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THE PHYSICS AND REGULARITIES OF THE NEUTRON-THERMOACOUSTIC INSTABILITY

The physics and regularities of the neutron-thermoacoustic instability (NTAI) in nuclear channels with subcooled nucleate boiling flows are explained. The method for obtaining the characteristic equation of NTAI in a VVER-type reactor is given. The influence of steam reactivity coefficient $\partial k/\partial\varphi$ on NTAI boundaries is studied and the effect of a negative $\partial k/\partial\varphi$ favouring the oscillatory instability of neutron flux and pressure is shown.

Keywords: steam reactivity effect, neutron-thermoacoustic instability, VVER-1000.

1. Introduction

High requirements for safety and efficiency of nuclear reactors will remain relevant during the predictable time period of several decades. This problem is largely due to existing problems in ensuring safety and efficiency of nuclear fuel operation [1].

Two major catastrophes in the history of civil nuclear power, Chernobyl and Fukushima accidents, have been characterized by the synergic effect appeared in the form of an unpermitted change of some physical parameter having a critical impact on nuclear fuel operation safety, at the expense of joint action of several decisive factors influencing on this safety-significant parameter. That is the nature of most hazardous accidents related to nuclear fuel has been synergic.

From the point of view of the stability theory, both Chernobyl and Fukushima accidents have been so-called aperiodic instabilities. As the safety of nuclear fuel operation can also be greatly influenced by oscillatory instabilities occuring in the reactor core, it may be helpful to analyse the nature of processes leading to self-organization in the form of periodic oscillations of reactor core parameters.

For example, let us first consider the physics of propagation of the oscillatory thermoacoustic instability in non-nuclear channels. In the beginning, when the heat flux density q_s (W/m^2) increases gradually from zero, there is no boiling in the channel and pressure transducers register turbulent noises only. However, by a further increase of q_s, when keeping the underheating of water below the saturation temperature Ts sufficiently high, pressure transducers register spontaneous high-frequency pres-sure oscillations at some point in time [2].

Thermoacoustic oscillations (TAO) have such features [3]: first the amplitude A_p of pressure oscillations increases with growing q_s, then A_p decreases; before the heat exchange crisis, regular high-frequency pressure oscillations are usually absent while pressure transducers register random low-frequency noises only; the amplitude of pressure oscillations is maximum when heated lengths are relatively small and under-heatings of water below T_s are significant; TAO may destroy channel walls if pressure pulsations with high amplitudes proceed for several hours.

Back actions energizing the oscillatory system and contributing to the thermoacoustic instability (TAI) development in non-nuclear channels can be described as follows [2]. Let a bubble be near the antinode of a harmonic of pressure oscillations, that is the pressure deviation gradient does not influence the bubble. Thus, the bubble volume and the heat transfer surface area decrease when the channel pressure increases. Hence, if the bubble is in water underheated to the saturation temperature, then the intensity of steam condensation decreases when pressure increases, that is the steam outflow from the bubble decreases compared to the unperturbed state of the bubble. If the unperturbed state of the bubble is assumed to be neutral, as the intensity of steam condensation decreases when pressure increases and the bubble surface area decreases, then a steam mass is supplied to the bubble at the moment of pressure increase. On the contrary, the bubble surface area increases and a steam mass is removed from the bubble at the moment of pressure decrease.

Thus, compared to the unperturbed state of the bubble, a steam supply to the bubble at the moment of pressure increase promotes a further increase of pressure, while a steam outflow from the bubble at the moment of pressure decrease promotes a further decrease of pressure. According to the Rayleigh condition, the described pressure deviation feedback leads to self-excitation of oscillations [2].

2. Neutron-thermoacoustic instability

If thermoacoustic oscillations can appear under certain conditions in non-nuclear heated channels with subcooled nucleate boiling flows, a more complicated oscillatory instability, the so-called "neutron-thermoacoustic instability" (NTAI) characterized by joint oscillations of neutron flux density, coolant pressure and flow may occur in reactor channels with surface boiling [4].

Let us consider a bubble boiling flow in the thermohydraulic channel of a shrouded fuel assembly (FA), which is placed in the active core of a VVER-1000 reactor operated under normal conditions. Although shrouded FAs had been accepted in first VVER-1000 designs only, before open or canless FAs were given preference, a FA cover is necessary to simulate a thermo-hydraulic channel with boundaries that do not allow the acoustic energy to dissipate in the radial direction.

Knowing that thermoacoustic oscillations in a non-nuclear steam generating channel may be excited by deviations of energy transfer through the bubble surface according to the Rayleigh condition, due to the dependence of bubble-water heat exchange conditions on pressure deviations, let us consider the onset of NTAI. A pressure wave brings a local pressure deviation, for example, a local pressure growth compressing bubbles and decreasing the local volumetric steam content φ. A local decrease of φ leads to a local increase of the moderating power ξ of steam-water mixture.

