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HEAT TRANSFER IN A NUCLEAR ROCKET ENGINE

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Special features of heat transfer in the reactor of a nuclear rocket engine (NRE) are dealt with. It is shown that the design of the cooling system of the NRE reactor is governed by its stability to small deviations of the parameters from the corresponding calculated values and the possibility of compensating for effects due to nonuniformities and disturbances of various types and scales.

The special features of heat transfer in a nuclear rocket engine stem from the rather high requirements on the reliability of the system for removal of heat from the nuclear energy source, i.e., the reactor, operating under conditions of high temperatures and temperature stresses. The severity of the thermal regime of the nuclear reactor follows from the compactness and high level of the specific thrust of the NRE.

For an ordinary heat exchanger with no internal heat sources, which may be part of the NRE, optimization of the shape and dimensions of the heat-exchange channels to attain the minimum volume and mass of the heat exchanger is performed from the condition of obtaining the smallest value possible for the criterion of thermohydraulic efficiency of the surface $K = (\xi/\mathrm{St}^3)^{1/2}$ for all known shapes of channels as a function of the Reynolds number (Re) [1].

In [1] an expression is derived for the area of the heat-exchange surface F per unit of transmitted thermal power Q:

$$\frac{F}{Q} = \frac{1}{2C_p}\left(\frac{\Delta T}{2\Delta P\rho\theta^3}\right)^{1/2}\left(\frac{\xi}{\mathrm{St}^3}\right)^{1/2}. \tag{1}$$

From expression (1) it follows that, other things being equal, the kind of heat-transfer agent (C_p, $\rho(P, T)$), the heating (cooling) of the heat-transfer agent (ΔT), factors governing extension of heat transfer (the pressure difference ΔP and the temperature difference θ), and the minimum of the heat-exchange surface correspond to the minimum of the criterion K. As a result of the analysis performed and generalization of experimental data on hydraulics and heat transfer using the criterion introduced it is shown (Fig. 1 from [1]), that, other things being equal, for all the experimentally examined surfaces the minimum value of the criterion K corresponds to the minimum realized Reynolds number. Thus, a possible reserve for improving heat exchange devices is realization of regimes in the range of Reynolds numbers $\mathrm{Re} \le 500$, which is examined insufficiently so far.

For the cooling system of a nuclear reactor, when determining the dimension of a characteristic individual channel, it should also be taken into account that 1) under conditions of a high thermal factor of the structure possible deviations of geometric, technological, and other parameters of the channel may lead to deviations of temperature that are much larger than in ordinary heat exchangers of the same capacity; 2) there are substantial nonuniformities of heat release in the reactor volume; 3) there are limitations on the ratio of the reactor dimensions (L/D) from the condition of minimization of the charge of fissionable material.

In operation close to the prescribed limiting values of temperatures of the reactor materials the optimum dimension for the characteristic channel of the reactor cooling system may differ from the dimension that provides the minimum surface in optimization over the mass-mean parameters of the heat-transfer agent. Thus, the optimum dimension of the characteristic channel should be determined with allowance for possible deviations of the parameters from the corresponding calculated values.

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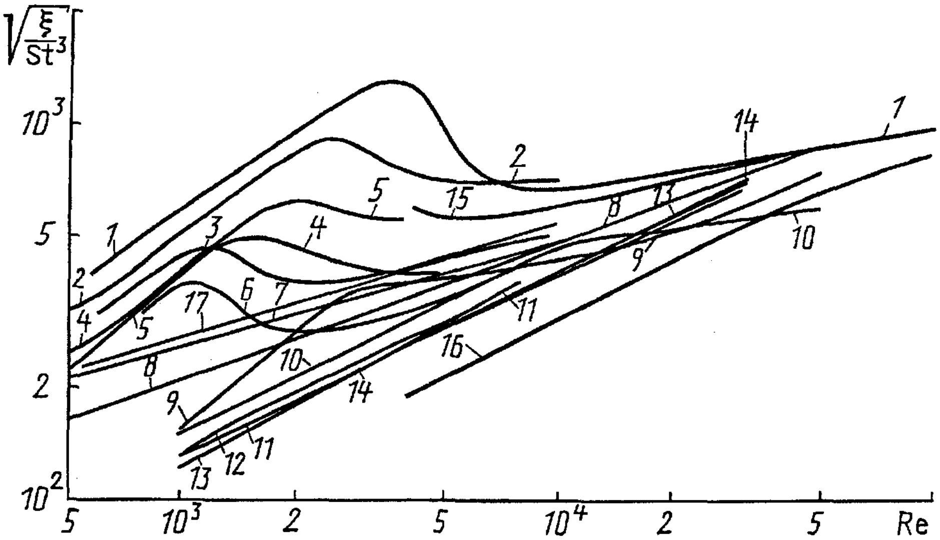


Fig. 1. Thermohydraulic characteristics of the surfaces: 1, 2) smooth pipe and flat channel; 3, 7, 9, 15, 17) channels with fins and of variable cross section; 4, 5, 6, 10, 11, 12, 13, 14, 16) nets, grids, and flow across the tube blanks; 8) ball fill.

