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CRITERION METHOD FOR DETERMINING THE CONDITIONS FOR OCCURRENCE OF THERMOACOUSTIC INSTABILITY IN THE REACTOR CORE

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The subject of research is the thermoacoustic instability (TAI) of the coolant of a nuclear reactor core. The occurrence of TAI in the reactor core leads to high-frequency and high-amplitude cyclic loads on internal reactor structures and can be one of the reasons for the loss of tightness of fuel elements. A criterion method has been developed for determining the boundaries of the coolant TAI area in the nuclear reactor core under operating, transient and emergency modes. Based on the developed method, the occurrence of TAI area in the coolant was determined, with the criteria of TAI being formulated. A dimensionless determining criterion of the TAI area was justified depending on the rate of heat release, flow rate and enthalpy of the coolant at the entry to the reactor core. Applying the format of dimensionless parameters, the area of TAI of a water-cooled reactor core has been determined, with the relative power of the reactor being more than 0.25 and the relative flow rate of the coolant being less than 0.75.

INTRODUCTION

When analyzing the safety of nuclear power plants, the conditions and consequences of various types of heat-hydrodynamic instability of the coolant in the active zone (AZ) of the reactors are not modeled. On the basis of many years of theoretical and experimental research, as well as experience in the operation of heat engineering equipment, three main types of thermohydrodynamic instability in two-phase flows have been established:

– aperiodic (pulse) instability;
– low-frequency oscillatory instability;
– high-frequency oscillatory instability.

The conditions of aperiodic instability are an increase in flow in accordance with the hydraulic characteristic, the pressure drop should increase, other things being equal. On the other hand, an increase in the flow leads to an improvement in heat exchange conditions, a decrease in the vapor content and a corresponding increase in the density of the two-phase flow and a decrease in the pressure drop in the channel. If the second of these factors prevails over the first, the system will be in a state of aperiodic thermohydrodynamic instability. In a state of aperiodic thermohydrodynamic instability, fluctuating flow deviations lead to an impulsive (jump-like) change in regime parameters and a transition to a new hydrodynamic state. Conditions of aperiodic thermo-hydrodynamic instability are characteristic of systems with relatively low flows and high steam content (for example, the contours of natural circulation of a two-phase heat carrier). The conditions for the occurrence of low-frequency oscillatory instability in two-phase flows are determined by the incompleteness of heat and mass transfer processes. At the same time, there are fluctuating deviations of regime parameters (flow rate, pressure, temperature, heat loads, and others) in two-phase flows with a pronounced separate structure and relatively high flow velocities. Conditions of low-frequency oscillatory instability can occur in the AZ of nuclear reactors of the WWER, PWR type in transient and emergency modes. They can also occur in the AZ of boiling reactors of the RBMK, BWR type, in the volumes of steam generators on the 2nd circuit, in regeneration and separation systems. The main frequency of parameter fluctuations under conditions of low-frequency thermohydrodynamic instability is inversely proportional to the time of passage of the flow in the system.

The conditions for the occurrence of high-frequency oscillatory instability in two-phase non-equilibrium flows are determined by the conditions of interphase interaction in acoustic waves. Therefore, this type of instability was named "thermoacoustic instability" (TAI). The main frequency of thermoacoustic oscillations of thermohydrodynamic parameters is inversely proportional to the time of passage of a sound wave in the system

The occurrence of thermoacoustic instability of the coolant in the AZ of the reactor is accompanied by high-amplitude, high-frequency loads on the heat-emitting elements (heaters) and internal reactor body devices [1, 2].

Deterministic accident modeling codes (RELAP, SOCRATES, CATHARE, etc.) do not determine the conditions and consequences of TAI in nuclear reactor reactors [3, 4]. Therefore, determining the criteria and conditions for the occurrence of nuclear power plants is an urgent issue for ensuring the reliability and safety of nuclear power plants (NPPs).

