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V. Skalozubov, DSc, Prof.,
Iu. Katsarskyi,
H. Derbenov,
Ye. Mazur,
V. Kochnieva
Odessa Polytechnic National University, Shevchenko Ave. 1, Odesa, Ukraine, 65044, e-mail: valer_nov13@ukr.net

METHODS FOR QUALIFYING THE THERMODYNAMIC STABILITY OF SAFETY VALVES AND STEAM DUMP DEVICES OF NUCLEAR POWER PLANTS

В. Скалозубов, Ю. Кацарський, Г. Дербеньов, Є. Мазур, В. Кочнєва. **Методи кваліфікації термодинамічної стійкості запобіжних клапанів та пароскидальних пристроїв ядерних енергоустановок.** Аналіз відомих розробок у напрямках аналізу надійності запобіжних клапанів і пароскидальних пристроїв реактора та парогенераторів ядерних енергоустановок з ВВЕР встановив необхідність розрахункової кваліфікації запобіжних клапанів і пароскидальних пристроїв в умовах аварійних режимів, які не передбачені експлуатаційними випробуваннями ядерних енергоустановок. Одним з таких питань є визначення умов імпульсної та коливальної термодинамічної нестійкості запобіжних клапанів і пароскидальних пристроїв у аварійних режимах. Наслідками термодинамічної нестійкості може бути порушення виконання критичних функцій безпеки в умовах управління аваріями. Експериментальна кваліфікація запобіжних клапанів і пароскидальних пристроїв в аварійних умовах не є можливою, тому потрібна розрахункова кваліфікація. Необхідність розрахункової кваліфікації також актуальна у зв'язку з перспективними програмами експлуатації реакторів в умовах підвищеної тривалості паливних кампаній, в яких зменшується кількість випробувань пасивних систем безпеки у планові ремонти енергоблоків. Розроблено метод кваліфікації пропускної спроможності запобіжних клапанів і пароскидальних пристроїв пасивних систем безпеки ядерних енергоустановок в умовах імпульсної та коливальної термодинамічної нестійкості. Встановлено необхідну умову імпульсної термодинамічної нестійкості – формування трансзвукового режиму потоку робочого середовища в конфузорній зоні запобіжних клапанів/пароскидальних пристроїв. Наслідки імпульсної термодинамічної нестійкості – гідродинамічний «удар» внаслідок перетворення кінетичної енергії потоку у внутрішню енергію гідродинамічного «удару» та гальмування потоку. Визначено максимальну амплітуду тиску гідродинамічного «удару» внаслідок імпульсної термодинамічної нестійкості при повному гальмуванні потоку. Встановлено умови і наслідки коливальної термодинамічної нестійкості в дозвукових режимах потоку в проточних зонах запобіжних клапанів/пароскидальних пристроїв на основі фундаментального принципу термодинамічної нестійкості рівноважних систем. На базі розробленого метода кваліфікації пропускної спроможності запобіжних клапанів/пароскидальних пристроїв визначено умови і підходи забезпечення термодинамічної стійкості потоку в проточних зонах запобіжних клапанів/ пароскидальних пристроїв та запобігання гідродинамічним «ударам».

Ключові слова: кваліфікація, пасивна система безпеки, арматура, реактор, парогенератор, термодинамічна стійкість, ядерна енергоустановка

