HEAT TRANSFER IN A TRANSIENT BOUNDARY LAYER ON A POROUS PLATE

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We present the results of an experimental study and a procedure for calculation of the effect of intense injection of various coolants on stability loss in laminar flow and on heat transfer in a transient boundary layer on a porous plate in a longitudinal flow.

The study of heat transfer and of the structure of a transient boundary layer under intense injection of various coolants is of great practical interest. This is explained by the circumstance that such studies are few in number and the production of experimental data by the use of modern research methods makes possible the accumulation and expansion of our ideas about this interesting field of hydrodynamics in ever increasing measure.

In this paper we present the results of a study of the effect of intense injection of various coolants on stability loss in laminar flow and on heat transfer in a transient boundary layer at a porous plate in a longitudinal flow.

The experimental studies were performed with the gasdynamic equipment described in [1]. As a test model we used a porous plate 275 × 40 mm^2 in size in a longitudinal flow which served as the bottom wall of a working channel 80 × 40 mm^2 in cross section. The lateral walls of the working channel were made of quartz plates of interferometric purity. The top wall of the working section was a movable cover which made it possible to change the transmission cross section of the channel in order to reduce the effect of the pressure gradient in the main flow.

The temperature of the working surface of the plate was measured with Chromel—Alumel thermocouples 0.2 mm in diameter with their junctions set at $\sim$0.1 mm from the surface of the plate. The junctions of the thermocouples measuring the temperature of the injected gas on entrance into the porous plate were placed in insulating shields in order to eliminate contact with the model. The emf of the thermocouples during calibration and experiment was measured with a P307 low-resistance potentiometer and an M 195/2 reflection galvanometer.

In the first set of experiments, we studied the effect of strong injection of carbon dioxide on stability loss in laminar flow for a nonisothermal boundary layer. In performing these experiments, an interferometric method was used for visualization of the region of stability loss and of the region of transition from laminar flow into turbulent flow during injection of a foreign gas. Measurement of velocity and temperature distributions in the boundary layer was made with an ÉTAM-3A thermoanemometer. Interferograms were taken at different settings with an A-39 aerial camera at intervals of 0.8 sec between frames and 15 frames per injection mode. A helium—neon laser was used as a light source in a Mach-Zehnder interferometer.

The exposure of 15 separate frames for each injection made it possible to use a classical method for analysis of the results. A set of measurements consisting of 15 interferograms is a random selection from a basic set in which the argument has a normal Gaussian distribution. The arithmetic mean of the random selection and the confidence interval were calculated for a given parameter on the basis of the measured data. The value of the standard

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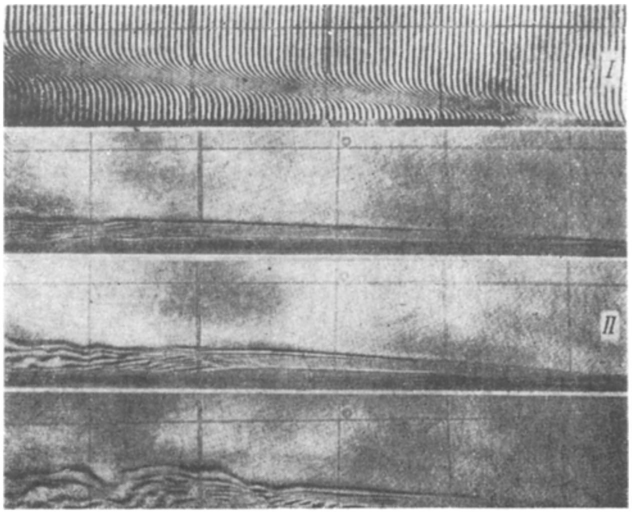

Fig. 1. Interferograms of laminar boundary layer and of region of flow stability loss at a plate in a longitudinal flow during injection of CO_2: I) $U_\infty = 2.1$ m/sec; $T_\infty = 350°$; $F = 0.047$; II) $U_\infty = 5.6$ m/sec; $T_\infty = 330°K$; $F = 0.0072$, 0.0112, and 0.015.

deviation (of the interval) was then the coordinate of the point of stability loss when determined by statistical methods. About 500 interferograms were analyzed by such a method.

Figure 1 shows typical interferograms (set on the "infinite" band) of the region of stability loss in a laminar boundary layer during injection of carbon dioxide. The experiments were performed with the following parameters for the main flow: $U_\infty = 2.1$ m/sec and 5.6 m/sec and $T_\infty = 330$-357°K in the range of injection intensity $F = \rho_w V_w / \rho_\infty U_\infty$ up to 0.065.

