EFFECT OF VARIABILITY OF PHYSICAL PROPERTIES ON HEAT TRANSFER IN THE TURBULENT PIPE FLOW OF GASES

L. I. Zaichik, E. V. Kuznetsov, and A. I. Leont'ev

UDC 536.24

The effect of variability of physical properties on heat transfer in the turbulent flow of different gases is studied on the basis of the limiting heat-transfer law.

We will examine the turbulent flow of gas in a heated pipe with large Reynolds numbers ($Re \geq 10^4$) in the region of stabilized heat transfer. It is assumed that the parameters of the thermodynamic state of the gas are far from the critical region; in this case, the temperature dependences of the thermophysical properties are monotonic in character and may be described by power relations.

Since the dependence of the Nusselt number on the Reynolds number for a nonisothermal flow is nearly the same in character as that for a quasiisothermal flow, the effect of variability of physical properties on heat transfer can be conveniently analyzed in the form of the dependence of the relative heat-transfer coefficient $\Psi = Nu_m/Nu_{0m}$ on the temperature factor $\Theta = T_w/T_m$ [1-3]. Here, Nu_m and Nu_{0m} are the Nusselt numbers with variable and constant physical properties and the same values of the flow parameters. Due to the slight effect of the number Re on $\Psi(\Theta)$, this relationship can be determined from the theory of limiting heat-transfer laws for flow of a fluid with vanishing viscosity ($Re \to \infty$) [1].

To construct the limit relation $\Psi(\Theta)$, we use the Prandtl laws for turbulent friction

$$\tau_t = \rho l^2 \left(\frac{\partial u_x}{\partial y}\right)^2 \quad (1)$$

and turbulent heat flow

$$q_t = \frac{c_p \rho l^2}{Pr_t} \frac{\partial u_x}{\partial y} \frac{\partial T}{\partial y}. \quad (2)$$

We obtain the following relations from (1) and (2):

$$q_t = \frac{c_p \rho^{1/2} l \tau_t^{1/2}}{Pr_t} \frac{\partial T}{\partial y}. \quad (3)$$

Integrating (3) with allowance for assumptions on the conservativeness of the mixing-length distributions, turbulent Prandtl number, shear stress, and heat flux relative to a change in physical properties, we obtain

$$\Psi = \left(\int_0^1 \bar{c}_p \bar{\rho}^{1/2} d\bar{T}\right)^2. \quad (4)$$

We will determine the dependences of density and specific heat on temperature from the Clapeyron–Mendeleev equation and a power relation, i.e., the expression

$$\bar{\rho} = [\Theta + (1-\Theta)\bar{T}]^{-1}; \quad \bar{c}_p = [\Theta + (1-\Theta)\bar{T}]^{n_c}, \quad (5)$$

which is valid at large Reynolds numbers ($T_0 \to T_m$ at $Re \to \infty$).

With allowance for (5) and (4), we obtain

G. M. Krzhizhanovskii Energy Institute, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 50, No. 4, pp. 533-535, April, 1986. Original article submitted April 3, 1985.

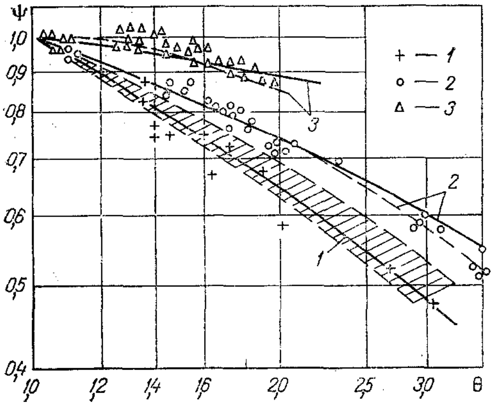

Fig. 1. Effect of the temperature factor on the relative heat-transfer coefficient: 1) helium; 2) nitrogen; 3) ammonia.

$$\Psi = \left[\frac{2(1-\Theta^{1/2+n_c})}{(1+2n_c)(1-\Theta)}\right]^2. \quad (6)$$

At $n_c = 0$, valid for monatomic gases, we obtain the following formula [1] from (6)

$$\Psi = 4/(1+\Theta^{1/2})^2.$$

Figure 1 compares Eq. (6) (solid lines) with experimental data at $x/d \sim 50$ and the empirical formulas (dashed lines) for nitrogen and ammonia presented in [2, 3]. In performing calculations by Eq. (6), we took $n_c = 0.1$ for nitrogen and $n_c = 0.36$ for ammonia in accordance with the temperature range [2, 3]. Figure 1 also compares Eq. (6) with experimental data on heat transfer for low-temperature helium at $x/d \sim 50$ [4]. The data was chosen for the region of parameters in which the properties of helium are described by Eqs. (5) with $n_c = -0.1$. Finally, Fig. 1 also compares Eq. (6) with the empirical formula in [5] (hatched region). Evident is the satisfactory agreement between the experimental and theoretical data for all of the gases examined.

It follows from analysis of Eq. (6) that an increase in the parameter n_c (corresponding to an increase in the number of atoms in the molecule) is accompanied by a reduction in the decrease in heat transfer during heating. At $n_c > 0.5$ (such as for methane CH_4), heat transfer even increases with an increase in θ. Such behavior of heat transfer is consistent with the empirical relation in [6] obtained from generalization of a large amount of experimental data from the heating of different gases. It should be noted that the absence of a dependence of $\Psi(\Theta)$ on viscosity and thermal conductivity is explained by the slight effect of molecular transport on the relative intensity of momentum and heat transfer in a turbulent flow in the case of large Reynolds numbers.

