ESTIMATION OF THE HEAT-TRANSFER CONDITIONS IN THE NEIGHBORHOOD OF THE STAGNATION POINT DURING IMPINGEMENT OF A JET ON AN OBSTACLE

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A functional dependence of the heat-transfer intensity at the stagnation line of plane jet impingement on an obstacle on the pulsation component of the stream velocity is established.

A line (point) of total stream deceleration is formed during impingement of uniform streams and jets on different obstacles (sphere, cylinder, flat and concave surfaces, turbine buckets, etc.), near which a special domain with a complex heat-transfer mechanism is formed.

Investigations of the heat transfer in the neighborhood of the stagnation line (point) are based, as a rule, on the representation of the heat transfer in the boundary layer being formed on the obstacle. Thus, the solution of a system of boundary-layer motion and energy equations is used in investigating the heat transfer in the neighborhood of the impinging line of a plane jet over the surface in [1]. It was hence noted that the velocity pulsations of the impinging jet exert substantial influence on the heat emission intensity. The magnitude of these pulsations is defined near the obstacle by both the degree of stream turbulence outside the domain of its interaction with the obstacle and the time-averaged velocity distribution in this domain.

Let us examine interaction between a plane turbulent jet and a wall. The degree of jet turbulence near the wall is taken equal to the degree of free jet turbulence at a corresponding distance from the nozzle exit in the majority of published papers. However, the results of determining the degree of turbulence on the jet axis sometimes differs more than two-fold [2, 3] according to the data of different authors. The velocity pulsations and the average velocity during impingement of a jet on an obstacle were measured in [1, 4, 5]. According to the data in [4, 5], a diminution in the average velocity occurs in an interaction domain whose dimension in the jet axis direction $\bar{y} = y/d_0$ does not exceed 1.2-1.3, and depends weakly on the initial degree of stream turbulence, the number Re, and the relative distance between the nozzle and the wall. A diminution in the pulsating velocity component is also observed in this domain; however, the rate or its variation is considerably less than for the average velocity.

We take the change in average velocity along the jet and the extent of the interaction domain as the parameters characterizing jet interaction with the obstacle.

Investigations were performed on an air test stand in which a plane jet is formed during the outflow of the working body from a flat channel through a slot in its wall. The peculiarity of such an outflow is the asymmetry of the velocity profile and the incomplete filling of the slot section by the jet. The case of jet outflow from the slot into a bounded volume representing a rectangular cavity is considered. The jet flow in such a cavity differs from the ordinary scheme of jet impingement on an infinite flat obstacle considered in that after collision with the wall the jet spreads along the surfaces bounding the cavity in opposite directions. Consequently, two circulation domains are formed whose interaction with the jet is evidently explained by the more intense diminution in the jet velocity along the axis than in the case of a free jet.

The maximum jet velocity c_0 at the slot exit varied between 35 and 120 m/sec, while the relative distance $\bar{h} = h/b_0$ varied within the range $5 \leq h \leq 37$. The number $Re_0 = c_0 b_0/\nu$ hence varied between $0.5 \cdot 10^4$ and $5 \cdot 10^4$, while the number M_0 did not exceed 0.35. The velocity profile at the slot exit varied between rectangular and a profile with compact boundary layers.

Traversing the jet along its length and in the domain of interaction with the wall was performed by total and static pressure microprobes with 0.6-mm diameter of the receiving section. In addition the pressure on

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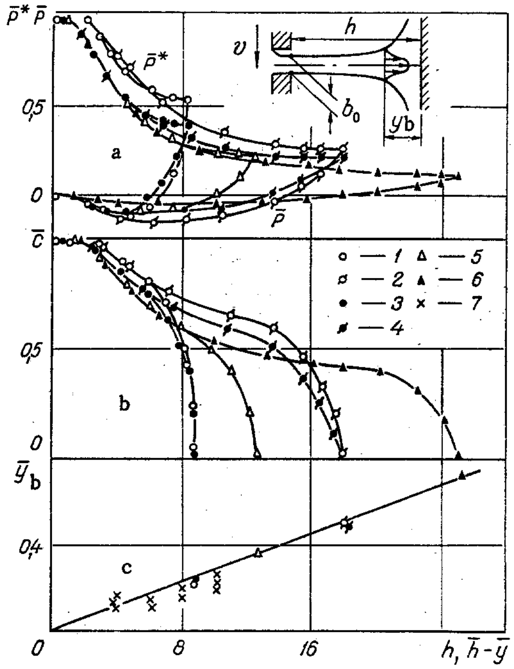