Typical neutron moderation and diffusion periods in a VVER-1000 reactor are: $T_{\mathrm{mod}} \approx 6.7\ \mu\mathrm{s}$ and $T_{\mathrm{dif}} \approx 0.1\ \mathrm{ms}$, respectively [5], while the period of thermoacoustic oscillations is: $T_{\mathrm{TAO}} \approx 6\ \mathrm{ms}$ [4], so

$$(T_{\mathrm{mod}} + T_{\mathrm{dif}}) \ll T_{\mathrm{TAO}}.$$

Hence it is arguable that a local deviation of pressure in the channel causes an almost instantaneous change of local neutron flux density Φ. Then the deviation $\delta\Phi$ of neutron flux density may influence the coolant temperature in two ways:

1. It leads to a change of fuel temperature δt_f, a change of fuel element (FE) cladding temperature δt_{clad} and, as a result of heat transfer from cladding to water, changes of coolant temperature δt_w and bubble-water heat flow density δq_b:

$$\delta\Phi \to \delta t_f \to \delta t_{clad} \to \delta t_w \to \delta q_b. \tag{1}$$

2. $\delta\Phi$ leads to a deviation of the rate of direct energy release in coolant $\delta q_{v,w}$, which occurs due to moderation of neutrons and absorption of fission gamma-ray quantums in water. This change of direct energy release in coolant immediately influences bubble-water heat exchange conditions:

$$\delta\Phi \to \delta q_{v,w} \to \delta t_w \to \delta q_b. \tag{2}$$

As a fuel element is the macroscopic object with a considerable inertia, the first way (1) of $\delta\Phi$ influence on coolant temperature t_w is rather slow in comparison to the second way (2). For example, the calculated time constant of heat transfer from a FE cladding to water is 160 ms, as compared to the characteristic period of TAO oscillations $T_{\mathrm{TAO}} \approx 6\ \mathrm{ms}$ [4].

Thus, when studying the onset of NTAI in a thermohydraulic channel with subcooled boiling flow existing in the core of a VVER-type reactor, it is wrong to consider water temperature deviations, caused by fuel temperature deviations, and pressure deviations simultaneously.

The second way of $\delta\Phi$ influence on the coolant temperature is essential because near 6 % of the reactor thermal power is released directly in the core coolant, at the expense of moderation of neutrons and absorption of fission gamma-ray quantums in water [5].

If the volumetric steam content decreases locally, then a thermal neutron flux density deviation happens and the local direct energy release in the coolant changes practically immediately also.

Supposing that the sign of interphase energy transfer for heat flowing from water to a bubble is positive, these local deviations can be considered as interrelated variables: a pressure increase $\to$ compression of bubbles and a decrease of φ $\to$ an increase of the moderating power ξ of steam-water mixture $\to$ an increase of thermal neutron flux density $\to$ an increase of direct energy release in water $\to$ an increase of interphase heat flow density $\to$ an increase of pressure, that is

$$\delta p > 0 \to \delta\varphi < 0 \to \delta\xi > 0 \to \delta\Phi > 0 \to$$

$$\delta q_{v,w} > 0 \to \delta q_b > 0 \to \delta p > 0.$$

Thus we have obtained the Rayleigh condition leading to self-excitation of pressure and neutron flux oscillations [4].

3. A model of NTAI

When considering reactor control problems, the one-group neutron diffusion model is usually applied to VVER-type thermal power reactors [6], so this neutron diffusion model may be used in the NTAI case also. Such key processes are modelled to describe the development of neutron-thermoacoustic instability: neutron diffusion; FE heat conductivity; two-phase flow; movement of bubbles in water after their lift-off.

Using a one-dimensional model of NTAI, the position is specified by axial coordinate z only. Thus, the Laplacian of neutron flux density $\Delta\Phi$ is written as

$$\Delta\Phi = d[d\Phi / dz] / dz, \tag{3}$$

where

$$d\Phi / dz = I / D, \tag{4}$$

where I - neutron current modulus; D - diffusion coefficient.

To describe underheated boiling flow in a reactor channel, well-known equations for neutron flux, FE conductivity, flow continuity, flow momentum conservation, flow energy, continuity of the number of bubbles, the balance between bubble interface forces, heat and mass transfer are considered. Also the equations connecting flow “macroparameters” and “microparameters” have been used [3]:

$$\varphi = \int_{z_k}^{z} N_b \cdot V_b \cdot d\xi, \tag{5}$$

$$G_s = \int_{z_k}^{z} \rho_s \cdot w_b \cdot N_b \cdot V_b \cdot F_c \cdot d\xi, \tag{6}$$

where $N_b(z,\xi,\tau)$ is the number of bubbles in a cubic unit at location z in moment τ, which are born at location ξ per unit length; $V_b(z,\xi,\tau)$ and $w_b(z,\xi,\tau)$ are the same for bubble volume and velocity, respectively; G_s and ρ_s are steam rate and density, respectively; F_c is the equivalent cross-sectional area corresponding to the triangular grid of fuel elements.

