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HYDRODYNAMICS AND HEAT EXCHANGE IN TURBULENT FLOWS

DETERMINATION OF THE SITE OF GENERATION OF ADDITIONAL TURBULENCE IN THE WALL PART OF A FLOW FOR VARIABLE THERMOPHYSICAL PROPERTIES OF THE FLUID

R. F. Kelbaliev

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A theoretical method of finding the thickness of the wall layer when an artificial turbulizer is installed in the flow is proposed. The site of location of the turbulizer is determined for maximum intensification of heat exchange in the case of constant and variable thermophysical properties of the fluid. It is established that incorrect selection of the site improves the heat transfer only slightly due to the growth in hydraulic resistance.

Intensification of the process of heat exchange is used to maintain the permissible temperature regime of equipment during its operation and to create small-size apparatuses and is also used in different technological processes. Numerous works [1–3] are devoted to this subject. To intensify the transfer of heat from the wall to the fluid and conversely it is necessary to generate additional turbulence in the wall part of the flow. Of great interest is to study this process for fluids of supercritical pressure (SCP). Substances at SCP are widely used in thermal power stations and for cooling of a high-temperature surface. In the objects in question, the fluid is used in a heated state in the first case and in a cold state in the second case.

A distinctive feature of the critical state of a fluid is a significant and diverse change in the thermophysical properties. Thus, the density and viscosity of the fluid sharply decrease, the heat capacity and the coefficient of volumetric expansion attain their maximum values, and the surface-tension force and the heat of evaporation tend to zero.

Experimental investigations of convective heat exchange have shown that it produces a change in the forces in the fluid, acceleration or deceleration of the flow, and thermoacoustic pressure self-oscillations and free convection. These effects can finally result in a reorganization of the flow and a change in the transfer of heat in the longitudinal and transverse directions.

In motion of the heat-transfer agent in a pipe, a near-critical state is attained between the wall and the pipe axis. In cooling of a high-temperature surface, the temperature of the wall is higher than the critical temperature, and that of the fluid on the pipe axis is lower ($t_w > t_{cr}$ and $t_{fl} < t_{cr}$). The structure of the flow and hence the intensity of convective heat exchange will depend on the site of location of this region on the cross section of the flow. Experimental investigations have proved that different regimes of convective heat exchange (of normal, improved, and impaired heat transfer) can exist at the SCP of the fluid.

In the work proposed, we consider the possibility of solving the process of intensification of heat exchange for a fluid flow with variable thermophysical properties.

Experimental data on determination of the velocity and temperature profiles and the turbulent coefficients of transfer for variable properties of the fluid are lacking in the literature. Those available mainly refer to substances that are far from the critical state, where the thermophysical properties change monotonically and relatively weakly.

The difficulty encountered in studying the above problem is associated with the fact that it is impossible to experimentally determine the quantities characterizing turbulence near the wall.

Attempts at describing theoretically a change in the turbulent coefficients of transfer for variable thermophysical properties of the fluid have been made in [4, 5].

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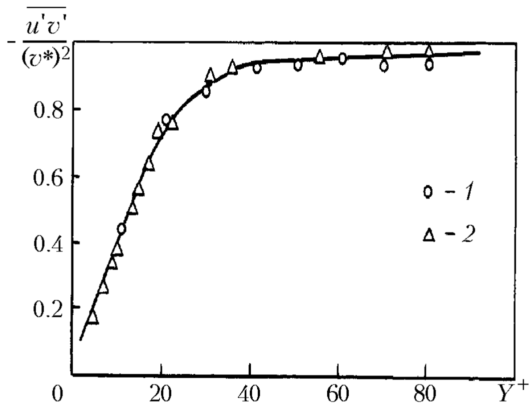


Fig. 1. Distribution of the turbulent friction stress in the wall region of the boundary layer: 1) experimental data of Laufer [6]; 2) the same, of Schubauer [7]; curve, calculation from Eq. (6).

For the wall layer, where we have molecular and turbulent mechanisms of transfer, the general coefficients of dynamic viscosity and thermal conductivity can be determined from the dependences

$$\mu = \mu_{fl} + \mu_\tau\,, \quad \lambda = \lambda_{fl} + \lambda_\tau\,.$$

In [5], the turbulent coefficients of viscosity and thermal diffusivity are found as

$$\varepsilon_\tau = \kappa y v^* \left[1 - \frac{1}{2} \frac{\mu_{fl} + \mu_\tau}{(\delta^*)^2 \rho_{fl}} \frac{\exp\left(-\kappa^2 \frac{y v^*}{\nu_w}\right)}{dU/dy} \right], \tag{1}$$

$$\varepsilon_q = \kappa y v^* \left[1 - \frac{1}{2} \frac{(\lambda_{fl} + \lambda_\tau)\,\mathrm{Pr}_{fl}^m T^*}{(\delta^*)^2 \rho_{fl} C_{pfl} v^*} \frac{\exp\left(-\kappa^2 \mathrm{Pr}_{fl}^k \frac{y v^*}{\nu_w}\right)}{dT/dy} \right], \tag{2}$$

where $\kappa = 0.4$.

