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Analytical estimations of pulse parameters in the modified integral neutron kinetics model for pulsed reactor and subcritical block

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Abstract

Application of modified integral neutron kinetic model to calculate principal characteristics of pulsed coupled reactor system consisting of pulsed reactor and subcritical block is discussed. The model is based on the use of respective time-dependent kernels of integral equation for reactor power and space-time Green's function for the subcritical block. It is possible to reduce the set of integral equations to the set of elementary algebraic and first-order differential equations by using exponential approximation of the kernels and Green's function.

Approximations of «inertialess» reactivity dumping and jump reactivity boost on prompt neutrons are used as the «reactivity-power» feedback in order to close the mathematical model. This allows integrating corresponding kinetic equations in analytical form notwithstanding the fact that the kinetic equation for reactor is nonlinear.

Analytical relations allowing estimating basic characteristics of the system such as energy and maximum pulse power in the reactor and in the subcritical block with accuracy sufficient in engineering practices were obtained.

The performed calculations showed applicability of the analytical dependences of energy characteristics of the system on the impact coefficient of subcritical block on the reactor, on the lifetime of neutrons in the reactor and on the «time» constant of the block for fixed value of pulse energy in the reactor. The obtained ratio is valid for the reactor within the whole range of variation of system parameters while for the subcritical block it is correct only for the system operated with fast neutron spectrum in the reactor and with thermal neutron spectrum in the subcritical block when the so-called "delta" approximation of the reactor pulse is realized. In the case when such approximation is not valid the "Gaussian" approximation to the shape of the reactor pulse is applied for which more accurate analytical formulas were also obtained for estimation of maximum pulse energy in the block. These formulas depend on the ratio of duration of start-up period of the pulsed coupled reactor system to the value of "time" constant of the subcritical block and are correct for the systems with similar neutron spectra.

The obtained analytical relations can be applied for optimization of parameters of coupled reactor-laser systems.

Keywords: Neutron kinetics; Laser system pumped by nuclear reactor; Pulse energy and maximum power.

Integral kinetics models

The use of the modified integral kinetics model [1–4] appears to be the most suitable for description of kinetics in the "fast pulsed reactor – thermal subcritical block" system [5–13].

This model is written in general form as follows [2]:

$$N_r(t) = \int_0^t [\alpha_{rr}(t-\tau)+\alpha_{rr}{}^s(t-\tau)+\alpha_{rb}(t-\tau)]\cdot N_r(\tau)d\tau,$$
$$N_b(\mathbf{r},t) = \int_0^t G_{br}(\mathbf{r},t-\tau)\cdot N_r(\tau)d\tau. \quad (1)$$

Assumption that intrinsic neutron distribution has sufficient time to shape in the reactor at any time moment division of variables into the amplitude and form-functions (as it is accepted in the derivation of usual equations of point kinetics model) [5–11,14] is valid was the main hypotheses used in the derivation of Eq. (1). No such restrictions were imposed on

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the space-time neutron distribution in the deeply subcritical block.

In Eq. (1) $N_r(t)$ is the reactor power (or fission rate) at the time moment t; $N_b(\mathbf{r},t)$ is the power of the subcritical block at the point with coordinate $\mathbf{r}$ at the time moment t; $G_{br}(\mathbf{r},t)$ has the meaning of space-time distribution of secondary fissions in the subcritical block under the condition that primary fission occurs in the nuclear reactor (analogue of Green's function for the subcritical block). Integral of this function is described by the following spatial dependence:

$$M(\mathbf{r}) = \int_0^\infty G_{br}(\mathbf{r}, t)dt,$$

which shows the distribution of total number of fissions taking place in the point with coordinate $\mathbf{r}$ of the subcritical block normalized to one fission event in the reactor. If this function is integrated over the volume of the block V_b than the zero moment of Green's function equal to the total number of fissions in the subcritical block per one fission in the reactor is obtained as follows:

$$M_b = \int_{V_b} M(\mathbf{r})d\mathbf{r} = \int_0^\infty \int_{V_b} G_{br}(\mathbf{r}, t)d\mathbf{r}dt. \quad (2)$$

The following characteristic of this process defined as the "time" constant of the block will be needed in the subsequent examination:

$$l_b = \int_0^\infty \int_{V_b} tG_{br}(\mathbf{r}, t)d\mathbf{r}dt \Big/ \int_0^\infty \int_{V_b} G_{br}(\mathbf{r}, t)d\mathbf{r}dt. \quad (3)$$

Special explanation is needed for the functions $\alpha_{rr}(t)$, $\alpha_{rr}{}^s(t)$ and $\alpha_{rb}(t)$.