The difference in the wall temperatures for two channels with the same temperature of the working medium at the inlet to the channels can be represented as

$$\delta T_w = \Delta T\,(\Delta\overline{T} - 1) + \theta\,(\overline{\theta} - 1)\,, \quad \Delta\overline{T} = \frac{\Delta T'}{\Delta T}\,; \quad \overline{\theta} = \frac{\theta'}{\theta}\,, \tag{2}$$

where ΔT, θ are the calculated values of the heating of the working medium on the considered portion of the channel and the temperature difference from the wall to the working medium ($\Delta T'$, θ' are the parameters of the channel with changed values as compared to the calculated ones); $\Delta\overline{T}$, $\overline{\theta}$ are the relative heating and temperature difference.

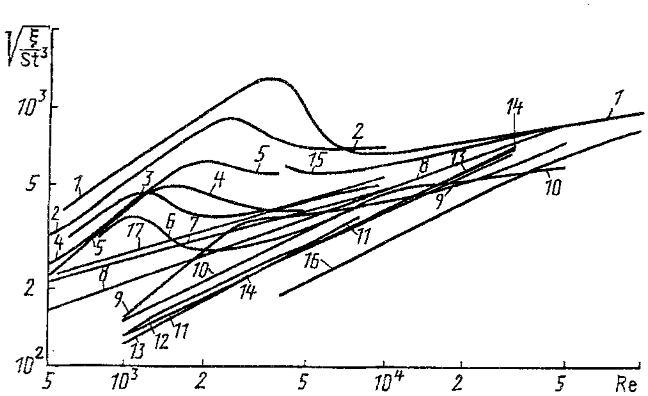
We will determine the change in the wall temperature from the change in $\Delta\overline{T}$ and $\overline{\theta}$ as a function of deviation of the parameters from the corresponding nominal values. In [2] expressions for $\Delta\overline{T}$ and $\overline{\theta}$ are obtained from a simultaneous consideration of the equations of energy, motion, continuity, and state of a gas for a channel with nominal parameters and a channel with small possible deviations of the parameters from the calculated values.

For the considered NRE $\Delta T \gg \theta$ and $\Delta\overline{T} > \overline{\theta}$ always, and therefore the usual methods of improving the heat-transfer conditions (by increasing the heat-transfer coefficient and correspondingly decreasing the value of θ) fail to provide the required mass-mean temperatures of the working medium in an actual design of a reactor with allowance for possible deviations and nonuniformities.

From the expression for temperature nonuniformities (2) it follows that in a fuel assembly (FA) made by the scheme of parallel isolated channels accumulation of the temperature nonuniformity along the channel length is possible (the term in (2) that is proportional to the heating of the working medium). Therefore the shorter the channel with unfavorably combined deviations, the less the difference between the channel temperatures and the calculated ones. It is appropriate to create an FA design from a series of blocks along the length, between which special mixing devices (mixing collectors) should be provided for, which would completely or partially equalize the temperature nonuniformities over the cross section.

The accumulated temperature nonuniformity, characteristic of channel elements, can be eliminated or decreased by changing over to FA designs with a unified flow cross section for gas (assembly design whose volumes adjacent to their elements and filled with a moving liquid communicate in a cross section that is perpendicular to the direction of the motion of the liquid).

Figure 2 gives as an example the results of optimizing the geometric characteristics of the flow portion of the cooling system of a model fuel assembly made according to the scheme of a system of parallel channels that



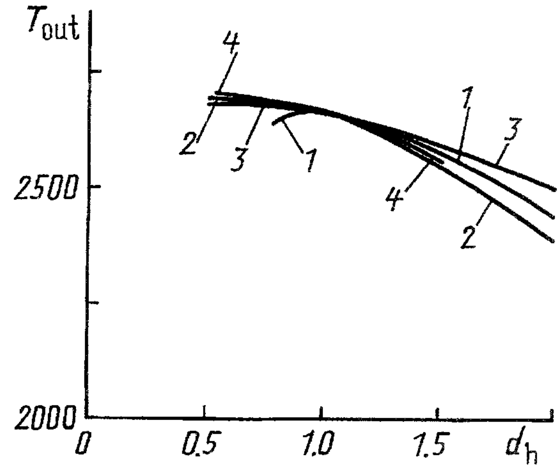


Fig. 2. Mass-mean temperature of the gas at the outlet from an FA T_{out} (K) vs geometric characteristics of the flow portion d_h (mm): 1, 2, 3, 4) first, second, third, and fourth variants of assemblies, respectively.

