https://doi.org/10.46813/2024-150-066

UDC 629.031

# CRITERIA AND CONDITIONS OF THERMAL HYDRODYNAMIC INSTABILITY IN THE CIRCUITS OF NATURAL CIRCULATION OF NUCLEAR POWER PLANTS IN CASE OF LEAK ACCIDENTS

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In today's extreme conditions of operation of nuclear power plants (NPP) of Ukraine, the need to improve systems and strategies for managing accidents with complete long-term blackout (CLTB) is especially urgent. A method of determining the conditions for the occurrence of thermal hydrodynamic instability (THI) in passive safety systems with natural circulation circuits (PSS NC) has been developed, based on the fundamental thermodynamic principles of analyzing the impact on stability of fluctuating deviations of pressure and mass flow of the working medium from the established (equilibrium) state. Using the examples of the small modular reactor (SMP) and the high power reactor (AP1000) of the Westinghouse company, the criteria and conditions of THI in accidents with leaks in the natural circulation circuits of the NPP are defined in a general format. The developed method of determining the criteria and conditions of THI in PSS NC can be applied by design, operating and regulatory organizations for deterministic analysis of the safety of NPPs of the AP/SMP type.

## INTRODUCTION

The lessons of the Fukushima accident determine the need for further improvement of accident management systems and strategies in nuclear power plants (NPP) [1]. One of the most important lessons for the global nuclear energy industry (including for Ukraine) is related to the need to improve systems and strategies for managing accidents with total CLTB in NPP. Thus, in just two years of military operations in Ukraine, several dozen emergency shutdowns of power units of the Zaporizhzhya NPP occurred due to external de-energization of the plant. The analysis of the organizational and technical measures carried out in the post-Fukushima period to improve the systems and strategies for the management of nuclear reactor accidents with CLTB at NPP with WWER plants showed the indisputable necessity of these measures. But they are not enough to reliably ensure the safety functions of emergency cooling of nuclear reactors in the event of accidents with PTZ.

Many years of experience in the operation of various types of NPP have established that pumps with an electric drive (electric pumps) are the least reliable element of safety systems (SS). It was the failure of the emergency power supply and electronic pumps of the SS that became one of the main reasons for the severe consequences of the accidents at the Fukushima-Daiichi NPP in 2011.

One of the promising directions for the further development of nuclear energy is related to the operation of NPPs, in which safety and accident management is ensured by the natural circulation (NC) of passive safety systems (PSS) [2–8]. Such NPPs (for example, the reactors of the Westinghouse company of high and low capacity AP/SMP) are usually classified as reactors of the new safety generation (3+). But additional substantiation of such a high level of safety of NPP with PSS-NC is necessary for the following reasons:

– In the traditional analysis of the safety of NPP of this type, the known deterministic codes [4, 6, 7] did not take into account the conditions and the negative consequences for reliability/safety of the occurrence of THI in the PSS-NC circuits in the process of accidents with the coolant flow.

– Negative consequences for the reliability/safety of NPPs of this type of THI in PSB-PC can be: violation of safety functions for emergency cooling of the active zone of reactors and refueling of steam generators, hydrodynamic and thermal shocks in systems important for safety, etc. [9–12].

The THI phenomenon consists in high-amplitude oscillatory or pulsed deviations of thermal hydrodynamic parameters from the established (quasi-equilibrium) state of the system. The following types of THI are distinguished: high-frequency (thermoacoustic) THI as a consequence of incomplete heat and mass transfer in acoustic waves of thermally unbalanced two-phase flows [9]; low-frequency THI as a consequence of the inertia of the non-porous-cost characteristic of pumps of safety systems in transient modes [10]; pulsed (aperiodic) THI in transsonic two-phase flows [11] and others. It should be noted that, despite the indisputable relevance of the problem, the conditions and consequences of THI in the contours of PSS-NC have not been sufficiently studied.

The aim of the work was to develop a method for determining the criteria and conditions of THI in passive safety systems with natural circulation circuits in NPP of the AP/SMP type in accidents with coolant leaks.

## THE METHOD OF DETERMINING THE CRITERIA AND TERMS OF THI IN PSS-NC

The method is based on the fundamental thermodynamic principles of analysis of the influence of fluctuating pressure and flow disturbances in PSS-NC circuits on the conditions and consequences of THI in the process of accidents with circulation circuit leaks. According to these principles, if pressure and mass increase (or decrease) simultaneously and independently of each other in an equilibrium system, the system is unstable [9–12].

