Investigation of the Mechanism of Generation of Acoustic Oscillations inside Complicated Curvilinear Channels

O V Mitrofanova, A S Bayramukov and A V Fedorinov
National Nuclear Research University "MEPHI", Moscow, Russia

Email: omitr@yandex.ru

Abstract. There are presented some results of computational-theoretical research on identifying thermo-physical features and topology of high-velocity curved and swirl flows, which are occur inside complicated channels of collector systems, active zones and nuclear power installations equipment with pressurized water reactors. Cylindrical curved channels of different configurations and various combinations of bends and cross sectional areas were considered as modeling objects. Results of computational experiments to determine velocity, pressure, vorticity and temperature fields in transverse and longitudinal sections of the pipeline showed that the complicated geometry of the channels can cause to large-scale swirl of flow, cavitation effects and generation acoustic fluctuations with wide spectrum of sound frequencies for the coolant in the dynamic modes.

1. Introduction
Russia is the only country in the world with a fleet of civil nuclear ships. Icebreakers with nuclear power installations (NPI) more than half a century have been successfully working in the Arctic, providing a reliable and safe the movement of cargo ships in all the areas of the Northern Sea route.

To optimize the operation of nuclear icebreaker fleet currently is constructing nuclear-powered icebreakers of the new generation, able to combine functions and linear icebreakers and icebreakers with a limited draught.

Data obtained in the process of operation of ship nuclear power installations, show that in the pipeline system in the area between the pressurizer and reactor's shell the effects of vortex formation, thermal cycling, generation of acoustic vibration and outgassing inside the channels have been observed. Experience of practical operation has proved that the occurrence of these effects significantly affects the efficiency of the nuclear power installations in general. Analysis of previous accidents showed that the pipe system of pressurizer is one of the most vulnerable structural elements of NPI, because the leakage of coolant or breakdown of pipeline of pressurizer leads to depressurization of the first circuit of a nuclear installation.

The objective of this work is the study aimed at improving the safety, reliability and service life of ship nuclear power installation of new generation and, in particular, the conduction of computational experiments to determine velocity fields, pressure, vorticity and temperature in different parts of the pipeline system pressure compensation.
2. Problem formulation
The main sources of excitation of oscillations in the first circuit NPI with pressurized water reactor are non-stationary hydrodynamic processes in the coolant (acoustic waves, turbulence, vortex formation, cavitation, etc.) and main circulation pumps. One of the important system properties that affect the appearance vibroacoustic resonances in the first contours of the NPI is the generation of acoustic oscillations in the spectrum of sound and infrasonic ranges. The mechanism of appearance of such oscillations is connected with the complicated geometry of the channels, leading to the emergence of large-scale vortices. Since, as shown in [3], the spectrum of natural frequencies of nuclear power units is also lays in the field of infrasonic and sound ranges, the problem of generation of large-scale vortices in the channels of the pipeline systems of nuclear power installations requires special consideration.

As geometrical model for the study of processes of hydrodynamics and heat transfer in the first numerical experiment, was chosen a simplified scheme of the channel, namely a pipe with two bends in the horizontal and vertical planes. The pipe diameter was taken to be 65 mm. The initial length of the horizontal section and the final vertical length were taken equal to 250 mm. The radius of bends at a 90° angle was equal to 65 mm. The length of the central horizontal section was 300 mm.

The computational domain was divided into tetrahedral cells. The number of cells amounted to 3·106 and their sizes have been determined by the program automatically based on the geometry. General view of the scheme of computational domain and the finite element mesh in the cross section of the channel are shown in Fig. 1. For a more detailed modeling of hydrodynamics in the near-wall region was created a zone with a thickness of 3 mm, which consists of ten layers of finite elements.

![Figure 1. The scheme of computational domain: a) - general view; b) - the finite element mesh in the cross section of the channel.](image)

The calculations were performed using the software package ANSYS CFX. For the simulation of hydrodynamics and heat transfer of fluid it were used the equation of continuity, equation of motion and equation of energy for description of the turbulent flow of water. As initial condition, it was selected motionless state of water in all volume of calculated domain at the temperature of 100 °C and a pressure of 15.7 MPa. The boundary conditions correspond to the uniformly distributed over the cross section of the pipeline of the fields of pressure at the level of 16 MPa at the inlet of the channel and 15.7 MPa at the exit from it.

In monograph [1] it was noted that the result of generalization of numerous experimental data is the fact that even the presence of a small curvature of the streamlined surface has a significant impact on processes of turbulent exchange, and the observed effects of changes in characteristics of heat transfer and friction can be much higher calculated ones.

