FEATURES OF TURBULENT HEAT TRANSFER ON PERMEABLE SURFACES

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The well-known fact of intensification of heat transfer in strongly accelerated flows because of destruction of the viscous sublayer by substance injected through a porous surface is analyzed experimentally.

The "laminarization" effects resulting in an abrupt reduction in the intensity of heat elimination are a characteristic feature of turbulent, accelerated, near-wall flows with the acceleration parameter $K=(\nu/U_\infty^2)/(dU_\infty/dX)>10^{-6}$. As is shown in [1], under these conditions, the number St can be diminished several times as compared with the case of gradient-free flow around a plate with the same number Re_T^{**}. The necessity of somehow preventing the reduction in the heat-transfer coefficients during realization of strongly accelerated turbulent flow regimes in their operating channels occurs in a number of heat-transfer and other power apparatus. Different turbulizers in the form of diaphragms, steps, etc. are not ordinarily applied in these cases since they raise the total hydraulic drag of the whole system substantially.

The problem is posed in this paper of studying the structure of accelerated, turbulent, near-wall flow to determine the causes of the reduction in heat-elimination intensity and to find the most optimal means to elevate it. To this end, a detailed investigation was performed of the turbulence structure in the expansion domain of the flow. The experimental investigation was executed in an open-type wind tunnel whose diagram and description of the working section are represented in [2, 3]. All the measurements were performed by the "hot-wire" method by using the thermoanemometer equipment DISA-55M. Standard one-wire and X-shaped two-wire sensors were used as was also a specially fabricated three-wire sensor with a wire thickness of 2.5 μm. The fundamental parameters and integrated characteristics of the boundary layer under investigation are presented in Table 1.

The distribution of the number St as a function of Re_T^{**} presented in Fig. 1 shows that in the "asymptotic," accelerated, turbulent, near-wall flow domain (the sections 982-1460 mm), the magnitudes of the heat-elimination coefficients are substantially below the values obtained from the "stationary" heat-transfer law. Analysis of the results of investigating the fluctuation structure permitted the assumption that diminution of the heat flux under the mentioned flow conditions is determined principally by the growth in the viscous sublayer thickness, which is, as is known, the fundamental thermal resistance between the wall and the turbulent flow. Longitudinal velocity fluctuations in the near-wall domain of the flow under investigation in the gradient-free (the section 737 mm) and strongly accelerated (the section 1460 mm) domains of the flow around a plate (Fig. 2) indicate the growth of the viscous sublayer thickness in the accelerated stream. Moreover, the laminarization effects that appear with diminution in the intensity of the fluctuation characteristics also result in a reduction in the turbulent heat flux level (Fig. 3), which also specifies a drop in the heat-elimination coefficients.

The information obtained permits the assumption that growth of the viscous sublayer thickness must be hindered to intensify heat transfer under the mentioned flow conditions. It is well known that the simplest means to solve this problem is either elevation of the surface roughness to dimensions commensurate with the viscous sublayer or organization of a transverse mass flow through a porous surface on the surface. The former of the two means mentioned causes, in addition to an increase in the heat-elimination coefficient, growth of the surface friction coefficient C_f, which diminishes the efficiency of heat-transfer intensification measures. The latter path of organizing porous injection, on the other hand,

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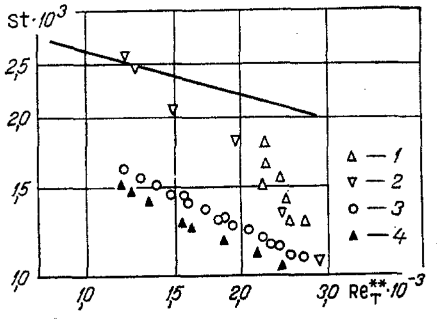

Fig. 1

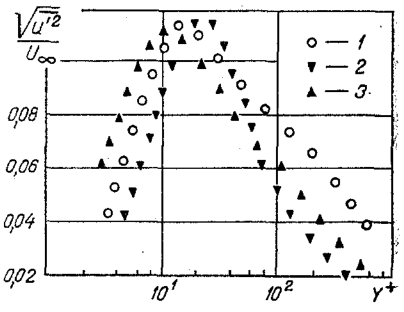

Fig. 2

Fig. 1. Distribution of the number St (the curve is St = $0.0144\mathrm{Re}_\mathrm{T}^{**-0.25}$): 1) b = 0.0033, K = $2.35\cdot10^{-6}$; 2) 0 and $2.35\cdot10^{-6}$, respectively; 3) 0.004 and 0 [1]; 4) 0.004 and $2.6\cdot10^{-6}$ [1].

Fig. 2. Longitudinal velocity fluctuations in the near-wall domain: 1) b = 0, K = 0; 2) 0 and $2.35\cdot10^{-6}$; 3) 0.0033 and $2.35\cdot10^{-6}$.