1 ANALYSIS OF LITERARY DATA AND STATEMENT OF THE PROBLEM

In [1], based on theoretical and experimental studies, it was established that the occurrence of TAI in the AZ of nuclear reactors is accompanied by high-frequency (hundreds of Hertz). They are also accompanied by high-amplitude pressure fluctuations (up to 50% of the average pressure), which can significantly affect the integrity of the reactor's in-body devices. However, the proposed methods of modeling the conditions for the occurrence of TAIs were of a general theoretical nature and difficult for practical application. In [1], an analysis of the well-known method of determining the conditions of TAI based on the non-equilibrium polydisperse model of the two-phase flow of the coolant was also carried out. A method of determining the conditions of the occurrence of TAI in the AZ of the reactor in operating, transitional and emergency modes was proposed [2]. As a result, it was established that this method is extremely difficult for practical application during the analysis of the safety of nuclear power plants. In work [5], the issue of the occurrence of thermal hydrodynamic instability of the coolant due to the transient processes of the circulation pumps was considered. As a result, it was established that under the considered conditions, only low-frequency hydrodynamic instability may occur due to the inertial delay of the response of the pressure-flow characteristics of the pumps in transient modes; and TAI conditions do not arise. The work [2] also presents numerous experimental data beyond the boundaries of the TAI in steam-generating channels in a wide range of operating parameters (including the conditions of nuclear power plants with WWER). As a result of experimental studies, it was established that a necessary condition for TAI in the steam-generating channels of thermal power equipment is the mode of non-equilibrium (“not superheated”) boiling. At the same time, steam formation occurs on the heating surface with condensation of the vapor phase in the cold flow of the coolant. The main frequency of thermoacoustic oscillations is determined by the time of passage of the acoustic wave in the channel. The amplitude of thermoacoustic oscillations reaches 50% of the average pressure in the channel. The development of thermoacoustic oscillations comes from higher-frequency harmonics to the main (energy) harmonic of oscillations. The conditions for the occurrence of thermoacoustic oscillations are significantly influenced by the distribution of heat emissions along the length of the heated channel, the gas saturation of the coolant and other factors. In [6], the question of the conditions for the occurrence of thermohydrodynamic instability in the safety valves of the reactor plant was considered. As a result, the conditions for the occurrence of aperiodic instability due to transonic regimes of two-phase flows of the heat carrier are established; and there are no conditions for the emergence of TAI. In work [7], the issue of the conditions for the occurrence of hydrodynamic instability in the channels of active safety systems, which provide power to the reactor plant in emergency modes, was considered. However, the impact of security systems on the conditions of the occurrence of TAIs was not considered in the paper [7]. The report of the International Atomic Energy Agency (hereinafter IAEA) [8] analyzed the causes and consequences of the Fukushima accident. However, the impact of various types of thermohydrodynamic instability on the conditions of severe (nuclear) accidents was not considered in this report.

Two main theoretical approaches to determining the conditions for the occurrence of TAI were considered – “resonance” and “thermodynamic” (an overview analysis of these studies is given, for example, in [2]).

The “resonance” approach is based on the resonance effect of the drop in the frequency of acoustic oscillations and the condensation of steam bubbles and is justified for relatively short channels (less than 1 m) and low pressures. The analysis of the known results of experimental data established that the “resonance” method does not correspond to most of the determining effects of the occurrence of thermoacoustic oscillations in heated channels. It can be dominant only for relatively short channels (less than 1 m) and large underheating of the coolant to volumetric boiling (over 80 degrees). These conditions are not typical for the AZ of high-power nuclear power plants (with reactors of the type WWER, PWR, BWR and others).

The “thermodynamic” approach is based on the thermodynamic laws of the occurrence of oscillatory processes due to the influence of acoustic disturbances on changes in thermodynamic parameters in the system and is more justified for the conditions of NPP with WWER. However, the known methods and calculation tools for determining the conditions for the occurrence of TAIs within the framework of the “thermodynamic” approach are based on certain insufficiently subsTAItiated assumptions. They do not take into account the full range of possible disturbances (deviations) of the thermohydrodynamic parameters of the coolant and the neutron-physical parameters of the nuclear fuel.

The analysis of known developments in the field of modeling of various types of thermodynamic instability established that the phenomenon of TAI as one of the types of thermodynamic instability has not been studied enough. In particular, there is currently no sufficiently subsTAItiated operational method for determining the conditions of TAI in the AZ of the WWER, which determines the goals and objectives of the proposed work.

2. PURPOSE AND OBJECTIVES OF THE RESEARCH

The purpose of the research is to develop a criterion method for determining the conditions for the occurrence of TAIs in the AZ of nuclear reactors, which will allow to increase operational safety and make it possible to develop an operational system for diagnosing conditions of TAIs in the AZ of high-power reactor installations.

