NONSTEADY HEAT AND MASS TRANSFER WITH AZIMUTHAL NONUNIFORMITY OF THE HEAT SUPPLY TO BUNDLES OF SPIRAL TUBES

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The nonsteady mixing of heat carrier in a bundle of spiral tubes with azimuthal nonuniformity of the heat supply is considered. The peculiarities of the solution of this problem using a two-temperature model of the flow of homogenized two-phase medium with motionless solid phase are shown. The nonsteady temperature fields of the heat carrier are investigated experimentally for the case of sharp increase and decrease in the thermal-load power over time. Recommendations are given regarding the calculation of the nonsteady coefficients used to close the initial system of equations.

Introduction

Nonsteady thermohydraulic processes in bundles of spiral tubes have a series of features associated with their design features [1]. It was shown in [1] that, in channels of complex shape formed by bundles of spiral tubes, significantly greater difference in the nonsteady heat-transfer coefficients than in circular tubes is seen. It is determined by the rates of variation in the quantities appearing in the boundary conditions, for example, the wall temperature. In [1-4], it was also found that, with variation in thermal-load power and heat-carrier flow rate over time, there is restructuring of the temperature fields, and the dimensionless effective turbulent-diffusion coefficient

$$K_n = D_t/ud_e \tag{1}$$

characterizing the intensity of interchannel mixing of the heat carrier in a bundle of spiral tubes is variable over time. The heat-transfer coefficients and effective turbulent-diffusion coefficients may be either larger or smaller than their quasi-steady values, depending on whether the thermal-load power (or heat-carrier flow rate) increases or decreases over time.

Since nonsteady heat- and mass-transfer processes are characterized by high rates of variation of the parameters, they may be determining factors for the efficiency of heat exchangers in startup, transient, and emergency conditions of operation. Therefore, thermohydraulic calculations of nonsteady operating conditions of heat exchangers must be based on detailed investigation of the transport properties of the flux. Reliable methods of calculation of nonsteady temperature fields must be developed and experimentally tested.

In [1-4], this was done for axisymmetric nonequilibrium heat supply (heat liberation). At the same time, it is of great practical importance to study the nonsteady heat and mass transfer with azimuthal nonuniformity of the heat supply (heat liberation), which is observed with lateral input (output) of the heat carrier in the intertube space of a heat exchanger with spiral tubes.

The results of theoretical and experimental investigation of the nonsteady mixing in bundles of spiral tubes with azimuthal nonuniformity of the heat liberation are outlined below.

1. Theoretical Calculation of Temperature Fields

The model of the flow of a homogenized two-phase medium with a motionless solid phase, used previously to solve the axisymmetric problem [1-4], is employed for theoretical calcula-

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tion of the three-dimensional temperature fields. In this case, the gas-dynamics equations are written in the quasi-steady approximation, and the equation for the flow rate is used instead of the continuity equation; the system of equations takes the form

$$\rho_s c_s \frac{\partial T_s}{\partial \tau} = q_V(r, \varphi, x, \tau) - \frac{4\alpha\varepsilon}{(1-\varepsilon)d_e}(T_s - T) +$$

$$+ \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda_{s_r}\frac{\partial T_s}{\partial r}\right) + \frac{\partial}{\partial x}\left(\lambda_{sx}\frac{\partial T_s}{\partial x}\right) + \frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(\lambda_{s\varphi}\frac{\partial T_s}{\partial \varphi}\right), \tag{2}$$

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

$$+ \frac{\partial}{\partial x}\left(\lambda_{ef}\frac{\partial T}{\partial x}\right) + \frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(\lambda_{ef}\frac{\partial T}{\partial \varphi}\right), \tag{3}$$

