TURBULENCE CHARACTERISTICS OF EXTERNAL FLOW AROUND TURBINE BLADES

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Local values of the turbulence characteristics of the external flow around and along convex and concave surfaces of turbine blades are calculated. By solving a system of differential equations of the turbulent-mixing energy transfer and the dissipation rate in flow around the blades, the distribution of the degree of turbulence, the turbulent viscosity, and the turbulence scale along the outline of the profile is obtained. The theoretical results are compared with experimental data on the local degree of turbulence at the back and saddle of the blades in turbine assemblies of active reactive types.

In determining the turbulence characteristics of fluid flows, it is usual to solve a system of differential equations describing the turbulent flow by means of two-parameter models of turbulence. In an approximate formulation, taking account of certain assumptions, an analytical solution of the system of turbulence kinetic-energy and pseudovorticity equations for external flow as obtained in [1]. The local values of the degree of turbulence at TS-1A and T-4 profiles calculated on the basis of this solution correctly reflect its variation along the turbine-blade outline as a whole in qualitative terms, but at the same time are higher than the experimental values on the convex surface of the blades and lower on the concave surfaces [2]. This is because no account was taken in [1] of the influence of the surface curvature on the turbulent pulsations, which lead, as is known, to some quenching of the turbulent pulsations at the convex surface and significant intensification at the concave surface.

Calculations of a turbulent boundary layer by Bradshaw, Meroni, Jones, Launder, and others indicate that the usual models of turbulence do not take adequate account of the influence of surface curvature. Wilcox and Chambers established, on the basis of detailed analysis of the physical laws of flow along a curvilinear surface, that the curvature principally influences the energy of turbulent mixing, which is proportional to the pulsational-velocity component v' along the normal to the surface. In connection with this, the replacement of the differential equation for the kinetic energy $k = 0.5(\overline{u'^2} + \overline{v'^2} + \overline{w'})$ by the differential equation describing the transfer of the turbulent-mixing energy $e = 2.25\overline{v'^2}$ was proposed in [3], adding terms that take account of the influence of surface curvature on the turbulent pulsations to the latter equation.

In [3], this equation was solved together with the equation for the rate of dissipation of the turbulence $\omega = (3\nu/\beta^*)(\overline{\partial v'/\partial y})^2/\overline{v'^2}$ (in some sources, for example, in [1], ω is referred to as the pseudovorticity). For gradient flows, it was recommended in [4, 5] that the turbulent-energy transfer be taken into account by means of the normal Reynolds stress, which may be written in the form $(\overline{u'^2} - \overline{v'^2})(du/dx) = 0.55e(du/dx)$. In [6], the generation of the turbulence dissipation rate was taken into account in the form $0.333\omega^2 du/dx$. Thus, on the basis of the recommendations of [3-6], the following initial system of equations is obtained

$$u\frac{\partial e}{\partial x} + v\frac{\partial e}{\partial y} + \frac{9}{2}\frac{u}{R}\nu_T\frac{\partial u}{\partial y} = \left[\alpha^*\left(\frac{\partial u}{\partial y} - \frac{u}{R}\right) - \beta^*\omega\right]e + \frac{\partial}{\partial y}\left[(\nu + \sigma^*\nu_T)\frac{\partial e}{\partial y}\right] - 0.55e\frac{\partial u}{\partial x};$$

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$$u\frac{\partial\omega^2}{\partial x}+v\frac{\partial\omega^2}{\partial y}=\left\{\alpha\left(\frac{\partial u}{\partial y}-\frac{u}{R}\right)-\left[\beta+2\sigma\left(\frac{\partial e}{\partial y}\right)^2\right]\omega\right\}\omega^2+$$
$$+\frac{\partial}{\partial y}\left[(\nu+\sigma\nu_T)\frac{\partial\omega^2}{\partial y}\right]+0.333\omega^2\frac{\partial u}{\partial x},$$

where

$$\alpha=\frac{1}{3}\left[1-\frac{10}{11}\exp(-2\,\mathrm{Re}_T)\right];$$
$$\alpha^*=0.3\left[1-\frac{10}{11}\exp\left(-\frac{1}{2}\mathrm{Re}_T\right)\right];$$
$$\beta=0.15;\quad \beta^*=0.09;\quad \sigma=\sigma^*=0.5;\quad \nu_T=\frac{e}{\omega};\quad \mathrm{Re}_T=\frac{e}{\omega\cdot\nu}.$$

For approximate determination of the turbulence characteristics along the outline of turbine blades in external flow, the terms containing derivatives with respect to the coordinate y are neglected and, after substitution of the values of α, α^*, β, β^*, Re_T, a system of differential equations for the turbulent-mixing energy and the dissipation rate beyond the limits of the boundary layer is obtained

$$U\frac{de}{dx}=-0.3e\left[1-\frac{10}{11}\exp\left(-\frac{1}{2}\cdot\frac{e}{\omega\nu}\right)\right]\frac{U}{R}-0.09\omega e-0.55e\frac{dU}{dx};\tag{1}$$

$$U\frac{d\omega^2}{dx}=-\frac{1}{3}\omega^2\left[1-\frac{10}{11}\exp\left(-2\frac{e}{\omega\nu}\right)\right]\frac{U}{R}-0.15\omega^3+0.333\omega^2\frac{dU}{dx},\tag{2}$$

where R is the radius of curvature of the surface and is taken with a plus sign at convex sections and with a minus sign at concave sections.

