THE APPROXIMATE THERMAL-MODEL-TESTING METHOD FOR NON-STATIONARY TEMPERATURE FIELDS IN CENTRAL ZONES OF FAST REACTOR ASSEMBLIES

V.I. MIKHIN, N.M. MATUKHIN
State Scientific Center of Russian Federation,
Institute of Physics and Power Engineering,
Obninsk, Kaluga Region, Russian Federation

Abstract

The approach to generalization of the non-stationary heat exchange data for the central zones of the nuclear reactor fuel assemblies and the approximate thermal-model-testing criteria are proposed. The fuel assemblies of fast and water-cooled reactors with different fuel compositions have been investigated. The reason of the non-stationary heat exchange is the fuel-energy-release time dependence.

For studying the non-stationary heat exchange processes in the nuclear reactor assemblies the approaches to the approximate modeling of such processes and the way of the experimental and calculated data generalization are necessary. Below the approach to the approximate modeling of the non-stationary nuclear-reactor-assembly heat exchange caused by the time change of the fuel energy release is stated. The approximate thermal-model testing is realized on the models which represent themselves as the assemblies of the fuel element imitators.

The imitator construction consisting of a tube heated outwards by an electric spiral [1,2] is considered. The electric spiral is isolated from the tube wall by the silicon-organic layer. The imitator tube may be one- or two-layer tube consisting of two subshells.

With purpose to obtain the approximate thermal-model-testing criteria the numerical investigations of the non-stationary assembly-central-zone temperature fields for the water-cooled and fast reactors have been carried out. The experimental an numerical investigations of the non-stationary temperature fields in the assembly models have been carried out also. The reason of the non-stationary behavior is the time energy-release variation in the fuel or in the imitators.

The maximum temperatures and maximum temperature irregularities take place at the assembly periphery. Determining these values by means of numerical solution of the detailed heat transport equations for the concrete fuel elements systems with the distant ridges seems to be not possible. That is why the research range is restricted to the central assembly zones, where the azimuth temperature irregularities are small and the distant ridge influence is not essential. The numerical results have been obtained from the joint solution of the non-stationary heat transport equations for the fuel elements and the heat-transfer agent (the method have been stated in detail in the work[3]). Such approach has permitted to avoid using the empirical quantities like the heat-transfer coefficient. Therefore the results obtained can be regarded as sufficiently reliable and adequate to the research aim.

The calculations have been carried out for the turbulent coolant flow regime for the wide Reynolds number range. The fuel assemblies with different coolants (water, sodium, lead) with uranium and uranium dioxide fuel have been investigated. The thermal resistance value of the contact sublayer between the fuel element core and shell has been varied in wide range.

The experimental and calculated results have been obtained for the energy-release jump. The generalization on the arbitrary energy-release lows is assumed to be achieved by

using the Duhamel integral. The numerical calculation results for the nuclear reactor fuel assemblies and the typical distributions of the non-stationary temperature fields in fuel and coolant have been stated in detail in the work[3]. The basic result of the research is in the following. At the energy-release jump the fuel-element shell temperature θ (or the relative coolant temperature) on the energy-release-zone exit is approximately described by the exponential relationship

$$\theta = \theta_\infty \left[1 - \exp\left(-t / t_p\right)\right], \tag{1}$$

where θ_∞ – is the established temperature value, t - is the time, t_p – is the temperature relaxation parameter for the fuel assemble. This relationship is universal for all fuel assembly variants if the relaxation parameter is determined by the formulae:

$$t_p = \frac{2}{\pi}\left(t_{TB} + t_q + h_q / w\right), \tag{2}$$

$$t_{TB} = \frac{d^2}{4a_0}\left[0.1729 + 0.9452\left(\frac{\Delta_1}{\lambda_1} + \frac{\Delta_K}{\lambda_K}\right)\frac{\lambda_0}{d_0}\right], \tag{3}$$

$$t_q = \frac{\pi d_0^2}{4\omega}\frac{\left(\rho c_p\right)_0}{\left(\rho c_p\right)_f}\frac{h_q}{w}, \tag{4}$$

where d – is the fuel element diameter; d_0 – the core diameter; Δ_1 – the shell thickness; Δ_K – the thickness of the contact sublayer between the core and the shell; $\lambda_0, \lambda_1, \lambda_k$ – the heat conductivity coefficients of the fuel, the shell and the contact sublayer; a_0 – the fuel temperature conductivity; $\left(\rho c_p\right)_0$ and $\left(\rho c_p\right)_f$ – the density and heat-capacity products for the fuel and the coolant respectively; h_q – the energy-release-zone length; w – the average coolant velocity; ω – the coolant passage cross-section.