The criteria and conditions of THI in NC are modeled on the basis of the influence of random (fluctuating) deviations of the determining thermal-hydrodynamic parameters ($\delta\vec{y}$) from equilibrium values ($\overrightarrow{y_o}$) [9]:

$$\delta\vec{y} \ll \overrightarrow{y_o} = col\,\{P_{R,}\,P_{g,}\,G_{R,}\,G_{g,}\,G_i\}_o\,, \quad (1)$$

where $P_{R\,,}\,P_g$ – average pressure in the reactor and SG; $G_{R,}\,G_g$ – mass flow rates in the reactor and SG; $G_i$ – mass costs in the i-th PSS.

Fluctuating deviations of dependent thermo-hydrodynamic parameters ($\delta\vec{x}$) from ($\delta\vec{y}$)

$$\delta\vec{x} = \sum(\frac{\partial x_o}{\partial\vec{y}})\cdot\partial\,\overrightarrow{y_o}\delta\vec{x} = \sum(\frac{\partial x_o}{\partial\vec{y}})\cdot\partial\,\overrightarrow{y_o}. \quad (2)$$

The criteria and conditions of THI in the active zone are determined on the basis of the general principle of conditions of thermodynamic instability in the system:

$$K_s(\overrightarrow{y_o};\ \overrightarrow{x_o};\ F_{li}) = \frac{\delta P_R}{\delta G_R} > 0\ . \quad (3)$$

Accordingly, the condition of thermal and hydrodynamic stability (THS) in the active zone of the reactor:

$$K_s(\overrightarrow{y_o};\ \overrightarrow{x_o};\ F_{lj} = \frac{\delta P_R}{\delta G_R} \leq 0\ , \quad (4)$$

where $F_{lj}$ – equivalent cross-sectional area of the *j*-th flow. Equations of movement and heat balance in the circuits of the SMP NC in the established emergency mode [9–12]:

$$\Delta\rho_R\cdot g\cdot H_a = \Delta P_R(\xi_R, G_R, P_R, P_{g,}\,F_{lg}, F_{l1}, G_1\,); \quad (5)$$

$$\Delta P_{in} = P_R - P_{G0} - \rho\cdot g\cdot H_1 + \Delta P_1(\xi_1, G_1, P_R,\ F_{l1}); \quad (6)$$

$$G_{lg} = \mu_{lg}\cdot F_{lg}\cdot\sqrt{\rho(P_R - P_g)}; \quad (7)$$

$$G_{l1} = \mu_{l1}\cdot F_{l1}\cdot\sqrt{\rho(P_R - P_{G0})}; \quad (8)$$

$$G_{l2} = \mu_{l2}\cdot F_{l2}\cdot\sqrt{\rho(P_G - P_{G0})}\,; \quad (8a)$$

$$G_R\cdot\Delta i_R = N + G_1\cdot i_1 - Q_{Rg} - G_{lg}\cdot i_R; \quad (9)$$

$$G_g\cdot\Delta i_g = Q_{Rg} + G_{lg}\cdot i_R - G_{l2}\cdot i_G\,, \quad (10)$$

where $\Delta\rho_R$ – the difference in the average density of the coolant in the descending and ascending sections of the NC circuit of the reactor core; $g$ – acceleration of gravity; $H_a$ – height of the NC circuits of the reactor core; $\xi_R, \xi_1,$ – total hydraulic resistance parameters of the NC circuits of the reactor core and PSS-1; $H_1$ – height of NC circuit of PSS-1; $\Delta i_R, \Delta i_G$ – changes in the specific enthalpy of the coolant in the NC circuits of the reactor core and SG; $N$– power of final heat emissions in the active zone; $i_g,\,i_R\,i_1$ – specific enthalpies of the medium at the exit from the reactor, PG and PSS-1; $Q_{lg}$ – he total heat flow between the reactor and SG; $P_{G0}$ – pressure in the hermetic volume;$\mu_{l1},\mu_{l2},\mu_{lg}$ – hydraulic flow parameters in the flow.

