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

UDC 629.031

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CRITERIA FOR CONDITIONS OF HYDRODYNAMIC INSTABILITY OF THE COOLANT IN ACCIDENTS WITH REACTOR CIRCUIT LEAKS

В. Кондратюк, В. Скалозубов, Ю. Комаров, О. Дорож, В. Філатов. **Критерії умов гідродинамічної нестійкості теплоносія при аваріях із течами реакторного контуру.** Сучасні детерміністські коди моделювання домінантних для безпеки ядерних енергоустановок груп аварій із течами реакторного контуру (у тому числі між контурні течі в парогенератори) не визначають умови й наслідки процесів гідродинамічної нестійкості теплоносія. Роботи по попередженню умов гідродинамічної нестійкості проводились для окремих систем безпеки реакторної установки в яких встановлений конкретний тип обладнання. Виникнення гідродинамічної нестійкості теплоносія змінює умови теплообміну в активній зоні реактора, призводить до циклічних високо амплітудних гідродинамічних навантажень на внутрішньо корпусні конструкції та інших негативних ефектів. Метою представленої роботи є створення методів моделювання умов гідродинамічної нестійкості теплоносія при аваріях із течами реакторного контуру. Методика реалізації роботи заснована на розробці термодинамічного методу визначення умов гідро динамічної нестійкості в умовах аварій з течами реакторного контуру з розробкою термодинамічної моделі аварії і аналізом отриманих результатів та визначення засобу їх практичного використання. На основі наближеного метода визначені мінімальні розміри теч реакторного контуру з ВВЕР області гідродинамічної нестійкості теплоносія: для системи аварійного охолодження активної зони реактора насосами високого тиску – 400 мм; для системи аварійного охолодження активної зони реактора насосами низького тиску – 100 мм. Виникнення гідродинамічної нестійкості теплоносія змінює умови теплообміну в активній зоні реактора, призводить до циклічних високо амплітудних гідродинамічних навантажень на внутрішньо корпусні конструкції та інших негативних ефектів. Представлено оригінальний метод визначення критерію умов виникнення гідродинамічної нестійкості теплоносія на етапі пуску насосів систем безпеки при аварії з течами реакторного контуру.
Ключові слова: аварія, гідродинамічна нестійкість, теча, реакторний контур

V. Kondratyk, V. Skalozubov, Ju. Komarov, O. Dorozh, V. Filatov. **Criteria for conditions of hydrodynamic instability of the coolant in accidents with reactor circuit leaks.** Modern deterministic codes for modeling the safety-dominant nuclear power plant accident groups with reactor circuit leaks (including inter-circuit leaks in steam generators) do not determine the conditions and consequences of the processes of hydrodynamic instability of the coolant. Work on preventing conditions of hydrodynamic instability was carried out for individual safety systems of the reactor installation in which specific equipment is installed. The occurrence of hydrodynamic instability of the coolant changes the conditions of heat exchange in the active zone of the reactor, leads to cyclic high-amplitude hydrodynamic loads on the internal body structures and other negative effects. The purpose of the presented work is to create methods for modeling conditions of hydrodynamic instability of the coolant during accidents with reactor circuit leaks. The method of implementation of the work is based on the development of a thermodynamic method for determining the conditions of hydrodynamic instability in the conditions of accidents with reactor circuit leaks. On the basis of the approximate method, the minimum dimensions of the reactor circuit leaks from the HPP in the area of hydrodynamic instability of the coolant were determined: for the emergency cooling system of the reactor active zone with high-pressure pumps - 400 mm; for the system of emergency cooling of the active zone of the reactor with low-pressure pumps - 100 mm. The occurrence of hydrodynamic instability of the coolant changes the conditions of heat exchange in the active zone of the reactor, leads to cyclic high-amplitude hydrodynamic loads on the internal body structures and other negative effects. The original method of determining the criteria for the occurrence of hydrodynamic instability of the coolant at the stage of starting the pumps of safety systems in the event of an accident with reactor circuit leaks is presented.
Keywords: accident, hydrodynamic instability, leaks, reactor circuit

