NONSTATIONARY HEAT-AND-MASS EXCHANGE DURING SIMULTANEOUS CHANGES IN HEAT POWER LOAD AND COOLANT EXPENDITURE

B. V. Dzyubenko, A. B. Bagdonavichyus,
A. V. Kalyatka, and M. D. Segal'

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Consideration is given to the problem of nonstationary mixing of the coolant during simultaneous changes in the heat power load and the expenditure of coolant in bundles of twisted oval-section tubes. Measurements of the nonstationary temperatures of the coolant and the walls of the tubes are compared with the results of theoretical calculations. Recommendations are made for the calculation of transfer coefficients necessary for closing the initial system of equations. As an example of a practical application of the results obtained, a numerical modelling is carried out for the transient thermohydraulic processes in the nuclear reactor of a space power unit.

Introduction. Problems of the calculation of the temperature fields in channels of complex shape, formed by bundles of twisted tubes, during nonsteady-state operating conditions have been considered in [1, 6]. Methods were developed there for calculating and measuring experimentally nonsteady-state mixing of the coolant for various types of thermal and hydrodynamic nonstationarity, enabling a closed system of equations to be obtained for determining the transfer coefficients in equations which describe the flow of a homogenized fluid in a bundle of twisted tubes.

For calculating the effective diffusion coefficient during increase in the heat power load N, with constant G, for a bundle with $Fr_M = s^2/dd_e = 57$, the equation proposed [2] was

$$\varkappa = K_n/K_{qs} = 0.114\cdot 10^{-4}\,Fo_M^{-2} - 0.1053\cdot 10^{-2}\,Fo_M^{-1} + 1.024, \quad (1)$$

where $Fo_M = [\lambda_b(\tau - \tau_0)/(c_p\rho_b d_c^2)]\,[0.043\text{-}0.263|\partial N/\partial\tau|_M]$.

Here, the quasisteady-state values of the effective diffusion coefficient can be determined from the equation [3]

$$K_{qs} = D_t/ud_e = 10.35\,Fr_M^{-1,4232+0,1857\lg Fr_M}. \quad (2)$$

The coefficient $\varkappa$, for the case of increased coolant expenditure, with constant N, is determined as a function of the measure $Fo_b = \lambda_0\tau/(c_p\rho_b d_c^2)$ [4] by

$$\varkappa = A\,Fo_b^n + C, \quad (3)$$

where A, n, and C are functions of the number Fr_M and ratio of the expenditures G_2/G_1. For the case of reduction in power N, with constant G, the equation obtained [5] was

$$\varkappa = 0.454\cdot 10^{-5}\,Fo_M^{-2} - 3,86\cdot 10^{-3}\,Fo_M^{-1} + 1,28. \quad (4)$$

For reduction in expenditure, with constant N, the value of $\varkappa$ may be found for $Fr_M = 57$ from the equations [6]:

For $Fo_b = 0\text{-}0.514\cdot 10^{-3}$

$$\varkappa = [2.95\cdot 10^{-4}\,(G_2/G_1)^{-11,94} + 0.993](1 + 927\,Fo_b), \quad (5)$$

for $Fo_b = 0.514\cdot 10^{-3} - 1.4\cdot 10^{-2}$ and $G_2/G_1 = 0,605 - 0,765$

$$\varkappa = [2.95\cdot 10^{-4}\,(G_2/G_1)^{-11,94} + 0.993](2.57\,Fo_b^{-0,0437} - 2.11). \quad (6)$$

Thus, in reports [1-6] were solved the problems of calculating the temperature field in bundles of twisted tubes for change in the power N with G constant, and for change in the expenditure of coolant G with N constant. At the same time, for a number of technical applications, for example a nuclear space power unit of a piloted Martian complex [7], simultaneous changes of power and coolant expenditure are typical. Since this type of nonsteady-state

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condition had not been investigated experimentally formerly, there arose the necessity to study experimentally changes with time of the temperature of the coolant and walls of the tubes from simultaneous increase in the coolant expenditure and heat power load, and from reduction in the power and coolant expenditure.

