With allowance for these assumptions we obtain the following equation for the velocity profile at the surface of a plate with simultaneous injection—suction of gas:

$$\omega_{\pm} = \frac{1}{2}\left[\left(1-\frac{b}{b_{cr}}\right)\omega_0 + \frac{b}{b_{cr}}\ \omega_0^2\right]\ \left[2+\frac{b}{b_{cr}}-\frac{b}{b_{cr}}\left(1-\frac{b}{b_{cr}}\right)\omega_0-\left(\frac{b}{b_{cr}}\right)^2\omega_0^2\right]. \tag{11}$$

For critical injection—suction, when $b = b_{cr}$, we obtain

$$\omega_{\pm\,cr} = \frac{3\omega_0^2-\omega_0^4}{2} \tag{12}$$

Equations (11) and (12) are compared with experimental data in Fig. 2. One can note that there is satisfactory correspondence between the calculated profiles and the experimental data. Some divergence of the profiles is observed at the outer limit of the boundary layer.

NOTATION

$\bar{j}_+$, $\bar{j}_-$, relative mass velocities of injected and sucked gas, respectively; δ_1^{**}, δ_2^{**}, thicknesses of momentum loss at start and end of perforated section, respectively, m; u, stream velocity, m/sec; $\bar{c}_f$, average coefficient of friction; b_+, b_-, permeability parameters for injection and suction, respectively; $Re_1^{**} = u_0\delta_1^{**}/\nu$, $Re_2^{**} = u_0\delta_2^{**}/\nu$, Reynolds numbers at start and end of perforated section, respectively; $\Psi_+ = c_{f+}/c_{f_0}$, $\Psi_- = c_{f-}/c_{f_0}$, relative friction laws with injection and suction; $\omega = u/u_0$, relative velocity.

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INVESTIGATION OF THE HYDRODYNAMIC CONDITIONS OF JET HEAT TRANSFER

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An impact jet model that can be used to explain the regularities of heat transfer is proposed.

The impact jet model which can best be used to analyze heat transfer to the real stress structure is apparently that in [1]. Three characteristic domains are isolated in this model: potential flow, external viscous mixing, and near-wall boundary layer of the obstacle. The authors did not determine the neighborhood of the stagnation point with a ratio between the radius r starting therefrom and the hole diameter d varying within the range $0 \leq r/d \leq 0.18$. The presence of a local maximum heat-emission coefficient at $r/d = 2.5$ is explained within the framework of this model by the highest turbulence level in this zone due to emergence of the viscous mixing domain on the obstacle surface; then the heat-transfer intensity drops because of the growth of the turbulent boundary layer and the diminution in the flow velocity of the gas film because of spreading.

However, it was not taken into account in the model [1] that centrifugal force, whose effect under definite conditions can result in the formation of spiral vortices [2, 3], i.e.,

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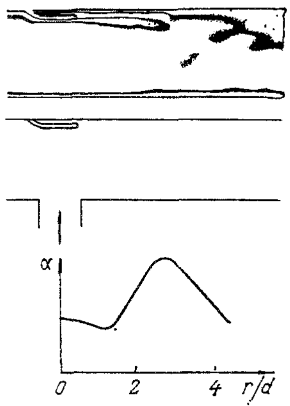

Fig. 1

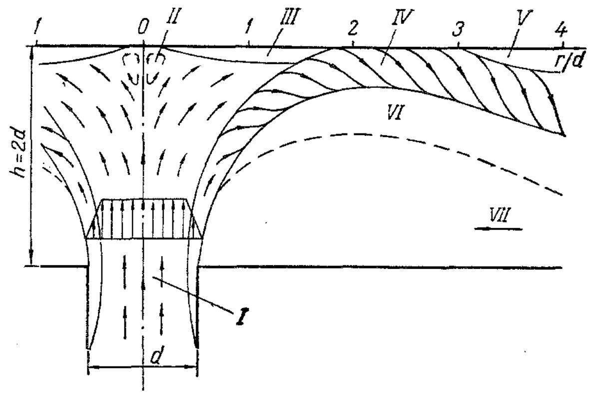

Fig. 2

Fig. 1. Equidensity of the Töpler diagrams, diagram of the gas channel, and dependence [5] of the heat-emission coefficient α on r/d (d = 10 mm, h = 20 mm. Exposure time 0.01 sec for the survey).

