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HEAT AND MASS TRANSFER, PROPERTIES OF WORKING FLUIDS AND MATERIALS

Effect of External Turbulence on the Efficiency of Film Cooling with Coolant Injection into a Transverse Trench

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Abstract—Film cooling is among the basic methods used for thermal protection of blades in modern high-temperature gas turbines. Results of computer simulation of film cooling with coolant injection via a row of conventional inclined holes or a row of holes in a trench are presented in this paper. The ANSYS CFX 14 commercial software package was used for CFD-modeling. The effect is studied of the mainstream turbulence on the film cooling efficiency for the blowing ratio range between 0.6 and 2.3 and three different turbulence intensities of 1, 5, and 10%. The mainstream velocity was 150 and 400 m/s, while the temperatures of the mainstream and the injected coolant were 1100 and 500°C, respectively. It is demonstrated that, for the coolant injection via one row of trenched holes, an increase in the mainstream turbulence intensity reduces the film cooling efficiency in the entire investigated range of blowing ratios. It was revealed that freestream turbulence had varied effects on the film cooling efficiency depending on the blowing ratio and mainstream velocity in a blade channel. Thus, an increase in the mainstream turbulence intensity from 1 to 10% decreases the surface-averaged film cooling efficiency by 3–10% at a high mainstream velocity (400 m/s) in the blade channel and by 12–23% at a moderate velocity (of 150 m/s). Here, lower film cooling efficiencies correspond to higher blowing ratios. The effect of mainstream turbulence intensity on the film cooling efficiency decreases with increasing the mainstream velocity in the modeled channel for both investigated configurations.

Keywords: gas turbine blades, film cooling efficiency, cooling injection configuration, turbulence, trenched holes, computer modeling

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Film cooling is widely used for thermal protection of gas turbine blades against high-temperature gas flow. The thermal efficiency of modern gas turbines can be increased by improving the used cooling techniques. The conventional configurations of film cooling based on a single- or two-row system of discrete holes inclined at an angle to the cooled surface feature certain disadvantages. First of all, note low efficiency of film cooling, η, at high blowing ratios ($m > 1.0$) due to formation of vortex structures inducing flow separation from the cooled surface. Thus, finding more effective film-cooling techniques is an urgent scientific-and-engineering problem, which is of special interest for modern gas-turbine building.

At present, researchers and designers of the leading world gas-turbine manufacturers extensively study new film cooling configurations with shaped holes, namely: fan-shaped, console, and several others [1–3]. However, making these holes with a diameter less than 1 mm involves considerable difficulties and requires expensive equipment. Therefore, engineering solutions for implementation of film cooling configurations with the efficiency not poorer than the efficiency of cooling systems with shaped holes, but which are simpler to make, have attracted considerable attention.

An analysis of the data from [4–6] has revealed that a configuration with coolant injection via one row of holes in a transverse trench is among the most promising film cooling methods combining high efficiency and a relatively simple technology for making a system of holes (Fig. 1b).

The flow over gas turbine blades under actual operating conditions is characterized by freestream turbulence affecting the film cooling efficiency. This effect manifests itself in a different manner in different coolant supply arrangements. Thus, it is shown in [7] that, if the coolant is fed via a slot, porous insert, or a system of inclined cylindrical holes, the freestream turbulence decreases the film cooling efficiency η at low blowing ratios m. However, it is stated in other publications [8, 9] that, under certain conditions, the freestream turbulence has a slight effect on the cooling efficiency, and, in certain cases, can even increase it.

In recent years, computer- or CFD-modeling of film cooling is widely used. With adequate turbulence models, it can predict the local and average efficiency