Results are considered in the present report of an experimental study of mixing of the coolant during simultaneous changes in power and coolant expenditure, and also features of the numerical modelling of transient processes in nuclear reactors for a space power unit [7], for which an increase in reactor power of several orders during the transition from power to motive operating conditions, and a power reduction during the transition from motive to power operating conditions is typical.

1. Theoretical Calculations of Transient Thermohydraulic Processes

To calculate the temperature field in bundles of twisted tubes, we have made use of a two-temperature model of the flow of a two-phase homogenized fluid with a motionless solid phase by writing the hydrodynamic equations in a quasisteady-state approximation. For the axially symmetrical problem, the initial system of equations is written in the form [1]

$$\rho_s c_s \frac{\partial T_s}{\partial \tau} = q_V - \frac{4\alpha\varepsilon}{d_e(1-\varepsilon)}(T_s - T) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda_{sr}\frac{\partial T_T}{\partial r}\right) + \frac{\partial}{\partial x}\left(\lambda_{sx}\frac{\partial T_s}{\partial x}\right), \quad (7)$$

$$\rho c_p \frac{\partial T}{\partial \tau} + \rho u c_p \frac{\partial T}{\partial x} = \frac{4\alpha}{d_e}(T_s - T) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda_{ef}\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial x}\left(\lambda_{ef}\frac{\partial T}{\partial x}\right), \quad (8)$$

$$\rho u \frac{\partial u}{\partial x} = -\frac{\partial p}{\partial x} - \xi\frac{\rho u^2}{2d_e} + \frac{1}{r}\frac{\partial}{\partial r}\left(\rho r\nu_{ef}\frac{\partial u}{\partial r}\right), \quad (9)$$

$$G(\tau) = 2\pi\int_0^{r_c}\varepsilon\rho u r\,dr, \quad (10)$$

$$p = \rho R T. \quad (11)$$

Here it is considered that perturbation of the parameters determining the flow processes is not large, and their duration significantly exceeds the propagation time of sound waves along the length of the bundle. In the numerical modelling of transient processes in nuclear reactors of a power unit, it is necessary to take account of the effect of a change in thermohydraulic parameters of the active zone of the reactor on its power. It is therefore necessary, first of all, to supplement equations (7)-(11) with the equations of neutron kinetics

$$l^* dN/d\tau = (\bar{\rho}_\Sigma - 1)N + \bar{N}, \quad (12)$$

$$dN_i/d\tau = \lambda_i(N - N_i), \quad i = 1, 2, \ldots, 6, \quad (13)$$

$$\bar{N} = \sum_{i=1}^{6}(\beta_i/\beta)N_i, \quad (14)$$

where N and $\bar{N}$ are the reactor power and the power caused by fission by delayed neutrons respectively; ℓ^* is the mean lifetime of fission neutrons, referred to the effective contribution of delayed neutrons β; λ_i is the decay constant of the i-th group of delayed neutrons; ρ_Σ is the total reactivity of the reactor, referred to the effective contribution of delayed neutrons. Equations (7)-(14) are supplemented by a correlation of reactivity effects, for calculating the effect of a change in thermohydraulic parameters on the properties of the medium being fissioned and the reactor power

$$\bar{\rho}_\Sigma = \bar{\rho}_{reg}\delta\Phi + \left(\int_V \bar{\rho}_s \delta T_s dV \Big/ \int_V dV\right) + \left(\int_V \bar{\rho}_\gamma \delta\gamma dV \Big/ \int_V dV\right), \quad (15)$$

and for calculation of the dependence of energy release on β- and γ-decay of fission fragments accumulating in the reactor, the Angermeyer–Weils equation

$$N_{st} = N_0 \cdot 0.1\,[(\tau_s + 10)^{-0,2} - 0.87(\tau_s + 2\cdot 10^7)^{-0,2} - (\tau_s + \tau_p + 10)^{-0,2} + 0.87(\tau_s + \tau_p + 2\cdot 10^7)^{-0,2}]. \quad (16)$$