Fig. 1. Parameter distribution during plane jet impingement on a wall [1, 2, for a rectangular velocity profile at the slot exit; 3, 4, for the intermediate profile; and 5, 6, for the profile with the compact boundary layers]: a) relative total and static pressure distribution as a function of the relative distance to the slot exit; b) maximum relative velocity distribution in the jet as a function of the relative distance to the slot exit; c) dependence of the extent of the interaction domain on the relative distance to the slot exit (7 is from data in [5]).

the wall surface was measured by drains and was compared with the results from the traversing.

The scheme of jet impingement on an obstacle is presented in Fig. 1, where the total and static pressure distribution along the jet and in the domain of interaction is represented in the form of the dimensionless quantities

$$\bar{P}^* = \frac{P^* - P_0}{\rho \frac{c_0^2}{2}}, \quad \bar{P} = \frac{P - P_0}{\rho \frac{c_0^2}{2}},$$

where P_0 is the static pressure at the slot exit and ρ is the air density.

The change in $\bar{P}^*$ along the jet (Fig. 1a) turns out to be analogous to the change in the total pressure in the free jet. The exception is a section of small extent near the wall, where its influence starts to be felt. As is seen from the figure, the distribution of $\bar{P}^*$ in the jet depends on the completeness of the velocity profile at the exit. As the boundary-layer thickness increases the kinetic energy losses increase and the curves of the change in $\bar{P}^*$ pass below. After the jet leaves the slot, the static pressure $\bar{P}$ is reduced somewhat while conserving a constant value for sufficiently high $\bar{h}$ just as is observed in free jets, and is elevated to the value $\bar{P} = \bar{P}^*$ at the wall in the domain of jet interaction with the wall. The initial velocity profile in the jet hence exerts a definite influence on the static pressure distribution.

The change in maximal velocity along the jet $\bar{c} = c/c_0$ is in good agreement with the regularities characteristic for free jets with a corresponding initial velocity profile. The exception is the domain of jet interaction with the obstacle. Its boundary cannot be defined rigorously in experiment since the stream parameters approach the free jet parameters asymptotically with distance from the wall. The curve of the velocity change during passage from the main jet section to the domain of interaction with the wall changes the curvature sharply. The distance between the wall and the point of the change in curvature $\bar{y}_b = y_b/b_0$, provisionally taken as the boundary between the jet and the interaction domain, is determined by starting from the following considerations. As is seen from Fig. 1b, the change in velocity along the jet outside the interaction domain has the same regularity for a different distance to the wall and the same initial velocity profile at the slot exit. The diminution in the velocity $\bar{c}$ in the domain of jet interaction with the wall is of self-similar nature and depends uniquely on the relative distance $\bar{y} = y/b_0$ measured from the wall, the number Re_0, the relative distance between the slot and the wall, and the coefficient of the velocity profile shape K_S. This dependence can be approximated by the expression

$$\bar{c} = 0.525 \cdot 10^{-4} \, Re_0 \, \bar{h}^{-0.68} \sqrt[3]{\bar{y}} \, K_S \,, \tag{1}$$

where $K_S = \frac{1}{c_{0\,\max} G_0} \int\limits_0^{G_0} c_0 dG_0$ and G_0 is the discharge of the working body through the slot.

Investigations of plane jet impingement on an obstacle in broad ranges of $\bar{h}$, Re_0, K_S showed that the extent of the interaction zone is determined uniquely by the relative distance $\bar{h}$:

$$\bar{y}_b = 0.28\,\bar{h}. \tag{2}$$

The dependence (2), which generalizes the experimental material of this research and of [5], is represented in Fig. 1c. Despite the fact that the initial degree of turbulence varied substantially in [5], and the impingement of an axisymmetric and not a flat jet was investigated, as occurs in this paper, the agreement between the results can be considered satisfactory.

The heat-emission coefficients on the wall surface were determined during the experiment by the method from [8], which permits taking account of heat losses by radiation and leakage along the electrical heater filaments. Heat leakage through the plate on which the electrical heater filaments were glued was determined by solving a two-dimensional stationary heat-conduction problem on an ÉGDA-9/60 integrator. As a result of taking all these heat losses into account, good reproducibility of the results was achieved successfully, and the random error in determining the heat-emission coefficients was reduced to 3-4%.

