Application of thermal-hydraulic model of RBMK reactor fuel channel to correction of power and coolant flow measurements

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Abstract. The effectiveness and the security of RBMK reactor operation depends on the accuracy of the control over reactor's parameters and their limitations. The processing of operational parameters archive helps to adjust different mathematical models and significantly widen their field of use. Pressure differential between common pressure header and steam separator is the sum of calculated pressure differential and friction loss on flow control valve. There is known mathematical software, which allows to adapt such model for each fuel channel using the archive. In this research it is suggested not to replace the regular mechanism with such approach, but to use the adapted mathematical model to calculate corrected values of power and flow, which were measured by regular means. Mathematical expressions and procedures for such approach are given.

1. Introduction

The effectiveness and the security of RBMK reactor operation depends on the accuracy of the control over reactor's parameters and their limitations. Two of the most important parameters are the coolant flow through fuel channel and the energy emission, or power of the channel. Currently used means of control and algorithms of information processing surely give a reliable solution to the problem [1]. Nevertheless, research of new methods of accuracy increase for control systems is always a problem of interest. At present, such methods may involve using an archive of nuclear reactor operational parameters for a long period of time. In particular, the processing of operational parameters archive helps to adjust different mathematical models and significantly widen their field of use. In this research it is suggested to use thermal-hydraulic mathematical model of the pressure differential in fuel channel to correct experiment-calculated values of power and coolant flow, derived by regular methods.

2. Design features of RMBK reactor

The core of RBMK-1000 contains 1661 fuel channels [1]. During operation, at temperature of 270 °C and at pressure of approximately 7 MPa is delivered by main circulating pumps into the common pressure header. Then through group distribution headers coolant flows to fuel channels. After passing the reactor core steam-water mixture enters a steam separator, where is separated into liquid and gaseous phases. Steam then proceeds to a turbine, while liquid water returns back to the reactor. All
channels are equipped with flow meters of coolant, which take part in flow measurement process, and flow control valves, which help to change the flow.

Pressure differential between common pressure header and steam separator is the sum of calculated pressure differential and friction loss on flow control valve: \( \Delta P_i = k_i \cdot G_i^2 \). Thus:

\[
\Delta P = \Delta P_{HDC}(G_i, W_i) + k_i G_i^2
\]

Here \( \Delta P_{HDC}(G_i, W_i) \) is hydrodynamic characteristic (HDC) of fuel channel. It is derived as a result of hydrodynamic calculation [2], based on mathematical model, expressed by thermal-hydraulic equations for two-phased coolant flow: the continuity equation and equations for dynamics and energy. One important feature of any reactor of RBMK type is that fuel channels are separated into large groups, each forming an isolated system, within which channels have the same pressure header at the input and the same steam separator at the output. Thus, pressure differential between pressure header and steam separator for each channel of a group is the same and is measured by regular means of pressure control.

In [3, 4] mathematical procedure and software is given, which allows to find the coefficient \( k_i \) for each fuel channel using the archive. (In what follows the index is omitted, supposing that some fixed channel is always being considered).

Thus, in the equation for pressure differential (1) \( \Delta P \) and \( k \) are given. Then, one of the parameters can be calculated using another, for example, with fuel channel power given, same channel's flow can be calculated, and vice versa. In such way the mathematical model became adapted with the use of operational parameters archive.

It is suggested not to replace the regular mechanism with such approach, but to use the adapted mathematical model to calculate corrected values of power and flow, which were measured by regular means.

3. The search of corrected values

Let \( W_{reg} \) and \( G_{reg} \) be values of power and flow calculated by regular means. These values are practically derived with given inaccuracy, which dispersions are \( D_W \) and \( D_G \) respectively.
Let the corrected values be calculated from the following conditions

$$\min_{W, G} \left[ \frac{(W - W_{\text{reg}})^2}{D_W} + \frac{(G - G_{\text{reg}})^2}{D_G} \right]$$  \hspace{1cm} (2)

$$\Delta P = \Delta P_{\text{HDC}}(G, W) + kG^2 = 0$$  \hspace{1cm} (3)

As for (3) the equality may be achieved by adjusting both $W$ and $G$. But as both parameters are already approximately calculated, then they should be corrected in such way to remain within declared inaccuracy.

