SEMIEMPIRICAL METHOD OF ESTIMATING THE HEAT TRANSFER LEVEL BEHIND THE BOUNDARY-LAYER SEPARATION POINT

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Relationships are obtained for computation of the heat transfer in the boundary-layer attachment domain and within the vortex zone on the basis of an extension of experimental material.

The progress of theoretical methods of computing the heat elimination during separation is still limited at this time: the one with the best foundation, based on examination of the turbulent momentum and enthalpy transfer, has not emerged beyond the framework of single papers and is too complicated for engineering computations. Computations based on turbulence energy balance require knowledge of empirical constants, which have no reliable recommendations. A number of semiempirical methods does not assure the necessary correspondence with experiment because of their nonrigorous underlying initial hypotheses.

Under these conditions, the results of experimental investigations and their generalization acquire special value. At this time, extensive test material has been accumulated, meanwhile the universality of the criterial dependences obtained, if such were proposed, is inadequate. This concerns not only the transfer of the results to other kinds of flows, but also to flows analogous to those being studied. It becomes evident that estimates characterizing the generality of the transfer processes during separation of a dynamic boundary layer are needed to systematize the available material.

The flow diagram for singular separation behind the broken line of a profile and a typical heat-elimination coefficient distribution are represented in Figs. 1 and 2. Physically it is more well-founded to speak about the attachment domain; however, for convenience we will henceforth use the concept of the point of attachment. It is the single critical point on both of whose sides the fluid flows. An estimate of the heat transfer is primarily of interest not only because the maximum heat elimination corresponds to the point of attachment but also because it can be utilized as the "reference" for estimating the heat transfer on conjugate sections of the surface.

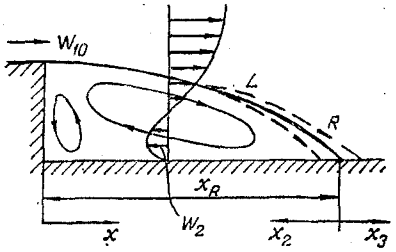

Fig. 1

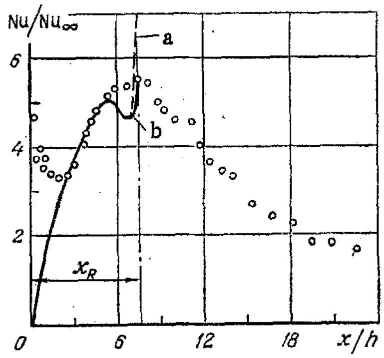

Fig. 2

Fig. 1. Diagram of a two-dimensional separation flow.

Fig. 2. Heat transfer behind a diaphragm in a tube: $\bar{d}_d = 0.3$; points are experiment [13]; curves are a computation using (4); a) $Re^{**}_{TO} = 0$; b) $Re^{**}_{TO} \neq 0$.

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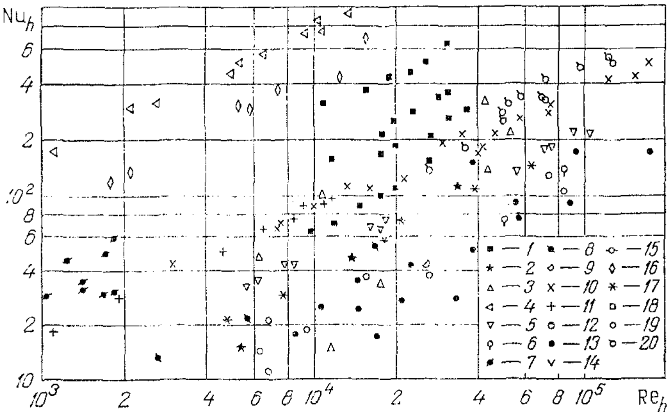

Fig. 3. Generalization of the experimental results over the height of the obstacle. The notation numbers correspond to positions in the references.

