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EFFICIENCY OF A PROTECTIVE GAS FILM WITH HIGH INJECTION RATIOS IN A HIGHLY TURBULENT MAIN FLOW

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A slotted gas-coolant film is widely used in industry to protect a wall from hot, reactive flows. The efficiency of a gas film is characterized by the distribution of the dimensionless temperature downstream from the coolant inlet point. The [main] flow turbulence $Tu_0 = \sqrt{\langle u'^2 \rangle}/u_0$ and the ratio of the film and main flow velocities $m = u_s/u_0$ have a large effect on the protective properties of the film. The slotted film has been well studied over a wide range of m only for low turbulence in the an main flow [1-4]. Experiments and theoretical analysis for high-turbulence flow have been done mainly for $m < 1$ [5, 6], where it was established that film efficiency drops substantially as the main turbulence increases. No similar investigations have been done in high-turbulence flows for $m > 1$.

In a low-turbulence flow, the coolant is most effective if the film velocity is the same as the main flow velocity ($m \simeq 1$) [1, 2], where there is little mixing between the flows. Decreasing the injection ratio ($m < 1$) reduces the gas flow and increases the velocity gradient at the stream boundary; consequently, the efficiency decreases.

As the coolant gas feed increases ($m > 1$), mixing between the wall film and the main flow starts to play an ever larger role, due to the growth in the velocity gradients; as a result the efficiency drops again.

Obviously, the way highly turbulent pulsations affect the flow mixing when m is large can differ greatly from when m is small. For $m < 1$, the velocity profile next to the wall soon follows a power law. For $m > 1$, a stream develops near the wall, and the velocity profile has an inflection, with a maximum near the wall. Thus, when $m > 1$, there are two distinct regions: a wall region with a power-law velocity profile and a streaming external region. This difference undoubtedly must affect both heat transfer and how external pulsations penetrate to the wall.

Our goal is to study the effect of increased turbulence on the behavior of a gas film over a wide range of gas injection ratios. The data presented here is a continuation of a previous paper [5] which includes a detailed description of the experimental set-up.

The experiments were done in a cylindrical channel (inner diameter $D_0 = 80$ mm) with adiabatic walls. The inlet to the working section has an annular tangential slot of width $s = 2$ mm, through which the secondary gas is fed. The experiments were done for a main-flow Reynolds number of $Re_0 = u_0 D_0/\nu = 8 \cdot 10^4$, an injection velocity ratio $m_1 = \rho_s u_s/\rho_0 u_0 \simeq 0.2$-$2.5$, and a temperature $T_0 = 292$ K in the main gas and $T_s = 360$ K in the injected stream; the turbulence intensity of the colliding flow at the inlet to the working section was $Tu_0 \simeq 0.2$-15%. The turbulence of the main flow was enhanced by a turbulence generator in the form of perforated disks. Different degrees of turbulence were attained by varying the number of perforations in the disks. In spite of the high degree of turbulence thus created, the pulsation profiles were smooth at the inlet to the working section, because a converging tube located between the turbulence generator and the working section recompressed the flow by a factor of 7.2. The integral turbulence scale at the inlet of the working channel was $L = 6$-10 mm. The minimum turbulence ($Tu_0 \simeq 0.2\%$) was attained in the experiments by replacing the turbulence generator by a fine-celled grid.

The dynamic characteristics of the air flow were measured by a DISA-55M constant-temperature thermoanemometer. An automated system [7] collected and processed the test data on the temperature, average velocity, degree of turbulence, and other characteristics. Prior data analysis [5] showed that the profiles of the velocity and the degree of turbulence are uniform at the inlet to the working section. The maximum nonuniformity in the velocity did not exceed 2% at $Tu_0 \simeq 0.2\%$, but was 10-12% at $Tu_0 \simeq 15\%$. The velocity profile in the boundary layer of the main flow in the section cut by the slot is well described (for $Tu_0 \simeq 0.2\%$) by a power function with an exponent $1/n = 1/7$; here the displacement is 0.37 mm.

