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The influence of dynamic bending of fuel rods on the dynamics of a pulsed reactor

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The paper investigates the influence of transverse thermoelastic deformations of fuel elements (fuel rods) on the dynamics of a pulsed reactor. Analysis of the fuel rod motion equation and numerical modeling of reactor dynamics made it possible to determine the parameters of stable operation and explain pulse energy fluctuations. Methods are proposed for eliminating the negative effect of dynamic bending of fuel elements in the design of the active zone of a future pulsed reactor.

Keywords: pulsed reactors, active zone, thermoelasticity, reactivity

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Current trends in the studies on neutron beams require development of pulse sources with the average density of thermal neutron flux not below $10^{14}\,\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$ [1]. The IBR-2M reactor that has been in service in the Neutron Physics Laboratory of the Joint Institute for Nuclear Reaearch since the 1980s till the present time generates a flux at the level of $10^{13}\,\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$, and its resource will be exhausted in 2030s. The experience of operation of pulsating reactors and theoretical works demonstrate that it is possible to achieve the required values of neutron flux density and pulse duration only with the new design of the reactor core [1,2]. We will call the reactor dynamics in this paper the nature of pulse energy change in time. The problem consists in appearance of oscillatory instability at the average power of the reactor above 1 MW — sever (30 % and more) and uncontrolled deviations of pulse energy from the average value. In paper [3] the spectral composition of the pulse energy was studied for IBR-2 and IBR-2M reactors. It was shown that these fluctuations could not be explained exclusively by vibrations of the reactivity modulator and vibrations of fuel elements when exposed to the coolant flow. The reason for this negative phenomenon may consist in the feedback by reactivity arising from non-stationary thermoelastic strains of the main elements in the reactor core: fuel pellets, fuel elements and fuel assemblies (FA) [4,5].

The objectives of this paper consist in studying the effect of the impact bending of fuel elements at the dynamics of the pulsating reactor and offering the methods to eliminate oscillatory instability in the development of the design of a new source of neutrons — NEPTUN reactor [1]. For this purpose the properties of the impact bending of the fuel element were studied as the oscillatory process. The numerical calculations were carried out for the dynamics of the reactor with account of the impact bending in the oscillatory approximation, the possibility for occurrence of the dynamics similar to the noise observed in the IBR-2 reactor was shown. To conclude, measures were proposed to reduce the oscillatory instability, which may be introduced into the design of the designed reactor core.

The solution to the problem of the transverse oscillations of the fuel element in the pulsating reactor in the approximation of the added mass [6]. The type of the solution is a sum of solutions for single-dimensional oscillators, the intrinsic frequencies of which depend on the fuel element design. Therefore, to account for the effect of the impact bending in the reactor dynamics model it is sufficient to consider one equation of forced oscillations of the single-dimensional oscillator at different values of the intrinsic frequency

$$\ddot{x} + \frac{2}{\tau}\dot{x} + (2\pi\nu)^2 x = A\hat{T}(t), \qquad (1)$$

where the point means a time derivative. Under x one should understand the effective (averaged along the fuel element length) displacement of fuel pellets [mm], ν — intrinsic frequency of transverse oscillations of the fuel element [Hz] (the fuel element has several intrinsic frequencies — harmonics, but the first harmonic with the least frequency is of the primary interest, which will become evident further), τ — attenuation time of free oscillations [s], $\hat{T}$ — fuel element shell temperature exceeding the coolant temperature [K], A — coefficient of proportionality between temperature $\hat{T}$ and effective transverse acceleration, arising as a result of bending thermoelastic voltages in the bar $[\mathrm{mm}/(\mathrm{s}^2\cdot\mathrm{K})]$. The coefficient A depends on the distribution of mass and temperature in the axis of the fuel element, the gradient of temperature in the transverse direction and the shell geometry [6]. The direction of bending relative to the reactor core center and accordingly the sign of parameter A depends on the method of fuel element fixation.

The upper boundary of the attenuation time τ was determined in the experiments with the model fuel