Function $\alpha_{rr}(t)$ is the distribution of secondary fissions in the reactor core under the condition that primary fission has also occurred in the core; it is assumed here that the subcritical block is completely removed. Integral of this function has the straightforward physical meaning of effective neutron multiplication factor in the "bare" reactor k_{rr} and the mean neutron lifetime in such reactor is expressed as follows [2]:

$$l_{rr} = \int_0^\infty t\alpha_{rr}(t)dt \Big/ \int_0^\infty \alpha_{rr}(t)dt.$$

Function $\alpha_{rr}{}^s(t)$ is the distribution of secondary fissions in the reactor core under the condition that primary fission has also occurred in the core following which fission neutrons penetrated the subcritical block and after reflection in the block (and, possibly, moderation as well) they "returned" in the reactor and induced new fissions there. Thus, function $\alpha_{rr}{}^s(t)$ describes the effects of the subcritical block serving as neutron reflector and moderator on the reactor performance. In monograph [2] integral of this function $\Delta k_{rr}{}^s$ is called the "passive" component of reactivity induced in the reactor by the subcritical block serving as neutron reflector and the mean lifetime of neutrons reflected, moderated and, after that, returned in the reactor core is described by the following parameter:

$$l_{rr}{}^s = \int_0^\infty t\alpha_{rr}{}^s(t)dt \Big/ \int_0^\infty \alpha_{rr}{}^s(t)dt.$$

Function $\alpha_{rb}(t)$ is the distribution of secondary fissions in the reactor core induced by fission neutrons from the subcritical block which, in turn, were born from the primary fission in the reactor core. Integral of this function k_{rb} is called the "active" component of reactivity induced in the reactor by the subcritical block serving as neutron multiplier and the mean lifetime of such neutrons in the reactor core is described by the following parameter:

$$l_{rb} = \int_0^\infty t\alpha_{rb}(t)dt \Big/ \int_0^\infty \alpha_{rb}(t)dt.$$

Differential kinetics model

Let us examine the first equation in the set (1).

In order to simplify its solution it is convenient to approximate functions $\alpha_{rr}(t)$, $\alpha_{rr}{}^s(t)$ and $\alpha_{rb}(t)$ in the form of exponentials [2] describing different processes of prompt neutron moderation, diffusion and transport including, in the general case, the processes on delayed neutrons. Taking into consideration that only fast processes induced by prompt neutrons will be dealt with in the subsequent analysis we will neglect the contribution from delayed neutrons in respective kernels.

Besides that, we can combine kernels $\alpha_{rr}(t)$ and $\alpha_{rr}{}^s(t)$ into one kernel $\alpha_{rr}(t) = \alpha_{rr}(t) + \alpha_{rr}{}^s(t)$ and limit the analysis with one-exponential approximation as follows:

$$a_r(t) = (k_r/l_r)\exp\{-t/l_r\}; \quad a_{rb}(t) = (k_{rb}/l_{rb})\exp\{-t/l_{rb}\}. \quad (4)$$

In such case the first equation in the set (1) can be rewritten in the form of the following set of algebraic and first-order differential equations the methods for solution of which are well developed:

$$\begin{aligned} N_r(t) &= n_r(t) + n_{rb}(t), \\ l_r dn_r/dt &= k_r N_r - n_r, \\ l_{rb} dn_{rb}/dt &= k_{rb} N_r - n_{rb}, \end{aligned} \quad (5)$$

where $n_r(t)$ is the intensity of fission reactions in the reactor induced by intrinsic neutrons and neutrons undergoing reflection in the subcritical block and subsequently initiating fissions in the reactor; $k_r = k_{rr} + \Delta k_{rr}{}^s$ is the effective neutron multiplication factor in the reactor taking into account the subcritical block serving as neutron reflector; $l_r = (l_{rr}k_{rr} + l_{rr}{}^s\Delta k_{rr}{}^s)/(k_{rr} + \Delta k_{rr}{}^s)$ is the mean neutron lifetime in the reactor taking into account neutrons reflected from the subcritical block; n_{rb} (t) is the intensity of fission reactions in the reactor resulting from neutrons born in the reactor from the primary fission, penetrating the subcritical block and inducing fissions there with neutrons produced in secondary fissions returning back the reactor and inducing secondary fissions there.