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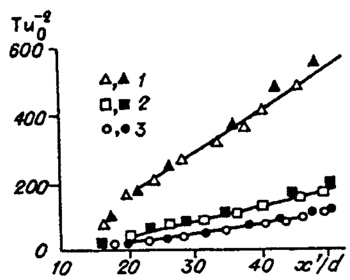

Fig. 1

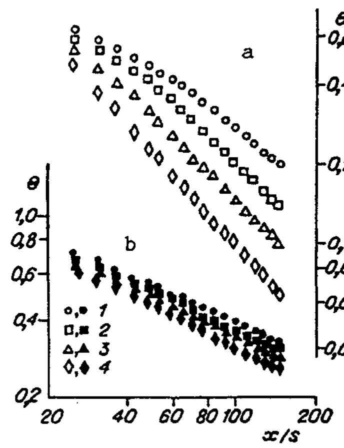

Fig. 2

The turbulence degeneracy is expressed by the equation [8]

$$1/\mathrm{Tu}^2 = C\,(x'/d - x_e/d)^N, \tag{1}$$

where C and N are constants; d is the dimension of the lattice cell, and x_e is the effective starting coordinate. However, Eq. (1) is usually used for a lattice with a large number of cells. A uniform quasi-isotropic field of turbulent pulses is established behind the turbulence generator. The anisotropy of the turbulent pulses $|\langle u'^2\rangle - \langle v'^2\rangle|/\langle u'^2\rangle \cdot 100\%$ is several percent, where u′ and v′ are the longitudinal and transverse pulse velocities. The turbulence generator disk has a nonuniform distribution of perforations and two characteristic scales — the diameter of the perforations and the distance between them. In spite of this, it can be seen (Fig. 1) that Tu_0 behind the disks is well described by Eq. (1) if the perforation diameter d is used as the characteristic scale. The origin of the longitudinal coordinate x′ starts at the location of the turbulence generator and is made dimensionless by dividing by d = 10 mm. The slot opening is located at coordinate x′/d = 26.4. Test data were taken for various values of the initial Tu_0: 7% (point 1, 25 perforations in the turbulence generator), 12% (point 2, 13 perforations), and 15% (point 3, 7 perforations). The open points characterize the turbulence change with no secondary flow; the dark points are for a secondary flow feed with m ≈ 2. It can be seen that the gas injection has little effect on reducing the turbulence.

The data in Fig. 1, which is presented in the same form as in [5], shows a significant decrease in the turbulence level Tu_0 near the turbulence generator and a rather weak decrease farther downstream. Therefore, in analyzing the test results on the efficiency of the gas film, Tu_0 is taken constant over the length of the working section at high and low initial turbulence levels.

Figure 2 shows the change in the gas film efficiency $\Theta = (T_w - T_0)/(T_s - T_0)$, where T_w is the wall temperature of the working channel, as a function of the dimensionless longitudinal coordinate x/s, where x is the distance downstream in the channel from the slot opening. Data are presented for various initial turbulence levels Tu_0: 0.2% (point 1), 7% (point 2), 12% (point 3), and 15% (point 4). The solid points correspond to $m_1 = 0.57$ and the open points to $m_1 = 2.0$. For $m_0 \approx 0.57$ (Fig. 2a), the effect of turbulence on the efficiency is large: as Tu_0 grows from 0.2% to 15%, Θ decreases by a factor of three. The effect of turbulence on the protective properties of the gas film drops substantially for larger values of the injection ratio. Consequently, large values of m_1 make the gas-film cooling more stable against turbulent pulsations from the external flow; for $m_1 \approx 2$ the layering of the experimental data for various levels of Tu_0 is insignificant.

Because the turbulence has a different effect on Θ for large and small values of m_1, we now analyze the change of Θ with m_1 in more detail. The function Θ = f(m) for various initial turbulence levels is shown in Fig. 3 for a fixed parameter $K_1 = 14$ ($K_1 = Re_{\Delta x}/Re_s^{1.25}$, $Re_{\Delta x} = \rho_0 u_0 \Delta x/\mu_0$, $Re_s = \rho_s u_s s/\mu_s$, and $\Delta x = x - x_0$, where x_0 is the length of the initial section where Θ ≈ 1); the notation for the points is the same as in Fig. 2.

If Tu_0 is low, the efficiency Θ rises to a maximum when m ≈ 1. The gas-film efficiency then decreases for further increases in m and asymptotically approaches the same Θ as for m ≈ 0.6. Increasing the external turbulence significantly degrades the protective properties for a wide range of m (as compared with the data for $Tu_0 \approx 0.2\%$). Moreover, the behavior of the gas film at high turbulence differs qualitatively from that at low turbulence: a high turbulence Θ increases monotonically

