NONSTEADY TRANSFER OF HEAT IN THE INITIAL SEGMENT OF A CYLINDRICAL TUBE

Yu. G. Volodin

UDC 536.24:532.52

We present the results of an experimental study of heat exchange in the case of a sharp increase (up to 12,000 K/sec) in the temperature of the heat carrier and with a temperature boost of up to 800 K.

In operating power-engineering installations and a heat-exchange apparatus we frequently encounter nonsteady operational regimes that are brought about by structural features or specific technological measures. The transfer of heat under various nonsteady conditions, predominantly in the case of a flow of heat directed from the wall to the working fluid, has been rather extensively covered in the literature [1-3]. Of the entire multiplicity of conditions for nonsteady heat exchange, the least studied are those in which the nonsteadiness is created by a change in the temperature of the working fluid. In our studies, which are a continuation of [4, 5], we have studied experimentally the nonsteady transfer of heat in the case of a sharp increase in the temperature of a gas flow and for the case of a large temperature boost.

The experiments were carried out in a fan-shaped wind tunnel where the working fluid was heated by means of a plasma over a range of Reynolds numbers from $3 \cdot 10^4$ to $6 \cdot 10^4$, intended for average flow-rate velocities. The nonsteady heat-exchange conditions were achieved by connection of a plasmotron. The experimental channel, fabricated out of stainless steel with a wall thickness of 10^{-4} m, is fashioned in the form of a cylindrical tube 7d in length, with a diameter of $d = 45 \cdot 10^{-3}$ m. The measuring system, consisting of Chromel—Alumel and Chromel—Copel microthermocouples, DMI-0.1 induction pressure sensors, and a K-20-22 recording loop oscillograph, recorded the total pressure and the temperature T_0 at the inlet to the experimental channel, the channel wall temperature T_w, and the dynamic increase in temperature. A detailed description of both the experimental and diagnostic equipment and its dynamic characteristics can be found in [5]. The relative error in the determination of the temperatures amounted to 4.5%, and the error in the determination of the heat-transfer coefficients was 14%.

The intensive increase in the temperature T_0 of the gas stream (Fig. 1) is accompanied by an equally intensive reduction in the density ρ_0 and an increase in the viscosity μ_0 of the working fluid, as a consequence of which the velocity w_0 of the flow outside of the boundary layer also increases. The elevation of the temperature T_0 and the increase in the velocity w_0 of the flow by a factor of more than 3 within a short interval of time leads to the formation of greater-magnitude values of the time derivatives of the temperature $dT_0/dt =$ 12,000 K/sec and of the velocity $dw_{01}/dt = 670$ m/sec^2. This means that the heat-transfer process in the interval of growth for the temperature T_0 of the heat carrier occurs with the simultaneous appearance of the effects of thermal and hydrodynamic nonsteadiness and a reduction in the Re_1 number (Fig. 1). Moreover, in the interval of time under consideration the flow is accelerated, and this is characterized by the derivative $\partial w_0/\partial x$ which represents yet another form of the nonsteadiness $\partial(\partial w_0/\partial x)/\partial t$. It was demonstrated in [6, 7] that the reduction in the Re number stimulates the appearance of nonsteady effects, while the thermal and hydrodynamic nonsteadiness exerts an opposite effect on the transfer of heat. Under the conditions of such influence exerted by the nonsteady effects we observe an initial increase (by a factor of 2-2.5) in the heat-transfer coefficient St relative to the quasisteady value (the straight line 1, Fig. 2) in all of the metering cross sections of the experimental channel. The change in the initial instants of time is a result of the predminant influence on

---

All-Union Pumping Machinery Technological Scientific Research Institute, Kazan'. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 57, No. 4, pp. 574-577, October, 1989. Original article submitted May 11, 1988.

