Application of cylindrical, triangular and hemispherical dimples in the film cooling technology

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Abstract. The results of film cooling numerical simulation over a flat plate with coolant supply through a single span-wise array of inclined (α = 30º) holes arranged inside cylindrical, triangular, and hemispherical dimples are represented in the paper. Such configurations are of a great practical interest for application in advanced blade cooling systems of high-performance gas turbines. The schemes with coolant supply into triangular and hemispherical dimples were first proposed and patented by the IET of the NAS of Ukraine. For numerical simulation the ANSYS CFX 14 commercial code was used. Numerical simulation were carried out in a wide range of the blowing ratio parameter varied from 0.5 to 2.0. For low blowing ratio parameter (m = 0.5) the laterally averaged film cooling efficiency is actually the same for all investigated schemes over the main film cooling area. In this area, the most simple in terms of the film cooling production technology configuration can be used. At the medium and high blowing ratios (m = 1.0 or higher) all investigated film cooling schemes allow to increase the laterally averaged film cooling efficiency in comparison with the traditional cooling scheme with single row of incline holes. In this case the configuration with coolant supply into triangular dimples of the “crater” type demonstrates the best film cooling efficiency due to significant reduction in the intensity and scale of the “kidney” vortex beyond configuration, as well as due to decrease in the coolant blowing non-uniformity factor.

1. Introduction
The film cooling is the most efficient technique for heat protection of the first stages of turbine blades in advanced high-performance gas turbines. At present, a large amount of experimental and theoretical research has been done in this area, led to creation of advanced cooling system and gas turbines. However, experience has shown that traditional film cooling technique with coolant supply through inclined cylindrical holes has a number of disadvantages. The main problem is the emergence of specific vortex structures, that reduces the film cooling efficiency, especially for \( m > 1.0 \). Therefore, the search for the alternative film cooling techniques providing the greater film cooling efficiency, lower coolant consumption, and relatively simple manufacturing technology is one of the main scientific and technical challenges in the gas turbine engineering. Such researches are carried out in the leading gas turbine centers around the world. The analysis of published papers [1-6] showed that greatest practical interest for gas turbine blade design represents film cooling schemes with coolant supply into various surface dimples of the “crater” type; namely the triangular [5], hemispherical [6] (both proposed and patented by the Institute of Engineering Thermophysics of NASU), and cylindrical indentations, investigated in [4]. The present work is dealing with study of these schemes.
efficiency. Four variants of investigated schemes are shown in figure 1. This is traditional single array of inclined cylindrical holes (figure 1 a) and schemes with coolant supply into cylindrical (figure 1 b), triangular (figure 1 c) and hemispherical dimples (figure 1 d).

Figure 1. The investigated film cooling schemes: a – traditional single array of inclined round holes; b, c, d – single array of inclined round holes with coolant supply into cylindrical, triangular and hemispherical dimples, respectively.

2. Numerical simulation of film cooling

The numerical simulation was performed using the ANSYS CFX 14 commercial code for similar geometric models of film cooling, which differ only in the shape of surface dimples. The 3D geometrical model was a rectangular channel in which the coolant supplies from receiver through array of cylindrical holes with an outlet into surface dimple of different geometry. All investigated schemes have the identical relative pitch and angle of hole inclination \( t/d = 3, \alpha = 30^\circ \); the relative dimple depth \( h \) was 0.5 \( d \); the diameter of cylindrical craters \( D \) was 2.0 \( d \); and the base width of triangular craters \( a \) was 2.25 \( d \). The diameter of film cooling holes \( d \) was of 0.8 mm. The non-dimensional length of the film cooling area \( x/d \) was 40.

For CFD numerical simulation performed, a nonstructural combined calculation mesh was built using the ANSYS Mesh grid generator (figure 2). The computational mesh inflation near the solid surfaces included 20 mesh cells. The \( y^+ \) parameter (non-dimensional normal coordinate) has changed in the range from 0.5 to 1.1.

Figure 2. Grid model, employed in CFD simulation.
The boundary conditions of calculations were established close to the conditions of the experimental tests, used in the experimental rig of the High-temperature Thermogasdynamics Department of the Institute of Engineering Thermophysics of NASU. The boundary conditions at the inlet and outlet of the calculating area corresponded to the values of the blowing ratio parameter close to \( m = 0.5; 1.0; 1.5; 2.0 \) are given in Table 1. The symmetry boundary conditions were set on the lateral surfaces of the calculation area. On the solid surfaces of the model, the adiabatic wall conditions were set.

| Parameters                      | Inlet №1 | Inlet №2 | Outlet |
|---------------------------------|----------|----------|--------|
| Average velocity, m/s           | 37       | -        | -      |
| Static temperature, °C          | 20       | 80       | -      |
| Mass flow rate, kg/s \( m = 0.5 \) | -        | 0.000036 | -      |
| Mass flow rate, kg/s \( m = 1.0 \) | -        | 0.000067 | -      |
| Mass flow rate, kg/s \( m = 1.5 \) | -        | 0.000107 | -      |
| Mass flow rate, kg/s \( m = 2.0 \) | -        | 0.000143 | -      |
| Static pressure, Pa             | -        | -        | 101325 |

All calculations were made using the RANS SST turbulence model, which is a superposition of the \( k-\omega \) model in the near-wall region and the \( k-\varepsilon \) model far away from the walls. The choice of the SST turbulence model is justified by its ability to simulate correctly fluid flow and heat transfer of complex near-wall flow with sufficient accuracy. This was shown in previous papers, published by the authors [7, 8].

