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# Modeling of Thermal-Hydraulic Processes in the Marine Power Installation Elements

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**Abstract.** The results of the current study presented the hydrodynamics and heat transfer features occur in the pipe systems of the thermal-hydraulic various elements of the ship nuclear power installations. A comparative analysis of the turbulent models choice, their approbation on typical elements of the curved pipelines, and comparison of the calculation results with experimental data were fulfilled. The conditions of the swirl flow crisis were determined on base of obtained results of theoretical studies and comparison with experimental data. The mechanism of occurrence of acoustic oscillations generated by large-scale vortex structures and causes of cyclic thermal loads were identified. The fundamental nature of the research, the use of the thermodynamic approach and the conclusions of the stability theory made it possible to predict the results of numerical calculations.

## 1. Introduction

The pipelines connecting the elements of the main equipment of the installation to each other and to additional devices are the most loaded elements in marine nuclear power installations from the point of view of operational impact. Impacts on pipelines can have the different nature. Thus, it is possible to distinguish vibration, thermocyclic loads and pressure loads. Their occurrence may be explained by the special conditions of the fluid dynamics of the coolant and working media in various elements of the thermal-hydraulic path of the nuclear power plant, which have the complex geometry. In [1, 2] it was shown that such special conditions can include conditions that contribute to the emergence of a crisis mode of the swirl flow associated with limiting the flow rate of the coolant and working media.

In this paper, a comprehensive analysis of thermal-hydraulic processes in the pipe elements of marine nuclear power installations was carried out. In the course of numerical calculations, both the geometry of the studied objects and the unambiguity conditions in the mathematical formulation of the problems to be solved were varied. The first set of problems included the study of hydrodynamic features in the pipelines of the pressurizer system. The transition from a simple geometry representing the pipelines with two and five elbows to the more complex elements simulating sections of real pipe systems allowed us to identify problem areas for the further optimization.

In the second block, it were considered the problems, devoted to the study of hydrodynamic features in the channels of steam generators of marine nuclear power installations, identification of ways to increase their heat and energy efficiency, explanation of the static and dynamic instability causes of steam generating channels, assessment of thermal efficiency and search for solutions to increase it.



## 2. Selection and verification of turbulence models

To solve the problems of hydrodynamics and heat transfer in the turbulent flow of a coolant in curved channels of complex geometry, a comparative analysis of the applicability of various turbulence models in numerical calculations was previously carried out. Based on the review of experimental [3, 4, 5, 6] and computational [7, 8] works, 11 turbulence models were considered. The applicability for the calculation and the quality of each of them were evaluated by the number of matches of the calculation results with experimental data with an error of no more than  $\pm 10\%$  at the selected points of the channel. As a result of the evaluation, it was found that for curved pipelines, secondary flows in the form of large vortex structures are best modelled using the standard  $k-\omega$ -SST turbulence model. The search and use of turbulence models adapted to a specific geometry in this work is considered impractical, due to the wide variety of the pipeline elements geometry. Modelling of hydrodynamics and heat transfer processes was carried out using the universal ANSYS software, which includes the CFX calculation package.

To build a three-dimensional grid, we used a method that allows us to generate grid elements in the form of tetrahedrons. Near the walls of the channels, an additional grid division consisting of five thin linearly increasing wall layers with an increase coefficient of 1.2 was used. The thickness of the thinnest layer was 0.0001 mm. The maximum size of a split cell face was 0.0008 mm. The total number of elements depended on the channel geometry and on average was  $1.4 \cdot 10^7$ .

