HEAT AND MASS TRANSFER IN TURBULENT FLOW OF THE $N_2O_4 \rightleftarrows 2NO_2 \rightleftarrows 2NO + O_2$ SYSTEM IN A ROD BUNDLE CONTAINED IN A HEXAGONAL JACKET

T. V. Besedina, B. E. Tverkovkin,
A. V. Udot, and A. P. Yakushev

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A model is presented for heat and mass transfer in a flowing dissociating liquid in a rod bundle. The temperature pattern in the liquid and in a heat-producing rod has been determined from the general solutions to the conduction equations for rods and shells.

When one designs a nuclear power station containing a reacting coolant, it is important to examine heat and mass transfer in the installations in the presence of reactions, including the core areas, where one most often finds a set of cylindrical rods having a longitudinal flow around them and producing bulk heat in multilayer cladding. If the rods are assembled in bundles and fitted into hexagonal jackets, there are at least three rod groups (central, lateral, and corner ones) having differing cooling conditions, and it may be inadequate to calculate temperatures only for the central rods when choosing reliable working conditions. Therefore, check calculations must be made on a core consisting of a rod bundle with longitudinal flow for each rod group. There are several studies [1-3] on heat and mass transfer for N_2O_4 coolant in the central channels in a rod bundle. Here we present calculations on the transfer in the peripheral channels (lateral and corner ones).

Figure 1 shows the channel cross sections. We assume that stoichiometric relations apply to the flow, as does the boundary-layer approximation. Then the heat and mass transfer are described by

$$\frac{\partial}{\partial x}\left[(\mu+\rho\varepsilon^t)\frac{\partial u}{\partial x}\right]+\frac{\partial}{\partial y}\left[(\mu+\rho\varepsilon^t)\frac{\partial u}{\partial y}\right]-\rho u=\frac{dP}{dz}, \tag{1}$$

$$\int\limits_D \rho u ds = \text{const}, \tag{2}$$

$$\frac{\partial}{\partial x}\left\{\left[\lambda_f\left(1+\frac{\varepsilon^t}{\nu}\frac{\text{Pr}}{\text{Pr}^t}\right)+\frac{Q_{r\text{I}}}{m_1}\rho D_1\varphi_2\left(1+\frac{\varepsilon^t}{\nu}\frac{\text{Sc}_1}{\text{Sc}_1^t}\right)\right]\frac{dT}{dx}\right\}+$$
$$+\frac{\partial}{\partial y}\left\{\left[\lambda_f\left(1+\frac{\varepsilon^t}{\nu}\frac{\text{Pr}}{\text{Pr}^t}\right)+\frac{Q_{r\text{I}}}{m_1}\rho D_1\varphi_2\left(1+\frac{\varepsilon^t}{\nu}\frac{\text{Sc}_1}{\text{Sc}_1^t}\right)\right]\frac{\partial T}{\partial y}\right\}= \tag{3}$$
$$=\rho u\left(c_{rf}+\frac{Q_{r\text{I}}}{m_1}\varphi_2\right)\frac{\partial T}{\partial z}-\left(\frac{Q_{r\text{I}}}{m_1}\varphi_1+\frac{Q_{r\text{II}}}{m_4}\right)J_4,$$

$$\frac{\partial}{\partial x}\left[\rho D_4\left(1+\frac{\varepsilon^t}{\nu}\frac{\text{Sc}_4}{\text{Sc}_4^t}\right)\frac{\partial C_4}{\partial x}\right]+\frac{\partial}{\partial y}\left[\rho D_4\left(1+\frac{\varepsilon^t}{\nu}\frac{\text{Sc}_4}{\text{Sc}_4^t}\right)\frac{\partial C_4}{\partial y}\right]=\rho u\frac{\partial C_4}{\partial z}-J_4, \tag{4}$$

$$\text{div grad } T_\text{т}+\frac{q_{V\text{т}}}{\lambda_\text{т}}=0, \tag{5}$$

$$\text{div grad } T_{0i}=0,\ i=1,2 \tag{6}$$

with the boundary conditions

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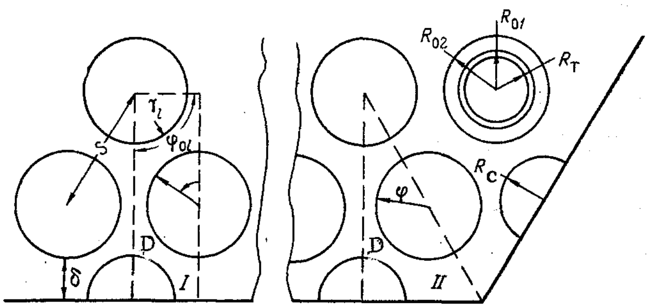

