REVIEW

INFLUENCE OF COOLANT SUPPLY ON HEAT TRANSFER AND FRICTION IN A TURBULENT BOUNDARY LAYER

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One of the effective methods of protecting the surfaces of bodies from the action of high temperature gas streams or streams with high kinetic energy is to cool the surface by injecting a liquid or gas coolant into the boundary layer through a porous wall. Then oppositely directed flows exist: a heat flux directed toward the wall from the hot gas, and a flow of coolant from the wall. The coolant absorbs heat from the hot gas, which results in decreased heat flux to the wall. Moreover, injection increases the dynamic and thermal boundary layer thicknesses, and thus further lowers the heat flux to the surface. When the coolant is supplied to the wall at a definite steady rate, it forms a stable protective layer on the surface adjoining the hot stream. Transpiration cooling derives its high efficiency from the developed surface of the porous material with which the coolant comes in contact in passing through the wall. As fast as heat reaches the wall, the coolant absorbs it. For this reason porous cooling has no equal in removing heat from bodies with internal energy sources, e.g., from the heat-generating elements of nuclear reactors.

Experiment shows that the coolant flow rate required to maintain a given wall temperature depends on whether the boundary layer formed on the immersed surface is laminar or turbulent, being considerably less for the laminar case.

In recent years a large number of theoretical and experimental investigations have appeared in the Soviet and foreign literature, dealing with the influence of transpiration on surface friction and heat transfer between a gas stream and a wall. Since these papers employ various assumptions and methods, their results require classification and criticism.

In this review recent theoretical and experimental papers on the influence of coolant supply to a turbulent boundary layer are generalized. Main consideration is given to experimental investigations as being the most consequential. Cases of injection of air and other gases and liquid coolants into the boundary layer of streams with and without longitudinal pressure gradient have been examined. Attention is given to papers which calculate the influence of thermal diffusion and the Dufour effect on heat transfer. Cases of chemical reaction at the wall or in the boundary layer have not been considered.

In theoretical investigations of a turbulent boundary layer on a permeable surface, nonrigorous assumptions similar to those adopted in the case of a turbulent boundary layer on a smooth impermeable surface, are introduced. As regards these assumptions, all the theoretical papers may be divided into two main groups: papers allowing for the influence of coolant injection on the characteristics of the viscous sublayer only, and papers allowing for its influence on the turbulent core of the boundary layer a and using the Prandtl-Karman semi-empirical turbulence theory.

Papers [1] and [2] belong to the first group. They assume that the boundary layer consists of a viscous sublayer and a turbulent core; that coolant injection alters the velocity profile in the sublayer but has no appreciable influence in the core, where turbulent transfer forces predominate; that in the vicinity of the permeable wall the variation of all flow parameters with x is negligibly small in comparison with their variation with y; that the temperature gradient is zero along the porous wall. The calculated relations obtained for friction and heat transfer coefficients overestimate the influence of coolant injection in comparison with those of other authors.

This is explained by the considerable simplification of the true picture of the physical process, the hypothesis of the coolant influence propagating only into the viscous sublayer being particularly suspect. In fact, the transverse mass flow makes the flow turbulent in the wall region, and it may be expected that the viscous sublayer is in general disturbed. The assumption of no heat flux along the wall is also unrealistic. In fact, at the beginning of the porous wall there is a transition line where the temperature distribution changes from that characterizing flow over an impermeable surface to that obtaining over a porous surface. For walls of good conducting material this line turns out to be significant. The theoretical data agree better with the experimental for poor conducting porous materials than for walls of porous copper. The divergence of the theoretical and experimental data decreases with increase of the length of the porous walls.

Solutions which allow for the influence of porous cooling on the turbulent boundary layer core are physically more valid. In a number of papers of this type [3-10], it is assumed that the expression for the shear stress at the wall

$$\tau_w = \tau - \rho_w v_w u \tag{1}$$

is valid for the whole section of the boundary layer.

Assuming, additionally, that the Prandtl mixing length hypothesis is suitable for the solution of this problem, the authors of the above papers obtain analytical expressions for the velocity, and in some cases, for the temperature distribution.

These expressions differ from one another, depending on the assumptions made by the individual authors in order to determine the constants of integration of the boundary layer equations (the quantity u_l/v_* is independent of coolant injection [5–7]; the solution obtained at $v_w = 0$ must give the velocity distribution on an impermeable plate [10], etc.).

Comparison of the data of these theoretical methods with experimental data shows that there is considerable disagreement. This is explained, on the one hand, by the fact that, as shown in [11], equation (1) is satisfied only in the immediate vicinity of the wall, and its extension to the whole layer leads to serious error, and, on the other hand, to the fact that in the conditions examined the mixing length varies with the transverse coordinate. Moreover, it is assumed in the theory that the flow of coolant in the direction normal to the wall is uniformly distributed over the porous wall surface. It is observed experimentally that the coolant leaves the surface as numerous individual jets. Therefore, for a given coolant flow rate, other conditions being equal, the cooling is in fact less effective than theory would indicate, and the measured values of wall temperature are correspondingly higher.

It is suggested in [12] that blowing decreases the stability of the laminar sublayer and that conditions at the porous wall approximate to those in the mixing region of a free turbulent jet. Assuming that the velocity profiles at different sections of the boundary layer are similar, and using the Prandtl mixing length hypothesis (with l = const over the section of the layer), the author obtained a dependence for the skin friction coefficient on the intensity of blowing in the case $v_w/u_1) Re_x^{0.2}$ = const.

