Comparative analysis of film cooling efficiency at coolant supply into a single array of triangular dimples

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Abstract. The purpose of this work is a comparative study of the physical structure and film cooling efficiency of the single array of inclined holes, placed in triangular dimples and in a trench. The software package ANSYS CFX 17.0 was used along with RANS SST turbulence model. Calculations were made in a wide range of the blowing ratio ranging from 0.5 to 2.0. Results of modeling have shown high efficiency of triangular film cooling configuration. At \(m \geq 1.5\), the triangular configuration is comparable with the trench configuration in terms of the film cooling efficiency.

1. Introduction

Increase in the flow temperature in front of the gas turbine is the main trend of thermodynamic efficiency growth of the gas turbine engine. In the modern power gas turbine engines the flow temperature at the combustion chamber exit reaches 1500-1800 K, that exceeds the operating temperature of the structural materials of the blade. The turbine blades made of the best heat-resistant materials can operate without cooling at the flow temperature that is not greater than 1000-1100 °C [1]. At the high gas temperature temperatures, the external cooling is used in addition to internal convective cooling to ensure a longer service time of gas turbines. For external cooling, the film cooling is widely used when the coolant from internal blade space is supplied onto external blade surface through a number of discrete inclined round holes with a diameter of 0.3...1.0 mm.

Analysis of the obtained results [2] shows that the traditional scheme of film cooling in the form of a single array of discrete inclined round holes has a few significant disadvantages. Some of them are the low film cooling efficiency at the blowing ratio greater than unity that is caused by the appearance of secondary vortex structures, destroying the coolant film and contributing to the suction of the hot flow to the cooled blade surface, as well as the coolant separation from the cooled surface. Therefore, the search for alternative cooling schemes with a coolant flow rate that is acceptable in terms of thermodynamic efficiency, higher cooling efficiency and relatively simple manufacturing technology is the main challenge of the modern gas turbine engineering. The most promising scheme is a coolant supply into the trench [3], but for gas turbine blades this configuration is not acceptable from the prospective of long service life, as well as reduction in the strength of the thermal-protecting blade coating.

The aim of this paper is to determine the physical structure and film cooling efficiency of the alternative film cooling scheme with a coolant supply into a single array of triangular-shaped dimples [4] (figure 1) and compare it with the trench-shaped scheme that demonstrates the best cooling.
efficiency. The numerical simulation was used in this study, based on the application of commercial package ANSYS CFX17.0. Investigation was performed at the boundary conditions close to the actual gas turbine.

2. Geometric and computer models

The geometric model of the flat plate film cooling with a coolant supply through a single array of round holes in the triangular dimples with a pitch ratio $t/d = 3$ (figure 1) was performed in the ANSYS Design Manager. All dimensions of the model are shown in figure 2a. To perform CFD simulations the combined calculation grid was constructed using the ANSYS Mesh grid generator (figure 2b).

The solid boundaries borders of the calculated region were defined as adiabatic walls ($q = 0$). The symmetry of boundary conditions was used on lateral surfaces of the computational model. The Reynolds averaged Navier-Stokes correlations were solved for a viscous heat-conducting gas in the steady-state formulation of the problem using the total energy correlations.

The uniform velocity distribution at the inlet for the main flow and the coolant flow rate for the secondary flow were used. assigned. The boundary conditions on two inlet regions (figure 2, regions for inlet No.1, inlet No.2 and outlet were marked by arrows) were set by the corresponding values of a blowing ratio $m = 0.5, 1.0, 1.55, 2.0$. The boundary conditions are given in table 1.

![Figure 1. The scheme of triangular dimples](image1)

![Figure 2. Geometric and grid models of the investigated film cooling configuration: a – geometric model, b - grid model](image2)

| Table 1. The boundary conditions |
|----------------------------------|
| Parameters                        | Inlet No.1 | Inlet No.2 | Outlet |
| Average velocity, m/s            | 37         | -          | -      |
| Static temperature, °C           | 20         | 80         | -      |
| 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   | -      |
Mass flow rate, kg/s \((m = 2.5)\) - 0.000173 - 
Static pressure, Pa - - 101315

The adiabatic film cooling efficiency, taking into account that \(C_p = C_p(T)\), has the following form (1):

\[
\eta = \frac{i^\text{aw}}{i^\text{aw}} - \frac{i^\text{C}}{i^\text{C}}
\]

where \(i^\text{aw}, i^\text{C}, i^\text{C}\) are the enthalpies of the main flow, adiabatic wall (film), and coolant, respectively.

The RANS SST model of turbulence model was used for these studies. This model was well proven at the modeling of film cooling in the previous publication of authors [5,6].

3. Results and discussion
Two well-studied schemes of the film cooling were chosen for comparative analysis, namely the traditional scheme of film cooling with coolant blowing through a single array of round inclined holes [6] and the alternative scheme with coolant supply into the trench [7].