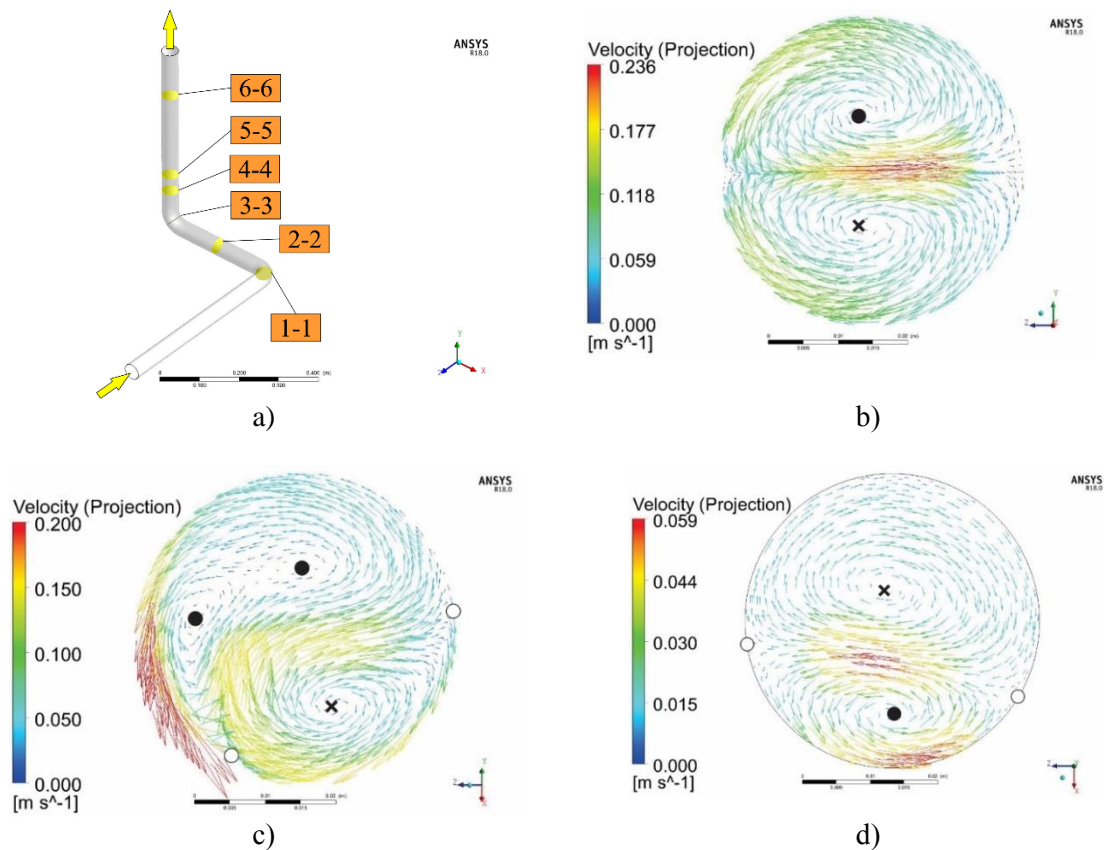
## 3. Modeling of the coolant flow in the elements of the pressure compensation system of the ship's nuclear power installation

### 3.1. Flow in a pipeline element with two bends

Previously, a large number of experimental works were devoted to the study of secondary flows after passing single curved sections. The pioneers of such investigations are Dean [3], Enayet [4], Sudo [6], and Kalpakli [7]. Secondary flows which constitute two symmetrical vortices occur when the flow pass through the pipeline bends. Their form shown in the Fig. 1, (b) and called Dean vortices. At the same time, relatively few works are devoted to the study of flows in channels with two or more bends in different planes, which is often found in the elements of marine nuclear power installations pipelines.

In this paper, as a typical example, a computational experiment was conducted to calculate the coolant flow on a section of a pipeline with two bends, the geometry of which is shown in Fig. 1, (a).

