ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

UDC 629.031

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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 перехідному 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 термогідроудару на обладнанні АЕС. встановлення та інші негативні наслідки. Негативними наслідками гідродинамічної нестійкості в системах безпеки АЕС можуть бути значне погіршення умов тепломасообміну та теплові гідроудари підвищеної потужності. Основними причинами гідродинамічної нестабільності в системах безпеки є інерційне запізнювання реакції регулюючої арматури та напорної характеристики насосів на «швидкі» зміни гідродинамічних параметрів систем АЕС. Метою цієї роботи є визначення методів мінімізації впливу причин виникнення гідродинамічної нестійкості у системах безпеки. Наведено методи обґрунтування ефективних конструктивно-технічних параметрів демпферних пристроїв для запобігання умов гідродинамічної нестійкості в стаціонарних робочих і перехідних режимах систем безпеки з насосами. Представлено методику обґрунтування ефективних конструктивно-технічних параметрів демпферних пристроїв для запобігання умов гідродинамічної нестійкості в перехідних режимах пускових насосів систем безпеки. Визначено умови стійкості в стаціонарних режимах роботи початкового парогазового об'єму демпферних пристроїв. Визначено мінімально допустимі розміри демпферних пристроїв, що відповідають умовам гідродинамічної стійкості в перехідних режимах насосів систем безпеки.
Ключові слова: гідродинамічна нестійкість, насос, система безпеки, ядерна енергоустановка

V. Kondratyk, V. Skalozubov, Ju. Komarov, S. Kosenko, D. 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 stability 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].

DOI: 10.15276/opu.1.65.2022.08

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]:

$$\Delta P_{\text{pu}}(G_0) = P_{\text{e}} - P_{\text{in}} + \xi_0 \frac{G_0^2}{\rho F^2}, \tag{1}$$

where ΔP_{pu} is the pressure of the pump;

P_{e}, P_{in} – pressure at the pump inlet and outlet;

ξ_0 is the total coefficient of hydraulic resistance of the SS channel;

G_0 is the mass flow rate in the SS channel;

ρ – 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]:

$$P_{\text{e}} V_{\text{v}} = f_{\text{v}}(P), \tag{2}$$

where V_{v} is the steam-gas volume in the DD in the stationary mode, respectively.

In the form of fluctuating perturbations of pump back pressure δP_{e} and flow rate δG in the channel of equations (1) and (2):

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

$$I_G \delta G = \delta P_e + 2\xi_0 \frac{G}{\rho F^2} \delta G, \tag{3}$$

$$V_v \delta P_e + P_e \delta V_v = \frac{df_v}{dP} \delta P_e, \tag{4}$$

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]:

$$\frac{\delta G}{\delta P_e} < 0. \tag{5}$$

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

$$\frac{P_e}{\left(V_v - \frac{df_v}{dP}\right)\left(I_G - 2\xi_0 \frac{G}{\rho_1 F^2}\right)} < 0. \tag{6}$$

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 ΔP_{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]:

$$v_m^2 \approx \frac{\Delta P_{pum} - P_e + P_{in}}{\rho \xi_0}. \tag{7}$$

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:

$$G_m - G_D = G_0. \tag{8}$$

where G_m – estimated pump flow.

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

$$\rho \frac{dV_l}{dt} + \frac{d(\rho_v V_v)}{dt} = G_D, \tag{9}$$

$$\rho i \frac{dV_l}{dt} + \frac{d(\rho_v V_v i_v)}{dt} = G_D i, \tag{10}$$

$$G_D = \mu F_D \sqrt{\rho (P_e - P_D)}, \tag{11}$$

$$V_l(t=0) = V_{l0};\ V_v(t=0) = V_{v0};\ P_D(t=0) = P_{in};\ P_D(t=t_0) = \max P_e;\ V_v(t=t_0) \to 0, \tag{12}$$

where $V_l = V_D - V_v$ is the volume of the liquid phase in the DD;

V_D – "free" volume of DP from structures;

μ 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):

$$K_1 \frac{dV_v}{dt} + K_2 \frac{dP_D}{dt} = G_D, \tag{13}$$

$$K_3 \frac{dV_v}{dt} + K_4 \frac{dP_D}{dt} = G_D i \,, \tag{14}$$

where: $K_1 = -(\rho - \rho_v)$;

$K_2 = \frac{V_v}{a_v^2}$;

$K_3 = -(\rho i - \rho_v i_v)$;

$K_4 = \frac{V_v i_v}{a_v^2} + \rho_v V_v \frac{di_v}{dP}$;

$a_v^2 = \frac{dP}{d\rho_v}$.