Introduction

The traditional approach to nuclear power plant safety analysis is based on probabilistic and deterministic modeling of initial emergency events – pipeline leaks/ruptures, de-energization of power units, failure of safety-critical systems, and others. The analysis of the results of modeling accidents in nuclear power plants with VVER reactors, given in industry reports on the safety analysis of Ukrainian nuclear power plants, established the need to model also the initial accident events associated with various types of thermodynamic and hydrodynamic instability in systems important for nuclear safety. The negative consequences of the occurrence of hydrodynamic instability in the safety systems of nu-

DOI: 10.15276/opu.2.66.2022.06

clear power plants can be a significant deterioration of the conditions of heat and mass exchange and the occurrence of thermal hydroshocks of increased power.

Analysis of recent research and publications

The phenomenon of hydrodynamic instability in energy systems is accompanied by high-amplitude oscillatory and impulse deviations of hydrodynamic parameters from the equilibrium state [1, 2]. The occurrence of hydrodynamic instability (HDI) of the coolant in the reactor circuit (RC) worsens the conditions of heat exchange in the active zone of the reactor, leads to high-amplitude hydrodynamic loads on equipment/pipelines and other negative consequences [3, 4, 5].

As a consequence of the occurrence of HDI in safety systems (SS), it is possible to note a significant deterioration in the conditions of heat and mass exchange in the reactor and steam generators during the accident; increased power of thermal hydraulic shocks on NPP equipment and other negative effects. A variety of reasons and conditions can lead to the occurrence of HDI. These include the inertia (incompleteness) of heat and mass transfer processes in acoustic waves of two-phase non-equilibrium flows, impulse braking of the flow at supersonic regimes in the armature, inertial delay of the response of the pressure-flow characteristic (PFC) of pumps to changes in hydrodynamic parameters at transitional regimes, and other reasons [6].

The conditions and consequences of hydrodynamic instability depend on the structural and technical parameters and the hydrodynamic state of the system.

Modern deterministic codes (RELAP, SOCRATES, CATHARE, etc.) for modeling groups of NPP accidents with RC leaks (including inter-loop leaks in steam generators) with the predominance of safety do not determine the criteria for HDI occurrence of the coolant [7, 8, 9, 10].

When analyzing the safety of nuclear power plants, which is performed using probabilistic codes [11, 12], the conditions and consequences of various types of heat-hydrodynamic instability of the coolant in the reactor core are not modeled. Therefore, it is important to create methods for modeling the state of the coolant in accidents with RC leaks, which determines the purpose and tasks of the presented work.

The purpose

The purpose of the article is to develop a method for determining the conditions of hydrodynamic instability in the conditions of accidents with reactor circuit leaks. At the same time, the following tasks must be solved:

Task 1. Development of a thermodynamic model of an accident with reactor circuit leaks;

Task 2. Analysis of the obtained results and determination of means of their practical use.

Presenting main material

When determining the criteria and conditions for the occurrence of thermoacoustic instability of a nuclear power plant in an emergency mode with reactor circuit leaks, the following basic provisions and assumptions were adopted:

Basic provisions and assumptions.

1. A necessary condition for the occurrence of hydrodynamic instability is the transient start-up mode of safety system pumps , when due to the inertial delay of the response of the pressure-flow characteristic (HFC) of the pumps to a rapid increase in flow rate, the deviation of the hydrodynamic parameters from the equilibrium state of the nominal operating mode occurs [13, 14].

2. A sufficient condition for the occurrence of hydrodynamic instability is based on thermodynamic laws of system instability (for example, [1, 15]). The consequence of the hydrodynamic instability of the reactor circuit is a simultaneous increase in the pressure and mass of the coolant.

3. The coolant in the RC and the pressure compensator (PC) is modeled as a system with volume-averaged hydrodynamic parameters.

4. Conservatively, the impact of the costs of the “running out” of the stopped main circulation circuit and natural circulation in the RC is not taken into account, and the failure of the PC heating elements is also assumed.

