclear reactor.

Figure 2. The velocity distribution of the coolant with account of the swirl flow in the input branch pipes: a) in cross section at a distance of 0.2 m under the core, b) – at the entrance to the core.

The results of calculations made with account of the radial vorticity introduced by the influence of centrifugal pumps (figure 2) indicate the formation of large-scale vortex with an offset relative to the center vertical axis. The presence of such vortex in the pressure header in front of the entrance to the core can lead to reduced coolant flow rate in the most energy-stressed central part of the core.

The results of calculations presented in figure 3 show that under irregular distribution of the coolant flow rate in the loop inlets, there is also the large-scale vortex motion. When supplying a flow in the pair loop inlets from one side of the reactor shell perimeter more of 12.5% compared to the other pair loop inlets at a constant total flow rate a powerful vortex with tangential velocity,
comparable with average flow velocity, is formed in the cross section of pressure chamber under the core. Formation of large-scale vortex leads to the decrease of coolant flow rate in the center of the reactor core.

![Figure 3. The coolant velocity distribution for the case of asymmetric supplying of coolant flow rate in the loop inlets: a) in cross section at a distance of 0.2 m under the core, b) – at the entrance to the core.](image)

**3. Generation of large-scale vortices in the pipe system of the pressurizer**

The nuclear power installation design includes a large number of auxiliary systems and mechanisms, ensuring reliable operation of the reactor in different modes. To main sources of vibration may be related rotating elements of pumps exposed to dynamic loads as well as generation of large-scale vortices, leading to the coolant flow swirling. The experience of previous years has showed that one of the most vulnerable parts of the construction of ship nuclear unit is the pipe system of the pressurizer.

In this work the generation of low frequency acoustic waves in the pipeline system of the pressurizer was considered by the example of the turbulent flow modeling in the pipeline section of complex geometry for the cases of increasing and decreasing power of the reactor unit.

Two series of computational experiments corresponding to these cases were conventionally called "hot" and "cold" tasks. In the "hot" task, we considered an instant increase of nuclear reactor power, corresponding to a pressure jump $\Delta P = 0.3$ MPa at nominal pressure $P_0 = 16.0$ MPa. Under the action of pressure difference hot water from a nuclear reactor at a temperature of $300^\circ$ C moved from the first to the last cross section along the pipeline, filled in initial time with water at a temperature of $100^\circ$ C.

In the "cold" task, the reverse initial condition was used. Under the action of negative pressure difference $\Delta P = -3$ MPa cold water motion started at a temperature of $100^\circ$ C from the last to the first cross section. The water temperature in the pipeline dropped from $300^\circ$ C to $100^\circ$ C while filling the entire pipeline with cold water from the pressurizer.

The results of calculations have revealed that in both cases, under the conditions of "hot" and "cold" tasks a large-scale flow swirling is formed in the entire cross section of the channel. Herewith, the angular flow velocity is comparable with the natural frequency of pump operation.

The calculations have showed that the field distribution of vorticity in the study of unsteady process of the coolant flow field topologically coincides with the field of local flow temperature. Therefore, the identification of conditions for the appearance of stable large-scale vortices allows avoiding the regimes of thermal cycling and enhances the reliability and lifetime of pipeline systems.

**4. Conclusion**
Computational experiments have shown that generation of large-scale vortices in pressure header is connected with selection of the scheme of coolant supply in the pressure chamber. The frequency of rotation in these vortices and the amplitude of the acoustical oscillations generated by them are dependent on the geometry of channels and on the distribution of the coolant flow rate.

Computational experiments have also revealed that the vortex flow structure in the channels of piping systems significantly depends on the geometry of the pipeline and the sequence of bends of different orientations.

The presence of areas with three-dimensional curvature of the channels leads to the generation of large-scale vortex motion and low frequency acoustic oscillations in the output section of the pipeline.

Large-scale spiral-vortex flow structure remains for over twenty calibers after passing the bends and has an effect on the flow pattern, which is formed in the bends downstream.

The formation of vortex movement of coolant flow in significant degree influences the propagation of the temperature field in the pipe wall. The study of this question is necessary to increase the strength and reliability of pipeline systems and the pressurizers of the ship nuclear power installations.

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