The studies of stability loss in laminar flow made it possible to discover the dependence on the injection parameter of the point of stability loss and of the critical Reynolds number Re_{xsl} based on the external flow velocity and the coordinate of the point of stability loss. The coordinate of the appearance of wave-shaped oscillations of concentration in the binary boundary layer was taken as the point of flow stability loss. In order to determine the effect of the boundary layer in the starting nonporous portion ahead of the test model on the loss of flow stability, experiments were performed both with and without a boundary layer ahead of the porous plate.

Using the well-known relation [2] $\delta = 4.67\sqrt{\nu x / U_\infty}$, estimates were made of the length of the starting nonporous portion. The development of a boundary layer in this section occurred in the nozzle and in the working channel ahead of the porous plate. Therefore, an estimate based on [2] yields an equivalent length of the boundary layer for flow conditions on the porous plate. For the specified construction of the working channel and our experimental conditions, the length of this section was $X_0 = 680$ mm.

The lack of a boundary layer in the starting section was achieved by means of suction ahead of the porous plate. The rate of suction was optimized by measurement of velocity profiles at the beginning of the porous plate until a practically uniform profile was achieved.

Typical experimental data on the effect of injection on stability loss in laminar flow are shown in Fig. 2. It is obvious that the quantity Re_{xsl} decreases monotonically as the parameter $F = \rho_w V_w / \rho_\infty U_\infty$ increases to 0.025 and is then almost independent of injection intensity. From a comparison of the values of Re_{xsl} with (curve 1) and without (curve 2) a boundary layer in the starting section, one can conclude that the developed boundary layer loses stability more rapidly in comparison with the layer on the porous plate when there is suction on the boundary layer. The presence of a laminar boundary layer decreased the value of the critical Reynolds number Re_{xsl} by a factor of 1.3 under our experimental conditions.

A comparison of the results of studies of flow stability loss for isothermal ($T_\infty = 290°K$) and nonisothermal ($T_\infty = 330°K$) injection of carbon dioxide showed good agreement between them.

Figure 3 shows temperature profiles for a laminar boundary layer ($L_x = 27.5$ mm, curve 2) and for regions of flow stability loss ($L_x = 82.5$ mm, curve 3; $L_x = 192.5$ mm, curve 4) for an

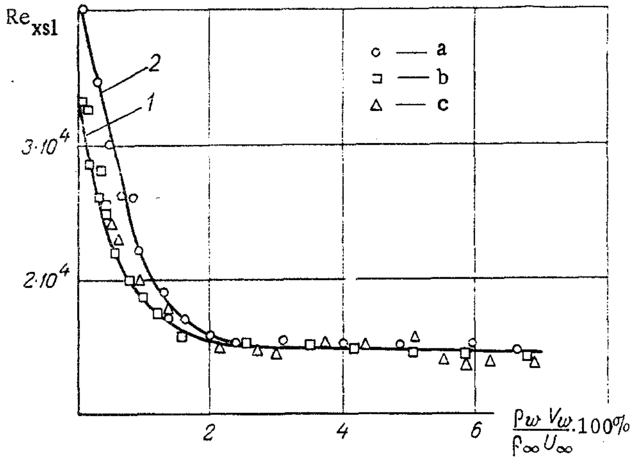

Fig. 2

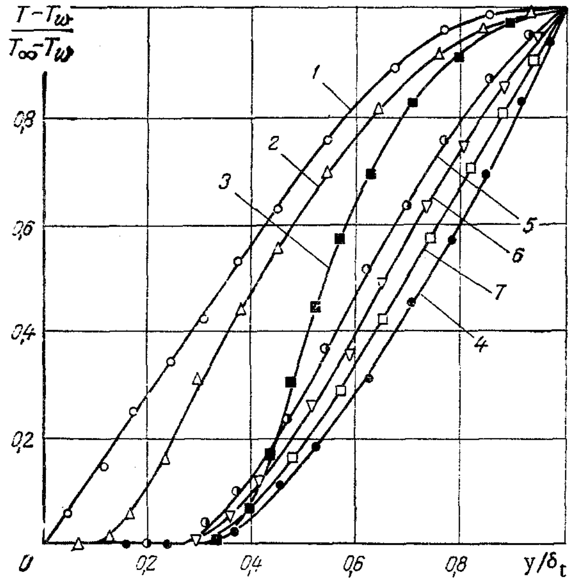

Fig. 3

Fig. 2. Dependence of critical Reynolds number on carbon dioxide injection intensity with (1) and without (2) a boundary layer in the starting nonporous section: a) $\delta_d = \delta = 0$; b) $\delta_d \neq \delta_t \neq 0$; c) $T_\infty = 290°K$; $U_\infty = 5.6$ m/sec; $T_\infty = 330°K$.

