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CRITERION METHOD FOR MODELLING THERMODYNAMIC INSTABILITY IN MIXING HEATERS OF TURBO INSTALLATIONS

В. Скалозубов, О. Дорож, О. Вєрінов, І. Вербило, А. Канівець, Є. Алєксєєнко. **Критеріальний метод моделювання термодинамічної нестійкості в змішувальних підігрівачах турбоустановок**. Актуальність питання моделювання умов та наслідків термодинамічної нестабільності у змішувальних підігрівачах підтверджена аналізом досвіду експлуатації турбоустановок та проблеми при виникненні гідродинамічних ударів та їх впливу на функціонування обладнання. Розроблена термодинамічна математична модель тепломасообмінних процесів в об'ємі змішувальних підігрівачів, яка, на відміну від відомих підходів, враховує вплив флуктуаційних відхилень термодинамічних параметрів від рівноважного стану на умови термодинамічної нестійкості. Виконаний аналіз отриманих критеріїв та умов термодинамічної нестабільності та гідродинамічних ударів. На основі розробленої моделі представлений оригінальний метод визначення умов та наслідків термодинамічної нестійкості в об'ємі змішувальних підігрівачів. Критерієм термодинамічної нестійкості в розробленому методі визначені умови одночасної зміни тиску та маси в двофазному об'ємі змішувального підігрівача. Визначені умови виникнення термодинамічної нестійкості в змішувальних підігрівачах, які суттєво залежать від співвідношення витрати пари та конденсату. Отримані в роботі результати можуть бути застосовані для: розробки систем діагностики стану змішувальних підігрівачів за штатно контрольованими параметрами турбоустановки, обгрунтування технічних рішень попередження термодинамічної нестійкості та гідродинамічних «ударів» на конструкції підігрівачів, обгрунтування технічних рішень по модернізації систем турбоустановок. Ці питання визначають необхідність подальшого аналізу обгрунтованості модернізації методів моделювання термодинамічної нестійкості в змішувальних підігрівачах турбоустановок АЕС.
Ключові слова: термодинамічна нестійкість, змішувальні підігрівачі турбоустановок

V. Skalozubov, O. Dorozh, O. Vierinov, I. Verbylo, A. Kanivets, Y. Alieksieienko. **Criterion method for modelling thermodynamic instability in mixing heaters of turbo installations**. The relevance of the issue of modelling the conditions and consequences of thermodynamic instability in mixing heaters is confirmed by the analysis of the experience of operating turbo installations and the problem of hydrodynamic shocks and their impact on the functioning of the equipment. A thermodynamic mathematical model of heat and mass transfer processes in the volume of mixing heaters has been developed, which, unlike known approaches, takes into account the influence of fluctuating deviations of thermodynamic parameters from the equilibrium state on the conditions of thermodynamic instability. The analysis of the obtained criteria and conditions of thermodynamic instability and hydrodynamic shocks was carried out. Based on the developed model, an original method of determining the conditions and consequences of thermodynamic instability in the volume of mixing heaters is presented. The criterion of thermodynamic instability in the developed method defines the conditions of simultaneous change of pressure and mass in the two-phase volume of the mixing heater. The conditions for the occurrence of thermodynamic instability in mixing heaters are determined, which significantly depend on the ratio of steam and condensate flow rates. The results obtained in the work can be applied for: development of systems for diagnosing the state of mixing heaters based on the regularly controlled parameters of the turbo installation, substantiating technical solutions for preventing thermodynamic instability and hydrodynamic "shocks" on the design of heaters, substantiating technical solutions for modernization of turbo installation systems. These issues determine the need for further analysis of the feasibility of modernizing thermodynamic instability modelling methods in mixing heaters of NPP turbo-installations.
Keywords: thermodynamic instability, mixing heaters of turbo installations

Introduction

Many years of experience in the operation of mixing heaters of the regenerative system of turbines of nuclear power plants with VVER reactors has established the possibility of powerful hydrodynamic "shocks" in the volume of mixing heaters, which can lead to an increased vibration state and destruction of the internal structures of mixing heaters.

One of the reasons for such phenomena may be the occurrence of conditions of thermodynamic instability in mixing heaters. Conditions of thermodynamic instability are accompanied by high-amplitude periodic fluctuations of thermodynamic parameters (pressure, flow rate, and feed water level). The consequences of thermodynamic instability can be water hammers on the internal structures of mixing heaters and corresponding negative events.

