EXPERIMENTAL STUDY OF TWO-DIMENSIONAL NONIMPULSIVE JETS

L. N. Ukhanova and M. O. Frankfurt

UDC 532.525.2

Results are presented from an experimental study of two-dimensional turbulent jets with zero excess momentum and different mutual locations of the sources of thrust and resistance.

Turbulent jets with zero excess momentum are seen in practice behind self-propelled bodies in steady rectilinear motion when the thrust is equal to the resistance. Study of the laws governing the development of such flows is of both practical and theoretical interest as a case of free turbulent flow with a complex initial velocity profile.

An experimental study was made of mean and pulsative characteristics of both the long-range [1] and short-range [2] regions of nonimpulsive axisymmetric turbulent jet flow. The results of these studies were used to develop an approximate integral method, based on a semi-empirical turbulence theory, for calculating characteristics of the field of mean velocities of axisymmetric jets with zero excess momentum [3].

The study [4] proposed simple power formulas to calculate the main parameters of such flows. These formulas are valid at large distances from the sources of perturbations. A detailed survey and analysis of the above investigations is contained in the monograph [5].

In recent years experimental studies have been made of nonimpulsive three-dimensional turbulent flows on models of solids of revolution with propellers and jet engines [6, 7]. Due to the complex three-dimensional character of the flow in these cases, no precise results were obtained in these works.

The present article uses a sepcially designed experimental unit to create and study two-dimensional turbulent nonimpulsive flows with different initial mean-velocity profiles.

We studied three types of flows, schematized in Fig. 1: a) flow with a symmetric initial profile of mean velocity, when the "wake" section corresponding to resistance is the internal section and the "jet" sections corresponding to thrust are external sections; b) flow with a nonsymmetric initial profile formed by one jet section and one wake section; c) flow with a symmetric initial mean-velocity profile, when the jet section is the internal section and the outer sections are wake sections.

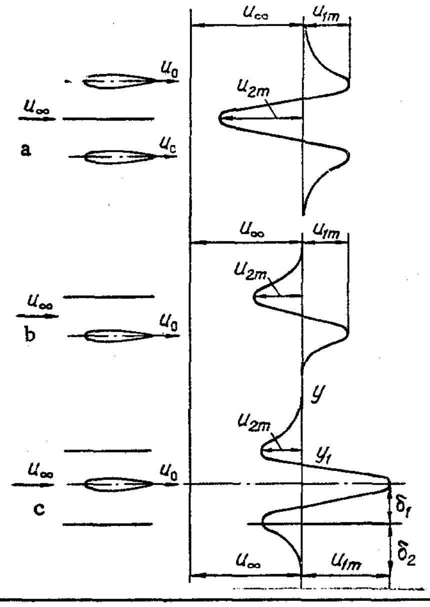

Fig. 1. Diagram of the investigated flows with symmetric (a and c) and nonsymmetric (b) initial mean-velocity profiles.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 47, No. 6, pp. 906-911, December, 1984. Original article submitted July 26, 1983.

 0022-0814/84/4706-1396$08.50

The above flows were formed by using longitudinally submerged flat plates and nozzles made in the form of hollow vanes rectangular in plan and having a lengthwise slit along the rear edge. The vanes had a symmetrical profile with a relative thickness of 0.12 mm and a chord of 100 mm. The width of the slit on the outlet section of the nozzle was 1 mm, while the span was 150 mm. Shielding rings were installed on the ends of the nozzles. The entire structure was rigidly secured in the outlet section of a closed wind tunnel with an open working part. The diameter of the tunnel nozzle was 440 mm.

The nonimpulsive flow regime was established by selecting the appropriate jet discharge velocity leaving the nozzle for a prescribed velocity of the main flow u_∞ = 15 m/sec. Before the experiment we obtained the pressure distribution in the measurement plane across and along the flow, as well as the pressure distribution in the boundary layer on the bottom shield plate, which was equipped with a drainage system. The results of these measurements showed that the pressure field is sufficiently equalized at a distance greater than 100 mm from the initial section, which corresponds to the edge of the nozzle. This data was used as the basis for selecting $\bar{x} = x/t = 180$ as the control section in which the nonimpulsive regime was chosen.

