PREVENTION OF HYDRODYNAMIC INSTABILITY CONDITIONS IN SAFETY SYSTEMS WITH PUMPS OF NUCLEAR POWER PLANTS

V.A. Kondratyuk, V.I. Skalozubov, Ju.A. Komarov, S.I. Kosenko, D.O. Fedorov. Prevention of hydrodynamic instability conditions in safety systems with pumps of nuclear power plants. The study of hydrodynamic instability in the safety systems of nuclear power plants is relevant. In the deterministic analysis of the safety of nuclear power plants based on accident simulation, it is necessary to take into account the possibility of hydrodynamic instability in the operational and transient modes of safety systems. The consequences of the emergence of hydrodynamic instability in safety systems can be following: a significant deterioration of the heat and mass exchange conditions in the reactor and steam generators during the heating process, an increased power of thermo-hydro-shock on the equipment of the nuclear installation and other negative effects. The negative consequences of the hydrodynamic instability in the safety systems of nuclear power plants can be a significant deterioration in the conditions of heat-mass exchange and the thermal water hammers with increased power. The main reasons for the hydrodynamic instability in safety systems are inertial lag in the response of control valves and head-flow characteristic of pumps to “fast” changes in hydrodynamic parameters in nuclear power plant systems. The purpose of this work is to determine methods for minimizing the impact of the causes of hydrodynamic instability in security systems. The methods of substantiating effective structural and technical parameters of damping devices to prevent conditions of hydrodynamic instability in stationary working and transient modes of safety systems with pumps are given. A method for substantiating effective design and technical parameters of damping devices to prevent conditions of hydrodynamic instability in transient modes of starting pumps of safety systems is presented. Stability conditions in stationary operating modes of the initial steam-gas volume of damping devices are determined. The minimum permissible dimensions of damping devices that meet the conditions of hydrodynamic instability in the transient modes of SB pumps are determined.

Keywords: hydrodynamic instability, pump, safety system, nuclear power plant

Introduction
In the deterministic analysis of the safety of nuclear power plants (NPP), based on accident simulation, it is necessary to take into account the possibility of the occurrence of hydrodynamic instability (HDI) in the operational and transient modes of safety systems [1, 2, 3, 4, 5, 6, 7, 8, 9, 10].

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In the case of HDI, there is an oscillatory or impulsive (aperiodic) deviation of the hydrodynamic parameters of the flow (flow rate, pressure) relative to the equilibrium values. The consequences of the occurrence of HDI in safety systems (SS) can be following: a significant deterioration of the conditions of heat and mass exchange in the reactor and steam generators in the process of evaporation; increased power of thermal hydro-shocks on nuclear power plant equipment and other negative effects.

**Analysis of recent research and publications**

Based on the analysis of published research results the negative effects are inertia (incompleteness) of heat and mass transfer processes in acoustic waves of two-phase non-equilibrium flows [11]; impulse braking of the flow at supersonic modes in the armature [12]; inertial delay of the response of the pressure-flow characteristic (PFC) of pumps to changes in hydrodynamic parameters in transient modes [13] and other reasons [1].

The main reason for the occurrence of HDI in the operating modes of the SB is the inertia of the adjustment parameters of the regulating armature to relatively “fast” changes in hydrodynamic parameters during nuclear power plant accidents [1].

The main reason for the occurrence of HDI in the transitional regimes of the SS start-up is the inertia of the delayed response of the PFC to the “rapid” change in hydrodynamic parameters in the SS channels and NPP equipment [14].

**The purpose**

The purpose of the article is to determine the cause of hydrodynamic instability in safety systems and to develop methods for substantiating effective structural and technical parameters of damping devices to prevent conditions of hydrodynamic instability in safety systems in stationary operating modes as well as substantiating effective structural and technical parameters of damping devices to prevent conditions of hydrodynamic instability in transients modes of starting pumps of safety systems.

**Presenting main material**

There are various types of damping devices (DD) have been widely used in the industrial power industry to prevent high pressure in equipment and pipeline systems

Analogue of DD for NPP with VVER is a pressure compensator in the reactor circuit. At the base of the DD is a closed vessel (capacity), in which, in the process of deviations of the hydrodynamic parameters from the equilibrium state, compression / expansion of the steam-gas volume of the DD and the corresponding “compensation” of the deviations occur. Thermohydrodynamic processes in the systems and their structural and technical characteristics determine the effective structural and technical parameters of the DD.

This paper presents the methods of substantiating the effective structural and technical parameters of the DD to prevent HDI in the working and transitional modes of the SS with pumps.

**Conditions for the efficiency of the DD in the work modes of the SS**

The equation of flow movement in the SS channel in stationary operating mode [14]:

\[
\Delta P_{pu}(G_0) = P_e - P_{in} + \xi_0 \frac{G_0^2}{\rho F},
\]

where \(\Delta P_{pu}\) is the pressure of the pump;
\(P_e, P_{in}\) – pressure at the pump inlet and outlet;
\(\xi_0\) is the total coefficient of hydraulic resistance of the SS channel;
\(G_0\) is the mass flow rate in the SS channel;
\(\rho\) – flux density;
\(F\) is the cross-sectional area of the flow in the SS channel.

The equation of state of the steam-gas volume in the DD [15]:

\[
P V = f_v(P),
\]

where \(V\) is the steam-gas volume in the DD in the stationary mode, respectively.