Fig. 2. Hydrodynamic diagram of the impact gas jet: 1) potential flow domain; II) circulation splitter; III) laminar sublayer; IV) vortex core; V) secondary laminar sublayer; VI) domain of external viscous mixing; VII) return flow domain.

the origination of a qualitatively different near-wall layer, exerts a strong influence on the formation of the hydrodynamic circumstances for a steep rotation of the stream relative to the stagnation point.

The first attempts to verify this assumption for a jet were performed by using microvanes, which were plates of drop shape fastened on a tungsten filament of 5 μ diameter threaded through a hole along the axis of symmetry of the plate. The span of the 0.2-mm-thick vane wings varied from 1 to 2 mm and the length along the profile chord was 2 mm. The filament was mounted rigidly along the radius from the stagnation point to the circumference. During the tests the vanes were placed in different regions of a cold air jet pulsing from a d = 10-mm hole onto a flat obstacle r = 70 mm perpendicular to the hole axis at a range of h = 10-30 mm.

Experiments permitted isolation of the stream domain directly at the obstacle surface r/d > 1.5 at which the microvanes started to rotate regularly with a number of revolutions on the order of tens to hundreds per second upon connection of the blast; their velocity of rotation increased with increase in the jet velocity. But the microvanes did not yield stable, reproducible results because of the imperfections of the friction nodes of the plate along the filament. Moreover, there was the danger that rotation of the vane might cause local misalignment of the stream. Hence, experiments were performed to visualize the flow in this jet domain by introducing carbon dioxide in the near-wall zone by means of a capillary of diameter 1/0.5 mm.* The exit rectilinear part of the capillary was fastened in such a way that its axis, directed along the radius of the obstacle, was at a range of 2 mm. The jet apparatus was mounted in the 300-mm-diameter optical field of a Töpler instrument so that the jet axis and the exit section of the capillary were perpendicular to its optical axis. The clearest shadowgraph was observed under conditions of overshooting of the air blast. The serious difficulties occurring in such investigations, which are due to the loss of image contrast, were overcome by developing the photographs by the equidensity method [4]. The equidensity of one of the shadowgraphs obtained, on which the vortex rings are seen clearly enough, is represented in Fig. 1. A graph of the change in the local heat-emission coefficient is reproduced below it according to the data of [5]. Comparing them shows that the vorticity grows along the radius from the point r/d ≈ 2 and the coefficient of heat emission increases correspondingly. The maximum heat transfer is also observed in the zone of maximum near-wall vortices. The Töpler diagrams, supplemented by the tests with microvanes, permit the assertion that vortices of Taylor—Goertler type comprise the structural basis of the turbulence in the impact gas jet.

*The quantity 1/0.5 mm is as in Russian original.

A model (Fig. 2) of a subsonic impact jet was formulated on this basis. The domain in the neighborhood of the stagnation point was first filled by a "circulation splitter," represented earlier in the model of a supersonic impact jet [6]. Later, a domain in which spiral gas motion — the "vortex core" — dominates is introduced. This domain starts at the bend in the stream, and its primary thickness equals the width of diminution in the potential core of the jet because of stream interaction with the hole surface and the secondary flow at the jet mouth, since the formation of spiral vortices occurs only under the effect of centrifugal force on a stream with a nonuniform velocity profile. The high-intensity vortex core emerging from the laminar sublayer splits it and approaches directly to the obstacle surface, which results in a maximum heat emission in this zone. The vortex intensity drops with broadening of the jet along the obstacle and the viscosity starts to play a governing role, whereupon a secondary laminar sublayer forms and the weakened vortices are forced back from the body surface. The effect of the return flows to the jet mouth through the viscous mixing domain can be a concomitant reason for vortex core standoff. The gas film spreading along the obstacle surface probably undergoes discontinuities, since the strongly expanding flow is unstable [7], which, in turn, can result in the growth of turbulent mixing and the intensification of heat transfer. Breaking down of the fluid film superposed on the obstacle surface under the effect of the gas jet is a certain qualitative confirmation of this assumption.

The model proposed permits a satisfactory explanation of the strong dependence of the heat-transfer intensity in impact jets on the artificial turbulence produced by cascades mounted at the stream entrance to the hole. The potential core of the jet is divided into sections with a deformed velocity profile which is swirled into vortices that limit the formation of the primary laminar sublayer during stream rotation and, therefore, magnify the heat transfer.

In conclusion, let us note that it is expedient to use this model of a jet for distances $h < 5d$.

NOTATION

d, hole diameter; r, radius in the plane of the obstacle starting from the stagnation point; h, distance between the hole and the obstacle; α, coefficient of heat emission.

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