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

$$+ \frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(\rho\nu_{ef}\frac{\partial u}{\partial \varphi}\right), \tag{4}$$

$$G = \varepsilon\int_0^{2\pi}\int_0^{r_c}\rho u r\,dr\,d\varphi, \tag{5}$$

$$p = \rho R T. \tag{6}$$

The boundary conditions of the problem for the thermally nonsteady case are as follows: when $\tau = 0$

$$\begin{gathered} p(x, 0) = p_0(x), \\ T_s(r, \varphi, x, 0) = T_{s0}(r, \varphi, x), \\ T(r, \varphi, x, 0) = T_0(r, \varphi, x), \\ u(r, \varphi, x, 0) = u_0(r, \varphi, x); \end{gathered} \tag{7}$$

the conditions at the bundle input ($x = 0$)

$$\begin{gathered} u(r, \varphi, 0) = u_{in}(r, \varphi), \\ T(r, \varphi, 0, \tau) = T_{in}(r, \varphi, \tau), \\ T_s(r, \varphi, 0, \tau) = T_{s.in}(r, \varphi, \tau); \end{gathered} \tag{8}$$

the periodicity conditions

$$\begin{gathered} u(r, \varphi, x) = u(r, \varphi + 2\pi, x), \\ T(r, \varphi, x, \tau) = T(r, \varphi + 2\pi, x, \tau), \\ T_s(r, \varphi, x, \tau) = T_s(r, \varphi + 2\pi, x, \tau); \end{gathered} \tag{9}$$

when $x = \ell$

$$\left.\frac{\partial T_s}{\partial x}\right|_{x=l} = 0, \quad \left.\frac{\partial T}{\partial x}\right|_{x=l} = 0; \tag{10}$$

when $r = r_c$

$$\left.\frac{\partial T_s}{\partial r}\right|_{r=r_c} = 0, \quad \left.\frac{\partial T}{\partial r}\right|_{r=r_c} = 0, \quad \left.\frac{\partial u}{\partial r}\right|_{r=r_c} = 0. \tag{11}$$

The finite-difference method with implicit schemes is used to solve the system of nonlinear equations of parabolic type in Eqs. (2)-(6) with coefficients depending on the parameters to be determined and with the boundary conditions in Eqs. (7)-(11) [5]. A stable solution may be obtained here with sufficiently broad variation in the ratio of the space-time steps. The algorithm for solution of the problem is based on the variable-direction method, which is facilitated by the assumption that the velocity vector is parallel to the bundle axis in Eq. (4). In the numerical analogs of the initial equations, the empirical coefficients are taken out from under the differentiation sign and averaged over points of the spatial grid as a function of the direction of differentiation.

Realization of the variable-direction method with respect to r and x entails knowing the value of the desired function at the first calculation point or the relation between the values of this function at the bundle axis and at the first calculation radius. In the case of solving an axisymmetric problem, this relation may easily be obtained by using the L'Hôpital rule to reveal indeterminacies of type $(1/r)\partial/\partial r$ at the point $r = 0$ with subsequent use of the symmetry condition at this point. In solving the spatial problem, the symmetry condition is not met in the general case; therefore, the well-known Gershgorin method is used to solve the problem: in the vicinity of the zero point ($r = 0$), the cylindrical region is replaced by a rectangular region, and the desired functions at the points of this region are determined as arithmetic means of the azimuthal values at the first calculation radius from the zero point. Using the Gershgorin method for an implicit finite-difference scheme, it is simple to obtain the relations for the first values of the fitting coefficients required for the fitting in the direction r.

To find the whole set of values of the desired functions over the radius in each ray of the spatial grid, the boundary condition at the external boundary of the bundle in Eq. (11) is used. In writing this condition in finite-difference form, the difference grid is constructed so that the physical boundary of the bundle is in the middle of the last calculation interval over the radius. Certain difficulties arise in fitting in the azimuthal direction ϕ, as a result of the presence of the specific boundary condition of periodicity of the functions in Eq. (9) over the azimuth. To solve the numerical analogs of the initial equations, the method of cyclic fitting considered by Samarskii is used: essentially, the initial three-point finite-difference equation is written in the form of the system

$$-a_1 y_{N-1} + c_1 y_1 - b_1 y_2 = f_1, \quad k = 1;$$

$$-a_k y_{k-1} + c_k y_k - b_k y_{k+1} = f_k, \quad 2 < k < N; \;\; y_N = y_1, \tag{12}$$

where y_k is the desired function; k is the index of the points over the azimuth; N is the number of points over the azimuth. Using the set of recurrence relations, the fitting factors are found, and using the condition $y_N = y_1$ the whole set of values of the desired functions over the azimuth is found.