The bubble flow microstructure is described supposing that $\Delta z = \text{const}$ is the length of a conditional piece of the channel; $n(z)$ is the number of the conditional piece corresponding to z coordinate; $N_{b,i}(z)$ is the concentration of bubbles at location z in a moment τ, which are born at the i-th conditional piece of the channel per unit length; $V_{b,i}(z)$ and $w_{b,i}(z)$ are the same for bubble volume and velocity, respectively [3].

So, the initial system of equations is written in the deviation form and linearized. Thereupon some remarks on the applicability of the linearization should be made. The specificity of neutron flux stabilization permits the use of reactor equations linearized with respect to small deviations (perturbations) from stationary parameter values, as deviations of neutron field are restricted by automatic regulators. Accordingly, if neutron field deviations are not sufficiently small, they are already too large from the safety point of view, and thus they activate the reactor protection system [6].

Assuming zero initial conditions, the Laplace transform is applied to the linearized system of equations. Denoting the Laplace variable as s, the system of equations for deviations of integral core parameters (neutron current modulus, neutron flux density, flow rate, pressure, etc.) and microstructural flow parameters (volume, velocity and concentration of bubbles) is obtained:

$$d\vec{Y} / dz = \mathbf{P} \cdot \vec{Y} + [\vec{L} \cdot (\mathbf{M} \cdot \vec{Y}) + \vec{N} \cdot (\mathbf{T} \cdot \vec{Y})] \cdot \Delta z, \tag{7}$$

where $\vec{Y} = [\delta I, \delta\Phi, \delta G, \delta P, \delta i_w, \delta N_{b,1} ... \delta N_{b,n(H)}, \delta w_{b,1} ... \delta w_{b,n(H)}, \delta V_{b,1} ... \delta V_{b,n(H)}]^{\mathrm{T}}_{\mathrm{L}}$, the vector length is $[3 \cdot n(H) + 5]$; δG, δP and δi_w are deviations of steam-water mixture flow rate, channel pressure and water enthalpy, respectively; $\mathbf{P}(z,s)$, $\mathbf{M}(z)$, $\mathbf{T}(z)$ are matrices of the order $[3 \cdot n(H) + 5] \times$ $\times [3 \cdot n(H) + 5]$; H is the channel length; $\vec{L}(z)$ and $\vec{N}(z)$ are vectors, their length is $[3 \cdot n(H) + 5]$.

After simple operations on matrices, it is obtained from (7):

$$d\vec{Y} / dz = \mathbf{S} \cdot \vec{Y}, \tag{8}$$

where $\mathbf{S}(z,s)$ is a matrix, its order is $[3 \cdot n(H) +$ $+5] \cdot [3 \cdot n(H) + 5]$, its elements are constructed of the elements of $\mathbf{P}(z,s)$, $\mathbf{M}(z)$, $\mathbf{T}(z)$, $\vec{L}(z)$ and $\vec{N}(z)$: $s_{k,j} = p_{k,j} + (l_k \cdot m_{k,j} + n_k \cdot t_{k,j}) \cdot \Delta z.$

The solution of (8) is found as [7]:

$$\vec{Y}(z) = \mathbf{\Phi}(z,s) \cdot \vec{Y}(z_k), \tag{9}$$

where $\mathbf{\Phi}(z,s)$ is the fundamental matrix normalized at the point of intensive vaporization start $z = z_k$, the order is $[3 \cdot n(H) + 5] \cdot [3 \cdot n(H) + 5]$, its elements are determined as

$$d\phi_{k,i} / dz = \sum_{j=1}^{3\cdot n(H)+5} s_{k,j} \cdot \phi_{j,i}, \quad (10)$$

where $\varphi_{k,i}(z_k) = 1$ if $k = i$; $\varphi_{k,i}(z_k) = 0$ if $k \neq i$.

Using (9), we obtain:

$$\vec{Y}(H) = \mathbf{\Phi}(H, s) \cdot \vec{Y}(z_k). \quad (11)$$

Like the method of [8], it is assumed that deviations of core inlet parameters are given as

$$\delta I_{in} \neq 0; \delta G_{in} \neq 0; \delta\Phi_{in} = \delta P_{in} = \delta i_{w,in} = 0. \quad (12)$$

