Influence of pipeline geometry on hydrodynamics and heat transfer processes by an example of a ship steam generator

O V Mitrofanova¹,², A V Fedorinov¹
¹National Research Center «Kurchatov Institute», Moscow, Russia
²National Nuclear Research University «MEPHI», Moscow, Russia
omitr@yandex.ru

Abstract. The theoretical and computational analysis proposed in this work is aimed at identifying the features of thermal and hydrodynamic processes carried out in the steam-generating channels of the ship type water-moderated nuclear power installations. It is shown that the complex geometry of the thermohydraulic tract curvilinear channels of the steam generating system has a significant effect on the efficiency of the transport nuclear power installation. In addition to the formation of large-scale vortex structures and swirling flow in the pipeline, the phenomenon of the swirling flow crisis is revealed, under which the low-frequency component of the acoustic spectrum is enhanced. The scientific and applied significance of the proposed research is associated with the need to ensure a wide range of operational changes in efficient and safe operation power modes of icebreaker nuclear power installations. The research, aimed at developing the principles of physical and mathematical modeling of complex vortex flows, is necessary to optimize the design parameters of the thermal power equipment elements of new generation ship nuclear power installations in order to ensure increased safety and reliability of their operation.

1. Introduction
As a result of the operation analysis of various generations transport nuclear power installations, including both direct-flow block-type steam generating systems and integral ones, it became necessary to simulate complex vortex flows in order to optimize the reliability and safety characteristics of the installations.

As practical results have shown, despite many years of operating experience, the problems arising during the operation of steam generating equipment are primarily associated with insufficient information in the field of scientific research. At nuclear power installations of the third and fourth generations, bay and cassette approaches are used to accommodate heat exchange equipment. In both versions of pipe systems, channels with a circular cross-section are used. The complication of the design of the steam-generating channel in the SSG (ship steam generator) of the cassette type did not lead to the elimination of the problems identified during the operation of coiled pipe systems, while creating additional difficulties in their manufacture.

Since the parameters of the superheated steam at the outlet of the steam generator with a cassette tube system do not significantly differ from the parameters of the superheated steam at the outlet of the steam generator with a coiled tube system, it is not possible to realize the possibility of increasing the thermal efficiency of a nuclear power installation. In addition, the planned use of cassette steam-generating channels in an integral type nuclear power plant with an underestimated maintainability can lead to difficulties in maintaining the nuclear power plant during the period of repair work.
The aim of the research carried out in this work is to simulate thermohydraulic processes in some rows of a ship nuclear power plant with different channel cross-sections at different power levels. The results of the calculations will help to identify a number of factors that need to be taken into account when designing new generation heat exchange equipment.

2. Construction of channel geometry and justification of the computational grids choice
Simulation of the hydrodynamics and heat transfer processes in the sections considered in the work, consisting of coil type pipes, was carried out using the universal software ANSYS, including the CFX calculation package. ANSYS CFX is a powerful tool for streamlining design and process training in computational fluid dynamics.

Based on the preliminary analysis, the Shear Stress Transport (SST) turbulence model was used as a working computational model, which is one of the best among the existing RANS turbulence models. The SST model is a combination of k-ε and k-ω models, providing a combination of their best qualities. The formulation of the model is written in terms of k (kinetic energy of turbulence) and ω (specific rate of its dissipation).

Figure 1 shows a pipe model built in a graphical editor (CAD system) of the ANSYS PC, as well as the structure of its computational grid. To generate a volumetric mesh on a 3D geometric area in ANSYS MESHING, the TETRAHEDRONS method was used, which allows generating mesh elements in the form of tetrahedrons. The processing and analysis of the results of the task was carried out in the ANSYS CFD-Post postprocessor. The geometric location of the sections on which the 2D fields of the calculated parameters were constructed was determined based on the location of the bends and the defining sections of the pipe.

Figure 1. Geometric models of design pipelines: a) the 1-st row of the SSG pipe;
b) the n-th row of the SSG pipe; c) grid construction for computational models.

3. Results of theoretical and computational analysis

On the basis of the performed computational experiments, the features of the swirling flow of the coolant and their effect on hydrodynamics, heat transfer, and generation of acoustic vibrations were considered under conditions of changing the direction of fluid movement, as well as a variable channel diameter. The calculations were performed for different power levels of the 3rd generation NPP in the economizer section of the pipeline. Figure 2 shows an example of a channel with marked characteristic sections selected for constructing 2D fields of calculated parameters.

