DETERMINING THE MEAN TEMPERATURE DIFFERENCE IN NUCLEAR REACTORS OF THE NONBOILING TYPE

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UDC 621.039.5/06

Relations are derived for the mean temperature difference in the center channel and within the active zone of a reactor with a heat carrier whose properties are almost constant.

It is well known that a nuclear power reactor constitutes a heat exchanger whose basic purpose is to raise the temperature of the heat carrier with the heat released during nuclear reactions. As far as nuclear reactors are concerned, however, no ideas have been developed yet on how to estimate one of the fundamental properties of any heat exchanger: the mean temperature difference. It is thus not possible to fully analyze the various reactors and to evaluate them comparatively with respect, for example, to the attainable compactness or the degree of irreversibility of the heat delivery process in the thermodynamic cycle of nuclear power apparatus.

The well known logarithmic-mean law for determining the mean temperature difference cannot be applied to reactors, essentially because the heat generation does not follow a monotonic trend. The temperature variation along the heat emitting elements is accordingly characterized by a boundedness (Fig. 1).

Another characteristic feature of a nuclear reactor as a heat exchanger with internal heat sources is the use of a single heat carrier whose temperature is raised by a unique process of heat transfer from the fuel. Eliminating the intermediate temperatures determined on the basis of a stage-by-stage analysis of the process, we have for the case of steady heat flow with a heat carrier whose properties are almost constant:

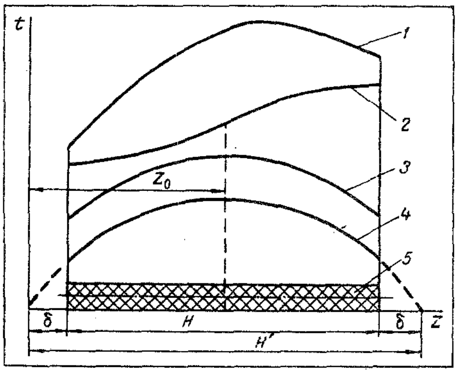

Fig. 1. Temperature variation along the center channel of a nonboiling-type reactor with a sinusoidal heat source distribution: temperature of the nuclear fuel t_{0f} (1), temperature of the heat carrier t (2), temperature difference Δt_z (3), heat generation (4), fuel element in the operating channel (5).

$$\Delta t \equiv t_{0f} - t = q(R_f + R_g + R_s + R), \tag{1}$$

$$K^* \equiv (R_f + R_g + R_s + R)^{-1} = 1/R_r, \tag{2}$$

$$dQ_r = K^* \Delta t dF, \ Q_r = \int_{F_r} K^* \Delta t dF = \bar{K}_r^* \Delta \bar{t}_r F_r. \tag{3}$$

Here $\Delta \bar{t}$ and $\Delta \bar{t}_r$ denote the local and the mean temperature difference along the active zone of a reactor; the conductive thermal resistances of the fuel R_f, of the gap R_g, and of the shell R_s, as well as the convective thermal resistance of the heat carrier R are determined according to published formulas and depend on the type, the shape, and the thermophysical properties of the heat emitting elements as well as on the heat transfer rate; K^* and $\bar{K}_r^*$ are the local and the mean heat transfer coefficients equal to the reciprocal of the respective total thermal resistances of the fuel and heat carrier system. When K^* varies appreciably within the active zone of a reactor, then

$$\bar{K}_r^* = \sum_{i=1}^{i=n} K_i^* F_i / F_r$$

Engineering Institute of the Refrigeration Industry, Odessa. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 24, No. 3, pp. 484-488, March, 1973. Original article submitted December 29, 1971.

The characteristics of heat generation within an active zone are usually assumed analogous to the neutron flux distribution, for the description of which one introduces nonuniformity factors $\bar{\mu}_z$ referred to the height of the most highly stressed operating channel and $\bar{\mu}_r$ referred to the radius of the active zone. Then

$$\bar{q}_{ch} = q_{max}/\bar{\mu}_z; \quad \bar{q}_r = q_{max}/\bar{\mu}_z \bar{\mu}_r. \tag{4}$$

Combining expressions (3) and (4), we obtain

$$\Delta\bar{t}_r = q_{max}/\bar{K}^*_r \bar{\mu}_z \bar{\mu}_r; \quad \Delta\bar{t}_{ch} = q_{max}/\bar{K}^*_{ch} \bar{\mu}_z. \tag{5}$$