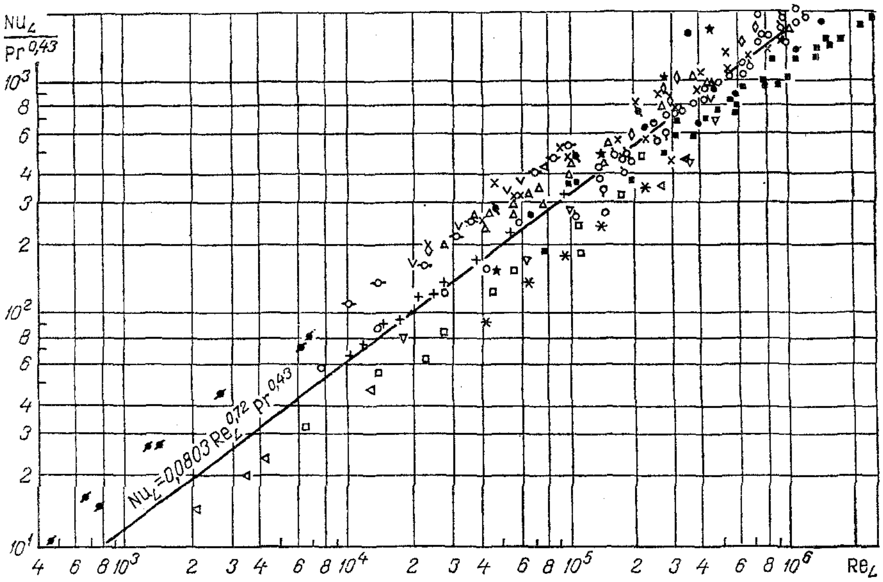

Fig. 4. Generalization of experimental results on the separating streamline. Same notation as in Fig. 3.

An increase in the heat elimination at the attachment point is explained by the slight thickness of the embryonic boundary layer. However, it is characteristic that this thickness and the level of the heat elimination coefficient α depend not only on the velocity of the leakage flow but also on its turbulization: estimates of α made by means of relationships for the stagnation points of bodies streamlined by a low-turbulent stream turn out to be substantially reduced. At the same time, agreement with the test data is observed considerably better when dependences taking account of the free stream turbulence are used. This fact, as well as the extraordinarily high turbulence level recorded experimentally in the attachment domain result in the necessity for a more detailed examination of the sources and role of turbulence in boundary-layer separation.

Known results of investigations of the stream kinematics during separation and natural observations of the authors indubitably indicate that the preferred generation of turbulence in such flows does not occur in the near-wall layer but in the jet shear layer between the forward and reverse flow: precisely there is the sharp blip in the fluctuation characteristics of the velocity, temperature, pressure observed in diagrams constructed over the stream cross section.

The distribution of the turbulence characteristics in the flow under consideration is not subject to known distribution laws in the near-wall layer. The flow during separation has more in common with jet than with near-wall flows. The "anomalous" distribution diagrams in the shear layer are determined not only by the transverse velocity gradient in this case but also by another characteristic of the liquid layer interaction, the absence of the laminarizing effect of the friction surface. Such a pattern is conserved although it can be distorted somewhat when the stream is quite nonisothermal.

In contrast to the near-wall flows, development of vortex zones behind the separation point depends less significantly on the roughness, external turbulence, Re in the postcritical, transition domains, and even in part of the laminar external flow domain. It is pertinent also to cite the known fact that if a rise in stream turbulence flowing transversely over a disc can cause a 50% increase in α on the forward surface, then it will be correspondingly 4% less on the rear. These facts are also explained by the fact that a predominant factor in the exchange process development is manifest during boundary layer separation: the powerful turbulence generator is the jet shear layer. Its existence is predetermined by the attempt to seed a certain regularity in the progress of these processes. Attention is turned to the established fact of the length of the vortex zone behind a plane obstacle and a circular diaphragm, and a nozzle on the height of the obstacle. Correspondingly $x_R^y \sim (5\text{-}6)h$ and $x_R^d \sim 10h$, $x_R^c \sim 8h$. Meanwhile, the majority of generalized experimental results correspond to the dependence $Nu = f(Re^n)$, where $n \sim 0.67$.

Results of generalizing the known experimental data on the heat transfer at the attachment point [1-20] in the similarity criterion $Nu_h = f(Re_h)$ are represented in Fig. 3. Such a form of the generalization is used most often when h is understood to be the height of the obstacle behind which the vortex zone is developed (in the case of bodies of revolution, half the difference between the diameters of the annular poorly streamlined element). The results presented refer to experiments with different working fluids and streamlining conditions. As is seen from Fig. 3, all the test data in these coordinates is not generalized successfully by a single dependence.

It should be noted that the function $x_R = f(h)$ is less general than $x_R = f(h/\delta_0^{**})$, say. The same can be said about the longitudinal pressure gradient, the nonisothermy, the initial turbulence, etc. It is legitimate to assume that, on the one hand, the length of the separating streamline L is a function of these factors. On the other hand, as investigations executed by the authors showed, the state of the jet shear layer, and therefore, the heat transfer at the point of attachment also, are functions of L to a definite extent. Then the problem of determining Nu_{max} is separated into thermal and dynamic, and the results of the former are generalized in the form

$$Nu_L = f(Re_L).$$

The fruitfulness of such a generalization is manifest in the applicability to different flows including the case of no kind of specific obstacle of height h, as well as in taking account of the influence of all the acting dynamic factors and the nonisothermy in terms of L, both to obtain the approximating dependence and to utilize it.