When the expression of the tangential stress and the heat flux is used, we obtain the equations describing the velocity and temperature profiles for the entire thickness of the internal region of the boundary layer for variable thermophysical properties of the fluid [5]:

$$\frac{dU^+}{dY_w^+} = \frac{\frac{\tau_{fl}}{\tau_w}}{\frac{\mu_{fl}}{\mu_w} + \kappa \frac{\rho_{fl}}{\rho_w} Y_w^+} + \frac{1}{2} \kappa Y_w^+ \exp\left(-\kappa^2 Y_w^+\right), \tag{3}$$

$$\frac{dT^+}{dY_w^+} = \frac{\nu_w}{\nu_{fl}} \frac{\frac{q_{fl}}{q_w}}{\frac{1}{\mathrm{Pr}_{fl}} + \frac{\nu_w}{\nu_{fl}} \kappa Y_w^+} + \frac{1}{2} \kappa Y_w^+ \mathrm{Pr}_{fl}^m \exp\left(-\kappa^2 \mathrm{Pr}_{fl}^k Y_w^+\right), \tag{4}$$

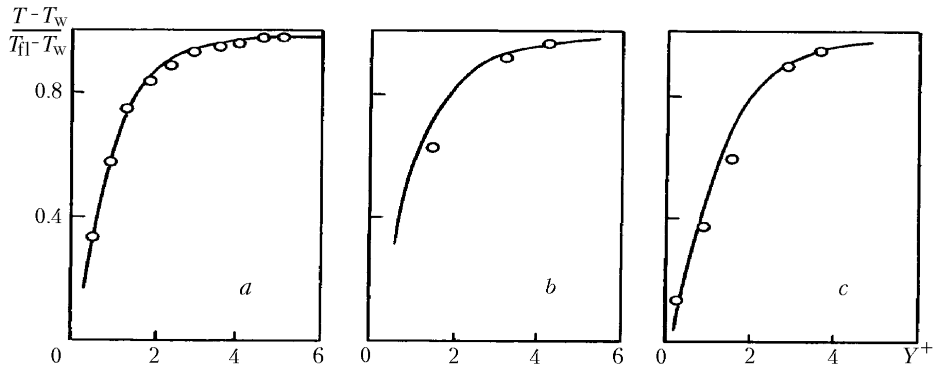


Fig. 2. Temperature and concentration profiles for high values of Pr and Sc: a) Sc = 900 and Re = 9700 [8]; b) Pr = 300 and Re = 10,000 [9]; c) Sc = 1000 and Re = 30,000 [9]; curve, calculation from Eq. (7).

where the value of the power k is equal to 0.5 and m = 1.85 for dropping liquids with an average value of the Prandtl number.

Below, we give calculations from these equations.

Constant Thermophysical Properties of the Fluid. The data of calculations from Eqs. (3) and (4) for constant thermophysical properties of the fluid are in good agreement with experimental data [5]. Using the above formulas, we can obtain certain results on turbulent characteristics of the flow. For example, from the equation

$$\tau = \mu \frac{dU}{dy} - \rho \overline{u'v'}$$

for the turbulent friction stress we obtain

$$-\frac{\overline{u'v'}}{(v^*)^2} = 1 - \frac{dU^+}{dY^+} . \tag{5}$$

With account for (3), for constant thermophysical properties of the fluid we have

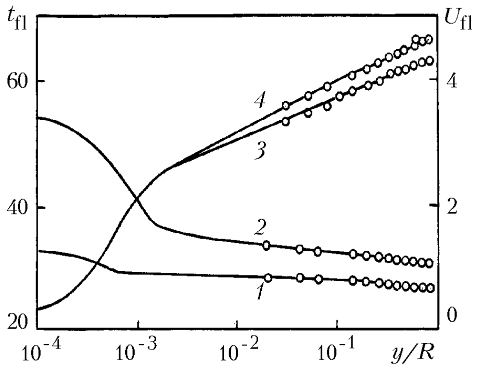
$$-\frac{\overline{u'v'}}{(v^*)^2} = 1 - \frac{1}{1 + \kappa Y^+} + \frac{\kappa Y^+}{2} \exp(-0.16 Y^+) . \tag{6}$$

Figure 1 compares the calculated and experimental values of the turbulent friction stress [6, 7]. It shows that they strongly change for $Y^+ < 20$; we observe a gradual increase in this quantity in the interval $20 < Y^+ < 60$ and a slight increase for $Y^+ > 60$.