The equations of hydrodynamics of non-stationary processes in the coolant of the RC and in the PC can be written in the following form [15, 16]:

$$\frac{\mathrm{d}M_{\text{т}}}{\mathrm{d}t} = -G_{\mathrm{l}}(P_{\text{т}}) + G_{\mathrm{c}}(P_{\text{т}}, P_{\mathrm{v}}, H) + G_{\mathrm{ss}}(P_{\text{т}}); \quad (1)$$

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

$$\frac{\mathrm{d}P_{\text{т}}}{\mathrm{d}t}=\frac{\mathrm{d}P_{\text{v}}}{\mathrm{d}t}+\rho g\frac{\mathrm{d}H}{\mathrm{d}t};\qquad \frac{\mathrm{d}(\rho_{\text{v}}V_{\text{v}})}{\mathrm{d}t}=0;\tag{2}$$

$$\frac{\mathrm{d}(P_{\text{v}}V_{\text{v}})}{\mathrm{d}t}=0;\quad \rho\frac{\mathrm{d}V_{\text{l}}}{\mathrm{d}t}=\rho F_{\text{c}}\frac{\mathrm{d}H}{\mathrm{d}t};\quad \frac{\mathrm{d}(\rho_{\text{v}}V_{\text{v}}i_{\text{v}})}{\mathrm{d}t}=0;\tag{3}$$

$$\frac{\mathrm{d}G_{\text{ss}}}{\mathrm{d}t}=\frac{F_{\text{ss}}}{L}\left(\Delta P_{\text{pu}}-P_{\text{т}}+P_{\text{ss}}-\xi_{\text{ss}}\frac{G_{\text{ss}}^2}{\rho F_{\text{ss}}^2}\right);\tag{4}$$

$$M_{\text{т}}(t=0)=M_{\text{т}0};\ P_{\text{т}}(t=0)=P_0;\ H(t=0)=H_0;\ G_{\text{ss}}(t=0)=G_{\text{ss}0},\tag{5}$$

where $M_{\text{т}}$ – the mass of the coolant in PC; t – time; $P_{\text{т}}$, P_{v}, P_{ss} – pressure in RC, steam-gas volume PC, and water capacity SS, respectively V_{v}, V_{l} – vapor-gas and liquid volume of PC, respectively ($V_{\text{v}}+V_{\text{l}}=V_{\text{c}}$ – internal volume PC "free" from structures); g – acceleration of gravity; G_{l}, G_{c}, G_{ss} – mass flow in the stream, with PC and with SS, respectively; F_{c}, F_{ss} – cross-sectional area of PC and SS pipelines, respectively; L – the length of the SS pipeline; ξ_{ss} – total coefficient of hydraulic resistance of the SS channel; ΔP_{pu} – pump back pressure SS; P_0 – pressure of turning on the SS pump; H – coolant level in PC.

Mass flow in RC flow:

$$G_{\text{l}}=\mu F_{\text{l}}\sqrt{\rho(P_{\text{т}}-P_{\text{e}})},\tag{6}$$

where F_{l} – equivalent flow area; μ – flow rate; P_{e} – pressure in the containment / steam generator.

Based on the thermodynamic laws of the instability of systems, the criteria for the minds of HDI in RC:

$$\mathbf{K}_{\text{n}}=\frac{\mathrm{d}P_{\text{т}}}{\mathrm{d}t}\bigg/\frac{\mathrm{d}M_{\text{т}}}{\mathrm{d}t}>0.\tag{7}$$

In the wild type, the criteria of the minds of HDI (7) can be assigned as a result of the integration of the system of non-linear equalities (1) – (6).

Next, an approximation of the method of assessing the criterion of the minds of the HDI in case of accidents with leaks of the RC is presented.

In the interval of one hour of the transitional process of starting the SS pump, the maximum speed of the increase in wicking in the SS channel is [14]:

$$\max\left(\frac{\mathrm{d}G_{\text{ss}}}{\mathrm{d}t}\right)\approx\frac{F_{\text{ss}}}{L}\left[\max\Delta P_{\text{pu}}(t=0)-P_{\text{т}}+P_{\text{ss}}-\xi_{\text{ss}}\frac{G_{\text{s}0}^2}{\rho F_{\text{ss}}^2}\right],\tag{8}$$

where N_0 – nominal operating flow SS; $t_0\approx\rho F_{\text{ss}}L/G_{\text{s}0}$ – the inertial delay time of the reaction of the HFC to the increase in the flow rate when the pump is started.