Results of revising the same experimental data and critical equations are represented in Fig. 4. The governing velocity and temperature are taken on the outer boundary layer boundary ahead of the separation point, as for Fig. 3. Taking into account the thermophysical properties of the working fluids, the results obtained are approximated by the dependence

$$Nu_L = 0.0803 Re_L^{0.72} Pr^{0.43}. \tag{1}$$

The affirmative result of the data processing performed is its universality for the different natures of the flows: plane and axisymmetric, inner and outer, with and without a strong pressure gradient, for long and short vortex zones with nonsymmetric separation, for fluids and gases with substantially different thermophysical properties, and even for the laminar nature of the flow preceding separation. Equation (1) is valid in the range $Re_L = 10^3 - 3 \cdot 10^6$ for flow around a surface with singular separation. Utilization of the dependences obtained becomes possible also when there is no simple obstacle and is associated with the solution of the dynamic problem in the general case. To find the length of the separating streamline, methods of integrating the equations of Navier–Stokes, of potential flow with a constant vorticity zone, methods of the theory of turbulent jets, semiempirical equations, etc. can be applicable. In the simplest case of separation behind a rectangular obstacle of height h, the length L can be estimated by means of h and x_R by using the known correlation $x_R(h)$.

Utilization of the proposed approach to generalize the heat transfer results at the point of attachment of a boundary layer being separated during interaction with a compression shock also yields affirmative results. However, appropriate experimental points are

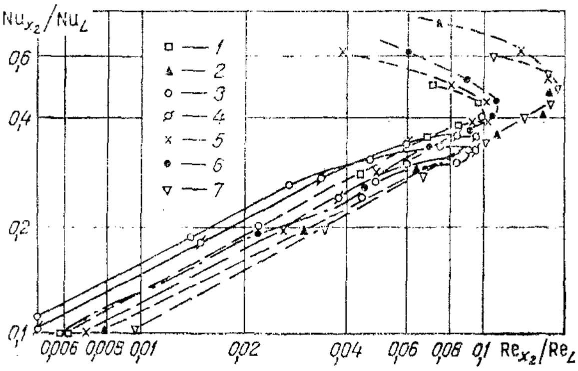

Fig. 5. Relative heat-transfer law within the vortex region [1) $\bar{d}$ = 0.32; 2) 0.68 [13]; 3) 0.48; 4) 0.68 [16]; 5) 0.3; 6) 0.4; 7) $\bar{d}$ = 0.7, authors' experiments].

above the approximating curve for subsonic flow. In this case additional intensification of the heat transfer associated directly with the pressure jump obviously occurs.

The question of estimating the heat transfer within the vortex zone between the separation and attachment points has been developed still less. No attempt is made in experimental research to generalize the appropriate materials although the qualitative pattern is followed in almost each of them. The criterial dependences proposed in [17, 21] do not correspond qualitatively to experimental results.

It is shown in [22] that heat transfer within the vortex zone can be considered as a process in the near-wall secondary boundary layer being developed from the point of attachment in a reverse direction to the main flow. The nature of the change in α over the length of the vortex zone (see Fig. 2) confirms the hypothesis of the near-wall boundary layer development. Precisely its growth along the coordinate x_2 depsite the increase in W_2 causes a reduction in the heat-transfer intensity. The increase in Nu near the point of separation is caused by the presence of a secondary vortex: it ruptures the boundary layer being formed, transports fresh fluid masses to the surface from the main flow. An estimate of the heat elimination due to the secondary vortex is still more difficult and is not always observed; consequently, its influence is later neglected.

Following the hypothesis on the origination of the near-wall layer [22], we have the heat-transfer law for the turbulent boundary layer

$$\mathrm{St} = \frac{B}{2}\,\mathrm{Pr}^{-0.75}\mathrm{Re}_{\mathrm{T}}^{**-m}. \tag{2}$$

In the simplest case

$$\frac{d\,\mathrm{Re}_{\mathrm{T}}^{**}}{d\bar{x}_2} = \mathrm{St}\,\mathrm{Re}_2, \tag{3}$$

then

$$\mathrm{St} = \frac{B}{2\mathrm{Pr}^{0.75}}\left[\frac{B(m+1)}{2\mathrm{Pr}^{0.75}}\int\limits_0^{\bar{x}_2}\mathrm{Re}_2 d\bar{x}_2 + \mathrm{Re}_{\mathrm{T0}}^{**m+1}\right]^{-\frac{m}{m+1}}. \tag{4}$$