Such conditions are at the core outlet:

$$\delta\Phi(H) = \delta P(H) = 0. \quad (13)$$

It is assumed that deviations of flow microparameters at the point of intensive vaporization start z_k are zero:

$$\delta N_b(z_k) = \delta w_b(z_k) = \delta V_b(z_k) = 0. \quad (14)$$

If $\mathbf{\Phi_0}$ denotes the fundamental matrix for the single-phase channel section, then

$$\delta I_{\mathrm{L}}(z_k) = \delta I_{in,\mathrm{L}} \cdot \phi_{0,11}(z_k) + \delta G_{in,\mathrm{L}} \cdot \phi_{0,13}(z_k). \quad (15)$$

$$\delta\Phi_{\mathrm{L}}(z_k) = \delta I_{in,\mathrm{L}} \cdot \phi_{0,21}(z_k) + \delta G_{in,\mathrm{L}} \cdot \phi_{0,23}(z_k). \quad (16)$$

$$\delta G_{\mathrm{L}}(z_k) = \delta I_{in,\mathrm{L}} \cdot \phi_{0,31}(z_k) + \delta G_{in,\mathrm{L}} \cdot \phi_{0,33}(z_k). \quad (17)$$

$$\delta P_{\mathrm{L}}(z_k) = \delta I_{in,\mathrm{L}} \cdot \phi_{0,41}(z_k) + \delta G_{in,\mathrm{L}} \cdot \phi_{0,43}(z_k). \quad (18)$$

$$\delta i_{w,\mathrm{L}}(z_k) = \delta I_{in,\mathrm{L}} \cdot \phi_{0,51}(z_k) + \delta G_{in,\mathrm{L}} \cdot \phi_{0,53}(z_k). \quad (19)$$

The elements of $\mathbf{\Phi_0}$ are determined as

$$d\phi_{0,k,i} / dz = \sum_{j=1}^{5} p_{k,j} \cdot \phi_{0,j,i}. \quad (20)$$

Based on (9) and (13), it is obtained:

$$\delta P_{\mathrm{L}}(H) = \delta I_{\mathrm{L}}(z_k) \cdot \phi_{41}(H) + \delta\Phi_{\mathrm{L}}(z_k) \cdot \phi_{42}(H) +$$
$$+\delta G_{\mathrm{L}}(z_k) \cdot \phi_{43}(H) + \delta P_{\mathrm{L}}(z_k) \cdot \phi_{44}(H) +$$
$$+ \delta i_{w,\mathrm{L}}(z_k) \cdot \phi_{45}(H). \quad (21)$$

$$\delta\Phi_{\mathrm{L}}(H) = \delta I_{\mathrm{L}}(z_k) \cdot \phi_{21}(H) + \delta\Phi_{\mathrm{L}}(z_k) \cdot \phi_{22}(H) +$$
$$+\delta G_{\mathrm{L}}(z_k) \cdot \phi_{23}(H) + \delta P_{\mathrm{L}}(z_k) \cdot \phi_{24}(H) +$$
$$+ \delta i_{w,\mathrm{L}}(z_k) \cdot \phi_{25}(H). \quad (22)$$

Substituting (15) - (19) in Eqs. (21) and (22), taking into account (13), the equation is obtained:

$$\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{pmatrix} \delta I_{in,\mathrm{L}} \\ \delta G_{in,\mathrm{L}} \end{pmatrix} = 0. \quad (23)$$

So, the characteristic equation of NTAI is derived from (23) as

$$h_{11} \cdot h_{22} - h_{21} \cdot h_{12} = 0. \quad (24)$$

The simultaneous consideration of deviations of both integral core parameters, especially neutron current modulus and neutron flux density, and flow microparameters, when solving the boundary-value problem, allows us to consider the influence of the neutron flux deviation feedback on the propagation of TAI in channels of a VVER-type reactor.

A deviation of bubble-water heat flow density δq_b is calculated as [5]:

$$\delta q_b = \delta\varphi \cdot \frac{\partial q_b}{\partial\varphi} + \delta p \cdot \frac{\partial q_b}{\partial p} + \delta\Phi \cdot \frac{\partial q_b}{\partial\Phi}, \quad (25)$$

where $\partial q_b / \partial\varphi \approx -8.8 \cdot 10^5$; $\partial q_b / \partial p \approx 0$;

$$\frac{\partial q_b}{\partial\Phi} = \frac{\partial q_b}{\partial q_{v,w}} \cdot \frac{\partial q_{v,w}}{\partial q_v} \cdot \frac{\partial q_v}{\partial\Phi}, \quad (26)$$

where heat radiation makes a major contribution to heat transfer at distances less than 1 mm, from heat release microcentres emerging due to moderation of neutrons and absorption of gamma-ray quantums in water.

Considering heat radiation as the main mechanism of heat transfer at microdistances in water, a partial derivative of bubble-water heat flow density q_b with respect to water volume energy release density $q_{v,w}$ is found. This partial derivative $\partial q_b / \partial q_{v,w}$ has been estimated for bubble diameters $d_b = 10^{-3}...10^{-4}$ m [4]:

$$\partial q_b / \partial q_{v,w} = \delta q_b / \delta q_{v,w} \approx 4 \cdot 10^{-3};$$

$$\partial q_{v,w} / \partial q_v \approx 0.03; \;\; \partial q_v / \partial\Phi \approx 2 \cdot 10^{-10}.$$

4. Results

The characteristic equation (24) of NTAI is represented as a function of complex variable s:

$$F(s) = 0, \quad (27)$$

and its solution is [9]:

$$s = j \cdot \omega, \quad (28)$$

where ω is cyclic frequency.

