Flat plate film cooling at the coolant supply into triangular and cylindrical craters

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Abstract. The results are given of the film cooling numerical simulation of three different schemes including single-array of the traditional round inclined holes, as well as inclined holes arranged in the cylindrical or triangular dimples (craters). The results of simulation showed that at the medium and high values of the blowing ratio ($m > 1.0$) the scheme with coolant supply into triangular craters improves the adiabatic film cooling efficiency by 1.5...2.7 times compared to the traditional array of inclined holes, or by 1.3…1.8 times compared to the scheme with coolant supply into cylindrical craters. The greater film cooling efficiency with the coolant supply into triangular craters is explained by decrease in the intensity of secondary vortex structures ("kidney" vortex). This is due to the partial destruction and transformation of the coolant jets structure interacting with front wall of the crater. Simultaneously, the film cooling uniformity is increased in the span-wise direction.

1 Introduction

The film cooling is the most efficient technique for protection of turbine blades in advanced high-performance gas turbines. The traditional film cooling technique (Fig.1 a) has a number of disadvantages; the primary of them is the low film cooling efficiency at the high value of blowing ratio ($m > 1.0$). It is caused by the appearance of specific vortex structures in the flow contributing to the detachment of coolant jets from the cooled surface and the hot gas flowing under the coolant jets. The analysis of published papers [1-4] showed the search for the alternative film cooling techniques is one of the main scientific and technical trends of the modern gas turbine engineering towards the greater film cooling efficiency, lower coolant consumption, and relatively simpler production technology.

In paper [5] the new configuration towards the film cooling efficiency growth with coolant supply into the craters of cylindrical shape (Fig.1 b) was proposed. The positive effect of such indentation shape was achieved via the partial flow structure destruction, and breaking of cooling jets while their interaction with front walls of craters, leading to a reduction in the power of "negative" vortex structures.

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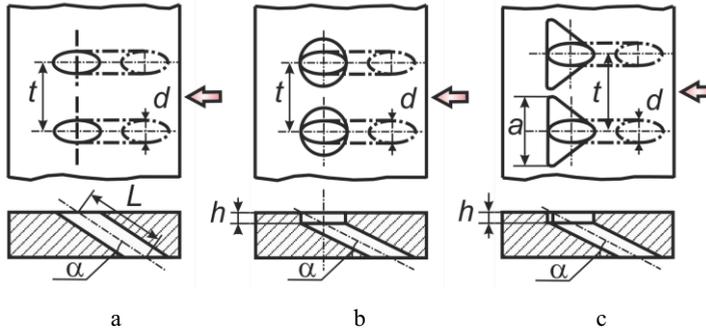
Fig. 1. The investigated film cooling schemes: a – traditional array of inclined round holes; b, c – single array of inclined round holes with coolant supply into cylindrical and triangular craters, respectively.

In the Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine the new film cooling configuration was proposed with a coolant supply through the single array of inclined round holes [6] arranged in the triangular-shaped craters (Fig.1 c). This leads to the transformation of separate coolant jets into the semi-bounded two-dimensional jet, reducing the coolant discreteness when supplying onto protected surface.

2 Numerical simulation of film cooling

The numerical simulation of three film cooling schemes was performed using ANSYS CFX 14 commercial code. All investigated schemes have the identical relative pitch and angle of hole inclination ($t/d = 3$, $\alpha = 30º$); the depth of craters h is 0.5 d; the diameter of cylindrical craters D is 2.0 d; and the base width of triangular craters a is 2.25 d. The diameter of film cooling holes d is 0.8 mm. The non-dimensional length of the film cooling area x/d is 40.

The boundary conditions were taken corresponding to the actual vane of power gas turbine. The blowing ratio m is 0.5…2.5; the jet to main flow density factor DR is 1.8…2.1; the flow turbulence Tu is 1%; the main flow speed is 400 m/s; the cooling jets and main flow temperature is 500ºC and 1100ºC, respectively.

The investigation was made using the RANS SST turbulence model, which demonstrated acceptable results still obtained in earlier film cooling studies of the authors [7, 8]. In calculations the unstructured combined computational grids were used, consisting of 1,1...1,5 million cells. The computational grid inflation near the solid surface included 20 grid cells. The y^+ parameter (non-dimensional normal coordinate) was about the unity order, which satisfies conditions of the SST turbulence model correct application at the film cooling computer numerical modelling.
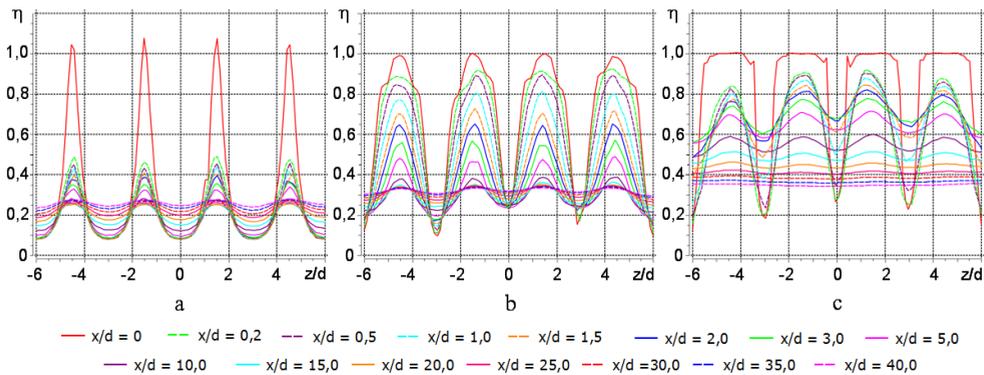
3 Results and discussion