The results of calculations in Fig. 1 (b-d) demonstrate the "evolution" of the vortex movement of the coolant downstream in various sections. Dots mark the centers of vortices with the left twist, and crosses mark the centers of vortices with the right twist. Arrows show the direction of rotation of the entire vortex structure. The presence of two consecutive bends of different directions leads to the restructuring of the vortex structure of the flow so that there are two large horizontal vortices at the outlet of the pipeline (Fig. 1 d), the direction of rotation of which is opposite to what is obtained after a horizontal bend (Fig. 1 b). The presence of a vertical bend after a horizontal one not only increases the vortex movement of the coolant, but also leads to twisting of screw-helical vortices with the opposite chirality (direction of rotation).



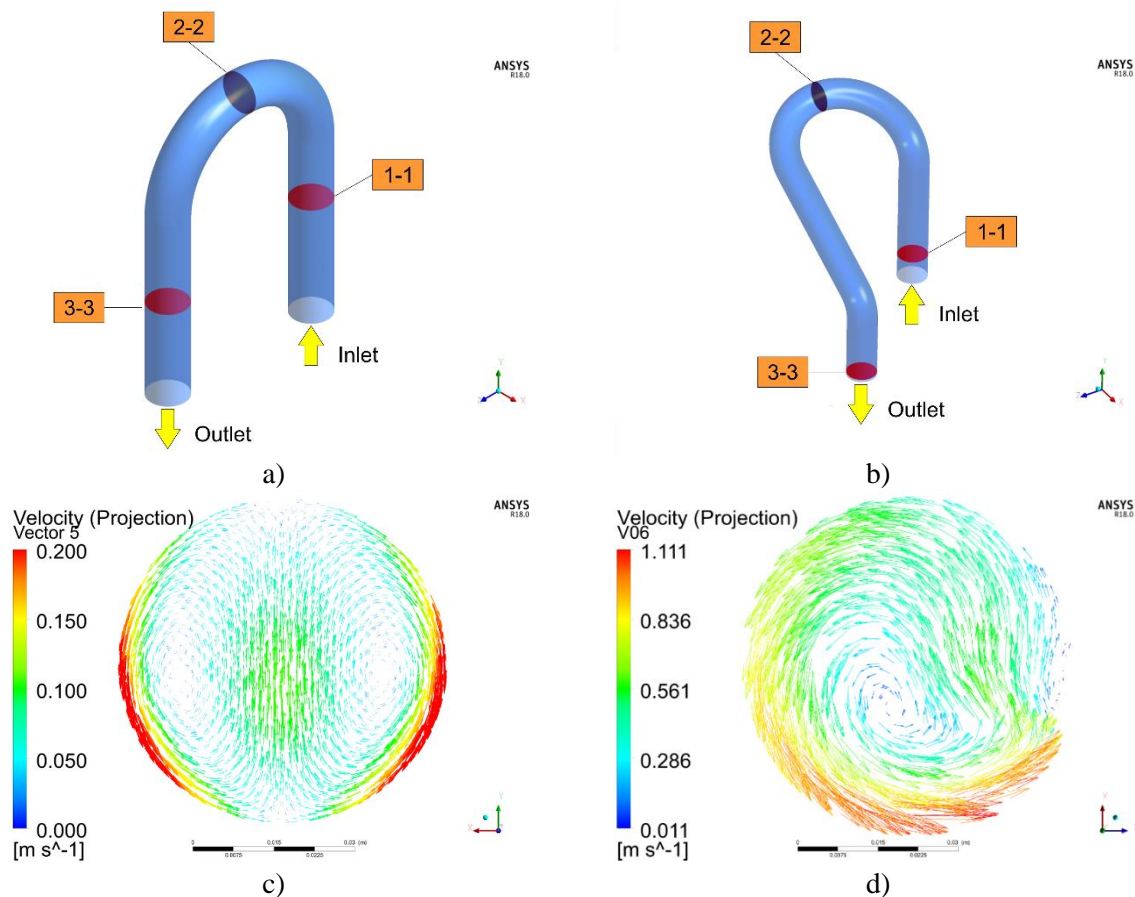
**Fig. 1.** Vortex flow structure in a channel with two bends: a) - geometry of the calculated section; b) - flow structure in section 2-2; c) - flow structure in section 3-3; d) - flow structure in section 5-5

As a result of further computational experiments, it was shown that if there are more consecutive bends of the pipeline in two mutually perpendicular planes, swirling of a flow can occur at the outlet section of the pipeline.