0022-0841/89/5704-1166$12.50

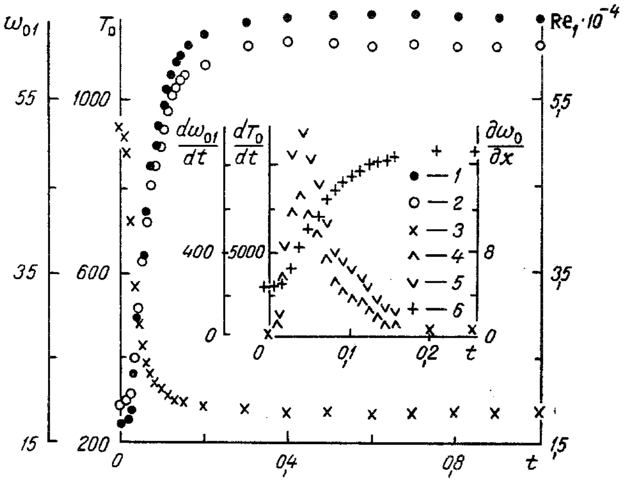

Fig. 1. Evolution, with time, of the initial conditions: 1) w_{01}; 2) T_0; 3) Re_1; 4) dw_{01}/dt; 5) dT_0/dt; 6) $\partial w_0/\partial x$, w_{01}, m/sec; T_0, K; t, sec; dw_{01}/dt, m/sec^2; dT_0/dt, K/sec, $\partial w_0/\partial x$, (m/sec)/m; t, sec.

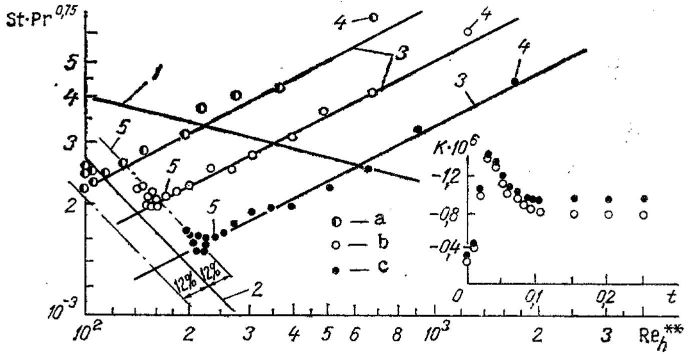

Fig. 2. Stanton number St as a function of the Reynolds number Re_h^{**}: a) X = 2.5; b) 4.5; c) 6.5. 1) $St_0 = \frac{0,0128}{Re_h^{**0,25} Pr^{0,75}}$; $2 - St_{0\ell} = \frac{0,22}{Re_h^{**} Pr^{4/3}}$; $3 - St = St_0 \left[\frac{1}{Re_h^{**} (T_0 - T_w)} \times \frac{d(T_0 - T_w)}{dt} \right]^{0,5}$; 4—$t = 0,03$ sec; 5—0,12 sec.

the structure of the flow by the thermal nonsteadiness and in the time interval up to t ≈ 0.06 sec the magnitude of the heat-transfer coefficient exceeds the values of its quasi-steady analogs. The hydrodynamic nonsteadiness and, to a greater extent, the increasing magnitude of flow acceleration (with the passage of time), becomes decisive in the subsequent instant of time, thus leading to a reduction in the processes of heat exchange and correspondingly to a reduction in the Stanton number, which occurs at all of the metering cross sections of the experimental channel along parallel rays 3 (Fig. 2). The absence of experimental data for the time interval 0-0.02 sec in Fig. 2 is associated with the insignificant change in the temperature of the gas and the walls of the channel, which in the determination of the quantities of heat flows and of the heat-transfer coefficients leads to great errors.

The increase in the heat-transfer coefficients by a factor of two and more, and their subsequent reduction, resulting from the influence exerted by the nonsteady effects in the case of a sharp change in the thermal state of the system, quantitatively and in terms of the nature of the change in the St = f(t) function, correlate with the results from [8, 9].

The experimental results on the transfer of heat in the case of a sharp increase in the temperature of the heat carrier have been generalized by an approximation function of the form

$$\Psi_h = \mathrm{St}/\mathrm{St}_0 = \left[\frac{1}{\mathrm{Re}_h^{**}(T_0 - T_w)}\,\frac{d(T_0 - T_w)}{dt}\right]^{0,5}. \tag{1}$$

The Re_h^{**} number, constructed for the energy-loss thickness, was determined in accordance with [10], from the expression

$$\mathrm{Re}_h^{**} = \frac{d}{\mu_0 g C_p (T_0 - T_w)} \int_0^X q_w(X)\,dX, \tag{2}$$

where $q_w = C_p \rho_w \Delta_w (\partial T_w/\partial t)$ represents the density of the thermal flow. The losses of heat in free convection and due to the radiative capacity of the surface of the experimental channel were determined from the criterial equations in [11] and amounted to no more than 10% of q_w.