Determining parameters of THI conditions in this case:

$$\vec{y} = col\,\{P_{R,}\,P_{g,}\,G_{R,}\,G_{g,}\,G_1\}\ . \quad (11)$$

Dependent parameters in this case:

$$\vec{x} = col\,\{\Delta\rho_{R,}\,\Delta P_{R,}\,\Delta P_{1,}\,\Delta P_{in,}\,G_{lg,}\,G_{l1,}\,Q_{Rg,}\,\Delta i_R, \Delta i_g, i_R, i_g, i_1, \rho\,\}\ . \quad (12)$$

After transformations of equations (5)–(10) taking into account (1), (2), (11), (12), we get the system of equations:

$$K_1(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta P_R + K_2(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta G_R + K_3(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta P_g + K_4(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta G_1 = 0\,; \quad (13)$$

$$K_5(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta P_R + K_6(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta G_R + K_7(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta P_g + K_8(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta G_1 = 0\,; \quad (14)$$

$$K_9(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta P_g + K_{10}(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta G_R + K_{11}(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta P_g + K_{12}(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta G_1 = 0\,; \quad (15)$$

$$K_{13}(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta P_R + K_{14}(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta G_R + K_{15}(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta P_g + K_{16}(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta G_1 = 0\,; \quad (16)$$

$$K_{17}(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta P_R + K_{18}(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta G_R + K_{19}(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta P_g + K_{20}(\overrightarrow{y_o},\ \overrightarrow{x_o})\cdot\ \delta G_1 = 0\ . \quad (17)$$

After the transformations of equations (13)–(17), we obtain in the general format the THI conditions (3) in the active zone of SMR in the event of an accident with leaks $F_{lg}$, $F_{l1}$, $F_{l2}$.

$$K_s(K_1,\dots,K_{20},\ F_{lg,}\ F_{l1,}F_{l2}\ ) = \frac{\delta\ P_R}{\delta G_R}\ > 0\,. \tag{18}$$

Accordingly, the conditions of THS:

$$K_s\ \leq 0\,. \tag{18a}$$

NPP with AP1000 differs from SMR both in design and technical parameters and in the number of PSS-NC circuits. In particular, unlike the SMR, the AP1000 provides PSS-NC emergency feeding with SG feed water.

Equations of movement and heat balance in the established emergency mode with the flow of NC circuits of were AP1000:

$$\Delta\rho_R\cdot g\cdot H_a =\ \Delta P_R(\xi_R, G_R, P_R, P_g, F_{lg}, F_{l1}, G_1, G_2, G_3,); \tag{19}$$

$$g(\Delta\rho_1\cdot H_1 + \Delta\rho_2\cdot H_2) =\ \Delta P_{12}(\xi_1,\xi_2, G_1, G_2, P_R, F_{l1}\ ); \tag{20}$$

$$\Delta\rho_3\cdot g\cdot H_3 =\ \Delta P_3(\xi_3, G_3); \tag{21}$$

$$\Delta\rho_g\cdot g\cdot H_g\ =\ \Delta P_g(\xi_g, G_g, F_{lg}, F_{12}); \tag{22}$$

$$G_R\cdot\Delta i_R = N +\ G_1\ \cdot i_1 + G_2\ \cdot i_2 + G_3\ \cdot i_3 - Q_{Rg} -\ G_{lg}\cdot i_R -\ Q_{CR}\,; \tag{23}$$

$$G_g\cdot\Delta i_g = Q_{Rg} + G_{\mathrm{Rg}}\ \cdot i_R -\ G_{l2}\cdot i_g -\ Q_{Cg}, \tag{24}$$

where $\Delta\rho_1,\Delta\rho_2,\Delta\rho_3,\Delta\rho_g$ – the difference in average densities in NC circuits of PSS-1, PSS-2, PSS-3, and SG PSS; $H_1, H_2, H_3, H_g$ – circuits height of PSS-1, PSS-2, PSS-3, and SG PSS; $\xi_1,\xi_2,\xi_3,\xi_g$ – total hydraulic resistance parameters of PSS-1, PSS-2, PSS-3, and SG PSS; $G_1,\ G_2,\ G_3, G_g$ – mass expenditure in NC circuits of PSS-1, PSS-2, PSS-3, and SG PSS; $i_1, i_2, i_3, i_g$ – specific enthalpies of flows at the exit from NC circuits of PSS-1, PSS-2, PSS-3, and SG PSS; $Q_{CR}, Q_{Cg}$ – otal heat flows in heat exchangers PSS-3 та SG PSS nuclear fuel storage pool.