V. Skalozubov, Iu. Katsarskyi, H. Derbenov, Ye. Mazur, V. Kochnieva. **Methods for qualifying the thermodynamic stability of safety valves and steam dump devices of nuclear power plants.** Analysis of known developments in reliability analysis of safety valves and steam dump devices of reactors and steam generators of nuclear power plants with VVER has recognized the need for calculation qualification of safety valves and steam dump devices under emergency conditions that are not provided for operational tests of nuclear power plants. One of such problems is determining the conditions for pulse and oscillatory thermodynamic instability of safety valves and steam dump devices under emergency conditions. The consequences of thermodynamic instability may be a violation of the performance of critical safety functions under accident management conditions. Experimental qualification of safety valves and steam dump devices under emergency conditions is not possible, therefore calculation qualification is required. The need for calculation qualification is also relevant for prospective programs for reactor operation in conditions of extended fuel campaign time, when the number of tests of passive safety systems during scheduled repairs of power units is reduced. A method for qualifying the throughflow capacity of safety valves and steam dump devices of passive safety systems of nuclear power plants under conditions of pulsed and oscillatory thermodynamic instability has been developed. A necessary condition for pulsed thermodynamic instability has been established. It is the formation of a transonic flow regime of the operating medium in the confusion zone of safety valves/steam dump devices. The consequences of pulsed thermodynamic instability are water "hummer" due to the conversion of kinetic energy of the flow into the internal energy of the water "hummer" and flow stagnation. The maximum pressure amplitude of the water "hummer" due to pulsed thermodynamic instability with complete flow stagnation has been determined. The conditions and consequences of oscillatory thermodynamic instability in subsonic flow regimes in the flow zones of safety valves/steam dump devices have been found based on the fundamental principle of thermodynamic instability of equilibrium systems. Based on the developed method for qualifying the throughflow capacity of safety valves/steam dump devices, the conditions and approaches for ensuring thermodynamic flow stability in the flow zones of safety valves/steam dump devices and preventing water "hummers" have been determined.

Keywords: qualification, passive safety system, armature, reactor, steam generator, thermodynamic stability, nuclear power plant

Introduction

Safety valves and spray devices of safety systems of nuclear power plants (NPP) are designed to prevent the destruction of equipment enclosures and pipelines of systems important for safety, as well as, if necessary, for accident management [1 – 5].

The safety valves of the pulse-safety device of the pressure compensator ensure the integrity of the reactor vessel and internal vessel devices at a pressure in the reactor circuit greater than the maxi-

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mum permissible value.

Safety valves of steam generators ensure the integrity of the body and internal devices of the steam generator at a pressure in the volume of the steam generator greater than the maximum permissible value.

Steam boilers of steam generators (high-speed reduction units for discharging steam from the steam generator to the environment/turbine condenser) regulate the pressure in the volume of the steam generator during emergency modes.

The main mode of operation of safety valves/vaporizers of safety systems is the “standby” mode of performing the necessary safety functions. Therefore, the technological regulations for the safe operation of nuclear power plants with VVER [2] provide for experimental qualification (justification) of operability and reliability of safety valves/vapor discharge devices of safety systems when performing the necessary safety functions by periodic operational tests during the periods of planned preventive maintenance (PM) of NPP power units.

The need to conduct operational tests of safety valves/vapor discharge devices of safety systems only during PM is due to the fact that the operation of safety valves/vapor discharge devices during operational tests actually corresponds to “artificial” emergencies with leaks in the reactor circuit and in the volume of the steam generator in the operating modes of the nuclear power plant.

The conditions for conducting operational tests by opening safety valves/vapor dumping devices during the PM may generally not correspond to the real conditions of emergency modes. For example, operational tests for opening safety valves/steam discharge devices of a steam generator during the PM are carried out on a steam-air environment. In the event of an accident with intercircuit leaks of the coolant into the volume of the steam generator, it may be necessary to qualify the reliable throughput of the safety valves/vapor discharge devices of the steam generator in the conditions of liquid phase or two-phase flow entering the working bodies of the safety valves/vapor discharge devices. Another typical example is related to the consequences of the accident at the Rivne NPP in 2009 during operational tests of the safety valves of the pulse-fuse device of the pressure compensator during the PM in the reactor hot shutdown mode. In the process of operational tests, after opening the safety valves of the pulse-fuse device of the pressure compensator, there was a failure to close the safety valves, which led to the release of the coolant under the nominal pressure into the pressurized volume of the nuclear power plant.

Thus, it is relevant to develop analytical (calculated) methods for qualifying the operability and reliability of safety valves/steam dumping devices of safety systems in conditions as close as possible to emergency modes of nuclear power plants.

The prospects for the nuclear power industry of Ukraine to switch to an 18-month fuel campaign of nuclear power plants with VVER also determine both the need to modernize the strategy of operational tests of safety valves/vapor discharge devices during the PM, and the development of analytical methods for the qualification of safety valves/vapor discharge devices of safety systems.

