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EFFICIENCY OF A THERMAL SCREEN BEHIND ROWS OF ORIFICES ON THE LEADING EDGE OF A GAS TURBINE BLADE

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Physical simulation of a thermal screen behind a row of standard orifices on the surface of the leading edge of a turbine blade is carried out by the heat and mass analogy method. A procedure is proposed for calculating the efficiency of thermal screens behind rows of orifices on the surface with a geometry typical of cooling systems on the leading edges of turbine blades.

The convective film method of cooling turbine blades with the use of an air film (a thermal screen) in the most thermally stressed areas of turbine blades, in particular, on the leading edge [1, 2, 3, 4], is widely used in modern gas turbine engines. Nevertheless, the data on cooling the leading edge with a thermal screen [3, 4] are inadequate since they are obtained for particular systems with film cooling in a narrow range of blowing upon the screen by a partial simulation of the heat transfer in the thermal screen of a life-size blade. Therefore, generalization and extension of these data to real objects must be done very carefully. In addition, there are some questions about the effect of some factors which should be answered to develop effective cooling systems. First of all, it is necessary to have information on differences in the influence of the following parameters on the screen efficiency compared to plane surfaces:

1) the geometrical characteristics of the blowing orifices, including blowing angles γ and β, orifice diameter, and spacing between the orifices in the perforation rows;

2) the position of the blowing orifices in relation to the splitting of the main flow on the cylindrical part of the tip (the angle φ_s) and local mass and velocity coefficients of blowing m and $\bar{u}$;

3) velocity, surface curvature, and flow separation gradients;

4) temperature nonuniformity of the flow, in particular, the ratio of the main to the blown flow densities ρ_1 and ρ_2 ($\Theta = \rho_1/\rho_2$).

It is also necessary to find the local efficiency of the thermal screen behind a row of orifices η, its relation to the average efficiency η_{av}, and characteristics of their distribution on the leading edge of the blade, since presetting η on the surface is necessary for calculating the three-dimensional temperature field in optimizing the heat protection system for the blade. Finally, it is necessary to find the conditions for extending the model test results to fullsize objects.

Thus, the goal of this study was:

to investigate the nature and peculiarities of developing a thermal screen blown through a perforation row typical of the leading edge of a gas turbine blade in a wide range of blowing regimes and for different positions of the perforation row on the leading edge; to determine experimentally the local and perforation pitch-averaged efficiencies of the heat screen;

to generalize the experimental data as a calculation method for the efficiency of the heat screen behind a perforation row on the leading edge using the theory of three-dimensional screens and the data generalization principles given in [1, 5-7, 10-12].

Some of the problems listed above were studied in thermal experiments by various researchers, including those at the Institute of Engineering Thermophysics of the Academy of Sciences of Ukraine [9, 10]. On the basis of generalization of the experimental results and the theory of heat screens developed, a procedure was proposed for

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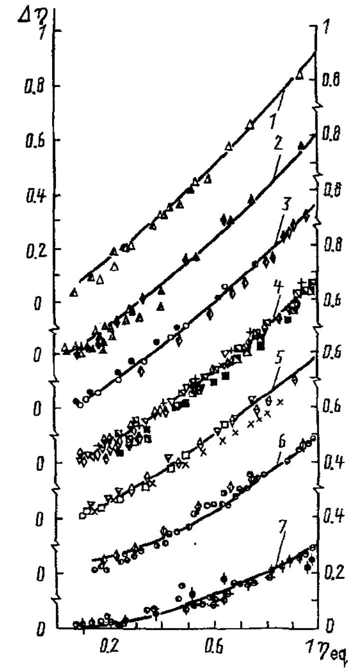


Fig. 1. Decrease in the efficiency of the thermal screen behind the perforation row $\Delta\eta$ in comparison with the efficiency of the screen behind the equivalent slot η_{eq} [7].

calculating the efficiency of the protective screens, which was implemented as PC programs (IBM PC AT and XT type) [11, 12]. The procedure can be represented by the following resultant relation

$$\eta = \eta_0 - \sum_i \Delta\eta_i, \tag{1}$$

where η_0 is the efficiency behind the tangential slot under idealized conditions, which is obtained from the experimentally corrected approximate analytical solutions of partial differential equations for a turbulent boundary layer, and $\Delta\eta_i$ are the correction functions obtained theoretically and experimentally, which take into account the difference between real and idealized conditions (injection angle and discreteness, velocity gradients and surface curvature, temperature nonuniformity and compressibility of the flow, etc.).