In the formula (2) t_{TB} – is the temperature relaxation parameter for the fuel assembly element under the isothermal condition on it's surface. The expression (3) for the parameter t_{TB} has been found from the analytical solution of the non-stationary heat conductivity task for the fuel assembly element under the zero boundary condition on it's surface.

The parameter t_q in the formula (2) is the time $t_q \equiv \left(\rho c_p\right)_0 \Delta T / q_v$ for the fuel temperature to rise on the relative coolant temperature value ΔT under the volume fuel-energy-release density q_v. Determining the relative coolant temperature from the energy balance we obtain for t_q the expression (4). The parameter t_q role is important at the Reynolds numbers about and less then 10^4. At such relatively small Reynolds numbers the coolant temperature variation in the flow direction leads to the essential axial irregularity of the fuel-assembly-element-core temperature [3].

The investigation of the non-stationary thermal conductivity task for the fuel element flowed around by the coolant flat flow shows on the necessity to consider the coolant transport time through the energy-release zone h_q / w. The influence of h_q / w on the temperature relaxation in the assembly becomes essential at the small Reynolds numbers and relatively low fuel heat capacity.

It is to be emphasized although the individual components of the parameter t_p have been found from analytical solutions of the heat conductivity task for the fuel element the final formula (2) has been obtained as the generalization result of much calculation data. The constant $2 / \pi$ in the formula (2) has been obtained as the result of such generalization.

The formulae (2)- (4) do not contain empirical values like the heat transfer coefficient. It indicates on the unessential influence of the coolant boundary layer thermal resistance on the assembly temperature relaxation.

In fig.1 in coordinates $\left(t / t_p, \theta / \theta_\infty\right)$ the exponential relationship (1) is presented by the solid line, by the dots the fuel-element-shell-temperature dynamics at the energy-release-zone exit is presented. The data for the annular channels formed by placing the fuel element in the circular pipe with the adiabatic condition on it's outside wall are presented also. The assembly and annular channel parameters are brought together in table 1.

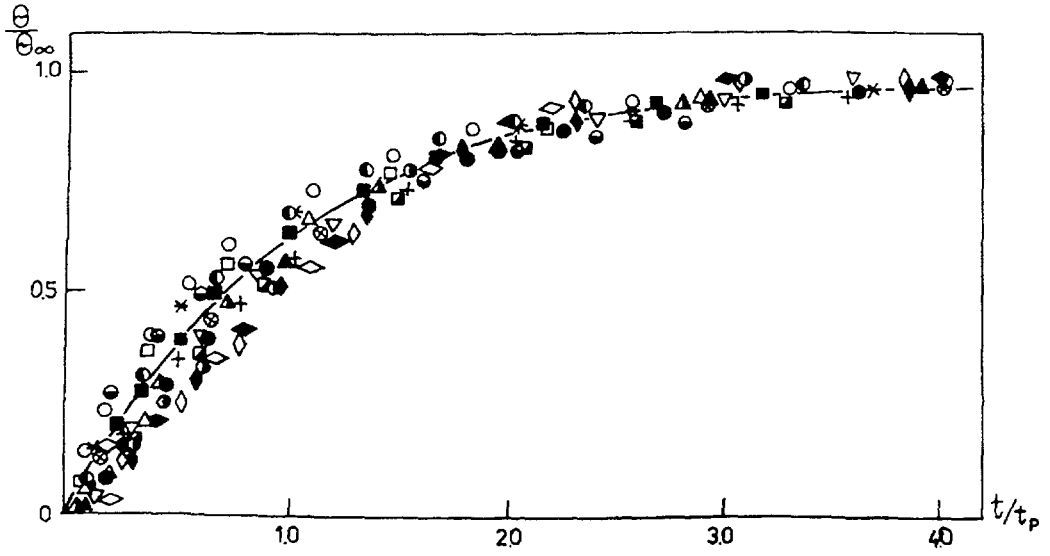

Fig. 1

In the table 1 the following notations are used:

$$R_0 = d_0 / d, \qquad R_1 = \left(d - 2\Delta_1\right) / d, \qquad H = 2h_q / d,$$
$$\Lambda_0 = \lambda_0 / \lambda_f, \quad \Lambda_1 = \lambda_1 / \lambda_f, \quad A_0 = a_0 / a_f,$$
$$A_1 = a_1 / a_f, \quad R_T = \left(\Delta_k / \lambda_k\right) / \left(2\lambda_f / d\right),$$

Re– Reynolds number; Pr– Prandtl number; õ - the relative assembly space; R_a – the ratio of the external to internal radiuses for the annular channel; λ_f and a_f – the coolant heart and temperature conductivity coefficients; a_1 – the fuel-element-shell temperature conductivity.