Expression (2) describes an ellipsis and (3) describes some other curve, which lies within intersection of a surface and plane. Combined, (2) and (3) form the optimization problem with (3) representing limitation function. Optimal solution lies in tangency point $(\tilde{W}, \tilde{G})$ of ellipsis and curve.

The equation for tangent to the curve (3) in point $(\tilde{W}, \tilde{G})$ is

$$\frac{\partial \Delta P_{\text{HDC}}}{\partial W} \bigg|_{\tilde{W}, \tilde{G}} (\tilde{W} - W) + \left( \frac{\partial \Delta P_{\text{HDC}}}{\partial G} \bigg|_{\tilde{W}, \tilde{G}} + 2kG \right) (\tilde{G} - G) = 0$$  \hspace{1cm} (4)

The equation for tangent to the ellipsis (2) in the same point is

$$\frac{2(\tilde{W} - W_{\text{reg}})}{D_W} (\tilde{W} - W) + \frac{2(\tilde{G} - G_{\text{reg}})}{D_G} (\tilde{G} - G) = 0$$  \hspace{1cm} (5)

The condition of concurrence of tangents gives the system of equations:

$$\frac{\partial \Delta P_{\text{HDC}}}{\partial W} \bigg|_{\tilde{W}, \tilde{G}} = \frac{2(\tilde{W} - W_{\text{reg}})}{D_W}$$  \hspace{1cm} (6)

Corrected values are calculated within iteration process.

4. Simulation results
The solution of the optimization problem, formed by (2) and (3), is derived by several steps. In this article the algorithm suggested includes the calculation of adaptation coefficient, the calculation of...
hydrodynamic characteristic and the search of optimum. The algorithm is assumed to be used together with the archive of operational parameters of RBMK reactor. The actual algorithm used in the background of this article is applied to the set of measurements at instants \( t_1, \ldots, t_N \), represented by triples \((\Delta P_i, G_i, W_i)\) of actual parameter values, where flow and power values require correction.

The adaptation coefficient, which is required for the calculation of HDC, adjusts proportionality between summands in (3). Given flow, power and pressure difference, such coefficient is uniquely defined at any instant. But the value of the coefficient can’t be calculated precisely owing to inaccuracy of flow and power measurements. The procedure for calculating the coefficient as the parameter of channel flow control valve is described in [3, 4].

The calculation of HDC implies the process of search of the valid pairs of flow and power values, which conform to the given pressure difference according to mathematical model from [2]. The result of the search is the set of points, which represent the curve in fig. 2, and then the search of optimal point is performed on it.

The optimal point is uniquely defined by (6), but for numerical calculations more practical approach is to use the equation for ellipsis as an expression for distance in compressed coordinates and choose the nearest point in such terms.

The example of the result of calculations is given in figure below:

![Figure 3](image)

Figure 3. Comparison of coolant flow measurements at 75 sequential instants: original values, derived by regular means (grey dash line, shifted by one measurement for convenience) and calculated by the suggested algorithm (black solid line).

The difference between new and original values lies around 0.1% for flow values and 1.5% for power values for the given sample.

It is important to note, that the suggested algorithm sets additional interconnection between hydrodynamic parameters of the reactor fuel channel. The results of the procedure do not replace the results of calculation, performed by regular means. New values of the parameters accommodate given errors of regular means of calculation. The algorithm may serve as supplementary mathematical instrument to standard algorithms, and also be used together with the archive of the reactor’s operational data to analyse and predict actual phase states of a reactor more precisely.

**Conclusion**

In this article method of correction of reactor hydrodynamic parameters is considered. The parameters taken into account are channel power, coolant flow and pressure difference. The method is based on
mathematical model, which conforms the parameters to each other. The correction algorithm is based on the procedure of the search of new parameters’ values. The result of the correction algorithm for one instant is the set of corrected values, which conform to each other taking into account given theoretical correlations from mathematical model. The algorithm suggested may be used as supplementary mathematical instrument to standard algorithms. Also it may be used along with the reactor’s operational data archive, which allows to analyze and predict reactor states more precisely.

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