The solution of Eqs. (1) and (2) is obtained by a fourth-order Runge–Kutta method. The point $\bar{x}_1 = x_1/p = 0.01$ is taken as the initial calculation point on the convex and concave surfaces of the blade. To determine the turbulent-mixing energy at point $\bar{x}_1$, the experimental relation between the degree of turbulence at this point Tu_1 and that in front of the blade input edge $\mathrm{Tu}_{\mathrm{in.ed}}$ is used, as well as the dependence $\mathrm{Tu}_{\mathrm{in.ed}} = 8.45\mathrm{Tu}_0(d/b)^{0.455}$ obtained in [2]. The dissipation rate of the turbulence at point $\bar{x}_1$ is determined from the relation obtained from the finite-difference approximation of Eq. (1) for this point

$$\omega_1=11.1\frac{U_1}{\Delta x_1}\left[1-\frac{e_1}{e_{\mathrm{in.ed}}}-0.3\frac{\Delta x_1}{R_1}-0.55\left(1-\frac{U_{\mathrm{in.ed}}}{U_1}\right)\right].$$

As shown by calculations, the term $(10/11)\exp(-e/2\omega\nu) \ll 1$ at the initial point x_1, and therefore it may be neglected in determining ω_1, without significant error.

TS-1A and T-4 turbine blades are investigated theoretically with a Reynolds number of the incoming flux $\mathrm{Re}_0 = 3.3\cdot10^5$ when $\mathrm{Tu}_0 = 1.5$-9.6 prior to the turbine assemblies.

The distribution of the turbulent-mixing energy e and the dissipation rate ω along the outline of the turbine profiles is obtained. The reliability of the theoretical results is tested by comparison with experimental data [2]. Since the degree of turbulence with respect to the longitudinal component of the velocity pulsations $\mathrm{Tu} = \sqrt{\overline{u'^2}}/U$ is determined in the experiments, the distribution $\overline{u'^2} = f(\bar{x})$ is obtained from the resulting distribution $e = f(\bar{x})$, using the experimental data in [5], according to which the following relations may be written for gradient flows over the whole thickness of the boundary layer and at its external boundary, within the limits of experimental error

$$k\approx0.75(\overline{u'^2}+\overline{v'^2});\quad 0.5k\approx(\overline{u'^2}-\overline{v'^2}),$$

and hence $k \simeq 1.1\overline{u'^2}$, $\overline{v'^2} = 0.45\overline{u'^2}$ and thus $e = 2.25\overline{v'^2} \simeq \overline{u'^2}$.

Analysis of the theoretical local values of the degree of turbulence in external flow along convex and concave surfaces of TS-1A and T-4 blades shows that, in all cases, the theoretical and experimental data are in good agreement. As an example, they are compared

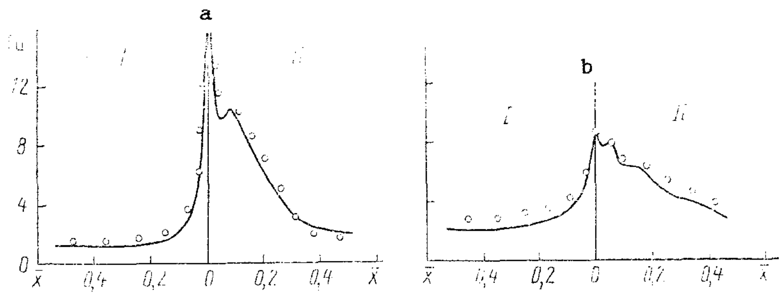

Fig. 1. Local values of the degree of turbulence along the outline of TS-1A profiles when Tu_0 = 96% (a) and T-4 profiles when Tu_0 = 6.3% (b): I) convex surface; II) concave surface. Tu, %.