To achieve the goal, the following tasks have been set:

– develop a criterion method for determining the conditions for the occurrence of TAI;

– to justify the defining criterion of the area of thermoacoustic instability in the AZ of the reactor;

– determine the areas of TAI in the AZ of the WWER.

3. OBJECT AND HYPOTHESIS RESEARCH

The object of the study is the conditions for the occurrence of TAI in the AZ of nuclear reactors.

The research hypothesis is an analysis of the influence of independent acoustic pressure fluctuations and a number of frequency fluctuation deviations of the coolant flow rate in the reactor core on the conditions of TAI in a two-phase non-equilibrium flow in accordance with the fundamental thermodynamic principle of instability of systems.

3.1. MATERIALS AND METHODS RESEARCH

The criterion method for determining the conditions for the occurrence of TAI in the AZ of nuclear reactors is based on the fundamental thermodynamic principle of instability of closed systems (Rayleigh's thermodynamic principle) – the simulTAIeous increase (or decrease) of pressure and mass in a closed system leads to its unstable state. The implementation of the fundamental thermodynamic principle of instability in the simulated non-equilibrium two-phase flow can be demonstrated by the following simplified example of a vapor bubble condensing in a relatively cold coolant flow. When the acoustic pressure increases in the sound wave, a corresponding compression of the vapor bubble occurs relative to the equilibrium state. There is also a corresponding relative decrease in the area of the interphase heat-mass transfer surface of the vapor condensing bubble, and therefore a relative increase in the mass in the system (unstable scenario of the process). However, a relative increase in pressure leads to a relative increase in the saturation temperature of the steam bubble. Accordingly, this will lead to a relative increase in the interphase temperature difference and a corresponding relative intensification of interphase heat and mass transfer in the process of vapor bubble condensation. Therefore, a relative increase in pressure leads to a relative decrease in mass in a thermodynamically closed system (stable scenario of the process). If the unstable process scenario dominates the stable process scenario, the state of the coolant in the reactor core is thermoacoustically unstable. If the stable process scenario prevails over the unstable process scenario, the state of the coolant in the AZ is thermoacoustically stable.

Similar results can be obtained with the acoustic pressure reduction in the vapor bubble that condenses in the relatively cold flow of the heat carrier.

The predominance of unstable or stable scenarios of the thermoacoustic state depends on the thermo-hydrodynamic parameters of the coolant flow, the power of heat release in the AZ of the reactor and other parameters that determine the conditions of interphase interaction.

An alternative approach to determining the conditions for the occurrence of thermoacoustic instability can be based on the well-known resonance principle of instability of systems. In the conditions considered in this paper, the resonance effect can dominate if the frequency of collapse of vapor condensed bubbles corresponds to the frequency of acoustic disturbances in a closed system. However, based on the results of experimental studies, it was previously established [1] that resonance effects can be significant only in relatively short system channels (less than 1 m). This does not correspond to the conditions of the AZ of nuclear power plants with WWER.

4. CRITERION METHOD DEFINITION OF THE TERMS OF TAI

When determining the criteria and conditions for the occurrence of thermoacoustic instability in the AZ of a nuclear power plant, the following basic provisions and assumptions were adopted:

1. AZ is modeled by a channel with equivalent real geometric dimensions, power of heat release and heat hydrodynamic parameters of the coolant (pressure, temperature, flow rate, hydraulic resisTAIce, etc.).
2. The structure of the coolant in AZ assumes a two-zone model: a two-phase zone on the surface of the heating element and a central single-phase zone of the coolant.
3. The heat carrier in the AZ is modeled as a system with thermohydrodynamic parameters averaged over the volume of the AZ.
4. The analysis of TAI is carried out on the basis of the linearization of the equations of thermo-hydrodynamic and neutron-physical processes in AZ in the form of perturbations of the determining parameters $\delta\vec{y} << \vec{y}_0$.
5. According to the “thermodynamic” approach, the conditions for the occurrence of TAI are determined by the positive ratio of simulTAIeous perturbations of the pressure and mass of the coolant in the AZ.

Next, the deterministic method of modeling the conditions and criteria of thermoacoustic instability was used. This method involves the development and analysis of the equations of thermal hydrodynamics of the AZ coolant in the stationary mode, which determine the power of the reactor plant and the mass flow rate of the coolant.