According to our representations, the heat transfer on the obstacle surface is due to the velocity of the impinging flow, the dissipation of its kinetic energy, the thermal radiation and heat conduction. Since the temperature of the incoming stream in our and analogous tests is close to the obstacle temperature, the radiant heat transfer can be neglected. Moreover, we note that in direct proximity to the wall the magnitude of the average velocity is $\bar{c} \approx 0$. Therefore, the heat transfer at the jet stagnation point on the wall can be determined by the longitudinal turbulent velocity pulsations near the wall, the phenomenon of heat conduction, and stream kinetic energy dissipation.

Taking the above into account, the equation of turbulent transfer in an incompressible fluid stream [9] can be written in the form

$$q = \rho c_p u_y T' - \lambda \frac{dT}{dy} - \frac{\lambda}{2\,c_p} \frac{d}{dy} (u_y^2). \tag{3}$$

The third term in the right side of (3) corresponds to the quantity of heat appearing because of dissipation of kinetic energy of the turbulent pulsations. This term can be discarded since it turns out to be of second order compared to the terms corresponding to the heat transfer by turbulent pulsations and heat conduction according to estimates made in the case of moderate flow velocities.

Taking this into account, we obtain from (3)

$$\alpha = \rho c_p u_y \frac{T'}{\Delta T} - \lambda \frac{d}{dy} \left(\frac{T}{\Delta T} \right). \tag{4}$$

Since the change in the average stream velocity $\bar{c}$ near the wall is universal in nature according to (1), it can be assumed that the change in the temperature and the pulsating velocity component in the interaction domain is also described by universal dependences for obstacles of different shape.

According to the Prandtl hypothesis, the pulsating temperature component in a stream can be represented in the form

$$T' = l_T \frac{dT}{dy}. \tag{5}$$

Dividing both sides of (5) by ΔT, we obtain the expression

$$\frac{T'}{\Delta T} = l_T \frac{d}{dy} \left(\frac{T}{\Delta T} \right),$$

which becomes after simple manipulations

$$\frac{T'}{\Delta T} = \tilde{l}_T \frac{d}{d\tilde{y}} \left(\frac{T}{\Delta T}\right), \tag{6}$$

where $\tilde{l}_T = l_T/y_b$; $\tilde{y} = y/y_b$.

It follows from the assumption of universality of the relative average temperature distribution in the dimensionless coordinate that for a given $\tilde{y}$ we have the ratio $T'/\Delta T$ = const. Therefore, (4) can be represented in the form

$$\alpha = Au_y + B, \tag{7}$$

where $A = \rho c_p T'/\Delta T$; $B = \lambda T'/(l_T \Delta T)$.

It is interesting that the expression presented in [1] for the local heat-emission coefficients at the stagnation point

$$\mathrm{Nu}_0 = \frac{3}{\bar{h}^{0.6}} \sqrt{\mathrm{Re}_0 \sin\varphi}\,(0.496 + 0.867\, K\varepsilon \bar{h}^{0.1} \sqrt{\mathrm{Re}_0 \sin\varphi}), \tag{8}$$

obtained by solving the system of boundary-layer equations, can be converted to a form similar to (7):

$$\alpha = A'u_y + B', \tag{9}$$

where

$$A' = \frac{30.867\, K\lambda}{\nu a}, \quad B' = \frac{30.496\,\lambda}{b_0 \bar{h}^{0.6}} \sqrt{\mathrm{Re}_0},$$

and a is a coefficient connecting the degree of turbulence determined by the local velocity in the jet and the velocity at the nozzle exit. Although the factor B' is not a constant in principle, its change is an order of magnitude less than the change in the first term, i.e., dependence (9), exactly as (7), can be approximated by a straight line.

Since the law of variation of the pulsating velocity component in the domain of jet interaction with the wall is unknown, it is expedient to connect the heat-emission coefficient to u_y on the boundary of this domain ($\tilde{y} = 1.0$) and to find the coefficients A and B in (7) by starting from this.