![Figure 2. Geometry of the pipe with marked characteristic sections](image)

As shown by the results of the computational study, a sequential system of bends in the vertical plane on the section of the pipeline leading to the coil generates in its cross section two vortices with the opposite direction of rotation, which then, after diffuser expansion and deviation of the channel in the horizontal direction, into a large-scale swirl of the flow. Such a structure of fluid movement, provided there is sufficient velocity and swirl of the flow, as well as the presence of a diffuser (in our case, this section is located immediately before the transition of a straight pipe into a coil) can lead to the phenomenon of a crisis of a swirling flow. The distributions of helicity and velocity fields in the sections described above for pipes of some rows are shown in Figure 3.
As shown by the results of the computational study, a sequential system of bends in the vertical plane on the section of the pipeline leading to the coil generates in its cross section two vortices with the opposite direction of rotation, which then, after diffuser expansion and deviation of the channel in the horizontal direction, into a large-scale swirl of the flow. Such a structure of fluid movement, provided there is sufficient velocity and swirl of the flow, as well as the presence of a diffuser (in our case, this section is located immediately before the transition of a straight pipe into a coil) can lead to the phenomenon of a crisis of a swirling flow. The distributions of helicity and velocity fields in the sections described above for pipes of some rows are shown in Figure 3.

The explanation of this phenomenon is based on the concepts laid down by I.I. Novikov [1], and associated with the discovery of the phenomenon of critical flow rate at the outflow of a swirling flow [3]. In works [3, 4], for the first time it was substantiated that the discovery [2] is applicable to closed circulation tracts. In [5], on the basis of the latest research, the conditions for the emergence of a swirling flow crisis were generalized and shown by the example of a typical section of a NPP pipeline. Physically, this phenomenon can be described as follows: if the flow rate reaches the speed of propagation of long centrifugal waves, then such a redistribution of pressure in the channel occurs at which the longitudinal pressure gradient becomes equal to the radial one. The region of the reversible spiral-helical flow formed under such conditions occupies almost the entire flow area of the channel, as a result of which the flow is blocked.
In order to reduce the likelihood of a crisis flow regime, in this work, a variant of transition from coil-type pipelines with a circular cross-section to an analogue of profiled twisted pipes was considered. As shown in [6], in addition to a significant advantage in the intensification of heat transfer in relation to a round pipe, a coil-type twisted channel will have a positive effect on the previously mentioned phenomenon of the swirl flow crisis. As can be seen in Figure 5, the "plug" formed in a pipe with a circular cross-section loses its stable configuration when passing into a twisted channel. While it does not completely solve the problem, the suggested configuration may be the first step towards resolving this issue.

The effects of vortex formation will also play a positive role in the evaporative section of the pipeline, since, due to the action of centrifugal forces, the liquid phase, being denser, will always be thrown to the peripheral region, which is a positive factor to prevent overheating of the wall.
4. Conclusion
As a result of the computational and theoretical analysis of hydrodynamics and heat transfer in the pipelines of the steam generating unit of the third generation ship nuclear power plant, the previously discovered phenomenon [2] was confirmed, in which a swirl flow crisis occurs in specific sections of the heat-hydraulic path. In addition to determining the conditions for the occurrence of this negative phenomenon, in this work, a version of the geometry is proposed that reduces the likelihood of "blocking" the flow.

Acknowledgments
This work was supported by the Russian Foundation for Basic Research, Grant No. 19-08-00223 and the Competitiveness Enhancement Program of the National Research Nuclear University MEPhI (Contract No. 02.a03.21.0005).

References
[1] Novikov I I 1984 Thermodynamics (Mechanical engineering) 316-366
[2] Novikov I I, Skobelkin V I, Abramovich G N, Klyachko L A Regularity of the flow rate of liquid in a swirling flow Discovery number 389 entered in the State. register of discoveries 10/18/1990
[3] Mitrofanova O V 2002 Methods of mathematical modeling of hydrodynamics and heat transfer of swirling flows in channels with swirlers Dis. doctors tech. sciences. (Moscow: MEPhI). 321.
[4] Mitrofanova O V 2010 Hydrodynamics and Heat Transfer of Swirling Flows in Channels of Nuclear Power Plants (FIZMATLIT) 288
[5] Mitrofanova O V Bayramukov A Sh, Ivlev O A, Urtenov D S, Fedorinov A V 2020 Generation of acoustic vibrations in a swirling flow crisis in the channels of nuclear power plants Proc. of the int. scientific-practical conf. Environmental, industrial and energy security (Sevastopol:Russia) 359–364.
[6] Mitrofanova O V Ivlev O A Fedorinov A VpCS 2018 On the possibility of using assemblies of coiled pipes in steam generating systems of transport nuclear power plants Therm. Proc. Tech. 10 (5-6) 238–244.