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Therefore, the development of methods for modeling the conditions and consequences of thermodynamic instability in mixing heaters is an urgent issue.

Analysis of literary sources and formulation of the problem

In work [1], an overview analysis of the current issues of improving the reliability and efficiency of operation of nuclear power plants is given. In particular, this work discusses issues related to the violation of the conditions of normal operation of NPP equipment due to thermodynamic instability and hydrodynamic shock.

In the review article [2], an analysis of known developments in modeling the consequences of hydrodynamic impact is carried out. But the causes and conditions of hydrodynamic shocks in various heat engineering systems and equipment (including mixing heaters) have not been sufficiently studied. The paper [3] presents an overview analysis of current developments in modeling thermal effects on the reactor body due to pulsed thermodynamic instability. But the conditions and consequences of thermodynamic instability in mixing heaters do not correspond to the results [3].

In work [4], the effects of hydrodynamic shocks on the body of the pressure compensator in transient modes are experimentally determined. But these results cannot be extrapolated to the operating conditions of the mixing heaters of the NPP turbine. In work [5] the conditions and consequences of hydrodynamic shocks as a result of low-frequency thermodynamic instability in the pressure compensator VVER-1000 are defined. But the results obtained in [5] also do not correspond to the operating levels of the mixing heaters of the turbo installation. The analysis of the conditions and consequences of hydrodynamic shocks as a result of impulse thermodynamic instability was carried out in [6]. But the obtained results also do not correspond to the conditions of operation of the mixing heaters of the turbo installation.

In work [7], a method of modeling the conditions and consequences of hydrodynamic shocks at low-frequency thermodynamic instability as a result of the inertia of the response of the pressure-flow (hydraulic) characteristics of pumps in transient modes was developed; and in work [8] this method is implemented for active safety systems of nuclear power plants with VVER-1000. But the causes and consequences of thermodynamic instability in mixing heaters are significantly different from the conditions of thermodynamic instability and hydrodynamic shocks in active safety systems.

Recently, many studies, including those performed by domestic researchers [9, 10], have been devoted to the problems of thermal physics of accidents at nuclear power plants and the use of computer thermohydraulic codes, in particular ANSYS and RELAP CODE, as well as to increasing the reliability indicators of the calculated determination of the heat transfer crisis analysis of serious accidents, their causes and consequences, conducted by foreign researchers [11, 12].

The works [13, 14] present the results of the application of a complex approach with the help of coupled calculations in thermohydraulic and strength codes, which make it possible to assess the current technical condition of equipment and pipelines.

Criterion methods for determining the conditions and consequences of hydrodynamic and thermal shocks due to thermodynamic instability are being developed for the main and auxiliary equipment of NPPs, in particular, steam generator units and turbo-units with the occurrence of high-amplitude periodic hydrodynamic and thermal “shocks” and, as a result, possible violations of the integrity of NPP equipment structures.

At the department of nuclear power plants of the Odessa Polytechnic National University under the leadership of prof. Skalozubova V.I. original and improved known methods of qualification of modernizations of accident management systems are proposed to prevent thermoacoustic and thermohydrodynamic instability of the coolant in the active zone, thermal shocks in the reactor and in systems important for ensuring safety, optimal thermophysical and neutron-physical properties of nuclear fuel are determined to ensure safe and effective operation of nuclear power plants.

Similar methods are being developed to assess the conditions of occurrence and consequences of hydrodynamic impacts on the functioning of pumps, pipelines, etc.

The criteria and conditions for the occurrence of thermodynamic instability, the conditions for prevention of the specified processes, the impact on the performance of other systems and the possible reduction of the reliability and safety of equipment operation in the working, transitional and emergency modes of NPP operation are analyzed.

Thus, the development of a method for modeling the conditions and consequences of thermodynamic leakage and hydrodynamic shocks in mixing heaters of turbo installations is an urgent issue.

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The purpose and objectives of the research

The purpose of the work is to develop a criterion method for determining the conditions and consequences of thermodynamic instability in mixing heaters to justify practical recommendations for increasing the reliability of operation.

To achieve it, the following tasks were solved:

1. To develop a mathematical model of the criterion thermodynamic method for determining the conditions and consequences of thermodynamic instability in mixing heaters.