In the case of inertialess dumping of reactivity the power feedback can be written in the following form:

$$k_r = k^0{}_r(t) - \gamma \int_0^t N_r(t)dt = k^0{}_r(t) - \gamma E_r(t). \quad (6)$$

Where γ is the quasi-static coefficient of reactivity dumping; and E_r (t) is the energy released by the time moment t.

Thus, taking into account (6) the initial set of kinetics equations will acquire the following form:

$$N_r(t) = n_r(t) + n_{rb}(t),$$
$$l_r dn_r/dt = (k^0{}_r - gE_r\ (t))N_r\ (t) - n_r\ (t),$$
$$l_{rb} dn_{rb}/dt = k_{rb}N_r\ (t) - n_{rb}\ (t). \tag{7}$$

Let us assume for simplicity that variation of reactivity at initial time moment occurs as the jump and $k^0{}_r\ (t) = k_r =$ const; initial conditions are following: $n_r(0) = n_0$, $n_{rb}(0) = 0$.

If Green's function integrated over the spatial coordinate is represented in the following form:

$$G_b(t) = \int_{V_b} G_{br}(\mathbf{r}, t)d\mathbf{r} = M_b \exp\{-t/l_b\}/l_b.$$

Than the second equation in the set (1) can also be reduced to ordinary differential equation as follows:

$$l_b dN_b/dt = M_b N_r(t) - N_b(t), \tag{8}$$

where $N_b\ (t)$ is the total power of the subcritical block at the time moment t.

It has to be noted that equations for description of power behavior in the separate laser-active element will have the form similar to (8).

Analytical estimations

Integrating Eqs. (7) and (8) and neglecting the initial and final values of power of the reactor and the subcritical block we obtain the following expressions for total energies released per one pulse in the reactor and in the subcritical block, respectively:

$$E^0{}_r = 2(\Delta k_r + k_{rb})/\gamma, \tag{9}$$

$$E^0{}_b = M_b E^0{}_r, \tag{10}$$

Where $\Delta k_r = k^0{}_r - 1$.

Let use determine the maximum power of reactor pulse $N_r{}^m$. We will use for this purpose the condition $dN_r/dt_r{}^m = 0$ and, as well, the approximate relation binding the energy $E_r{}^m$ released by the time moment corresponding to the maximum of reactor pulse $t_r{}^m$ and the maximum power $N_r{}^m$ in the pulsed reactor operated in self-quenching mode [15–19]: $E_r{}^m = 2\tau_r\ N_r{}^m$, where τ_r is the initial period of excursion of the "pulsed reactor – subcritical block" system realized prior to the triggering of power and temperature feedbacks.

Omitting the transformations let us present the solution for $N_r{}^m$:

$$N_r{}^m = [\Delta k_r l_{rb} + \Delta k_{rb} l_r + 2(\Delta k_r + k_{rb})\tau_r]/[2\gamma\tau_r(l_{rb} + \tau_r)]. \tag{11}$$

Where τ_r can be found from the solution of standard equation for the set (7) in which the element $\gamma E_r(t)$ can be neglected:

$$\tau_r = 2\Big[\Delta k_r/l_r + \Delta k_{rb}/l_{rb} + \sqrt{(\Delta k_r/l_r + \Delta k_{rb}/l_{rb})^2 + 4(\Delta k_r + k_{rb})/(l_r l_{rb})}\Big]^{-1}. \tag{12}$$

Maximum value of function $n_{rb}{}^m$ realized at the time moment $t_b{}^m$ different from $t_r{}^m$ can be found using the approximations for the "strongly" and "loosely"-coupled system described in [16]. The resulting expression for estimation of $n_{rb}{}^m$ has the following form:

$$n_{rb}^m = \begin{cases} \left(E_r^0 - 2k_{rb}\right)k_{rb}/l_{rb}\ if\ 0 < k_{rb} < k_{rb}^s \\ \gamma E_r^{0\ 2}/(8l_{rb})\ if\ k_{rb} > k_{rb}^s \end{cases}. \tag{13}$$

Where parameter $k_{rb}{}^s = \gamma E^0{}_r/4$ conditionally separates the regions of "loose" and "strong" coupling of the system.