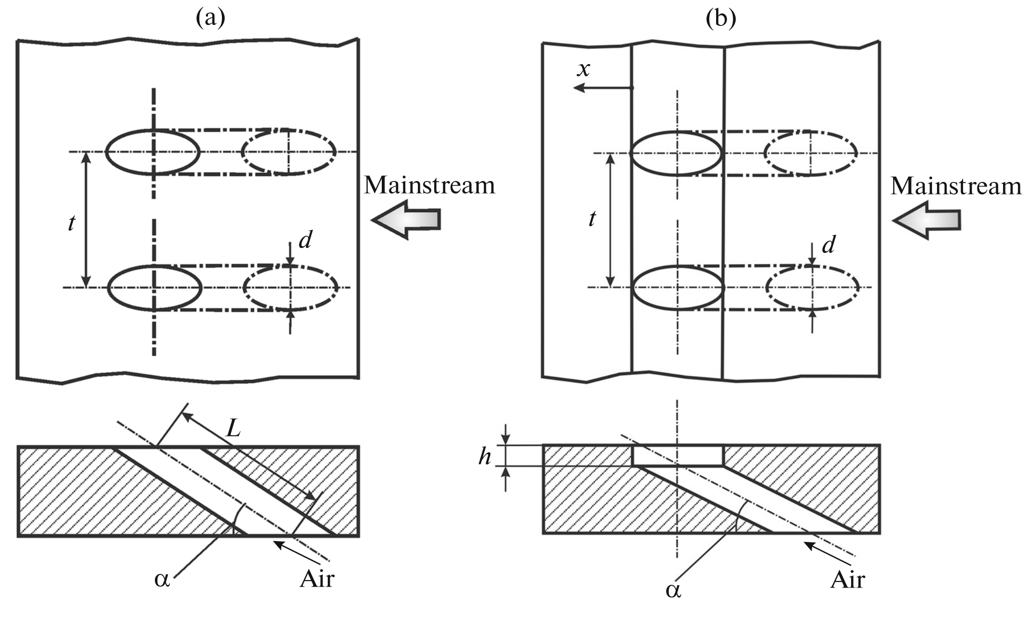

Fig. 1. Arrangement for injecting cooolant onto a cooled surface. (a) Row of conventional inclined holes, (b) row of trenched holes.

of film cooling quite accurately and reveal the features of a flow pattern that are difficult or, sometimes, impossible to determine from the experiments. In this case, the validity of the used mathematical model and the computational grid created in the flow domain have come into importance [10].

Most investigations involving computer modeling of the film cooling systems were performed for the conditions of model experiments to check the specific turbulence models for validity. At the same time, of particular interest are the results of modeling of actual flow conditions (when the flow parameters characteristic of blade channels in modern gas turbines are specified) under which the film cooling efficiency may differ considerably from the efficiency determined for the model conditions.

The present study is an investigation of the effect of the blowing ratio and the freestream turbulence on the efficiency of film cooling of a flat plate for two arrangements of coolant supply: through a conventional system of inclined holes or a row of inclined trenched holes (see Figs. 1a, 1b, respectively) that are used in modern gas turbine building. The investigation was performed using CFD simulation.

FILM COOLING SIMULATION

The computer simulation was run using the ANSYS CFX 14 commercial software package. The investigations were carried out based on the RANS SST turbulence model that has proven itself successful in simulating film cooling, which was demonstrated in our previous publications [10, 11].

The studied 3D-model of film cooling of a flat surface using coolant injection via a row of trenched holes was constructed in the ANSYS Design Manager package. The model is a rectangular channel into which a coolant is fed from a plenum (or an injected coolant service receiver) via trenched holes (Fig. 2). For the configuration of a system with trenched coolant feed, see Fig. 1. The film cooling test section had the following geometry: the diameter of coolant injection holes was $d = 0.8$ mm, the transverse pitch was $t = 2.4$ mm ($t/d = 3.0$), and the trench depth was $h = 0.6$ mm ($h/d = 0.75$). The inclination angle the holes made with the trench bottom was $\alpha = 30°$. The longitudinal distance x was measured from the trench trailing edge. The relative lengths of the main and upstream sections were $x/d = 40$ and 10, respectively.

In the numerical simulation, an unstructured combined computational grid with 1.1 million elements was used. The grid had clusters of 20 cells each in the

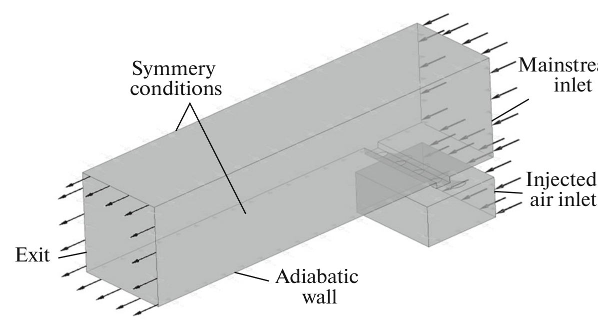

Fig. 2. 3D-model of film cooling of a flat surface with coolant injection via trenched holes.