The calculation procedure for the average efficiency of the thermal screen was tested with experimental data in a wide range of geometric and injection characteristics reported in the literature using the relation [7]

$$\frac{1}{\eta_{av}} = \frac{1}{\Delta q_2} + \left(\frac{1}{\eta_{eq}} - 1\right), \tag{2}$$

where $\eta_{av} = \frac{1}{t}\int_0^t \eta dz$; $\eta \equiv (T_1^0 - T_{w.a})/(T_0^1 - T_2^0)$; η_{eq} is the screen efficiency behind a slot with the area equivalent to the flow cross-sectional area, height $s_{eq} = \pi d^2/4t$, and equal slope γ at the azimuth angle β, where d and t are the hydraulic diameter and the perforation pitch; T_1^0 and T_2^0 are the total gas and screen temperatures; $T_{w.a}$ is the adiabatic wall temperature at the specified point; $\Delta q_2 \to \eta_{av}$ $(x \to 0)$ is a constant for specified conditions, which is determined theoretically and experimentally [1, 5, 6, 7].

Figure 1 shows the decrease $\Delta\eta \equiv \eta_{eq} - \eta_{av}$ in the efficiency of the screen behind a row of uniform (round, rectangular, etc.) perforations as compared to the efficiency of the screen behind the equivalent slot. Predicted $\Delta\eta$ (lines) agree well with experimental data (dots) both on plane and cylindrical surfaces. The efficiency for a screen blown upon through an equivalent slot at an angle to the protected surface was calculated for a plane wall in [1] and for a surface simulating the leading edge of the blade in [10]. Experimental and predicted values agreed within the experimental error.

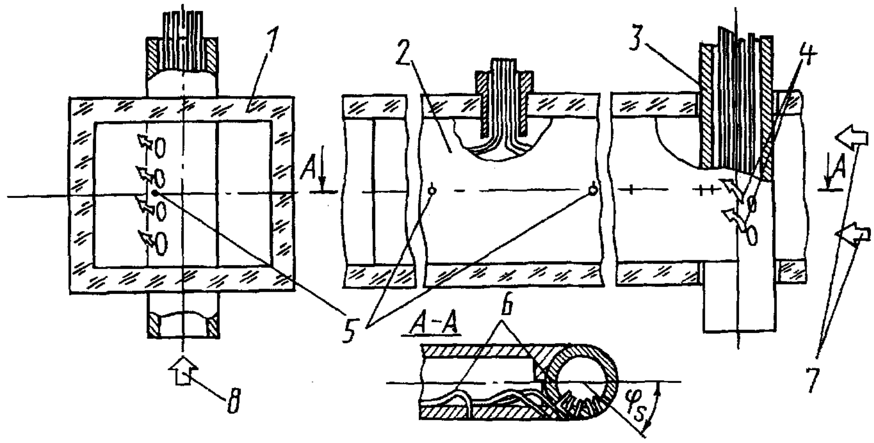


Fig. 2. The setup for investigating the screen efficiency behind a perforation row on the surface of the leading edge of the model blade: 1) working passage; 2) fairing; 3) cylinder; 4) screen (CO_2); 5) sampling point; 6) sampling line; 7) main (air) flow; 8) secondary (CO_2) flow.

