HEAT EXCHANGE AT THE CRITICAL POINT OF A CYLINDER WITH INTENSE INJECTION

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UDC 532.526

The results of a study of the heat exchange and structure of the zone of stream mixing at the front critical point of a porous cylinder transverse to the flow in the presence of intense injection are presented.

The problem of the study of heat exchange at the front critical point of blunt bodies has recently taken on great importance not only from the point of view of the thermal protection of the latter from high-temperature chemically aggressive gas streams, but also from the point of view of protection from very intense radiative heat fluxes. As studies show, the strong injection of substances of low transparency (from the aspect of radiative heat exchange) is a very effective method of protection.

It is just the study of the structure of zones of stream mixing under conditions of intense injection which determines the interest in the study of such modes of flow.

In the report we present the results of a study of heat exchange and the structure of the zone of stream mixing at the front critical point of a porous cylinder transverse to the flow in the presence of intense injection of various coolants.

The experimental studies were conducted on a subsonic wind tunnel operating on the atmosphere–vacuum scheme. Atmospheric air entered an ohmic electric heater, was heated to the required temperature, and was then discharged through a nozzle of 80 × 40 mm^2 cross section into an Eifel chamber. The secondary gas was supplied to the test model from high-pressure tanks through a reducer, receiver, filters, and a flowmeter line.

The gasdynamic installation was equipped with a large complex of control-measuring apparatus, including a thermoanemometer, a Mach–Zehnder interferometer with laser light sources, etc. [1].

The use of lasers, providing high radiation intensity, permitted considerable magnification of the image of the interferometer pattern. In addition, the use of lasers considerably simplified work with the interferometer and increased the accuracy of the method used.

A porous cylinder with an outer diameter $d = 30$ mm, a length of 40 mm, and a wall thickness of 3 mm, placed transverse to the flow, was used as the test model. The cylinder was made from a blank of porous nickel with a porosity on the order of 69% and a powder grain size of ~2 μ. In performing the experiments the cylinder was placed transverse to the flow between optical quartz plates of interferometer purity, the presence of which results in the two-dimensionality of the impinging air stream. To eliminate the creation of flow conditions characteristic of channels under the conditions of strong injection the upper and lower walls of the working channel were absent in the tests.

The temperature of the outer surface of the porous cylinder at the front point was measured with a Chromel–Copel thermocouple 0.2 mm in diameter whose junction was caulked flush with the outer surface of the cylinder, while the leads were laid along the generatrix of the cylinder and glued to the surface of the cylinder with special glue.

G. M. Krzhizhanovskii Scientific-Research Institute of Power Engineering, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 33, No. 1, pp. 5-10, July, 1977. Original article submitted March 17, 1976.

The temperature of the injected gas inside the cylinder was measured with a Chromel–Copel thermocouple whose junction was placed in an insulating screen to eliminate contact between the thermocouple and the cylinder.

The distribution of velocity and temperature in the zone of stream mixing was measured with a thermoanemometer.

The experiments were conducted with the following parameters of the main stream: U_∞ = 2.65-6.75 m/sec, $Re_d = 3 \cdot 10^3 - 7.5 \cdot 10^3$, and T_∞ = 400-500°K; the range of variation of the injection intensity was

$$F = \frac{\rho_w V_w}{\rho_\infty U_\infty} = 0 - 0.48 \left(f_w = \frac{1}{2} \frac{\rho_w V_w}{\rho_\infty U_\infty} \sqrt{\mathrm{Re}_d} = 0 - 12 \right).$$

Typical experimental data on the effect of the injection of different cooling substances on the temperature at the front critical point of the outer surface of the cylinder are presented in Fig. 1. From an analysis of these data it is seen that (as one would expect) helium is the most efficient coolant.

Experimental and calculated data on heat exchange at the front critical point of the cylinder in comparison with the results of other authors [6-8] are presented in Fig. 2.

The value of the Stanton number in the absence of injection was determined from the equation [2]

$$\mathrm{St}_0 = \frac{1.04}{\sqrt{\mathrm{Re}_d}\sqrt[3]{\mathrm{Pr}}}, \tag{1}$$

$$\mathrm{St} = \frac{q_w - q_r - q_\lambda}{\rho_\infty U_\infty C_{P\infty} (T_\infty - T_w)}, \tag{2}$$

$$q_w = \rho_w V_w C_{P\mathrm{cool}} (T_w - T_{\mathrm{cool}}),$$

$$q_r = 5.76 \varepsilon_{\mathrm{re}} \varphi \left[\left(\frac{T_w^*}{100} \right)^4 - \left(\frac{T_w}{100} \right)^4 \right],$$

$$q_\lambda = - \left(\frac{\lambda}{x} \right)_{\mathrm{cyl}} (T_w - T_w'),$$

where q_w, q_r, and q_λ represent the heat flux absorbed by the coolant, the radiative flux to the cylinder, and the heat flux along the perimeter of the cylinder due to the heat conduction of the porous material, respectively.

The values of the emissivity of the quartz plates and channel walls and of the reduced emissivity ε_{re} and coefficient of mutual irradiation φ were determined from [3].