The insignificant data dispersion, fig.1, for the fuel-element-shell-temperature dynamics shows that t_p is the generalized dynamic characteristic of the fuel assembly.

The reactor constant t_{PE}, representing itself as the sum of two components (the fuel element constant t_0 and the constant depending on the coolant outlay through the assembly) has been proposed in the work [4] as an assembly dynamic characteristic. We make here use of the terms of the work [4] for t_{PE} and t_0. The significant data dispersion for the fuel-element-shell-temperature dynamics is observed if data are presented in coordinates $\left(t / t_0, \theta / \theta_\infty\right)$, fig.2, or in coordinates $\left(t / t_{PE}, \theta / \theta_\infty\right)$, fig.3.

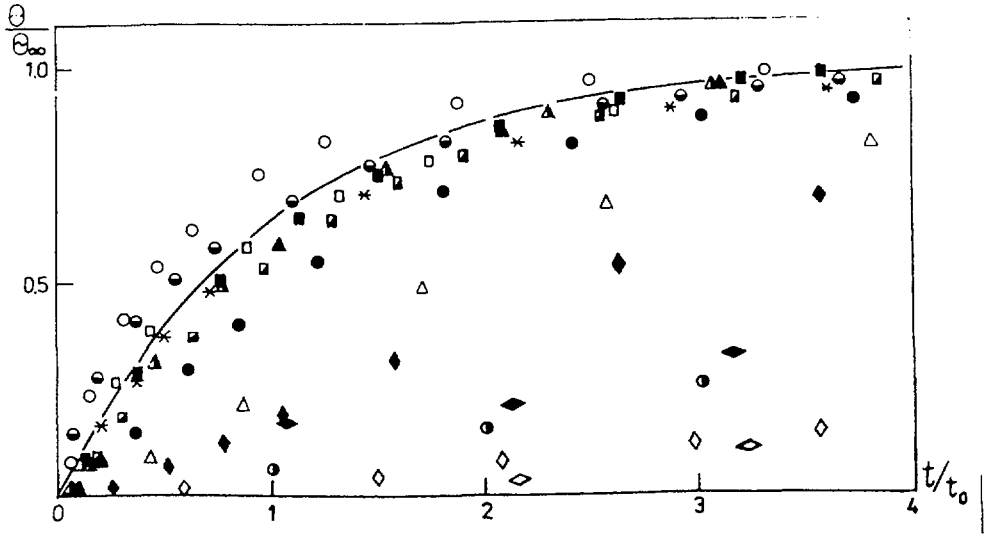

Fig. 2

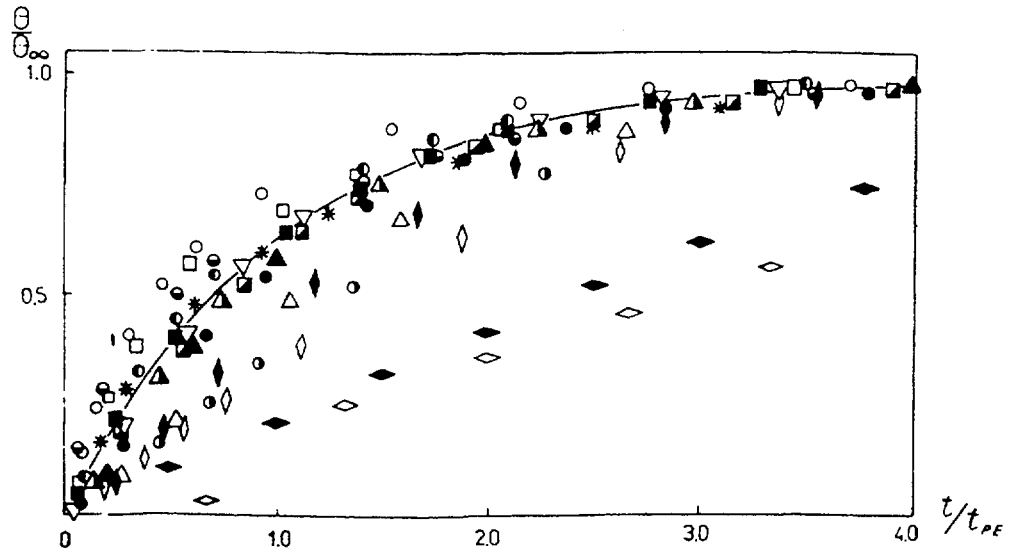

Fig. 3

Thus neither the fuel element constant nor the reactor constant can be regarded as the generalized dynamic characteristic of the assembly.