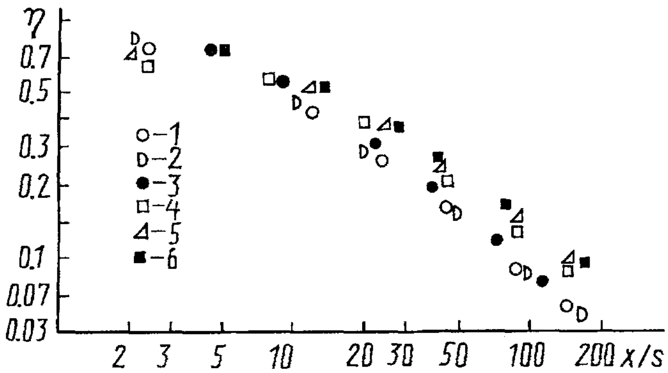
The results obtained for flat slots by simulation of the blade tip showed [9, 10] that the efficiency of the screen behind the slots could be determined by the methods used to calculate efficiencies of flat slots on a plate [1, 2, 12]. In this case the calculation must be based on local injection characteristics ($m \equiv \rho_2 c_2/\rho_1 u_1$; $\bar{u} \equiv c_2/u_1 \equiv m\Theta$) and consideration of the effects of longitudinal velocity gradients on the surface and the surface curvature [10, 11] (ρ_1 and u_1 are the local density and the projection of the main flow velocity on the curvilinear axis x, and ρ_2 and c_2 are the density and velocity of the injected flow).

A disadvantage of thermal experiments is the presence of heat fluxes between measurement surfaces at large temperature ratios of the main flow and screen (characteristic of real conditions, which are difficult to realize in the laboratory) and complexity of measuring the local surface temperature with the required accuracy. Therefore in this study the heat and mass analogy was used to simulate thermal screens, which easily provides for similarity between the thermal screens of a model and fullsize objects and high accuracy of measuring the local efficiency of the thermal screen on flat and curvilinear surfaces. This analogy is widely used in practice for the solution of such problems [8]. The method ensures equality of the density ratios Θ since in the case of perforation and a velocity gradient its influence on the efficiency of the screen on a curvilinear surface is substantial.

In this experiment the main air stream flowed at the velocity $u_{1\infty} = 18.5$ m/sec around a cylinder with the diameter D = 50 mm whose surface changed smoothly to a plane formed by a plate with the thickness equal to the cylinder diameter (see Fig. 2). This model allows all the characteristics and conditions of screens developing on the cylindrical part of the leading edge to be taken into account. Orifices with the diameter $d \doteq 3.8$ mm and the typical pitch $\bar{t} \equiv t/d = 6.5$ were located along a cylinder element to cool the leading edge. The axes of the orifices were placed in the same radial plane and inclined at an angle of 45^o ($\gamma = 45^o$, $\beta = 90^o$) to the cylinder element. A secondary CO_2 flow was blown through the orifices to develop a screen. The position of the blowing orifice in relation to the separation line of the main flow on the cylinder surface was determined by the radial angle, whose values in the experiments were $\varphi_s = 20$, 35, 45, 65, and 83^o.

The screen efficiency was determined by measuring the CO_2 concentration in the boundary layer on the model surface as a function of the distance from a blowing port and the position relative to the orifice pitch; the efficiency at a specified distance was measured at four points along the orifice pitch width: $\bar{t}^i \equiv t^i/t = 0$, 0.25, 0.5, and 0.75, where t^i is the distance from the orifice axis. The data were used to plot the distribution of the local screen efficiency at a specified position of the perforation row (φ_s = idem).

The CO_2 concentration in the boundary layer at a given surface point was determined by extracting a gas sample through a drain hole with a diameter of 0.6 mm at an extraction rate not exceeding $0.1u_1$ using an LKhM-80 chromotograph. In this case the error in determinating the screen efficiency, which was found experimentally, was less than 5% at $0.2 < \eta < 1.0$ and less than 10% at $0.03 < \eta < 0.1$.