Fig. 1. Calculation-region scheme: I) lateral channel; II) corner channel.

$$\left.\begin{aligned} \lambda_{\text{T}} \frac{\partial T_{\text{T}}}{\partial n} &= \lambda_{01} \frac{\partial T_{01}}{\partial n} \\ T_{\text{T}} &= T_{01} \end{aligned}\right|_{\gamma_1}, \tag{7}$$

$$\left.\begin{aligned} \lambda_{01} \frac{\partial T_{01}}{\partial n} &= \lambda_{02} \frac{\partial T_{02}}{\partial n} \\ T_{01} &= T_{02} \end{aligned}\right|_{\gamma_2}, \tag{8}$$

$$\left.\begin{aligned} \lambda_{02} \frac{\partial T_{02}}{\partial n} &= \left(\lambda_f + \frac{Q_{\text{r I}}}{m_1} \varphi_2 \rho D_1\right) \frac{\partial T}{\partial n} \\ T_{02} &= T \end{aligned}\right|_{\gamma_l}, \tag{9}$$

$$u = \frac{\partial C_4}{\partial n} = 0, \tag{10}$$

$$\left.\frac{\partial u}{\partial n} = \frac{\partial T}{\partial n} = 0\right|_{\gamma_{1i}}, \tag{11}$$

in which γ_1 and γ_2 are the boundaries between the fuel core and the first sheath and between the sheaths correspondingly, with γ_s and γ_{li} correspondingly the solid and liquid boundaries, while l is the rod index.

The turbulent transfer coefficients have been calculated from Buleev's model [4].

The solution to (1), (3), and (4) may be found as the minima in the functionals

$$\Phi(u) = \frac{1}{2} \int_D [F_1 (\text{grad}\, u)^2 + M_1 u]\, ds, \tag{12}$$

$$\Phi(T) = \frac{1}{2} \int_D [F_2 (\text{grad}\, T)^2 + M_2 T]\, ds + \sum_{l=1}^{L} \int_{\gamma_l} F_2 T \frac{\partial T}{\partial n} d\gamma, \tag{13}$$

$$\Phi(C_4) = \frac{1}{2} \int_D [F_3 (\text{grad}\, C_4)^2 + M_3 C_4]\, ds, \tag{14}$$

where

$$F_1 = \mu + \rho \varepsilon^t; \quad M_1 = \rho u \frac{\partial u}{\partial z} + \frac{dP}{dz};$$

$$F_2 = \lambda_f \left(1 + \frac{\varepsilon^t}{\nu} \frac{\text{Pr}}{\text{Pr}^t}\right) + \frac{Q_{\text{r I}}}{m_1} \rho D_1 \varphi_2 \left(1 + \frac{\varepsilon^t}{\nu} \frac{\text{Sc}_1}{\text{Sc}_1^t}\right);$$

$$M_2 = \rho u \left(c_{pf} + \frac{Q_{\text{r I}}}{m_1} \varphi_2\right) \frac{\partial T}{\partial z} - \left(\frac{Q_{\text{r I}}}{m_1} \varphi_1 + \frac{Q_{\text{r II}}}{m_4}\right) J_4;$$

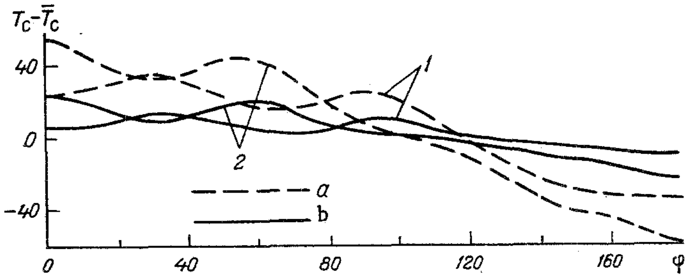

Fig. 2. Temperature distribution at the perimeter of a side rod (curves 1) and a corner rod (curves 2); (z = 0.74 m; δ = 0.71 mm; R_c = 0): a) frozen flow; b) chemically reacting flow.

