FACTORS AFFECTING THE HEATING OF THE HEAT TRANSFER AGENT IN A PRESSURIZED-WATER REACTOR

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Relations are presented that make it possible to determine the temperature rise in a pressurized-water reactor for various starting conditions.

The total useful cross section for heat transfer agent in the core fuel assemblies can be determined in two ways:

$$F_{use} = \frac{Q}{c_p \Delta t_{max} K_1 \gamma_{av} W_{av} K_2} \qquad (1)$$

or

$$F_{use} = \varepsilon \frac{\pi D^2}{4}. \qquad (2)$$

From the second equation, using (1), we find the core diameter

$$D = \sqrt{\frac{4Q}{\varepsilon \pi c_p \Delta t_{max} K_1 \gamma_{av} W_{av} K_2}}. \qquad (3)$$

The thermal capacity of the reactor

$$Q = F_{su}\, q_{su.av}. \qquad (4)$$

In general form the average heat load on the fuel element surface is given by the formula [1]

$$q_{su.av} = \frac{q_{cr\,X\min}}{K_{r\max} K_{HX\min} K_a K_{s.f}}. \qquad (5)$$

If rod-type fuel elements are employed the heat transfer surface of the core

$$F_{su} = \frac{\pi (d_f + \delta_H) HD (1-\varepsilon)}{d_f^2}. \qquad (6)$$

Hence, using (3)–(5), we find the height of the reactor core:

$$H = \frac{K_{r\max} K_{HX\min} K_a K_{s.f} K_1 K_2 \varepsilon c_p \Delta t_{max} \gamma_{av} W_{av} d_f^2}{4 q_{cr\,X\min} (d_f + \delta_H)(1-\varepsilon)}. \qquad (7)$$

Using (3) and (7) and introducing the notation A = = H/D, we obtain the average heating of the heat transfer agent in the reactor core:

$$\Delta i_{av} = \frac{2.74\, A^{2/3} q_{cr\,X\min}^{2/3} (1-\varepsilon)^{2/3} Q^{1/3} (d_f + \delta_H)^{2/3}}{K_{r\max}^{2/3} K_{HX\min}^{2/3} K_a^{2/3} K_{s.f}^{2/3} K_2 d_f^{4/3} \varepsilon \gamma_{av} W_{av} K_1}. \qquad (8)$$

If in designing atomic power plants the power on the shaft of the main turbomechanical unit is given, in

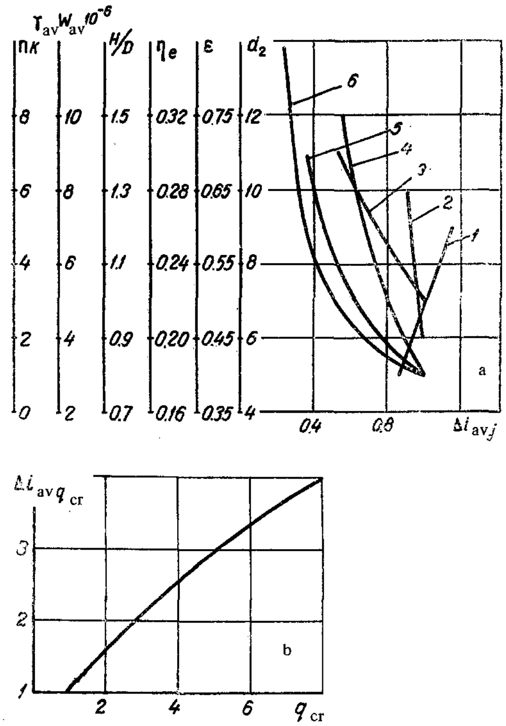

Fig. 1. a) Effect of individual parameters and b) critical heat load on the average heating of the heat transfer agent in the reactor.

(8) it is desirable to express the thermal capacity of the reactor in terms of the shaft power N_e and the plant efficiency η_e; then

$$\Delta i_{av} = \frac{2{,}74\, A^{2/3} q_{cr\,X\min}^{2/3} (1-\varepsilon)^{2/3} N_e^{1/3} (d_f + \delta_H)^{2/3}}{K_{r\max}^{2/3} K_{HX\min}^{2/3} K_a^{2/3} K_{s.f}^{2/3} \eta_e^{1/3} K_2 d_f^{4/3} \varepsilon \gamma_{av} W_{av} K_1}. \qquad (9)$$

It follows from (9) that the heating of the heat transfer agent is affected by the following parameters of the reactor and the plant: the critical heat flux in the section along the length of the fuel element where the safety factor is at a minimum $q_{crX\min}$; the porosity of the core with respect to the heat transfer agent ε, the coefficients of nonuniformity of heat release with respect to height $K_{r\max}$, and fuel assembly K_a; safety factor $K_{s.f}$; diameter of fuel element d_f; mass velocity $\gamma_{av} W_{av}$; power N_e; and plant efficiency η_e.

