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STUDY OF LOCAL HEAT TRANSFER ON END SURFACE OF STATOR MODEL

A. A. Khalatov, K. I. Kapitanchuk, A. S. Kovalenko,
and A. N. Trufanov

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We present the results of an experimental study of the local heat transfer on the end surface of a gas turbine engine (GTE) turbine stator model. On the basis of the proposed method for correlating the experimental data we obtain a single similarity equation, accounting for the influence of streamline curvature, three-dimensional nature of the flow, flow acceleration along the channel, and flow laminarization.

The primary tendency in the improvement of aircraft gasturbine engines is increase of the turbine inlet temperature [1]. The present period of engine development is characterized by the temperature level 1600-1650 K, which is increasing on the average by 7-10 degrees a year.

The stators of the first stages of the high-temperature turbines of modern aircraft gas turbine engines have a highly developed convective-barrier cooling system [2]. In the best foreign engines the relative cooling air flow reaches 10-15%, which requires optimization and rational organization of the cooling system for all the stator surfaces - the vanes and the upper and lower end surfaces.

Reliable similarity equations, characterizing the local heat transfer coefficients, are necessary for cooling system analysis. These equations for the stator vanes have been presented in the literature [1,2]. Data on the local heat transfer coefficients on the end surfaces [3,4] are scarce and relate to the average parameters, and the techniques used to represent the final results do not make it possible to consider the obtained equations adequately universal. The complex three-dimensional nature of the flows, streamline curvature, flow acceleration, and other factors require the development of physically substantiated calculatin methods, accounting for the peculiarities of the aerodynamics of the flow on the end surface of the stators.

We shall examine three-dimensional incompressible isothermal flow on the end surface of the stator with the presence of a longitudinal pressure gradient (Fig. 1). The equations of motion in the Meidzher coordinate system with account for streamline curvature have the following form [5]:

$$\bar{u}\frac{\partial\bar{u}}{\partial\bar{x}}+\bar{v}\frac{\partial\bar{u}}{\partial\bar{y}}+\bar{w}\frac{\partial\bar{u}}{\partial\bar{z}}+\bar{u}^2\frac{L}{R}\frac{\bar{w}}{\bar{u}}=\bar{c}_x\frac{\partial\bar{c}_x}{\partial\bar{x}}+\frac{\nu}{c_1L}\frac{\partial^2\bar{u}}{\partial\bar{y}^2};\qquad(1)$$

$$\bar{u}\frac{\partial\bar{w}}{\partial\bar{x}}+\bar{v}\frac{\partial\bar{w}}{\partial\bar{y}}+\bar{w}\frac{\partial\bar{w}}{\partial\bar{z}}+\bar{u}^2\frac{L}{R}=\bar{c}_x^2\frac{L}{R}+\frac{\nu}{c_1L}\frac{\partial^2\bar{w}}{\partial\bar{y}^2};$$

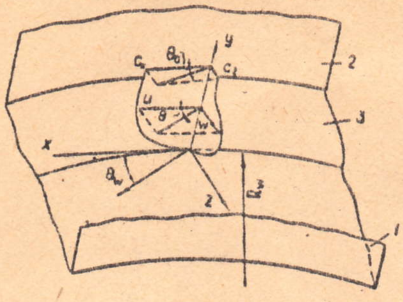

Fig. 1. Velocity profiles in three-dimensional boundary layer on the end surface: 1) back of blade; 2) face of blade; 3) end surface.

$$\frac{\partial \bar{u}}{\partial \bar{x}} + \frac{\partial \bar{v}}{\partial \bar{y}} + \frac{\partial \bar{w}}{\partial \bar{z}} + \bar{w}\frac{L}{R} = 0. \qquad (1)$$

Here $\bar{u} = \bar{u}/c_1$, $\bar{v} = \bar{v}/c_1$, $\bar{w} = \bar{w}/c_1$ are the dimensionless longitudinal, vertical, and transverse components of the velocity (Fig. 1); c_1 is the characteristic flow velocity; L is the characteristic profile dimension; R is the streamline radius of curvature; $\bar{c}_x = c_x/c_1$, $\bar{c}_z = c_z/c_1$ are the dimensionless longitudinal and transverse components of the flow velocity at the outer edge of the boundary layer; ν is the kinematic viscosity of the stream.

