# AN EXPERIMENTAL INVESTIGATION OF THE MEAN AND OSCILLATORY CHARACTERISTICS OF A JET MOVING ALONG A POROUS CYLINDER

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The results of an experimental investigation of the effect of injection and suction on the mean and oscillatory characteristics of an isothermal turbulent jet propagating along a porous cylinder are given.

The problem of the movement of a turbulent jet along a solid porous surface with suction and injection of gas through this surface is of scientific and practical interest as, for instance, in the investigation of heat and mass transfer on sublimating, evaporating, or burning surfaces with boundary-layer control. It has been found for a uniform gas stream on a permeable surface [1-3] that even a slight modification of the boundary layer in some way can reduce the surface friction, alter the position of the region of transition from laminar to turbulent flow, and prevent the breakaway of the boundary layer. Most investigations, however, have been concerned with the averaged flow field, whereas in the investigation of these processes it is important to consider the microstructure of the flow. In the literature, on the other hand, attention has been centered mainly on the movement of a uniform stream along a surface, although semiinfinite jet flows have several interesting features. In a semiinfinite jet we can distinguish two characteristic regions: a wall region, in which, up to maximum velocity, the wall plays the main role in turbulization, as in an infinite stream, and the external jet region, where the properties of free turbulence are mainly manifested. The oscillatory characteristics in a semiinfinite jet at the wall are similar to those of a wall boundary layer, and in the external part they are similar to those of a free jet. The profile of the averaged velocity, as distinct from a free jet, is asymmetric in the region of the maximum value. This will affect the distribution of tangential stresses and velocity oscillations in this part of the jet. The present paper is devoted to an investigation of these questions with due consideration of the effect of injection and suction of gas through the surface.

We investigated the propagation of an isothermal air jet issuing from an annular gap 2.1 cm wide with an initial velocity of $u_0 = 29$ m/sec along a vertical porous cylinder of diameter 4.8 cm, through the surface of which gas is injected or sucked at such a rate that in the investigated region the flow is not "pushed away" from the surface. The velocity field at the nozzle outlet in the experimental apparatus was uniform and symmetric and there was uniform injection or suction of gas over the whole length of the curved surface of the cylinder. The permeable surface of the cylinder consisted of several layers of stainless steel gauze (made of wire 40 $\mu$ thick) on a cylindrical frame filled with Porolon. The uniformity of air injection was tested beforehand with a steady flow through the cylinder surface in the absence of the jet flow. In these conditions the injection velocity was measured directly with a hot-wire anemometer at a distance of 0.5 mm from the cylinder surface. As the measurements showed, the injection velocity $v_W$ was constant along the whole length of the cylinder and was about 1% of the jet velocity in the nozzle outlet. The total flow rate of injected and sucked gas through the side surface of the cylinder varied in the range 10-40 kg/h.

The values of the mean velocity were measured with a Pitot tube with a receiving orifice 0.5 mm high, and the oscillatory characteristics (three components of the velocity oscillations and the turbulent

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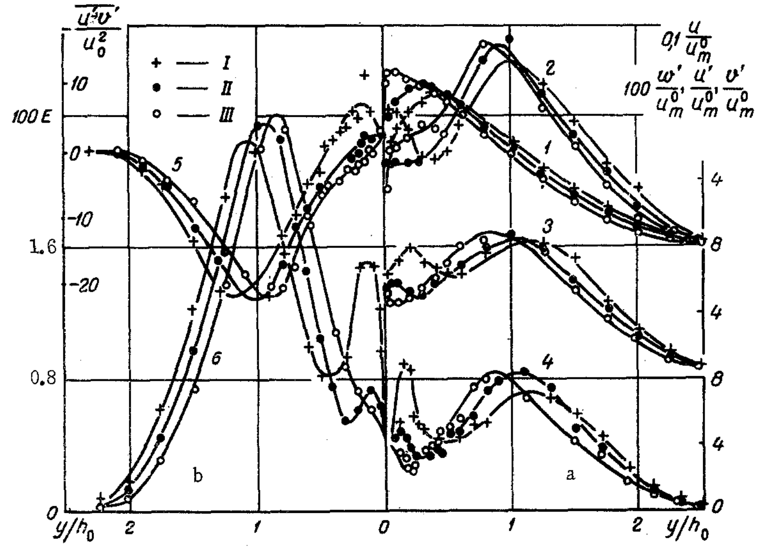