The power of the reactor plant is determined both by thermodynamic parameters (specific enthalpy of the coolant at the inlet and outlet of the reactor, specific enthalpy of interphase processes of condensation and vaporization), and by neutron-physical parameters of the nuclear fuel state. This is done by compiling the equations of the heat-hydrodynamics equation of the coolant in AZ in the form of perturbations of heat-hydrodynamic and neutron-physical parameters.

The mass flow of condensation of the vapor phase is determined depending on the power corresponding to the beginning of surface underheated boiling, physical and geometric characteristics of the vapor phase.

The criteria of thermoacoustic instability are obtained after transformations of the equations of the heat-hydrodynamics equation of the coolant in AZ in the form of perturbations of heat-hydrodynamic and neutron-physical parameters.

The equation of the thermo-hydrodynamics of the AZ coolant in the stationary mode [4, 5]:

$$(G_{\text{c}})_0 = (G_{\text{v}})_0;\ (G_{\text{c}} i_{\text{c}})_0 = (G_{\text{v}} i_{\text{vl}})_0, \qquad (1)$$

$$N = G_0 (i_{\text{l}} - i_0);\ G_0 = F_{\min} \sqrt{\rho \Delta P_{\text{pu}} / \xi}, \qquad (2)$$

where G_{c}, G_{v} – mass flow during condensation and evaporation; i_{c}, i_{vl} – specific enthalpy of interphase processes of condensation and vaporization; i_0, i_{l} – specific enthalpy of the coolant at the inlet and outlet AZ; G_0 – mass flow of coolant; ρ – density of coolant; ξ – total coefficient of hydraulic resisTAIce of the reactor circuit; ΔP_{pu} – pressure of the main circulation pump; $F_{\min}$ – the minimum cross-sectional area of the coolant in the reactor circuit.

Power of heat release in AZ depending on the neutron-physical parameters of the state of nuclear fuel [1, 2]:

$$N = \sum_i n_i C_i \sigma_i Q_i, \qquad (3)$$

where n_i – dimensioned neutron flux density of the i-th nuclidey; C_i – concentration of nuclei of the i-th nuclide; σ_i – fission cross section of the i-th nuclide averaged over the energy spectrum of neutrons; Q_i – average thermal energy of fission of one nucleus of the i-th nuclide.

In the general case, the equations of heat-hydrodynamics of the coolant in the AZ (1) and (3) in the form of disturbances of heat-hydrodynamic and neutron-physical parameters:

$$\delta M_{\text{l}} = \left[\left(\frac{\partial G_{\text{c}}}{\partial P} \right)_0 \delta P + \left(\frac{\partial G_{\text{c}}}{\partial n} \right)_0 \delta n + \left(\frac{\partial G_{\text{c}}}{\partial i_{\text{l}}} \right)_0 \delta i_{\text{l}} + \left(\frac{\partial G_{\text{c}}}{\partial G} \right)_0 \delta G \right] t_a; \qquad (4)$$

$$\delta M_{\text{v}} = \left[\left(\frac{\partial G_{\text{v}}}{\partial P} \right)_0 \delta P + \left(\frac{\partial G_{\text{v}}}{\partial n} \right)_0 \delta n + \left(\frac{\partial G_{\text{v}}}{\partial i_{\text{l}}} \right)_0 \delta i_{\text{l}} + \left(\frac{\partial G_{\text{v}}}{\partial G} \right)_0 \delta G \right] t_a; \qquad (5)$$

$$\delta (M_{\text{l}} i_{\text{l}}) = \left[\left(\frac{\partial G_{\text{c}} i_{\text{c}}}{\partial P} \right)_0 \delta P + \left(\frac{\partial G_{\text{c}} i_{\text{c}}}{\partial n} \right)_0 \delta n + \left(\frac{\partial G_{\text{c}} i_{\text{c}}}{\partial i_{\text{l}}} \right)_0 \delta i_{\text{l}} + \left(\frac{\partial G_{\text{c}} i_{\text{c}}}{\partial G} \right)_0 \delta G \right] t_a; \qquad (6)$$