3. Results and discussion

The numerical simulation results of the laterally averaged film cooling efficiency for the investigated schemes for different values of the blowing ratio are shown in Figure 3. For low blowing ratio \( (m = 0.5) \) increase of the film cooling efficiency for the investigated schemes is observed over the initial and stabilization area \( x/d = 0...20 \) in comparison with traditional scheme. Over the main film cooling area the laterally averaged film cooling efficiency is actually the same for all investigated schemes (Figure 3 a). At the medium and high blowing ratio \( (m \geq 1.0) \) the difference in efficiency for all considered film cooling schemes becomes significant, especially for the scheme with a coolant supply into triangular dimples (Figure 3 b, c, d).

The flat plate area averaged adiabatic film cooling efficiency versus the blowing ratio for the investigated schemes is given in Figure 4. As seen, for a cooling scheme with a coolant supply into triangular dimples the area-averaged adiabatic film cooling efficiency increases with growth of the blowing ratio in the range of blowing ratio studied \((0.5 \leq m \leq 2.0)\). At the coolant supply into hemispherical dimples the area-averaged adiabatic film cooling efficiency remains approximately constant with increase of the blowing ratio. For traditional film cooling scheme with array of inclined holes and for the coolant supply into cylindrical dimples the area-averaged adiabatic film cooling efficiency decreases with increase in the blowing ratio.

The vortex flow structures at the outlet of holes \((x/d = 2.0)\) for the investigated film cooling schemes at the blow ratio \( m=1.5 \) is given in Figure 5 a-d. An analysis of the vortex structure for various film cooling schemes shows the "kidney" vortex structure has the highest intensity for the traditional array of inclined holes. The scheme with the coolant supply into cylindrical dimples (Figure 5 b) provides some decrease in intensity of the "kidney" vortices. A significant reduction in the intensity and scale of the "kidney" vortex structure is observed for the scheme with the coolant supply into triangular dimples (Figure 5 c).

The contours of the local adiabatic film cooling efficiency on the flat plate surface for investigated schemes are given in Figure 6. As seen from the pictures the most efficient scheme among all the...
Figure 3. The laterally averaged film cooling efficiency for the investigated schemes. \( m = 0.5 \) (a), 1.0 (b), 1.5 (c), 2.0 (d): 1 – traditional inclined holes configuration; 2 – coolant supply into cylindrical dimples; 3 – into triangular dimples; 4 – into hemispherical dimples.

Figure 4. The averaged flat plate adiabatic film cooling efficiency versus the blowing ratio for the investigated schemes: 1 – traditional inclined holes configuration; 2 – coolant supply into cylindrical dimples; 3 – into triangular dimples; 4 – into hemispherical dimples.
Figure 5. The vortex flow structure at the distance $x/d = 2.0$ for the blow ratio $m=1.5$: 

- **a** – traditional inclined holes configuration;
- **b** – coolant supply into cylindrical dimples;
- **c** – into triangular dimples;
- **d** – into hemispherical dimples.

Figure 6. The contours of the local adiabatic film cooling efficiency on the flat plate surface for the investigated schemes at the blow ratio $m = 1.5$ for the area $0 \leq x/d \leq 40$: 

- **a** – traditional inclined holes configuration;
- **b** – coolant supply into hemispherical dimples;
- **c** – into cylindrical dimples;
- **d** – into triangular dimples.
investigated film cooling schemes, is the scheme with the coolant supply into triangular dimples of «crater» type (figure 6 c). It also follows from the presented figures the scheme with coolant supply into triangular craters provides the best lateral uniformity of the film cooling efficiency.

4. Conclusions
This paper presents results of numerical simulation of flat plate film cooling with coolant supply into dimples of different shape, as well as into traditional row of discrete inclined cylindrical holes. The numerical simulation was performed for a wide range of the blowing ratio parameter \( m \) from 0.5 to 2.0. For low blowing ratio parameter \( m = 0.5 \) in the main film cooling area the laterally averaged film cooling efficiency is actually the same for all investigated schemes. In this case, the most simple configuration in terms of the film cooling production technology can be selected for application. At the medium and high blowing ratios \( m = 1.0 \) or higher) all investigated film cooling schemes allow to increase the laterally averaged film cooling efficiency in comparison with traditional cooling scheme with array of incline holes. In this case the configuration with coolant blowing into triangular dimples of «crater» type demonstrates the best film cooling efficiency due to significant reduction in the intensity and scale of the "kidney" vortex beyond this configuration, as well as due to decrease in the coolant non-uniformity factor. The scheme with blowing of coolant into triangular dimples provides the greatest lateral cooling uniformity.

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