Fig. 1. Effect of injection velocity in semiinfinite jet on distribution of oscillatory characteristics over width of jet: I) $v_W/u_0 = 0.007$; II) 0; III) 0.001. a: 1) curves of averaged velocity $u/u_m^0$; 2) azimuthal oscillation $\sqrt{\overline{w'^2}}/u_m^0$; 3) longitudinal oscillation $\sqrt{\overline{u'^2}}/u_m^0$; 4) radial oscillation $\sqrt{\overline{v'^2}}/u_m^0$. b: 5) curves of turbulent tangential stress $\overline{u'v'}/u_0^2$; 6) turbulent energy $E = (\overline{u'^2} + \overline{v'^2} + \overline{w'^2})/\overline{u}_0^2$.

friction stress) were measured with a P. V. Chebyshev All-Union Electrotechnical Institute ÉTAM-3 electric hot-wire anemometer. The hot wire probes and Pitot tube were mounted in a traversing device with three degrees of freedom and could be positioned to within 0.5 mm along the jet and to within 0.1 mm in a radial direction. The coordinate origin in the boundary layer was fixed by an electric contact with the cylinder surface. The hot-wire probes were made of wire 15 $\mu$ thick and 4 mm long and were calibrated beforehand for temperature and velocity in a free stream with low turbulence intensity ($\varepsilon_0 \sim 1\%$). The width of the investigated jet was 2.1-8 cm, i.e., the dimensions of the probe were much smaller than those of the jet. Observation of the spectra of turbulent oscillations showed that most of the oscillation energy lay in the frequency range 20-500 Hz. In view of this the amplification factors and time constant were calculated for this frequency range. Control measurements of the velocity oscillations in the free jet were in good agreement with similar measurements known in the literature [10].

The root-mean-square velocity oscillations $\sqrt{\overline{u'^2}}$, $\sqrt{\overline{v'^2}}$, $\sqrt{\overline{w'^2}}$, and the turbulent friction stress $\overline{u'v'}$ in the whole flow field were measured by the method of three rotations of the wire relative to the longitudinal component of the velocity vector [4]. With this method velocity oscillations can be measured to an accuracy of 15%. The scatter of the experimental data in our measurements lay within this accuracy range. The skin friction coefficient was measured by Preston's method, and was also calculated from the available mean velocity profiles from Clauser's diagram [5]. Preston tubes of diameters 0.385, 0.535, 0.815, and 1.09 mm were calibrated in a calibrated tube.

Our experiments showed that the supply of air to, or removal of air from, the boundary layer formed when the air jet flowed over the cylinder alters the structure of the whole flow field. Injection shifts the velocity maximum away from the surface, while suction moves it towards the surface [6]. A characteristic feature of the flow is that injection reduces the maximum velocity, while suction increases it in comparison with the corresponding value of the maximum velocity in a jet without injection or suction (Figs. 1a, 2a). The variation of the maximum velocity and boundaries of the jet along the cylinder surface also depends on whether injection or suction occurs. The results presented in Fig. 2a show that injection of gas into the boundary layer causes the jet to expand, while suction causes it to contract. The length of the initial section is accordingly greater with suction and smaller with injection.

The results of measurements of the mean velocity, beginning at a certain distance from the nozzle exit section, can be represented, as shown in Fig. 3a, by a single universal relationship. With change in treatment the self-similar velocity profile is deformed. Gas suction causes it to approach the surface, while injection moves it away from the surface. If we assume, as is usually done for jet flows [7], that there is a universal dependence of the velocity on the coordinate of the form

$$u/u_m = F'(\varphi);\quad u_m = Ax^{\alpha};\quad \varphi = y/ax^{\beta},$$

where $\alpha$ and $\beta$ are self-similarity constants which characterize, respectively, the reduction of maximum velocity along the jet and the expansion of its boundaries, while x is the coordinate measured from the jet pole $S/h_0$, then in the conditions of the conducted experiment the jet boundary is a straight line in all cases of action ($\beta = 1$), and the values of $\alpha$ and $S/h_0$ are given below.