Analogously we can obtain an expression for determination of the changes in the temperature or concentration near the wall:

$$\frac{T - T_w}{T_{fl} - T_w} = \frac{\sqrt{\xi/8}}{\mathrm{Pr}^{0.6}} T^+ . \tag{7}$$

Figure 2 shows the temperature and concentration profiles at high values of the Prandtl and Schmidt numbers [8, 9]. The constructed plots show a sharp decrease in the local characteristics and the average values characterizing turbulence at different distances from the wall. From these plots it follows that additional turbulence for intensification of heat exchange must be generated in that part of the wall flow where we have significant changes in the above quantities. Therefore, the wall-layer thickness in the case of a strong change in the turbulence must be determined for each individual problem.



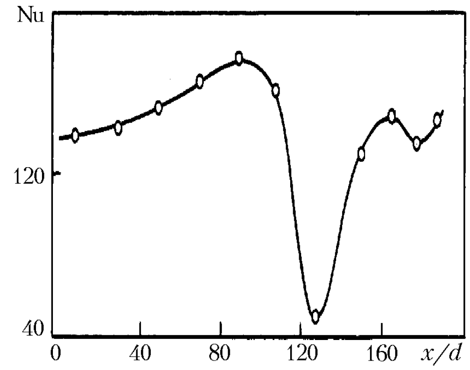
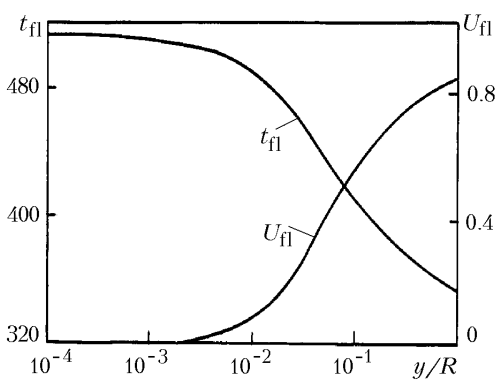


Fig. 3. Change in the velocity and temperature of carbon dioxide at supercritical pressure: 1 and 2) temperature profiles respectively at t_{fl} = 27.50°C, t_w = 33.35°C and t_{fl} = 31.65°C, t_w = 56.20°C; 3 and 4) velocity profiles respectively at t_{fl} = 30°C, U = 3.91 m/sec and t_{fl} = 28.95°C, U = 4.22 m/sec [10]; curves, calculation from Eqs. (3) (1 and 2) and (4) (3 and 4) respectively.

Fig. 4. Change in the Nusselt number along the pipe length in the impaired regime of heat transfer for water at P = 22.56 MPa and ρU = 430 kg/(m^2·sec) [11].



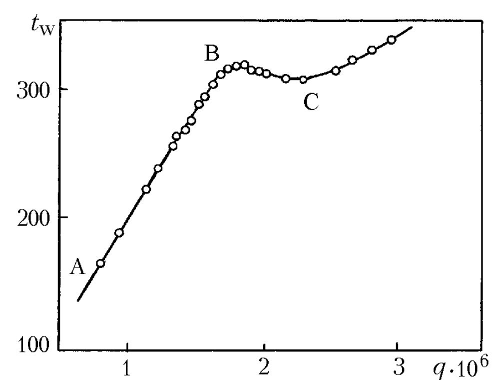


Fig. 5. Change in the velocity and temperature over the cross section of the flow in the impaired regime of heat transfer of water at P = 22.56 MPa and ρU = 430 kg/(m^2·sec) [11].

Fig. 6. Wall temperature vs. heat-flux density for toluene at P = 4.5 MPa and ρU = 3160 kg/(m^2·sec).

Variable Thermophysical Properties of the Fluid. The above analysis holds true for constant thermophysical properties of the fluid. When their values are variable, calculation is carried out by expressions (1)–(4). Figure 3 gives changes in the velocity and temperature profiles and compares them to experimental data [10]. Unfortunately, there are no corresponding experimental results for the region of the wall flow for $y/R < 10^{-3}$. From the figure it follows that the velocity and temperature profiles strongly change at a distance of $y/R \le 10^{-3}$ from the wall. Therefore, intensification of heat exchange and generation of turbulence must be realized in the layer of thickness $y/R \approx 10^{-3}$.