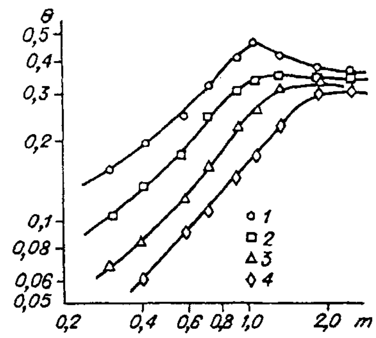

Fig. 3

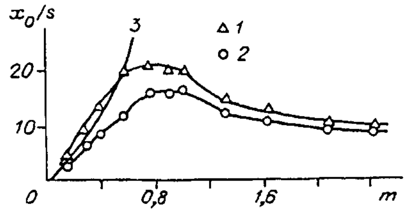

Fig. 4

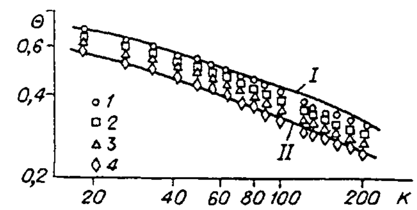

Fig. 5

as m increases over its whole measured range. Even when m > 1 the efficiency continues to increase, and asymptotically approaches the value of Θ for low Tu_0.

Starting with m ≃ 2-2.5, the efficiency becomes almost independent of the flow of secondary gas. Therefore, further increase in the coolant gas flow does not improve the protective properties of the gas film significantly and therefore is not energy-efficient.

In analyzing the test data on the film efficiency, it usually is necessary to know the length of the initial section x_0 — the distance downstream from the slot opening where Θ ≃ 1. We now analyze the change in x_0 for the flow conditions of interest. The initial thermal section x_0 is determined from a graph of Θ = f(x/s) from the point where the line Θ = 1 intersects the extrapolation of a line that fits the experimental points (see Fig. 2) on a semi-logarithmic scale [9].

Figure 4 shows the effect of the injection ratio on the length of the initial section x_0 for various two levels Tu_0: 0.2% (point 1) and 15% (point 2). From the graph it can be seen that increasing the turbulence decreases the length of the initial section for almost the whole interval of measured m. The effect of m on x_0 is not unique. The length of the initial section x_0 has a maximum for m = 0.8-1.0 and decreases for smaller or larger values of m. Here the change in x_0 is greater when m < 1.0.

Curve 3 for m < 1 from [10]:

$$x_0/s = (0{,}112 + 0{,}036/m)^{-1}(m + 1)/(m - 1)$$

is shown in Fig. 4 for comparison with the experimental data. It can be seen that this curve satisfactorily describes the experimental data in the region m < 0.6 for a low external turbulence.

Figure 5 shows experimental data on the film efficiency for large injection ratios (m = 2) as a function of K for various turbulence levels Tu_0: 0.2% (point 1), 7% (point 2), 12% (point 3), and 15% (point 4). Increasing the initial turbulence lowers the efficiency, but not as much as for gas films with low injection ratios (m < 1) [5].

Curve I in Fig. 5 is calculated for a low-turbulence film with m = 2 [2]:

$$\Theta = [(1 + 62{,}5/K)^{0{,}2}(1 + 62{,}5/K\,|1 - m|^{1{,}25})^{-0{,}086} - 1]^{0{,}8}/(1 + 0{,}016\,K)^{0{,}16}.$$

The figure shows that the curve is in satisfactory agreement with the experimental data at low Tu_0, but that it lies above all the measured values of K at high turbulence ($Tu_0 \simeq 15\%$).

Curve II in Fig. 5 is an analytical function for the film efficiency for $m \gg 1$:

$$\Theta = [1 + (62{,}5/((\Delta x/s)\, Re_s^{-0{,}25} + 0{,}143))^{0{,}114} - 1\,]^{\,0{,}8}. \qquad (2)$$

As can be seen, this function forms a lower bound on the experimental points. Thus, Eq. (2) can be used to estimate the film efficiency in a highly turbulent flow for large injection ratios m. However, a better description of this complex process requires a detailed consideration of all features of the interaction of the high-turbulence flow with the streaming gas film at the wall.

Thus, we have shown that increasing the turbulence of the on-coming flow lowers the efficiency of a slotted gas film and have revealed the basic features of how Θ depends on the injection ratio m. While Θ decreases when $m > 1$ in low-turbulence flow, in high-turbulence flow the film efficiency continues to increase. At large m, of turbulence has less effect on the efficiency. Starting from $m \geq 2$, the value of Θ hardly changes and depends only weakly on the turbulence level of the oncoming flow.

The turbulence level is hardly the only characteristic of turbulent flow. Today there are not enough experimental data to show other effects on the turbulence scale characteristic. Additional information is required on how the external turbulence interacts with the turbulence of the mixing layer and the wall turbulence. Possibly such data will help in developing a more efficient means for protecting the surface and for increasing the accuracy of the calculations.

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