Profiles of mean velocity were obtained for all of the investigated types of flow in the section $\bar{x} = 180$ with different values of the wake parameter $m = u_\infty/u_0$. We then found the corresponding values of kinematic momentum

$$I = \int_{-\infty}^{+\infty} u\,(u - u_\infty)\,dy.$$

The laws of change in kinematic momentum in relation to the wake parameter I(m) were used to determine the jet discharge velocity at which nonimpulsive flow was realized in each variant examined. The relations $I(\bar{x})$ obtained showed that at the thus-chosen discharge velocities nearly nonimpulsive flow regimes were realized in the long-range (isobaric) regions. In connection with this, the main studies of the laws of development of the three chosen types of two-dimensional turbulent flows with zero excess momentum were conducted at distances $\bar{x} \geqslant$ 180-300 from the initial section.

Measurements of the main flow parameters over the span of the slit showed that flow was two-dimensional on the section $\bar{x} \leqslant 320$. All subsequent measurements were made as an average over the span of the section, in the symmetry plane.

Profiles of mean velocity and three components of turbulence intensity were obtained at several stations of each of the flow variants examined along with distributions of the coefficients of a one-point correlation between the longitudinal and transverse pulsations of velocity. The results of these measurements were used to calculate the Reynolds shear stresses

$$\overline{u'v'}/u_\infty^2$$

and the kinetic turbulence energy

$$e = (\overline{u'^2} + \overline{v'^2} + \overline{w'^2})/2.$$

The test data obtained showed that the intensities of the lengthwise and transverse pulsations of velocity are of roughly the same order, while the transverse distributions change little along the flows: the Reynolds shear stresses take zero values at points practically corresponding to the maximum and minimum values of mean velocity. The extreme values of the shear stresses and the maximum values of kinetic turbulence energy occur in the regions of the maximum transverse velocity gradients in the wake and jet sections of the flows. Thus, the transverse distributions of the pulsative parameters of two-dimensional nonimpulsive flows have the same features as were noted earlier in studies of axisymmetric turbulent flows with zero excess momentum [3, 5].

Figure 2 shows typical profiles of mean velocity in several sections and distributions of the Reynolds shear stresses and kinetic turbulence energy in one section ($\bar{x} = 260$) for all of the types of flow investigated.

One more important feature of the mean-velocity profiles is evident from examining them. Since velocity defects diminish rapidly along the flow and there is negligible increase in the transverse dimensions, the local Reynolds number determined from the local value of the velocity defect and the local transvserse dimension decreases along the flow. This is evidence of the tendency, typical of two-dimensional flows with zero excess momentum, for turbulence to decay at large distances from the source of the perturbation.

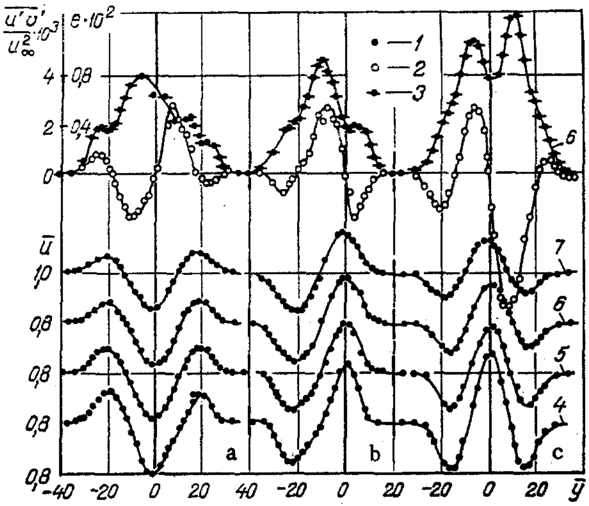

Fig. 2. Profiles of mean and pulsative parameters of nonimpulsive two-dimensional flows with symmetric (a and c) and nonsymmetric (b) velocity profiles: 1) mean velocity; 2) Reynolds stresses; 3) kinetic turbulence energy; 4) $\bar{x}$ = 180; 5) 220; 6) 260; 7) 300.