The quantitative effect of these factors on the heating of the heat transfer agent is shown in Fig. 1. At H/D = 0.8–1.2, Δi_{avA} varies little (Fig. 1a, curve 1).

The effect of η_e is also slight (curve 2); thus, as η_e increases from 20 to 28%, $\Delta i_{av\eta_e}$ decreases by 12%, whereas as ε increases from 0.5 to 0.7, $\Delta i_{av\varepsilon}$ falls by 50% (curve 3). An increase in the fuel element diameter is accompanied by a decrease in the heating of the heat transfer agent. It follows from Fig. 1a (curve 4) that increasing the diameter from 5 to 12 mm leads to a fall in Δi_{avd_f} by 50%. The quantities $\Delta i_{av\gamma_{av}W_{av}}$ and $\Delta i_{av\Pi K}$ are strongly influenced by the velocity of the heat transfer agent in the core (curve 5) and the product $\Pi K = K_{s.f}K_{rmax}K_{HXmin}K_aK_1K_2$ (curve 6).

For existing and projected reactors [3, 4] ΠK = = 9.5–4.0. From Fig. 1a (curve 6) it follows that as ΠK increases from 1 to 4, $\Delta i_{av\Pi K}$ falls by 60%, after which this effect diminishes and in the range from 4 to 9.5 the heating falls by 18%. Therefore to obtain an important increase in $\Delta i_{av\Pi K}$ it is necessary to reduce ΠK to less than 4. The effect of critical heat flux is shown in Fig. 1b. As q_{cr} increases from 2 to 8 mW/m², $\Delta i_{avq_{cr}}$ changes by a factor of 2.5.

We will consider in greater detail the determination of the critical heat flux (9) in the section along the fuel element in which the burnout safety factor is minimum. In [1] a relation was obtained for determining the critical heat flux and the coefficient of nonuniformity of heat release with respect to height in a particular section for the case of a cosinusoidal distribution and subheating of the heat transfer agent at the channel outlet $\geq 10°$ C. We will consider the case in which, to increase the thermal economy or improve the weight characteristics of the plant, the temperature of the heat transfer agent at the outlet of the most heavily stressed channel is assumed to be equal to the saturation temperature. The lack of a convenient general analytic dependence of the critical heat flux on subheating embracing the entire range of variation of that parameter down to zero precludes an absolutely rigorous calculation. However, since in the range of variation of subheating from 10 to 0° C the critical heat flux remains practically constant for [4], we can assume that the minimum safety factor will occur in the section along the length of the fuel element where $\Delta t_H = 10°$ C. On the basis of [2] the coordinate of the section in which the safety factor is minimum with

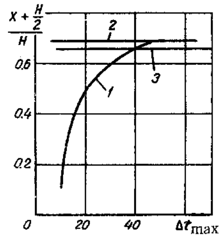

Fig. 2. Design complexes as a function of the heating of the heat transfer agent (°C) in the most heavily stressed fuel element: 1) $(X_{pr} + H/2)H$; 2) $(X_{min} + H/2)H$ at $H/H' = 0.835$; 3) $(X_{min} + H/2)H$ at $H/H' = 0.925$.

$\Delta t_{Hout} = 0$ is determined from the formula

$$X_{\min} = \frac{H'}{\pi} \times \arcsin \frac{\sin\frac{\pi H}{2H'} - \sqrt{\sin^2\frac{\pi H}{2H'} - 4f(1-f)}}{2(1-f)}, \qquad (10)$$

where $f = 0.33$, $H' = H + 2\delta_{eff}$.

The plus sign in front of the root in (10) has been discarded, since it is equivalent to the extension of (10) to an unspecified range ($\Delta t_{Hout} < 10°$ C).

For the same reason in some cases it is not possible to employ (10) even with a minus sign in front of the root. We will consider these cases. X_{pr} is found from the following relation:

$$X_{pr} = \frac{H'}{\pi}\arcsin\left[\sin\frac{\pi H}{2H'}\left(1-\frac{20}{\Delta t_{\max}}\right)\right]. \qquad (11)$$

The ratio $(X_{pr} + H/2)H$, determined from (11) as a function of the temperature rise in the most heavily stressed channel, is shown in Fig. 2; the same figure gives the ratio $(X_{min} + H/2)H$ calculated from (10). It follows from the graphs that the use of (10) is valid when $H/H' = 0.925$–0.835 for $\Delta t_{max} \geq 40$–$48°$ C; at smaller values of Δt_{max} the section corresponding to the minimum safety factor lies in the region $\Delta t_H <$ $< 10°$ C and, consequently, if we employ q_{cr} from [5] we cannot use the coordinate determined from (10). It follows that the determination of the coefficient of nonuniformity of heat release with respect to height and the critical heat load in the absence of subcooling at the outlet from the most heavily stressed channel and in the presence of a cosinusoidal distribution of heat release for use in calculating the subcooling of the heat transfer agent averaged over the core must be made in accordance with formulas (21) and (22) of [1] with $X = X_{min}$ in accordance with formula (10) for $\Delta t_{max} \geq 40$–$48°$ C and $X = X_{pr}$ in accordance with formula (11) for $\Delta t_{max} \leq 40$–$48°$ C. We note that at Δt_{max} $\Delta t_{max} = 20°$ C, $X_{pr} = 0$, $K_{HX} = K_{Hmax}$, and