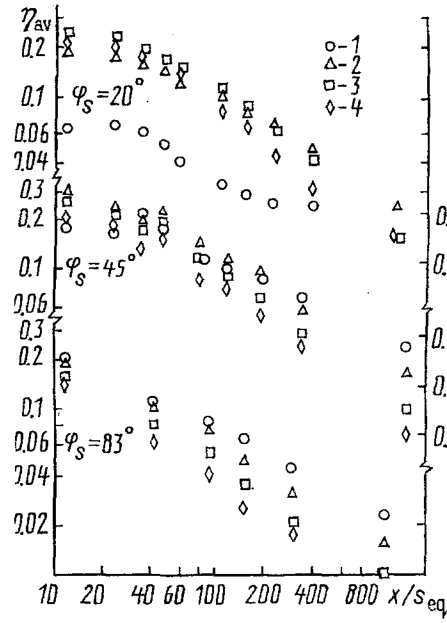


Fig. 3. Comparison of the screen efficiencies behind the slot $\eta(x/s)$. The screen is blown in at the angle $\gamma = 90^0$, $Re_1 \equiv \rho_1 u_1 s_1/\mu_1 = 2.5 \cdot 10^3$ for $\Theta = 0.66$: 1) $\bar{u} = 0.34$, 4) 0.52; $\Theta = 0.90$: 2) $\bar{u} = 0.34$, 5) 0.57; $\Theta = 1.17$: 3) $\bar{u} = 0.35$, 6) 0.58.

Fig. 4. Averaged efficiency $\eta_{av}(x/s)$ behind a row of circular orifices ($\bar{t} = 6.5$; $\gamma = 45^0$; $\beta = 90^0$) for the blowing locations $\varphi_s = 20$, 45, and 83^0 and the following blowing conditions: 1) $m_\infty = 1.6$; 2) 0.8; 3) 0.49; 4) 0.36.

The experimental conditions were characterized by the dimensionless parameters $Re_\infty \equiv \rho_1 u_{1\infty} D/\mu_1 = 5.75 \cdot 10^4$ and $\Theta = 0.63$; the screen blowing rate in each of the experiments was specified by the coefficient $m_\infty \equiv \rho_2 c_2/\rho_{1\infty} u_{1\infty}$ ($0.35 < m_\infty < 1.62$) and the angle φ_s because ρ_1 and u_1 depend on φ_s at the place of screen blowing, while the flow parameters $\rho_{1\infty}$ and u_1 in front of the model are constant.

The error in Re_∞, Θ, m_∞ was within 3% and the procedure and equipment developed provided the required accuracy of simulation.

Figure 3 shows the distribution of the efficiency η of the thermal screen blown in at the angle $\gamma = 90^0$ to the plate surface through a slot of height s. The distribution is described by the relation $\eta = \eta(x/s)$, where x is distance from the place of blowing. Here the values of η at $\Theta = 0.66$ and 0.9 obtained in this study using the heat and mass analogy (clear circles) and data from a heat experiment (dark circles) at $\Theta = 1.17$ [1] are shown.

It follows from a comparison of the results that the velocity coefficient $\bar{u}$ is a generalizing parameter for η in the screen flows without separation. The insignificant increase of η with Θ, under otherwise equal conditions, may be compared with the experimental error. A similar result was obtained in thermal experiments with a tangential slot ($\gamma = 0$). For the generalization of well-known efficiency data it was recommended, in calculation of the generalized length coordinate τ_1^+, that the Reynolds numbers be determined using a kinematic viscosity coefficient based on parameters of the injected flow [1].

As a result of simulation of the thermal screen on the surface of the leading edge, it was found that the local and pitch-averaged screen efficiencies η and η_{av} depended substantially on both the blowing conditions ($\bar{u}$, m, m_∞ = const) and blowing location, characterized by the position angles φ_s (see Fig. 2). The efficiencies η and η_{av} at different blowing locations on the surface of the leading edge surface were compared at the same mass flow rates of the blown coolant, i.e., at m_∞ = idem (see Figs. 4, 5). The averaged efficiency presented in Fig. 4 was determined by numerical integration of the local efficiencies.