After fitting in all three directions, iteration with respect to the values of the coefficients in the equations is undertaken. The convergence is monitored from the pressure value, to an accuracy of 0.01%.

The coefficients λ_{ef} and ν_{ef} in Eqs. (3) and (4) are related to the coefficient D_t in Eq. (1) as $\lambda_{ef} = D_t \rho c_p$ and $\nu_{ef} = D_t$, under the assumption that the turbulent Lewis and Prandtl numbers are unity.

2. Experimental Investigation of Heat-Carrier Mixing

The dimensionless effective turbulent-diffusion coefficient in Eq. (1) required for closure of the system in Eqs. (2)-(6) is determined experimentally by the method of heat diffusion from a group of heated tubes [1]. It is known that, with asymmetric nonuniformity of the heat supply, peculiarities of the heat and mass transfer are only observed in the peripheral region of the bundle close to the casing wall, within the limits of a single row of tubes [6]. Since the influence of the peripheral flow region in many-tube bundles on the heat and mass transfer in the central cells of the bundle is not significant, it is expedient to investigate the nonsteady temperature fields of the heat carrier and the coefficient K_n with asymmetric nonuniformity of the heat liberation using a heated zone of the bundle in the form of an equilateral trapezium, when peripheral effects are minimal.

A zone containing 46 heated tubes (Fig. 1) is electrically insulated by means of coated (with organosilicate lacquer) sleeves of glassfiber tissue which are slipped onto the unheated tubes surrounding the heated zone of the bundle. Experiments are conducted with a bundle of 151 spiral tubes with maximum dimensions of the oval profile d = 12.2 mm and s = 152 mm on the experimental apparatus described in [1]. The temperature field of the heat carrier is measured in the output cross section of the bundle using a set of 11 thermocouples in a coordinate mechanism at the centers of the cells with coordinates $\phi = \pi$ and r/r_c

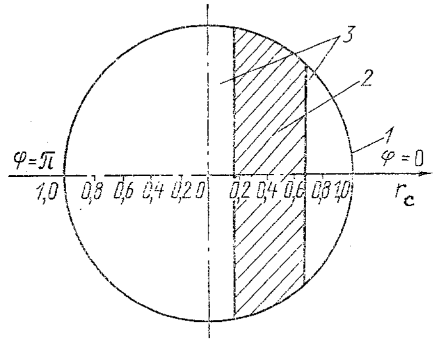

Fig. 1. Position of heating zone in bundle: 1) casing; 2) group of 46 heated tubes; 3) unheated tubes

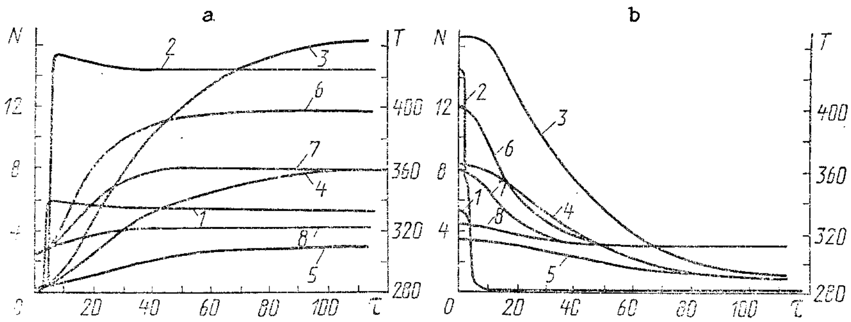

Fig. 2. Temperature variation of heat carrier over time with sharp increase (a) and decrease (b) in thermal load: 1, 2) power with Re = $4.13\cdot10^3$ and $1.625\cdot10^4$; 3-5) temperature for $\phi = 0$ and r/r_c = 0.482, 0.739, 0.865 with Re = $4.13\cdot10^3$; 6-8) the same with Re = $1.625\cdot10^4$; N, kW; T, K; τ, sec.