In the presented paper, a new deterministic method for qualifying the throughput capacity of safety valves/steam discharge devices of safety systems of nuclear power plants under conditions of thermodynamic instability has been developed.

Analysis of known literature data and problem statement

Most of the works on the study of the influence of hydrodynamic “shocks” on the throughput of valves (analytical reviews of these works are given, for example, in [1 – 4] are based on the well-known formula of M.E. Zhukovsky for determining the maximum amplitude of water hammer ΔP_g at complete flow braking:

$$\Delta P_{\mathrm{g}} \leq \rho_1 a_1 v_1, \tag{1}$$

where ρ_l – Fluid density; a_l – Speed of sound; v_l – flow rate to water hammer.

Analysis of the validity of formula (1) for the conditions of safety valves/vapor dispensing devices allows us to make the following basic comments.

1. Formula (1) takes into account only the effect of fluid compressibility (parameter a_l) on ΔP_{g}. However, the dominant effect during a water hammer may be the conversion of the kinetic energy of the flow into the internal energy of the water hammer impulse [5].

2. Formula (1) does not generally determine the causes and conditions of water hammer [7].

In works [6, 7, 8], water hammer in the channels of active safety systems of nuclear power plants was modelled as a result of hydrodynamic oscillatory instability of flow in transitional modes of pump start-up. These works established that the occurrence of water hammer due to hydrodynamic flow instability is determined by the inertia of the "delayed" response of the pressure-flow characteristics of pumps to sufficiently "rapid" changes in flow rates in transient modes.

However, the causes and conditions of water hammer due to hydrodynamic instability of flows in the flow zones of safety valves/vapor dispensers of passive safety systems may differ significantly from the corresponding conditions in the channels of active safety systems (with pumps).

In the papers [9,10], the issues of conditions and consequences of high-frequency thermodynamic instability of the coolant (thermoacoustic instability) in the reactor core were studied. It has been established that the conditions for the occurrence of thermoacoustic instability are the inertia of heat-mass exchange processes of vapor phase condensation in acoustic disturbances (waves) of the coolant. Under conditions of thermoacoustic instability in the core of the VVER reactor, the maximum amplitudes of pressure fluctuations can reach 50% of the average value, and the fundamental frequency of oscillations (1st harmonic) is several hundred Hertz. At such parameters of thermoacoustic instability, high-frequency and high-amplitude hydrodynamic actions (water hammers) occur on the reactor in-vessel devices (including fuel rods).

However, the causes and conditions of thermodynamic instability in the reactor core can differ significantly from the conditions for the occurrence of thermodynamic instability in the flow zones of safety valves/steaming devices.

Thus, it is relevant to develop deterministic methods for analyzing the conditions and consequences of water hammer due to various types of thermodynamic instability in the systems of safety valves/vapor dumping devices.

The aim of the study is to develop a method for assessing the reliability of safety valves and steam release devices in VVER nuclear power plant safety systems under conditions of thermodynamic instability.

Main tasks

1. Analysis of known approaches/methods for qualifying the reliability of systems important for nuclear reactor safety.
2. Development of the main provisions of an alternative method for qualifying the reliability of safety valves and steam release devices under conditions of thermodynamic instability.
3. Analysis of the results obtained and practical recommendations.

Method for qualifying the flow capacity of safety valves/steam traps

Key assumptions and assumptions:

1. The flow zone model of safety valves/steam traps is conditionally divided into a confuser zone (*K*), a working body zone (*O*) and a diffuser zone (*D*) (Fig. 1*a*).

2. Conditions of thermodynamic instability are modelled in two modes of working medium flow in the flow zones of safety valves/steam traps:

– transonic flow mode in the confluence zone (Fig. 1*b*);

– subsonic flow mode (Fig. 1*c*).

3. In the confluence zone, the average flow velocity v increases due to a decrease in the cross-sectional area $F(z)$ and reaches its maximum value in the working body zone (*O*). Pressure P decreases due to an increase in flow velocity and reaches its minimum value in the working body zone.