In order to be specific, we will consider the common case of a cylindrical active zone with a regular symmetrical distribution of neutron flux: sinusoidal along the height and according to a zeroth-order Bessel function of the first kind along the radius [1]:

$$\bar{\mu}_z = 1{,}57\left(1 + \frac{2\delta}{H'}\right)^{-1}; \quad \bar{\mu}_r = 2{,}31\left(1 + \frac{2\delta}{H'}\right)^{-1}, \tag{5'}$$

$$\Delta t = q_{max} \sin \frac{\pi z}{H'} \Big/ K^*. \tag{6}$$

According to (6), the temperature difference along the height varies sinusoidally, first increasing and then decreasing. In the general case this variation follows the actual pattern of heat generation along the operating channel. With the aid of expression (6) and assuming that $K^* = \bar{K}^*_{ch}$ = const., we will determine the maximum local temperature difference as follows:

$$\frac{\partial \Delta t}{\partial z} = \frac{\pi}{H'} \cos \frac{\pi z_0}{H'} = 0; \quad \frac{\pi z_0}{H'} = 0{,}5\pi; \quad z_0 = \frac{H'}{2},$$
$$\Delta t_{max} = q_{max} \sin \frac{\pi z_0}{H'} \Big/ \bar{K}^*_{ch} = q_{max} \Big/ \bar{K}^*_{ch} \tag{7}$$

In this way, Δt_{max} occurs approximately at the center of the active zone. The Law of the Mean yields

$$\Delta\bar{t}_{ch} = \frac{1}{F_{ch}} \int_F \Delta t dF = \frac{1}{H'} \int_\delta^H \Delta t_{max} \sin \frac{\pi z}{H'} dz,$$
$$\Delta\bar{t}_{ch} = \frac{\Delta t_{max}}{\pi} \left(\cos \frac{\pi\delta}{H'} - \cos \frac{\pi H}{H'}\right). \tag{8}$$

When $\delta \ll H$ (the effect of the reflector is negligible), then

$$\Delta\bar{t}_{ch\,\delta=0} = 2\Delta t_{max}/\pi. \tag{8'}$$

Considering expression (7), we have instead of (5)

$$\Delta\bar{t}_{ch} = \Delta t_{max}/\bar{\mu}_z; \quad \Delta\bar{t}_r = \Delta t_{max} \mu_{ch} \mu_r \tag{9}$$
$$\Delta\bar{t}_r = \Delta\bar{t}_{ch}/\mu_{ch} \mu_r. \tag{10}$$

Here $\bar{\mu}_{ch} = \bar{K}^*_r / \bar{K}^*_{ch}$ is the nonuniformity factor referred to the heat transfer within the active zone. In view of the importance of determining $\Delta t_{max} = (t_{0f} - t)_{z=0.5H}$, we will examine the following expressions:

$$t_{z=0,5H} = t' + \frac{q_{max}}{\pi W} \cos \frac{\pi\delta}{H'}; \quad t_{z=H'-\delta} = t'' = t' + 2\frac{q_{max}}{\pi W} \cos \frac{\pi\delta}{H'};$$
$$t_{z=0,5H} = t' + 0.5\delta t = 0.5(t' + t'') = \bar{t}, \tag{11}$$
$$\Delta t_{max} = q_{max}(R_f + R_g + R_s + R) = (t_{0f} - t)_{z=0.5H}.$$

For the purpose of determining Δt_{max}, therefore, the temperature of the heat carrier at the center section of the channel can be defined as the arithmetic mean of the temperature at the entrance and the exit. It is also worthwhile to note the relation between Δt_{max} and the shell temperature at the channel entrance and exit ($\Delta t' = t'_s - t'$, $\Delta t'' = t''_s - t''$) as well as at the "hottest" section at the distance z_{ref}:

$$\Delta t_{max} = \frac{\Delta t' + \Delta t''}{2 \sin(\pi\delta/H')}, \tag{12}$$

$$\Delta t_{max} = (t_{s,max} - t) \operatorname{cosec} \frac{\pi z_{ref}}{H'} \tag{13}$$

It follows from (9) and (10) that the mean temperature differences in the channel and within the active zone depend on the nonuniformity of heat generation and heat transfer, constituting a part of the maximum temperature difference in the channel Δt_{max}, that a lesser degree of nonuniformity, with other conditions unchanged, will increase the mean temperature difference, and that the temperature difference in a reactor is always smaller than the temperature difference in the center channel. With an ideal design of both the neutron-physical and the heat transfer processes in the active zone of a reactor, the nonuniformities vanish while $\bar{\mu}_z$, $\bar{\mu}_r$, and $\bar{\mu}_{ch}$ approach unity. Then, according to (9) and (10), $\Delta\bar{t}_r \to \Delta\bar{t}_{ch} \to \Delta\bar{t}_{max}$, i.e., under ideal conditions the mean temperature differences attain their maximum possible values.