= 0.310, 0.172, 0.085; $\phi = 0$ and r/r_c = 0.088, 0.229, 0.347, 0.482, 0.606, 0.739, 0.865, and 0.997. The heat-carrier temperature at the bundle input is measured by three thermocouples. An automated system is used for control of the experiment and data collection and processing [1]. The experiment is conducted with Re = $3.5\cdot10^5$-$2.1\cdot10^4$, G = 0.08-0.55 kg/sec, N ≤ 15 kW with increase and decrease in thermal load and with the number $Fr_m = s^2/dd_e$, which characterizes the intensity of flow swirling in bundles of spiral tubes, equal to 220.

The experimental results for the nonsteady temperature fields of the heat carrier in the output cross section of the bundle are shown in Fig. 2a for asymmetric nonuniformity of the heat carrier with sharp increase in thermal load over time and constant heat-carrier flow rate, and in Fig. 2b with sharp decrease in thermal load and G = const. It is evident that, with sharp increase in thermal load, the heat-carrier temperature increases over time, gradually tending to steady conditions. The rate at which the temperature approaches steady conditions increases with increase in Re. The time for the temperature to reach steady conditions is greater in the heated zone of the bundle, for nonsteady conditions of the given types (Fig. 2).

The dimensionless effective diffusion coefficients for nonsteady conditions of the given type and asymmetric nonuniformity of the heat liberation are determined by comparing the experimental and theoretical temperature fields of the heat carrier, as in the case of axisymmetric nonuniformity of the heat supply [1]. It is established here that the nonsteady effective coefficient K_n with sharp increase in thermal load may be described by the dependence established in [1] for the case of axisymmetric nonuniformity of heat liberation

$$\varkappa = \frac{K_r}{K_{qs}} = 0{,}307\cdot10^{-4}\,\mathrm{Fo}_m^{-2} - 0{,}226\cdot10^{-2}\,\mathrm{Fo}_m^{-1} + 0{,}91, \qquad (13)$$

which is valid when Fe_m = 220 and Re = $3.5\cdot10^3$-$2.1\cdot10^4$. In Eq. (13), the modified Fourier number is defined by the expression

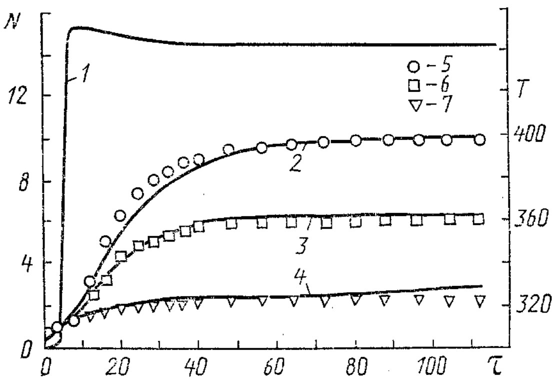

Fig. 3. Comparison of experimental and theoretical heat-carrier temperatures with sharp increase in thermal load: 1) power with Re = $1.625 \cdot 10^4$; 2-4) theoretical temperature for $\phi = 0$ and r/r_c = 0.482, 0.739, and 0.865, respectively; 5-7) experimental temperature at the same values of ϕ and r/r_c.