It is also assumed in [13–15] that blowing disturbs the sublayer, causing the flow picture to approximate to that when $Re \to \infty$, where the limiting turbulent boundary layer relations derived by the authors are applicable. Taking various laws of gas density distribution in the boundary layer, the authors obtained dependences of the friction and heat transfer coefficient distributions on the coolant supply rate which confirmed the known test data. In particular, values were obtained for the limiting flow rates of various coolants which lead to contractions of the boundary layer. The test data in these regions are insufficient, however, to verify the analytical results.

The authors of [16] have extended the previously obtained semi-empirical methods of calculating the turbulent boundary layer on an impermeable wall to the case of flow over a porous curved surface. A two-layer flow model was assumed, with arbitrary constant values of the Pr and Le numbers.

The distributions of total heat content, relative mass concentration of injected substance, and shear stress in the laminar sublayer and turbulent core are expressed in the form of polynomials whose coefficients are determined from the usual conditions at the wall, sublayer edge, and outer edge of the boundary layer. The unwieldy expressions for velocity profiles in semilogarithmic coordinates are well approximated by a straight-line equations. The result is a resistance law in the form

$$u_1 \delta^{**}/\nu_w = \overline{D} \sqrt{\overline{\rho_w}/\overline{\rho_1}}\, l^{(E/\overline{U}_w)\varkappa\zeta}. \tag{2}$$

Here $\zeta = u_1/v_*$; $\overline{D}$, E, $\overline{U}_\omega$ are complex functions evaluated from the known parameters of the flow.

An additional relation between δ^{**} and ζ is given by the integral momentum equation. The resulting dependences of friction coefficient on intensity of transverse mass flow and longitudinal pressure gradient agree satisfactorily with the known experimental data. A method of calculating heat transfer in the conditions examined is also put forward.

An investigation was made in [17] of the turbulent boundary layer on a porous wall in the presence of longitudinal pressure gradients. A two-layer flow model was taken. The velocity profile in the viscous sublayer, obtained with account for v_W and dp/dx, are compared with the velocity profile in the turbulent core

$$u/u_1 = (y/\delta)^{m\left(v_w,\, \frac{dP}{dx}\right)}. \tag{3}$$

The method of [17] may be used to estimate the friction on a porous surface with coolant injection in a turbulent boundary layer with negative longitudinal pressure gradient. It must not be extended, however, to the positive pressure gradient region, since the supposition that the velocity profile is uniparametric is not valid there.

In [18–22] an examination is made of turbulent flow in porous tubes and plane channels with suction and blowing. By means of the usual semi-empirical methods, the authors obtained expressions for the velocity and temperature distributions, as well as calculation formulas for the friction and heat transfer coefficients for injection of homogeneous coolants. In these papers the important deduction is made that the mixing length depends on the intensity of blowing.

A review is given in [23] of the work of foreign authors on porous cooling.

In order to create a reasonable theory of the influence of blowing on surface friction and heat transfer, we need to accumulate experimental data on the influence of rate of intake of coolant on the shear stress at the wall, the velocity profile of the main flow, and the laminar sublayer thickness, under various gasdynamic flow conditions. Known experimental investigations of coolant injection into a turbulent boundary layer do not give the necessary data for a broad theoretical generalization. The main object of many experiments is to establish the relation between temperature of the porous material surface and coolant mass flow rate at various flow velocities and temperatures of the hot gas, as well as to determine the friction and heat transfer coefficients at the wall as functions of coolant flow rate under various flow conditions.

The integral momentum equation is widely used to determine local values of the friction coefficient on the surface of a porous wall. From measured distributions of velocity and temperature at various sections of the boundary layer on the porous surface, as well as the main gas stream temperature, and the flow rate of hot gas and porous wall surface coolant, corresponding values of the momentum thickness are determined. From graphs of variation of the momentum thickness, and velocity, temperature, and density of the main gas stream, and of the wall temperature along the immersed surface, values are determined for the derivatives of the quantities mentioned with respect to the longitudinal coordinate, and then local values of the friction coefficient at various relative flow rates of the injected coolant are determined from the integral momentum equation. Local values of the heat transfer coefficient are determined in a similar way from the integral energy equation.

In such a method of determining the friction and heat transfer coefficients, graphical differentiation of the original test parameters must be used, which leads to substantial errors in calculation. The situation is further complicated by the fact that with contemporary measurement techniques it is difficult to obtain reliable data on velocity and temperature in the immediate vicinity of the wall, and, when different gases are injected, on the distributions of density, viscosity, and thermal conductivity through the boundary layer. Direct measurement of friction forces on the wall is attended by great technical difficulties, and also is not free from appreciable errors.

The majority of investigators, in processing their test data, determine heat transfer coefficient values from the heat balance equation. It is usually assumed that under steady flow conditions all the heat reaching the wall from the main gas stream goes to heat the injected gas from the temperature at which it arrives at the porous wall to that of the immersed wall surface. In this case the heat flux is expressed by the equation

$$q_w = c_{p_w} \rho_w v_w (T_w - T_c). \qquad (4)$$

The dimensionless heat transfer coefficient is

$$\mathrm{St} = c_{p_w} \rho_w v_w (T_w - T_c)/c_{p_1} \rho_1 u_1 (T_e - T_w). \qquad (5)$$

The assumption of equal temperatures of the injected gas leaving the porous wall and of the external wall surface requires experimental verification in each specific case, since the heat transfer between gas and wall inside the porous material is influenced by the porosity, length of capillaries, ratio between capillary length and diameter, and coolant flow rate. In particular, this condition is satisfied in the experimental work of [24] with $\delta \geq 8$ mm. Heat transfer inside the porous material has been examined in [25, 26].

