On monitoring and forecasting of graphite stack temperature in transient modes

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Abstract. The paper presents a method of monitoring and forecasting of the graphite stack temperature of the RBMK reactor in transient modes. The method is based on processing the in-core information about macro-distribution and mathematical model of distribution of temperature changes of the graphite stack in the reactor core. It is shown that the use of archival neutron field monitoring data allows determining the graphite stack temperature in the on-line mode.

1. Introduction

One of the requirements for the control process of the RBMK reactors is the effective and safe operation of the reactor under changes in power level [1-3]. In this regard, the task of monitoring and forecasting of changes of the operational reserve in space and time is relevant, as the operational reactivity margin determines the reactor maneuverability (the operational reactivity margin below refers to the value $K(\vec{r},\tau)-1$, i.e. the excess of birth rate over one).

The change of the propagation coefficient in the RBMK reactors due to the influence of feedback can be represented as follows [3, 4]:

$$\Delta K(\vec{r},\tau) = \Delta K_{\varphi}(\vec{r},\tau) + \Delta K_F(\vec{r},\tau) + \Delta K_C(\vec{r},\tau) + \Delta K_X(\vec{r},\tau), \quad (1)$$

where $\Delta K_{\varphi}(\vec{r},\tau), \Delta K_F(\vec{r},\tau), \Delta K_C(\vec{r},\tau), \Delta K_X(\vec{r},\tau)$ is the change of the propagation coefficient due to the following reactivity effects: steam, fuel and moderator temperature, and xenon concentration, respectively.

In this article the problem of the forecasting of the propagation coefficient changes under the moderator temperature changes is considered. It is assumed that the following relationship is true:

$$\Delta K_C(\vec{r},\tau) = \alpha_C(\vec{r},\tau)\Delta T_C(\vec{r},\tau), \quad (2)$$

where $\alpha_C(\vec{r},\tau)$ is the graphite reactivity coefficient (a known function).

Thus, under the assumption made above, the task of monitoring and forecasting of the reactivity changes is reduced to the problem of monitoring and forecasting of the graphite temperature changes in transient modes of the reactor.

2. Mathematical model

To describe the behavior of macro-distribution of the graphite temperature changes in the RBMK reactor core we use the following mathematical model, which is applied in the study of RBMK reactors dynamic characteristics [5-7]:

$$\begin{cases} C_V \dfrac{\partial \Delta T_C}{\partial \tau} == -\beta \Delta T_C + A\Sigma_f \Delta \Phi(\vec{r}, \tau); \\ \Delta T_C(\vec{r}, 0) = 0. \end{cases} \tag{3}$$

where $\Delta T_C(\vec{r},\tau) = T_C(\vec{r},\tau) - T_C(\vec{r},0)$ is the deviation of the graphite stack temperature at the time τ in the coordinate $\vec{r}$ from the initial value of the graphite stack temperature (further this value for the sake of brevity is called macro-distribution of graphite temperature); C_V is heat capacity of graphite; $\Sigma_f(\vec{r})$ is fission cross section; β is the proportionality coefficient, depending on the conditions of heat transfer from the graphite to the coolant; A is the proportionality coefficient between the changes of energy release density and the changes of the graphite temperature; $\Delta\Phi(\vec{r},\tau) = \Phi(\vec{r},\tau) - \Phi(\vec{r},0)$ is deviation of neutron flux distribution at time τ from the initial value.

The model (3) does not account for the leakages of heat over the height and radius of the reactor. Let us present the equation (3) in a dimensionless form. To do this, we introduce a new variable

$$\Theta(\vec{r},\tau) = \frac{\Delta T_C(\vec{r},\tau)}{\overline{T_C - T_S}}, \tag{4}$$

where $\overline{T_C - T_S}$ is the average temperature difference in the reactor in the steady state at nominal power level.

$$\beta(\overline{T_C - T_S}) = A\overline{\Sigma_f \Phi},$$

where T_S is the water saturation temperature under the working pressure in the channel.

Then the original problem (3) can be written as:

$$\begin{cases} \dfrac{\partial \Theta}{\partial \tau} == -\dfrac{1}{\tau_C}\Theta + \dfrac{1}{\tau_C} K\varphi(\vec{r},\tau); \\ \Theta(\vec{r},0) = 0. \end{cases} \tag{5}$$

3. Solution

The solution of the problem (5) presents no difficulties on condition that the values τ_C and $K\varphi = \Sigma_f \Delta\Phi / \overline{\Sigma_f \Phi}$ are given.

$$\Theta(\vec{r},\tau) = \frac{K}{\tau_C} \exp\left(-\frac{\tau}{\tau_C}\right) \int_0^{\tau} \varphi(\vec{r},t) \exp\left(\frac{t}{\tau_C}\right) dt \tag{6}$$

However, with a real RBMK reactor the problem of definition of macro-distribution of the graphite temperature using the model (5) is complicated by the following circumstances:

1) the parameter τ_C may be a function of coordinates and significantly depend on the operating conditions, in particular, the composition of the gas mixture of the graphite stack [3, 5, 9];

2) the experimental information on the energy release distribution in the reactor core is available only in a finite number of coordinates (at the locations of sensors) and is presented in the form of currents of sensors at discrete moments of time;

3) the impact of a large number of perturbing factors leads to the fact that the distribution of energy release under the reactor power change may differ from the forecast. Strictly speaking, this difference is random and from a mathematical point of view is described with a random function.

