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

В.А. Кондратюк, В.И. Скалозубов, Ю.А. Комаров, С.И. Косенко, Д.О. Федоров. Попередження умов гідродинамічної нестійкості у системах безпеки з насосами ядерних енергоустановок. Вивчення гідродинамічної нестійкості у системах безпеки ядерних енергоустановок є актуальним. При детерміністичному аналізі безпеки АЕС на основі моделювання аварій необхідно враховувати можливість гідродинамічної нестійкості в робочому та переходному режимах систем безпеки. Наслідками виникнення гідродинамічної нестійкості в системах безпеки можуть бути значне погіршення умов тепломасообміну в реакторі та парогенераторах у процесі нагріву, підвищення потужності термогідродуву на обладнанні АЕС, встановлення та інші негативні наслідки. Негативними наслідками гідродинамічної нестійкості в системах безпеки АЕС можуть бути значне погіршення умов тепломасообміну та теплові гідродування підвищеної потужності. Основними причинами гідродинамічної нестабільності в системах безпеки є інерційне запізнення реакції регульювальної арматури та напорної характеристики насосів на швидкі зміни гідродинамічних параметрів систем АЕС. Метою цієї роботи є визначення методів ініціації виникнення гідродинамічної нестійкості у системах безпеки. Встановлено методи обґрунтування ефективних конструктивно-технічних параметрів демпферних пристроїв для запобігання умов гідродинамічної нестійкості в стаціонарних робочих і переходних режимах систем безпеки з насосами. Представлена методика обґрунтування ефективних конструктивно-технічних параметрів демпферних пристроїв для запобігання умов гідродинамічної нестійкості в переходних режимах пускових насосів систем безпеки. Визначено умови стійкості в стаціонарних режимах роботи насосів на «швидкі» зміни гідродинамічних параметрів систем АЕС.

Keywords: гідродинамічна нестійкість, насос, система безпеки, ядерна енергоустановка

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].
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]:

\[
P_e V_c = f_c(P),
\]

where \( V_c \) 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):
\[ I_G \delta G = \delta P_v + 2 \xi_0 \frac{G}{\rho F^2} \delta G, \]  
(3)

\[ V_c \delta P_v + P_c \delta V_v = \frac{df_c}{dP} \delta P_v, \]  
(4)

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

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

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

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

\[ \left( \frac{V_v - df_c}{dP} \right) \left( I_G - 2 \xi_0 \frac{G}{\rho \xi F^2} \right) < 0. \]  
(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]:

\[ v_m^2 \approx \frac{\Delta P_{pum} - P_v + P_m \xi}{\rho_0^2}. \]  
(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:

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

where \( G_m \) – estimated pump flow.

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

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

\[ \rho_i \frac{dV_v}{dt} + \frac{d(\rho_i V_v)}{dt} = G_D i, \]  
(10)

\[ G_D = \mu F_D \sqrt{P_v - P_D}, \]  
(11)

\[ V_v(t = 0) = V_{v0}; \quad V_v(t = 0) = V_{v0}; \quad P_D(t = 0) = P_m; \quad P_D(t = t_0) = \max P_v; \quad V_v(t = t_0) \to 0, \]  
(12)

where \( V_v = V_D - V_v \) 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):

\[ K_1 \frac{dV_v}{dt} + K_2 \frac{dP_D}{dt} = G_D, \]  
(13)
\[ K_3 \frac{dV_v}{dr} + K_4 \frac{dP_v}{dr} = G_0 i, \]  

where: \( K_1 = -(\rho - \rho_s) \);  
\[ K_2 = \frac{V_v}{a_v}; \]  
\[ K_3 = -(\rho i - \rho_s i_v); \]  
\[ K_4 = \frac{V_v i_v}{a_v} + \rho_v V_v \frac{dP}{dt}; \]  
\[ a_v^2 = \frac{dP}{dp_v}. \]

**Results**  
In part of conditions for the efficiency of the DD in the work modes of the SS:  
Taking into account \( PV_v \approx P_m V_v \), the condition of hydrodynamic stability in stationary “working” modes of the initial steam-gas volume of the DD:  
\[ V_v > \max \frac{P_m}{P_m} \frac{dP}{dP}. \]

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:  
\[ \frac{dV_v}{dr} \approx -\frac{V_v}{t_0}; \quad \frac{dP}{dt} \approx \max \frac{P_m - P_m}{t_0}; \quad t_0 \approx \frac{\rho LF}{G_0}, \]

an approximate solution for the minimum dimensions of the DD:  
\[ F_D = F_D \left( K_1, K_2, K_3, K_4, \max P_m, \mu, t_0 \right), \]
\[ V_D = V_D \left( K_1, K_2, K_3, K_4, \max P_m, \mu, t_0 \right). \]

**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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