Let us address now Eq. (8) describing variation of power in the subcritical block. This equation completely coincides with the third equation in (7) for $n_{rb}(t)$ with $l_{rb} = l_b$ if the following designation is introduced $N_b(t) = (M_b/k_{rb})\cdot n_{rb}(t)$. Then formulas (13) can be used for estimation of maximum power of the unit, which acquire the following form:

$$N_b^m = \begin{cases} \left(E_r^0 - 2k_{rb}/\gamma\right)M_b/l_b\ if\ 0 \le k_{rb} \le k_{rb}^s. \\ M_b\ \gamma E_r^{0\ 2}/(8l_b k_{rb})\ if\ k_{rb} > k_{rb}^s\ . \end{cases} \tag{14}$$

It has to be noted, however, that estimation (14) is valid only for the case of "loosely"-coupled "reactor-block" system when the following relation is satisfied:

$$\epsilon = \tau_r/l_b << 1. \tag{15}$$

Physically the above condition is equivalent to the situation when initial period of excursion of the coupled system is much smaller than the time constant of the block and in mathematical terms it gives the grounds for neglecting the last element in (8) (approximation of "delta-shaped" reactor pulse). In practical terms the relation (15) is realized in the cases when neutron spectrum in the reactor is fast while that in the block is thermal.

If, however, the relation (15) is not satisfied, than even in the completely "uncoupled" system (with $k_{rb} = 0$) estimation (14) will be unsatisfactory and the shape of reactor pulse must be taken into account.

In order to do this the approach accepted in Ref. [2] can be used and the shape of the fast part of the pulse in the reactor can be approximated by the Gaussian as follows:

$$N_r(t) = N_r{}^m \exp\{-\pi(t - t_r{}^m)^2/(16\tau_r{}^2)\}, \tag{16}$$

with maximum corresponding to $t_r{}^m$.

Application of representation (16) allows integrating Eq. (8) and finding the expression for $N_b(t)$ in the following analytical form:

$$\begin{aligned} N_b(t) &= \frac{M_b N_r{}^m}{l_b} \int_{-\infty}^{t} \exp\{-\pi\xi^2/(16\tau_r{}^2) - (\xi - t + t_r{}^m)/l_b\} d\xi \\ &= 2N_r{}^m \varepsilon M_b \exp\{4\varepsilon^2/\pi - (t - t_r{}^m)/l_b\} \\ &\quad \times \left[1 + \mathrm{erf}(\sqrt{\pi}(t - t_r{}^m)/(4\tau_r) - 2\varepsilon/\sqrt{\pi})\right]. \end{aligned} \tag{17}$$

In order to determine the maximum of function (17) it is necessary to find the time between maximums of pulses in the block and in the reactor $\Delta t_{br} = t_b{}^m - t_r{}^m$ corresponding to it. This time interval can be found from the solution of transcendental equation as follows:

$$2\varepsilon(1 + \mathrm{erf}(y)) = \exp(-y^2). \tag{18}$$

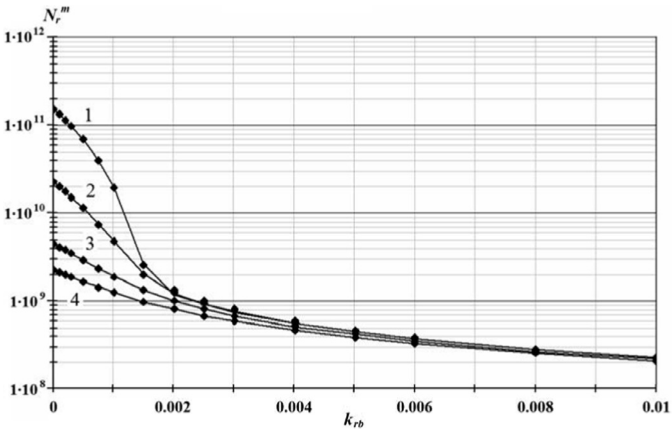

Fig. 1. Dependences of $N_r{}^m$ on k_{rb} calculated numerically using model (7) (points) and using formula (13) (solid curves) for $l_b = 10^{-3}$ and for different $l_r = 1.5{\cdot}10^{-8}$ (1); $1{\cdot}10^{-7}$(2), $5{\cdot}10^{-7}$(3) and $1{\cdot}10^{-6}$ s (4).