The method of small perturbations [4] was used to obtain laws governing this decay for two-dimensional laminar nonimpulsive flows with symmetric and nonsymmetric initial mean-velocity profiles similar to those realized in the above experiment. It turned out that in all three cases the asymptotic law of velocity defect decay is independent of the initial form of the profile and is expressed by a simple power equation:

$$\bar{u}_{1m} \sim \bar{u}_{2m} \sim \bar{x}^{-3/2},$$

with the characteristic transverse dimension of the flow here also changing along the flow in accordance with a power relation:

$$\bar{\delta}_1 \sim \bar{\delta}_2 \sim \bar{x}^{1/2}.$$

Application of the above laws of development of laminar nonimpulsive two-dimensional flows to the case of a turbulent regime with the assumption of constancy of the turbulent transfer coefficient across the flow [5] made it possible to obtain corresponding asymptotic formulas for the long-range region of two-dimensional turbulent flow with zero excess momentum:

$$\bar{u}_{1m} \sim \bar{u}_{2m} \sim \bar{x}^{-3/4}; \quad \bar{\delta}_1 \sim \bar{\delta}_2 \sim \bar{x}^{1/4}.$$

Figure 3 compares experimentally obtained laws of velocity defect decay corresponding to jet and wake flow regions along the investigated two-dimensional nonimpulsive flows against the above power relation (the solid lines represent the calculated results). Values of velocity defects in the section $\bar{x}$ = 180 were chosen as the initial data. With different mutual locations of the sources of thrust and resistance in a certain initial section of two-dimensional turbulent nonimpulsive flows, the laws of decay in the long-range regions, where velocity defects $\bar{u}_{1m}$ and $\bar{u}_{2m}$ are on the order of 0.1, prove to be practically the same and are satisfactorily described by a simple power relation (Fig. 3a and b). When the velocity defects are substantial, the asymptotic formulas prove to be too coarse and thus do not fully agree with the experimental relations (the solid lines in Fig. 3c). The reason for such disagreement is evidently linearization of the initial boundary-layer equations. This can be seen if we examine the solution of the corresponding nonlinear problem on the development of nonimpulsive two-dimensional turbulent flows.

Having this goal in mind, we used a well-known integral method of calculation [8] to evaluate parameters of a two-dimensional nonimpulsive turbulent flow with a symmetrical initial velocity profile, schematized in Fig. 1c; this corresponds to the experimental variant with the greatest defects in the profiles of mean velocity (see Fig. 3c).

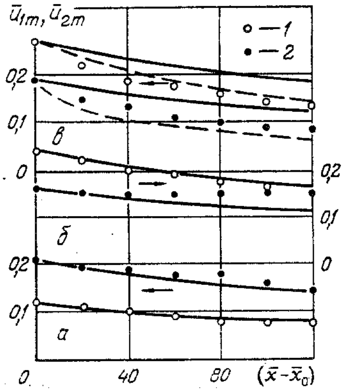

Fig. 3. Decay of maximum defects of mean velocity along the jet (1) and wake (2) regions of nonimpulsive flows. The solid line corresponds to the relation $\bar{u}_{1m} \sim \bar{x}^{-3/4}$, while the dashed line shows the numerical calculation; $\bar{x}_0 = 180$.