In (15) and (16), $\delta\Phi$ is the displacement of the control members, δT_s and $\delta\gamma$ are temperature changes in the material of the active zone, and coolant density respectively; N_0 is the reactor power in the nominal parameter regime before switching; τ_s is the time elapsing after stopping the reactor; τ_ρ is the time of working of the reactor with nominal operating parameters. The problem is solved with the following boundary conditions:

For x = 0

$$u = u_{in}(r), \quad p = p_{in}, \quad T = T_{in}(r, \tau), \quad T_s = T_{sin}(r, \tau),$$

for r = 0 (on the axis of the bundle)

$$\left.\frac{\partial T_s(r, x, \tau)}{\partial r}\right|_{r=0} = 0, \quad \left.\frac{\partial T(r, x, \tau)}{\partial r}\right|_{r=0} = 0, \quad \left.\frac{\partial u(r, x, \tau)}{\partial r}\right|_{r=0} = 0,$$

for $r = r_c$

$$\left.\frac{\partial T_s(r, x, \tau)}{\partial r}\right|_{r=r_c} = 0, \quad \left.\frac{\partial T(r, x, \tau)}{\partial r}\right|_{r=r_c} = 0, \quad \left.\frac{\partial u(r, x, \tau)}{\partial r}\right|_{r=r_c} = 0,$$

for $x = \ell$

$$\left.\frac{\partial T_s(r, x, \tau)}{\partial x}\right|_{x=l} = 0, \quad \left.\frac{\partial T(r, x, \tau)}{\partial x}\right|_{x=l} = 0.$$

At $\tau = 0$, the temperature distributions $T_s(r, x)$ and $T(r, x)$ are given. In Eq. (7), describing the temperature distribution in the solid phase (in the spiral-shaped tubes), the quantities ρ_s, λ_{sr}, λ_{sx} are determined from equations in [1], as are the quantities α in (7), (8), and ξ in (9). The effective thermal conductivity λ_{ef} in (8) and viscosity ν_{ef} coefficient in (9) must be determined experimentally for the given type of nonstationarity. Taking the turbulence numbers of Prandtl $Pr_s = \rho\nu_{ef}c_p/\lambda_{ef} = 1$, and of Lewis $Le_s = \rho D_t c_p/\lambda_{ef} = 1$, it is sufficient to determine by experiment the effective coefficient of turbulent diffusion D_t, which in dimensionless form is written $K = D_t/ud_e$. Usually in reactors, bundles of pivotal "twirls" with spiral fins are used, in which coefficients D_t are determined by the same functions as D_t in bundles of twisted tubes [1].

In the calculation of temperature fields T and T_s in experiments with electrical heating of a gro of twisted tubes, the system of Eqs. (7)-(11) was solved, and in the calculation of these temperature fields in the reactor, by the system of Eqs. (7)-(16). These problems were solved by numerical methods [1].

