Studies of the generation mechanisms of steady vortex formations in the channels of nuclear-power installations for purposes of improving the reliability and safety of their work

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Abstract. The analysis of the results of experimental researches on revealing the mechanisms of vortex formation in channels of complex geometry in the neutral and conductive media is carried out. The directions of researches related to the study of mechanisms of vortex generation and accumulation of energy by large-scale vortex structures are considered for the possibility of predictions of the man-made accidents and catastrophic natural phenomena. The main goal of ongoing investigations is the solution of the task aimed at improving the safety of nuclear power installations and, in particular, of the fast neutron reactors with liquid-metal coolants, and the prevention of emergency modes arising from acoustic, magnetic and hydrodynamic resonance effects.

1. Introduction

The use of the swirl flows in the engineering is associated in the first place with the solution of the problem of enhancement of heat and mass transfer processes in order to improve the current and create new power plants, propulsion systems and heat exchangers. The positive effects derived from the swirling of a flow in technical devices, include also the equalization of temperature irregularities, the stabilization of the flows and various physical and chemical processes in fluid media [1, 2]. The swirl flows has been successfully used in the separation devices, for thermal protection of the walls of the channels, provide an efficient and cleaner burning of fuel in combustion chambers, etc [3]. Thus, the generation of organized vortex or swirl flow in technical devices, usually is carried out purposefully, and the mechanism of vortex formation is connected with the effect on the flow of different arrangements creating a mechanical torque.

However, it should be noted that in some cases the spontaneous vortex formation and swirling of the flow can play a negative role. For example, appearance of large-scale vortexes in the collectors of nuclear reactors, leads to the decrease of mass flow rate in the most power-stressed channels of the core, owing to pressure fall in the central region of collector.

It was found that the formation of large-scale vortex structures in the pressure chambers of nuclear reactors is caused by the design features and conditions of coolant inlet from the loops. In this regard, a comprehensive study of the influence of hydrodynamics effects on the operating parameters and conditions of heat removal in nuclear reactors is one of the most important aspects of ensuring the safety nuclear power installations.

In [4] it was shown that vortex structures arising both in the external flow over bodies and in internal flows can be the sources of acoustic oscillations. Swirl and curved flows, the presence of which leads to appearance of steady vortex structures, may occur in various elements of thermal-hydraulic circuit of NPI. The reliability and safety of operation of nuclear power systems essentially depend on intensity of vibrations, resulting from hydrodynamic effects of the flow of coolant on the internal elements of the core. Vibrations are usually accompanied by pervasive acoustic noise. Due to the fact that the spectrum of the generated oscillations is determined by the elastic characteristics of the elements of the channels and the internal vortex structure of the flow, it carries great information about the state of the hydromechanical system. It is known that if the power spectrum at low frequencies corresponds to the inversely proportional dependence of the oscillation frequency, the system undergoes the development of so-called flicker-noise process, when the power spectrum of pulsations unlimited grows with lower frequencies of oscillations, and may lead to catastrophic consequences and the destruction of the system itself [5].

In this regard, in the ongoing scientific research a special place is given to the development of the acoustic method of research and the establishment of experimental techniques for the simulation of resonant effects related to the emergence of stable vortex structures.

The use of liquid metal as a coolant requires a study of the effects of the emergence of self-excitation of magnetic fields in the turbulent process of movement of a conductive medium. It is known that turbulence is not always is the cause of the destruction of large-scale vortex structures, but under certain conditions is able to create them, bringing the instability in the flow of conductive coolant [6]. Even more dangerous phenomenon, which leads to violations of flow of liquid-metal coolant, may be the emergence of large-scale vortex motion with non-zero helicity [7, 8].

This article presents some results of experimental researches of mechanisms of the emergence of stable vortex structures leading to acoustic, resonance and electromagnetic effects in complicated hydro mechanical systems.

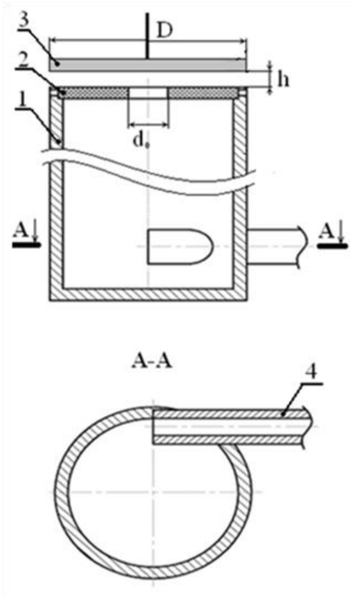
2. Generation of acoustic oscillations

The mechanism of generation of acoustic oscillations associated with the formation of stable vortex structures in fluid flows is considered on the example the impact swirl flow.