At the instant of time t = 0.12 sec the nonsteady process of heat transfer may be regarded as having been concluded, since in the interval t ≥ 0.12 sec, which is characterized by a large temperature boost of ~800 K, the experimental points grouped about straight line 2, representing the "standard" law of heat transfer for laminar flow regimes. Thus, on reaching a constant flow temperature we note the formation of conditions under which the turbulent boundary layer (TBL) becomes laminar. Of interest here is the change and the magnitude of the acceleration parameter

$$K = -\frac{\nu}{w_0^2}\frac{\partial w_0}{\partial x} - \frac{\nu}{w_0^3}\frac{\partial w_0}{\partial t}, \tag{3}$$

by means of which we normally characterize the laminarization of the TBL. The parameter K in the temperature-rise interval for the flow attains its limit value $-1.42\cdot10^{-6}$ because of the velocity derivative $\partial w_0/\partial t$. Beyond the limits of the interval of the nonsteady transfer of heat the contribution to the magnitude of K on the part of the second term is insignificant and the parameter K, as was the case in steady flows in converging channels, is determined exclusively by the first terms. Based on the direction of the flow, the magnitude of the parameter K diminishes, varying from $-0.63\cdot10^{-6}$ (in the metering cross section having the coordinate X = 2.5) to $-0.93\cdot10^{-6}$ (X = 6.5).

NOTATION

T, temperature; w_0, velocity; d, channel diameter; t, time; x, longitudinal coordinate, m; X = x/d, dimensionless longitudinal coordinate; g, acceleration of free fall; ρ, density; ν, μ, kinematic and dynamic viscosity; C_p, specific heat capacity; Δ, thickness of channel walls; Re_1, Reynolds number, constructed on the basis of the average flow rate at the inlet to the experimental channel; $\mathrm{Re}_h^{**} = w_0 \delta_h^{**}/\nu$, Reynolds number constructed for the energy loss thickness; St, Stanton number; Ψ, relative heat-transfer coefficient; K, acceleration parameter. Subscripts: w, conditions at the wall; 0, conditions at the outer edge of the boundary layer; 1, conditions at the inlet to the experimental channel; h, thermal parameters.

LITERATURE CITED

1. G. A. Dreitser, V. D. Evdokimov and É. K. Kalinin, Inzh.-Fiz. Zh., 31, No. 1, 5-12 (1976).
2. I. S. Kochenov and V. F. Falii, Teplofiz. Vys. Temp., 16, No. 4, 791-795 (1978).
3. Kawamura Hiroshi, Int. J Heat Mass Transfer, 20, No. 5, 443-450 (1977).
4. A. V. Fafurin and K. R. Shangareev, Inzh.-Fiz. Zh., 30, No. 5, 821-824 (1976).
5. Yu. G. Volodin and A. V. Fomin, Contemporary Problems in Thermophysics [in Russian], Novosibirsk (1987), pp. 297-305.
6. A. V. Fafurin, Heat and Mass Exchange in Aircraft Engines [in Russian], Hazan' (1979), Issue 2, pp. 62-69.
7. Yu. G. Volodin and A. V. Fafurin, Increaisng the Efficiency and Refining the Processes and Apparatus of Chemical Production [in Russian], Kharkov (1985), Chap. 3, pp. 71-73.
8. É. K. Kalinin, G. A. Dreitser, and V. A. Kuz'minov, Heat and Mass Transfer [in Russian], Minsk (1972), Vol. 1, pp. 368-372.
9. I. M. Lagun, Inzh.-Fiz. Zh., 45, No. 5, 797-802 (1983).
10. S. D. Kutateladze and A. I. Leont'ev, Heat Exchange and Friction in a Turbulent Boundary Layer, 2nd ed. [in Russian], Moscow (1985).
11. M. A. Mikheev, The Fundamentals of Heat Transfer [in Russian], Moscow—Leningrad (1956).