2. Experimental Results

An experimental investigation of the process of interchannel mixing and nonsteady-state temperature fields of the coolant and walls of the twisted tubes was carried out in a test rig described in detail in [1, 6]. The coolant was air. Experiments were carried out on a bunch of twisted tubes of oval section, made of type 12Kh18N10T steel, with maximal dimension of the oval section d = 12.3 mm, and spiral pitch s = 6.1d ($Fr_M = 57$) and length 0.5 m, by the method of heat diffusion from a heated central zone of 37 tubes in a bundle with 151 twisted tubes. The coolant temperature was measured in the input section of the bundle with a comb of 10 thermocouples, placed at the points with coordinates $r/r_c = 0.073$, 0.128, 0.193, 0.264, 0.334, 0.407, 0.552, 0.697, 0.842. The coolant temperature at the input of the bundle was measured by three thermocouples. The temperature of the walls of the twisted tubes was measured with 15 thermocouples welded to the internal walls of the tubes at points with coordinates $r/r_c = 0.078$, 0.109, 0.132, 0.170, 0.187 and in sections with $x/\ell = 0.7$, 0.8, 0.9, 0.95. For automatic control of the experiment, the collection and processing of data was done by an automatic system, consisting of the IVK-2 measurement and computing complex, a constant current generator, pressure transducer, regulator of the generator power, turbocompressor, arrangment for changing the consumption, and information transformer [1]. For simultaneous stepwise changes in the coolant expenditure and power of the heat generation, the system worked in the following way. By means of the power regulator and arrangement for changing the expenditure, the initial generator power and carrier expenditure were established. For the information transformer of the IVK-2 trigger pulse, a signal is given at a given moment to the device for changing the expenditure and to the power regulator, which change the expenditure and establish the final power. Measured temperatures and pressure are transformed into electrical signals which are amplified and recorded by the information converter, converting analog signals into digital and passing them to the IVK-2 for further processing and storage. The time lag in the system for measuring the variable expenditure of air, as determined experimentally, was not greater than 0.1 sec. The time lag of the Chromel–Alumel thermocouples made from 0.1 mm wires was estimated as 0.04-0.2 sec.

Experiments were carried out for the range of coolant expenditure G = 0.075-0.31 kg/sec and heat generation power N = 0-20 kW.

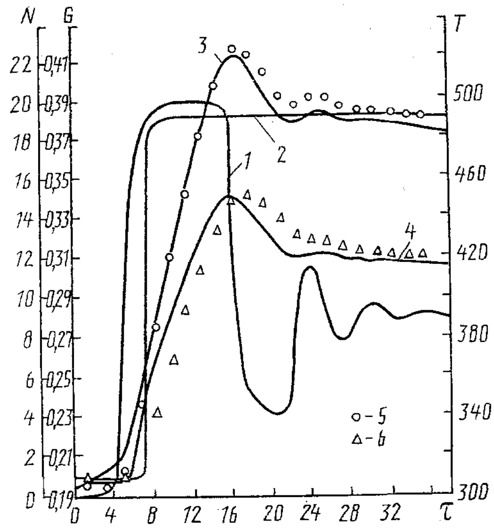

Fig. 1

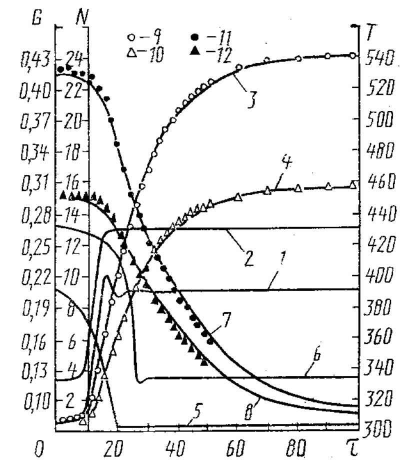

Fig. 2

Fig. 1. A comparison of measured and computed temperatures at the points $x/\ell = 0.95$ and $r/r_c = 0.073$ during smooth changes of N and G: 1, 2) changes of power and coolant expenditure with time; 3, 4) computed temperatures of the solid phase and coolant respectively, for $K_n = K_{qs} = 0.08$; 5, 6) experimentally measured temperatures of the walls of the tube and of the coolant respectively. N in kW, G in kg/sec, T in K, τ in sec.

Fig. 2. A comparison of measured and computed temperatures at points with coordinates $x/\ell = 0.95$ and $r/r_c = 0.073$, for smooth changes in N and G: 1, 5) power; 2, 6) expenditure; 3, 4) computed temperatures of the solid phase and coolant, respectively, for $K_n = K_{qs} = 0.08$ with growth in N and G; 7, 8) the same for decrease in N and G; 9,10) measured temperatures of the tube walls and the coolant with growth in N and G; 11, 12) the same for decrease in N and G.