The beginning of the experiment, as in many actual processes, proceeds under unsteady conditions, and the heat balance equation inside the porous wall has the form [86]

$$\lambda_w \frac{\partial^2 t}{\partial y^2} - c_{p_w} \rho_w v_w \frac{\partial t}{\partial y} = c_w \frac{\partial t}{\partial \tau}, \qquad (6)$$

where y is the transverse coordinate, calculated from the lower wall surface; c_ω is the heat capacity of unit area of the wall. The boundary and initial conditions for (6) are

$$\lambda_w \frac{\partial t(0, \tau)}{\partial y} = c_{p_w} \rho_w v_w [t(0, \tau) - t_c],$$

$$\lambda_w \frac{\partial t(\delta, \tau)}{\partial y} = q, \quad t(y, 0) = t_c, \qquad (7)$$

where δ is the thickness of the porous wall. A long time is required to achieve small enough values of

$$\frac{\partial t}{\partial \tau} \left(\frac{\partial t}{\partial \tau} \to 0 \right).$$

The operating time of high-power aerodynamic installations may not be long enough to achieve steady conditions. In this case it may prove very effective to use the regular thermal regime method which has been used with success to determine values of the heat transfer coefficient on impermeable surfaces.

We shall examine the main experimental work of Soviet and foreign authors.

Data are obtained in [27] on the dependence of the heat transfer coefficient on the intensity of air injection into an air stream inside a tube. From the heat balance in an element of the boundary layer consisting of turbulent core and viscous sublayer, a relation is obtained between the temperatures of the wall, the injected air, the free stream, and the velocity of injections:

$$\frac{T_w - T_c}{T_1 - T_c} = \frac{r}{\exp(r\Phi) + 1 + r}, \qquad (8)$$

where

$$r = (T_l - T_\omega)/(T_1 - T_w), \quad \Phi = v_w c_p/\alpha.$$

To evaluate r the hypothesis is made that the distributions of velocity and temperature are similar. Then Prandtl's data may be used, according to which for $\mathrm{Re} \approx 3 \cdot 10^5$ $u_l/u_1 = 2.26\mathrm{Re}^{-0.125} \approx 0.5$. On the graph $(T_\omega - T_c)/(T_1 - T_c) = f(\Phi)$ the experimental points give good confirmation of (8) with $r = 0.5$.

The authors of [28] investigated heat transfer with injection of hydrogen and nitrogen into the boundary layer of a porous tube along which passed the combustion products of liquid and gaseous fuel. The experimental data were generalized in the form of the dependence

$$\vartheta = \frac{T_1 - T_w}{T_w - T_c} = f\left(\frac{\rho_w v_w}{\rho_1 u_1}\right). \quad (9)$$

The analytical expression for this relation took the form

$$\vartheta_w = 117\,\mathrm{Pr}\,\frac{\rho_w v_w}{\rho_1 u_1}\left(1 - 2.73\,\frac{c_{p_w}}{c_{p_1}}\right). \quad (10)$$

When injecting hydrogen and nitrogen, we have from (10), respectively,

$$\vartheta_w = 4050\,\frac{\rho_w v_w}{\rho_1 u_1}, \quad \vartheta_w = 348\,\frac{\rho_w v_w}{\rho_1 u_1}. \quad (11)$$

The authors' experimental data confirm (11) only for small blowing values. At $\rho_\omega \nu_\omega / \rho_1 u_1 > 0.001$ (for hydrogen) and $\rho_\omega \nu_\omega / \rho_1 u_1 > 0.004$ (for nitrogen), the experimental points lie below the theoretical lines of (11).

Results are given in [29, 30–37] of experimental investigations of friction and heat transfer with injection of air, helium, nitrogen, and other gases into the turbulent boundary layer of subsonic and supersonic air flows on a flat plate and cone. In the experiments the temperature of the immersed plate did not vary along the length. To achieve this it was made in sections and the flow rate of cooling gases was controlled according to the longitudinal coordinate.

It has been established that the recovery factor decreases as blowing increases, and the more so, the lighter the injected gases. The transition from a laminar to a turbulent boundary layer has also been examined. On a porous cone in the absence of blowing, transition occurred earlier than on a smooth impermeable cone, but blowing of helium and air did not change the position of the transition point. This is apparently due to the fact that blowing thickens the boundary layer and makes the flow less stable, while cooling stabilizes the boundary layer.

The heat transfer coefficient was determined from the heat balance equation. To determine the friction coefficient, Preston's method [38] was used. It was established experimentally that there is a logarithmic part of the velocity profile, described in coordinates $u/u_1 = f(\lg \mathrm{Re}_y)$ by the straight-line equation

$$u^+/C = A \lg (y^+/C) + B, \quad (12)$$

where

$$C = \sqrt{c_{f_0}/c_f}, \quad A = 5.6, \quad B = 4.9.$$

From pressure tube measurements of dynamic head at a fixed point in the logarithmic part of the velocity profile, and from the known parameters of the injected gas and of the stream gas, the friction coefficient is determined using the equation

$$A \lg (c_f/c_{f_0}) = (u - u_0)/u_1 \sqrt{c_{f_0}/2}\,. \quad (13)$$

This method of determining c_f is unreliable, since it is based on readings of a probe at one fixed location. The conversion of these readings to c_f is based on a number of assumptions. Moreover, as shown in [39], the boundary layer over a porous surface is nonuniform in width. The authors of [39] conducted tests with injection of helium, air and Freon 12 into the turbulent boundary layer formed by air flowing over a porous fiberglass cone. The skin-friction coefficient was determined from the drop in dynamic pressure along the immersed model. The friction coefficient data of [39] proved to be in excess of those of other authors (Figs. 2, 4). It is evident that the drop in dynamic pressure in the flow over the model examined is determined not only by surface friction, but also by internal friction, depending on the geometry of the model and other factors.