The results of the numerical studies (Fig.2) have shown that at the medium and high value of the blowing ratio ($m > 1.0$) the scheme with coolant supply into triangular craters increases the average (throughout the cooled surface) adiabatic film cooling efficiency by 1.5...2.7 times compared to the traditional scheme of a single array of inclined round holes, and by 1.3…1.8 times compared to the scheme with coolant supply into cylindrical craters.
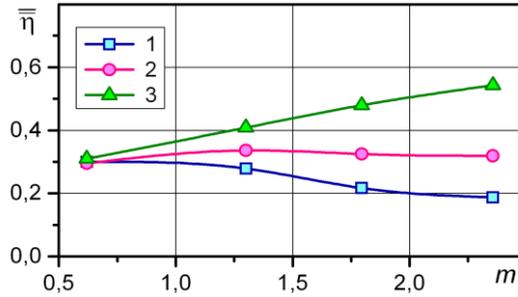
Fig. 2. The average adiabatic film cooling efficiency versus the blowing ratio:
1 – traditional array of inclined holes; 2, 3 – single array of inclined round holes with a coolant supply into cylindrical and triangular craters, respectively.
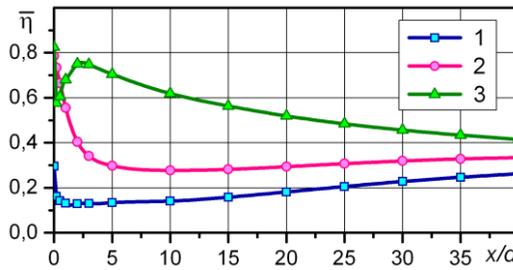
Fig. 3. The average adiabatic film cooling efficiency for m = 1.8: 1 – traditional array of inclined holes; 2, 3 – single array of inclined round holes with coolant supply into cylindrical and triangular craters, respectively.

— x/d = 0	-- x/d = 0,2	-- x/d = 0,5
— x/d = 1,0	-- x/d = 1,5	— x/d = 2,0
— x/d = 3,0	— x/d = 5,0	— x/d = 10,0
— x/d = 15,0	— x/d = 20,0	— x/d = 25,0
-- x/d =30,0	-- x/d = 35,0	-- x/d = 40,0

Fig. 4. The local laterally adiabatic film cooling efficiency for different values of x/d for three investigated schemes, m = 1,8: 1 – traditional array of inclined holes; 2, 3 – coolant supply into cylindrical and triangular craters, respectively.

As follows from Fig. 2, within the studied range of blowing ratio the average film cooling efficiency for the traditional array of holes is decreased with the blowing ratio growth. It is approximately constant (weak maximum at $m = 1.30$) at the coolant supply into cylindrical craters, while increases at the coolant supply into triangular-shaped craters.

The comparison of average adiabatic film cooling efficiency at $m = 1.8$ is given in Fig. 3 for three investigated film cooling schemes. As seen, significant difference in the film cooling efficiency is observed for considered cooling schemes both in the initial and primary axial distance area ($x/d = 0…20$), especially for the scheme with a coolant supply into triangular craters.

In addition, for the scheme with a coolant supply into triangular craters, the significant increase in the span-wise film cooling uniformity is observed (Fig. 4). This is due to specific feature of the coolant jets interaction with rectangular-shaped front edge of the triangular craters. In this case there is a transformation of coolant round jets into the semi-bound two-dimensional jet over the cooled surface. This provides a more uniform coverage of the cooled surface by means of the coolant and leads to significant decrease in the intensity of "negative" vortex structures, contributing to cooling jets detachment from the cooled surface and the hot gas supply from the main flow to the cooled surface at the high blowing ratio.

Conclusions

The new method of the film cooling with coolant supply through round holes arranged in the indentations of the triangular shape significantly improves the average adiabatic film cooling efficiency both at the medium and high values of the blowing ratio ($m \geq 1.0$). This increase is by 1.5...2.7 times compared to the traditional array of inclined round holes, and by 1.3…1.8 times compared to the scheme with coolant supply into cylindrical craters. The greater film cooling efficiency with a coolant supply into triangular craters is explained by decrease in the secondary vortex structures ("kidney" vortices) and transformation of cylindrical cooling jets into two-dimensional semi-bounded jet due to interaction with front walls of triangular craters. At the high blowing ratio, the lifting force contributing to the cooling jets separation from the cooled surface is reduced and the film cooling uniformity in the span-wise direction is substantially improved due to decrease in the cooling jets discreteness over the cooled surface.

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