Fig. 3. Temperature distribution in laminar boundary layer (curve 2, $L_x = 27.5$ mm, $F = 0.047$) and in a region of flow stability loss during injection of carbon dioxide: 1) $L_x = 192.5$ mm, $F = 0$; 3) $L_x = 82.5$ mm, $F = 0.047$; 4) $L_x = 192.5$ mm, $F = 0.047$; 5, 6, 7) $L_x = 192.5$ mm, $F = 0.022$, 0.028, and 0.035.

injection parameter $F = \rho_w V_w/\rho_\infty U_\infty = 0.047$. A comparison of these profiles showed a significant difference between them. The temperature fields in a region of flow stability loss have less filled profiles of rather improper S-shape resulting from the presence of a considerable isothermal region near the wall. Temperature profiles at the plate section $L_x = 192.5$ mm obtained at lower values of the injection parameter (curves 5, 6, and 7) also differ significantly from the temperature profile in the laminar boundary layer (curve 2).

In a second set of experiments, heat transfer was investigated for a transient flow mode with intense injection of nitrogen and carbon dioxide into a main flow with the parameters $U_\infty = 10.5$ m/sec and $T_\infty = 380°K$ for a range of injection intensity $F = \rho_w V_w/\rho_\infty U_\infty = 0$–$0.05$. The experiments were performed with suction on the boundary layer in the starting section.

Preliminary studies of the boundary layer with an interferometer and by means of photographs taken with an SKS-1 high-speed camera showed that production of turbulence in the boundary layer occurred at the end of the porous section of the plate for the given incoming flow velocity $U_\infty = 10.5$ m/sec and weak injection of carbon dioxide. With an increase in injection intensity, a pattern of vortex breakdown was clearly observed in the central portion of the plate with subsequent production of turbulence downstream.

The experimental data on heat transfer were treated in the form of the relation $St = f(\rho_w V_w/\rho_\infty U_\infty)$, where the Stanton number was calculated from the expression

$$St = \frac{q_w - q_r - q_\lambda}{\rho_\infty U_\infty C_{p\infty}(T_\infty - T_w)},$$

$$q_w = \rho_w V_w C_{p\text{cool}}(T_w - T_{\text{cool}}); \quad q_\lambda = -(\lambda/\delta)_{\text{pl}}(T''_w - T'_w); \tag{1}$$

$$q_r = 5.76\,\varepsilon_{\text{pl}}\,\varphi\left[\left(\frac{T'''_w}{100}\right)^4 - \left(\frac{T_w}{100}\right)^4\right],$$

where q_w, q_r, and q_λ are the thermal flux absorbed by the coolant, the radiative flux to the porous wall, and the intensity of thermal influx from the nonporous walls of the model because of thermal contact.

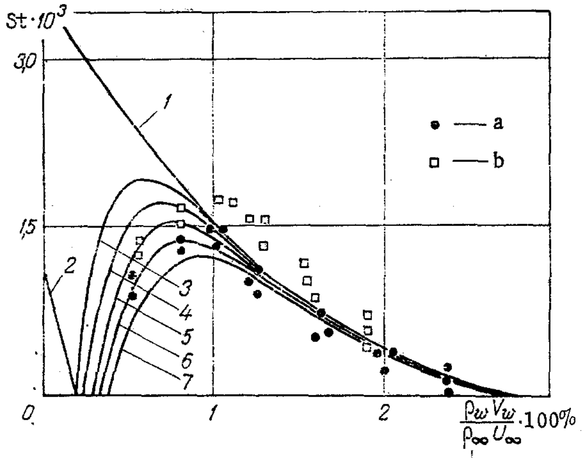

Fig. 4. Effect of nitrogen (a) and carbon dioxide (b) injection on heat transfer in a transient boundary layer at a porous plate. $U_\infty = 10.5$ m/sec; $T_\infty = 380$°K; $Re_x = 6.85 \cdot 10^4$: 1) [5]; 2) [4]; 3) $F_{tr} = 0.002$; 4) $F_{tr} = 0.0025$; 5) $F_{tr} = 0.003$; 6) $F_{tr} = 0.0035$; 7) $F_{tr} = 0.004$.