Hence, if we find a value of ω making (27) true, when the frequency characteristic $F(j \cdot \omega)$ passes through point $(0; j \cdot 0)$, we obtain the frequency at which the stability boundary is crossed by any variable of the set $(\delta I, \delta\Phi, \delta G, \delta P, \delta i_w, \delta N_{b,1}...\delta N_{b,n(H)}, \delta w_{b,1}...\delta w_{b,n(H)}, \delta V_{b,1}...\delta V_{b,n(H)})$.

To determine instability areas, evidently stable points are marked on the complex frequency response (CFR) plane [9]. For example, the one-phase mode is evidently stable.

Such conditions of a shrouded FA are considered: the surface boiling area (SBA) inlet water temperature is constant: $t_{w,b,in} = 335\,°\mathrm{C}$; the SBA inlet axial coordinate is constant: $z_{b,in} = 2.6$ m; the SBA length varies: L_b = 10; 20; 40; 50 cm. By increasing the SBA heat flux density, lower instability boundaries for zero steam reactivity coefficient $\partial k / \partial\varphi$ are found (Table).

Lower instability boundaries at $\partial k / \partial\varphi = 0$

L_b, cm	$< q_{s,lb} >$, %	$< \varphi_{lb} >$, %
10	18	0.2
20	23	0.3
40	70	1.6
50	113	3.2

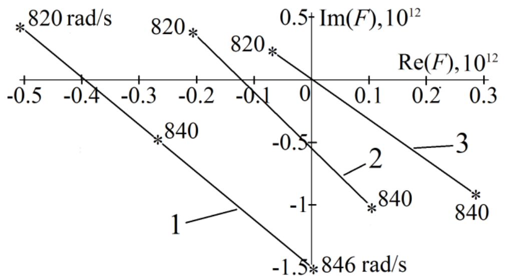

Fig. 1. CFR at L$_b$ = 10 cm and $\partial k / \partial\varphi = 0$: *1*, *2*, *3* – $< q_s > = 0.11$, 0.16 and 0.19 MW / m^2, respectively (the calculated oscillation frequency is 823 rad/s).

As the lower instability boundary at L_b = 50 cm and $\partial k / \partial\varphi = 0$ is 113 % of the nominal $< q_s >$, hence the lower boundary cannot be achieved at $L_b \geq 50$ cm and $< q_s > =$ 100 %, while it is crossed at L_b = 10…40 cm. Showing CFR segments as straight lines, the lower boundary for L_b = 10 cm is given in Fig. 1.

If $\partial k / \partial\varphi < 0$, then neutron flux, direct energy release in the coolant and heat influx to bubbles increase at increasing pressure, and the Rayleigh condition for self-excitation of oscillations is satisfied.

On the contrary, if $\partial k / \partial\varphi > 0$, then NTAI will be suppressed.

If L_b = 30 cm and $\partial k / \partial\varphi = -2$, the lower border is crossed at $< q_{s,lb} > = 30...35$ %, while it is not reached for $\partial k / \partial\phi = 0$ and $< q_{s,lb} > = 35$ %. Thus, compared to $\partial k / \partial\varphi = 0$, NTAI is aggravated at $\partial k / \partial\varphi < 0$ (Fig. 2).

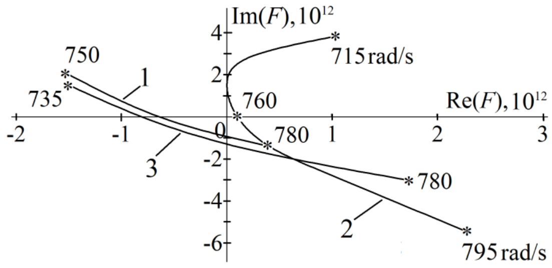

Fig. 2. CFR at L$_b$ = 30 cm: *1*, *2* – $< q_s > = 30$ and 35 % at $\partial k / \partial\varphi = -2$, respectively; *3* $< q_s > = 35$ % at $\partial k / \partial\varphi = 0$.

For L_b = 30 cm, it has been found that NTAI is supressed if $\partial k / \partial\varphi = 2$. Considering L_b = 40 cm and $\partial k / \partial\varphi = -2$, the lower border is at $< q_s > = 65...69$ %, while NTAI is suppressed if $\partial k / \partial\varphi = 2$. Finally, if L_b = 45 cm, the aggravation ($\partial k / \partial\varphi = -2$) and the suppression ($\partial k / \partial\varphi = 2$) of NTAI are shown in Fig. 3.