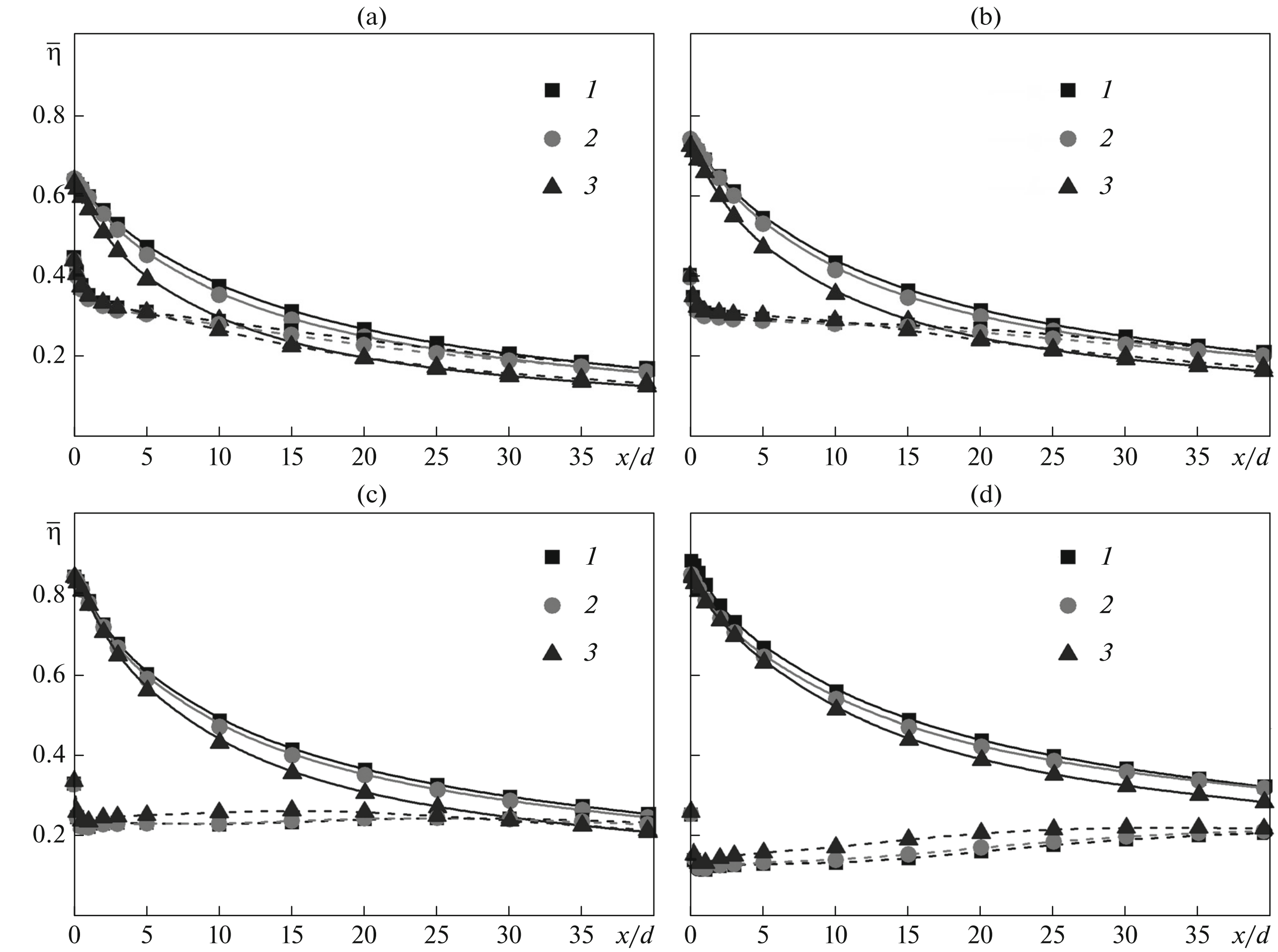

Fig. 3. Pitch-averaged film cooling efficiency at different mainstream turbulence intensities. w_1 = 150 m/s; DR = 1.79; ε, %: (*1*) 1; (*2*) 5; (*3*) 10; *m*: (a) 0.65, (b) 0.9, (c) 1.3, (d) 1.8. Cooling arrangement: (– – –) conventional, (——) with trenched holes.

immediate vicinity of the plate surface, the holes, and the plenum walls. The value of y^+ (dimensionless coordinate) was approximately 1.0 in all the calculations that met the criteria for application of the SST turbulence model ($y^+ < 2$).