It is to be noted that the fuel element constant t_0 includes the heat transfer coefficient representing itself as the empirical value called to consider the influence of the thermal coolant resistance on the temperature relaxation time in the assembly [4].

The formulae for the fuel-element and reactor constants [4] have been obtained with the aid of the approaches stated in [5] and containing a number of assumptions. In particular they suppose the fuel-element-shell thickness to be small with respect to the fuel-element radius. Therefor it is possibly to neglect the curvature of the fuel-element-core surface. Such assumption is quite not suitable for the fuel-element imitators. The heat capacity of the imitator electric spiral effects on the imitator temperature relaxation time. At that time the internal and external radiuses of the electric spiral essentially differ from the imitator shell radius.

The numerical investigation results for the different assembly models including the models with the triangular and square imitator packing have shown the imitator temperature relaxation parameter t_p to be the sum of three items [6] by analogy with the expression (2):

$$t_p = \frac{2}{\pi}\left(t_{им} + t_q + h_q / w\right).$$

Here

$$t_q = \frac{\pi\left(d_0^2 - d_{in}^2\right)}{4\omega} \frac{\left(\rho c_p\right)_0}{\left(\rho c_p\right)_f} \frac{h_q}{w}$$

is the time for the heater electric spiral temperature to rise on the value being equal to the relative coolant temperature in the model; $\left(\rho c_p\right)_0$ – is the density and heat-capacity product for the electric spiral; d_0 and d_{in} are the external and internal diameters of the effective electric spiral layer. The value of d_{in} is determined from the condition the layer mass on the imitator length unit is equal to the actual mass of the electric spiral.

The imitator structure complexity has not allowed to obtain the explicit expression for the parameter $t_{им}$ representing itself as the imitator temperature relaxation parameter at the isothermal condition on the imitator surface. For determining $t_{им}$ the one-dimensional non-stationary heat-conductivity-task solution for the imitator with the zero boundary condition on it's surface and at the energy-release jump has been used. The value of t_p was found from the condition

$$\theta\left(2t_{им} / \pi\right) / \theta_\infty = 1 - e^{-1} \cong 0.632, \qquad (6)$$

where $\theta\left(2t_{им} / \pi\right)$ is the temperature at the internal surface of the electrical spiral layer at the time $t = 2t_{им} / \pi$, θ_∞ is the established value of that temperature. The coefficient $2 / \pi$ has been introduced in the definition of $t_{им}$ for obtaining the t_p formula like (2).

In reality the heat transfer from the electrical spiral to the silicon-organic layer is realized through the some air layer. For the values t_p determined by the way stated above to correspond the actual assembly models the effective thickness h_B of the air layer must be known. From comparing the calculated and experimental values of t_p it has been determined that the ratio of h_B to the electrical spiral wire radius r_n is the same for the different models:

$$h_B / r_n = 0.45.$$

In fig.4 in coordinates $\left(t / t_p, \theta / \theta_\infty\right)$ the exponential relationship (1) is presented by the solid line, by the dots the imitator shell temperature dynamics at the energy-release-zone exit is presented. The model parameter are brought together in table 2.

In the table 2 the following notations are used:

$$\tau_{им} = \frac{t_{им} \cdot w}{h_q}, \quad \tau_p = \frac{t_p \cdot w}{h_q}.$$

In fig.5 in coordinates $\left(t / t_p, \theta / \theta_\infty\right)$, where t_p is the experimental relaxation parameter value the data on the imitator shell temperature dynamics at the exit of the energy release zone are presented. The data have been obtained at the different models under the instantaneous cut-off of the electrical loading.