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Regarding the first comment let us assume that the time constant of the graphite τ_C does not depend on the coordinate and can be determined experimentally. The rest of the comments can be considered as follows.

Deviations of currents of discretely located sensors of energy release from the initial values are approximated with a set of test functions according to the methodology [8, 10]. This approach to determination of the graphite temperature macro-distribution can be justified by the fact, proven by the archival experimental information, that the distribution of the graphite temperature changes is a fairly smooth function.

The readings of the thermocouples in transient modes along with the readings of energy release sensors allow to determine the conversion factor *K*. Indeed, supposing the macro-distribution $\varphi^*(\vec{r},\tau_i)$ is restored at discrete moments τ_i according to the readings of in-core sensors, let us interpolate the macro-distribution $\varphi^*(\vec{r},\tau_i)$ in time using the stepwise interpolation method.

$$\varphi^*(\vec{r},\tau)=\varphi^*(\vec{r},\tau_i), \quad \tau_i \le \tau \le \tau_{i+1}.$$

The interval between the time counts is considered to be constant: $\tau_0=\tau_{i+1}-\tau_i$. Then the expression for the macro-distribution of the graphite temperature changes is as follows:

$$\delta\Theta = K\frac{\tau_0}{\tau_C}\sum_{i=0}^{N-1}\varphi^*(\vec{r},\tau_i)\exp\left(\frac{\tau_{0i}-\tau}{\tau_C}\right), \tag{7}$$

where $N=\dfrac{\tau}{\tau_0}$ is the number of time counts per τ. The estimated value of graphite temperature changes in the locations of the sensors is

$$\delta\Theta(\vec{r}_{th_j}) = K\frac{\tau_0}{\tau_C}\sum_{i=0}^{N-1}\varphi^*(\vec{r}_{th_j},\tau_i)\exp\left(\frac{\tau_{0i}-\tau}{\tau_C}\right), \tag{8}$$

where $\vec{r}_{th_j}$, j=1,…,24 are locations of the thermocouples in the reactor core.

On the other hand, using the thermocouples readings we can detect changes in the temperature $\Theta(\vec{r}_{th_j})$.

The conversion factor *K* can be defined, for example, from the following requirement:

$$\sum_{j=1}^{24}\left[\left(\delta\Theta(\vec{r}_j)-\Theta(\vec{r}_j)\right)^2\right]=\min. \tag{9}$$

With this in mind, the forecast for the change of graphite temperature in the reactor core can be carried out according to the formula:

$$\Theta(\vec{r},\tau)=\frac{K}{\tau_C}\exp\left(-\frac{\tau}{\tau_C}\right)\int_0^{\tau}\varphi(\vec{r},t)\exp\left(\frac{t}{\tau_C}\right)dt, \tag{10}$$

where $\varphi(\vec{r},t)$ is the proposed change of the energy release macro-distribution in the transient mode.

It should be mentioned that the expression (10) allows to restore a detailed distribution of the graphite temperature $T(\vec{r},t)=T_0(\vec{r},t_0)+\delta\Theta(\vec{r},t)$, on condition that the graphite temperature distribution at the initial moment of time $T_0(\vec{r},t_0)$ and the behavior of the neutron flux density $\varphi(\vec{r},\tau)$ during the interval $(2\div 3)\tau_C$ preceding time t are known.

4. On accuracy of monitoring macro-distribution of the graphite stack temperature

To evaluate errors in graphite temperature macro-distribution let us assume the following [8]:

1) the random error of restoration of the neutron flux space distribution does not depend on the neutron flux density;
2) the systematic error of the restoration of neutron flux density is absent;
3) the space interpolation errors are not time-correlated, i.e.

$$K_{\Delta}(t,t') = \begin{cases} 0, & when\ t \neq t'; \\ D, & when\ t = t'. \end{cases}$$

In this case it is possible to show that the error of monitoring the behavior of macro-distribution of graphite stack temperature under the steady mode of measurements is determined by the period of getting the sensors readings τ_0, by the parameters of the neutron flux correlation function and variance of the error of restoration of neutron flux space distribution, and does not exceed 4% in stable mode.

5. Conclusions

The methodology of monitoring and forecasting of the graphite temperature changes in the RBMK reactor core is proposed.

The methodology is based on using both experimental information (current of sensors and thermocouples in the graphite stack) and the mathematical model of the distribution of the graphite temperature changes in the reactor core. The mathematical model is obtained considering the number of assumptions, namely: the reactor height and radius heat leaks are not considered, the graphite time constant is considered to be constant within the reactor core. The algorithms for the monitoring and forecasting of the graphite stack temperature changes in the reactor core are easy for computer implementation and require small amount of RAM. Estimation of the errors of the graphite stack temperature forecasting and monitoring allows us to conclude that the proposed algorithms can be used to forecast and monitor with a reasonable degree of accuracy.

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