As in the thermal experiments [9], analysis of the present experimental data showed that the screen efficiency reached a maximum at $\varphi_s \sim 45^0$ with the same coolant gas flow rates. This was caused by various factors affecting the screen in opposite directions: local mass and velocity blowing coefficients; the surface curvature and the curvilinear

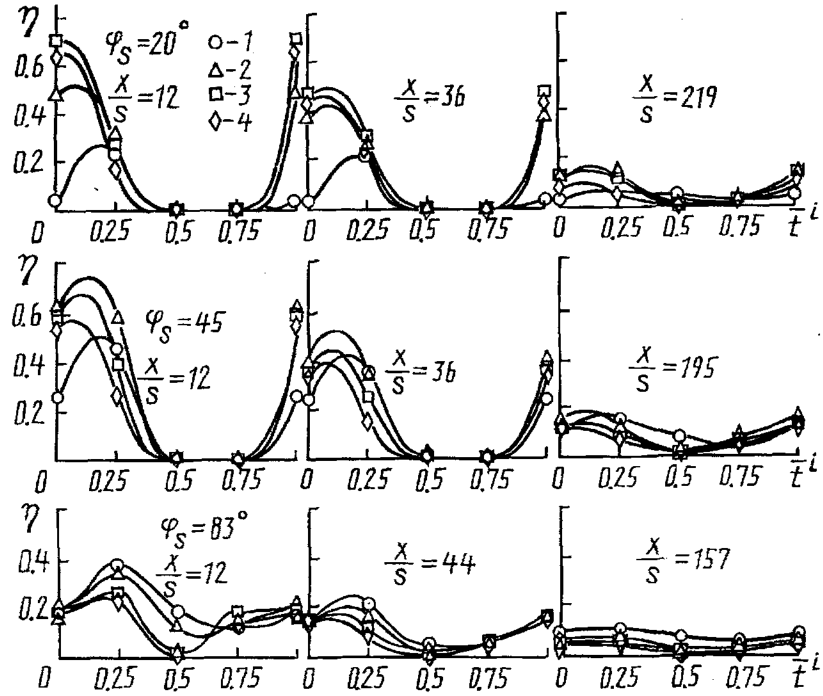


Fig. 5. Local screen efficiency versus orifice pitch width $\bar{t}^i$: 1) $m_\infty = 1.6$; 2) 0.8; 3) 0.44; 4) 0.36.

section length; the positive velocity gradient of the main flow; the nature of the velocity variation (the sign of the velocity gradient at $\varphi_s \sim 80^o$).

Thus, the main stream flow conditions at the surface of the leading edge affect the distribution of the local and averaged screen efficiencies substantially. For example, when the screen is blown in at $\varphi_s \sim 80^o$, there is intense mixing of coolant jets with the main stream; the screen efficiency is leveled over the orifice pitch and its averaged value appears substantially reduced (see Figs. 4 and 5).

In Fig. 6 experimental correction factors $\Delta\eta$ for the leading edge model (circles) and their predicted values (lines), obtained by the procedure in [7], are presented. The difference between the experimental data and predictions is about 10%, which is consistent with the errors and confirms the results obtained earlier in the thermal experiments (see Fig. 1).

The following relation can be used to generalize the local efficiency of a screen behind a row of circular orifices [5, 6]:

$$\eta = \eta_{av}[1 + F(x, z)], \tag{3}$$

where

$$F(x, z) \equiv \frac{1}{\Delta q_2} \sum_n^\infty a_n \cos\left(\frac{2\pi nz}{t}\right) \exp\left[-\left(\frac{2\pi n\mu_1}{t\rho_1 u_1}\right) \overset{+}{\tau_2}\right] \tag{4}$$

is the decay function of the screen nonuniformity; a_n and $\overset{+}{\tau_2}$ are the Fourier coefficients and the generalized length function [1, 5]; x is the curvilinear coordinate directed along the main stream flow, and z, across the main stream flow.