With intense injection the values of the heat fluxes q_r and q_λ comprised 1 and 8% of the total heat flux.

Using the relation obtained in [4] in the solution of the boundary-layer equations as the dimensionless temperature gradient, we define the relative heat flux with the injection of a homogeneous gas (in our case nitrogen) as

$$\frac{q}{q_0} = \frac{\exp [\mathrm{Pr} f_w^2][1 + \Phi(\lambda_0 \sqrt{\mathrm{Pr}})]}{[1 + \Phi(\lambda_* \sqrt{\mathrm{Pr}})]}, \tag{3}$$

where $\lambda_* = {}^3/_2 f_w$.

A comparison of the experimental data with the calculated functions [6, 8] presented in Fig. 2 shows their satisfactory agreement in the region of moderate injection. However, with the injection of nitrogen and carbon dioxide there is a disruption of the monotonic decrease in the convective heat flux to the surface of the cylinder beginning with an injection parameter $f_w = 1$, and an increase in heat exchange is observed with a further increase in the injection intensity.

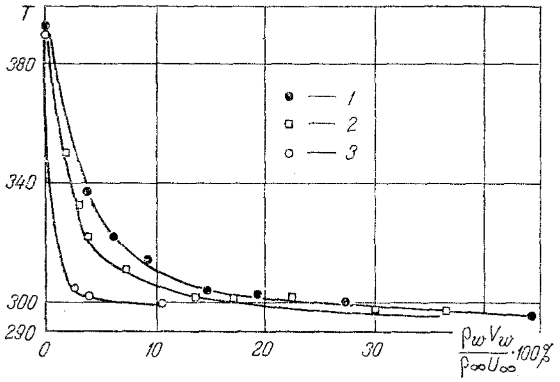

Fig. 1. Dependence of temperature of outer surface at the front critical point of a cylinder placed transverse to the flow on the intensity of injection of: 1) CO_2; 2) N_2; 3) He. T, °K.

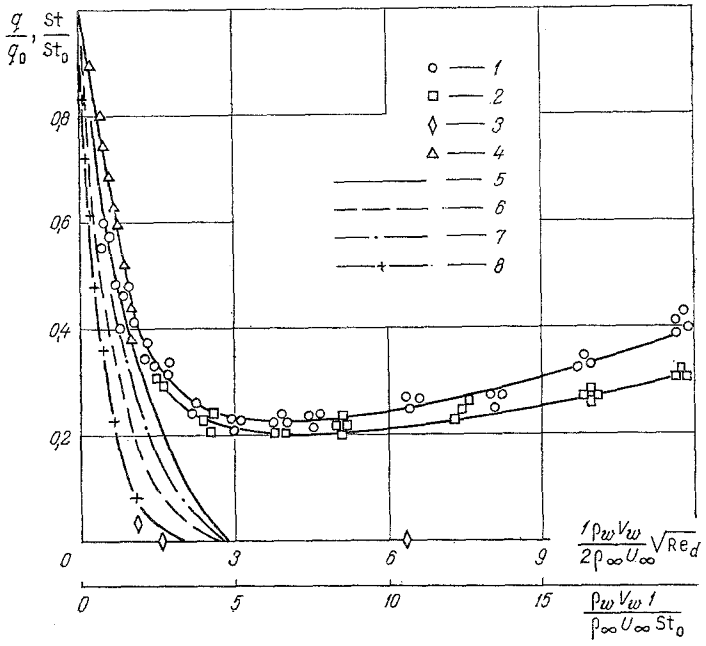

Fig. 2. Effect of injection of N_2, CO_2, and He on heat exchange at the front critical point of a porous cylinder placed transverse to the flow: $U_\infty = 2.65$ m/sec; $Re_d = 3\cdot 10^3$; $T_\infty = 400$°K; 1) CO_2; 2) N_2; 3) He; 4) air [7]; 5) air, calculation by Eq. (3); 6) air [6]; 7) air [8]; 8) helium [8].

Such an anomalous nature of the variation in the heat flux to the wall is due to the disruption of the stability of the laminar mode of flow in the front region of the cylinder. This is illustrated by the interferograms of the nonisothermal boundary layer with the injection of carbon dioxide (Fig. 3).

The sharpness and contrast of the interference bands of the interferograms of the pattern of flow over the cylinder with moderate injection, taken in the light of a helium–neon laser, indicate the absence of pulsations of concentration and consequently the presence of a laminar mode of flow in the front region of the cylinder.