Fig. 3. Diagram of adjusting the cooling system channels to the prescribed distribution of the flow rates of the heat-transfer agent: 1-12) channel numbers; n) number of further improvements.

has four mixing collectors along the length and is intended for tests in a pulsed graphite reactor [3]. Optimization was performed under the following basic assumptions:

a) the temperature of the material at the outlet from each block of the assembly with allowance for disturbances attains the maximum allowable value;

b) temperature nonuniformities of the scale of the distance between the channels are equalized in the mixing collectors;

c) absolute deviations of geometric dimensions (the channel diameter, the distance between the channels) from the corresponding calculated values are the same for assemblies with different hydraulic diameters of the channels.

In calculations with consideration of the rather narrow hydraulic diameter range 0.5 mm < d_h < 2 mm we took limiting tolerances for the basic geometric dimensions that were equal to the errors in the corresponding dimensions that were recorded in examining a batch of manufactured fuel blocks (for the channel dimension ~1 mm the measured limiting deviation was ~0.04 mm). Under these assumptions with variation of the hydraulic diameter of the channel we considered four variants of assemblies, the following groups of parameters being the same in each: 1) porosity of the working medium, length of the assembly blocks, flow rate of the working medium; 2) dimension of the connector between the channels, length of the blocks, flow rate of the working medium; 3) volume of the core material in the assembly, connector dimension, flow-rate intensity of the working medium; 4) volume of the core material, connector dimension, pressure difference on the length of the assembly.

For all the variants with the optimum law of longitudinal profiling of heat release the dependence of the mass-mean temperature of the working medium on the channel diameter has a flat maximum in the region of hydraulic diameter values ~1 mm. A further decrease in the channel diameter does not lead to an increase in the heating temperature since the same absolute deviations of the geometric dimensions from the corresponding calculated values lead to larger temperature nonuniformities as the absolute dimensions decrease, owing to increased relative deviations.

For the assembly variant with d_h ~1 mm under well-known limitations on the temperature of fuel element materials, other things being equal, the introduction of mixing collectors into the design provides a ~1000 K increase in the mass-mean temperature of the gas at the outlet from the assembly.

The set of channels with a characteristic dimension thus chosen and a distribution of the density of the channels in the reactor volume over the zones in accordance with the heat release level in each zone forms the cooling system of the reactor. To provide reliable cooling of the reactor an actually realized system of channels with an unpredictable distribution (within the tolerances) of deviations of the dimensions from the nominal ones should be adjusted hydraulically so that the flow rate of the heat-transfer agent through each channel or a group of channels provides removal of heat from the corresponding volume of the reactor at material temperatures not exceeding the limiting ones. Optimization of the reactor cooling system enables us to improve its stability to small deviations of the parameters from the nominal values and to prevent an excess over the allowable temperature and thermostress levels. A series-parallel system of cooling channels for the reactor core that enables us to experimentally determine deviations of the hydraulic resistance of each channel or a group of channels from the optimized value and is equipped with controlling devices provides hydraulic adjustment that decreases substantially the nonuniformities of the distribution of the flow rate of the heat-transfer agent over identical channels.

Figure 3 gives as an example the diagram of adjusting 12 identical channels of the cooling system of the lateral reflector of the IRGIT reactor [4] to the prescribed distribution of flow rates of the working medium accurate to ±5%. Ensuring this accuracy involved as many as four cycles of simultaneous refinement of the hydraulic characteristics of the controlling elements and the channels.

Data on hydrodynamic characteristics of the units of the cooling path obtained in the process of adjustment are used for predictive calculations of the flow-rate distribution over the channels of the cooling system and determination of the working medium temperatures in operating regimes of the reactor.

In summary we note that the design scheme of the cooling system of the NRE reactor is governed mainly by its stability to small deviations of the parameters from the corresponding calculated values and the possibility of compensating for effects due to nonuniformities and disturbances of various types and scales.

NOTATION

F, heat-exchange surface area; Q, thermal power of the heat exchanger; C_p, heat capacity of the heat-transfer agent; ρ, density of the heat-transfer agent; ΔP, pressure difference; ΔT, change in the temperature of the heat-transfer agent in the direction of its motion; θ, difference in the wall and heat-transfer agent temperatures; ξ, hydraulic resistance (drag) coefficient; St, Stanton number; K, criterion of the thermohydraulic efficiency of the surface; Re, Reynolds number; L/D, reactor length-to-diameter ratio; d_h, hydraulic diameter; T_w, wall temperature; FA, fuel assembly; G, flow rate of the heat-transfer agent (G_n is the nominal value).

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