HYDRAULIC DRAG AND LOCAL HEAT TRANSFER WITH BLOWING INTO THE CHANNEL OF AN IMPACT JET SYSTEM

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The authors give theoretical relations for the coefficients of hydraulic drag of jet and channel flows and a semiempirical method of calculating local heat transfer on the wall of a planar channel with blowing by a system of impact jets.

We consider a flow scheme typical for deflector blades of gas turbines with transverse flow of cooled air. In such blades to intensify heat transfer on the cooler side they use jet blowing on the internal surface of the profile via apertures in the partially or fully perforated walls of the deflector [1]. Here the hydraulic drag and the local heat transfer depend not only on the geometric parameters of the jet system, but also on the intensity of the removal flow, which either already exists in the channel ahead of the jet blowing zone, or is formed because of the air blown by the jets. In this sense the flow scheme investigated is called jet-channel, and the pressure losses are calculated, respectively, for jet and channel flows as if in evacuating hydraulic tees [2].

The analysis performed in [3] shows that there is no theoretical solution to the problem of local heat transfer in the conditions considered, and the available experimental information is directed to individual aspects of the problem (without a unified physical approach). The hydraulic characteristics of jet-channel systems, and also the influence of the removal flux on local heat transfer coefficients have been investigated only sporadically [4-7]. In constructing correlations of heat transfer results practically all the authors used the so-called jet approach, in which the governing parameters in the Nusselt and Reynolds numbers are d and $(\rho\bar{v})$; the influence of the geometric parameters of the jet systems here are taken into account by appropriate simplexes (see Table 13 in [3]).

Below we suggest a semiempirical method, based on unique physical postulates, for analyzing a broad class of topics associated with the hydraulic and heat transfer characteristics of jet-channel systems. It has generally been checked by comparison with the test data of other authors.

1. Pressure Losses. We use the model of [4] and replace discrete blowing into the channel with velocity ρv in separate series of jets by a uniformly distributed blowing with velocity $\rho v^* = \bar{f}\rho v$, where $\rho v = \sqrt{2\rho(p_0 - p)}$. Then the continuity equation for a volume element of liquid in the channel can be written in the form $\rho v^* = h[d(\rho u)/dx]$. From these equations we obtain an expression for calculating the change of static pressure in the channel along the blowing zone

$$p = p_0 - \frac{1}{2\rho}\left(\frac{h}{\bar{f}L\mu_0}\right)^2\left(\frac{d(\rho u)}{d\bar{x}}\right)^2. \tag{1}$$

Since the unknown quantity is also a velocity (ρv), we add the momentum equation

$$dp = \rho u^2 - \rho(u + du)^2 \tag{2}$$

to Eq. (1). From Eqs. (1) and (2) we obtain

$$\frac{d^2(\rho u)}{dx^2} - A^2(\rho u) = 0, \tag{3}$$

where $A = \sqrt{2}\mu_0 f_0/f_c$. Since $\mu_0 = (\rho\bar{v}^2/2\Delta p)^{0.5}$, the parameter A is the ratio of the dynamic head at the exit from the planar channel to the pressure losses in the apertures of the perforation, and is the modified Euler number $A = Eu_{j,c}^{-0.5}$, describing hydrodynamic similarity of discharge flows. With the boundary conditions

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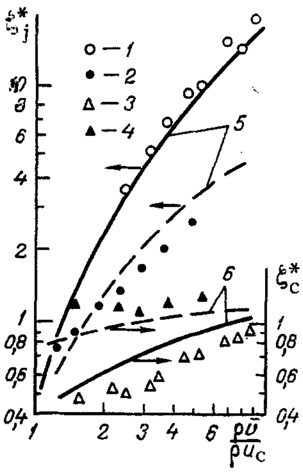

Fig. 1

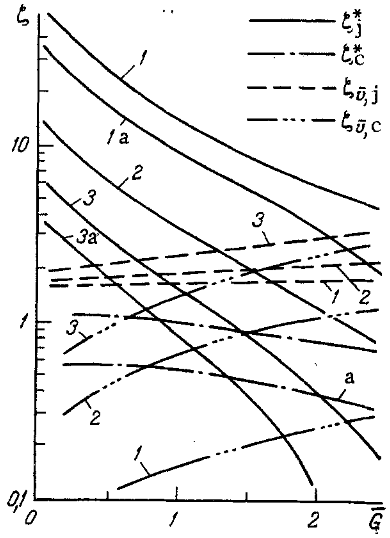

Fig. 2

Fig. 1. Comparison of calculated hydraulic drag coefficients in jet and channel flows with the test data of [5]: 1, 3) A = 0.205; $\bar{h}$ = 3.2; 2, 4) A = 0.524; $\bar{h}$ = 1.25; 1, 2) ζ_j^*; 3, 4) ζ_c^*; 5) using Eq. (6a); 6) using Eq. (5a).