In the other extreme case, for an active zone with $2\delta \ll H'$ and $2\delta \ll R'$, especially in a reactor without reflector ($\delta = 0$), expression (5') yields $\bar{\mu}_z = 1.57$, $\bar{\mu}_r = 2.31$, and $\bar{\mu}_v = 1.57 \cdot 2.31 = 3.62$. Assuming that $\bar{\mu}_{ch} = 1$, for simplicity, we find the minimum possible mean temperature differences:

$$\Delta\bar{t}_{ch.min} = 0.637\Delta t_{max}, \quad \Delta\bar{t}_{r.min} = 0.273\Delta t_{max}.$$

The result for $\Delta\bar{t}_{ch,min}$ is identical to expression (8'). Generally,

$$0.637 < \Delta\bar{t}_{ch}/\Delta t_{max} < 1; \quad 0.237 < \Delta\bar{t}_r/\Delta t_{max} < 1. \tag{14}$$

Inequalities (14) indicate the availability of large margins for increasing the mean temperature difference (and, consequently, improving the compactness) in nuclear reactors by bringing $\Delta\bar{t}_r$ closer to Δt_{max}. Inasmuch as the ratio of these two quantities has been established as a measure of the nonuniformity of heat generation and heat transfer within the active zone of a reactor, it becomes obvious that any means of reducing the nonuniformities will be effective in raising the utilization of the maximum available temperature difference.

An analysis of the neutron flux distribution in a non-monogroup approximation makes it possible to both account for the effect of a reflector and estimate the nonuniformity factor $\bar{\mu}_r$ more accurately than according to formula (5'), while thus refining the lower limit of inequality (14). There are also methods known for estimating the nonuniformities in reactors with nonhomogeneous active zones.

With an arbitrary heat source distribution, which can be established by such conventional methods as neutron-physical or hydraulic profiling, or transposition of regulating and compensating rods, or burnout of fuel, etc., subsequent calculations are performed after the heat source curve has been subdivided into equal segments.

In this case we have for the middle of each segment

$$\Delta\bar{t}_{i,z} = (t_{0f} - t)_i = \bar{q}_i/K_i^*, \tag{15}$$

and for the entire channel (n segments)

$$\Delta\bar{t}_z = \frac{\sum\limits_{i=1}^{i=n} K_i^* F_i \Delta\bar{t}_{i,z}}{\bar{K}_{ch}^* F_{ch}} = \frac{1}{n} \sum_{i=1}^{i=n} \frac{\bar{q}_i}{\bar{K}_{ch}^*} = \frac{\sum\limits_{i=1}^{i=n} \bar{q}_i}{\sum\limits_{i=1}^{i=n} K_i^*}. \tag{16}$$

In the design for rated operating conditions one disregards the superheat factors. In order to estimate the most severe operating modes, one introduces coefficients which account for the unfavorable departure from the rated heat generation (m_q) and for the reliability of the design $K_i^*(m_{ch})$. Instead of (15) and (16), then, we have

$$\Delta\bar{t}_{i,z} = q_i m_q \Big/ K_i^* m_{ch}; \quad \Delta\bar{t}_z = \sum_{i=1}^{i=n} q_i m_q \Big/ \sum_{i=1}^{i=n} K_i^* m_{ch} \tag{17}$$

A comparison of $t_{s,max}$ and $t_{f,max}$ with their allowable values will indicate whether the values obtained for $\overline{\Delta t_{i,z}}$ are valid. It is also useful to know $\overline{\Delta t_{i,z}}$ for estimating the range where local surface boiling of a liquid or an organic heat carrier may occur.

NOTATION

t_{0f}	is the temperature of nuclear fuel at the axis of the element, °C;
t	is the temperature of heat carrier, °C;
H', H	is the effective and actual height of active zone, m;
δ	is the effective extension, m;

q	is the instantaneous thermal flux density, W/m^2;
$\bar{q}$	is the mean thermal flux density, W/m^2;
q_{max}	is the maximum thermal flux density, W/m^2;
K^*	is the coefficient of heat transfer from fuel to heat carrier, $W/m^2 \cdot °C$;
Δt	is the temperature difference, °C;
F	is the outside surface of shell, m^2;
μ	is the nonuniformity factor.

Subscripts

ch refers to channel;
r refers to reactor.

Superscripts

' refers to parameter values at the channel entrance;
" refers to parameter values at the channel exit;
- denotes averaging.

LITERATURE CITED

1. V. S. Aleshin, N. M. Kuznetsov, and A. A. Sarkisov, Shipboard Nuclear Reactors [in Russian], Izd. Sudostroenie (1968).