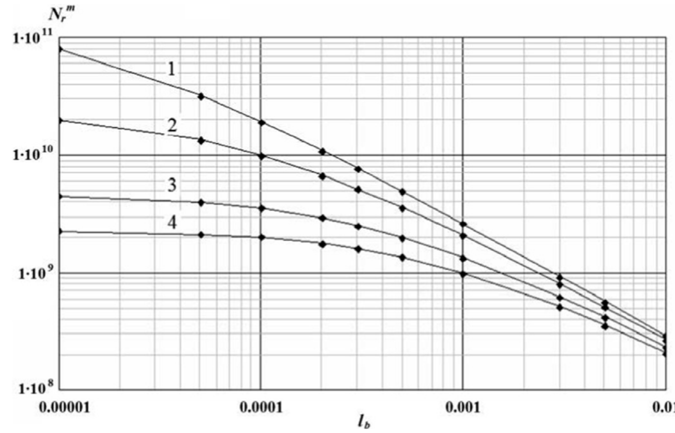

Fig. 2. Dependences of $N_r{}^m$ on k_{rb} calculated numerically using model (7) (points) and using formula (13) (solid curves) for $k_{rb} = 1.5{\cdot}10^{-3}$ and for different $l_r = 1.5{\cdot}10^{-8}$ (1); $1{\cdot}10^{-7}$(2), $5{\cdot}10^{-7}$(3) and $1{\cdot}10^{-6}$ s (4).

Where $y = \pi^{1/2}\Delta t_{br}/(4\tau_r) - 2\varepsilon/\pi^{1/2}$.

Using expressions (17) and (18) it is not difficult to demonstrate that the value of maximum pulse power in the block is described by the following expression:

$$N_b{}^m = N_r{}^m \cdot M_b \cdot \exp\{-\pi\,\Delta t_{br}{}^2/16\}.$$

Eq. (18) does not have analytical solution but, however, certain approximate estimations can be made for different values of ε. Then general solution for $N_b{}^m$ will have the following form:

$$N_b{}^m(\varepsilon) = N_r{}^m M_b \times \begin{cases} 4\varepsilon\exp\{-4\varepsilon^2/\pi \\ \quad -4\varepsilon\sqrt{\ln(1/(4\varepsilon))}/\sqrt{\pi}\}, & 0 < \varepsilon \le 0.1617; \\ \exp\{2\varepsilon - 1 - 4\varepsilon^2/\pi\}, & 0.1617 \le \varepsilon \le 0.9133; \\ \exp\{-\pi/(16\varepsilon^2)\}, & \varepsilon > 0.9133. \end{cases} \quad (19)$$

Numerical calculations

Calculations of model system consisting of pulsed reactor and subcritical block were performed in order to verify applicability of the obtained relations in the estimation of $N_r{}^m$ and $N_b{}^m$ for different values of k_{rb}, l_r and l_b. Coefficient of reactivity dumping $\gamma = 0.5{\cdot}10^{-10}$ J^{-1}, reactor pulse energy $E^0{}_r = 6$ MJ and the Green's function zero moment $M_b = 1$ were assumed to be constant in the calculations.

Dependences of maximum reactor pulse power $N_r{}^m$ on the k_{rb} coefficient and on the time constant l_b calculated numerically using the model (7) with application of MathCad complex [20] and using formulas (11) and (12) are presented in comparison in Figs. 1 and 2, respectively.

It has to be noted that calculations of $N_r{}^m$ presented in Fig. 2 were performed for the value of $k_{rb} = 1.5{\cdot}10^{-3}$ because in this case the reactor does not "undergo excursion" into the prompt super-criticality conditions ($\Delta k_r = \gamma E^0{}_r/2 - k_{rb} = 0$) and the pulse shape in the reactor significantly differs from Gaussian.