4. When the flow velocity v is reached in zone *O*, the sound velocity v_a (the speed of propagation of acoustic disturbances in the flow) creates conditions for transonic flow of the working medium in safety valves/steam traps (see Fig. 1*b*) [1, 2, 3]:

$$M(z=L_{\text{K}})=\frac{v(z=L_{\text{K}})}{v_a(z=L_{\text{K}})}\geq 1, \tag{2}$$

where M – Mach criterion, L_{K} – confusion zone length.

When the transonic regime condition (2) is reached, impulse flow deceleration occurs and conditions for a water hammer with an impulse pressure increase arise, and the kinetic energy of flow deceleration is converted into the energy of the water hammer impulse [10]. Consequences of transonic flow regime – conditions of water hammer due to impulsive thermodynamic instability and corresponding impulsive reduction in the throughput capacity of safety valves/steam traps.

5. At subsonic flow regimes of the working medium (M<1), conditions of oscillatory thermodynamic instability may arise in the flow zones of safety valves/steam blowdown devices (see Fig. 1*c*).

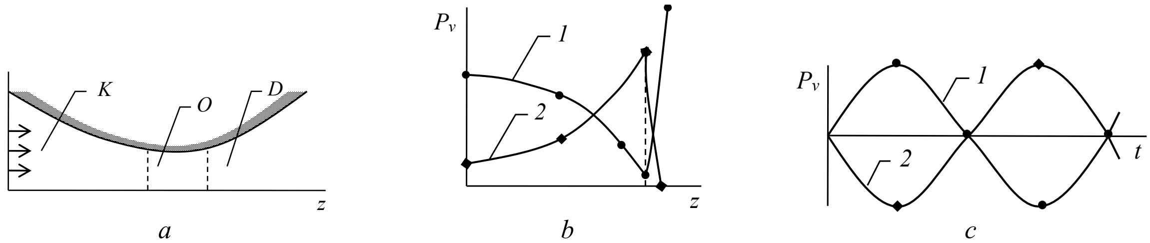

Fig. 1. Models of impulse thermodynamic and oscillatory thermodynamic instability in safety valves/steam traps: safety valve/steam trap model (*a*): *K* – confuser zone, *O* – working body zone, *D* – diffuser zone; model of impulse thermodynamic instability (*b*) and oscillatory thermodynamic instability (*c*): *1* – pressure *P*, *2* – velocity *v*

The conditions for the occurrence of oscillatory thermodynamic instability in the flow zones of safety valves/steam blowdown devices are determined based on the fundamental principle of thermodynamic instability of systems in equilibrium [1 – 6]:

$$\frac{\delta P}{\delta v} > 0, \tag{3}$$

where δP, δv – simultaneous deviation from the equilibrium state of pressure and flow velocity in the system.

Pressure and velocity fluctuations occur in antiphase (see Fig. 1*b*), and the frequency of fluctuations ω [1, 2, 3]:

$$\omega \sim v / L_0, \tag{4}$$

where L_0 – total length of the flow zone of the safety valve/steam trap.

The occurrence of oscillatory thermodynamic instability violates the conditions of normal throughput capacity of safety valves/steam release devices, and in extreme cases can lead to pulsating thermodynamic instability with complete flow inhibition.

Based on the presented provisions, the conditions for thermodynamic stability of the throughput capacity of safety valves/steam release devices:

$$M(z = L_K) < 1, \tag{5}$$

$$\frac{\delta P}{\delta v} < 0. \tag{6}$$

Under conservative assumptions of no irreversible thermal and hydraulic losses in the confuser zone, the equations of conservation of mass, momentum, and energy in the format of parameters distributed along the length of the K-zone in a steady-state homogeneous condition [1, 2, 3]:

$$\frac{d(\rho\, v\, F)}{dz} = 0, \tag{7}$$

$$\frac{d(\rho\, v^2\, F)}{dz} = \frac{d(PF)}{dz}, \tag{8}$$

$$\frac{d(\rho\, i\, F)}{dz} = \frac{d(PF)}{dz}, \tag{9}$$

where $\rho = \rho_l - (\rho_l - \rho_v)\varphi$, ρ_l, ρ_v – density of liquid and vapour phases, $\varphi = i - i_l/(i_v - i_l)$ – vapour content parameter, i, i_l, i_v – specific enthalpy of flow, liquid and vapour phases, P – pressure, v – average flow rate, $F(z)$ – area of the confluent zone's passage cross-section, z – longitudinal coordinate.