Fig. 2. Hydraulic drag coefficients as a function of the intensity of the removal flow $\bar{G}$ and the similarity number A for jet-channel systems, h/L = 0.06: 1) $\bar{f}$ = 0.01; A = 0.184; 2) 0.02 and 0.376; 3) 0.03 and 0.553; curves 1a, 3a, and a were calculated from the data of [2].

$$x = 0 \quad \rho u = G_c/f_c,$$
$$x = L \quad \rho u = (G_0 + G_c)/f_c$$

the solution of Eq. (3) will be

$$\rho u = \rho\bar{v}\frac{A}{\sqrt{2}\mu_0 \operatorname{sh} A}\{(1+\bar{G})\operatorname{sh} A\bar{x} + \bar{G}\operatorname{sh}[A(1-\bar{x})]\}. \tag{4}$$

Finding the values of $d(\rho u)/d\bar{x}$ for $\bar{x}$ = 0 and 1 from Eq. (4) and substituting them into Eq. (1), we obtain the static pressure in the channel at the beginning and end of the jet blowing zone, and therefore, also the pressure losses in the jet and channel flows.

Finally, for the coefficients of hydraulic drag the following relations were obtained:

for the channel

$$\zeta_c^* = \frac{2\Delta p_c^*}{\rho u_r^2} = \frac{1+3\bar{G}}{(1+\bar{G})^2}, \tag{5a}$$

$$\zeta_{\bar{v},c} = \frac{2\Delta p_c}{\rho\bar{v}^2} = \frac{A^2}{\mu_0^2}(1+2\bar{G}); \tag{5b}$$

for the jet flow

$$\zeta_j^* = \frac{2\Delta p_j^*}{\rho u_r^2} = \frac{2j_j(\bar{G})}{(1+\bar{G})^2\operatorname{sh}^2 A} - 1, \tag{6a}$$

$$\zeta_{\bar{v},j} = \frac{2\Delta p_j}{\rho\bar{v}^2} = \frac{A^2}{\mu_0^2\operatorname{sh}^2 A}j_j(\bar{G}), \tag{6b}$$

where $j_j(\bar{G})^2 = \bar{G}^2 + (1+\bar{G})^2\operatorname{ch}^2 A - 2\bar{G}(1+\bar{G})\operatorname{ch} A$. Relations (5) and (6) include the main regime and geometry parameters and can be used to analyze the pressure losses in jet-channel systems.

In the results obtained the condition $\bar{G} = 0$ corresponds to jet blowing through the wall of a planar channel with a damped entrance section. In this case $j_j(\bar{G}) = \mathrm{ch}^2 A$, and therefore

$$\zeta_j^{*0} = \frac{2}{\mathrm{th}^2 A} - 1. \tag{7}$$

The test data of the authors for a broad range of variation of the geometric parameters of jet-channel systems [3] confirm the relation derived, Eq. (7). Analysis shows that as the number A increases the coefficient of hydraulic drag $\zeta_{\bar{v},c}$ in the conditions examined increases either due to increase of velocity in the channel u_b with a decrease of its height, or due to a decrease of $\rho\bar{v}$ with an increase of the area of the apertures of the perforation f_0.

The variation of the calculated coefficients ζ_j^* and ζ_c^* with blowing into a planar channel of a three-series system of circular jets with an initial removal flow of intensity $\bar{G} = 0.5$-6 (Fig. 1) agrees satisfactorily with the test data of [5] for the values $\bar{h} = 1.25$; some divergence between the test and calculated values of pressure losses is observed in the planar channel for $\bar{h} = 3.2$, that is evidently associated with increased error of measurement of small pressure drops with increase of h.