TABLE 1

|  | $v_w>0$ | $v_w=0$ | $v_w<0$ |
|---|---|---|---|
| $\alpha$ | 0,72 | 1,00 | 1,12 |
| $S/h_0$ | 2,8 | 4,1 | 5,2 |
| Recr | $5{,}2\cdot10^5$ | $5{,}8\cdot10^5$ | $6{,}2\cdot10^5$ |

As Fig. 2a shows, there is no common relationship between the jet width and the longitudinal coordinate over the whole jet length. For the flow region far from the nozzle exit section the jet boundary is a straight line, but close to this section (beyond the limits of the initial section) the boundary is distorted. This obvious restructuring of the flow evidently indicates transition of the semiinfinite jet from laminar to turbulent flow in the wall region. The transition is also confirmed by the change in nature of the skin friction and longitudinal velocity oscillations close to the wall (Fig. 2b). We will characterize the transition region by a Reynolds number $Re_{cr} = (u_m x/\nu)_{cr}$, where x is the distance from the "pole" to the jet section with maximum velocity oscillation at the wall; $u_m$ is the maximum velocity in this section.

Turbulization of the wall boundary layer results in earlier (nearer the start of the jet) transition from laminar to turbulent flow in the case of injection than in the absence of injection. Suction of gas from the boundary layer extends the region of laminar flow and the transition occurs at a relatively large distance from the nozzle. The corresponding values of the critical Reynolds number are given below.

The effect of injection and suction of gas through the boundary surface on the skin friction coefficient is shown in Fig. 2b. Injection causes the jet to move away from the surface, and the velocity gradient at the wall decreases, which leads to a reduction of the skin friction. Suction causes the opposite effects. As Fig. 2 shows, the results of measurement of the surface friction by the two independent methods mentioned above are in good agreement with one another.

Mass transfer at the surface greatly alters the microstructure of the flow. Figure 1a shows the results of measurements of the root-mean-square velocity oscillations along the three coordinate axes and the calculated profiles of oscillation energy in the same section $x/h_0 = 11$. In this section (before the self-similarity of the oscillation profiles is established) we find two velocity oscillation maxima, the greater of

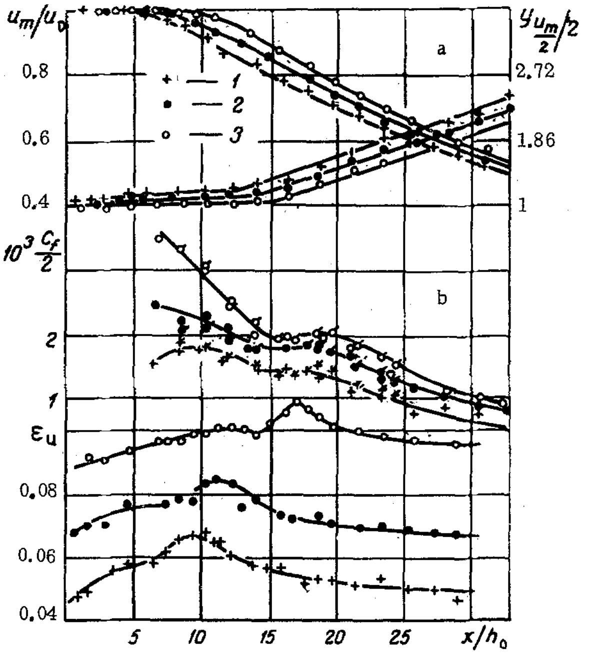

Fig. 2. Maximum velocity $u_m/u_0$ and jet width $y_{u_m/2}/h_0$ as functions of the distance from nozzle exit section (a) ($1-v_w/u_0 = 0.007$; 2) 0; 3) 0.001) and variation of turbulence intensity at wall $\sqrt{u'^2}/2$ and skin friction coefficient $c_f/2$ (b) (points with dashes – calculation by Preston's method, points without dashes by Clauser's method).