After transformations (6) – (8), we obtain:

$$a_1 \frac{dv}{dz} + a_2 \frac{dP}{dz} + a_3 \frac{di}{dz} + a_4 \frac{dF}{dz} = 0, \tag{10}$$

$$b_1 \frac{dv}{dz} + b_2 \frac{dP}{dz} + b_3 \frac{di}{dz} + b_4 \frac{dF}{dz} = 0, \tag{11}$$

$$c_1\frac{di}{dz}+c_2\frac{dP}{dz}+c_3\frac{dF}{dz}=0, \tag{12}$$

where $a_1 = \rho F$, $a_2 = vF/v_a^2$, $a_3 = vF\partial\rho/\partial i$, $a_4 = \rho v$, $b_1 = 2v\rho F$, $b_2 = (M^2 - 1)F$, $b_3 = v^2F\partial_\rho/\partial_i$, $b_4 = \rho v^2 - P$, $c_1 = \rho F + iF\partial\rho/\partial_i$, $c_2 = iF/v_a^2 - F$, $c_3 = b_4$, $v_a^2 = dP/d\rho$ [1].

After transforming equations (10) – (12), the system of nonlinear differential equations in dimensionless format:

$$\frac{dv}{dz}=\mathbf{K}_v[\mathbf{v}(z),\mathbf{P}(z),\mathbf{i}(z),\mathbf{F}(z)], \tag{13}$$

$$\frac{dP}{dz}=\mathbf{K}_P[\mathbf{v}(z),\mathbf{P}(z),\mathbf{i}(z),\mathbf{F}(z)], \tag{14}$$

$$\frac{di}{dz}=\mathbf{K}_v[\mathbf{v}(z),\mathbf{P}(z),\mathbf{i}(z),\mathbf{F}(z)], \tag{15}$$

$$\mathbf{v}(z=0)=1, \tag{16}$$

$$\mathbf{P}(z=0)=1, \tag{17}$$

$$\mathbf{i}(z=0)=1, \tag{18}$$

where $\mathbf{v}=v/v_0$, $\mathbf{P}=P/P_0$, $\mathbf{i}=i/i_0(\varphi_0)$, $\mathbf{z}=z/L_K$, v_0, P_0, i_0, φ_0 – working medium flow parameters at the inlet to the flow zone of safety valves/steam traps.

Solutions to equations (13)–(18) in general form:

$$\mathbf{v}(L_K)=1+\int_0^{L_K}\mathbf{K}_v dz, \tag{19}$$

$$\mathbf{P}(L_K)=1+\int_0^{L_K}\mathbf{K}_P dz, \tag{20}$$

$$\mathbf{i}(L_K)=1+\int_0^{L_K}\mathbf{K}_i dz. \tag{21}$$

Then the conditions for impulsive thermodynamic instability (2):

$$\int_0^{L_K}\mathbf{K}_v dz \geq \mathbf{v}_a - 1, \tag{22}$$

where $\mathbf{v}_a = v_a L_K / v_0$.

In general, solutions (19) – (22) can be obtained by numerical methods of integrating nonlinear differential equations (13)–(18).

The maximum pressure pulse of the water hammer ΔP_g due to the condition of impulse thermodynamic instability (22) is determined by the conversion of the kinetic energy of flow deceleration rv_a^2 into the energy of the water hammer pulse $\Delta\rho_{ig}$.