The author of [40] investigated the turbulent boundary layer of an incompressible fluid on a porous flat plate with air injection. The friction coefficient was determined by Stanton tubes, using the Preston method. The velocity profiles were measured at several sections of the boundary layer, and it was shown that blowing alters them considerably. The data of [40], processed in the form of the relation $c_f/2\,\mathrm{Re}_x^{0.2} = f(\rho_\omega \nu_\omega/\rho_1 u_1\,\mathrm{Re}_x^{0.2})$, considerably overestimate the effectiveness of blowing, in comparison with the data of other authors. One cause of this is the unreliability of the method of determining c_f.

An investigation was made in [41] of the influence of injecting nitrogen, argon, and hydrogen, on heat transfer in a supersonic flow of air over a porous plate, and over the front face of a porous cylinder aligned with the flow. The heat transfer coefficients were determined from the heat balance equation. The test data were generalized in the form of the dependence of the distribution of the porous surface temperature and heat transfer on relative mass flow rate of the injected gases.

An investigation was made in [24, 42–44] of the subsonic turbulent boundary layer on a porous surface, with injection of air, helium, carbon dioxide, and Freon 12. The tests were made in a plane channel, in the lower wall of which a porous copper plate was embedded. The side walls could be moved, allowing positive and negative longitudinal pressure gradients to be set up. The velocity and temperature distributions were measured at several sections along the plate. Heat transfer coefficients were determined from the heat balance equation and from the integral energy relation. No influence of longitudinal pressure gradient on heat transfer was observed in the range of parameters examined. The integral energy relation may be written in the form

$$\frac{d\,\mathrm{Re}_\varphi}{dx} + \mathrm{Re}_\varphi\,\frac{1}{(T_e - T_w)}\,\frac{d}{dx}(T_e - T_w) = \mathrm{Re}_L\left(\mathrm{St} + \frac{c_{p_w}\rho_w v_w}{c_{p_1}\rho_1 u_1}\right). \quad (14)$$

Using the experimentally established dependence of heat transfer coefficients on rate of injection of the various gases, equation (14) may be reduced to a differential equation of first order in Re_φ, integration of which offers a simple method of calculating the thermal boundary layer.

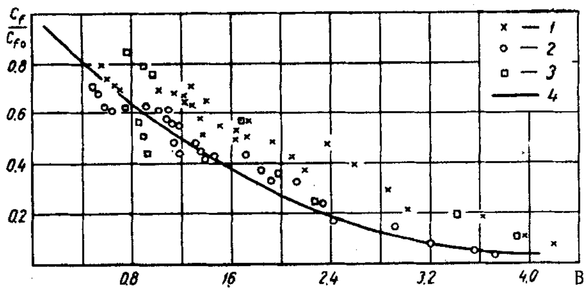

Fig. 1. Influence of temperatue factor on skin friction with air injection [$B \equiv (\rho_w v_w/\rho_1 u_1)(2/c_{f0})$]. 1) test values of c_f [75]; 2) c_f [75], corrected for nonisothermal conditions by means of equation (15); 3) data of [77]; 4) data of [10].

Skin-friction coefficients have been determined from the integral momentum relation, and also by a method which is essentially as follows. Using semi-empirical turbulence theory and a two-dimensional flow model, an equation is obtained for the velocity distribution in the form $u/u_1 = f(y; \bar{T}_\omega; R'/R_1; \rho_\omega v_\omega/\rho_1 u_1; c_f)$. Then, for the values $\bar{T}_\omega$; R'/R_1; $\rho_\omega v_\omega/\rho_1 u_1$ obtaining in the tests, in coordinates $u/u_1 = f(\lg Re_y)$, a theoretical net of velocity profiles is constructed with c_f as parameter. The experimentally measured velocity profiles are plotted on this net. From coincidence of the given profile with one of the theoretical ones, the local value of the friction coefficient in the section examined is determined.

Since the experiments were conducted with different temperature factors, corrections for lack of isothermal conditions were applied in generalizing the test data on friction coefficients. The relation obtained in [45] was used:

$$c_f = c_f' \left(\frac{\sqrt{\bar{T}_w} + 1}{2} \right)^2, \tag{15}$$

where c_f' is the experimental value of the friction coefficient; c_f is the friction coefficient reduced to isothermal conditions.

It may be seen from Fig. 1 that when the above correction is included, the test data for air injection on a plate [75] show good agreement with the known results of isothermal flow.

For a laminar boundary layer in flows with longitudinal pressure gradient, the velocity profile obtained by the Karman-Pohlhausen method depends uniquely on the parameter $B(\rho_\omega v_\omega/\rho_1 u_1, dP/dx)$. Since it is impossible to obtain an analytical expression for the velocity profile in the turbulent boundary layer in such circumstances, it is assumed that the characteristics of the layer will depend on some parameter $K(\rho_\omega v_\omega/\rho_1 u_1, dP/dx)$, similar in structure to parameter B.

