CALCULATION OF HEAT-TRANSFER COEFFICIENTS USING A TWO-ZONE MODEL OF TURBULENT FLOW

V. A. Men'shchikov

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A model for the description of radial temperature profiles in a gas flow is proposed and used in the calculation of heat-transfer coefficients.

In calculating the heat transfer at the walls of a tube in which turbulent flow is occurring, the model of the turbulent flow is of paramount importance. Many works have been devoted to the description of turbulent flow [1-4], and there exist various models of the process, differing both in numerical values for the same structure and also in the structure itself. Two-, three-, and even four-zone models of the turbulent flow in a tube are known. The more complex models provide a more accurate description of the phenomenon, but their use in practice is difficult.

We will use a two-zone flow model [1], comprising a boundary layer at the wall surface and a flow core throughout the remaining space. In the boundary layer, heat and mass transfer occurs by molecular diffusion and heat conduction. This model grossly simplifies the phenomenon, but, where satisfactory results are obtained, its use is entirely justified.

To confirm its effectiveness, the chosen model will be used for the computer calculation of a temperature profile and, from the results obtained and also experimental data, the heat-transfer coefficient will be determined [5] and compared with results given by known formulas [6]. If the results coincide, the use of the chosen model can be regarded as acceptable.

The temperature profile is calculated by solving the equation

$$\frac{u_r}{L} C_p \rho R_0^2 \frac{\partial T}{\partial x} = \frac{1}{r} \cdot \frac{\partial}{\partial r}\left[\lambda_r r \frac{\partial T}{\partial r}\right] \tag{1}$$

with boundary conditions

$$\begin{aligned} &\text{for} \quad x = 0 \quad T = f(x), \\ &\text{for} \quad r = 0 \quad \frac{\partial T}{\partial r} = 0, \\ &\text{for} \quad r = 1 \quad \frac{\partial T}{\partial r} = \frac{qR_0}{\lambda_M}. \end{aligned} \tag{2}$$

To determine λ_r, it is assumed that heat transfer occurs as a result of molecular motion in the boundary layer, but additionally by radial diffusion in the flow core. Then

$$\text{for} \quad R_0 (1 - r) \leqslant \Delta \quad \lambda_r = \lambda_M, \tag{3}$$

$$\text{for } R_0 (1 - r) > \Delta \quad \lambda_r = \lambda_M + C_p \rho \varepsilon. \tag{4}$$

Equation (1) and the boundary conditions in Eq. (2) are replaced by finite-difference equations and solved over a nonuniform grid [7] using a Minsk-2 computer.

The dependence of the linear flow velocity u_r on the tube radius is taken in the form

$$u_r = u_c (1 - r)^{1/n}. \tag{5}$$

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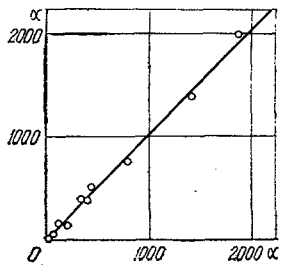

Fig. 1

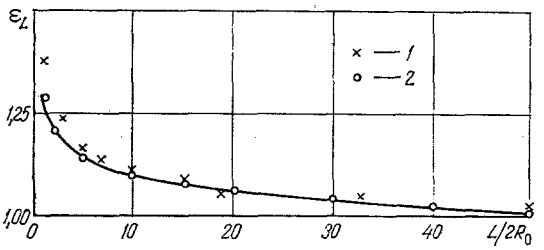

Fig. 2

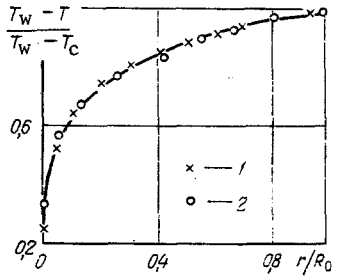

Fig. 3

Fig. 1. Comparison of heat-transfer coefficients calculated from the radial temperature profile (abscissa) and from Eq. (10) (ordinate). α, W/m^2·°C.

Fig. 2. Dependence of heat-transfer coefficient on the length of the heated section: 1) calculated from the radial temperature profile; 2) experimental [10]. $\varepsilon_L = dL/\alpha^\infty$.

Fig. 3. Dependence of dimensionless temperature on dimensionless radius (Re = 10^4, Pr = 0.7, L = 3.6 m, R_0 = 0.062 m, q = 46,500 W/m^2 (40,000 kcal/m^2·h), λ_M = 0.1396 W/m·°C (0.12 kcal/m^2·h·°C), $\bar{u}$ = 1.785 m/sec, n = 7); 1) calculated from radial temperature profile; 2) experimental [11].