In the extreme case (complete flow stoppage):

$$\boldsymbol{\rho}\mathbf{v}_a^2=\Delta(\boldsymbol{\rho}_1\mathbf{i}_g)=\frac{d(\boldsymbol{\rho}_1\mathbf{i}_1)}{\mathrm{d}\mathbf{P}}\Delta\mathbf{P}_g. \tag{23}$$

From (23) follows the maximum pressure pulse of the water hammer:

$$\Delta\mathbf{P}_g=\left[\frac{d(\boldsymbol{\rho}_1\mathbf{i}_1)}{\mathrm{d}\mathbf{P}}\right]^{-1}\boldsymbol{\rho}\mathbf{v}_a^2. \tag{24}$$

Formula (24) for determining the maximum pressure pulse of a water hammer due to impulsive thermodynamic instability in safety valves/steam traps differs significantly from the corresponding Zhukovsky formula (1).

The conditions for impulse thermodynamic stability in safety valves/steam release devices follow from (22):

$$\int_0^{L_K} \mathbf{K}_v d\mathbf{z} < \mathbf{v}_a - 1. \tag{25}$$

The conditions for oscillatory thermodynamic instability in the flow zone of safety valves/steam traps are determined for subsonic conditions.

Equations of motion and energy conservation in the flow zones of safety valves/steam traps in equilibrium [1, 2, 3]:

$$P_0 - P_A = \xi \frac{G^2}{\rho F_{\min}^2} = 0\,, \tag{26}$$

$$G(i_0 - i_A) = \xi \rho^{-1} L_0 G^2, \tag{27}$$

where $G = \rho v F_{\min}$ – mass flow rate of the working medium, $F_{\min}$ – minimum cross-sectional area in the flow section of safety valves/steam traps, ξ – parameter (hydraulic resistance coefficient), L_0– total length of the flow section of safety valves/steam traps, P_A, i_A – pressure and specific enthalpy of the working medium at the outlet of safety valves/steam traps.

When assuming $\partial(P_0 - P_A) / \partial G = \partial(P_0 - P_A) / \partial P = 0$ equations (26) and (27) in the format of simultaneous fluctuation-independent deviations $\delta G << G$ and $\delta P << P$:

$$A_1 \delta P = A_2 \delta G\,, \tag{28}$$

$$B_1 \delta P = B_2 \delta G\,, \tag{29}$$

where:

$$A_1 = G \frac{d(\rho^{-1})}{\mathrm{d}P}\,, \tag{30}$$

$$A_2 = -2G\rho^{-1}\,, \tag{31}$$

$$B_1 = G(i_0 - i_A) - \xi L_0 G^2 \frac{d(\rho^{-1})}{\mathrm{d}P}\,, \tag{32}$$

$$B_2 = 2\xi\rho^{-1} L_0 G - (i_0 - i_A)\,. \tag{33}$$

Equations (28) and (29) give rise to the conditions for the oscillatory thermodynamic stability of safety valves/steam traps [1 – 6].

$$\frac{\partial P}{\partial G} = \frac{A_2}{A_1} < 0\,, \tag{34}$$

$$\frac{\partial P}{\partial G} = \frac{B_2}{B_1} < 0\,. \tag{35}$$

Analysis of the results obtained

1. The obtained conditions for thermodynamic stability of the working medium in the passage zone (25), (34), (35), which ensure the necessary throughput capacity of safety valves/steam blowdown devices, can be determined in general by numerical integration using the Runge–Kutta method for given initial conditions (16)–(18) and design and technical parameters (L_K,L_0,$F(z)$,ξ).

2. Regulation of thermodynamic stability conditions can be ensured by modernising/reconstructing the structural and technical parameters of safety valves/steam traps.

3. The maximum pressure pulse of a water hammer with complete flow braking (lack of throughput capacity of safety valves/steam traps) due to pulsed thermodynamic instability is determined by the conversion of the kinetic energy of the flow into the energy of the water hammer pulse (24). Unlike the well-known Zhukovsky formula (1), the solution obtained takes into account the causes and conditions of water hammer occurrence, as well as the combined effect of energy effects and liquid phase compressibility on the maximum amplitude of water hammer back pressure.

4. Analysis of equations (13) – (15) for forming conditions of water hammer due to impulse thermodynamic instability in the confluence zone of safety valves/steam traps established the following.