In the papers cited the boundary layer shape factor was obtained, which takes into account simultaneously the influence of longitudinal pressure gradient and transverse mass flow on the characteristics of the turbulent boundary layer.

$$K = 2\frac{\rho_w v_w}{\rho_1 u_1} Re_\Theta^{0.25} - \frac{\Theta}{u_1}\frac{du_1}{dx} Re_\Theta^{0.25}. \tag{16}$$

The test data, processed in the form of the relation $\zeta = f(K)$, confirm the effectiveness of the parameter K. Friction data for a porous plate ($dp/dx = 0$; $\nu_\omega \neq 0$), and for diffusers with impermeable walls ($\nu_\omega = 0$; $dp/dx \neq 0$), processed in the form of relation $\zeta = f(K)$, fall on a single curve [24, 43] ($\zeta = c_f/2\, Re_\Theta^{0.25}$).

Thus, equation (16) confirms the conclusions of [46] and other authors, viz., that the influence of gas injection on the boundary layer characteristics is similar to that of a positive longitudinal pressure gradient. For a turbulent boundary layer with longitudinal pressure gradient and coolant injection, the integral momentum relation may be written in the form

$$\frac{1}{Re_L}\frac{d}{dx}(Re_\Theta^{1.25}) = 1.25[\zeta - (H+1)\Gamma + J], \tag{17}$$

where

$$J = \frac{\rho_w v_w}{\rho_1 u_1} Re_\Theta^{0.25}.$$

It has been shown from experimental data that the right side of (17) is a linear function

$$F\left(\frac{\rho_w v_w}{\rho_1 u_1};\ \frac{dp}{dx}\right).$$

This fact may be used to reduce (17) to a differential equation of first order in Re_Θ, integration of which yields a simple method of calculating the dynamic boundary layer in the conditions examined.

In [46–48] an investigation is made of the turbulent boundary layer on a flat plate with injection of air and other gases into a subsonic and supersonic air stream. The tests were conducted on a porous plate with a working area of 49 cm^2 (monel metal with 40% porosity), mounted flush with the lower wall of a wind tunnel working section. The temperature and velocity profiles were measured over the boundary layer (two independent methods: pitot tube and interferometer), together with the concentration of injected carbon dioxide (by means of sampling tubes and subsequent gas analysis). For various blowing values, it was found that the velocity and relative concentration profiles were approximately similar. The velocity profiles with identical blowing param-

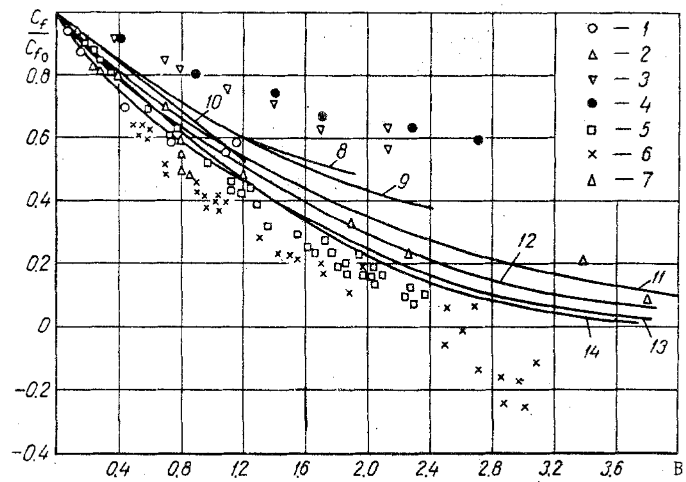

Fig. 2. Influence of air injection on friction: $[B \equiv (\rho_w v_w/\rho_1 u_1) \times \times (2/c f_0)]$: 1) [30];($M_1$ = 0.3); 2) [39] (M_1 = 0.7); 3) [39] (M_1 = 3.21); 4) [39] (M_1 = 4.3); 5) [42]; 6) [40]; 7) [78]; 8) [79]; 9) [80]; 10) [12]; 11) [7]; 12) [17]; 13) [10]; 14) [45].

eter and different Mach numbers M_1 (M_1 = 0 and 2.5) were similar.

The author of [46] proposed an approximate method of calculating skin friction and heat transfer with air injection, based on the fact that the influence of blowing on the boundary layer characteristics is similar to the influence of a positive longitudinal pressure gradient. The momentum equation

$$\frac{d\Theta}{dx} = \frac{c_f}{2} + \frac{\rho_w v_w}{\rho_1 u_1} \tag{18}$$

is reduced to the form

$$\frac{d}{dx}\left(\Theta \mathrm{Re}_\Theta^{0.25}\right) = 1.25(\zeta + J). \tag{19}$$

It was shown experimentally that the right side of (19) may be approximated by the equation of the straight line

$$F(J) = 1.25(\zeta + J) = aJ + b$$

with values of the constants a = 0.91; b = 0.016. Thus (19) may be integrated and a solution obtained in the form

$$\left(\frac{a}{b}J_x\right)^5 = \frac{5}{b}\left[\frac{1}{4}\left(\frac{a}{b}J\right)^4 - \frac{1}{3}\left(\frac{a}{b}J\right)^3 + \right.$$

$$\left. + \frac{1}{2}\left(\frac{a}{b}J\right)^2 - \frac{a}{b}J + \ln\left(\frac{a}{b}J + 1\right)\right],$$

where

$$J_x = \frac{\rho_w v_w}{\rho_1 u_1}\mathrm{Re}_x^{0.2}.$$

Subsequent calculation is similar to that for a turbulent boundary layer with longitudinal pressure gradient on an impermeable surface [49]. Linear empirical dependences of the heat transfer coefficient on intensity of injection of various coolants are proposed. The conclusion is reached that compressibility has no influence on heat transfer with blowing, but the data of other authors do not support this conclusion. At large coolant flow rates on an impermeable wall, tests by the author showed the formation of a protective layer of injected gas, further increase of its flow rate having little effect.