The validity of (7) can be illustrated by the results of experimental investigations to determine the heat-emission coefficient at the stagnation point for different jet impingement conditions on the obstacle. The dependences of the heat-emission coefficient α at the stagnation point on the pulsating velocity component of the impinging stream are presented in Fig. 2. The lines I, VI, VII constructed from the results of our experiments

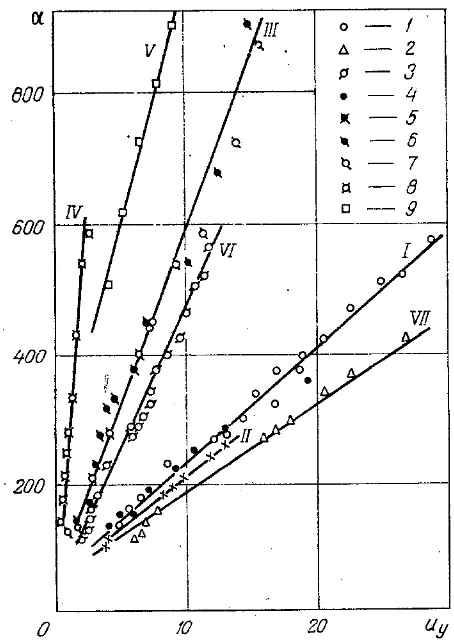

Fig. 2. Dependence of the heat-emission coefficient α, $W/m^2 \cdot deg$, at the stagnation point (line) on the longitudinal pulsating velocity component u_y, m/sec, of the impinging stream; for a plane jet according to the authors' data: 1) u_y determined by [2]; 2) by [3]; 3) by [7]; according to data from [1]: 4) under the assumption that the velocity profile is at the exit of a nozzle with compact boundary layers; 5) a rectangular velocity profile; for a cylinder according to data in [6]: 6) Tu = 7%; 7) 15; 8) 1.2; 9) for an axisymmetric jet according to data in [4].

correspond to heat-emission conditions on the spreading line of a plane jet for $12 \leq \bar{h} \leq 37$ and $0.5 \cdot 10^4 \leq Re_0 \leq 5 \cdot 10^4$, when the magnitude of the pulsating velocity component was determined as a function of the degree of turbulence on a free jet axis by data presented in [2, 3, 7], respectively. Let us note that the line I corresponds well to the experimental values of α presented in [1] for $\bar{h} = 12$ if it is assumed that a velocity profile with compact boundary layers occurred at the nozzle exit in these experiments. A rectangular velocity profile alters the curvature of the dependence of the heat-emission coefficient on the pulsating velocity component somewhat (line II). Since no assumptions were made constraining the form of the impinging stream in deriving (7), it can apparently be applied to determine α for other shape obstacles and stream impingement cases. In fact, the line III in Fig. 2 corresponds to heat transfer at the forward stagnation point of a circular cylinder (50-mm diameter) under a transverse flow around it by a uniform air stream with the degree of turbulence 7 and 15%, the number $Re = (0.3\text{-}8) \cdot 10^5$, and the blockage factor 0.25 [6]. Results of an experiment for even a comparatively low (1.2%) degree of incoming stream turbulence (line IV) are approximated well by a line.

The dependence of α on the pulsating velocity component, obtained for an axisymmetric jet [4], can also be described by (7) although it has coefficients A and B different from the corresponding coefficients obtained in other tests (curve V).

In conclusion, we note that the different slope of the lines (Fig. 2) obtained on the basis of processing the results of our experiments and the data of other authors is caused by the fact that authors determine the pulsating velocity components differently. Moreover, as a rule the conditions for conducting the experiment are not identical (the possibilities of the experimental setups and the measuring apparatus are distinct, the tests are conducted for different working body parameters). With regard to the heat-emission coefficients obtained by the dependences presented in Fig. 2, they turn out to be sufficiently close for comparable experimental conditions (the discrepancy does not exceed 15%).

NOTATION

b_0, jet width at the slot exit; h, distance between the slot exit and the wall; $\bar{h} = h/b_0$, its dimensionless form; P^*, P, total and static pressures on the jet axis; ρ, density; c, average stream velocity; y_b, extent of jet interaction with the wall in the y direction; K_S, coefficient of profile shape; G, working body discharge; T, average stream temperature; T', temperature pulsation in the stream; v, average velocity in the channel; u_y, pulsating velocity component in the y direction; ΔT, difference between the wall and the average stream temperatures; λ, heat-conduction coefficient; q, specific heat transferred to the plate; c_p, specific heat; α, heat-emission coefficient; l_T, mixing path of the turbulent temperature pulsations; ν, kinematic viscosity coefficient; φ, angle between the plane of jet symmetry and the plate; $Nu = \alpha b_0/\lambda$, Nusselt number; $Re = cb_0/\nu$, Reynolds number. The subscript 0 refers to the parameters at the slot exit.

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