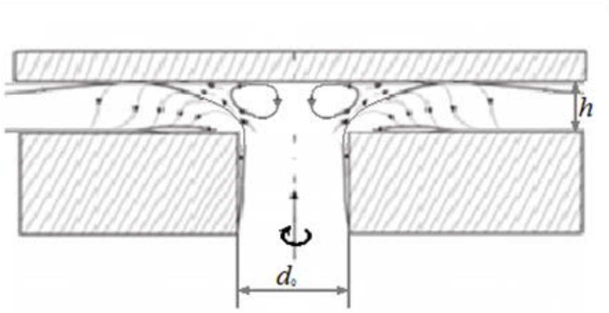
The results of the experiments revealed a correlation between the existence of large-scale vortex flow structure and excitation of acoustic oscillations, leading to vibration processes in hydro mechanical systems.

Detailed description of the experimental setup and the results of the experiments which helped to identify the self-regulatory effect of acoustic oscillations in the impact swirl flow were presented in [9]. The experiments were conducted using the vortex chamber (figure 1a), which is a rigid metal hollow cylinder 1 with a tangential air supply 4 in its bottom part and a Plexiglas plate 2 glued in the upper end of the vortex chamber, through a small hole in which swirl stream flows out. Above the outlet of the vortex chamber was located loose obstacle 3, made in the form of a flat disk. The hydrodynamic scheme of the flow is shown in figure 1 b. The geometric dimensions of the obstacles, the vortex chamber and velocity parameters of a swirl flow were varied. It was found that the excitation of oscillations under condition of the critical flow out of the swirl air jet from the vortex chamber, its upper end surface is subjected to the action of the asymmetrical force that causes bending oscillations.

It was considered two conditions of the outflow of the impact swirl jet: subcritical, in the absence of matching the frequency of the vortex flow with the eigenfrequencies of the hydro mechanical system, and critical, corresponding to the condition of resonance of vortex frequency with the eigenfrequency of the elastic upper surface of the vortex chamber. It was shown that in the both outflow conditions the flow moves under the obstacle at the complicated closed trajectories, imageries of which correspond to the Lissajous figures with the certain ratios of frequency of harmonic oscillations in mutually perpendicular directions.



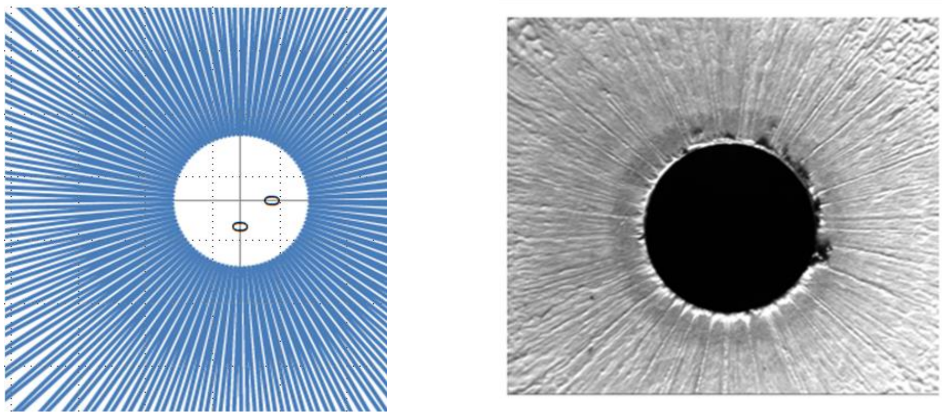
a)



b)

Figure 1. Experimental study of the impact swirl flow: a) scheme of the work area of the experimental set: 1 - vortex chamber, 2 – a Plexiglas plate glued in the upper end of the vortex chamber, 3 – obstacle, 4 - tangential supply of air, b) hydrodynamic scheme of the flow

As it was shown in [9], at coincidence of the flow velocity with the limited critical velocity of flow rate in the swirl jet, the flow acquires a well-defined vortex structure, separating into a thin longitudinal spiral vortices (figure 2), the frequency of rotation which coincides with the closest natural frequency oscillation of the vortex chamber. In considered case this frequency is the frequency of the bending oscillations of the upper Plexiglas plate 2.



a) b)

Figure 2. The comparison of calculation results with visualization of the flow pattern in the resonance mode: (a) the result of the addition of harmonic oscillations with frequencies f_1 = 2796 Hz and f_2 = 27 Hz in the form of Lissajous figures in cylindrical coordinates; b) – a picture of the vortex wake on the bottom surface of the gap.

