Swirl Flow Crisis and Its Manifestation in Various Energy Systems

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Abstract. Conducted analytical studies have shown that in complex geometry channels with three-dimensional curvature, and a variable cross-section area, the conditions leading to large-scale vortex formation and swirl flow. In this case, not only the mode of swirl flow can be implemented, but also the effect of locking the flow due to the crisis of the swirl flow. It is shown that the crisis of swirl flow can take place in various power, motor, chemical-technological devices and other technical devices associated with the use of high-speed swirl flows of liquids or gases. A characteristic feature of such devices is the presence of large pressure losses required for the organization of flow swirling in channels of complex geometry. In the present paper, the manifestation of the swirl flow crisis is considered on the example of modeling the processes of hydrodynamics and heat exchange in the channels of an icebreaker steam generating installation.

1. Introduction
Phenomena related to changes in the internal vortex structure of the flow are widely known in phenomenological hydrodynamics. These include cases of structuring flows with the formation of so-called secondary flows-Taylor vortices, Taylor-Gertler, Dean vortices, generation of a deterministic vortex structure of the flow in acoustic flows, etc. A characteristic feature of these phenomena is their crisis manifestation, i.e. the presence of experimentally identified critical conditions (critical numbers), under which the structural restructuring of the flow field occurs with the formation of stable vortex structures.

In this paper, the approach developed by academician I. I. Novikov in the monograph [1] on the basis of a previously made discovery [2] is used to theoretically describe the crisis of swirl flow, which is one of the striking manifestations of the crisis of thermodynamic stability associated with the formation of ordered vortex structures and the transition of a dynamic system to an energetically more advantageous state. The essence of this discovery is to define the swirl flow crisis as a flow mode in which the flow rate of the swirl liquid flow reaches its limit value equal to the propagation speed of long centrifugal waves. In [3], it was proved that the discovery [2] is also applicable to closed circulation tracts.

2. The phenomenon of the swirl flow crisis
Centrifugal waves occur when the fluid is swirled (translational-rotational) in an open pipe under the action of centrifugal forces [4]. These waves are small perturbations that propagate from the source of the perturbation throughout the liquid. If the length of the centrifugal waves is large compared to the radius of the pipe, they are called long centrifugal waves. Analogous to such waves in the field of another mass force - gravity force - are longitudinal gravitational waves propagating in an incompressible liquid. In [4] it is shown that the velocity of propagation of long centrifugal waves in a pipe of constant radius can be determined similarly to the formula for the velocity of long gravitational waves.
Since the flow rate acquired by the moving liquid in the channel depends on the value of the longitudinal pressure drop, at a given initial pressure at the entrance to the channel, it is necessary to reduce the pressure at the exit of the channel to increase the flow rate. The decrease in pressure in the current liquid is transmitted in all directions, including inside the channel upstream, with the speed of propagation of small perturbations, which causes a redistribution of pressure inside the channel, namely, an increase in the pressure gradient.

When the flow velocity reaches the value of the propagation speed of weak waves (in this case, the propagation speed of long centrifugal waves), the pressure decrease will not be transmitted inside the channel and cause an increase in speed due to the fact that it propagates at the same speed as the current liquid moves. At the same time, no matter how the pressure at the outlet of the channel decreases, it will not lead to a change in the pressure in the current liquid and to an increase in the flow rate.

In General, the described phenomenon of "locking" the flow from external influence is called a flow crisis, and the velocity of the liquid flow at the time of the crisis is the critical velocity equal to the velocity of propagation of small perturbations (weak waves) in the liquid.

The crisis of swirl flow can occur in various power, propulsion, chemical-technological devices and other technical devices associated with the use of high-speed swirl flows of liquids or gases. In some cases, the implementation of the crisis mode of the swirl flow, which provides the appearance of a zone of recirculating (returning movement) flow, is a necessary condition for achieving sufficient efficiency of the flow of the physical or technological process itself, for example, in the combustion chambers of aircraft and rocket engines, cyclones, separators, burner devices, flame stabilizers, etc. However, in [5] it is noted that a characteristic feature of such devices is the presence of large pressure losses required for the formation of large scale vortices or swirling in the flow.

3. Modeling of hydrodynamic and heat transfer processes in channels of complex geometry

Modeling of hydrodynamics and heat transfer processes was carried out using the universal PC software ANSYS, which includes the CFX calculation package. Solutions to the problems are obtained using the equations of motion, continuity, and energy when setting the appropriate initial and boundary conditions.

Based on the preliminary analysis, the Shear Stress Transport (SST) turbulence model was used as a working calculation model. The SST model is a combination of $k$-$\varepsilon$ and $k$-$\omega$ models, providing a combination of their best qualities. The rationale for choosing the model of turbulence $k$-$\omega$ SST for solving the problems under consideration in complex curved channels is given in [6, 7].

The calculation grids were constructed in the graphical editor (CAD system) of the ANSYS PC. The structure of the calculated grids was selected according to the recommendations of [8]. To build a three-dimensional grid in 3D geometry, the TETRAHEDRONS method was used, which allows generating grid elements in the form of tetrahedrons. For the most qualitative calculation of the movement of the working media near the wall, an additional grid splitting was used, consisting of five thin linearly increasing wall layers with an increase coefficient of 1.2. The thickness of the thinnest layer is 0.0001 mm. A linear increase in layer thickness is necessary for the best resolution when moving from the wall area to the main grid elements. The maximum size of a split cell face is 0.0008 mm. The total number of elements (nodes), according to the conditions of the tasks, varied from $5 \times 10^6$ to $1.5 \times 10^7$. 