The method is based on the possibility of approximating the mean-velocity profile by two normal flow profiles corresponding to a section of jet flow (internal, $y \leqslant \delta_1$) and wake flow (external, $\delta_1 \leqslant y \leqslant \delta_1 + \delta_2$) (see Fig. 1c): on the section $y \leqslant \delta_1$, $\bar{u} = 1 - \bar{u}_{2m} + (\bar{u}_{1m} + \bar{u}_{2m})f(\eta_1)$, $\eta_1 = y/\delta_1$; on the section $\delta_1 \leqslant y \leqslant \delta_2$, $\bar{u} = 1 - \bar{u}_{2m}f(\eta_2)$, $\eta_2 = (y - \delta_1)/\delta_2$.

Analysis of the results of the above tests showed that the jet and wake parts of the mean-velocity profiles can be considered similar and, as in [5], can be represented in universal form:

$$f(\eta) = 1 - 6\eta^2 + 8\eta^3 - 3\eta^4.$$

The following four relations were used to calculate the laws of change in the parameters of two-dimensional nonimpulsive flows: the condition of triviality of the excess momentum; the momentum equation for the internal region of the flow bounded by the surface $y = y_1$, on which $u = u_\infty$, with the coordinate y_1 being determined from the formula for the mean-velocity profile on the jet section of the flow $f(y_1/\delta_1) = \bar{u}_{2m}/(\bar{u}_{1m} + \bar{u}_{2m})$; the symmetry condition on the jet axis ($y = 0$); the "symmetry" condition on the lines of minimum velocities ($y = \delta_1$), at the junction of the wake and jet velocity profiles. The last two conditions follow from the boundary-layer equations, since at $y = 0$ and $y = \delta_1$ the transverse gradient of longitudinal velocity is equal to zero. The relations mentioned above have the form

$$\int_0^\delta u(u - u_\infty)\,dy = 0;\ \frac{d}{dx}\int_0^{y_1} u(u - u_\infty)\,dy = \frac{\tau_1}{\rho},$$

$$\rho(u_\infty + u_{1m})\frac{du_{1m}}{dx} = \left(\frac{\partial\tau}{\partial y}\right)_{y=0};\ \rho(u_\infty - u_{2m})\frac{du_{2m}}{dx} = \left(\frac{\partial\tau}{\partial y}\right)_{y=\delta_1}.$$

The shear stress was determined by the semiempirical Prandtl relation $\tau = \rho\nu_t\partial u/\partial y$. Meanwhile, in this calculation, as in the linearized solution presented above, the turbulent transfer coefficient ν_t was assumed constant across the entire section and proportional to the total velocity-profile defect and the total flow width, i.e.,

$$\nu_i = \varkappa(\delta_1 + \delta_2)(u_{1m} + u_{2m}),$$

where $\varkappa$ is an empirical constant.

By means of simple transformations the problem is reduced to integration of a system of four ordinary first-order differential equations solved relative to the derivatives of the sought functions δ_1, δ_2, u_{1m}, and u_{2m} with respect to the longitudinal coordinate. This system can easily be solved numerically on a computer. In the calculations, the initial values of the parameters $\bar{\delta}_1$, $\bar{u}_{1m}$, and $\bar{u}_{2m}$ were chosen from experiment and corresponded to the section $\bar{x} = 180$; the initial value of the parameter $\bar{\delta}_{2m}$ in the calculation was chosen on the basis of the condition of triviality of the excess momentum. The dashed lines in Fig. 3 show the results of numerical calculation.* With a value of the empirical constant $\varkappa = 0.0105$, we obtained satisfactory agreement between the theoretical relations and experimental data.

Thus, the disagreement noted in Fig. 3c between the calculated (by asymptotic formulas) and experimental values of the velocity defect are explained by the imperfection of the lin-

*The numerical calculation was performed on a computer by engineer A. E. Usachov.

earized theory. Deviation from linearization led to a significant improvement in the agreement between the calculated and experimental values of $\bar{u}_{1m}$ and $\bar{u}_{2m}$.