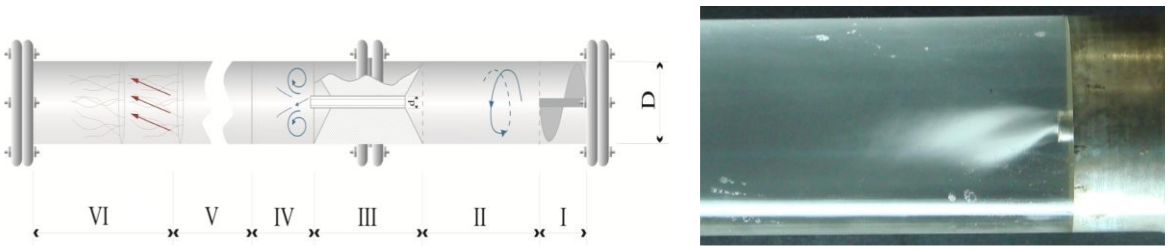
The effect of self-regulation of acoustic oscillations is expressed in a resonant amplification of the amplitude of the natural frequencies of the hydro mechanical system due to the capture of energy of acoustic oscillations generated by vortex structure of the flow.

On the basis of this study it can be concluded that the formation of the vortex flow structure can lead to resonant amplification of the amplitude of oscillation of the hydro mechanical system and consequently to provoke the beginning of the vibration process.

3. Cavitations process in a channel of variable cross-section

Experimental studies of the formation of the vortex flow structure in a channel of variable cross-section were carried out on a hydrodynamic bench using the method of registration of acoustic oscillations and optical visualization of the vortex structure of the flow. The working section of experimental setup was made to vary the geometry of the flow part of the channel and swirl flow arrangements that serve as the generators of vortexes or creating a swirling of the flow in the scale of all channel. The scheme of the work area is presented in figure 3a.

Using the developed system for registration of acoustic signals, experiments were conducted to identify natural frequencies of the working outline and to detect the field of local vorticity corresponding to the visualized vortex structure of the flow in the channel of variable cross-section. Thermal measurements were carried out using thermocouples installed along the length of the work area. The amplitude-frequency characteristics of the detected acoustic waves were measured at various points in the work area for various flow rates of water and conformed to the sound spectrum. The Reynolds number Re ranged from $7.5 \cdot 10^3$ to $1.5 \cdot 10^5$.



a) b)

Figure 3. The scheme of the working section of experimental setup (a); the flow pattern at the exit of the narrow part of the channel in the area of acoustic cavitations IV (b).

Numerical calculations of the velocity fields, pressure and temperature showed that in the area IV (see figure 3a) the effect of throttling has occurred. It followed by a temperature drop to the saturation temperature corresponding to the cold boiling of liquid (i.e. the cavitations process). Analysis of measured amplitude-frequency characteristics showed that at the entrance of the flow into the cavitations zone after its exit from the narrow part of the channel, the spectrum of acoustic oscillations changes sharply. The maximum amplitude of acoustic oscillations corresponds to the frequencies in range 10000 - 20000 Hz.

Studies have shown that the flow regimes of the water coolant, in which can be realized cavitations processes in channels of variable cross-section, is highly undesirable, as can lead to destruction of elements of heat power equipment of nuclear power installations.