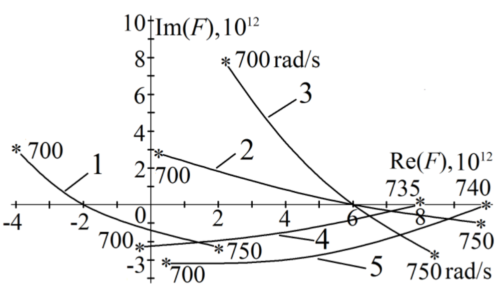

Fig. 3. CFR at L$_b$ = 45 cm: *1* – $< q_s > = 91$ % at $\partial k / \partial\varphi = -2$; 0 and 2; *2*, *3* – $< q_s > = 92$ % at $\partial k / \partial\varphi = 0$ and – 2, respectively; *4*, *5* – $< q_s > = 92$ and 93 % at $\partial k / \partial\varphi = 2$, respectively.

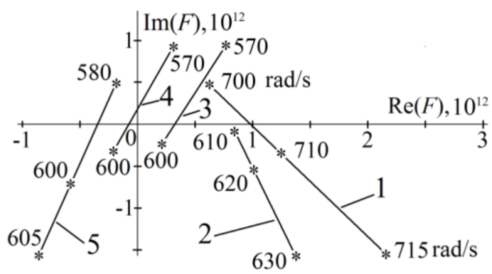

Fig. 4. Determination of the NTAI upper boundary at L$_b$ = 40 cm and $\partial k / \partial\varphi = 0$: *1*, *2*, *3*, *4*, *5* – $< q_s > = 77$, 83, 85, 86 and 87 %, respectively.

Thereby, here is a contradiction:

on the one hand, a negative steam coefficient of reactivity is obligatory for insuring the safety of VVER-1000 type reactors, at the expense of self-regulation of the heavy nuclei fission reaction;

on the other hand, considering a shrouded FA with maximum permitted LHRs, which is normally operated in a VVER-1000 core, the process of NTAI propagation is aggravated at $\partial k / \partial\varphi < 0$.

Now the following remark should be given. The neutron flux deviation feedback cannot function at extremely low volumetric steam contents $<\varphi_b>$ in the surface boiling area, when the steam-water mixture density practically does not depend on oscillations of $<\varphi_b>$.

Hence, at very low $<\varphi_b>$, thermoacoustic oscillations of pressure practically do not change the moderating power of steam-water mixture, thermal neutron flux density, direct energy release in the coolant and interphase heat flow density. So, thermoacoustic oscillations of pressure are not able to make the neutron flux feedback work in this case. It has been found that, if $<\varphi_b> \approx 0.2\,\%$, then there is no dependence of NTAI lower boundaries on steam reactivity coefficient $\partial k / \partial\varphi$. Thus, in the NTAI physics, the neutron flux feedback is turned off at average volumetric steam contents in the surface boiling area near $0.2\,\%$.

4.1. Influence of $\partial k / \partial\varphi$ on NTAI upper boundaries

As shown above, NTAI lower boundaries shift downward under the influence of neutron flux feedback at $\partial k / \partial\varphi < 0$ and, to some extent, TAI regions expand. The next question is whether the steam coefficient of reactivity influences NTAI upper boundaries. It has been found for $L_b = 40$ cm and $\partial k / \partial\varphi = 0$ that the NTAI upper boundary is achieved at $<q_{s,ub}> = 85...86\,\%$ (Fig. 4).

As the lower NTAI boundary under these conditions is $<q_{s,lb}> = 69...70\,\%$, the instability for $\partial k / \partial\varphi = 0$ exists in the range: $<q_{s,in}> \approx 69...86\,\%$. But, for $L_b = 40$ cm and $\partial k / \partial\varphi = -2$, the upper boundary has not been found until $<q_s> = 110\,\%$. Thus, while the upper boundary at $\partial k / \partial\varphi = 0$ $<q_{s,ub}> \approx 86\,\%$, it is above 110 % for $\partial k / \partial\varphi = -2$. So, the steam coefficient of reactivity greatly affects the NTAI upper boundary position.

Accepting $L_b = 45$ cm, the calculated NTAI upper boundary at $\partial k / \partial\varphi = 0$ lies in the range: $<q_{s,ub}> = 110...113\,\%$. As the lower boundary under these conditions is $<q_{s,lb}> = 91...92\,\%$, then the instability at $\partial k / \partial\varphi = 0$ exists in the range: $<q_s> \approx 91...113\,\%$. But, if $\partial k / \partial\varphi = -2$, the upper boundary has not been found until $<q_s> = 140\,\%$. The CFR curve goes round (0; $j\cdot 0$), then goes far from the zero point with increasing $<q_s>$. While the upper boundary at $\partial k / \partial\varphi = 0$ is $<q_{s,ub}> \approx 113\,\%$, it is above 140 % at $\partial k / \partial\varphi = -2$.