Location of characteristic regions for prescribing boundary conditions is shown in Fig. 2. The boundary conditions typical for operation of actual power gas turbines were adopted in the calculations. The inlet temperature of the mainstream was 1100°C, and the injected coolant temperature was 500°C. The average mainstream velocity at the channel inlet was set at 150 and 400 m/s, which were approximately the velocity levels at the inlet to and in a blade channel of an actual gas turbine. The boundary conditions set for the coolant injection via holes (mass flowrate of the coolant) gave five blowing ratios of *m* = 0.6; 0.9; 1.3; 1.9; 2.3. The calculations were performed for three inlet mainstream turbulence intensities of 1, 5, and 10%. The injected coolant-to-mainstream density ratio (DR = ρ_2/ρ_1) was in the range. The average static pressure at the channel outlet was set at 10^6 Pa. The calculations were performed in the range of Reynolds numbers based on film-hole diameter and injected coolant velocity of $Re_d = (5.6–61) \times 10^3$.

To assess the efficiency of the examined configuration, film cooling was also modeled under the same boundary conditions for the conventional film cooling arrangement with a single row of inclinded cylindrical holes at the same pitch (t/d = 3.0).

EFFECT OF MAINSTREAM TURBULENCE ON THE FILM COOLING EFFICIENCY

As indicated above, the numerical investigation into film cooling of a flat plate were performed at two mainstream velocities of w_1 = 150 and 400 m/s and the mainstream turbulence intensities of ε = 1, 5, and 10%. Figures 3 and 4 show the transverse-averaged film cooling efficiency $\bar{\eta}$ for a convention single-row system of inclined holes and a single-row system of trenched holes. It is evident in Fig. 3 that, at moderate