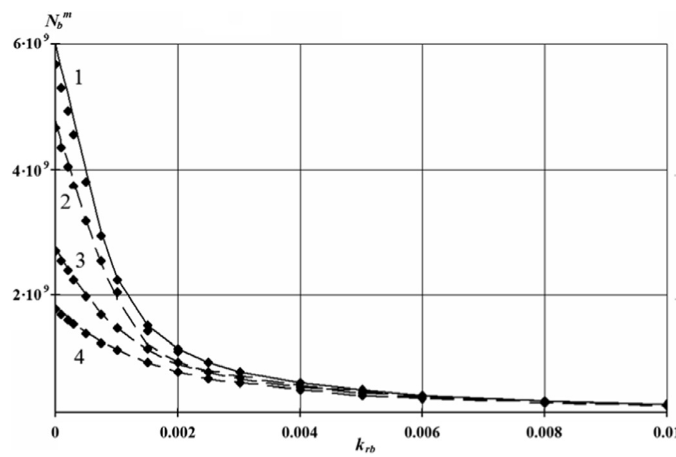

Fig. 3. Numerical (points) and analytical estimations of $N_b{}^m(k_{rb})$ for $l_r = 1.5{\cdot}10^{-8}$ (curve 1); $1{\cdot}10^{-7}$(2), $5{\cdot}10^{-7}$(3) and $1{\cdot}10^{-6}$ s (4).

However, as it is evident from the figures, solution (11) is valid for all the examined values of parameters for the cases of both "loosely"- and "strongly"-coupled systems [2,16] with discrepancy between the analytical estimation and numerical calculation not exceeding 1–3% anywhere.

Results of calculations of maximum power in the subcritical block are presented in Fig. 3 depending on k_{rb} with fixed time constant of the block equal to $l_b = 10^{-3}$ s and with different values of neutron lifetimes in the reactor. Results of calculations performed using model (7) are represented with dots while the curves represent the estimation made using analytical formulas as follows: solid curve 1 was calculated according to formula (14) and dashed curves 2–4 were obtained using formulas (19).

As it was demonstrated by the performed calculations, formula (14) produces good estimation for $N_b{}^m$ for all values of k_{rb} for the cases when the initial period of system excursion is significantly shorter that the "time" constant of the block ($e << 1$) which is realized with fast neutron spectrum in the reactor core and with thermal neutron spectrum in the block.

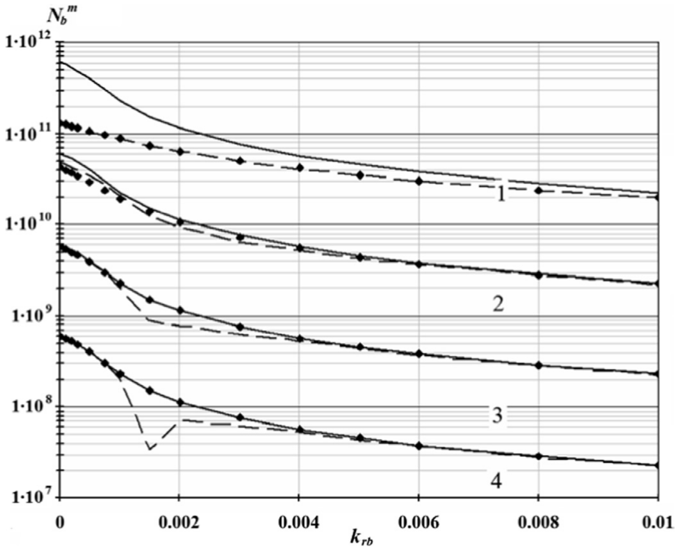

Fig. 4. Numerical calculations (points) and analytical estimations (curves) of $N_b{}^m(k_{rb})$ for l_b values equal to 10^{-5} (curve 1), 10^{-4} (2), 10^{-3} (3) and 10^{-2} s (4).

In the case when ε is comparable to or is greater than unity (curves 2–4) good results are produced by formula (19).

Results of calculations of dependence of maximum unit power on k_{rb} for fixed $l_r = 1.5{\cdot}10^{-8}$ s and different values of "time" constant of the block are presented in Fig. 4. Dots represent results of numerical modeling according to model (7); analytical estimations were made using formulas (14) (solid curves) and (19) (dashed lines). Comparison shows that formula (14) produces satisfactory (not worse than 20–25%) agreement with numerical calculations for $l_b \geq 10^{-4}$ s (curves 2–4). Formula (19) must be applied for $l_b < 10^{-4}$ s (curve 1) when neutron spectrum in the block is not thermal any more (19). The latter formula produces in turn unsatisfactory estimations for intermediate region of coupling between the block and the reactor ($k_r{}^b \approx 1.5{\cdot}10^{-3}$, curves 3 and 4). This is explained by the fact that Gaussian approximation of reactor pulse shape of (16) is not satisfactory in this case (Fig. 5).