Hence, a negative $\partial k / \partial\varphi$ greatly expands NTAI areas due to significant shift of upper instability boundaries, compared to the neutral case of $\partial k / \partial\varphi = 0$.

NTAI lower boundaries are also shifted under the influence of neutron flux feedback, but this shift is not substantial. So, although the neutron flux deviation feedback is not sufficiently strong to make a considerable effect on NTAI lower boundaries, nevertheless this feedback is powerful enough to keep the neutron-thermoacoustic instability in a much wider range of heat fluxes compared to the case of non-nuclear thermoacoustic oscillations, at the expense of considerable shifting NTAI upper boundaries.

4.2. The "Alpha" parameter

It has been found that the steam reactivity coefficient $\partial k / \partial\varphi$ is a key parameter in functioning of the neutron flux feedback influencing the propagation of NTAI. But, according to (25), there is some parameter that determines the degree of $\partial k / \partial\varphi$ influence on the scenario of instability development: the partial derivative of bubble-water heat flow density with respect to neutron flux density $\partial q_b / \partial\Phi$. In its turn, according to (26), $\partial q_b / \partial\Phi$ depends on $\partial q_b / \partial q_{v,w}$, which is found as

$$\frac{\delta q_b}{\delta q_{v,w}} = \frac{\alpha}{[q_{v,w} / q_b]_0}, \qquad (29)$$

where α is the ratio of a dimensionless deviation of bubble-water heat flow density $\bar{\delta} q_b$ to a dimensionless deviation of the rate of direct energy release in the coolant $\bar{\delta} q_{v,w}$:

$$\alpha = \frac{\bar{\delta} q_b}{\bar{\delta} q_{v,w}} = \frac{\delta q_b / q_{b,0}}{\delta q_{v,w} / q_{v,w,0}}, \qquad (30)$$

where $[q_{v,w} / q_b]_0 \approx 22\ \text{m}^{-1}$.

Considering a shrouded FA with maximum permitted LHRs and steam contents, which is placed in a VVER-1000 reactor operated under normal conditions, keeping constant the SBA inlet temperature $t_{w,b,in}$ and coordinate $z_{b,in}$ ($t_{w,b,in} = 335\,°\text{C}$; $z_{b,in} = 2.6\,\text{m}$), the lower NTAI boundary is achieved by increasing the SBA heat flux density. Denoting the NTAI region width through $\text{WID} \equiv < q_{s,ub} > - < q_{s,lb} >$, and the width change through ΔWID, the dependency of ΔWID on α for $L_b = 45$ cm is shown in Fig. 5.

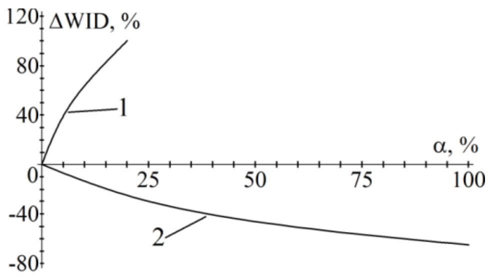

Fig. 5. NTAI region width depending on α for $L_b = 45$ cm: *1*, *2* – $\partial k / \partial\varphi < 0$ and $\partial k / \partial\varphi > 0$, respectively.

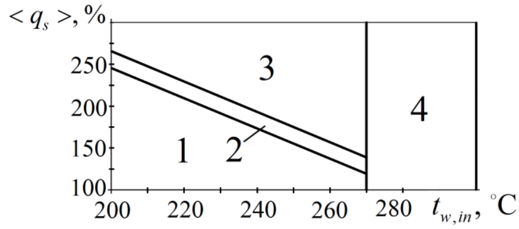

Fig. 6. NTAI in a shrouded FA, VVER-1000 type reactor: *1*, *2*, *3*, *4* – boiling-free, NTAI, bulk boiling and stability areas, respectively.

For $L_b = 40$ cm and $L_b = 45$ cm, the analysis of TAI boundaries at $\partial k / \partial\varphi = 0$ has given the instability regions, respectively, $< q_{s,in} > \approx 69...86\,\%$ and $< q_s > \approx 91...113\,\%$, and these instability regions may significantly expand under the influence of a negative $\partial k / \partial\varphi$, hence a VVER-1000 type reactor having a sufficient number of shrouded FAs with intense surface boiling may be unstable with respect to the neutron-thermoacoustic instability.

It should be noted that, though the stability of a linearized system allows us to conclude that the original nonlinear system is "stable in the small" also, however, the linear analysis gives only a qualitative picture of the effect of a parameter on stability boundaries. So, quantitative estimates of stability boundaries obtained using the linear approximation must be experimentally verified [9].

Nevetheless, based on the above analysis, we can conclude that if some requirements are satisfied, the neutron-thermoacoustic instability is likely to influence the safety of nuclear fuel operation in a VVER-1000 type reactor.