![Figure 1. Geometry of the element with a narrowing insert](image)
4. Topological features of a swirl flow at swirl flow crisis conditions

In the present paper, the manifestation of the swirl flow crisis is considered on the example of modeling the processes of hydrodynamics and heat exchange in the pipeline system of an icebreaker steam generating installation.

In computational experiments, topological features of the swirl flow of the heat carrier and their influence on hydrodynamics, heat exchange, and generation of acoustic vibrations when the flow rate changes in channels with constricting devices were considered. The geometry and design sections of a structural element in one of these channels are shown in figure 1.

Figures 2-4 show the results of computational experiments under the condition that the crisis mode of the swirl flow is reached in the area of expansion of the passage section of the channel after the narrowing zone (section 3-3 ÷ 5-5).

When performing variant numerical calculations, the swirl flow crisis mode is detected by the presence of a recirculation zone of the return flow with a pronounced large-scale vortex structure.

As it was shown in [6, 7], the flow twist in complex curved channels can occur unintentionally and, depending on the three-dimensional geometry of the pipeline structural elements and flow modes, reach significant values.

For the channel under consideration (Fig. 1), the calculated distributions of the tangential and longitudinal flow velocity components in the cross section of the channel 4-4 are shown in Fig. 2 a, b. These distributions are obtained at the average value of the axial velocity component $u_z = 5$ m/s in the section 1-1 when the tangential velocity component $u_\phi$ changes to the values corresponding to the condition of the swirl flow crisis.

As can be seen in Fig. 2 a, b, in the central part of the channel there is a return flow (recirculation zone), and the entire flow of liquid is displaced to the peripheral, wall-mounted area, where there is an increase in the longitudinal velocity (Fig. 2 b). In addition, the distribution of the tangential velocity component in Fig. 2 a indicates the presence of local helical vortices around the perimeter of the pipeline after exiting the diffusor part of the channel.

Fig. 2 c, d shows the distribution of the longitudinal component of the velocity in the longitudinal section of the tube in the crisis and post-crisis modes of the flow. The existence of a post-crisis mode of swirl flow is possible and actually carried out in practice (but with disproportionately large pumping losses) for the same reason that it is possible to carry out supersonic gas flow in a special nozzle – the Laval nozzle. Here, the role of controlling the change in the passage section of the channel, in contrast to the channel geometry in the Laval nozzle (the transition from narrowing to expanding the channel) is played by the "stopper" itself. This is clearly seen in the illustrations presented in Fig. 2 b, d.

In [3], it was shown that in closed circulating thermo-hydraulic tracts, the condition for swirl flow crisis is the equality of pressure gradients in the longitudinal and radial directions. The radial pressure gradient, which occurs due to the action of centrifugal forces when the flow is swirled, balances the action of the longitudinal gradient. This leads to deceleration and stopping of the flow, and with the spiral-screw nature of the flow - to the formation of a recirculation zone that takes the form of a large-scale toroidal vortex.
Figure 2. Distribution of tangential and axial components of the velocity of the swirl flow in critical mode: a) tangential velocity field in section 4-4 when $\bar{u}_\phi = 5$ m/s, $\bar{u}_z = 5$ m/s; b) - longitudinal velocity field in cross-section 4-4 when $\bar{u}_\phi = 5$ m/s, $\bar{u}_z = 5$ m/s; c), d) - distributions of longitudinal velocity along the channel length: c) - $\bar{u}_\phi = 5$ m/s, $\bar{u}_z = 5$ m/s; d) - $\bar{u}_\phi = 6$ m/s, $\bar{u}_z = 5$ m/s.

The pressure and longitudinal flow velocity graphs presented in Fig. 3 show the absence of dynamic head in the central area of the pipe and an increase of the dynamic head and longitudinal flow velocity in the peripheral zone (Fig. 3 a, b).

Figure 3. Distributions of pressure and flow velocity in section 4-4 at $\bar{u}_z = 5$ m/s, $\bar{u}_\phi = 5$ m/s: a) - full and static pressure; b) - profile of the longitudinal velocity component.

Figure 4 illustrates the topological picture of the flow when the swirl flow velocity is equal to the critical flow rate velocity.
The vortex stopper formed in sections 3-3 ÷ 5-5 is essentially a toroidal vortex in which the flow moves along its outer surface along the flow direction and in the central part – against. In the inner part of the toroidal vortex formation, the flow is slowed down, its longitudinal speed becomes alternating and fluctuates around zero, there is no forward movement. The formation of such a stable large-scale vortex structure is impossible without a large expenditure of energy. Therefore, the onset of a crisis mode and its overcoming are associated with large pressure losses and require additional power consumption for pumping the coolant.

Earlier in [6], the mechanism of generating acoustic oscillations associated with the formation of stable vortex structures in a moving medium was considered [7]. Under condition of the maximum flow rate of the swirl flow the effect of self-regulation of acoustic oscillations was discovered and researched. This effect is expressed in a resonant amplification of the amplitude of the natural frequencies of the hydro-mechanical system due to the absorption component of the spectrum of acoustic oscillations generated by vortex flow structure. Comparison of the amplitude-frequency characteristics and visualization pictures with the results of numerical modeling allowed us to identify the topological features of the swirl flow and establish a relationship between the generation of sound oscillations and the geometric and operating parameters of the hydro-mechanical system.

5. Conclusion
The results of computational experiments obtained in this work have shown that the implementation of the mode corresponding to the vortex flow crisis leads not only to a sharp increase in hydraulic losses and a decrease in the thermal-hydraulic efficiency of the installation, but also to the generation of acoustic oscillations, increased vibrations and the appearance of dangerous resonant effects that lead to the development of strength defects and accidents. It is the presence of a blocked circulation flow in the toroidal vortex formation zone during a swirl flow crisis leads to the generation of low-frequency acoustic vibrations in the modes of forced movement of the coolant or working medium.

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