Calculations of maximum power of the block dependent on its "time" constant were performed in order to investigate applicability of analytical formulas in the intermediate region for fixed $k_{rb} = 1.5{\cdot}10^{-3}$ and different values of l_r (Fig. 6). Results of numerical modeling are presented, as in the preceding cases, as dots, while curves represent the estimations obtained using analytical formulas (14) (solid curve) and (19) (dotted curve). Analysis of calculated results confirms that for small values of neutron lifetimes in the reactor and large "time" constants of the block (when $\varepsilon << 1$ conditions is realized) good estimations are produced by formula (14) (solid curve) while for ε of the order or in excess of 1 good estimations are produced by formula (19).

Analysis of the performed calculations demonstrates the evident enough result that in order to enhance pulse characteristics of the subcritical block (i.e. simultaneous increase of energy and maximum power of the block at fixed pulse

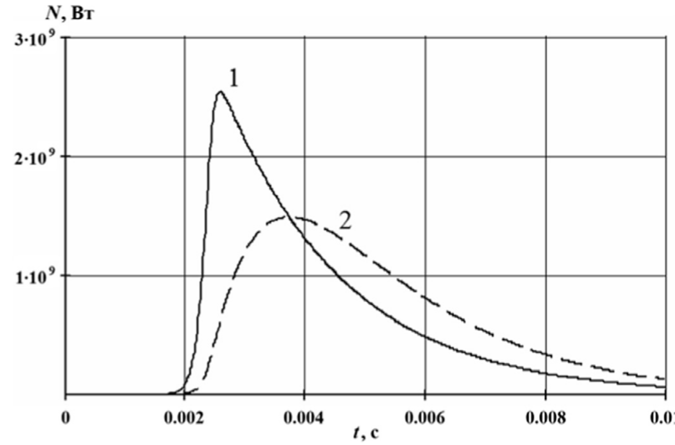

Fig. 5. Pulses in the reactor (1) and in the block (2) for $l_r = 1.5{\cdot}10^{-8}$ s, $k_{rb} = 1.5{\cdot}10^{-3}$ and $l_b = 10^{-3}$ s.

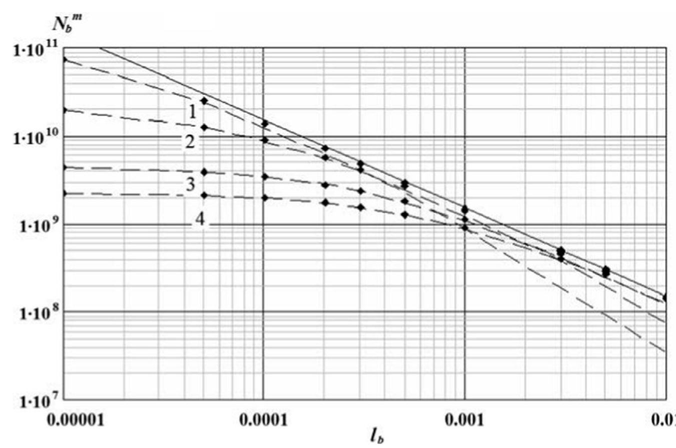

Fig. 6. Numerical calculations (points) and analytical estimations (curves) of $N_b{}^m(l_b)$ for l_r equal to $1.5{\cdot}10^{-8}$ (curve 1); $1{\cdot}10^{-7}$(2), $5{\cdot}10^{-7}$(3) and $1{\cdot}10^{-6}$ s (4).

energy in the reactor) increase of zero moment from Green function M_b, decrease of "time" constant of the unit l_b and of impact factor k_{rb} are needed. This is not difficult to achieve in the calculations by maximum "uncoupling" of the reactor from the subcritical block at $k_{rb} \to 0$ and is fairly difficult to be implemented practically.

Conclusion

Analytical relations were obtained for estimation of energies and values of maximum pulse power in the coupled reactor system consisting of pulsed reactor and subcritical block. The performed calculations demonstrated accuracy acceptable for practical applications. The obtained relations are applicable both for systems with fast reactor and thermal subcritical block, and for systems with close neutron spectra of component parts.

The obtained analytical relations can be useful in the optimization of energy characteristics of coupled reactor-laser systems.

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