The values of the thermal fluxes q_r and q_λ were, respectively, 1 and 12% of the total thermal flux during moderate injection. As injection intensity was increased, the value of q_r remained almost unchanged, while q_λ decreased because of the increase in the intensity of heat transfer between the porous plate and the injected gas.

A model for the transient phenomena was presented in [3] and an interpolation formula constructed for calculating the parameters determining the transient processes. We used this model for analysis of heat transfer during injection and transient flow.

Let the Stanton number St characterize the process as a function of the injection parameter F. For laminar flow, the expression [4]

$$St_{lam} = St^0_{lam}\left[1 - 1.82\left(\frac{\mu_w}{\mu_\infty}\right)^{1/3} F\sqrt{Re_x}\right], \tag{2}$$

where $St^0_{lam} = 0.3/\sqrt{Re_x}$, approximates the experimental data satisfactorily. For computational simplicity, we calculate heat transfer during injection into a turbulent boundary layer from asymptotic theory with vanishing viscosity [5]. We take the approximate critical value b_c from experiment so that the expression

$$St_{tur} = St^0_{tur}[1 - (F/St^0_{tur})/b_c]^2 \tag{3}$$

will be extended to finite values of the Reynolds number ($St^0_{tur} = 0.0292/Re_x^{0.2}Pr^{1/3}$).

We introduce the "disorder measure"

$$\omega = \frac{St_{tur} - St}{St_{tur} - St_{lam}} \tag{4}$$

as a fundamental generalized characteristic of transient heat transfer and take $\varkappa = F - F_{tr}$ as a state coordinate, where F_{tr} is the injection intensity at which transition to the turbulent mode occurs. From a physically justified hypothesis [3],

$$-\frac{d\omega}{\omega} = \alpha^2 d\varkappa. \tag{5}$$

We assume that the constant of proportionality $\alpha^2 = 1/F_{tr}$. Integrating Eq. (4), we obtain an expression for calculating heat transfer in the transition region:

$$St_{tr} = St_{tur} - (St_{tur} - St_{lam}) \exp\left(\frac{F - F_{tr}}{F_{tr}}\right). \tag{6}$$

In this equation, St_{lam} and St_{tur} are defined, respectively, by Eqs. (2) and (3).

Figure 4 presents the experimental data for heat transfer during the injection of nitrogen. In the transition region, curve 6 corresponds to $F_{tr} = 0.0035$.

The experimental data for carbon dioxide fall somewhat above the values for nitrogen and the corresponding calculated values which were obtained for $\mu_w/\mu_\infty = 1$ and $b_c = F_c/St^0_{tur}$. The nature of the dependence of St on injection for carbon dioxide remains qualitatively the same as that for nitrogen and confirms the theoretical relations given. Consideration of the ratio of molecular weights and of the somewhat greater value of the critical injection for carbon dioxide in the equations given above leads to results which agree satisfactorily with the experimental values.

Thus, the calculated and experimental data (for example, see curves 3-7) indicate that a situation may occur during injection where the thermal flux in the wall increases significantly in comparison with the thermal flux which existed in the laminar flow prior to injection. It is necessary to keep this circumstance in mind in the development of designs involving protection against convective heat fluxes by injection.

Analysis of the experimental material and comparison of experimental data with calculation allows one to recommend Eqs. (2), (3), and (6), respectively, for practical calculations of the effect of injection on heat transfer in laminar, turbulent, and transient flows. The empirical parameters in these calculations are the value of the injection parameter at which transition to the turbulent mode occurs for a given Reynolds number and the value of the injection parameter for which the turbulent boundary layer is pushed away from the surface. In our opinion, it is preferable to use the "critical" injection parameters given in [6-8] at the present time.

NOTATION

$F = \rho_w V_w / \rho_\infty U_\infty$, $b = F/St_0$, injection parameters; St, Pr, Re, Stanton, Prandtl, and Reynolds numbers; q, thermal flux, W/m^2; U, V, longitudinal and vertical velocity components, m/sec; T, temperature, °K; ρ, density, kg/m^3; μ, ν, dynamic and kinematic viscosities, $kg/sec \cdot m^2$ and m^2/sec; X, longitudinal coordinate; L, length; δ, thickness of boundary layer and distance, m; λ, thermal conductivity, $W/m \cdot °C$; C_p, heat capacity, $J/kg \cdot °C$; ω, disorder measure; $\varkappa$, state coordinate; α, constant; ε, emissivity; φ, coefficient of mutual irradiation. Indices: ∞, unperturbed; w, wall; 0, without injection; cool, coolant; tur, turbulent; lam, laminar; tr, transient; pl, plate; r, radiative; c, critical.

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