An asymptotic value of the function F(x, z) (the first term of the series) was used in the tentative predictions. In this case the coordinate origin (x = 0, z = 0) on the surface was chosen at the point of intersection with the line passing through the orifice cross section and the corresponding maximum of η.

The tentative predictions show that under quasi-isothermal conditions when $\Theta \cong 1$ the experimental values are approximated by the asymptotic value of the decay function at $\bar{t} < 3$ with an error less than 20% of η_{av}. For short distances from the blowing place splitting of the local efficiency curves is observed before the flow separation, and less steep variations of the efficiency over the flow width correspond to larger ρ_2/ρ_1. The physical constants of the blown

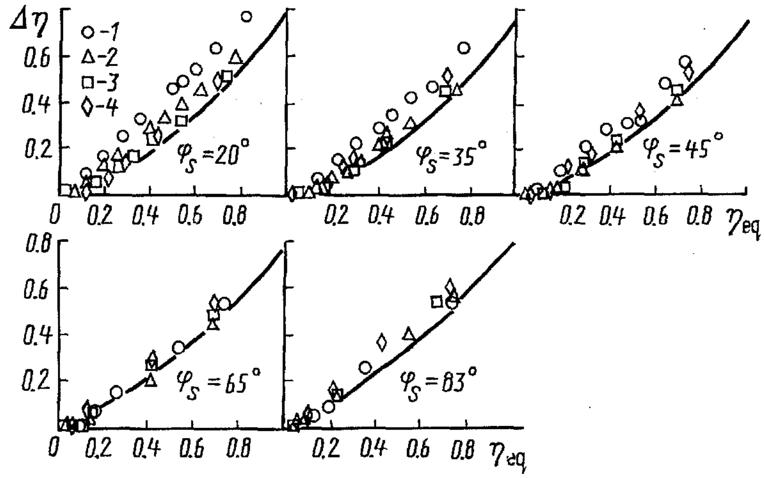


Fig. 6. Decrease of the heat screen efficiency $\Delta\eta$ on the surface of the leading edge model for various blowing locations φ_S: $\varphi_s = 20^o$: 1) $\bar{u} = 1.16$; 2) 0.58; 3) 0.35; 4) 0.26; $\varphi_s = 35^o$: 1) $\bar{u} = 0.76$; 2) 0.37; 3) 0.22; 4) 0.16; $\varphi_s = 45^o$: 1) $\bar{u} = 0.64$; 2) 0.32; 3) 0.19; 4) 0.14; $\varphi_s = 65$ and 83^o: 1) $\bar{u} = 0.52$; 2) 0.26; 3) 0.16; 4) 0.11.

flow may be recommended for use in calculating the function for nonisothermal and nonuniform blowing, or more exactly, the physical constants it contains [5]. At $\bar{t} > 3$ more terms (n = 3-5) should be used to determine the function F(x, z).

This study with the blade tip surface model yielded the following conclusions.

1. The thermal screen efficiency behind continuous slots depends on the local blowing conditions and, considering all the factors involved, reaches a maximum at the radial angle $\varphi_s = 45^o$. It is described by the equations for a screen on a flat plate with a turbulent boundary layer if the calculation is carried out in terms of the local blowing velocity coefficient while taking into account the longitudinal velocity gradients and the surface curvature.

2. The local and averaged efficiencies of the heat screen behind a row of similar orifices are described by the same equations as for a flat plate. In the description the efficiency of the equivalent slot is used while accounting for the local blowing velocity separation coefficients, whose values depend on the blowing angles γ and β and the radial angle φ_s, and for a possible shift of the symmetry planes of the thermal flow pattern relative to the symmetry planes of the row of orifices, the shift depending on the azimuth blowing angle β and the local blowing coefficient m.

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