Vortex structures for the traditional scheme and for two alternative schemes (trench and triangular dimples) are shown in figure 3 (hereinafter comparisons are given for the blowing ratio \(m = 1.5\) at \(x/d = 2.0\)). It can be seen that scheme with a single array of inclined holes (traditional scheme) demonstrates the greatest intensity of twin vortex structures. Significant decrease in the intensity of twin vortex is observed for a scheme with triangular dimples. Each pair of vortices tightly adhere each other, thus forming a protective cooling film, which prevents the main flow suction towards the cooled surface. Quite a similar effect is also observed for the scheme with a trench. However in this case the vortex structure becomes more complicated by additional vortices of low intensity, generated by the neighbor jets.

**Figure. 3.** The vortex flow structure at the distance \(x/d = 2.0\) for the blowing ratio \(m=1.5\): 
\(a\) – traditional inclined holes configuration; \(b\) – coolant supply into triangular dimples; \(c\) – coolant supply into the trench

**Figure. 4.** The flow separation zone: \(a\) – traditional inclined holes configuration; \(b\) – coolant supply into triangular dimples; \(c\) – coolant supply into the trench
The decrease in the intensity of twin vortices leads to a decrease in the absolute value of the lift force, which acts on the flow and prevents it from being detached with formation of separation zone in the region of the plate leading edge at large blowing ratio. When triangular dimples are used, the dimensions of the coolant separation zone are significantly reduced in comparison with the traditional scheme (figure 4). The axial length of separation zone for a triangular dimples is about \( x/d = 1.0 \).

The above mentioned features influence the adiabatic film cooling efficiency. The distribution of local adiabatic film cooling efficiency in a spanwise cross section is presented in figure 5. For a triangular shape, there should be a significant increase in the uniformity of film cooling in comparison with traditional scheme. When blowing into a trench, the coolant film almost completely covers a flat (protected) surface.

Axial distribution of the laterally averaged adiabatic film cooling efficiency for different blowing ratios is presented in figure 6. For comparison, the calculated data for traditional scheme of inclined holes [6] and experimental data for the trench [7] were used.

From the analysis of these results it is apparent that for small value of the blowing ratio \( m = 0.5 \), in the region of \( x/d \leq 15 \) the laterally averaged film cooling efficiency for the triangular configuration is 10-20% higher than this data for the traditional scheme. At \( m = 1.0 \), the scheme with coolant supply into triangular dimples has much greater laterally averaged adiabatic film cooling efficiency in comparison with the traditional scheme in the whole area, but it is inferior to the trench scheme data. At \( m = 1.5 \) and 2.0, the scheme using triangular dimples is not inferior the scheme with coolant supply into the trench.

Figure 7 shows the dependence of the averaged adiabatic film cooling efficiency on the blowing ratio. The averaged adiabatic film cooling efficiency was calculated from the following correlation:

\[
\bar{\eta}_{\text{film}} = \frac{1}{N} \sum_{n=1}^{N} \eta_{\text{film}}^{n},
\]

where \( \eta_{\text{film}}^{n} \) is the laterally averaged film cooling efficiency for each blowing ratio, and \( N \) is the number of sections.

As can be seen from figure 7, the traditional scheme of film cooling is characterized by insignificant decrease in the film cooling efficiency with blowing ratio growth. An important feature of the film cooling scheme with blowing into triangular dimples is a significant increase in the
adiabatic film cooling efficiency with an increase in the blowing ratio. The same feature is also inherent in the scheme with the coolant blowing into the trench.

From these results it may be concluded that a single-array of triangular dimples is characterized by high values of the averaged film cooling efficiency, compared to the traditional scheme of inclined round holes, and is of great interest for practical application.

**Figure. 6.** The laterally averaged film cooling efficiency at different blowing ratios for investigated schemes: 1 – traditional inclined holes configuration [6]; 2 – coolant supply into triangular dimples; 3 – coolant supply into the trench [7]

**Figure. 7.** The averaged flat plate adiabatic film cooling efficiency versus the blowing ratio for the investigated schemes: 1 – traditional inclined holes configuration [6]; 2 – coolant supply into triangular dimples; 3 – coolant supply into the trench [7]
4. Conclusions
The paper theoretically studies the physical mechanism and film cooling efficiency over a flat plate at the coolant supply through a single array of inclined holes in the triangular dimples.

The results of research have proved high adiabatic film cooling efficiency of the scheme using triangular dimples in comparison with traditional scheme of inclined holes. The averaged flat plate adiabatic film cooling efficiency using triangular dimples for the blowing ratio $m = 0.5$ does not differ from the traditional scheme and that using the trench. For $m = 1.0$ and more, the scheme with triangular dimples is better than the traditional scheme by 10...60%. At $m \geq 1.5$, the scheme with triangular dimples is not inferior to the scheme using a trench.

The reasons of such a high efficiency of the alternative scheme of film cooling with triangular dimples are decrease in the intensity of "twin" vortices, as well as reduction of the separation zone length in the region of dimple leading edge. For the scheme with triangular dimples, the separation zone length $x/d$ near dimples is 1.0.

Further research aims at studying the effects of rotation of cooled surface under conditions of temperature factor and external turbulence.

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