However, with departure from the critical point of the cylinder the sharpness and contrast of the bands were gradually lost, which indicated the appearance of a zone of loss of stability of laminar flow. From the interferogram (Fig. 3, I) illustrating the injection of carbon dioxide at $F = 0.358$ ($f_w = 9.82$) it is seen that even in the zone of the front

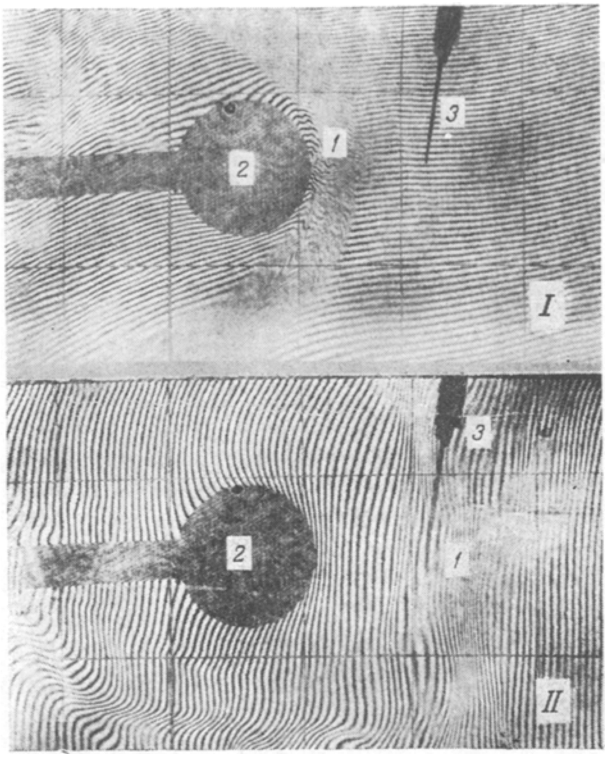

Fig. 3. Interferograms of zone of stream mixing with intense injection of CO_2 and He through porous surface of cylinder: $U_\infty = 2{,}65$ m/sec; $Re_d = 3 \cdot 10^3$; $T_\infty = 400$°K; I) CO_2, F = 0.358; II) He, F = 0.108; 1) zone of stream mixing; 2) porous cylinder; 3) thermoanemometer pickup.

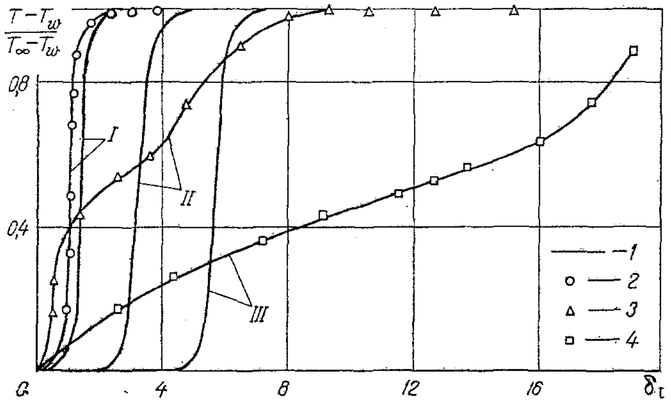

Fig. 4. Temperature distribution in zone of stream mixing at front point of cylinder with injection of CO_2: $U_\infty = 2.65$ m/sec; $Re_d = 3 \cdot 10^3$; $T_\infty = 400$°K; I) F = 0.125; II) 0.28; III) 0.48; 1) calculation [4]; 2,3,4) experiment. δ_t, mm.

critical point of the cylinder one observes the loss of flow stability and the presence of considerable pulsations of the concentrations of the gas mixture.

It should be noted that, in contrast to nitrogen and carbon dioxide, with the intense injection of helium one does not observe a loss of flow stability and with F = 0.04 ($f_w = 1$) the convective heat flux without allowance for the diffusion thermoeffect approaches zero. This is also confirmed by the interferogram (Fig. 3, II) from which one can conclude that the laminar mode of flow of the zone of stream mixing is retained even with very strong injection

(F = 0.108), with the almost isothermal zone of the injected component in the front zone of the cylinder becoming comparable in size with the diameter of the test model.

In the case of the injection of nitrogen and carbon dioxide the region around the cylinder fills with the injected gas, an increase in the rate of injection is accompanied by a decrease in the negative pressure gradient along the mixing zone, and in the limit this case is analogous to the case of the flow of two opposite streams, the mixing zone of which can pulsate. But in the case of the injection of helium very considerable additional negative pressure gradients, which promote the retention of the laminar mode of flow up to the driving off of the boundary layer from the surface of the porous cylinder, develop in the zone of stream mixing owing to the considerable difference in densities of the gases [8].

A comparison of the calculated [4] and experimental temperature profiles in the zone of stream mixing at the front critical point of the cylinder, presented in Fig. 4, shows thei satisfactory agreement in the region of moderate injection (F = 0.125) and a considerable difference with intense injection.

NOTATION

$F = \rho_w V_w / \rho_\infty U_\infty$, $f_w = \frac{1}{2} F \sqrt{Re_d}$, injection parameters; Pr, Prandtl number; q, heat flux, W/m^2, Re, Reynolds number; T, temperature, °K; St, Stanton number; U, longitudinal velocity component, m/sec; ρ, density, kg/m^3; C_p, heat capacity, J/kg·°C; λ, thermal conductivity, W/m·°C; δ, thickness of cylinder wall, m; ε_{re}, reduced emissivity; φ, coefficient of mutual irradiation. Indices: ∞, undisturbed; w, wall; 0, absence of injection; cool, coolant; d, diameter of cylinder.

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