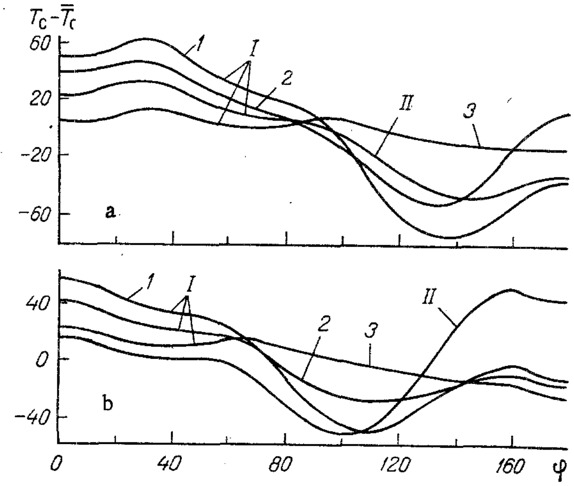

Fig. 3. Temperature distributions over a side rod (a) and a corner rod (b) (z = 0.74 m) [I) δ = 0.71 mm; II) 0.4): 1) R_c = 0; 2) 1 mm; 3) 1.5.

$$F_3 = \rho D_4\left(1 + \frac{\varepsilon^t}{\nu}\frac{\mathrm{Sc}_4}{\mathrm{Sc}_4^t}\right);\ M_3 = \rho u\frac{\partial C_4}{\partial z} - J_4.$$

The contour integral in (13) can be transformed [5] via analytic solutions to the conduction equations for the fuel and cladding as Fourier series. We use difference analogs to approximate the derivatives along the channel axes du/dz, dT/dz, dC_4/dz, and then the finite-element method [6] is used to derive the unknown quantities u, T, and C_4 at the corner points by solving algebraic equations at each step along the axis. The pressure gradient dP/dz is found from the condition for constant flow rate along a channel.

The algorithm has been used to derive the velocity, temperature, and concentration patterns for the side and corner channels for various radii for the filling components and gaps between the peripheral rods and the jacket. Uniform velocity, temperature, and concentration profiles were specified for the inlets. The calculations were performed for a 169-rod bundle (S/d = 1.12; $d = 2R_{02} = 6.2 \cdot 10^{-3}$ m). The coolant flow rate was 6.54 kg/sec. The rates in the side and corner channels were taken from the condition for equal pressure differences in the channels. The other working parameters were taken as: T_{in} = 471 K; P_{in} = 167 bar; $C_{4in} = C_{4e}(T_{in}, P_{in})$; $q_l = 4.53 \cdot 10^4$ W/m·sec.

Figure 2 shows perimeter-temperature distributions for peripheral rods for frozen flow and for reacting; the temperature nonuniformity on a peripheral rod is less in the reacting case, because heat is transported in the azimuthal direction as a result of concentration-dependent diffusion.

Figure 3 shows the effects of the filling components and gap between the jacket and peripheral rods on the temperature distributions around the perimeters of the side and corner rods. The gap and the filling-component radius can be varied to reduce the temperature nonuniformity very considerably, which should be borne in mind in choosing these components and the jacket dimensions.

NOTATION

u, velocity; μ, dynamic viscosity; ε, turbulent viscosity; ν, kinematic viscosity; ρ, density; c_p, specific heat; D, diffusion coefficient; q_V, volume heat production; q_l, linear heat flux; λ, thermal conductivity; m, molecular mass; Q_r, heat of reaction; z, longitudinal coordinate. Subscripts: I and II, reactions $N_2O_4 = 2NO_2$ and $2NO_2 = 2NO + O_2$ correspondingly; 1) N_2O_4; 2) NO_2; 3) NO; 4) O_2; fu, fuel; c, cladding; f, frozen value; w, wall.

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NUMERICAL MODELING OF MOTION OF AN AXISYMMETRIC BODY THROUGH A TUNNEL

O. G. Goman, V. I. Karplyuk, and M. I. Nisht UDC 532.5

The method of discrete vortices is used for a numerical investigation of the nonlinear unsteady problem of passage of an axisymmetric body through a coaxial thin-walled cylindrical tube of finite length.

Because of the increased speed of trains and the development of tube-borne transport and other areas of technology it is becoming increasingly important to study the interaction of moving bodies and the solid boundaries surrounding them.

The first approximate schemes for calculating the drag of a train moving within a tunnel were proposed at the end of the thirties and were based mainly on experimental data. For instance, in [1] a semiempirical method was developed of calculating the drag of a train on an open track and in a long tunnel (the tunnel was considered long if we can neglect the unsteady effects due to its ends).

At present quite a wide circle of topics in the aerodynamics of fast trains has been investigated [2]. However, nonlinear problems have been examined only for steady motion [3, 4], and [4] presented the results of calculated steady flow of an infinite chain of containers on the basis of numerical solution of the full Navier—Stokes and Reynolds equations.

Unsteady problems of the aerodynamic effect of a tunnel on a train have been investigated only approximately, in linear formulation, within the framework of planar and other models [5-8]. However, for short tunnels, the unsteady effects due to the entrance of the

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