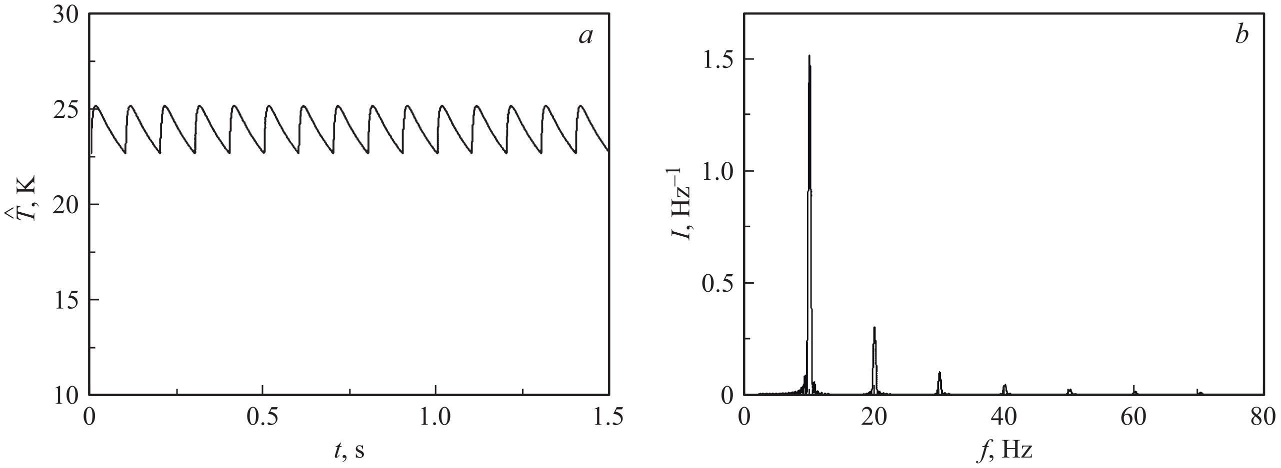

Figure 1. Temperature $\hat{T}(t)$ at constant pulse energy (a) and its spectrum $I(f)$ (b).

elements in paper [7] and is equal to 3 s. Since the reduction in the attenuation time knowingly causes more stable solutions in the dynamics model, in all calculations of this paper the value τ is accepted as equal to 3 s. The intrinsic frequency ν strongly depends on the method of fuel element fixation and is of the primary interest in this paper, since the final design of the new reactor core has not yet been approved. Therefore, further calculations will be carried out with the different values of parameter ν.

To determine the interval of intrinsic frequency values that may affect the dynamics of the pulsating reactor, let us consider the view of function $\hat{T}(t)$. The periodical mode of reactor operation makes it possible to calculate the shell temperature of the fuel element $\hat{T}$ as the sum of contributions from the previous pulses [6]:

$$\hat{T}(t) = \sum_{l=i-1}^{0} \Theta\left(\frac{1}{\nu_0}(i-l) + t'\right) Q_l, \tag{2}$$

where i — number of another pulse, t' — interval of time between the last pulse and the current moment t [s], ν_0 — frequency of reactor pulsations [Hz], Q_l — energy of lth pulse [MJ]. Function $\Theta(t)$ — growth in fuel element shell temperature after a single pulse of unit power [K/MJ]. The numerical calculation of the function $\Theta(t)$, made in paper [5], makes it possible to build a chart $\hat{T}(t)$ for the case of pulses of the same energy $Q_l = 1.25$ MJ and its spectrum $I(f)$, normalized by one (Fig. 1).

The spectrum in Fig. 1 contains a series of peaks with frequencies multiple to the primary frequency of pulsations ($\nu_0 = 10$ Hz for the NEPTUN reactor). The area of the first four peaks is 98 % of the area of the entire spectrum (dynamic effect at the fuel element happens mostly in the range from 0 to 50 Hz). It means that there is probability of resonance oscillations of the fuel element shell, if its intrinsic frequencies are below 50 Hz. Besides, the maximum amplitude $x(t)$ was calculated in equation (1) at intrinsic frequency $\nu = 50$ Hz. The amplitude $x(t)$ was $2 \cdot 10^{-4}$ mm, which is a negligibly low value from the point of view of the reactivity disturbances. These arguments make it possible to limit the range of the studied values of parameter ν by value of 50 Hz.

Note the important property of forced oscillations with the periodical external impact, which consists in the phase shift between the oscillator position and the external force. The phase shift depends on the friction value, intrinsic frequency and spectrum of external impact [8]. In particular, if the intrinsic frequency of the oscillator is close to the primary frequency of the external force, the oscillator is in the antiphase with the external force. This means that fuel elements bending towards one side under stationary heat release in case of periodical heat release will be bent to the opposite side at the reactor pulse moments. Accordingly, the reactivity effects will also be opposite. This fundamental difference of the impact bending from the static one must be considered when selecting the reactor core design for the pulsating reactor.