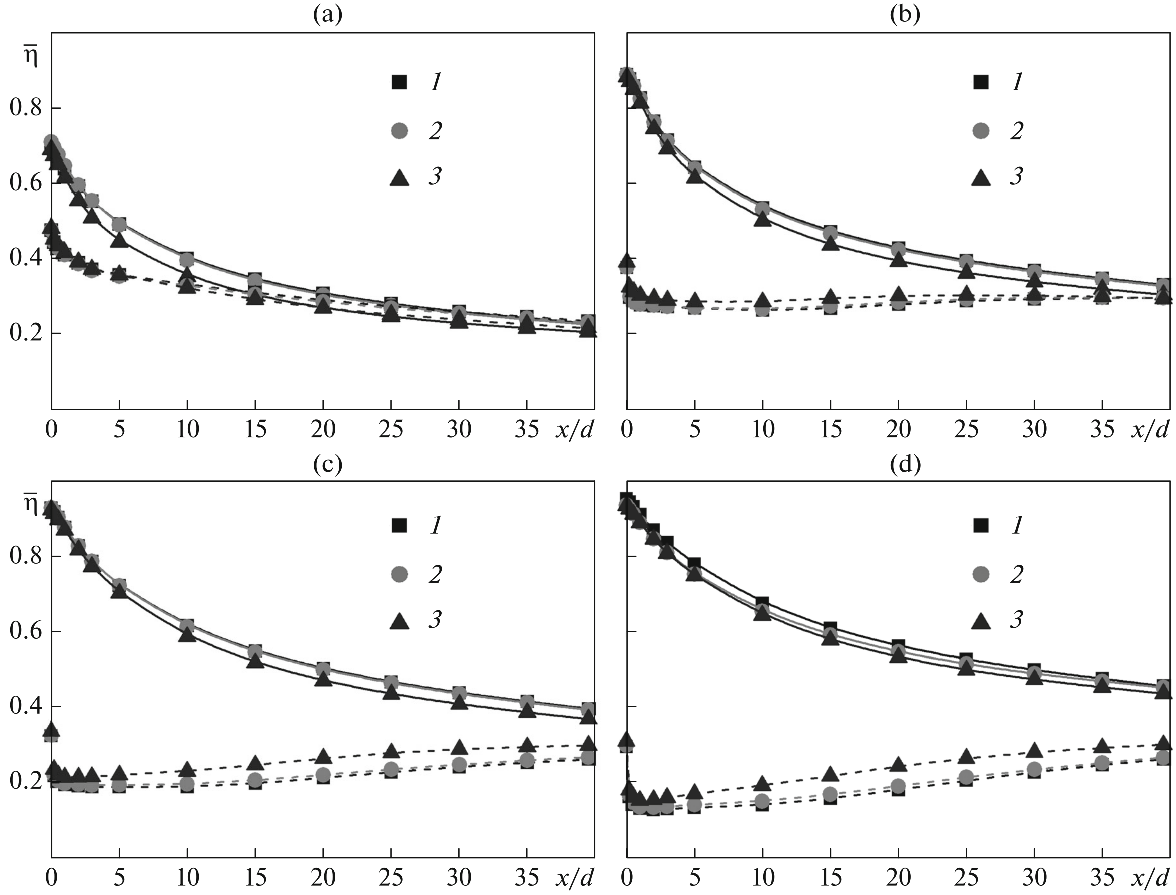

Fig. 4. Pitch-averaged film cooling efficiency at different mainstream turbulence intensities (w_1 = 400 m/s). ε, %: (*1*) 1; (*2*) 5; (*3*) 10; DR: (a) 1.85, (b) 1.9, (c) 2.0, (d) 2.1; *m*: (a) 0.65, (b) 1.3, (c) 1.85, (d) 2.1. Cooling arrangement: (– – –) conventional, (——) with trenched holes.

mainstream velocities (w_1 = 150 m/s) and low blowing ratios ($m < 1.0$), an increase in the mainstream turbulence intensity ε decreases the transverse-averaged efficiency of film cooling by 15–20% for the conventional configuration. This effect is observed within the $5 \leq x/d \leq 40$ section. At a blowing ratio of $m = 1.3$ and high mainstream turbulence intensity (ε = 10%), the average film cooling efficiency increases by 8–12% in the $0 < x/d < 25$ section and drops slightly in the $25 < x/d < 40$ section. It is evident from this figure that an increase of ε from 1 to 5% has a slight effect on the film cooling efficiency.

The dependence of $\bar{\eta}$ (for the convention hole system) on the mainstream turbulence becomes clearly defined at ε = 7–10%. The effect of turbulence on the film cooling efficiency is most pronounced at blowing ratios well above 1.0 ($m = 1.9$): increasing the turbulence intensity raises the film cooling efficiency by 20–40% in the entire investigated range of x/d. The conditional “bifurcation” point of a manifestation of this effect corresponded to a blowing ratio of m = 1.1–1.2.

At high mainstream velocities (w_1 = 400 m/s) the effect of mainstream turbulence on the efficiency of conventional film cooling has the same features, but it is much less pronounced (see Fig. 4). Thus, increasing the mainstream turbulence to 10% reduces the average efficiency of film cooling over the relative length x/d of the cooled plate by 8–12% at low blowing ratios (m = 0.65) and increases the film cooling efficiency by 15–30% at high lowing rates ($m > 1.5$).

It is evident from Figs. 3 and 4 that, in contrast with the convention single-row system of inclined holes, for a single-row film cooling arrangement with coolant injection via trenched holes, the effect of mainstream turbulence intensity features a unique character. In both cases, an increase in the mainstream turbulence intensity decreases the film cooling efficiency throughout the plate length in the entire range of investigated blowing ratios. An analysis of Figs. 3 and 4 demonstrates that, for coolant injection via trenched holes, the film cooling efficiency rises with increasing blowing ratio up to m = 2.4 (see Fig. 4) for all investigated mainstream turbulence intensities. In addition, it follows from the presented data that increasing the mainstream velocity

w_1 from 150 to 400 m/s enhances the film cooling efficiency by 15–40% for a trench film cooling system.

On the whole, the predictions agree with the experimental results [7, 12, 13].

ANALYSIS OF THE OBTAINED RESULTS

Figure 5 shows the film cooling efficiency $\bar{\bar{\eta}}$ averaged over the surface of the cooled plate as a function of the blowing ratio at two mainstream velocities and various turbulent intensities ε for the conventional single-row system of inclined holes and the system with trenched holes coolant injection. It is evident that, for the conventional film cooling arrangement, the surface averaged film cooling efficiency decreases with increasing m, and it also drops with ε at $m \leq 1.1$ but it rises at $m > 1.2$. It is seen in Fig. 5 that, at a mainstream turbulence intensity of $\varepsilon \leq 5\%$, it has a slight effect on $\bar{\bar{\eta}}$. However, at $\varepsilon = 10\%$ and $m > 1.2$, the average film cooling efficiency increases by 10–27% at a moderate mainstream velocity at the channel inlet (w_1 = 150 m/s) and by 7–18% at a high velocity (w_1 = 400 m/s); furthermore, with the higher m, the greater the efficiency enhancement.