Figure 4 gives a change in the Nusselt number along the pipe length in experiments with water in an impaired regime of heat transfer [11]. A decrease in heat exchange because of the violation of the temperature regime of the wall is observed above the central part of the pipe (x/d = 127). For the normal process of heat transfer on this portion of the pipe we must install an artificial turbulizer. The thickness of the wall layer where we have the attenuation of turbulence must be known. Therefore, in this cross section of the pipe, we determine changes in the velocity and temperature profiles of water. From Fig. 5, it is clear that, in the impaired regime of heat transfer (x/d = 127), they strongly change at a distance of $y/R \approx 0.1$ from the wall.

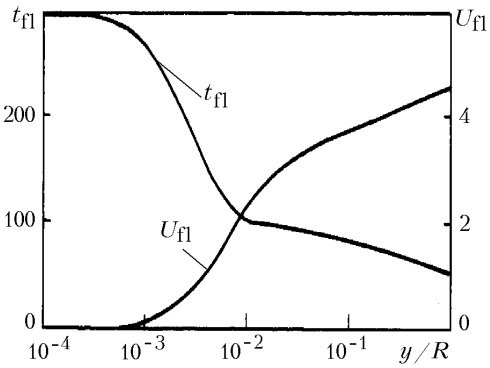


Fig. 7. Change in the velocity and temperature over the cross section of the flow in the improved regime of heat transfer of toluene at P = 4.5 MPa and ρU = 3160 kg/(m^2·sec).

The experiments on the heat exchange of SCP toluene have shown that, as the heat flux increases, the temperature of the wall first increases, just as in the normal regime (portion AB), but then at $t_w \approx t_m$ we obtain a horizontal portion BC and heat transfer is improved (Fig. 6) [12]. It is of interest to determine the regions of reduction of turbulence. Figure 7 shows that strong changes in the velocity and temperature profiles for the improved regime of heat transfer occur at a distance of $y/R \le 10^{-2}$ (0.01) from the wall.

The data at SCP and different temperatures for a number of substances (see Figs. 3, 5, and 7) show that, as the wall is approached, the turbulence is attenuated at different distances from it. The intensity of the transfer of heat depends on correct selection of the site of location of a turbulizer, since the generation of additional turbulence increases not only the intensity of heat exchange but the hydraulic resistance as well. For example, under the conditions of variation of the velocity and the temperature shown in Fig. 3, installation of a turbulizer at a distance of $y/R > 0.10$ from the wall will increase hydraulic resistance but virtually will not change the intensity of heat transfer. Analogous effects are also observed under other conditions. In the impaired regime of heat transfer of water [11] (Fig. 5), one should install turbulizers at a distance of $y/R \approx 0.1$ from the wall. When $y/R > 0.10$ turbulizers increase the hydraulic resistance and do not change the intensity of heat transfer. When $y/R < 0.10$ turbulizers are inefficient, since most of the energy will be expended on turbulizing the flow in the layer of thickness from $y/R < 0.10$ to $y/R \approx 0.10$. In certain cases the condition $\mathrm{Nu}/\mathrm{Nu}_{sm} \ge \xi/\xi_{sm}$ is not satisfied.

Experimental investigation of the intensification of heat exchange shows that incorrect selection of the site of location for the turbulizer is inefficient.

NOTATION

d and R, diameter and radius of the pipe, m; C_p, heat capacity, kJ/(kg·°C); P, pressure, MPa; Pr, Sc, and Nu, Prandtl, Schmidt, and Nusselt numbers; q, heat-flux density, W/m^2; T and t, temperature, K and °C; $T^* = q/(\rho C_p v^*)$, temperature scale, K; $T^+ = (T_w - T_{fl})/T^*$, dimensionless temperature; t_m, temperature corresponding to the maximum heat capacity at $P > P_{cr}$, °C; U, velocity, m/sec; $U^+ = U/v^*$, dimensionless velocity; u' and v', velocity pulsations in the directions of the coordinates x and y, m/sec; $Y^+ = yv^*/\nu$, dimensionless coordinate; $\delta^* = \nu/v^*$, dynamic length, m; ε_q, coefficient of turbulent thermal diffusivity, m^2/sec; $v^* = \sqrt{\tau/\rho}$, dynamic velocity, m/sec; λ and λ_τ, molecular and turbulent coefficients of thermal conductivity respectively, W/(m·°C); μ and μ_τ, molecular and turbulent dynamic viscosities, N·sec/m^2; ν and ε_τ, molecular and turbulent kinematic viscosities, m^2/sec; ξ, coefficient of hydraulic resistance; ρ, density of the fluid, kg/m^3; ρU, mass velocity, kg/(m^2·sec); τ, tangential stress, N/m^2. Subscripts: sm, smooth; fl, fluid; cr, critical; w, wall; m, maximum; p, pressure.

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