The dynamics model describing the behavior of the pulsating reactor in the self-control mode consists of the equation of single-point kinetics of the pulse reactor in the approximation of the δ-pulse, equations of the sources of retarded neutrons in the eight-group approximation, equations for the fuel temperature. To account for the impact bending of fuel elements, the oscillator equations (1), (2) were added to the system:

$$Q_i = S_i M\big(\varepsilon + R_{ax} T_i + R_{tr} x(i/\nu_0)\big), \tag{3}$$

$$c_{ji} = \big(c_{ji-1} + Q_{i-1}\eta\beta_j\big)\exp\big(-\lambda_j/\nu_0\big), \tag{4}$$

$$S_i = \sum_{j=1}^{8} c_{ji}\lambda_j, \tag{5}$$

$$T_i = \big(T_{i-1} + Q_{i-1}T_0\big)\exp\big(-p/\nu_0\big), \tag{6}$$

$$\ddot{x} + \frac{2}{\tau}\dot{x} + (2\pi\nu)^2 x = A\hat{T}(t), \tag{7}$$

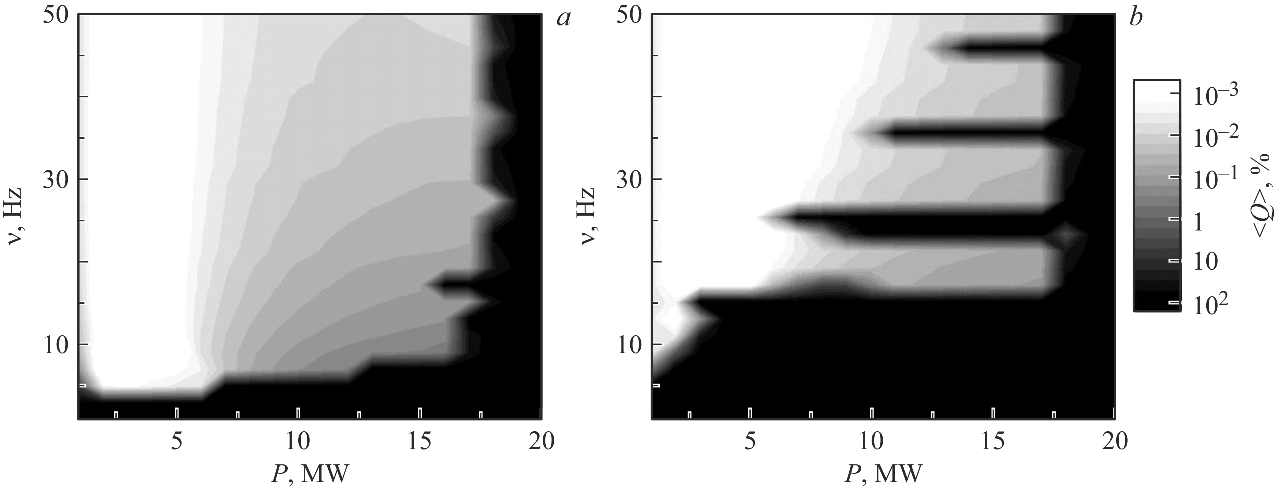

Figure 2. Dependence of the pulse energy spread on intrinsic frequency ν and average reactor power P. a — case $A > 0$, b — case $A < 0$.

$$\hat{T}(t) = \sum_{l=i-1}^{0} \Theta\left(\frac{1}{\nu_0}(i-l)+t'\right) Q_l. \tag{8}$$

In these recurrent relations the dynamic variables are energy of the ith pulse Q_i [MJ], fuel temperature T_i [K], number of nuclei of the sources of retarded neutrons of the jth group before the pulse c_{ji}, speed of generation of the retarded neutrons before the pulse S_i [s^{-1}]. The constants are the temperature coefficient of reactivity of fuel R_{ax} [K^{-1}], coefficient of reactivity of transverse displacement of fuel R_{tr} [mm^{-1}], average yield of neutrons from fission η [MJ^{-1}], a share of retarded neutrons of the jth group β_j, a constant of sources decay in the jth group λ_j [s^{-1}], repetition rate of reactor pulses ν_0 [s^{-1}], fuel heating per pulse of unit power T_0 [K/MJ], average speed of fuel cooldown p [s^{-1}]. Function M — multiplication factor [$\mathrm{MJ}\cdot\mathrm{s}$]. The type of function M and its calculation are described in [6]. The control parameter of equilibrium supercriticality ε serves to bring the system to the required level of the average power of the reactor and imitates the reactor control rods. The values of the constants and other parameters of the calculations are taken for the design of the NEPTUN reactor [9]. Coefficients R_{tr} and R_{ax} are calculated in advance by the Monte Carlo method in the full geometry of the reactor core. In the calculation of R_{tr} it is assumed that the displacements of all fuel elements happen synchronously and proportionately to the gradient of energy release across the axis of the reactor core (the method of the detailed calculation is given in [4]). Similarly, in the calculation of R_{ax} the fuel extension in the axial direction is taken into account in accordance with the heat release in fuel elements. Therefore, the model is built in the approximation of the synchronous motion of the group of non-interacting fuel elements.

Two methods were considered to fix the fuel elements ($A > 0$ and $A < 0$), for each of which the diagram is built for the dependence of the $\langle Q \rangle = (\max Q_i - \min Q_i)/Q_0$ pulse energy spread on intrinsic frequency ν and average power of the reactor P (Fig. 2).