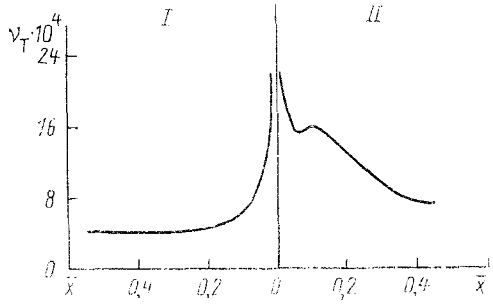

Fig. 2. Distribution of turbulent viscosity ν_T in external flow along the convex (I) and concave (II) surfaces of a TS-1A blade when Tu_0 = 7.2%, ν_T, m^2/sec.

in Fig. 1 for some values of the degree of turbulence of the incoming flow Tu_0. The results obtained indicate that, in both active and reactive turbine assemblies, the distribution of local values of the degree of turbulence along the blade outline is considerably nonuniform. Note that, with an overall tendency to reduction turbulence intensity from the input to the output edge, its level at concave surfaces is significantly higher than at convex surfaces, for both types of blade. This is explained by the additional generation of turbulent-mixing energy in flow around concave surfaces.

Using the well-known dependences for the turbulent viscosity $\nu_T = e/\omega$ and the scale of turbulence $L_T = e^{0.5}/\omega$, these parameters are determined along the convex and concave surfaces of the TS-1A and T-4 turbine blades. As an example, the distribution of the turbulent viscosity over the outline of the TS-1A profile when Tu_0 = 7.2% is shown in Fig. 2.

The results of theoretical investigation permit the conclusion that Eqs. (1) and (2) adequately reflect the physical laws of variation in the turbulence characteristics in external flow along the convex and concave surfaces of turbine blades. The theoretical results obtained are in good qualitative and quantitative agreement with experimental data.

The local values of the turbulence characteristics along convex and concave surfaces of turbine blades obtained by solving the above differential equations may be used in engineering practice to take account of the influence of turbulence on the coordinates of transition from a laminar to a turbulent boundary layer and on the intensification of heat transfer at the blade surface.

NOTATION

k, kinetic energy of turbulence; e, energy of turbulent mixing; ω, dissipation rate of turbulence (pseudovorticity); ν_T, turbulent viscosity; x, y, longitudinal and transverse coordinates; u, U, longitudinal velocity within and outside the boundary layer; R, radius of curvature of surface in flow; p, profile perimeter; b, d, chord and diameter of input edge of blade; Tu_0, degree of turbulence of incoming flow; $Tu_{in.ed}$, degree of turbulence immediately preceding the input edge of the blade; Tu, local value of the degree of turbulence at the surface; Re_0, Reynolds number of incoming flow in terms of the parameters preceding the turbine assembly.

LITERATURE CITED

1. V. D. Sovershennyi, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 4, 31-35 (1984).
2. V. M. Kapinos, A. F. Slitenko, and V. B. Titov, Izv. Sib. Otd., Akad. Nauk SSSR, Ser. Tekh. Nauk., Issue 4, No. 15, 24-28 (1987).
3. D. Wilcox and T. Chambers, Rak. Tekh. Kosmon., 15, No. 4, 152-161 (1977).
4. I. K. Rotta, Turbulent Boundary Layer in Incompressible Liquid [in Russian], Leningrad (1967).
5. A. I. Leont'ev, E. V. Shishov, V. P. Afanas'ev, and V. P. Zabolotskii, in: Heat Transfer VI [in Russian], Vol. 1, Part 2, Minsk (1980), pp. 136-146.
6. R. M. Traci and D. C. Wilcox, AIAA J., 13, No. 7, 890-896 (1975).

STARTUP AND STEADY OPERATING CONDITIONS OF SUPERSONIC DIFFUSER

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An engineering method is proposed for calculating the gas dynamics, friction, and heat transfer of steady and nonsteady flows in supersonic diffusers. The calculation results are compared with experimental data for theoretical Mach numbers M = 2 and 3 preceding the diffuser.

1. Introduction

An urgent problem in increasing the operational efficiency of power plants is the creation of a supersonic diffuser with reduced total-pressure losses in operating and variable conditions. Decrease in the startup pressure difference is especially important, since in real diffusers with uncontrollable geometry the total-pressure losses in startup conditions are at least twice the losses in operating conditions [1]. The actual flow pattern in the startup of a supersonic diffuser is very complex and depends significantly on the startup method, channel geometry, the methods used to control the boundary layer and the heat-transfer shielding of the walls, and a number of other factors. It is necessary to create a reliable engineering method of calculating the gas-flow parameters in supersonic diffusers since the application of shaped diffusers permits significant reduction in total-pressure loss [2].

In creating an engineering method, it is necessary to solve the problem of calculating the nonsteady turbulent boundary layer, taking account of perturbing factors such as the compressibility, nonisothermal conditions, significant positive longitudinal pressure gradient, surface roughness, interaction with density discontinuities, and flow singularities due to the methods used to control the boundary layer and the heat-transfer shielding of the walls.

Experimental data on the startup and steady operating conditions of a supersonic diffuser are outlined below, and an engineering method of calculating the gas dynamics, friction, and heat transfer in gas flow in a supersonic diffuser is proposed.

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