TABLE 1. Fundamental Accelerated Flow Parameters

X, mm	U_∞, m/sec	δ, mm	H	$C_f\cdot10^3$	Re**	St·10³	δ_T, mm	$\mathrm{Re}_\mathrm{T}^{**}$
737	6,70	19,1	1,42	4,54	986	2,63	24,9	1224
862	7,01	22,5	1,38	4,60	1035	2,51	23,6	1123
982	7,64	23,0	1,35	4,53	1000	2,50	23,3	1219
1212	10,65	16,9	1,34	4,47	801	1,87	23,4	2043
1332	13,40	14,6	1,36	4,30	754	1,36	23,0	2540
1460	19,47	11,0	1,38	4,20	767	1,07	18,4	3131
1950	35,84	12,5	1,65	1,42	3318	1,07	15,8	7134
2120	29,34	18,9	1,85	0,94	5839	1,14	21,8	7200

ordinarily results in a reduction of the surface friction coefficients, and thereby intensifies the heat transfer still more. At the same time, it is known that a transverse mass flow during gradient-free flow around a plate causes a drop in the heat-elimination coefficients, which confirms the necessity for a more detailed investigation of the fluctuating interaction mechanisms to clarify the possibility of utilizing porous injection in order to intensify the heat transfer in strongly accelerated, turbulent, near-wall flows.

To this end, the structure of the turbulent boundary layer on a permeable surface (Table 2) was investigated in detail. Analysis of the results obtained confirmed the diminution of the viscous sublayer thickness (see Fig. 2), as had been hypothesized. Reasons for the increase in the fluctuating characteristics on the permeable surface can be illustrated by the example of the production of the kinetic energy of turbulence. It is known [2] that the component characterizing the production of turbulence energy in strongly accelerated flows, which equals $-(\overline{u'^2} - \overline{v'^2})dU/dX - \overline{u'v'}dU/dY$, can, because of "normal" stresses, exceed the production due to Reynolds stresses, and can thereby transform the whole complex of turbulence energy production into the Stokes term, which indeed determines the diminution in the fluctuating characteristics level. The transverse flow being injected diminishes the difference $\overline{u'^2} - \overline{v'^2}$ by turbulizing the near-wall domain, whereupon the role of the "normal" stresses in the production of turbulence energy ceases to be "laminarizing" (Fig. 4).

Another characteristic feature of the flow on permeable surfaces is due to the presence of two opposite flows, the injected and the fundamental, caused by the two-dimensional nature of the flow in an accelerated boundary layer. Interaction of these flows results in the appearance of velocity fluctuations v' that are not correlated with both longitudinal fluctuations in the velocity u' and with fluctuations in the temperature θ' because of the different mechanisms of generation. The validity of this assumption also confirms the analysis of the correlation coefficient distributions $R_{\overline{UV}}$ and $R_{\overline{V\theta}}$ (Table 3), indicating a diminution of the interrelation between the near-wall and outer boundary layer domains.

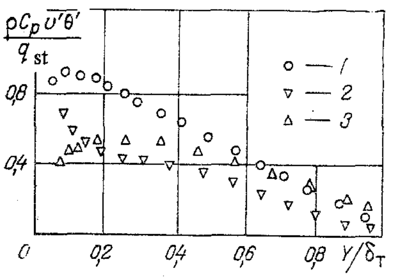

Fig. 3

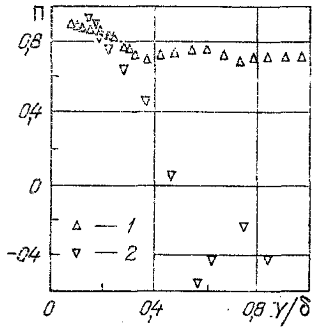

Fig. 4

Fig. 3. Turbulent heat flux density: 1) b = 0, K = 0; 2) 0 and $2.35 \cdot 10^{-6}$; 3) 0.0033 and $2.35 \cdot 10^{-6}$.

Fig. 4. Role of the "normal" stresses in turbulence energy production in accelerated flows ($\Pi \equiv [\overline{u'v'}\partial U/\partial Y - (\bar{u}'^2 - \bar{v}'^2)\partial U/\partial X] / \overline{u'v'}\partial U/\partial Y$) : 1) b = 0.0033, K = $2.35 \cdot 10^{-6}$; 2) 0 and $2.35 \cdot 10^{-6}$.

TABLE 2. Accelerated Flow Parameters on a Permeable Surface

X^*, mm	U_∞, m/sec	ΔT_∞, K	δ, mm	δ_T, mm	δ^{**}, mm	δ_T^{**}, mm	$C_f \cdot 10^3$	$St \cdot 10^3$
539	6,95	7,22	23,83	25,75	3,14	4,87	2,73	1,75
662	7,25	7,21	25,48	25,32	3,28	5,06	2,97	1,49
747	7,70	7,19	22,41	23,57	2,79	5,28	3,11	1,22
946	9,75	8,81	19,61	20,35	1,77	3,80	3,48	1,26
975	10,25	9,50	19,58	20,24	1,74	3,68	3,48	1,29
1143	14,24	13,01	16,52	19,06	1,28	2,15	3,64	1,51
1248	19,11	17,20	10,08	16,86	0,84	1,72	3,56	1,63

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*X is the distance from the beginning of the porous plate.