### 3.2. Flow in the U-shaped element of the pipeline

U-shaped sections of pipelines are used to compensate the temperature stresses that occur in pipelines when hot coolant periodically flows from the reactor to the pressurizer tank and vice versa. To study the structure of the coolant flow after passing the bending section, two configurations of U-shaped elements were selected: without deviation from the vertical plane and with a deviation from it at a certain angle, as shown in the Fig. 2 (a, b).

The results of calculations showed that in the case of channel's geometry with a curvature in the same plane, there is no swirling of the flow (Fig. 2, c). At the exit from the site Dean's vortices occur. These vortices maintain stability on a fairly short length of the pipeline, passing into the zone of turbulence of the flow. If there is a curvature in two directions at the output, there is a swirl of the flow (Fig. 2, d). The length of the relaxation path reaches 10 calibres.



**Fig. 2.** Channel geometry and vortex flow structure in the U-shaped section of the pipeline:  
 a) - geometry of the tube with 2D curvature; b) - geometry of the tube with 3D curvature;  
 c) - flow structure in the cross section 3-3 of the tube with 2D curvature;  
 d) - flow structure in the cross section 5-5 of the tube with 3D curvature

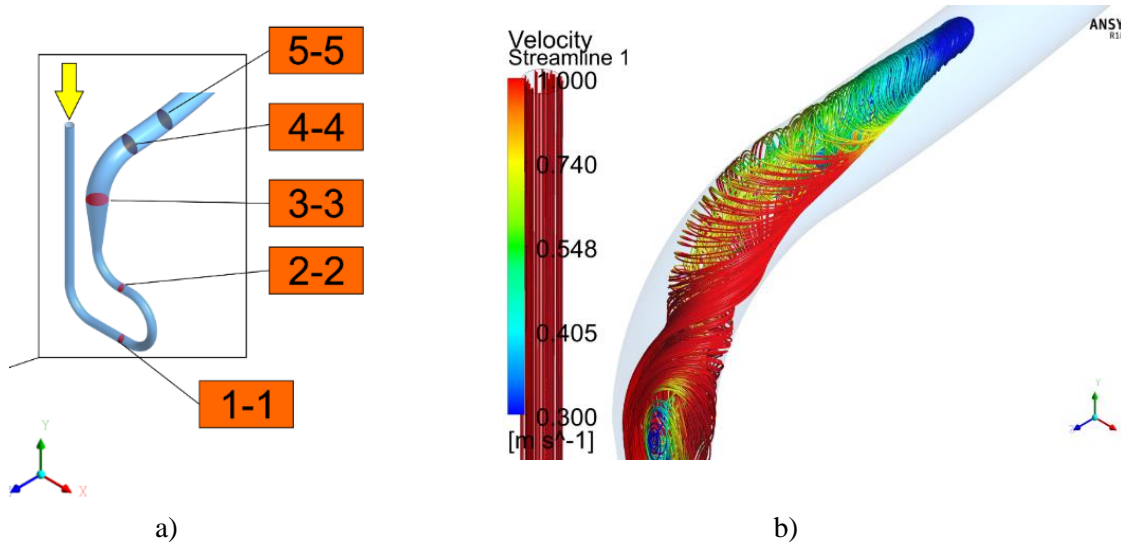
#### 4. Crisis of swirl flow in curved channels with variable cross-section

##### 4.1. Flow in the turning zone of water movement in the steam generating channel

The experience of operation of steam generators of marine nuclear power installations has shown that steam generating channels, due to the features of complex hydrodynamics of one - and two-phase flow states, have static and dynamic instability of hydraulic characteristics. Static instability can be suppressed by eliminating the ambiguity of the hydraulic resistance of the channel by introducing throttle devices. However, dynamic instability cannot always be eliminated using passive methods. One of the reasons for dynamic instability may be the processes associated with the generation of large-scale stable vortex motion and the implementation of the swirl flow crisis mode.