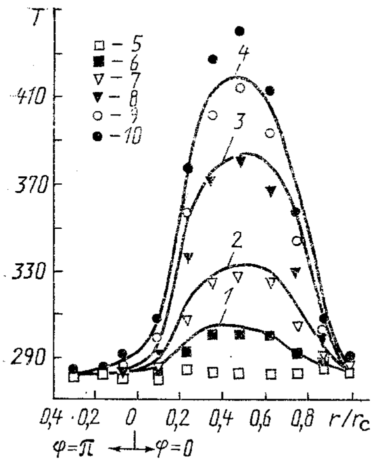

Fig. 4. Temperature field of heat carrier in output cross section of bundle with increase in power from 0 to 5.2 kW when Re = $4.13 \cdot 10^3$: 1-4) calculation with τ = 10, 20, 40, and 60 sec, respectively; 5-10) experiment at τ = 0, 10, 20, 40, 60, and 100 sec, respectively.

$$\mathrm{Fo}_{\mathrm{m}} = \frac{\lambda_b(\tau - \tau_0)}{c_{pb}\rho_b d_c^2}\left[0{,}043 + 0{,}263\left|\frac{\partial N}{\partial \tau}\right|_{\max}\right], \qquad (14)$$

where τ_0 is the time preceding the onset of sharp increase in the power N. When $|\partial N/\partial t|_{\max} \geq 3.64$, the expression in square brackets in Eq. (14) is equal to unity.

In the case of sharp increase in thermal load, K_n conforms to the following dependence with azimuthal nonuniformity of the heat liberation

$$\varkappa = \frac{K_r}{K_{qs}} = 0{,}454 \cdot 10^{-5}\,\mathrm{Fo}_{\mathrm{m}}^{-2} - 3{,}86 \cdot 10^{-3}\,\mathrm{Fo}_{\mathrm{m}}^{-1} + 1{,}28, \qquad (15)$$

when Re = $3.5 \cdot 10^3$-$2.1 \cdot 10^4$ and $\mathrm{Fo}_m \leq 1.4 \cdot 10^{-2}$. In Eq. (15), Fo_m is determined from Eq. (14) ($\tau_0 = 0$). The coefficient K_{qs} in Eqs. (13) and (15) is determined from the formula of [7].

The experimental temperatures at the output cross section of the bundle for various times at points with the coordinates r/r_c = 0.482, 0.739, and 0.805 and $\phi = 0$ are compared with the theoretical temperature fields of the heat carrier, with closure of the system in

Eqs. (1)-(6) by means of Eq. (13), in Fig. 3. The good agreement between the experimental and theoretical heat-carrier temperatures seen in Figs. 3 and 4 for various times may serve as the experimental basis for the model of flow of the homogenized medium used to solve the given problem and the method developed for calculating the temperature fields in bundles of spiral tubes with azimuthal nonuniformity of the heat supply.

Conclusion

The model of flow developed and experimentally tested here, with the corresponding method of thermohydraulic calculation, taking account of interchannel mixing of the heat carrier, may be used, together with the experimental dependences for calculating the effective diffusion coefficients, in determining the nonsteady temperature fields in heat exchangers with spiral tubes, and permit the estimation of their conditions of safe operation in transient situations.

NOTATION

K, dimensionless effective tubulent diffusion coefficient; N, thermal-load power; τ, time; G, heat-carrier flow rate; D_t, effective diffusion coefficient; ν_{ef}, effective viscosity; T, temperature; u, velocity; d_e, equivalent diameter; Fr_m, number characterizing the intensity of swirling of the flow in a bundle of spiral tubes; s, turn length of spiral tube; d, maximum dimension of tube profile; Fo, Fourier number; d_c, r_c, diameter and radius of heat-exchanger casing; ℓ, length of tube bundle; λ, thermal conductivity; c_p, specific heat; ρ, density; x, r, ϕ, longitudinal, radial, and azimuthal coordinates; Re, Reynolds number; α, heat-transfer coefficient; q_V, volume density of energy liberation; p, pressure; κ, relative diffusion coefficient; ξ, hydraulic drag; ε, porosity of tube bundle with respect to heat carrier. Indices: s, solid phase; n, nonsteady; qs, quasi-steady; b, mean-mass; ef, effective; m, modified.

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