2. Discussion of research results and development of practical recommendations.

Research methods

Mathematical model of the criterion method for determining the conditions and consequences of thermodynamic instability in mixing heaters.

Basic provisions and assumptions.

1. The criterion and conditions of thermodynamic instability in mixing heaters are determined on the basis of the fundamental thermodynamic principle of instability of systems – a simultaneous increase or decrease of pressure and mass in the system leads to a state of instability (for example, [6, 7, 8].

2. The modeled system consists of: mixing heater; steam pipeline from the turbine; pipeline with a pump for supplying condensate to the mixing heater.

3. The initial thermodynamic state is equilibrium.

4. Independent fluctuation deviations from the equilibrium state of pressure in mixing heaters and condensate flow are modeled.

Taking into account the accepted assumptions of the heat balance equation and the condensate movement equation:

$$G_v i_v = G_l (i_l - i_{lo}), \tag{1}$$

$$\Delta P_p = P + \xi G_l^2 (\rho_i F^2)^{-1} - P_o, \tag{2}$$

where G_v, G_l – mass consumption of steam and condensate;

i_v, i_l, i_{lo} – specific enthalpy of steam, condensate at the outlet and inlet to the mixing heater;

ΔP_p – the pressure head developed by the pump;

P, P_o – pressure in the mixing heater and at the pump inlet;

ξ_{mp} – total coefficient of hydraulic resistance;

ρ_l – condensate density;

F – cross-sectional area of the pipeline.

In the format of independent fluctuation deviations of pressure $\delta P \ll P$ and condensate flow rate $\delta G_{\_1} \ll G$ of equations (1) and (2):

$$a_1 \delta G_v + a_2 \delta G_l + a_3 \delta P = 0, \tag{3}$$

$$b_1 \delta G + b_2 \delta P = 0, \tag{4}$$

where $a_1 = i_v$;

$a_2 = -(i_l - i_{lo})$;

$a_3 = G_v \dfrac{di_v}{dP} - G_l \dfrac{di_l}{dP}$;

$b_1 = \dfrac{dP_p}{\partial G} - 2\xi G_l (\rho_l F^2)^{-1}$;

$b_2 = -1$.

Taking into account the accepted assumptions and provisions after transforming equations (3), (4), the criterion of thermodynamic instability in mixing heaters:

$$K = \frac{\delta G_v}{\delta P} = \frac{a_2 b_2 b_1^{-1} - a_3}{a_1}. \tag{5}$$

A necessary condition of thermodynamic stability in mixing heaters:

$$K < 0\,. \tag{6}$$

The condition of thermodynamic instability in mixing heaters:

$$K \geq 0\,. \tag{7}$$

In a state of thermodynamic instability (7) in mixing heaters, fluctuating deviations from equilibrium of steam pressure and condensate flow lead to high-amplitude periodic fluctuations of the defining thermodynamic parameters.

The consequence of high-amplitude periodic fluctuations of thermodynamic parameters can be hydrodynamic impacts on the internal structures of mixing heaters. The cause of hydrodynamic shocks in mixing heaters can be pulsed braking of the flow of condensate on internal structures during high-amplitude periodic fluctuations of condensate flow due to low-frequency thermodynamic instability (transition of low-frequency thermodynamic instability into pulsed thermodynamic instability). Under such conditions, the kinetic energy of condensate flow braking is transformed into the internal energy of the hydrodynamic shock pulse:

$$\rho_l V^2 = \Delta(\rho_l \Delta i_l) = \frac{d}{dP}(\rho_l i_l)\ \Delta P_A\,, \tag{8}$$

where ΔP_A – the maximum amplitude of the hydrodynamic shock pressure pulse.

After transformations (8), we get:

$$\Delta P_A = \rho_l V^2 \left(i_l V_a^{-2} + \rho_l \frac{di_l}{dP} \right)^{-1}, \tag{9}$$

where $V_a = \sqrt{\dfrac{dP}{d\rho_l}}$ – speed of sound in condensate;

V – condensate flow rate before braking.

The consequences of a hydrodynamic shock with the amplitude of the pressure pulse (9) can be unacceptable hydrodynamic loads on the structure of the mixing heater, increased vibration and other negative effects.