To identify the hydrodynamic features that may occur in such channels, a numerical experiment was performed on the flow of the working fluid in the steam generating channel, the geometry of which is shown in Fig. 3, (a). As a result of the calculation, it was found that at the outlet from the expanding section, a vortex stopper with the axis of rotation shifted relative to the center of the pipeline occurs.

The characteristic configuration of a vortex stopper formed in the conditions of a swirl flow crisis and locking the passage section of the channel is shown in Fig. 3, (b).



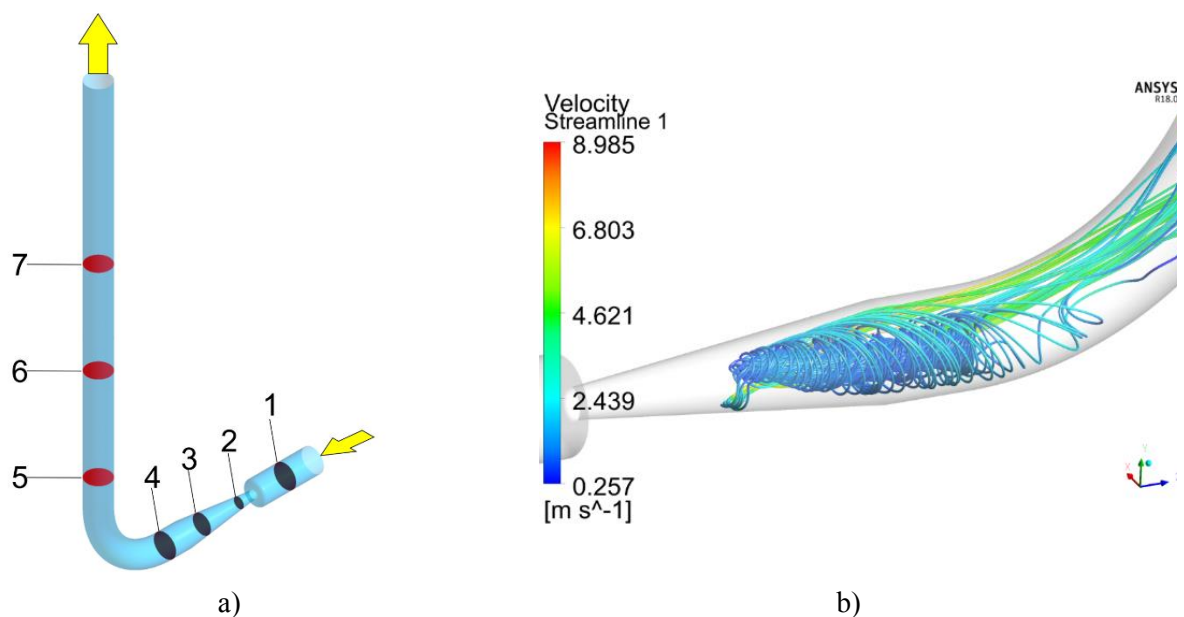
**Fig. 3.** Formation of a recirculating flow zone (vortex stopper) in the conditions of the swirl flow crisis: a) - element of the steam generating channel with the designation of design sections; b)-3-dimensional picture of the return flow streamlines in the zone of bending and expansion of the passage section of the steam generating channel in the area of sections 3-3, 4-4, 5-5.