It follows from analysis of (1) that kinematic similarity of the flows requires satisfaction of the following conditions:

$$\bar{c}_x \frac{\partial \bar{c}_x}{\partial \bar{x}} = \text{idem}; \ \text{Re} = \text{idem}; \ \bar{c}_x^2 \frac{L}{R} = \text{idem}; \ \text{tg}\,\theta_w = \text{idem}.$$

From combined examination of the complexes $\bar{u}^2 \frac{L}{R} \frac{\bar{w}}{\bar{u}}$ and $\bar{u}^2 \frac{L}{R}$, in (1) there follows the requirement $\bar{w}/\bar{u} = \text{idem}$. Most important for description of the heat transfer processes is the condition $\text{tg}\,\theta_w = \left[\frac{d\bar{w}}{d\bar{u}}\right]_{\bar{y}=0}$, where $\text{tg}\,\theta_w$ is the tangent of the surface (limiting) angle of streamline deviation from the longitudinal direction (Fig. 1).

In the examined case the similarity equation for local heat transfer on the end surface has the form

$$\text{Nu} = \text{Nu}\left(\text{Re}, \ \bar{c}_x \frac{\partial \bar{c}_x}{\partial \bar{x}}, \ \bar{c}_x^2 \frac{L}{R}, \ \text{tg}\,\theta_w\right). \qquad (2)$$

The second of the similarity conditions in (2) accounts for the influence of the longitudinal pressure gradient, while the third and fourth respectively account for the influence of streamline curvature and transverse flows in the boundary layer. We must also introduce into (2) the Prandtl number, and if necessary the other similarity numbers reflecting additional factors (nonisothermicity, compressibility, and so on).

We note that the similarity number $\bar{c}_x^2(L/R)$ differs from the similarity numbers obtained in [6,7] in use of the aerodynamic characteristics of the stream; for $\bar{c}_x = 1$ it coincides with the similarity number obtained in [6].

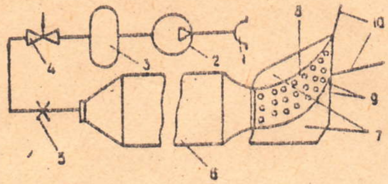

Fig. 2. Experimental setup: 1) intake; 2) compressor; 3) receiver; 4) valve; 5) diaphragm; 6) stilling chamber; 7) back and face of stator model; 8) end surface; 9) heat flux sensors; 10) regulating flaps.

The experimental part of the work was performed on a setup in which we used as the working section a two-dimensional model of the stator passage of a high-temperature turbine of an aircraft GTE (Fig. 2). The facility is an open-circuit type wind tunnel. The stator model walls 7 were made of wood, and the end surfaces were made of textolite. The width and height of the passage at the entrance are respectively 160 and 100 mm, the profile chord b_0 = 243 mm. The ratio of the inlet and exit areas is 3.24, the angle of flow discharge from the model is 18°.

The conduct of the studies in the channel made it possible to eliminate the intake horseshoe vortex, the influence of which on the structure of the boundary layer would have made it impossible to identify the degree of influence of each of the factors in Eq. (2) on the heat transfer.

The local heat transfer coefficients were determined with the aid of heat flux sensors, operating on the basis of the principle of the regular thermal regime of the first kind. All the recommendations of [8] were considered in the development of the sensors. The developmental tests and calibration of the sensors were performed on an adiabatic plate of the same thickness and of the same material as the surface being studied. The error of determination of the heat transfer coefficients with gradient-free flow over the plate was ±8%.

The sensors were installed on the lower end surface near the back (6 points) and the face (5 points), and also on the centerline (5 points) (Fig. 2). The thermal unsteadiness necessary for realization of the regular regime method was created by simultaneous cooling for 5-7 seconds of all the sensors through a system of tubes introduced from the upper end surface. The aerodynamic part of the study included measurements of the resultant velocity profile and the angle θ of flow "twist" in the boundary layers with the aid of miniature three-point probes.

The results of primary correlation of the experimental heat transfer data are shown in Fig. 3. The governing velocity in the Reynolds number was the local flow velocity c_x (Fig. 1), and the governing dimension in the Nu_x and Re_x numbers was the distance x from the entrance to the examined section along the corresponding line. Analysis of Fig. 3 shows that the experimental data significantly exceed the results obtained in the calculation using the equation of local heat transfer on a flat plate:

$$Nu_x = 0.029\, Re_x^{0.8} Pr^{0.4}. \qquad (3)$$

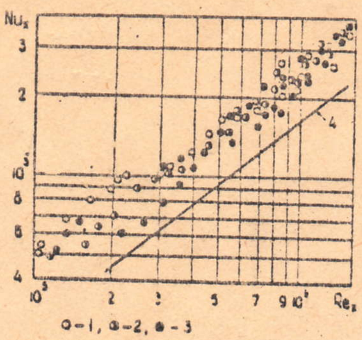

Fig. 3

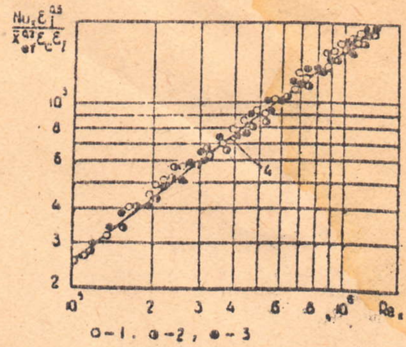

Fig. 4

Fig. 3. Results of initial correlation of experimental data: 1) face of vane; 2) centerline; 3) back of vane; 4) Eq. (3).

Fig. 4. Results of experimental data correlation based on local heat transfer on the end surface (for notations see Fig. 3).

This is explained by the fact that formula (3) does not take into account al the factors existing in the experiments: longitudinal pressure gradient, str line curvature, transverse flows in the boundary layer, and possible laminar zation of the boundary layer. The differing in magnitude and direction natu of the action of the curvature and the secondary flows at various points on end surface leads to a situation in which the experimental data for the indiv dual lines scatter noticeably, particularly in the low Reynolds number regio

Figure 4 shows the results of correlation of the experimental data with account for the influencing factors. With no more than ±8% error, the experi mental points for the individual lines of the end surfaces are correlated by the single equation

$$Nu_x = 0{,}029\, Re_x^{0.8} Pr^{0.4}\, \bar{x}_{ef}^{-0.2} \varepsilon_c \varepsilon_l \varepsilon_t^{-0.5}. \quad (4)$$

Here $\bar{x}_{ef} = \left[\int_0^{\bar{x}} \rho\bar{c}_x d\bar{x}\right] / (\rho\bar{c}_x\bar{x})$ is the effective length, determining the influenc of the longitudinal velocity gradient [9] (introduced in place of the comple $\bar{c}_x \frac{\partial \bar{c}_x}{\partial \bar{x}}$); $\varepsilon_c = 1 + 1{,}28(\bar{c}_x^2 b_0/R)^{-0.33}$ is a function accounting for the streamline curva- ture; $\varepsilon_t = 1 + tg\,\theta_w$ is a function accounting for the influence of the transvers flows in the boundary layer (three-dimensionality of the flow). The experi- mental data were reduced by the traditional method. The exponents of ε_c, ε_l, ε were determined by selecting experimental points with two unknown parameters and subsequent graphical construction.

As the characteristic velocity c_1 in the calculation of $\bar{c}_x$ we took the mass-average velocity at the entrance to the setup.

Analysis of the results of the aerodynamic and thermal studies showed th because of flow acceleration starting at some section the effects of flow lam narization appear. This situation is accounted for by the function ε_l, which in the examined case has the following form:

$$\varepsilon_l = 1 - 0{,}2\,\mathrm{Eu}_x^{-0{,}33} \quad \text{for} \quad \mathrm{Eu}_x/\mathrm{Re}_x < 2\cdot 10^{-6};$$

$$\varepsilon_l = \mathrm{Eu}_x^{-0{,}25} \quad \text{for} \quad \mathrm{Eu}_x/\mathrm{Re}_x > 2\cdot 10^{-6}.$$

Here $\mathrm{Eu}_x = \frac{x}{c_x}\frac{\partial c_x}{\partial x} = k\mathrm{Re}_x$ is the Euler number [8]; $k = \frac{\nu}{c_x^2}\frac{\partial c_x}{\partial x}$ is the flow laminarization parameter.

Thus, the method proposed herein for correlating the experimental local heat transfer data has made it possible to obtain a single similarity equation, which can be used to calculate the local heat transfer coefficients at an arbitrary point of the end surface. The boundary layer aerodynamic characteristics necessary for this are determined on the basis of solution of the gasdynamic problem or from experiment. Equation (4) was obtained in the following ranges of variation of the governing parameters:

$$\bar{c}_x = 1{,}34 \ldots 4{,}76;\ \mathrm{tg}\,\theta_w = 0 \ldots 21;\ \mathrm{Eu}_x = 0 \ldots 1{,}66;$$

$$\bar{c}^2 b_0/R = 2{,}64 \ldots 34{,}6;\ \bar{x}_{ef} = 1 \ldots 0{,}54;\ M_x = 0{,}1 \ldots 0{,}35;$$

$$\mathrm{Re}_x = 0{,}8\cdot 10^5 \ldots 3\cdot 10^6.$$

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