Knowledge of the reverse flow velocity at the outer boundary of the near-wall boundary layer W_2 is necessary for computations by means of (4). A computed curve for the heat-transfer in the vortex zone behind a diaphragm of d = 15 mm in a D = 50-mm tube is represented in Fig. 2. The experimental law $W_2(\bar{x}_2)$ was used here. Because of the nonsymmetrical nature of $W_2(\bar{x}_2)$ relative to the center of the zone, and in order to investigate the significance of $\mathrm{Re}_{\mathrm{TO}}^{**}$, an approximation is applied for this law under the assumption that $W_{02} \neq 0$:

$$W_2 = \frac{0.05W_{01}}{\frac{D-d}{2D} - 0.024}\left[1 - 3.8(\bar{x}_2 - 0.5)^2\right]. \tag{5}$$

As follows from Fig. 2, the influence of $\mathrm{Re}_{\mathrm{TO}}^{**}$ is manifest only for very small $\bar{x}_2$ (the branch *a* is $\mathrm{Re}_{\mathrm{TO}}^{**} = 0$ and b is $\mathrm{Re}_{\mathrm{TO}}^{**} = f(\mathrm{Nu}_{\mathrm{R}}) \neq 0$).

Taking this as well as the worse correspondence, as a whole, between the computation of the experiment for $\bar{x}_2 < 0.15$ and the presence of a very "blurry" heat-elimination maximum near $\bar{x}_2 = 0$ into account, we arrive at the deduction about no practical necessity to estimate Re_{T0}^{**}. In this case the section of the curve α for small $\bar{x}_2$ is determined expediently as connective between the computed curve $\alpha(\bar{x}_2 > 0.15)$ and the point $\alpha_R(\bar{x}_2 = 0)$.

Constant heat-transfer laws (2) different from the appropriate values for the near-wall flows

$$B = 0.2; \quad m = 0.5 \tag{6}$$

are obtained by processing the experimental results the authors obtained for flow in a tube with $d/D = 0.32$-0.8. Their magnitude noticeably exceeds the values characteristic for the distribution law $\bar{W} = \xi^{1/7}$, in which the acceleration of exchange processes also is manifest as a result of intensive turbulence generation in the jet boundary layer and its diffusion in the near-wall layer.

The characteristics (6) should later be refined on the basis of a special investigation of near-wall flows in the vortex zone, more extensive experimental material, and refined expressions of the type (3). Because of the absence of wide approval of the solution (4), the experimental results were also generalized by a simpler method. A hypothesis on the origination of the near-wall layer and the form of the critical dependences for the initial phases of the flow around surfaces is used. Taking account of the flow specifics, the value of Nu_L was used as "reference" point. Results of processing the authors' experiments and results borrowed from [16, 17] are presented in Fig. 5. The behavior of the curves is of interest: their good agreement is observed up to $\bar{x}_2 \sim 0.6$-0.7, after which their nature changes abruptly: part of them is completely in the field of experimental points formed, i.e., the heat-transfer intensity dimishes as $\bar{x}_2$ grows and W_2 changes by the same regularity. Part of the points substantially "drops out." It has been established that the first group of experiments refers to the vortex zone without a secondary vortex behind the step (see Fig. 1), and the second to zones with it, here $\mathrm{Nu}_x/\mathrm{Nu}_L$ tends approximately to 1. Considering these branches nonworking, we obtain the approximation

$$\frac{\mathrm{Nu}_{x_2}}{\mathrm{Nu}_L} = 1.21\sqrt{\frac{\mathrm{Re}_{x_2}}{\mathrm{Re}_L}}. \tag{7}$$

Dependences (1), (2), (5), (7) obtained are applicable for engineering estimates of the heat-transfer during separation under different flow conditions. Good results have been obtained when using them for exhaust channels and collectors of internal combustion engines characterized by the very complex geometry of the flow-through part and the stream structure.

NOTATION

α, heat-elimination coefficient; Re, Reynolds number; Re_T^{**}, Reynolds number constructed over the energy loss thickness; x, longitudinal coordinate ($\bar{x} = x/x_R$); Nu, Nusselt number; St, Stanton number; Pr, Prandtl number; h, obstacle height; δ^{**}, momentum loss thickness; m, B, constants; W, velocity; D, d, diameters of the tube and diaphragm ($\bar{d} = d/D$); ξ, dimensionless transverse coordinate. Subscripts: R, attachment region, L, length of the separating streamline; 1, direct flow; 2, reverse flow from the point x_R; 0, coordinate $x = 0$; c, nozzle; d, diaphragm; and y, obstacle.

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