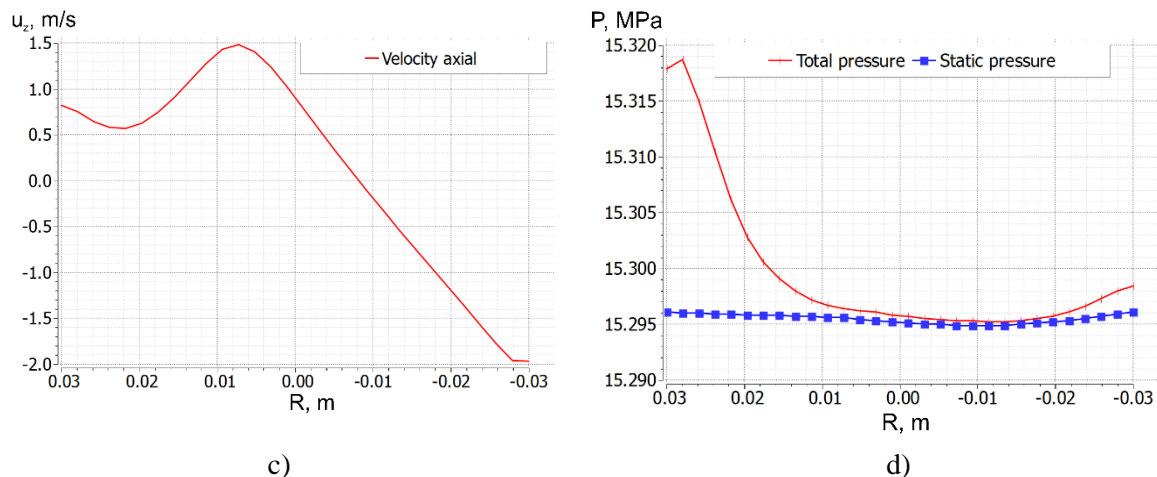
The occurrence of the flow locking phenomenon can initiate both static and dynamic instability of the steam generating channel. Operation of ship's nuclear power installations in conditions of instability of steam generating channels is highly undesirable.

#### 4.2. Flow in a pipeline element with a diffuser section

Very common elements in the pipeline systems of various parts of shipboard nuclear power installations are the diffuser sections of the pipeline with their preceding narrowing inserts.

Calculations have shown that if there is swirling of the flow in the inlet to such pipeline area, the crisis swirl flow mode can also be realized with the formation of a recirculation zone in the form of the precessing 3-dimensional vortex stopper.





**Fig. 4.** Formation of the recirculation flow zone in the channel with the bend and the diffuser area: a) - geometry of the calculated domain; b) - velocity streamlines in the recirculation zone; c) - profile of the axial velocity  $u_z$  in cross section 4; d) - total pressure and static pressure profiles in cross section 4.

Fig. 4, (a) shows a scheme of the pipeline element with indication the characteristic passing cross-sections. As a result of the computational experiment, it was found that this channel geometry contributes to the emergence of large-scale vortical formation. Fig. 4, (b) shows that the three-dimensional distribution of streamlines in the zone of recirculating (returning) flow in the area of sections 2-2, 3-3, 4-4 forms the vortex stopper that occurs before the vertical bend of the channel. The illustrations shown in Fig. 4, (c), (d) indicate an asymmetry in the shape of the recirculation zone (formation zone of the large-scale vortex), that is confirmed by the distributions of longitudinal velocity (Fig. 4, c) and pressure (Fig. 4, d) in the cross section of the channel.

## 5. Conclusion

As a result of numerical solution of the hydrodynamics and heat transfer problems, sections of the ship's thermal-hydraulic path of nuclear power installations were identified, where the effects of "locking" of the flow associated with the implementation of the swirling flow crisis mode may occur. The results obtained in this study on the examples of the occurrence of recirculating flow zones in complex curved channels of the nuclear power installation confirm the theoretical conclusions of [1, 2] that the effect of locking the flow in closed circulation loops arises when the swirl flow is present and the condition of equality of the average flow velocity and the propagation speed of long centrifugal waves is occur.

## Acknowledgments

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