An interesting special feature of the solutions obtained for the jet flow is the practical similarity with respect to the number A of the dependence of the relative variation of the quantity $\tilde{\zeta}_j^*$ on the intensity of the removal flow. Here in the range of numbers $A \leqslant 0.9$ most mportant in practice, the calculated values of $\tilde{\zeta}_j^*$ for $\bar{G} < 2$ are approximated by the relation

$$\tilde{\zeta}_j^* \simeq (1+\bar{G})^{-2}. \tag{8}$$

For $A \geqslant 1.5$ the influence of the removal flow on the total pressure loss is somewhat attenuated.

Since the general analysis of the influence of the main regime and geometric parameters of jet-channel systems on the hydraulic drag coefficients is given first, Fig. 2 shows the calculated curves for the case when the number A varies only due to an increase of the diameter of the apertures of the perforation (i.e., of the parameter f_0), other conditions being unchanged. The drag coefficient ζ_j^* decreases as the removal flow increases; for the value $A \simeq 0.8$-0.9 even in the range $\bar{G} < 3$ the total pressure losses in the jet flow are negative, i.e., energy is pumped from the removal flow to the jet. However, as can be seen from Fig. 2, the quantity $\zeta_{\bar{v},j}$, according to static pressures, increases with increase of $\bar{G}$ and the number A (when h is decreased).

As the intensity of the removal flow increases the coefficient ζ_c^* varies insignificantly, and here calculations show that the geometrical parameters of the jet-channel system do not influence it noticeably — in this sense the dependence $\zeta_c^*(\bar{G})$ is universal. The static pressure losses in the channel, as one should expect, increase with increase of $\bar{G}$ and A.

For comparison Fig. 2 shows curves for the intake tees, calculated from the data of [2]. With the same characteristics of variation of ζ with respect to total pressure, the numerical values of the drag coefficients of the tees are lower by a factor of about 5 than for the jet-channel systems.

Data analogous to those shown in Fig. 2 can be obtained also when the number A is varied due to channel height, flow coefficient of the apertures, or number of apertures. However, in all cases, as follows from Eqs. (5) and (6), the same A numbers will correspond to the same curves $\zeta(\bar{G})$. Finally, it should be noted that, since the length of the blowing zone does not appear in the relations obtained for ζ, the longitudinal pitch of the series of apertures for blowing does not influence the drag coefficients (to an accuracy on the order of the pressure loss due to flow friction on the channel wall). This is confirmed by the test data of [5] for three-series blowing, when the value of ζ_j^* increases by approximately 20% for a change of $\bar{s}_x$ in the range 7-11.

<u>2. The Jet Blowing Parameter.</u> In the assumed model of the jet-channel system the local velocity of blowing of the jets through the series of apertures is determined from the continuity equation $\rho v^* = h[d(\rho u)/dx]$, taking account of Eq. (4). Since references [3, 4, 6, 7] give quite a detailed analysys of the influence of regime and geometric parameters, including the intensity of the removal flow, on the distribution of velocities of both flows along the blowing zone, we shall limit ourselves here to some brief comments.

First, in contrast with the determination assumed in [4] of the local blowing parameter as the quantity $(\rho u)_{i-1}/(\rho v)_i$, in the method proposed below for calculating the heat transfer