Fig. 2, a ($A > 0$) clearly shows the instability areas caused by thermal expansion of fuel ($P > 18\,\mathrm{MW}$) and impact bending ($\nu < 10\,\mathrm{Hz}$). The case $A < 0$ (Fig. 2, b), when the fuel element bends aside from the center of the reactor core under stationary energy release demonstrates a much worse dynamics. This is explained by the shift in the phases of the oscillator and energy release. In general both diagrams show the trend of improved stability of dynamics with the increased intrinsic frequency of the fuel element.

Let us add to equations (3)−(8) the reflection condition for the oscillator: if $x = d$, then $\dot{x} \to -\dot{x}$. This condition simulates the fuel element collision with the near design elements (for example, a fuel assembly wall). At certain parameters the model generates fluctuations of the pulse energy that are visually similar to the observed noise of IBR-2 reactor (Fig. 3).

These results do not explain fully the reason for the fluctuations of pulse energy, but specify impact bending of fuel elements and collision as one of the possible negative factors of reactor dynamics. It should also be noted that more detailed study of the collision effects requires complication of the model, since the condition of fuel element motion at this is violated.

The analysis of the equation of the impact bending and temperature of the fuel element wall made it possible to determine the maximum value of intrinsic frequency, when the phenomenon of the dynamic bending is dangerous for the reactor. The principal difference is also shown in the nature of the transverse fuel displacement in the reactors with stationary and pulsating energy release. The development of the design of the pulsating reactor may not be carried out similarly to the reactor of stationary action. It is recommended to conduct a modal analysis at the design

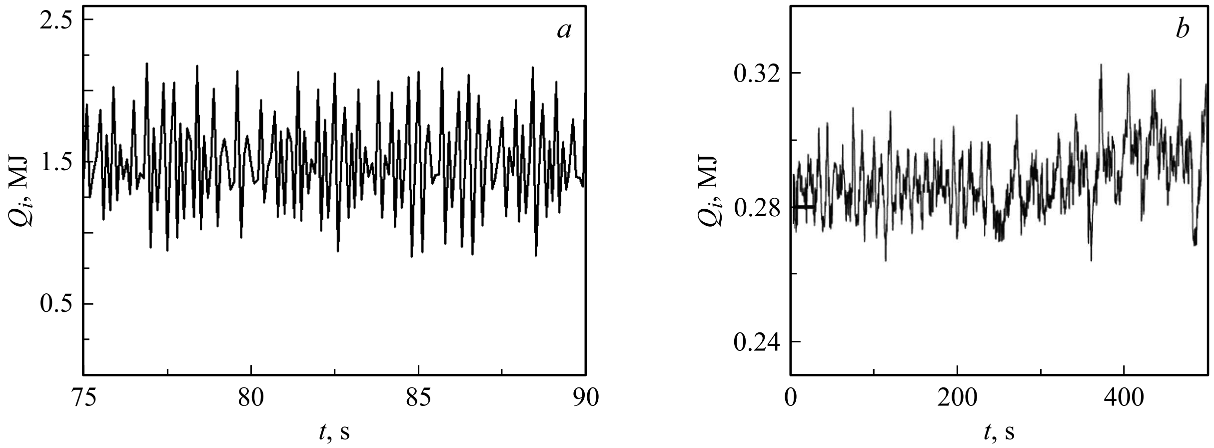

Figure 3. a — model calculations of pulse energy ($P = 15\,\text{MW}$, $\nu = 17\,\text{Hz}$, $d = 0.05\,\text{mm}$, $A > 0$); b — experimental values of IBR-2 pulses energy [10].

stage and vibrodiagnostics of the main elements in the reactor core, and to avoid the structures with low values of intrinsic frequencies.

Certain measures may be proposed to reduce the negative effect of the studied phenomenon at the dynamics of the future reactors. If the reactor core consists of the fuel assemblies, the ideal solution is the maximum stiff fixation of fuel elements relative to the fuel assembly wall, which prevents their free transverse displacement. If the reactor core is charged by fuel elements, it is preferable to fix the fuel elements at both ends (case $A > 0$) and to increase their stiffness as much as possible. This will make it possible to increase their intrinsic frequency and adjust the phase of oscillations.

The parameters of the model obtained in this paper were received for the oscillations of one individual fuel element in liquid medium [7]. The motion of the group of closely located fuel elements with account of potential collisions and disturbances from the side of the turbulent flow of liquid sodium has a more complicated, collective nature. Therefore, for further development of the model the additional theoretical and experimental studies of the collective motion of fuel elements are required with account of the coolant motion.

Conflict of interest

The author declares no conflict of interest.

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