Results

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

Taking into account $P_e V_v \approx P_{in} V_{v0}$ the condition of hydrodynamic stability in stationary "working" modes of the initial steam-gas volume of the DD:

$$V_{v0} > \frac{\max P_e}{P_{in}} \frac{df_v}{dP} \,.$$

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:

$$\frac{dV_v}{dt} \approx -\frac{V_D}{t_0}; \quad \frac{dP_D}{dt} \approx \max \frac{P_e - P_{in}}{t_0}; \quad t_0 \approx \frac{\rho L F}{G_0},$$

an approximate solution for the minimum dimensions of the DD:

$$F_D = F_D\left(K_1, K_2, K_3, K_4, \max P_e, P_{in}, \mu, t_0\right),$$

$$V_D = V_D\left(K_1, K_2, K_3, K_4, \max P_e, P_{in}, \mu, t_0\right).$$

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.

Література

1. International Fact Finding Expert Missing of the Fukushima Accident . Report of IAEA. Viena. 2011. 160 p.
2. OECD. Specialist Meeting on Severe Accident Management. Niantic (USA). June 2015. 237 p.

 ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

3. IAEA International Fact Finding Expert Mission of the Fukushima Dai-Ichi NPP Accident Following the Great East Japan Earthquake and Tsunami: IAEA Mission Report (IAEA, 2019) 78 p.
4. Воробьев Ю.Б., Кузнецов В.Д., Динь Ч.Н. Использование генетического алгоритма в динамическом вероятностном анализе безопасности АЭС. Обеспечение безопасности АЭС с ВВЭР: материалы 6-й междунар. науч.-техн. конф.. Подольск. Россия. 26–29 мая 2009 г. Подольск : ОКБ «Гидропресс».
5. Борисенко В.И. О некоторых закономерностях последствий аварий на АЭС. *Проблеми безпеки АЕС і Чорнобиля.* 2012 №18. С. 6–15.
6. Применение вероятностных методов анализа безопасности АЭС при ис-следовании нарушений хрупкой прочности корпуса реактора / Б.Ю. Грищенко, М.А. Полянский, А.Е. Севбо, И.А. Семенюк и др. *Ядерна та радіаційна безпека.* 2013. №1(57). С. 22–25.
7. Вышемирский М.П., Мазурок А.С, Носовский А.В. Анализ влияния начальных и граничных условий на формирование термоудара корпуса реактора. *Ядерна та радіаційна безпека.* 2013. №1(57). С. 26–30.
8. Дробышевский Н.Д. Верификация и предложение механического модуля кода СОКРАТ к задачам расчета на прочность. Обеспечение безопасности АЭС с ВВЭР: материалы 6-й междунар. науч.-техн. конф., Подольск. Россия. 26-29 мая 2009 г. Подольск : ОКБ «Гидропресс».
9. Мазурок А.С., Алексеев Ю.П., Крушинский А.Г., Корницкий А.В. Валидация теплогидравлической модели реакторной установки с детальной разбивкой опускного участка для анализа термических нагрузок на корпус реактора. *Ядерна та радіаційна безпека.* 2012. №1(53). С. 16–21.
10. Sauvage T. Nuclear Reactor Severe Accident. SARNET. Hungary. April 2018. 198 p.
11. Antonyuk, N. Gerliga V., Skalozubov. Excitation of thermoacoustic oscillations in a heated channel. *Journal of Engineering Physics and Thermophysics.* 1990. 59, №4. P. 1323–1328.
12. Гідродинамічні удари в обладнанні ядерних енергоустановок при трансзвукових режимах течії парорідинних потоків / В.И. Скалозубов, І.Л. Козлов, О.О. Чулкин, Ю.О. Комаров та ін. *Ядерна та радіаційна безпека*. 2019. № 2(82). С. 46–49.
13. Аналіз критичних для надійності умов гідравлічного удару в системах активної безпеки АЕС ВВЕР-1000 / В.И. Скалозубов, І.Л. Козлов, О.О. Чулкин, Ю.О. Комаров та ін. *Ядерна та радіаційна безпека*. 2019. № 1(81). С. 42–45.
14. Методика моделювання умов критичних по надійності гідравлічних впливів на насоси теплових і атомних електростанцій / В.И. Скалозубов, І.Л. Козлов, О.О. Чулкин, Ю.О. Комаров та ін. *Проблеми атомної науки і техніки*. 2017. №4(110). С. 74–78.
15. OECD. Specialist Meeting of Severe Accident. Rome (Italy). September. 1999. 343p.