It is seen in Fig. 5 that, for the system of inclined trenched holes, the value $\bar{\bar{\eta}}$ rises with an increase in the blowing ratio in its entire investigated range. In contrast with the conventional arrangement of inclined holes, in case of trench coolant injection, the value of $\bar{\bar{\eta}}$ drops with increasing ε in the entire range of investigated blowing ratios. At $\varepsilon \leq 5\%$, the effect of this factor on the average film cooling efficiency with trench coolant injection is negligible. At $\varepsilon = 10\%$, the average film cooling efficiency decreases by 3–10% at high mainstream velocities (w_1 = 400 m/s) and by 12–23% at moderate mainstream velocities (w_1 = 150 m/s), with lower values of $\bar{\bar{\eta}}$ corresponding to higher m. That is, for the system with trench coolant injection, the effect of ε on the surface-averaged film cooling efficiency becomes less pronounced with increasing m.

This dependence of the film cooling efficiency on the mainstream turbulence for the investigated arrangements can be explained based on an analysis of turbulent heat and mass transfer between the coolant jets and the hot mainstream. The simulation demonstrates that coolant jets outflowing onto the cooled surface have their own turbulence generated right in the film cooling channels and at their exits. In this case, the kinetic energy of turbulent velocity fluctuations (k_T) in the coolant jets is much greater that in the mainstream upstream of the injection plane. The turbulence intensity in the coolant jets at the hole exits depends on such factors as channel length, channel inlet conditions, and coolant velocity in the film cooling holes, which, in turn, affects the coolant blowing ratio.

Coolant injection via a conventional system of inclined holes. Figures 6a–6c represent the plots demonstrat-

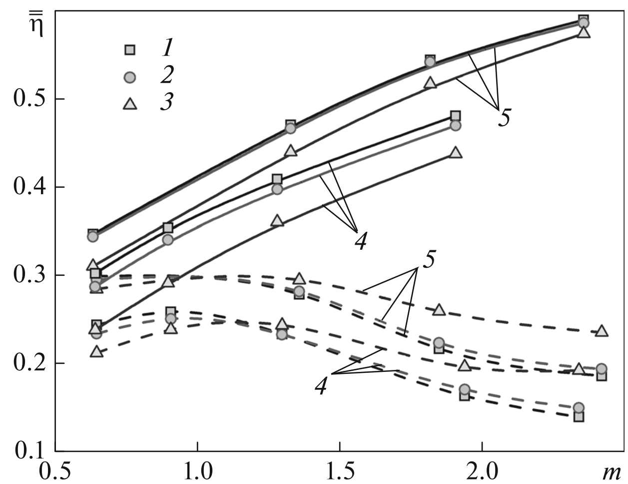

Fig. 5. Surface-averaged film cooling efficiency as a function of the blowing ratio at different mainstream turbulence intensities. ε, %: (*1*) 1; (*2*) 5; (*3*) 10; w_1, m/s: (*4*) 150; (*5*) 450. Cooling arrangement: (– – –) conventional, (——) with trenched holes.

ing variation in the turbulent fluctuation energy along the plate for the conventional hole system at different blowing ratios and turbulent intensities. It is evident that an increase in m results in a quick decrease in k_T in the coolant jets in the near wall layer downstream of the film cooling channels. This effect is induced by an increase in the coolant velocity at the cooling channel exits and separation of the cooling jets from the cooled surface at high blowing ratios m. With increasing m from 0.65 to 2.34, k_T in the near-wall layer on the plate surface decreases by a factor of 8–10.

From an analysis of the curves in Fig. 6, it also follows that the turbulent energy transfer between the coolant jets and the mainstream considerably increases k_T in the hot gas mainstream in the region between film cooling holes. With low or moderate blowing ratios (m < 1.2), increasing ε in the mainstream results in a substantial augmentation of rise k_T in the cooling jets and in the mainstream in the region between film cooling holes thereby enhancing the effect of turbulent heat and mass transfer between the coolant jets and the mainstream (Fig. 7a). This causes intensive heating of the coolant jets, and, hence, the film cooling efficiency decreases with increasing turbulent intensity.