The experimentally measured nonsteady-state temperatures of the coolant and walls of the twisted tubes from simultaneous increase in power and coolant expenditure are given in Figs. 1 and 2, where they are compared with the results of solving the system of equations (7)-(11) for values of the dimensionless effective diffusion coefficient $K_n = K_{qs}$. It may be seen that agreement of measured and calculated temperatures, both for abrupt and smooth changes in power and coolant expenditure, is good. This is explained by the fact that since in correspondence with (1) and (3), with growth in N at constant G, $K_n > K_{qs}$, and with growth in G at constant N, $K_n < K_{qs}$, then with simultaneous increase in N and G, these effects practically compensate each other, and, to a first approximation, it may be taken that $K_n \approx K_{qs}$, and the calculation of K_n is carried out from Eq. (2). At the same time, it is seen from Fig. 1, that after N and G reach steady-state values at $\tau \approx 16$ sec, there was in the experiments a sharp fall in the thermal load by about five times, which led to a temperature increase in the coolant and walls compared with the calculated values, through a reduction in K_n compared with K_{qs}, in accordance with Eq. (4).

The experimental results of the temperature field of the coolant and walls of the twisted tubes from simultaneous reduction in the thermal load power and expenditure are shown in Fig. 2, where the results are also plotted from solving the system of equations (7)-(11) with $K_n \approx K_{qs}$. The agreement between experimental and calculated data is good, which is explained by the opposing effects on the coefficient K_n of such types of nonstationarity as reduction in thermal load power with constant G (Eq. (4)), and reduction in coolant expenditure with constant N (Eqs. (5) and (6)).

Thus, the experimental investigations of the temperature fields in the bundle of twisted tubes make it possible to conclude that the computational model for the flow describes well the two-dimensional temperature fields with simultaneous change of thermal load power and coolant expenditure.

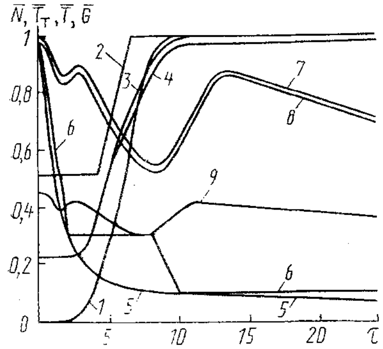

Fig. 3. Transient processes with increase and decrease of reactor power: 1,5) heat generation power; 2,6) expenditure of coolant; 3,4) temperatures of the solid phase and of the coolant at the output of the reactor with growth in N; 7,8) the same with reduction in N; 9) temperature of the solid phase at a distance of 100 mm from the input in the active zone; $\bar{N}$, $\bar{T}_s$, $\bar{T}$, $\bar{G}$) ratios of the nonstationary values of the parameters to their nominal values.

3. Computational Results of Transient Processes, as Applied to the Nuclear Reactor of a Motive Power Unit

The transient processes with increase in reactor power and expenditure of hydrogen, and with reduction in power and expenditure, would desirably be carried out sufficiently quickly and with maximal effectiveness from the point of view of using hydrogen as a heat transfer agent. In this connection it is necessary to realize the law of change of reactivity ensuring safe working of the reactor, and taking into account limits on the thermomechanical properties of the fuel composition. Numerical modelling was carried as applied to the channel-body variant of a nuclear reactor. As a result of carrying out a significant number of numerical experiments, we chose a variant of the transient process according to the law of change of reactivity and coolant expenditure shown in Fig. 3. In this case, the reactivity changes linearly and the coolant expenditure reduces to the nominal value. The realization of such a transient process enables the demanded temperature of the hydrogen coolant at the output of the reactor to be attained ~ 2900 K in 10 sec after moving the controllers, and the power to be increased from the level of the power regime (~200 kW) to that of the motive regime (300 MW) in ~9 sec. The process occurs smoothly without re-regulating the values of power or temperature.

In the case of the damping regime in transition from motive to power regime, a stepwise reduction of expenditure may be recommended. Then by means of the control members, the reactor passes into the subcritical state, with reduction in the thermal power to 10% of the nominal value in ~5 sec, and the coolant expenditure falls to 30% of the value in the motive regime (Fig. 3), which enables in 10 sec an economy of ~ 60% to be made in the mass of coolant, compared with damping down at nominal expenditure. In the future, with reduction in the power from β- and γ-decay of fission products, it is necessary also to reduce the expenditure. The duration of the stepwise regime of damping down will grow, since the rate of power reduction slows with time.