After transforming equations (1) – (5) taking into account (8), we get a system of equations in the interval $0\le t\le t_0$.

$$\frac{\mathrm{d}M_{\text{l}}}{\mathrm{d}t}=a_1\frac{\mathrm{d}P_{\text{т}}}{\mathrm{d}t}+a_2\frac{\mathrm{d}H}{\mathrm{d}t},\tag{9}$$

$$\frac{\mathrm{d}P_{\text{т}}}{\mathrm{d}t}=b_1\frac{\mathrm{d}H}{\mathrm{d}t},\tag{10}$$

where

$$a_1=-\frac{\mathrm{d}G_{\text{l}}}{\mathrm{d}P_{\text{т}}}t_0+\frac{\mathrm{d}}{\mathrm{d}P_{\text{т}}}\left[\max\left(\frac{\mathrm{d}G_{\text{ss}}}{\mathrm{d}t}\right)\right]t_0;\quad a_2=-\rho F_{\text{c}};\quad b_1=F_{\text{c}}\frac{P_{\text{v}0}\rho_{\text{v}}i_{\text{v}}}{\rho_{\text{v}0}V_{\text{v}0}i_{\text{v}0}}+\rho g.\tag{11}$$

According to the thermodynamic approach, the condition of hydrodynamic instability at the initial stage of the accident after transforming equations (9) and (10):

$$\mathbf{K}_{\text{п}} = \frac{\mathrm{d}P_{\text{т}}}{\mathrm{d}t} \Bigg/ \frac{\mathrm{d}M_{\text{т}}}{\mathrm{d}t} = \left(a_1 + \frac{a_2}{b_1}\right)^{-1} > 0\,. \quad (12)$$

The condition of thermodynamic instability for the minimum flow size RC:

$$a_1(\min F_1) = a_2 / b_1\,. \quad (13)$$

At $F_1 > \min F_1$ $(a_1 > a_2 / b_1)$ in RC hydrodynamic instability occurs at the accident stage of the transient process of starting the SS pump.

For the system of emergency cooling of the active zone of the VVER reactor with high-pressure pumps, the minimum equivalent size of the RC flow at the beginning of hydrodynamic instability was about 400 mm, for the system of emergency cooling of the active zone with low-pressure pumps - about 100 mm.

Results

The developed method for determining the criteria and conditions of hydrodynamic instability in the emergency mode with reactor circuit leaks, unlike known approaches, is based on thermodynamic models of accidents that exclude the effects of differences in codes and code users.

The obtained results – the minimum equivalent size of the RC flow at the beginning of hydrodynamic instability was about 400 mm, for the system of emergency cooling of the active zone with low-pressure pumps – about 100 mm can be used for modeling accidents of nuclear power plants with VVER reactors when conducting safety analyzes, as well as when forming effective accident management strategies.

Conclusions

1. Modern deterministic modeling codes of nuclear power plant safety-dominant groups of accidents with reactor loop leaks (including inter-loop leaks in steam generators) do not determine the conditions and consequences of the processes of hydrodynamic instability of the coolant. The occurrence of hydrodynamic instability of the coolant changes the conditions of heat exchange in the active zone of the reactor, leads to cyclic high-amplitude hydrodynamic loads on the internal body structures and other negative effects.

2. The original method of determining the criteria for the occurrence of hydrodynamic instability of the coolant at the stage of starting the pumps of safety systems in the event of an accident with reactor circuit leaks is presented. The method is based on the thermodynamic laws of the occurrence of hydrodynamic instability depending on the ratio of simultaneous changes in mass and pressure in the reactor circuit.

3. On the basis of the approximate method, the minimum dimensions of the reactor circuit leaks from the VVER of the region of hydrodynamic instability of the coolant were determined: for the emergency cooling system of the active zone of the reactor with high-pressure pumps – 400 mm; for the system of emergency cooling of the active zone of the reactor with low-pressure pumps – 100 mm.

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Received November 03, 2022

Accepted December 17, 2022