$$\delta (M_{\text{v}} i_{\text{v}}) = \left[\left(\frac{\partial G_{\text{v}} i_{\text{vl}}}{\partial P} \right)_0 \delta P + \left(\frac{\partial G_{\text{v}} i_{\text{vl}}}{\partial n} \right)_0 \delta n + \left(\frac{\partial G_{\text{v}} i_{\text{vl}}}{\partial i_{\text{l}}} \right)_0 \delta i_{\text{l}} + \left(\frac{\partial G_{\text{v}} i_{\text{vl}}}{\partial G} \right)_0 \delta G \right] t_a; \qquad (7)$$

$$\left(\frac{\partial N}{\partial n} \right)_0 \delta n = (i_{\text{l}} - i_{\text{l0}}) \delta G + G_0 \delta i_{\text{l}}; \qquad (8)$$

$$\delta G = \left(\frac{\partial G_0}{\partial G} \right)_0 \delta G + \left(\frac{\partial G_0}{\partial P} \right)_0 \delta P, \qquad (9)$$

where M_{l}, M_{v} – the mass of the central and two-phase zone of the coolant in AZ; $t_a = H/a$ – propagation time of acoustic vibrations in the AZ with a height of H; a – the speed of propagation of acoustic vibrations (speed of sound) in the coolant.

Mass flow rate of vapor phase condensation:

$$G_{\text{c}} = \begin{cases} 0,\ N < N_0, \\ \alpha_{\text{c}} F_{\text{v}} (T_{\text{v}} - T_{\text{l}}),\ N \ge N_0, \end{cases} \qquad (10)$$

$$G_{\text{v}} = \begin{cases} 0,\ N < N_0, \\ \rho_{\text{v}} F_{\text{b}} n_{\text{w}} \nu_{\text{b}},\ N \ge N_0, \end{cases} \qquad (11)$$

where N_0 – power corresponding to the beginning of surface subheated boiling; α_{c} – coefficient of heat transfer on the surface of the vapor phase; F_{v} – vapor phase surface area; T_{v}, T_{l} – the temperature of the vapor and liquid phase of the central zone; ρ_{v} – vapor density; V_{b} – average vapor bubble volume; n_{w} – the density of vaporization centers on the surface of the fuel element; ν_{b} – steam bubble generation frequency.

Semi-empirical formulas for determining parameters depending on thermohydrodynamic states of the coolant are given in [1, 2, 5] and other works.

After transforming the equations of heat-hydrodynamics of the coolant in the AZ (4)–(9), we obtain:

$$\delta P = \text{K}_{\text{P0}} \delta n, \qquad (12)$$

$$\delta M_{\text{l}} = \text{K}_{\text{M0}} \delta n, \qquad (13)$$

where TAI criteria:

$$\text{K}_{\text{P0}} = \text{K}_{\text{P0}} \left[\left(\frac{\partial \vec{y}}{\partial P} \right)_0 ; \left(\frac{\partial \vec{y}}{\partial n} \right)_0 ; \left(\frac{\partial \vec{y}}{\partial i_{\text{l}}} \right)_0 ; \left(\frac{\partial \vec{y}}{\partial G} \right)_0 ; t_a \right], \qquad (14)$$

$$\text{K}_{\text{M0}} = \text{K}_{\text{M0}} \left[\left(\frac{\partial \vec{y}}{\partial P} \right)_0 ; \left(\frac{\partial \vec{y}}{\partial n} \right)_0 ; \left(\frac{\partial \vec{y}}{\partial i_{\text{l}}} \right)_0 ; \left(\frac{\partial \vec{y}}{\partial G} \right)_0 ; t_a \right]. \qquad (15)$$

According to the "thermo-hydrodynamic" approach, the conditions for the occurrence of TAI are:

$$\frac{\delta P}{\delta M} = \frac{\text{K}_{\text{P0}}}{\text{K}_{\text{M0}}} > 0. \qquad (16)$$

The conditions for the occurrence of thermoacoustic instability is a value determined by the ratio of TAI criteria, which in turn are derivatives of parameters from pressure, enthalpy, and mass flow.

A positive value of the condition for the occurrence of TAI indicates an unstable mode of operation of the reactor installation.

The criterion method developed in this way is based on the fundamental principle of conditions of thermodynamic instability of systems (16), linearization of the mathematical model (1)–(15) of the coolant in the AZ of the reactor in the form of acoustic pressure deviations and fluctuation deviations of the flow of the coolant from the established (equilibrium) state and influence of these deviations on the terms of TAI.