References

1. International Fact Finding Expert Missing of the Fukushima Accident. (2011). *Report of IAEA.* Viena. 160 p.
2. OECD. (2015). *Specialist Meeting on Severe Accident Management*. Niantic (USA). June 2015. 237 p.
3. IAEA International Fact Finding Expert Mission of the Fukushima Dai-Ichi NPP Accident Following the Great East Japan Earthquake and Tsunami. (2019). *IAEA Mission Report* (IAEA, 2019). 78 p.
4. Vorobyov, Y., Kuznetsov, V., & Ding, Ch. (2009). Use of genetic algorithm in dynamic probabilistic analysis of NPP safety. Ensuring the Safety of Nuclear Power Plants with VVER: *Proceedings of the 6th Intern. scientech. Conf.*, Podolsk, Russia, May 26-29, 2009. Podolsk: OKB Gidropress.
5. Borisenko, V. (2012). On some patterns of consequences of accidents at nuclear power plants. *Problems of security AES and Chornobil*, 18, 6–15.
6. Grishchenko, B., Polyansky, M., Sevbo, E., & Semenyuk, I.A. (2013). Application of probabilistic methods of safety analysis of nuclear power plants in the study of impaired fragile strength of the reactor hull. *Nuclear and radiation safety*, 1(57), 22–25.
7. Vyshemirsky, M.P., Mazurok, A.S., & Nosovsky, A.V. (2013). Analysis of the influence of initial and boundary conditions on the formation of thermal shock of the reactor pressure vessel. *Nuclear and radiation safety*, 1(57), 26–30.
8. Drobyshevsky, N. (2009). Verification and proposal of the mechanical module of the SOCRAT code for strength calculation problems. Ensuring the Safety of Nuclear Power Plants with VVER: *Proceedings of the 6th Intern. sci.-tech. Conf.* Podolsk. Russia. May 26–29. Podolsk: OKB Gidropress.

9. Mazurok, A. Alekseev, Yu., Krushinsky, A., & Kornytskyi, A. (2012). Validation of a thermal-hydraulic model of a reactor plant with a detailed breakdown of the downcomer section to analyze thermal loads on the reactor vessel. *Nuclear and radiation safety*, 1(53), 16–21.
10. Sauvage, T. (2018). *Nuclear Reactor Severe Accident.* SARNET. Hungary. April 2018. 198 p.
11. Antonyuk, N. Gerliga, V., & Skalozubov, V. (1990). Excitation of thermoacoustic oscillations in a heated channel. *Journal of Engineering Physics and Thermophysics,* 59, 4, 1323–1328.
12. Skalozubov, V., Kozlov, I., Chulkin, O., & Komarov, Yu. et al. (2019). Hydrodynamic shocks in the equipment of nuclear power plants in transonic flow regimes of vapor-liquid flows. *Nuclear & Radiation Safety*, 2(82), 46–49.
13. Skalozubov, V., Kozlov, O. Chulkin, Yu., & Komarov Yu. et al. (2019). Analysis of Reliability-Critical Hydraulic Impact Conditions at WWER-1000 NPP Active Safety Systems. *Nuclear & Radiation Safety,* 1(81), 42–45.
14. Skalozubov, V., Kozlov, O., Chulkin, Yu., & Komarov, Yu. et al. (2017). Modeling method of conditions for reliability-critical hydraulic impacts on pumps of thermal and nuclear power plants. *Problems of Atomic Science and Technology*, 4(110), 74–78.
15. OECD. (1999). *Specialist Meeting of Severe Accident.* Rome (Italy). September. 343 p.

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Received January 13, 2022

Accepted March 21, 2022