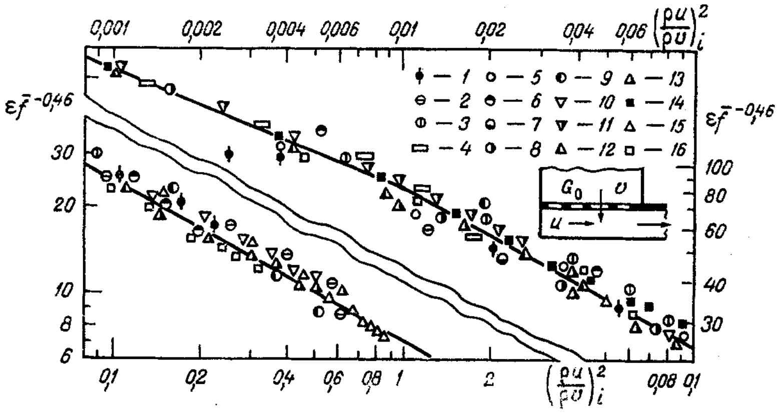

Fig. 3. Correlation of the data of local heat transfer at the wall of a planar channel with blowing of a system of jets, $\bar{G}$ = 0: 1) $\bar{f}$ = 0.0224; $\bar{h}$ = 2.5; Re_d — 10; 2) 0.0505; 1.67; $8.1\cdot10^3$; 3) 0.0127; 3.33; $6.6\cdot10^3$; 4) 0.0127; 7.67; $4.2\cdot10^3$ (1–4 are the data of the present authors); 5) $\bar{f}$ = 0.02; $\bar{h}$ = 1; $Re_d = 6\cdot10^3$; 6) 0.0195; 3.9; $3.9\cdot10^3$; 7) 0.005; 3.5; $4.28\cdot10^3$; 8) 0.011; 3.83; $4\cdot10^3$; 9) 0.042; 2.7; $7.8\cdot10^3$; (5–9 are the data of [8]); 10) $\bar{f}$ = 0.0196; $\bar{h}$ = 1; 11) 0.0196; 6; 12) 0.0196; 3; 13) 0.0098; 3 (9–13 are the data of [9] for $Re_d = 10^4$); 14) $\bar{f}$ = 0.0196; $\bar{h}$ = 3; 15) 0.0392; 1; 16) 0.0392; 3 (14–16 are the data of [6] for $Re_d = 10^4$). The curve is from Eq. (11).

we use the ratio of the velocities, reduced to the coordinate x:

$$\left(\frac{\rho u}{\rho v}\right)_i = \frac{1}{\sqrt{2}\mu_0}\,\frac{(1+\bar{G})\,\mathrm{sh}\,A\bar{x}+\bar{G}\,\mathrm{sh}\,[A(1-\bar{x})]}{(1+\bar{G})\,\mathrm{ch}\,A\bar{x}-\bar{G}\,\mathrm{ch}\,[A(1-\bar{x})]}. \tag{9}$$

With this determination of the blowing parameter we can generalize the calculation method also to the condition $\bar{G}$ = 0, since the ratio ρu/ρv can be found for the first series of jets for G_c = 0.

Second, it should be noted that the uniformity of blowing of jets in series is higher, the smaller is the similarity number A; here the jet flow predominates above the channel flow, and usually $(\rho u/\rho v)_{max} \leqslant 0.2$–0.3 for $\bar{G}$ = 0. As the intensity of the removal flow increases the nonuniformity of blowing increases, but not significantly. For example, for A ≃ 0.5 and $\bar{G}$ = 1, the ratio ρu/ρv varies from 0.8 to 1.2 along the blowing zone. Jet-channel systems having A ≃ 1 are characterized by large nonuniformity of blowing; for $\bar{G}$ = 0 the minimum and maximum values are 0.8 and 1.4, respectively; for $\bar{G}$ = 1 the same values are 0.2–0.3 and 1.8–2. Finally, for A ⩾ 2 the removal flow deforms the distribution of $\rho v/\rho\bar{v}$ to such an extent that even for $\bar{G}$ = 1 the first series of apertures is in fact blocked, and the mass flow rate G_0 is distributed over the remaining roughly 2/3 of the length of the perforation zone.

These laws remain unchanged independently of what caused an increase of the similarity number A — an increase of the open area of the perforation, or a decrease of the channel height.

3. Local Heat Transfer. References [3, 7] first proposed a correlation of the experimental data on local heat transfer to the wall of a channel over which there is blowing by a system of impact jets with $\bar{G}$ = 0 in accordance with the so-called channel approach. The novelty is that the heat transfer intensification on the surface is evaluated in comparison with the local heat transfer coefficients which would have occurred on the wall of a planar channel with a variable (i.e., an increasing) mass flow rate of air along the length x. In any section of the blowing zone the ambient value of mass flow rate is assumed equal to the flow rate of the blown impact jets at the section x. Then with Pr = 0.71 we can write

$$\varepsilon = \frac{\mathrm{Nu}\mu^{0,8}}{0.018\,(\rho u)^{0,8}\,(2h)^{0,8}}, \tag{10}$$

where the flow mass velocity in the channel is found from Eq. (4).

A subsequent analysis of the data of different authors [3, 7] permitted a correlation for the case $\bar{G}$ = 0 for the type $\varepsilon = \varepsilon(\bar{f};\ x/2h)$. However, the simplex x/2h is proportional to the quantity $A\bar{x}$, which, according to Eq. (9), is defined and is the local blowing parameter.