5. THERMAL ACOUSTIC AREA INSTABILITY OF REACTORS INSTALLATION

Analysis of solution (16) allows us to draw the following conclusions.

1. A necessary condition for the occurrence of TAI is intense "underheated" boiling ($i_1 < i_1'$) at:

$$N > N_0, \tag{17}$$

where i_1' – specific enthalpy of liquid saturation.

2. A sufficient condition for the occurrence of TAI is the incompleteness of the interphase processes of heat and mass transfer during vaporization and condensation, which is determined by the heat-hydrodynamic state of the two-phase coolant in the AZ.

3. The determining parameter of the conditions for the occurrence of TAI in AZ:

$$\Pi_0 = \frac{N > N_0}{G i_0}. \tag{18}$$

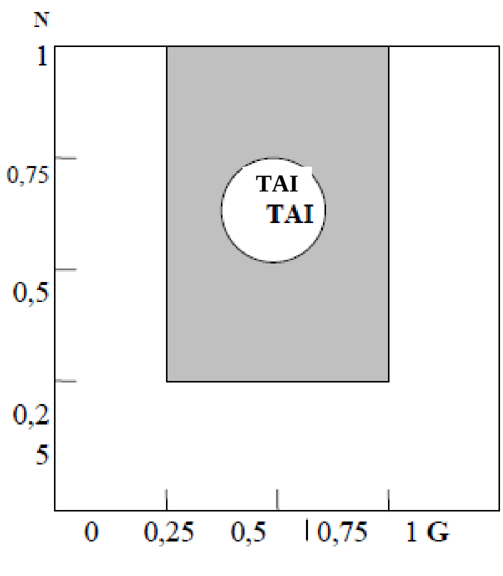
TAI area :

$$0 < \Pi_0 (i_1 < i_1') < \Pi_0 (i_1 \geq i_1'). \tag{19}$$

The upper limit of the TAI region (11) is determined by the beginning of volume boiling of the coolant in the AZ. Conditions for reaching the upper limit of TAI has the form:

$$\frac{N}{G_0} \geq i_1' - i_0 . \tag{20}$$

According to the presented method, the conservative range of conditions for the occurrence of TAI in the AZ of the WWER-1000 reactor is given in the format of dimensionless determining parameters.



Conservative region of thermoacoustic instability of the AZ of the WWER-1000 reactor

These parameters are the ratio of the current power of the reactor plant to the nominal power and “working” mode N and the ratio of the current mass flow of the medium to the nominal “working” flow G. The values of the dimensionless determining parameters are shown in Figure.

The obtained results can be used for the development of operational systems for diagnosing the conditions of the occurrence of TAI in the AZ of reactor installations with WWER reactors; and also adapted for other types of high power reactors.

6. DISCUSSION OF THE RESULTS CALCULATION MODELING

A mathematical model for determining the conditions of TAI in a two-phase non-equilibrium flow of the coolant (1)–(11) was developed. Model, unlike known approaches (for example, [9–14] and others), takes into account the influence of acoustic pressure fluctuations and low-frequency fluctuation fluctuations of the flow rate on the conditions of occurrence of TAI.

On the basis of the mathematical model (1)–(11), a criterion method for determining the conditions of TAI in the AZ of the WWER in the form of independent acoustic pressure deviations, low-frequency deviations of the flow of the heat carrier from the established (equilibrium) state (12)–16) is presented, and the area is determined TAI in the format of relative parameters of reactor power and coolant consumption (see Figure).

Based on the thermodynamic approach, the criteria and conditions of thermoacoustic instability of the coolant in the AZ of the reactor were obtained. They depend on the defining thermodynamic parameters – reactor power, coolant consumption, pressure and temperature of the coolant at the entrance and exit of the AZ. All the specified parameters are controlled by the regular reactor control system of the WWER. The developed criteria made it possible to determine the area of thermoacoustic instability of the coolant in the AZ of the WWER 1000 reactor in the format of the parameters thermal power – coolant consumption (see Figure). It was established that in the nominal operating mode of the reactor, the coolant is stable with respect to thermoacoustic fluctuations. Conditions of TAI may occur, for example, when several main circulation pumps are jammed.