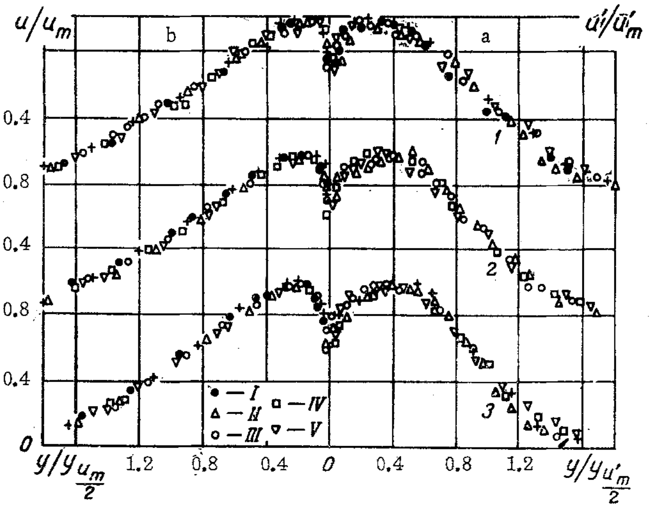

Fig. 3. Self-similar profiles of longitudinal oscillatory velocity (a) and self-similar profiles of averaged velocity (b): 1) $v_w/u_0 = 0.007$; 2) 0; 3) 0.001; I) $x/h_0 = 16$; II) 21; III) 24; IV) 28; V) 33.

which occurs in the outer part of the jet, in the mixing zone, where $u = u_m/2$ [9]. Near the surface there is a weaker maximum, similar to the oscillation maximum in a stream (turbulization at wall) [1]. Gas injection increases the wall maximum (particularly the vertical component of the oscillatory velocity $\sqrt{\overline{v'^2}}$), while suction greatly constricts the wall layer and there is hardly any oscillation maximum. With increasing distance from the nozzle exit section the two maxima fuse and the oscillation profiles become self-similar. Shortly after this the averaged velocity profiles become self-similar (Fig. 3). It should be noted that the universal profile of oscillatory velocity is formed a little earlier ($x/h_0 \sim 10$) with gas injection, and a little later ($x/h_0 \sim 16$) with gas suction, than in an unmodified jet ($x/h_0 \sim 13$). This is probably due to the effect of direction of the transverse velocity component on the wall on the transition of the laminar boundary layer to a turbulent layer. In accordance with the distribution of the oscillatory velocity components the oscillation energy also varies over the cross section of the jet (Fig. 1b). The main energy maximum is located in the outer part of the jet and injection into the jet moves this maximum away from the surface; the turbulent energy maximum in the wall layer is increased when gas is injected through the surface.

Figure 1b shows the reduction of the averaged value of the dimensionless turbulent tangential stress ($\overline{u'v'}/u_0^2$) over the width of the jet. Near the surface the turbulent friction is positive; it increases appreciably with injection and decreases with suction. In the outer part of the jet the turbulent friction has its sign reversed due to stagnation of the flow and has a second extremum in the region $y \sim y_{u_m/2}$. In this part of the jet it is several times greater than the friction at the surface. It may also be noted that gas injection through the surface mainly affects the magnitude of turbulent friction in the wall boundary layer, while in the outer part of the jet the turbulent friction is only displaced. The curves of dimensionless turbulent tangential stress near the wall are extrapolated to the values of the skin friction coefficient obtained by Preston's and Clauser's method. We noted that the turbulent friction, varying over the jet width, passes through zero at a point a little closer to the surface than the point of maximum velocity. The magnitude and direction of the transverse velocity component at the wall have some effect in this case.

## NOTATION

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| $x, y, z$ | are the longitudinal, transverse, and azimuthal coordinates; |
| $u, v$ | are the longitudinal and transverse velocity components; |
| $\sqrt{\overline{u'^2}}, \sqrt{\overline{v'^2}}, \sqrt{\overline{w'^2}}$ | are the longitudinal, transverse, and azimuthal root-mean-square velocity oscillations; |
| $v_w$ | is the injection (suction) velocity; |
| $E$ | is the oscillation energy; |
| $\varepsilon$ | is the turbulence intensity; |
| $u_m$ | is the maximum velocity in cross section of jet; |

| | |
|---|---|
| $u_0$ | is the velocity of jet on emergence; |
| $y_{u_m/2}$ | is the coordinate at which $u = u_m/2$; |
| $y_{u'_m/2}$ | is the coordinate at which $\sqrt{u'^2} = \sqrt{u'^2_m}/2$; |
| $h_0$ | is the gap width; |
| $c_f$ | is the skin friction coefficient; |
| $\tau$ | is the tangential stress; |
| $u^0_m$ | is the maximum velocity in jet on impermeable surface. |

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