After similar transformations of equations (19)–(24) taking into account (1), (2), (7), (8), (8a), we obtained the criteria and conditions for THI/THS circuits of NC AP1000 in accidents with inter-circuit leaks:

$$K_S(\overrightarrow{y_o},\ \overrightarrow{x_o}, F_{lg,}\ F_{l1,}F_{l2}\,)\frac{\delta\ P_R}{\delta G_R}\ > 0, \tag{25}$$

$$K_S(\overrightarrow{y_o},\ \overrightarrow{x_o}, F_{lg,}\ F_{l1,}F_{l2}\,)\frac{\delta\ P_R}{\delta G_R}\ \leq 0, \tag{26}$$

where $\vec{y} = col\ \{\,P_{R,}\ P_{g,}\ G_{R,}\ G_{g,}\ G_1, G_2, G_3\}_0\vec{y} = col\ \{\,P_{R,}\ P_{g,}\ G_{R,}\ G_{g,}\ G_1, G_2, G_3\}_0.$ (27)

In contrast to known approaches to modeling accidents in NPP with deterministic codes, the proposed method allows to determine the conditions for the occurrence and consequences of THI in PSS-NC in the process of accidents with the flow of coolant circulation circuits.

On the basis of the developed method, the criteria and conditions of THI in PSS-NC for modular reactors of low power SMP (18) and high power AP1000 (25) were determined, which depend on regime and structural and technical parameters, as well as the sizes of currents in the circulation circuits. The occurrence of THI conditions in the PC circuits of the SMP/AP1000 require appropriate actions by accident management operators. The implementation of these actions is complicated by the lack of identifiers/symptoms of emergency processes with leaks in the circuits of the PC, as well as the limitation of information about the causes and consequences of the occurrence of THI. As a result, this may lead to unintended operator errors in managing such accidents, which can be reflected both in the overall SMP/AP1000 safety level ratings and in the effectiveness of regulated accident management strategies.

Symptoms/identifiers of THI conditions in the PSS-NC are high-amplitude fluctuations in the level of the coolant in the active zone of the reactor and pressure compensator, as well as the level of water in the volume of the PG. The practical implementation of the developed method is possible with sufficiently complete information about the parameters of reactor installations and allows determining the limit sizes of circulation circuit currents that violate safety conditions.

## CONCLUSIONS

1. The developed method for determining the conditions for the occurrence of THI in the natural circulation circuits of nuclear power plant systems is based on the analysis of the impact on stability of fluctuating viations of pressure and mass flow from the established (equilibrium) state.

2. Using the examples of the Westinghouse low-power modular reactor (SMP) and high-power reactor (AP1000), the criteria and conditions of THI in accidents with leaks in natural circulation circuits are defined in a general format.

3. The necessity of conducting an additional analysis of the safety of NPP of the AP/SMP type, taking into account the criteria and conditions of THI in the PSS-NC, has been established.

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*Article received 20.11.2023*

## КРИТЕРІЇ ТА УМОВИ ТЕПЛОГІДРОДИНАМІЧНОЇ НЕСТІЙКОСТІ У КОНТУРАХ ПРИРОДНЬОЇ ЦИРКУЛЯЦІЇ ЯДЕРНИХ ЕНЕРГОУСТАНОВОК ПРИ АВАРІЯХ З ТЕЧАМИ

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У сучасних екстремальних умовах експлуатації атомних електростанцій (АЕС) України необхідність удосконалення систем та стратегій управління аваріями з повним тривалим знеструмленням (ПТЗ) є особливо актуальною. Розроблено метод визначення умов виникнення теплогідродинамічної нестійкості (ТГН) у пасивних системах безпеки з контурами природної циркуляції (ПСБ ПЦ), заснований на фундаментальних термодинамічних принципах аналізу впливу на стійкість флуктуаційних відхилень тиску та масової витрати робочого середовища від стана, що встановився (рівноважного). На прикладах малого модульного реактора (ММР) та реактора великої потужності (АР1000) компанії Westinghouse визначені у загальному форматі критерії та умови теплогідродинамічної нестійкості при аваріях з течами контурів природньої циркуляції ЯЕУ. Розроблений метод визначення критеріїв та умов ТГН у ПСБ ПЦ може бути застосований проектною, експлуатуючою та регулюючою організаціями для детерміністичного аналізу безпеки ЯЕУ типу АР/ММР.