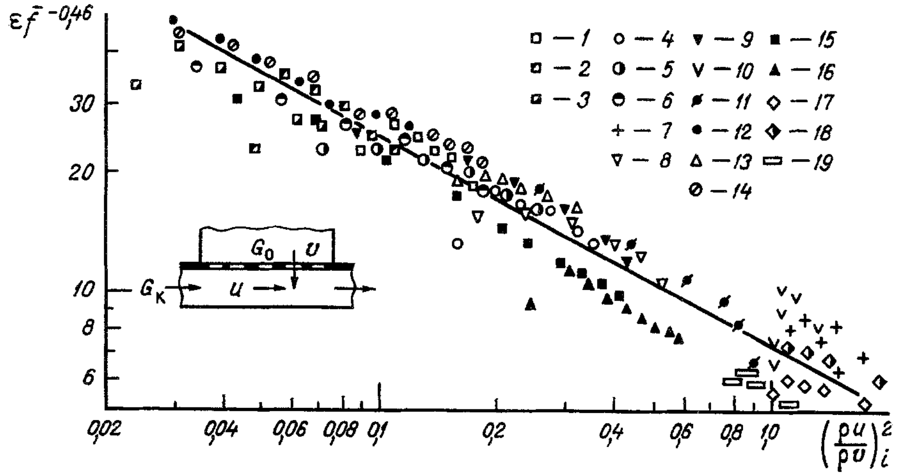

Fig. 4. Correlation of the data on local heat transfer on the wall of a planar channel with blowing of a system of jets, $\bar{G} \neq 0$: for $\bar{G}$ = 1.91; 2) 1.31; 3) 0.88 (for $\bar{f}$ = 0.0127; $\bar{h}$ = 7.67; $\bar{s}_x = \bar{s}_y$ = 8); 4) $\bar{G}$ = 0.93; 5) 0.59; 6) 0.37 (for $\bar{f}$ = 0.0127; $\bar{h}$ = 3.33, $\bar{s}_x = \bar{s}_y$ = 8); 7) $\bar{G}$ = 1.38; 8) 0.46; 9) 0.31 (for $\bar{f}$ = 0.0224; $\bar{h}$ = 2.5; $\bar{s}_x = \bar{s}_y$ = 6); 10) $\bar{G}$ = 0.31; 11) 0.13 (for $\bar{f}$ = 0.0505; $\bar{h}$ = 1.67; $\bar{s}_x = \bar{s}_y$ = 4); 1-11) are the data of the authors; 12) $\bar{G}$ = 0.2; 13) 0.5; 14) 1.02 (for $\bar{f}$ = 0.0196; $\bar{h}$ = 3, $\bar{s}_x$ = 5; $\bar{s}_y$ = 8); 15) $\bar{G}$ = 0.5; 16) 1.01; (for $\bar{f}$ = 0.0392; $\bar{h}$ = 1, $\bar{s}_x$ = 5; $\bar{s}_y$ = 4); 17) $\bar{G}$ = 0.2; 18) 0.47; 19) 1.0 (for $\bar{f}$ = 0.0392; $\bar{h}$ = 3; $\bar{s}_x$ = 5, $\bar{s}_y$ = 4); 12-19) data of [6]. The curve is from Eq. (11).

Therefore a correlation which takes into account the local flow hydrodynamics in the jet-channel system could describe intensification of local heat transfer without reference to the fact that the channel flow is formed by the operating jets of air ($\bar{G}$ = 0) or that the initial removal flow ($\bar{G} \neq 0$) is superimposed on it.

The results of correlating the data of [6, 8, 9] and the present investigation on local heat transfer in the conditions $\bar{G}$ = 0 are shown in Fig. 3, and on Fig. 4 in the conditions $\bar{G} \neq 0$. All the data used were obtained in experimental facilities which had plug-in electro-calorimeters positioned across the channel, and each of these had blowing by 1-6 series of jets. In [6, 9] the number of series of jets was unchanged and equal to the number of electro-calorimeter units. In the tests of ITTF of the Academy of Sciences of the Ukrainian SSR a heat transfer surface of length 132 mm was formed by the edges of 6 copper units of size 20 × 20 × 150 mm with thin thermal insulation spacers between them. Thus, in the present work the local heat transfer coefficient was determined as an average heat transfer coefficient in the transverse direction occurring on an area of extent 20 mm in the direction of the x axis. Each unit had blowing by two transverse series of jets. The other regime and geometric parameters of the jet-channel systems investigated were as follows: A = 0.16-1.5; $\bar{f}$ = 0.0127-0.0505; $\bar{h}$ = 1.67-7.7; $Re_c = 3.7\cdot10^3$-$3.9\cdot10^4$, $\bar{G}$ = 0.13-1.9; μ_0 = 0.76-0.84.