Study of the influence of coolant injection on the total resistance of a body in a supersonic flow is important, since in this case, in parallel with decreased friction drag, there must be increased wave drag due to boundary layer thickening. It was shown in [50] that, in a laminar supersonic flow over a cone, the total drag dropped considerably, while injection of air proved more effective than injection of helium. Data of this kind have not been published for turbulent flow.

The most effective means of protecting a surface from heating is evaporative cooling; a liquid is injected through a permeable surface and vaporizes in the channels of a porous body, absorbing a large amount of heat and entering the flow as a vapor. The effects of gas injection and evaporative cooling on the heat transfer process in the boundary layer are similar. However, in this case, the effectiveness is questionable, since, according to the data of a number of experimental papers, the heat flux to the wall increases when there is evaporation from the surface.

Based on an analysis of papers [52–55], the author of [51] came to the conclusion that intensification of heat transfer with evaporative cooling does not conform to reality, since the experimental work on which this conclusion was based was either incorrectly interpreted or involved large errors.

Intensified heat transfer was noted in [56–59] as a result of evaporation from the surface. An examination was made in [56] of evaporation of liquids (water, acetone, benzene, butyl alcohol) from a free surface, covered with a special grid to avoid wave motion of the liquid. It was established that the intensity of mass transfer was influenced by the humidity of the main stream and the molecular weight of the evaporating liquid. The relative humidity of the flow was φ = 10–80%. The influence of evaporation from the surface is allowed for very well by introducing the mass transfer number Gu into the parametric equations for calculating heat and mass transfer.

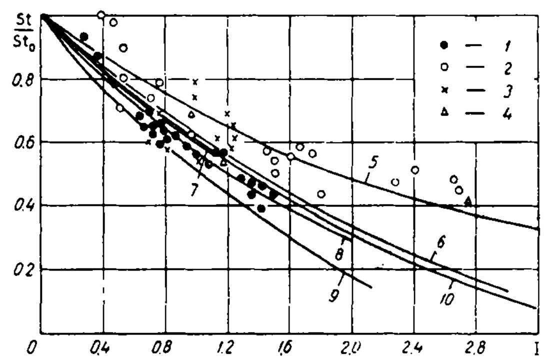

Fig. 3. Influence of air injection on heat transfer: $[I \equiv (\rho_W v_W/\rho_1 u_1)(1/St_0)]$: 1) [42]; 2) [27]; 3) [78]; 4) [35]; 5) [29]; 6) [7]; 7) [12]; 8) [10]; 9) [27]; 10) [45].

Parametric equations were obtained in [57] for calculating heat and mass transfer with evaporation of liquid from a porous ceramic plate. Evaporation is allowed for through the number Bu or the ratio T_d/T_W, where T_d and T_W are the dry and wet bulb air temperatures.

An investigation of evaporative cooling in flows over bodies of various shapes (sphere, cone, and disk) was made in [58], and the data processed in the form of criterial relations. It was found that the influence of mass transfer on heat transfer depends on body geometry.

An investigation was made in [59] of evaporative cooling of bodies of various shapes (sphere, cone, disk, and cylinder) in steady turbulent flow, and in flow oscillating at a frequency of 47 cps. Increased heat transfer of 30–70% was noted, in comparison with dry flow, the increase differing for the different shapes. In these papers the heat transfer coefficient was determined from the heat balance equation and the measured flow rate of coolant.

In investigations of evaporative cooling [60–66], on the other hand, a relative reduction in heat transfer was noted with increase of mass transfer. Papers [60, 61] are devoted to an investigation of evaporative cooling heat and mass transfer on a porous copper plate in a plane channel with water injection. The heat transfer coefficient was determined from the heat balance equation. The data were processed in criterial form. Heat transfer to the wall decreased with increased intensity of evaporation. The tests were carried out with and without a depressed evaporation zone.

Evaporation of water from a porous ceramic made according to the method described in [62] was investigated in [63]. Evaporation took place without depression into the body of the plate. The velocity and temperature fields were measured at several sections along the surface, and integral characteristics computed. The heat transfer coefficient was determined from the heat balance equation, and from integration of the energy relation. The skin-friction coefficient at the wall was calculated with the aid of the solution of the integral momentum relation. The case of a longitudinal pressure gradient was also investigated, and the experimental results were generalized in the form of dimensionless relationships. The conclusions reached in the paper were: with increase of transverse mass flow the relative heat transfer coefficient falls, while in the conditions of the experiment the pressure gradient has little influence on heat and mass transfer.

As was shown in [60–63], the introduction into the dimensionless equation of the parameters Gu, K or the parameter $b = \rho_\omega v_\omega/\rho_1 u_1$ makes satisfactory allowance for the influence of mass transfer on heat transfer.