NOTATION

x, longitudinal coordinate reckoned from the pipe inlet; y, transverse coordinate reckoned from the wall; u_x, longitudinal velocity; T, temperature; ρ, density; c_p, specific heat; ℓ, mixing length; Pr_t, turbulent Prandtl number; d, pipe diameter; $\bar{T} = (T - T_w)/(T_0 - T_w)$; $\bar{\rho} = \rho/\rho_0$; $\bar{c}_p = c_p/c_{p0}$. Indices: w, 0, and m, flow parameters on the wall and axis and at the mean-mass temperature T_m.

LITERATURE CITED

1. S. S. Kutateladze and A. I. Leont'ev, Heat Transfer and Friction in a Turbulent Boundary Layer [in Russian], Énergiya, Moscow (1972).
2. B. S. Petuhov, V. V. Kirillov, and V. N. Maidanik, "Heat transfer experimental research for turbulent gas flow in pipes at high temperature difference between wall and bulk fluid temperature," Proc. 3rd Int. Heat Transfer Conf., Chicago, AIChE, 1, 285-292 (1966).
3. B. S. Petukhov, V. A. Kurganov, and A. I. Graduntsov, "Experimental study of heat transfer to a turbulent flow of a monatomic gas with large temperature heads," Teplofiz. Vys. Temp., 8, No. 6, 1311-1315 (1970).
4. M. A. Valyuzhinich and E. V. Kuznetsov, "Heat transfer to SCP helium on the initial section of a circular pipe under strongly nonisothermal conditions," in: Heat and Mass Transfer-VII, Vol. 1, Pt. 1, ITMO Akad. Nauk Belorussian SSR, Minsk (1984), pp. 36-49.

5. V. M. Eroshenko and E. V. Kuznetsov, "Analysis of heat transfer in the heating of helium in the supercritical thermodynamic state under conditions of forced convection," in: Heat and Mass Transfer in the Boiling and Flow of Cryogenic Fluids, ITMO Akad. Nauk Belorussian SSR, Minsk (1980), pp. 33-49.
6. V. A. Kurganov and B. S. Petukhov, "Analysis and generalization of experimental data on heat transfer in pipes during the turbulent flow of gases with variable physical properties," Teplofiz. Vys. Temp., 12, No. 2, 304-315 (1974).

FEATURES OF HEAT AND MASS TRANSFER IN BUNDLES OF SPIRAL TUBES

B. V. Dzyubenko

UDC 621.564-71:536.423

An analysis of published data on heat and mass transfer and a study of the process of equalization of velocity-field nonuniformity due to an inlet pipe are used to make recommendations on calculation of the velocity and temperature fields in bundles of spiral tubes.

Heat exchangers in which the fluid flow is twisted by spiral tubes of oval cross section are distinguished by favorable dimensional characteristics thanks to the intensification of heat transfer as the heat-transfer agent flows in the space between tubes and inside the tubes [1]. Such heat exchangers are also characterized by intensive equalization of temperature- and velocity-field nonuniformities in the cross section of the tube bundle [2-5]. The velocity-field nonuniformities may be the result of a nonuniform heat-carrier temperature field due in turn to a specified distribution of heat supply about the radius of the bundle or to inlet pipes bringing the heat carrier into the intertube space. The process of equalization of these nonuniformities for an axisymmetric problem is described in the equation of motion by the diffusion term $1/r\partial/\partial r(r\bar{\rho}D_t\partial\bar{u}/\partial r)$ and the term $\xi\bar{\rho}\bar{u}^2/2d_e$ characterizing the effect of sources of fluid resistance:

$$\bar{\rho}\bar{u}\frac{\partial\bar{u}}{\partial z} = -\frac{dp}{dz} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\bar{\rho}D_t\frac{\partial\bar{u}}{\partial r}\right) - \xi\frac{\bar{\rho}\bar{u}^2}{2d_e}. \quad (1)$$

Here, we use a flow model in which the bundle is replaced by a porous mass with a diameter equal to the bundle diameter. The mass contains a flow of a homogenized medium — the flow of heat carrier with sources of volumetric energy release q_v and fluid resistance $\xi\bar{\rho}\bar{u}^2/2d_e$ distributed in it. The intensity of these sources changes over the radius of the bundle [3]. Having determined the displacement thickness of the boundary layer δ^* and having hypothetically accumulated a layer of material of equal thickness δ^* on the tube wall, we can examine a free flow in new boundaries with slip of the homogenized medium. Here, we assume that the velocity vector is parallel to the bundle axis and that $\partial p/\partial r = 0$. Thus, in Eq. (1) $\bar{u}$ is the velocity in the core of the flow (outside the boundary layer), while there are no convective terms with transverse velocity components in the left side of (1). The diffusion term in (1) accounts for the effect of different transport mechanisms on the velocity field in cross sections of the bundle [3]. Thus, replacement of the flow in an actual tube bundle by a flow of a homogenized medium is an engineering method which should be substantiated experimentally for use in calculating the velocity and temperature fields of the heat carrier.

One of the goals of the present study is to experimentally validate equation of motion (1) in the case of flow being examined, as well as to analyze data from different investigations of heat and mass transfer in bundles of spiral tubes.

To calculate the velocity and temperature fields in a bundle of coiled tubes, it is necessary to solve a system of differential equations which, apart from (1), includes equations of energy, flow rate, and state:

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 50, No. 4, pp. 535-542, April, 1986. Original article submitted January 30, 1985.

0022-0841/86/5004-0373 $12.50