In reducing the test data the heat transfer coefficients were referred to the temperature difference between the surface of the calorimeter unit t_w and the mixture of jet and channel flows t_i at the center of the i-th volume of liquid. The temperature t_i was determined with allowance for heating of the flow by the amount of heat Q_i transmitted by the i-th unit.

$$t_i = \left\{\left[(t_{i-1}+\vartheta_{i-1})\left(G_c+\sum_1^{i-1} G_i^{(c)}\right)+t_0 G_i^{(c)}\right]\Big/\left(G_c+\sum_1^{i} G_i^{(c)}\right)\right\}+\vartheta_i,$$

where

$$\vartheta_i = Q_i/2c_p\left(G_c+\sum_1^{i} G_i^{(c)}\right).$$

The physical properties of air were determined at the temperature $(t_w + t_i)/2$.

As can be seen from Figs. 3 and 4, the data of the different authors can be approximated satisfactorily by unique correlations both with an initial removal flow present, and with $\bar{G}$ = 0;

$$\varepsilon \bar{f}^{-0.46} = c\,(\rho u/\rho v)^{-m}, \tag{11}$$

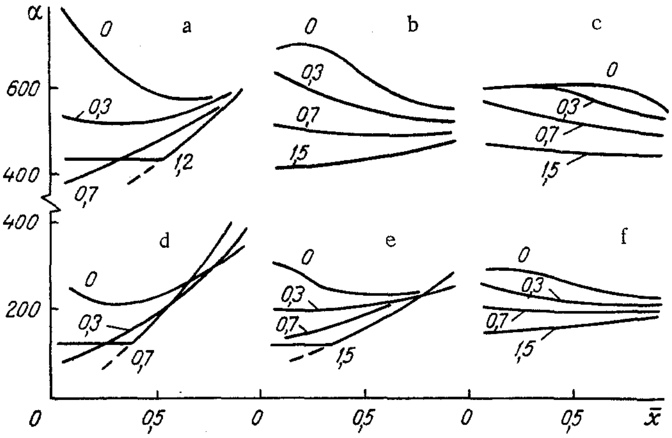

Fig. 5. Influence of the intensity of the removal flow G and the similarity number A on the distribution of local heat transfer coefficients on the wall of a planar channel in the blowing zone of a system of jets, $Re_c = 1.95 \cdot 10^4$; a-c) $\bar{f} = 0.01$; $Re_d = 1.4 \cdot 10^4$; a) A = 0.8; h/L = 0.014; b) 0.4; 0.028; c) 0.188; 0.060; d-f) $\bar{f} = 0.05$; $Re_d = 6.28 \cdot 10^3$; g) A = 1.79; h/L = 0.032; h) 0.94; 0.060; e) 0.47; 0.12. The numbers on the curves are values of $\bar{G}$. Values of α are in $W/(m^2 \cdot K)$.

where for $10^{-3} < (\rho u/\rho v)^2 \leqslant 0.1$, c = 13.4; m = 0.8; for $0.1 < (\rho u/\rho v)^2 < 2$ c = 7.2; m = 1.07. With allowance for the correlation of the data of [6] the correlation (11) is valid for A = 0.1-2.5; $\bar{f}$ = 0.01-0.05; $\bar{h}$ = 1-7; $\bar{s}$ = 4-8; $\bar{G}$ = 0-2; $Re_c = 2 \cdot 10^3 - 3.9 \cdot 10^4$.

The single flow model used to calculate the pressure losses in the flows, the velocity ratio $\rho u/\rho v$, and the local heat transfer coefficients indicate uniformity of the processes of interaction of the flows with blowing of jets into the channel both with the initial removal flow and without it, when the longitudinal flow is formed only as a result of the blowing of the jets. In this sense the approximation of Eq. (11) is universal, and the parameter A should undoubtedly be regarded as the governing number of the hydrodynamic similarity of the scheme of mixed flows investigated.