In [64, 65] an investigation was made of skin-friction, heat transfer and mass transfer in a flow of hot air over the free surface of a highly viscous solution of phenol-formaldehyde resin in ethyl alcohol. The heat transfer and friction coefficients were determined from the integral energy and momentum relations. The heat transfer coefficient was also determined from the heat balance equation, and the mass transfer coefficient was found. The data were processed in the form of the relations $St/St_0 = f(b_T)$; $c_f/c_{f_0} = \varphi(b)$, and the dimensionless expression for the diffusion Stanton number was found.

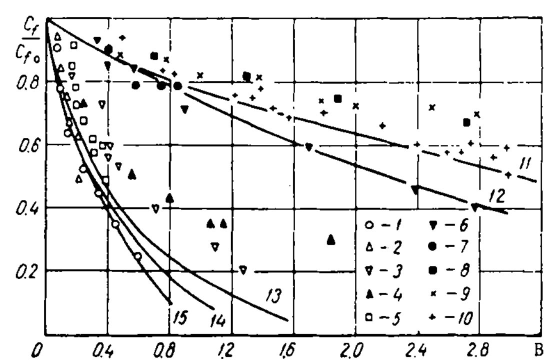

Fig. 4. Influence of injection of helium and Freon 12 on friction: $[B \equiv (\rho_W v_W/\rho_1 u_1)(2/c_{f_0})]$: 1–4) (helium)—see Fig. 1; 5) (helium)—[42]; 6–9) (Freon 12)—see 1–4 of Fig. 1; 10) (Freon 12)—[42]; 11) [13]; 12) [7]; 13) [7]; 14) [13]; 15) [17].

These relations were used to solve the integral momentum and energy equations for the boundary layer, on whose solution was based a proposed method of calculating friction, heat transfer, and mass transfer for the conditions examined. Measurement of the fields of velocity, temperature, and concentration of ethyl alcohol vapor at sections of the boundary layer indicated that these fields are noncongruent.

Experimental data were presented in [66] on evaporative cooling of a copper plate, using water and ethyl alcohol as coolants. The evaporation zone was depressed 2–3 mm into the plate. The heat transfer coefficient was determined from the heat balance and from the integral energy equation. Heat transfer decreased as the intensity of evaporation increased. The data on cooling with ethyl alcohol were in good agreement with the results of [64].

An analysis was given in [67] of heat and mass transfer with surface evaporation. The conclusion was reached that appreciable reduction of heat transfer was possible only at large heat loads, which do not occur in drying processes. The author of this paper showed that the influence of mass transfer on heat transfer may be neglected in drying. It was established that with a depressed evaporation surface the heat transfer coefficient is increased. It was shown that because of the dynamics of the processes of sorption and desorption, it was possible for drops of liquid to be carried into the boundary layer and subsequently evaporated; due to processes of nucleate condensation, some of the liquid droplets may be carried away from the evaporation surface.

In the final evaluation of experiments on evaporative cooling, it is extremely complex to account for all the noted factors, and this may explain the contradictory nature of the attested results.

The conclusion was reached in [68], based on a comparison of experimental and theoretical data on heat transfer with injection of coolant into a laminar boundary layer, that the systematic discrepancy between the experimental and theoretical data with helium injection can only be explained by the influence of thermal diffusion and the Dufour effect. The paper gave an analytical method of calculating the influence of thermal diffusion and the Dufour effect on heat transfer. A further study of this question was made in [67–72], in which an analytical determination was made of the influence of the above factors on heat transfer and friction in a laminar boundary layer. It was established that the Dufour effect has a great influence on heat transfer, while the influence of thermal diffusion on friction is small. The Dufour effect was most significant for injection of light gases (H_2; He), its influence being small for blowing of heavy gases. With injection of light gases the Dufour effect increased the heat flux to the wall, decreasing it with heavy gas injection. To allow for the Dufour effect, it was suggested that the difference $(T_e - T_\omega)$ be used instead of $(T_1 - T_\omega)$ in the equation for the heat transfer coefficient, where T_e is the equilibrium wall temperature. Here the dependence of T_e on the intensity of blowing of the various coolants is determined analytically.

An attempt was made in [70] to determine experimentally the dependence of T_e on the blowing of helium through the wall of a cylinder washed with a transverse flow of air. The results obtained agree well with the analytical solution of [68].

An investigation of the influence of the Dufour effect on the equilibrium wall temperature for a longitudinal turbulent flow over a cylinder and helium injection was performed in [73, 74]. It was shown in [73], that the Dufour effect may appreciably increase the equilibrium temperature even in turbulent flow. At moderate blowing intensity, the discrepancy between the flow temperature and the adiabatic wall temperature reached 40° C. In [74] the dependence of equilibrium wall temperature on blowing intensity was obtained. The test data corrected to allow for this dependence are in good agreement with the theoretical solution (15) (Fig. 4).

Results are presented in [75, 76] of an experimental determination of the dependence of equilibrium temperature on the rate of injection of different gases (helium, argon, carbon dioxide, Freon 12) into a turbulent boundary layer of air on a plate.

It is shown in [71, 72] that the Dufour effect also occurs in evaporative cooling. There the injection of water vapor into a boundary layer increased the equilibrium temperature. It was noticed that the flow temperature and the Re number influenced the dependence of equilibrium temperature on blowing intensity. However, there are no theoretical or experimental data to reflect this dependence in turbulent flows.

It may be seen from an analysis of [68–76], that the Dufour effect, which occurs with injection of coolant other than the main stream, has an appreciable influence on the heat transfer process. The relative influence of the diffusion heat flux on the total heat flux increases with increase of injected coolant. With decrease of convected heat flux, the relative influence of diffusion heat flux on the total heat flux also increases.