CONCLUSIONS

1. From computation of the nonsteady-state temperature fields with the simultaneous increase of power and coolant expenditure, or with their simultaneous reduction, we may, to a first approximation, use the functions to determine the effective diffusion coefficient under steady-state operating conditions.

2. The results of experimental and theoretical investigations of nonstationary temperature fields may be used to calculate transient processes in a nuclear space power unit from simultaneous changes in the reactor power and coolant expenditure.

NOTATION

ϰ, relative diffusion coefficient; K, dimensionless effective coefficient of turbulent diffusion; Fr_M, measure of the intensity of swirling flow in a bundle of twisted tubes; Fo, Fourier criterion; N, thermal load power; G, coolant expenditure; s, spiral pitch of tube; d, maximal dimension of tube section; d_e, equivalent diameter; d_c, r_c, diameter and radius of casing of heat exchanger (bundle of tubes); τ, time; ρ, density; c_p, specific thermal capacity; p, pressure; u, velocity; T, temperature; x, r, longitudinal and radial coordinates; ε, cellularity of the bundle of tubes for the coolant; α, ξ, coefficients of heat transfer and hydraulic resistance; q_V, volume density of energy release; λ_{ef}, ν_{ef}, effective coefficients of heat conduction and viscosity; V, volume; ℓ, bundle length. Indices: s, solid phase; n, nonstationary; qs, quasistationary; b, average-mass; m, modified.

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IMPROVED HEAT TRANSFER AT SUPERCRITICAL PRESSURES OF ORGANIC HEAT-TRANSFER AGENTS

I. G. Kulieva, I. T. Arabova,
F. Kh. Mamedov, and G. I. Isaev

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It was found that under certain experimental conditions with increasing heat flux the temperature t_w of the wall of the heat-transfer tube decreases to values below the critical temperature of the liquid under study.

In order to switch to heat-exchangers operating with heat-transfer agents at supercritical pressures, the operation of such exchangers must be studied carefully and in detail in order to provide scientific-research and design organizations with reliable data on convective heat transfer at supercritical pressures of the heat-transfer substances and different conditions in a wide range of values of the process parameters. In this connection, in the present paper we present some results of experimental investigations of heat transfer in the case of flow of organic heat-transfer agents in a tube under supercritical pressures. The experiments were performed on the apparatus described in [1]. The experimental section consisted of an 0Kh18N10T stainless steel tube with an inner diameter of 2.09 mm, wall thickness of 0.46 mm, and heated length of 220 mm. The tube was heated by passing through it ac current at low voltage. The maximum error in the determination of the heat-transfer coefficient was equal to 14%.

We shall examine, for the example of n-heptane (P = 2.736 MPa, t_{cr} = 267.01°C), the temperature of the tube wall as a function of the heat-flux density. Figure 1 shows such curves for ascending motion of a liquid at supercritical pressures and constant mass velocity and temperature of the liquid at the input. Comparing the two curves shows that up to $t_w \approx t_m$ the experimental points for different pressures fall quite well on the same straight line. For $t_w \gtrsim t_m$ the curves diverge. On the sections B'C' and BC the divergence will be determined by the difference of the pseudocritical temperatures, while on the sections C'D' and CD the temperature difference increases with increasing heat-flux density. It should be noted that for processes with the same values of ρW and t_{liq}^{in} and different pressures the appearance of a secondary state of improved heat transfer corresponds to approximately the same value of the heat-flux density ($q \approx 3.0$-3.1 MW/m²). Investigations showed that the drops in the wall temperature on the section DE at different pressures are

M. Azizbekov Azerbaidzhan Industrial University, Baku. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 62, No. 3, pp. 356-359, March, 1992. Original article submitted April 18, 1991.

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