Analysis of the received criteria and conditions of thermodynamic instability in mixing heaters

The analysis of the obtained criteria for conditions of thermodynamic instability and hydrodynamic shocks in mixing heaters allows a priori to consider:

$$a_1 > 0,\ a_2 < 0,\ b_1 < 0,\ b_2 < 0\,. \tag{10}$$

Then, taking into account (10) the condition of low-frequency thermodynamic instability in the volume of the mixing heater (7):

$$a_3 \left\langle 0; \left| a_3 \right| \right\rangle \left| a_2 b_2\, b_l^{-1} \right|. \tag{11}$$

Thus, the main cause of thermodynamic instability in a mixing heater may be the incompleteness of interphase heat and mass exchange processes, which significantly depends on the ratio of steam and condensate flow rates.

The necessary condition for thermodynamic stability in a mixing heater:

$$a_3 > 0\,. \tag{12}$$

Under conditions (11), hydrodynamic shocks with the maximum amplitude of the pressure pulse (9) may occur.

It should be noted that traditionally the pressure pulse of a hydrodynamic shock is determined by a well-known formula (for example, see [6 – 8]:

$$\Delta P_A = \rho_l V_a^2 (v - v_c)\,, \tag{13}$$

where v_c – flow velocity after hydrodynamic shock.

In the received decision (9):

$$\Delta P_A \sim \rho_l V_a^2 V^2\,.$$

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Thus, the power of the hydrodynamic shock according to (9) can be significantly greater than predicted by formula (13).

Research results and practical recommendations

In accordance with the set goals and objectives, a mathematical thermodynamic model (1) – (4) of the mixing heater was developed, which, unlike known models of two-phase media (for example, [5, 6, 7], takes into account the influence of fluctuating deviations of thermodynamic parameters from the equilibrium state.

Based on the developed model, an original criterion method for determining the conditions and consequences of thermodynamic instability in a mixing heater is presented, (5) – (7). The criterion of thermodynamic instability is the conditions of simultaneous increase (or decrease) of steam pressure and mass in the volume of the mixing heater.

The presented criterion method, in contrast to the known ones (for example, [2, 4, 6], allows to assess the state of the mixing heater in relation to the conditions of thermodynamic instability based on the regularly controlled parameter of the turbine compartment.

The developed model of hydrodynamic shock in the mixing heater (8) – (9) due to low-frequency thermodynamic instability in the volume of the mixing heater, which, unlike known approaches (for example, presented in the review article [2], defines the conditions and consequences of hydrodynamic shock as an impulse thermodynamic instability due to the transition of the kinetic energy of condensate braking on the structures of the mixing heater into the "internal" energy of the hydrodynamic shock pulse.

The results obtained in the work can be applied to:

– development of systems for diagnosing the state of the mixing heater in relation to thermodynamic instability and hydrodynamic impact;

– substantiation of technical solutions to increase reliability and prevent hydrodynamic impact in mixing heaters;

– substantiation of technical solutions for the modernization of the turbo installation.

One of the areas of modernization of the NPP turbine installation with VVER to increase the efficiency of operation is associated with the use of heat pumps to ensure secondary reheating of the condensate of low-pressure heaters. The results of the presented work determine additional requirements for the corresponding heat pumps in terms of ensuring the conditions of thermodynamic stability (12) in the mixing heater of low-pressure heaters.

The developed model and method are not justified for the conditions of transient modes of operation of turbo installations, which determines the subject of further research in this direction.

Conclusions

1. The relevance of the work is determined by many years of experience in operating low-type mixing heaters, as well as the lack of sufficiently substantiated methods for modeling the conditions and consequences of thermodynamic instability in mixing heaters.

2. A thermodynamic model of heat and mass transfer processes in the volume of mixing heaters was developed, which, unlike known approaches, takes into account the influence of fluctuating deviations of thermodynamic parameters from the equilibrium state on the conditions of thermodynamic instability.

3. Based on the developed model, an original method of determining the conditions and consequences of thermodynamic instability in the volume of mixing heaters is presented. The criterion of thermodynamic instability in the developed method defines the conditions of simultaneous change of pressure and mass in the two-phase volume of the mixing heater. The conditions for the occurrence of thermodynamic instability in mixing heaters are determined, which significantly depend on the ratio of steam and condensate flow rates.

4. The results obtained in the work can be used for: developing systems for diagnosing the state of mixing heaters based on regularly controlled parameters of the turbo installation, substantiating technical solutions to prevent thermodynamic instability and hydrodynamic "shocks" on the design of heaters, substantiating technical solutions for modernization of turbo installation systems.

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