With high blowing ratios (m > 1.2) due to a considerable reduction in k_T near the cooled surface, the effect of turbulent heat and mass transfer between the coolant jets and the hot gas mainstream resulting in intensive heating of the coolant jets becomes negligible. In this case, the film cooling efficiency is governed by the fact that k_T in the coolant jets is higher directly in the near-wall layer due to the effect of the mainstream turbulence. As a result, increasing the main-

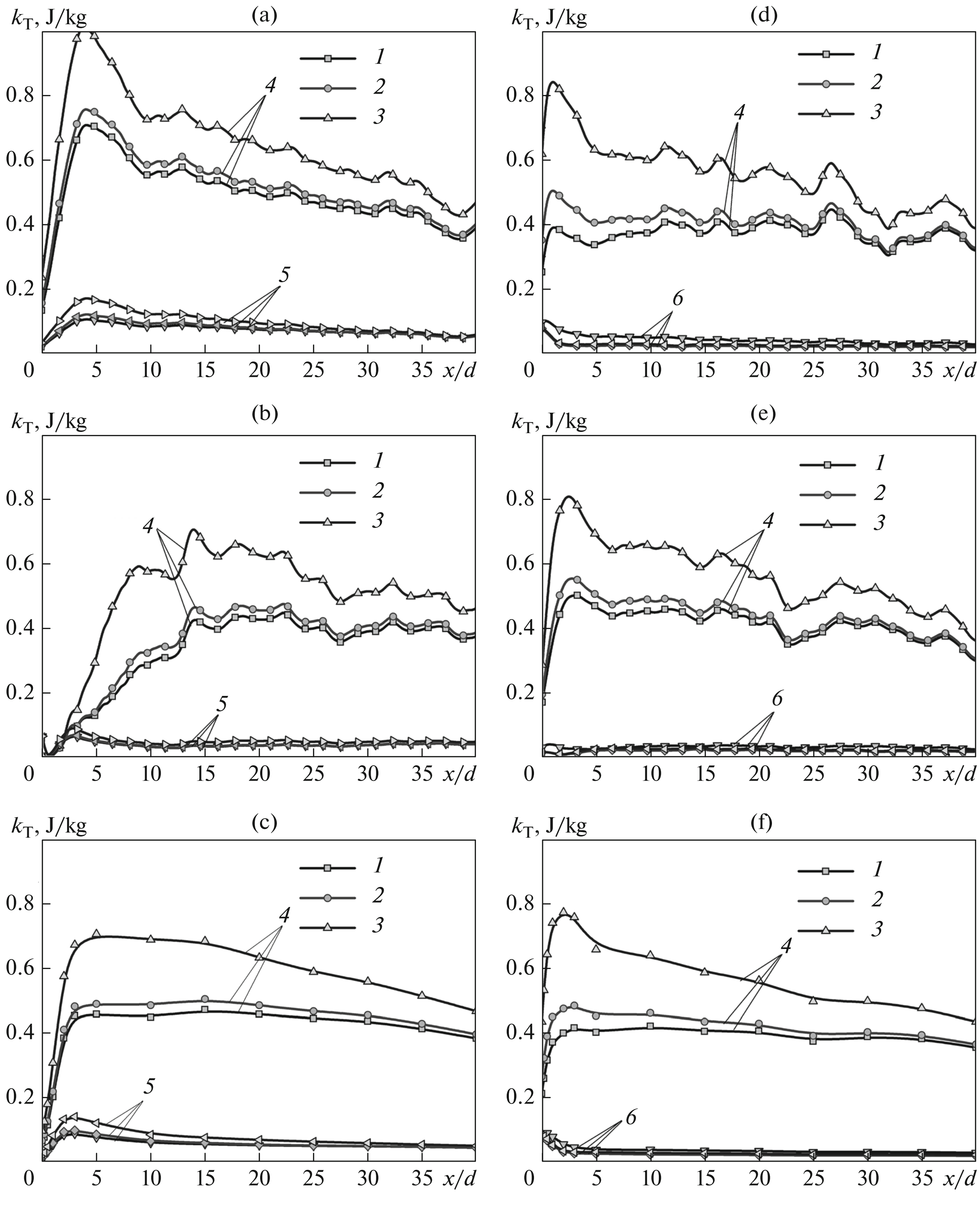

Fig. 6. Distribution of the kinetic energy of turbulent fluctuations in the near-wall region along the length of cooled plate for injection via the (a–c) conventional hole system and the (d–f) trenched holes. (a, d) coolant jet, (b, e) between holes, (c, f) pitch-averaged value; ε, %: (*1*) 1; (*2*) 5; (*3*) 10; *m*: (*4*) 0.65; (*5*) 2.34; (*6*) 1.91.

stream turbulence intensity improves the film cooling efficiency.