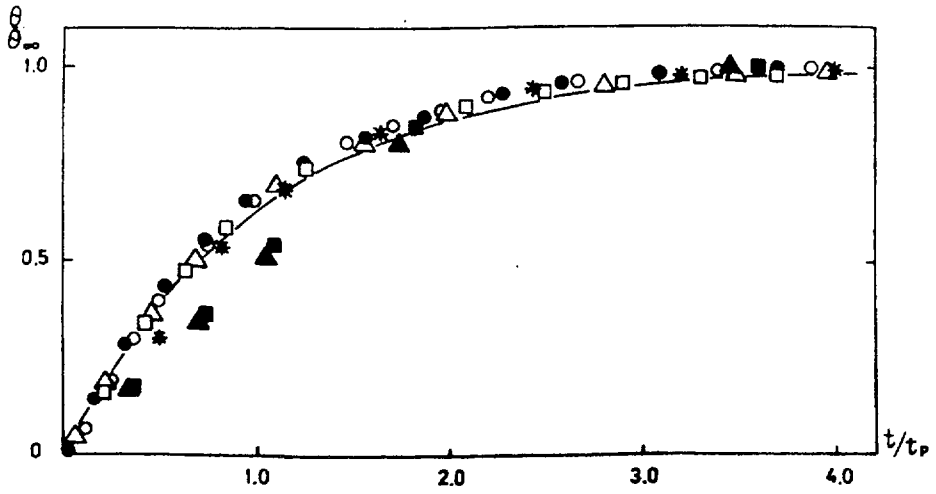

Fig. 4

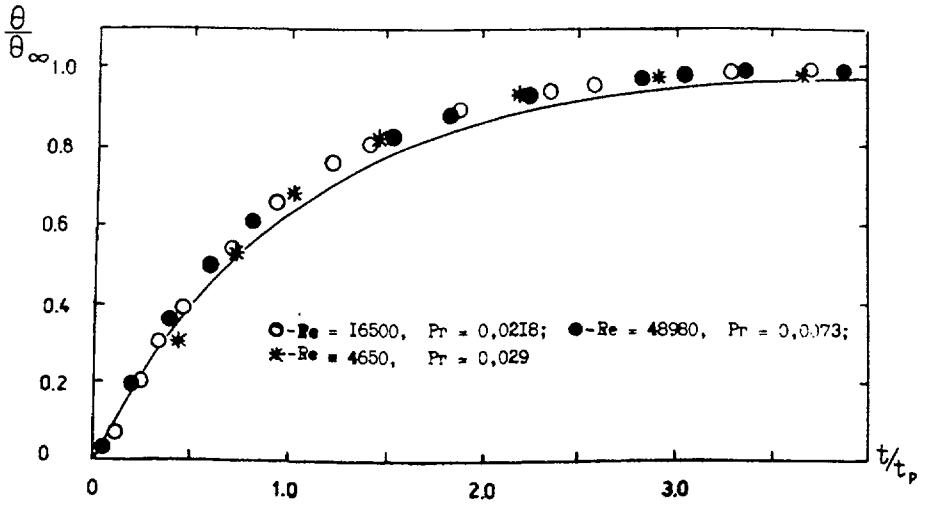

Fig. 5

Figures 4 and 5 show that the relaxation parameter t_p can be regarded as the generalized dynamic characteristic of the model. It allows to state the approximate modeling condition as the equality of the non-dimensional relaxation parameter values for the assembly and it's model. If the coolant transport time through the energy-release zone is taken as the time scale then the approximate modeling condition is

$$\left(\frac{wt_p}{h_q}\right)_{assembly} = \left(\frac{wt_p}{h_q}\right)_{model}$$

CONCLUSIONS

(1) The simple formula containing no empirical quantities and determining the assembly temperature relaxation parameter through the assembly parameters was obtained.

(2) The relaxation parameter is the generalized dynamic assembly characteristic allowing to present the fuel-element-shell-temperature dynamics or the relative coolant temperature as the universal time relationship.

(3) The method of determining the temperature relaxation parameter for the assembly model was worked out.

(4) The approximate modeling condition for the non-stationary heat exchange in the fuel assembly was stated as an equality of the non-dimensional parameter relaxation values in the assembly and it's modal.

REFERENCES

[1] USHAKOV P.A. The Aproximated Thermal Modeling of Cylindrical Elements.- Liquid Metals. M: Atomizdat, 1967, p.137-148.

[2] MIKHIN V.I. For the Aproximated Thermal Modeling of Fuel Pins with Non-uniform Heat Allocation.- IPPE Preprint-1497, Obninsk, 1983.

[3] MIKHIN V.I., FETISOVA L.N. The Numerical Investigation of Non-stational Themperature Fields in Central Zones of Nuclear Reactors Fuel Subassemblies – IPPE Preprint-2240, Obninsk, 1992.

[4] KOUZNETSOV I.A. Accident and Trasient Processes in Fast Reactors. M.: Energoatomizdat, 1987.

[5] KRAMEROV A.YA., SHEVELIOV YA.V. Engineering Calculations of Nuclear Reactors. M.: Energoatomizdat, 1984, 736 ps.

[6] MIKHIN V.I., MATJUKHIN N.M. The Questions of Transient Processes Numerical and Experimental Modeling in WWER Cores // Proceedings of the International Conference "Thermal-Physics–95", Obninsk, 1995, v. 1.