On the basis of the developed method of determining the conditions for the occurrence of TAI in the AZ of the WWER, the following was established:

a) The area of TAI in the format of dimensionless parameters with respect to the nominal values of the reactor power and heat carrier consumption: for relative power – more than 25% and for relative heat carrier consumption – not less than 25% and not more than 75%.

b) The conditions for the occurrence of TAI in the AZ of the WWER can occur in working, transitional and emergency modes associated with insufficient cooling of the AZ of the reactor. A typical example can be a situation with “jamming” of one or more main circulation pumps.

It should be noted that the pressure compensator of reactor installations with WWER is not sensitive to the frequency of thermoacoustic oscillations. It regulates only low-frequency fluctuations of the hydrodynamic parameters of the coolant, in which the frequency of oscillations is determined by the characteristic time of the coolant passing through the closed reactor circuit. Therefore, elimination of possible modes of thermoacoustic instability can be carried out by the operator by controlling the thermal hydrodynamic state of the coolant in the AZ of the reactor installation.

Operational systems of nuclear reactor diagnostics are not designed to determine and eliminate TAI conditions in the AZ of nuclear reactors. The main reason for this situation is the lack of sufficiently subsTAItiated methods for modeling the conditions for the occurrence of TAI in the AZ of reactor installations.

The developed criterion method of the conditions for the occurrence of TAI can be the basis for the development of an appropriate operational system for the diagnosis of a reactor installation of the WWER type, as well as adapted to reactor installations of other types.

The obtained results require experimental verification.

To carry out further developments in this direction, it is necessary:

– conducting further experimental verification of the results of computational modeling of the TAI WWER area;

– expanding the application of the developed criterion method for determining the conditions of TAI for other types of reactor installations (for example, Westinghouse reactors of large and small capacity);

– expanding the possibilities of the developed method to the conditions of significantly dynamic emergency modes.

CONCLUSIONS

1. A criterion method for determining the conditions for the occurrence of TAI of the coolant in the AZ of a nuclear reactor in operating, transient and emergency modes has been developed. It is based on the modeling of the influence of acoustic and neutron-physical perturbations on the completion of interphase heat and mass transfer in the processes of vaporization and condensation of non-equilibrium two-phase flows.

2. On the basis of the obtained solutions, the determining criterion of the area of TAI in the AZ of the reactor, depending on the power of heat release, flow and enthalpy of the coolant at the entrance to the AZ, is substantiated. According to the obtained results of the calculation area, in the nominal operating mode, the reactor is stable with respect to thermoacoustic oscillations. In transient or emergency modes with disconnection or failure of more than one main circulation pump, the AZ of the reactor is unstable with respect to thermoacoustic oscillations.

3. On the basis of the developed method, the conditions criteria and the area of occurrence of thermoacoustic instability of the coolant in the AZ of the reactor were established. The criteria for the occurrence of thermoacoustic instability of the coolant in the AZ of the reactor depend on the determining mode parameters (pressure, flow rate, enthalpy of the coolant) in the stationary approximation.

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КРИТЕРІАЛЬНИЙ МЕТОД ВИЗНАЧЕННЯ УМОВ ВИНИКНЕННЯ ТЕРМОАКУСТИЧНОЇ НЕСТІЙКОСТІ В АКТИВНІЙ ЗОНІ РЕАКТОРА

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Об’єктом дослідження є термоакустична нестійкість (ТАН) теплоносія в активній зоні (АЗ) ядерного реактора. Виникнення ТАН в АЗ реактора призводить до високочастотних та високоамплітудних циклічних навантажень на внутрішньореакторні конструкції і може бути однією з причин порушення герметичності оболонок твел. Розроблено критеріальний метод визначення меж області ТАН теплоносія в АЗ ядерного реактора у робочих, перехідних і аварійних режимах. На основі розробленого метода встановлена область виникнення ТАН теплоносія, і були сформульовані критерії ТАН. Обґрунтований безрозмірний визначальний критерій області ТАН у залежності від потужності тепловиділень, витрати та ентальпії теплоносія на вході в АЗ реактора. У форматі безрозмірних параметрів визначена область ТАН в АЗ водо-водяного енергетичного реактора – відносна потужність реактора більше 0,25 і відносна витрата теплоносія менше 0,75.