Analysis of scientific publications allows select the most appropriate turbulence models for calculation of internal flows in pipes with horizontal and vertical bends at an angle of 90 and 180
degrees. It models $k-\omega$ and SST, which contain two equations for kinetic energy of turbulence and the equation for the dissipation rate of turbulent energy. Authors of the work [2] investigated several models of turbulence applied to simulation of swirl flows and propose to use models that allow more accurately describe the large-scale vortices in turbulent flows. In particular, good results can be obtained using the method of detached eddy simulation - DES. Numerical calculations were carried out using the above-mentioned models. Comparative analysis of the results and comparison with experimental data showed that for most calculations, the model SST gives the best results.

3. Calculations results
Examples of the estimated distributions of the calculated parameters are presented in figures 2 – 5. The illustrations in Fig. 2 show that the distribution of the pressure field varies along the length of the pipeline with a very high speed. The greatest pressure gradient in the cross section is maintained in horizontal bending.

Figure 2. Pressure distribution on the channel wall after increasing pressure by 0.3 MPa at the entrance before horizontal bending: a, b) - pressure distribution along the length of the pipeline through 0.25 s (a) and 0.5 s (b) after pressure jump; c) - pressure field in the first horizontal bending; d) - pressure field in the second vertical bending.

In the transient unsteady process of field variation of temperature in the pipe after the abrupt pressure increase in the reactor there is a clear correlation between the distributions of temperature and
vorticity in the cross sections of the channel. This is to illustrate the results of calculation presented in Fig. 3.

![Temperature and Vorticity Fields](image)

**Figure 3.** Correlation of temperature and vorticity fields in the cross sections of the first bending through 0.25 s after pressure jump: a) – temperature distribution; b) - vorticity (curl) distribution.

After the first bending, the flow is experiencing structural changes: in the core flow rate decreases drastically up to 27-35 m/s, and on the periphery there is a significant acceleration of the flow where the velocity reaches 55-60 m/s. In the transition to the stationary regime of the flow in the cross section are formed by two large-scale vortex with opposite chirality, having an elongated shape in the horizontal direction. It need also notice that on the inner portion of the first bending originates stagnant zone, extending further along the length of the pipeline.

Fig. 4 illustrates the paintings of vortex motion in various cross sections of the curved channel.

![Velocity Distribution](image)

**Figure 4.** The distribution of the flow velocity in different cross sections of the curved channel: a) - in the area of first horizontal bend; b) - in the area of second vertical bend; c) - in the output cross section after second vertical bend (see Fig.1 a).

The velocity field in the cross section of the first bend (Fig. 4) indicates a vortical structure, formed by two spiral vortices. The dividing line between these vortices coincides with the plane of curvature and has a horizontal position. The fact that in the cross section of the second vertical bending it is observed structure, also consisting mainly of two horizontal vortices (Fig. 4 b), at the time, as it is known that in vertical bending is to be observed the presence of two vertical vortices, can be explained by the influence of channel geometry upstream and the stability of vortex structure which was formed in the first bending. At the output from channel the vortex structure of flow consists of three vortices, which are formed due to the total action of the horizontal and vertical bendings (Fig. 4 c).

Vortex structure of the flow and direction of rotation in the large-scale helical vortices in the cross sections corresponding to Fig. 4 b,c, shown in Fig.5.
Figure 5. Distribution of helicity [1] through 0.5 s after pressure jump: a) - in the area of second vertical bend; b) - in the output cross section.

Computational experiments to determine velocity fields, pressure, vorticity and temperature in different sections of the channels have shown that the complex geometry of the piping systems can cause large-scale swirling of flow and generation of a wide spectrum of acoustic oscillations of the coolant in the dynamic regime.

4. Conclusion
Numerical calculations aimed to identify features of the hydrodynamics of the water coolant in the piping system of vessel-type nuclear reactors were fulfilled. The question about the influence of the curvature of the thermal-hydraulic tract on the formation of the inner vortex structure of the flow was considered.

It is shown that by changing the power of a nuclear reactor, followed by a sharp increase in pressure in the pipeline system with complex curved channels formed the large-scale vortex flow structure, which determines the nature of the field changes of the coolant temperature.

Essentially non-stationary process of heat transfer in the presence of flow swirling and temperature stratification may lead to thermal cycling and excitation of vibrational processes, which in turn has a significant impact on the performance and durability of piping systems of pressurized water nuclear reactors.

The results can be used to formulate recommendations for optimizing the design, improving the efficiency of the gas system pressure compensation and work efficiency of NPI with pressurized water reactor for icebreakers of the new generation and transportable nuclear power plants of low power, developed on the basis of ship technologies for use in the far North.

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