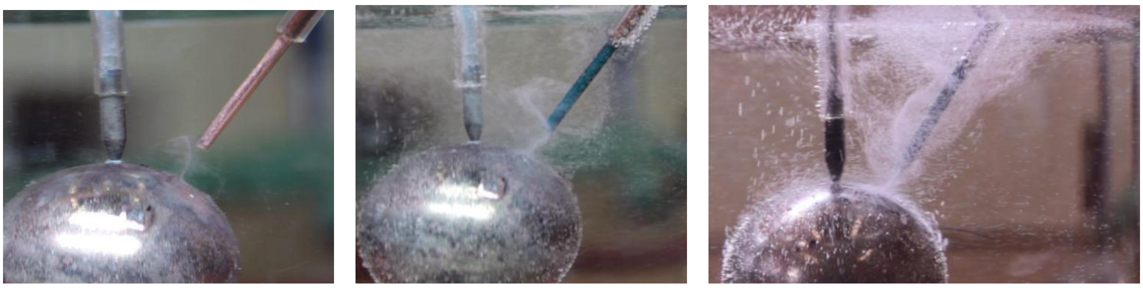
4. Investigation of the mechanisms of vortex formation in conductive environments. The interaction of vortex and electromagnetic fields

The studies aimed at identifying the mechanisms of vortex generation and accumulation of energy in conductive media are very essential nowadays. Theoretical analysis and experiments show that the effect of these mechanisms is determined by the interdependence of electric, magnetic and vortex fields in conductive media and their influence on the processes of heat and mass transfer in a conductive environment.

An experimental setup was designed to explore the relationship of electromagnetic forces and inertial forces in the liquid conductive media and to identify the mechanism of generation of large-scale vortex motion in the conductive fluid, placed in a magnetic field [10]. The main components of the setup were: a container with an electrolyte, embedded permanent magnet in the form of a ball, the movable electrodes of various configurations, power supply and recording equipment for photo and video.

In experiments managed to obtain the reproducible and well-rendered pictures of the spiral vortex structures, leading to the large-scale swirling of the flow. With the aim of obtaining quantitative data on the distribution of the velocity field of a moving electrolyte there were produced photographs of the swirl flow. The distribution of flow velocity was determined due to obtained parameters of the tracks left by gas bubbles that are indicators of vortex motion in the liquid. Images were obtained at different polarity of the power source and change of the amperage flowing through the circuit. Tangential and angular velocity of rotation were determined on base of measuring the lengths of tracks and their distances to the center of rotation.

As an illustration figure 3 shows the dynamics of development of vortex flow obtained for acetic acid at the position of a positively charged electrode at an angle 55^0 relative to the horizontal axis. On the video shots are represented successive stages of the formation of spiral-vortex structures of the flow while passing an electric current through the immobile electrolyte solution. Gas bubbles formed in the process of electrolytic reactions are the indicators of vortex motion.



a) b) c)

Figure 3. Visualization of the occurrence of vortex motion in the electrolyte solution: (a) the stage of generation of vortex motion, (b) the formation of a stable spiral-vortex structure, (c) the two-layer helical vortex with downward and upward movement.

It was proposed a physical model of vortex flow generated in a conductive medium placed in a constant magnetic field while creating a potential difference between the electrodes and at their various orientations relative to the magnetic field lines.

Operating experience of fast neutron reactors, as well as the results of experimental studies conducted at the sodium fast reactor BN-600 [7], show that in the implementation of the integrated circuit arrangement of the structural elements of the active zone and collector system of fast reactors in specific areas of a thermal-hydraulic path of the primary circuit can arise large-scale vortices with a spiral-helix motion of liquid metal coolant. In the monograph [1], it was noted that thermal physical properties of liquid metals may contribute to the formation of stable helical vortex structures.

Non-zero helicity of the velocity field $H \neq 0$ ($H = \mathbf{u} \cdot \boldsymbol{\omega} \neq 0$, where $\boldsymbol{\omega} = \nabla \times \mathbf{u}$ is a curl of local flow velocity $\mathbf{u}$) may lead to appearance of “abnormal” electromotive force (EMF). This effect described in [6, 7] as the hydro dynamical alpha-effect is reduced to the emergence of large-scale hydro dynamical instabilities in fluid flows.

Numerical computations for various cases of turbulent flow of liquid metal coolant in complicated channels when applying an external transverse magnetic field have shown that the presence of large-scale vortices leads to the generation of induced magnetic field on the same scale. The configuration of the induced vortex magnetic field in the moving conducting medium depends on the mutual orientation of spiral-vortex motion and direction of an external magnetic field.

The results of the calculations point to the crucial role of convective transfer magnetic field, which reveals "freezing" magnetic field, which is transported due to spiral-vortex structures.

The fulfilled studies are devoted the solution of problems of reliability and safety of operation of nuclear reactors of vessel type with water and liquid metal coolants.

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