The velocity gradient along the length of the confluence zone increases in proportion to the gradient of the cross-sectional area change:

$$\frac{dv}{dz} \sim -\frac{dF}{dz} > 0. \tag{36}$$

The flow velocity reaches its maximum value in the area with the minimum cross-sectional area $F_{\min}$.

In extreme cases, under certain conditions, the flow velocity reaches the speed of sound at this intersection (see Fig. 1*b*):

$$M = v / v_a = 1. \tag{37}$$

Pressure gradient along the length of the confluence zone:

$$\frac{dP}{dz} \sim \frac{-(dv/dz)}{(1-M^2)} < 0, \tag{38}$$

when transonic mode is reached (37) according to (38), there is a sudden increase in back pressure in the $F_{\min}$ cross-section (water hammer condition) and a corresponding deceleration of the flow (see Fig. 1*b*).

In the extreme case of complete flow deceleration, the maximum amplitude of the counterpressure pulse can be determined using formula (24).

5. The conditions of oscillatory thermodynamic instability in subsonic flow regimes are determined by the effects of simultaneous independent fluctuation deviations (disturbances) in pressure δ*P* and flow rate *δG* on the thermodynamic state of the system.

Let us consider a specific case of simultaneous fluctuation increase in pressure ↑δ*P* and flow rate ↑δG.

The consequence of ↑δP in a thermodynamic equilibrium state should be a corresponding decrease in flow rate ↓δGp. However, in the case of ↑δG > |↓δGp|, the total relative flow rate will increase with a relative increase in pressure – the system is in an unstable thermodynamic equilibrium state (3) and conditions of oscillatory thermodynamic instability arise with an oscillation frequency (4) (see Fig. 1*c*).

In the case of ↑δG<|↓δGp|, the system is in a stable equilibrium thermodynamic state (34), (35) and the amplitudes of the initial fluctuation deviations of the thermodynamic parameters decrease.

In the case of ↑δG=|↓δGp|, the system is at the boundary of the region of oscillatory thermodynamic instability.

Thus, the conditions of thermodynamic stability in subsonic modes are determined by the actual thermodynamic state of the system, which is reflected in the values of parameters A_1, A_2, B_1, B_2 in formulas (34), (35).

Conclusions

1. A method has been developed for qualifying the throughput capacity of safety valves and steam release devices in passive safety systems of nuclear power plants under conditions of pulsating and oscillatory thermodynamic instability.

2. The necessary condition for impulse thermodynamic instability has been established – the formation of a transonic flow regime of the working medium in the confluence zone of safety valves/steam ejectors.

The consequences of pulsed thermodynamic instability are a hydrodynamic "shock" due to the conversion of the kinetic energy of the flow into the internal energy of the hydrodynamic "shock" and the deceleration of the flow. The maximum pressure amplitude of the hydrodynamic "shock" due to pulsational thermodynamic instability at full flow deceleration has been determined.

3. The conditions and consequences of oscillatory thermodynamic instability in subsonic flow regimes in the flow zones of safety valves/steam blowdown devices have been established based on the fundamental principle of thermodynamic instability of equilibrium systems.

4. Based on the developed method for qualifying the throughput capacity of safety valves/steam traps, conditions and approaches have been determined to ensure thermodynamic stability of flow in the flow zones of safety valves/steam traps and to prevent hydrodynamic “shocks”.

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Скалозубов Володимир Іванович; Volodymyr Skalozubov, ORCID: https://orcid.org/0000-0003-2361-223X
Кацарський Юрій Сергійович; Iurii Katsarskyi, ORCID: https://orcid.org/0009-0001-9932-2880
Дербеньов Гліб Сергійович; Hlib Derbenov, ORCID: https://orcid.org/0009-0005-1881-2853
Мазур Євгеній Вікторович; Yevhenii Mazur, ORCID: https://orcid.org/0009-0005-0936-4411
Кочнєва Валерія Юріївна; Valeriia Kochnieva, ORCID: https://orcid.org/0000-0001-7397-3573

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