From the data obtained we can establish the character of the influence of the basic geometric parameters of the jet-channel systems and the intensity of the removal flow on the distribution and level of local heat transfer on the wall of a channel on which there is blowing of impact jets. For greater clarity Fig. 5 shows a comparison performed on absolute values of local heat transfer coefficients with an unchanged value of G_0 (or $Re_c = 1.95 \cdot 10^4$), and also with the width of a planar channel and the length of the perforation zone kept constant. On Fig. 5 the value of A decreases from left to right because of increase of h with f_0 = const; from top to bottom the value of A increases due to increase of f_0. It can be seen that for $\bar{f}$ = 0.01 the heat transfer coefficients are larger by roughtly a factor of 3 than for $\bar{f}$ = 0.05; with an increase of the intensity of the removal flow the variation of α is larger, the higher is the similarity number A (Fig. 5a, d).

For specific values of the initial removal flow regimes are possible for which for a certain length of the blowing zone of the jets the flow still remains the properties of channel flow, and therefore there is no intensification of heat transfer at the channel wall (Fig. 5a, d, e). The theoretical analysis and also the data of [9] show that such regimes set in for $A \leqslant 1$ in conditions where $A\bar{G} \approx 1$. If A = 1.5-2.5, then the values of α for the initial removal and jet flows are still equal for $A\bar{G} \approx 0.5$. Consequently, calculations using Eq. (11) must be compared with the value of α_c occurring for a given G_c, and in the case $\alpha_i < \alpha_c$ we must take $\alpha_i = \alpha_c$, which was done in the construction of Fig. 5a, d, e.

Equation (11) describes the experimental data with a root mean square error not exceeding 15%. However, in the region $\rho v/\rho v \to 1$, the deviation of the test points increases, since the limit of the assumptions made in the theoretical model begins to appear. In reality for $\rho u/\rho v \geqslant 1$ the mass flow coefficients of the apertures do not remain constant, but sharply decrease [4, 10], causing a substantial redistribution of ρv along the blowing zone. In addition, when there is interaction of the jets with the flow there is an increase of the other surface forces (because of friction at the walls, flow over the jets, mixing of the jets with the flow), which one should take into account in the momentum equation, along with acceleration of the flow in the channel due to blowing of the jets.

NOTATION

d, diameter of apertures of the perforation; h, δ, L, height, width of the planar channel, and length of the jet blowing zone, respectively; $\bar{h} = h/d$, $f_c = h\delta$; f_0, total area of the apertures; $\bar{f} = f_0/L\delta$, relative area of the perforations; x, coordinate directed along the axis of the planar channel, and reckoned from a point displaced upstream by a distance $s_x/2$ from the axis of the first series of jets; s_x, x_y, longitudinal and transverse pitch of the jets; $\bar{s}_x = s_x/d$, $\bar{s}_y = s_y/d$, $\bar{x} = x/L$; ρu, ρv, mass velocity of the removal and jet flows, respectively; v, average velocity of the jets over the performation area; μ_0, average mass flow coefficient of the apertures over the perforated area; G_c, mass flow rate of the initial removal flow; G_0, mass flow rate of the jet flow; $\bar{G} = G_c/G_0$, intensity of the removal flow; G_i, ambient mass flow rate of one of the flows in the i-th volume of the planar channel; Δp_c, drop of static pressures in the channel between the sections x = 0 and x = L; Δp_j, drop of static pressures in the jet flow between the reservoir and the channel section x = L; Δp_c^*; Δp_j^*, the same with respect to total pressures; $\bar{\zeta}_j^* = \zeta_j^*/\zeta_j^{*0}$, relative coefficient of hydraulic drag of the jet flow; $Re_d = \rho\bar{v}d/\mu$, jet Reynolds number; $Re_j = 2G_0/\delta\mu$; $Re_c = 2G_c/\delta\mu$; $Re = 2\rho uh/\mu$; $\varepsilon = Nu/\tilde{N}u$, coefficient of intensification of local heat transfer; $Nu = 2\alpha h/\lambda$, Nusselt number; $\alpha = Q_i/(t_w - t_i)$, local coefficient of heat transfer; $\tilde{N}u = 0.018\ Re^{0.8}$; t, temperature; λ, thermal conductivity; μ, dynamic viscosity; c_p, specific heat; ϑ_i, flow heating. Subscripts: j, jet flow; c, channel flow; w, wall; i, ambient value of the i-th volume of the channel.

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