TABLE 3. Distribution of the Correlation Coefficients $R_{\overline{UV}}$ and $R_{\overline{V\theta}}$

Y, mm	Impermeable plate				Permeable plate			
	Y/δ	$-R_{\overline{UV}}$	Y/δ_T	$-R_{\overline{V\theta}}$	Y/δ	$-R_{\overline{UV}}$	Y/δ_T	$-R_{\overline{V\theta}}$
1,3	0,078	0,270	0,068	0,260	0,118	0,370	0,072	0,250
2,5	0,150	0,410	0,132	0,425	0,228	0,460	0,140	0,345
5,0	0,300	0,540	0,264	0,560	0,455	0,435	0,280	0,465
7,0	0,420	0,550	0,370	0,590	0,637	0,385	0,393	0,520
10,0	0,600	0,560	0,528	0,600	0,910	0,370	0,561	0,580
13,0	0,780	0,575	0,686	0,600	1,181	0,370	0,739	0,580
16,0	0,960	0,585	0,845	0,600			0,897	0,410

Reduction of the correlation between the fluctuations v' and θ' causes a drop in the turbulent heat flux level (see Fig. 3), which is apparently also the main reason for diminution in the number St on a permeable surface for gradient-free flow around a plate. Therefore, injection through the porous surface exerts a complex effect on the heat-transfer process, it reduces the heat-elimination coefficient for a gradient-free flow, and in accelerated flows that hinder growth of the viscous sublayer thickness, the injection exerts an intensifying effect on the heat elimination.

Analysis of the results presented on the heat-elimination coefficients (see Fig. 1) shows that under the mentioned flow conditions not only the "standard" heat-transfer law is spoiled, but also, as is most important, it is impossible to analyze the results obtained on the heat transfer by starting from the principle of independence of the influence of flow acceleration and injection therein.

The results obtained confirm the necessity for a deep analysis of the fluctuating structure to create reliable methods of computing the heat transfer.

NOTATION

C_f, local friction coefficient; $K=\frac{\nu}{U_\infty^2}\frac{dU_\infty}{dX}$, acceleration parameter; $R_{\overline{UV}}$ and $R_{\overline{V\theta}}$, correlation coefficients; $Re_T^{**} = U_\infty \delta_T^{**}/\nu$, Reynolds number; U, V, mean velocity components in the X and Y directions, m/sec; u', v', fluctuating velocity components, m/sec; St, Stanton number; X, Y, longitudinal and transverse coordinates, m; Y^+, "wall" coordinate; δ, boundary layer thickness, m; δ_T, thermal boundary layer thickness, m; δ^{**}, displacement thickness, m; δ_T^{**}, thickness of loss of energy, m; θ', temperature fluctuations, °K; ν, viscosity, m^2/sec. Subscripts: ∞, in the free stream.

LITERATURE CITED

1. A. F. Orlando, R. J. Moffat, and W. M. Kays, "Turbulent transport of heat and momentum in a boundary layer subject to deceleration, suction, and variable wall temperature," Report HMT-17, Stanford University (1974).
2. A. I. Leont'ev et al., "Investigation of the fluctuating structure of the thermal turbulent boundary layer under flow laminarization conditions," Heat and Mass Transfer-VI [in Russian], Vol. 1, Pt. 2, Minsk (1980), pp. 136-146.
3. V. P. Zabolotskii, P. S. Roganov, and E. V. Shishov, "Experimental apparatus and results of investigating the characteristics of an accelerated, turbulent boundary layer with injection," Trudy MLTI, No. 138, 72-81 (1981).

INFLUENCE OF PERMEABILITY OF AXISYMMETRIC SURFACES ON THEIR SEPARATION FLOW

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The separation flow of an ideal incompressible fluid around axisymmetric permeable surfaces is investigated on the basis of the model of a uniformly perforated surface.

1. Interest in the investigation of the separation flow around axisymmetric surfaces is related primarily to their utilization as different braking apparatus, of parachutes, say. General approaches to diagramming such separation flows within the framework of an ideal incompressible medium and effective numerical methods for their analysis on an electronic computer are proposed in [1]. On this basis the separation flow around axisymmetric surfaces of different shape, including during motion with acceleration, is studied [2]. It was here assumed in the computations that the streamlined body is impermeable.

As a rule, however, braking apparatus are fabricated from materials that are capable of transferring fluid particles under the effect of a pressure difference, i.e., are permeable. In addition to fabrics, among permeable surfaces are also different grids, perforated plates, shells, and other structures.

A periodic change in the velocities and pressures that is associated with the alternation of the impermeable and permeable surface sections is observed in its neighborhood during the flow around a permeable surface. The wake being formed behind it is shaped under the effect of both the external flow and the internal flow through the permeable surface. Exact modeling of the permeability phenomenon is a very complex hydrodynamic problem; consequently, analysis of the fluid flow through a permeable surface is performed expediently at the "hydraulic" level by means of the average flow characteristics by introducing a certain discontinuity surface. Such an approach to studying the aerodynamics of permeable surfaces was proposed

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