Coolant injection via a row of inclined trenched holes. Figures 6d–6f represent the curves for the kinetic energy of turbulent fluctuations in the near-wall layer along the plate for the arrangement with coolant injection via trenched holes. From an analysis of Figs. 6d and 6e, it follows that the curves for k_T along the length of the plate demonstrate almost the same behavior in the jet immediately behind the holes and in the region between the holes. This stems from the fact that, when the coolant is fed into the trench, partial mixing of the

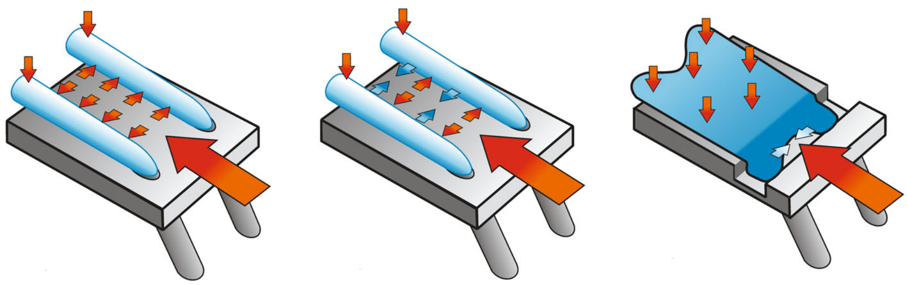

Fig. 7. Turbulent heat and mass transfer with film cooling. Cooling arrangement: (a) conventional with $m < 1.1$, (b) the same with $m > 1.2$, (c) with trenched holes.

coolant jets already occurs within the trench and then the coolant exits out of the trench to the cooled surface in the form of a continuous film. As a result, the turbulent heat and mass transfer between the hot gas mainstream and the coolant film takes place only on the outer surface of the film.

As well as for the conventional system of inclined holes, an increase in the mainstream turbulence intensity ε with coolant injection into the trench enhances k_T in the near-wall flow region. However, unlike the conventional system, for the trenched coolant injection, due to much larger total area available for turbulent heat and mass transfer between the coolant film and the mainstream, an increase in ε augments heating of the coolant film, thereby reducing the film cooling efficiency (see Fig. 7c). It also follows from Figs. 6d–6f that, for the trenched coolant supply, an increase in m brings about a more pronounced decrease in k_T in the near-wall layer. Thus, increasing the blowing ratio m from 0.65 to 1.91 reduces the value of k_T in the near-wall layer by a factor of 17–23. This decreases the influence of the turbulent heat and mass transfer between the coolant film and the mainstream on the film cooling efficiency at high blowing ratios.

CONCLUSIONS

(1) The results of investigation of two coolant injection arrangements with the use of actual parameters of the gas stream demonstrate that the effect of the mainstream turbulence intensity ε on the film cooling efficiency depends considerably on the blowing ratio m and the mainstream velocity.

(2) The results of investigation of both arrangements (conventional and with trenched holes) suggest that the mainstream turbulence hardly affects the average film cooling efficiency at $\varepsilon \le 5\%$, but the effect becomes quite pronounced at higher values of ε (7–10%).

(3) With coolant injection via one row of inclined holes (conventional arrangement), increasing the mainstream turbulence intensity results in a decrease in the surface-averaged film cooling efficiency $\bar{\bar{\eta}}$ at $m \le 1.1$ and in its enhancement at $m > 1.2$. As ε rises from 1 to 10% at $m > 1.2$, the efficiency $\bar{\bar{\eta}}$ increases by 10–27% at a moderate mainstream velocity at the channel inlet (w_1 = 150 m/s) and by 7–18% at higher velocity (w_1 = 400 m/s). As m reduces from 1.1 to 0.6, the film cooling efficiency decreases by 12% at w_1 = 150 m/s and by 6% at w_1 = 400 m/s.

(4) For both cooling arrangements, the effect of mainstream turbulence intensity on the film cooling efficiency decreases with increasing the mainstream velocity. For the arrangement with cooling injection via trenched holes, an increase in the mainstream turbulence intensity reduces the film cooling efficiency in the entire range of investigated blowing ratios ($0.6 \le m \le 2.3$). As ε rises from 1 to 10%, the film cooling efficiency $\bar{\bar{\eta}}$ drops by 3–10% at high mainstream velocities (w_1 = 400 m/s) and by 12–23% at moderate velocities (w_1 = 150 m/s), with lower $\bar{\bar{\eta}}$ corresponding to higher m.

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