In the form of fluctuating perturbations of pump back pressure \(\delta P_e\) and flow rate \(\delta G\) in the channel of equations (1) and (2):
\[ I_0 \delta G = \delta P_e + 2\xi_0 \frac{G}{\rho F^2} \delta G, \]  
(3)

\[ V_e \delta P_e + P_e \delta V_e = \frac{df_e}{dP} \delta P_e, \]  
(4)

where \( I_0 \leq 0 \) is the sensitivity parameter of the PFC pump [13, 14].

Conditions of hydrodynamic stability in the SS channel with DD [11]:

\[ \frac{\delta G}{\delta P_e} < 0. \]  
(5)

After transforming equations (3) and (4), the stability condition (5):

\[ \left( V_e - \frac{df_e}{dP} \right) \left( I_0 - 2\xi_0 \frac{G}{\rho_F F^2} \right) < 0. \]  
(6)

Conditions for the effectiveness of the DD in the transitional regimes of the SS with the DD

The transient mode of pump start-up is limiting in terms of the rate of change of hydrodynamic parameters in SS channels. As a result of the inertial delay in the reaction of the PFC pumps SS, a rapid increase in the flow rate (flow speed) occurs at the maximum pressure pressure \( \Delta P_{pum} \) of the pumps. During the delay time \( t_0 \) when the pump is started, the maximum average flow rate in the SS channel [13, 14]:

\[ v_m^2 = \frac{\Delta P_{pum} - P_e + P_{in}}{\rho^2}. \]  
(7)

In the SS channel from the DD, part of the flow, which increases when the pump is started, \( G_D \) goes directly to the DD. The condition of hydrodynamic stability when starting the pump:

\[ G_m - G_D = G_0. \]  
(8)

where \( G_m \) – estimated pump flow.

The equation of conservation of mass, energy and pressure in the DD:

\[ \rho \frac{dV_i}{dt} + \frac{d(\rho V_i)}{dt} = G_D, \]  
(9)

\[ \rho i \frac{dV_i}{dt} + \frac{d(\rho_i V_i)}{dt} = G_D i, \]  
(10)

\[ G_D = \mu F_D \sqrt{P_e - P_p}, \]  
(11)

\[ V_i(t = 0) = V_{i0}; V_e(t = 0) = V_{e0}; P_D(t = 0) = P_{in}; P_D(t = t_0) = \max P_e; V_e(t = t_0) \to 0, \]  
(12)

where \( V_i = V_D - V_e \) is the volume of the liquid phase in the DD;

\( V_D \) – “free” volume of DP from structures;

\( \mu \) is the hydraulic coefficient of flow in the DD;

\( F_D \) – the area of the through section in the DD;

\( t \) – time;

\( P_D \) – pressure in DD;

\( i, i_v \) – specific enthalpy of the liquid and vapor-gas phases in the DD, respectively.

After transforming equations (11) and (12):

\[ K_1 \frac{dV_i}{dt} + K_2 \frac{dP_D}{dt} = G_D, \]  
(13)
\[
K_3 \frac{dV}{dt} + K_4 \frac{dP}{dt} = G_0 i, \quad (14)
\]

where:

\[
K_1 = -(\rho - \rho_i); \\
K_2 = \frac{V_i}{a_i^2}; \\
K_3 = -(\rho i - \rho_i i_i); \\
K_4 = \frac{V_i i_i}{a_i^2} + \rho V_i \frac{dii}{dP}; \\
\]

\[
a_i^2 = \frac{dP}{d\rho_i}. \\
\]

**Results**

In part of conditions for the efficiency of the DD in the work modes of the SS:

Taking into account \( PV_i \approx P_m V_{i0} \) the condition of hydrodynamic stability in stationary “working” modes of the initial steam-gas volume of the DD:

\[
V_{i0} > \frac{\max P_i}{P_m} \frac{df}{dP}. \\
\]

In part of conditions for the effectiveness of the DD in the transitional regimes of the SS with the DD.

In a result of equations integration (7) – (14), the minimum allowable dimensions of the DD are determined, which satisfy the condition of hydrodynamic stability in the transient mode of starting the pumps of SS.

Assuming:

\[
\frac{dV}{dt} \approx -\frac{V_i}{t_0}; \quad \frac{dP}{dt} \approx \max \frac{P_i - P_m}{t_0}; \quad t_0 \approx \frac{\rho LF}{G_0}, \\
\]

an approximate solution for the minimum dimensions of the DD:

\[
F_D = F_D \left(K_1, K_2, K_3, K_4, \max P_i, P_m, \mu, t_0 \right), \\
V_D = \frac{V_D}{K_1, K_2, K_3, K_4, \max P_i, P_m, \mu, t_0}. \\
\]

**Conclusions**

1. Negative consequences of the occurrence of hydrodynamic instability in the safety systems of nuclear power plants can be a significant deterioration of the conditions of heat and mass exchange and the occurrence of thermal hydroshocks of increased power.

2. The main causes of hydrodynamic instability in safety systems are the inertial delay in the reaction of the regulating fittings and the pressure-flow characteristic of the pumps to “rapid” changes in hydrodynamic parameters in the systems of nuclear power plants.

3. The method of substantiating effective structural and technical parameters of damping devices to prevent conditions of hydrodynamic instability in safety systems in stationary operating modes is presented.

4. The method of substantiating effective structural and technical parameters of damping devices to prevent conditions of hydrodynamic instability in transient modes of starting pumps of safety systems is presented.

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