$$q_{cr\,x} \approx 1275\,(W_{av}\gamma_{av})^{0.5}\left(\frac{v''-v'}{v''}\right)^{-1.8}.$$

Using (9), we can find the average subcooling in the core for specific conditions. In this case, since the values of the critical heat flux and the coefficient of nonuniformity of heat release with respect to H entering into the formula depend on Δt_{max}, it is necessary to specify the value of Δt_{max}, which, if necessary, can be corrected in accordance with the Δi_{av} obtained from (9). The relation between Δi_{av} and Δt_{max} is given by

$$\Delta i_{av} = \Delta t_{\max} c_p / K_1.$$

For atomic power plants with fixed capacity it is also possible to solve the inverse problem of determining the necessary reactor parameters (d_f, K_1, K_r, K_a, K_H, γ_{av}, W_{av}) ensuring a given subcooling of the heat transfer agent in the core.

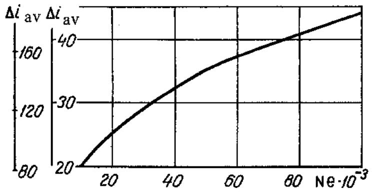

Fig. 3. Average heating of heat transfer agent in reactor core as a function of the capacity (hp) of the power plant.

To simplify the multivariant calculations based on (9), we have plotted in Fig. 3 the dependence of the heating of the heat transfer agent in the reactor core Δi_{av0} on the capacity of the plant for the following starting data: ΠK = 5, H/D = 1.0; $\eta_e = 0.2$; $W_{av}\gamma_{av} = 3 \cdot 10^6$ kg/m^2·hr, $\varepsilon = 0.5$; $d_f = 5$ mm, $\delta_H = 0.5$ mm; $q_{cr} = 4$ mW/m^2.

The average heating of the heat transfer agent over the core under conditions differing from those indicated can be determined using the graphs presented in Fig. 1a, b as a result of multiplying the value determined from Fig. 3 by correction coefficients that take into account the deviation from the original variant:

$$\Delta i_{av} = \Delta i_{av0}\, \Delta i_{avW_{av}\gamma_{av}}\, \Delta i_{av\eta_e}\, \Delta i_{av\varepsilon}\, \Delta i_{avq_{cr}} \times \\ \times \Delta i_{avd_f}\, \Delta i_{av\Pi K}\, \Delta i_{avA}. \qquad (12)$$

NOTATION

Q is the thermal capacity of reactor; c_p is the specific heat of the heat transfer agent; F_{use}, F_{su}, and $q_{su.\,av}$ are useful cross sections for the heat transfer agent in the fuel assemblies, heat transfer surface, and average heat load on core surface, respectively; ε is the fraction of the core cross section occupied by the heat transfer agent; D and H are the diameter and height of the core, respectively; δ_{eff} is the effective reflector savings; d_f and δ_H are the diameter of the fuel rod and twice the thickness of the can, respectively; N_e and η_e are the capacity and efficiency of the plant, respectively; q_{cr} is the critical heat flux; Δt and Δt_H are the temperature rise of the heat transfer agent and subheating, respectively; v" and v' are the specific volume of the vapor and water on the saturation line, respectively; $\gamma_{av}W_{av}$ is the mass velocity of the heat transfer agent in the core; K_1, K_H, K_r, K_a are the coefficients of nonuniformity of heating in the fuel assemblies and with respect to the height, radius, and fuel assembly of the core, respectively; K_2 is the coefficient by means of which we take into account the heat transfer agent cooling the shielding and elements of the moderator control system; $K_{s.f}$ is the burnout safety factor; ΠK is the product of the coefficients K; Δi_{av}, Δi_{av0} are the average heating (enthalpy increase) of heat transfer agent in the reactor core (Fig. 3); Δi_{avj} is the change in the value of the average heating of the heat transfer agent in the reactor core owing to parameter j (j = η_e, ε, q_{cr}, d_f, A, ΠK, $\gamma_{av}W_{av}$); X_{pr} is the coordinate of the fuel element cross section up to which the formula for q_{cr} from [5] is valid; X_{min} is the coordinate of the fuel element cross section in which the safety factor is minimum. Subscripts: max is the maximum value of the parameter; out is the value of the parameter at the reactor channel outlet.

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