The quantity n, which is a function of the Reynolds number, is taken from the data of [8]. The thickness of the boundary layer Δ is given by [1]

$$\Delta = R_0 \frac{65}{\mathrm{Re}\sqrt{\xi}}. \tag{6}$$

The coefficient of resistance of turbulent flow in the circular tube is calculated from the formula [1]

$$\xi = 0.0032 + 0.221\,\mathrm{Re}^{-0.237}. \tag{7}$$

In accordance with the method of [9]

$$\varepsilon = \frac{\xi}{8}\bar{u}r(1-r)^{1-\frac{1}{n}}\frac{2n^3}{(n+1)(2n+1)}R_0. \tag{8}$$

As in experimental investigations [5], the heat-transfer coefficient is determined from the relation

$$\alpha = \frac{q}{T_w - T_m}. \tag{9}$$

Results for the heat-transfer coefficient calculated from the temperature profile according to the known formula [6]

$$\alpha = 0.023\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \tag{10}$$

are shown in Fig. 1. The parameters vary over the following ranges: $\bar{u}$ = 2.6-260 m/sec, R_0 = 0.006-0.062 m, λ_M = 0.1396 W/m·°C (0.12 kcal/m^2·h·°C), Re = 10^4-10^6, Pr = 1.02.

From Fig. 1 it follows that the values calculated by different methods are in good agreement.

As is known, the heat-transfer coefficient is higher on the initial portion of the tube than that given by Eq. (10), which is valid for $L \geq 100R_0$. From the radial temperature profile obtained by computer, we calculated the heat-transfer coefficient on the initial portion of the tube ($\bar{u}$ = 16.8 m/sec; R_0 = 0.062 m; n = 8.35; Re = $1.8 \cdot 10^5$; Pr = 1.02) and compared it with the data of [10]. The results, given in Fig. 2, show that the agreement between our data and those of [10] is good for $L/2R_0 > 5$. The discrepancy of approximately 10% that appears for $L/2R_0 < 2$ may be explained by the reduction in accuracy of the experiment when the heated portion of the tube is small.

Comparison of the calculated temperature profile in a flow of air with an experimental profile [11] (Fig. 3) shows good agreement.

NOTATION

r, dimensionless radius; x, dimensionless length; u_r, flow velocity as a function of the radius; λ_r, thermal conductivity as a function of the radius, λ_M, molecular thermal conductivity; C_p, specific heat; ρ,

density; R_0, tube radius; T, temperature; q, specific heat flow on tube surface; u_c, flow velocity on tube axis; ξ, hydraulic resistance coefficient; Δ, boundary-layer thickness; ε, turbulent-diffusion coefficient; $\bar{u}$, mean flow velocity; α, heat-transfer coefficient; Re, Reynolds number; Pr, Prandtl number; L, tube length; T_m, mean flow temperature; T_w, wall temperature.

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EFFECT OF ABSORPTION-TIME DIFFERENCES ON GAS FLOW IN CAPILLARIES

V. V. Levdanskii

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The effect of differences in absorption time at a capillary surface on the free-molecular gas flow is analyzed, taking into account surface diffusion.

In the analysis of gas flow in capillaries, it is often necessary to take into account the specific properties of the interaction of gas molecules with the capillary wall. On contact of the gas with the solid surface, physical adsorption and surface diffusion of the adsorbed molecules usually occur [1]. The surface-diffusion process may lead to a selective inleakage of a gas-mixture component through the porous body [2]. In this context, it is of interest to carry out a kinetic investigation of the gas flow in a single capillary.

We consider free-molecular gas flow in a microcapillary of finite length. We assume that the diffusional-transfer potential $\varphi = P/\sqrt{T}$ is the same at both ends of the capillary (i.e., in the absence of surface diffusion there is no resultant molecular flux in the system). It is known that molecules incident on the surface of the solid usually remain on it for an adsorption time τ, the magnitude of which, generally speaking, may vary over the length of the capillary. Apart from nonisothermal conditions, the change in τ may be caused by the incidence of various kinds of radiation on the surface [3].

To elucidate the effect of differences in adsorption time, we consider the following model problem. It is assumed that the adsorption times on the inner capillary surface (τ_2) and its ends (τ_1 and τ_3) may differ and that $\tau_1 \geq \tau_2 \geq \tau_3$. In addition, it is assumed that the degree of filling of the surface by adsorbed molecules is sufficiently low for Henry's law to be applied. Then the difference in τ may create conditions for the appearance of

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk.
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