4.3. Influence of the heating length on NTAI

These two cases have been simulated: short heating lengths (40 - 45 cm) and long heating lengths (3 - 3.5 m). In the case of short heated channels, when the SBA width may be above 100 % of the nominal $< q_s >$ value, the upper TAI boundary lies below the lower bulk boiling area and all the above conclusions are true. But, in the case of long heated channells characteristic for a VVER-1000 type reactor, the upper TAI boundary is not achieved in that narrow $< q_s >$ range, which is typical for transfer from surface water boiling to bulk boiling (20…25 % on the $< q_s >$ scale). So, practically the upper TAI boundary is limited by the lower bulk boiling boundary.

As the TAI area is expanded by the neutron flux deviation feedback thanks mainly to shifts of the upper TAI boundary, hence the neutron feedback has no considerable influence on the propagation of TAI in the case of long heated channels. Thus, the simplified task of TAI may be considered instead of the NTAI problem in the case of long heated channels – of course, while taking into account the neutron-physics characteristics of the reactor core.

Using the described NTAI model, considering a shrouded maximally loaded FA operated in a VVER-1000 type reactor, it has been found that the calculated instability region lies in the range of core coolant inlet temperatures $t_{w,in} = 200 - 270\,°\text{C}$ (the case of $t_{w,in} < 200\,°\text{C}$ has not been considered). If $t_{w,in} = 200\,°\text{C}$ and $270\,°\text{C}$, NTAI starts at $< q_s > = 246\,\%$ and 119 % of the nominal $< q_s >$ value, respectively (Fig. 6).

5. Conclusions

1. The oscillatory neutron-thermoacoustic instability, which could potentially influence the safety and efficiency of nuclear fuel operation, has been theoretically predicted considering a fuel assembly with intense surface boiling operated in the core of a VVER-1000 type reactor, and by taking into account:

the effect of fuel assembly shroud on flow boundary conditions;

the influence of neutron flux deviation feedback on propagation of thermoacoustic oscillations in shrouded FAs – the synergic effect of simultaneous consideration of processes having different physical mechanisms and proceeding on different structural levels of the reactor core;

life histories of distinguished groups of steam bubbles, from their birth to their condensation.

2. Having calculated NTAI boundaries, it has become clear that, compared to the neutral case $(\partial k / \partial \varphi = 0)$, a negative $\partial k / \partial \varphi$ favours the thermoacoustic instability, while a positive $\partial k / \partial \varphi$ stems it. Thus, according to the commonly accepted idea, the effect of a negative steam reactivity coefficient is necessary to ensure the self-regulation and safety of the chain fission reaction, but nevertheless, this effect favours the oscillatory instability of neutron flux and pressure under some conditions. Probably, due to a huge pressure in the reactor core, these oscillations will be low-amplitude, high-frequency and hard-to-detect.

3. As operating modes with core coolant inlet temperatures $t_{w,in} = 200 - 270\,°\mathrm{C}$ are possible for a VVER-1000 type reactor, such reactors may be unstable to the neutron-thermoacoustic instability on condition that there is a sufficient number of shrouded FAs having developed surface boiling areas in the core.

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ФІЗИЧНИЙ МЕХАНІЗМ І ЗАКОНОМІРНОСТІ НЕЙТРОННО-ТЕРМОАКУСТИЧНОЇ НЕСТІЙКОСТІ

Розглядаються фізичний механізм і закономірності нейтронно-термоакустичної нестійкості (НТАН) в ядерних каналах із недогрітим бульбашковим киплячим потоком. Пояснюється метод отримання характеристичного рівняння НТАН у реакторі типу ВВЕР. Вивчено вплив парового коефіцієнта реактивності $\partial k / \partial \varphi$ на межі НТАН, а також показано, що від'ємний $\partial k / \partial \varphi$ сприяє розвитку коливальної нестійкості нейтронного потоку та тиску.

Ключові слова: паровий ефект реактивності, нейтронно-термоакустична нестійкість, ВВЕР-1000.

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ФИЗИЧЕСКИЙ МЕХАНИЗМ И ЗАКОНОМЕРНОСТИ НЕЙТРОННО-ТЕРМОАКУСТИЧЕСКОЙ НЕУСТОЙЧИВОСТИ

Рассматриваются физический механизм и закономерности нейтронно-термоакустической неустойчивости (НТАН) в ядерных каналах с недогретым пузырьковым кипящим потоком. Объясняется метод получения характеристического уравнения НТАН в реакторе типа ВВЭР. Изучено влияние парового коэффициента реактивности $\partial k / \partial \varphi$ на границе НТАН и показано, что отрицательный $\partial k / \partial \varphi$ способствует развитию колебательной неустойчивости нейтронного потока и давления.

Ключевые слова: паровой эффект реактивности, нейтронно-термоакустическая неустойчивость, ВВЭР-1000.

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