A comparison is given in Fig. 2 of the theoretical and experimental data of the various authors on the effect of blowing air into the turbulent boundary layer of an air stream. It can be seen that the experimental data are quite scattered, the data of [40] being the lowest. At $b > 2$ even negative values of the friction coefficient are obtained, which is not very probably, since $c_f < 0$ indicates reverse flow at the wall. The data of [39], obtained at $M_1 = 3.21$ and $M_1 = 4.3$, lie above the others, indicating that blowing efficiency diminishes as M_1 increases.

Figure 3 shows the data of various authors on the effect of blowing air on the heat transfer coefficient. The scatter of the experimental points falls within the limits of the possible accuracy of experiment at the present time. The data of all the investigators indicates that the heat transfer coefficient decreases as the intensity of blowing increases.

A comparison is made in Fig. 4 of the effects of injecting helium and Freon 12 on the surface friction coefficient. It can be seen that blowing of helium is considerably more effective than blowing Freon 12. As M_1 increases (data of [39]), the effectiveness of blowing decreases.

It can be seen from Fig. 5 that helium injection

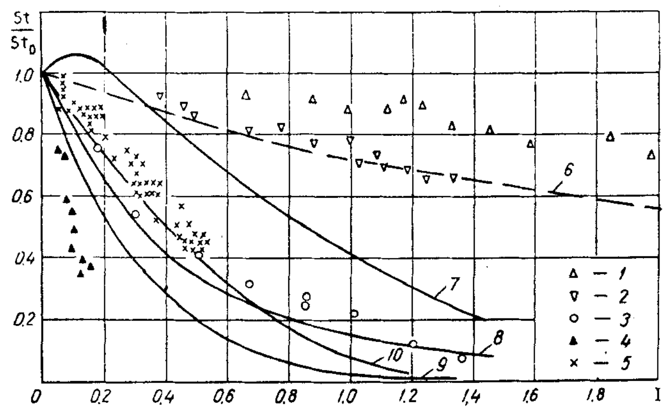

Fig. 5. Influence of injection of helium, carbon dioxide, and Freon 12 on heat transfer [$I \equiv (\rho_w v_w/\rho_1 u_1)(1/St_0)$]: 1) (Freon 12)—[42]; 2) (CO_2)—[42]; 3) (helium)—[35]; 4) (He)—[42]; 5) (Freon 12)—[7]; 6) (helium)—[74]; 7) [80]; 8) [7]; 9) [77]; 10) [15].

gives the greatest decrease in heat transfer coefficient, but the data of various authors on the influence of helium injection show considerable divergence. It is not possible to give a comprehensive explanation of the causes of this divergence, since not all of the papers include a description of the experimental procedure or the processing and generalization of the results.

From the analysis performed the following conclusions may be drawn:

1. Injection of coolants into the boundary layer decreases friction and heat transfer on the surface washed by the gas stream, and injection of gases with lower molecular weight and greater heat capacity gives a greater effect. It may be considered that the discrepancy in the data of the various authors on the influence of blowing on friction falls within the present limits of experimental accuracy.

2. At large blowing parameters, a protective film of injected coolant is formed on the permeable wall, and further increase of the blowing rate is ineffective. In this range of flow rates, however, there are not many experimental data; moreover, the theoretical solutions do not usually extend to this region.

3. A longitudinal pressure gradient, and also the Reynolds number, exert a notable influence on the coolant flow rate and the wall temperature. Under a negative pressure gradient the intensity of heat transfer at the wall increases by almost a factor of two in comparison with a flat plate. The presence of even a small positive pressure gradient leads to an appreciable reduction in heat flux in comparison with the flat plate. The surface friction coefficient varies similarly, the only difference being that it is more sensitive to a longitudinal pressure gradient than is the heat flux.

4. The influence of injection of gases on the characteristics of the dynamic boundary layer is similar to the influence of a positive pressure gradient.

5. The data of different authors on the influence of compressibility on blowing effectiveness are conflicting. There are few reliable data on the influence of the temperature factor on friction and heat transfer in blowing.

6. Since porous materials are usually rough, the effect of roughness on blowing efficiency should be investigated.

7. There are few reliable data on the influence of blowing on the transition from a laminar to a turbulent boundary layer.

8. The experimental data for injection of liquids are very conflicting, this being due to the complexity of the heat balance in such experiments.

9. The assumptions about similarity of temperature, velocity, and concentration fields, made in the theoretical solutions, are based on insufficient experimental material. In addition to data confirming these assumptions [47, 48, 52], there are papers where it is demonstrated that there is no such similarity [64, 65].

10. For multicomponent boundary layers with relatively small convective heat fluxes, neglect of the diffusion heat flux may lead to large errors. There have been almost no experiments to determine these heat fluxes.

11. There is a need to generalize existing experimental data on the influence of coolant thermophysical properties on the effectiveness of blowing, as well as to accumulate experimental data at high values of the parameters M_1, Re, T_1; $\rho_\omega v_\omega/\rho_1 u_1$.

NOTATION

x, y—longitudinal and transverse coordinates; u, v—longitudinal and transverse components of flow velocity; t, T—temperature; $\overline{T}_\omega = T_\omega/T_1$—temperature factor; R—gas constant; τ—friction shear stress, time; c_f—dimensionless friction coefficient; St—Stanton number. Subscripts: 1—parameters at outer edge of boundary layer; w—parameters at wall: 0—parameters on an impermeable plate; a prime—denotes parameters of the injected gas in the boundary layer.

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