NOTATION

t, width of slit; $\bar{x} = x/t$, $\bar{y} = y/t$, dimensionless longitudinal and transverse coordinates; u_∞, velocity of incoming flow; u_0, velocity of discharge of jet from slit; $m = u_\infty/u_0$; $\bar{u} = u/u_\infty$, relative value of the longitudinal component of mean velocity; $\bar{u}_{1m} = u_{1m}/u_\infty$, $\bar{u}_{2m} = u_{2m}/u_\infty$, dimensionless defects of mean velocity; u', v', w', pulsations of the velocity along the flow, across the flow, and along the span of the slit; $\overline{u'v'}$, Reynolds shear stresses; e, kinetic turbulence energy; δ_1, δ_2, characteristic transverse dimensions; ρ, density; τ, shear stress; ν_t, eddy viscosity coefficient; ϰ, constant.

LITERATURE CITED

1. E. Naudasher, "Flow in the wake of self-propelled bodies and related sources of turbulence," J. Fluid Mech., 22, Pt. 4, 625-656 (1965).
2. A. S. Ginevskii, K. A. Pochkina, and L. N. Ukhanova, "Turbulent jets with zero excess momentum," in: Resistance and Navigability of Ships [in Russian], No. 89, NTO SP, Sudostroenie, Leningrad (1967), pp. 43-50.
3. A. S. Ginevskii, K. A. Pochkina, and L. N. Ukhanova, "Laws of propagation of a turbulent jet with zero excess momentum," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 6, 164-166 (1966).
4. G. Birkhoff and E. H. Zarantonello, Jets, Wakes, Cavities, Academic Press (1967).
5. A. S. Ginevskii, Theory of Turbulent Jets and Wakes [in Russian], Mashinostroenie, Moscow (1969).
6. J. A. Schetz and A. K. Jabukowski, "Experimental studies of the turbulent wake behind self-propelled slender bodies," AIAA J., 13, No. 12, 1568-1575 (1975).
7. J. A. Schetz, E. B. Daffan, and A. K. Jakubowski, "The turbulent wake behind slender propeller driven bodies at angle of attack," AIAA Pap., No. 133 (1977).
8. V. M. Arbekova, L. N. Voitovich, A. S. Ginevskii, et al., "Calculation of turbulent wakes with allowance for initial nonuniformity of the velocity profile," in: Applied Aerodynamics [in Russian], Vol. 30, Mashinostroenie, Moscow (1973), pp. 120-136.

EXPERIMENTAL STUDY OF HEAT TRANSFER BETWEEN A HOT WALL AND IMPINGING DROPS

V. G. Labeish and A. G. Pimenov

UDC 536.24

We have studied heat transfer between the wall and impinging drops by using quick-response temperature sensors. We have obtained transient surface-temperature profiles and the heat-removal characteristics.

In spite of the wide use of high-efficiency cooling by spray jets, data on heat transfer between a wall and impinging drops are meager and contradictory [1-3]. It was noted in [4] that under similar conditions the results of various experimenters on heat removal of a drop differ by an order of magnitude and more, which is accounted for by the imperfection of the experimental methods, mainly the large and uncontrollable inertia of the surface-temperature sensors (STS). Transient profiles $T_t(\tau)$ were first obtained in [5, 6], but there are no data on the dynamic characteristics of the temperature sensors.

We present the results of experiments performed in the development of [7, 8].

Measuring System. We have employed thermocouple STS similar to those used earlier for the thermometry of barrels of rapid-firing guns [9, 10]. A Chromel thermoelectrode 0.3 mm in diameter was placed in a hole in a nickel calorimeter (a cylinder 30 mm in diameter and 20 mm high) and electrically insulated from it by an oxide film formed by preliminary annealing in an oven. When the heat-transfer surface (the end of the calorimeter) was polished together

Northwestern Correspondence Polytechnic Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 47, No. 6, pp. 911-919, December, 1984. Original article submitted September 19, 1983.

 0022-0841/84/4706-1400$08.50