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Validation of three dimensional film cooling modeling on convex surface for gas turbine blade[☆]

N.M. Yusop, A.H. Ali [*], M.Z. Abdullah

School of Mechanical Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Penang, Malaysia

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ABSTRACT

In this study, three dimensional computational predictions on the film cooling performance of single row and simple cylinder on the convex surface have been studied and compared with corresponding experimental data reported in the literature to validate the model. This computational prediction serves as the baseline for future studies of optimization in determining the film cooling effectiveness. Realizable κ–ϵ turbulent model has been employed and energy equation has been solved. Grid independence study has been fulfilled using two kinds of meshing approach for the plenum and the cooling holes. Results of grid independence study showed that fine meshed plenum and cylinders of tetrahedral grids case have provide a good agreement with the related experimental data. Study of temperature ratio between the coolant and mainstream hot gas T_c/T_g has been performed using four values of temperature ratios that are 0.5, 0.6, 0.7, and 0.8. In all of these tests the mainstream duct of the models was generated with multigrid hexahedral mesh. Based on the heat-mass transfer analogy, results of this study showed good agreement of the film cooling effectiveness and temperature distribution in comparison to the related experimental data. The case in which combination of both plenum and cylinders in one volume with tetrahedral fine mesh generation and temperature ratio of $T_c/T_g = 0.6$ was found to be in good agreement with the experimental data among all of the other models. Computational prediction results have found an agreement with the experimental data, thus the approach is verified.

1. Introduction

Gas turbines are widely employed in many applications. The demand for higher overall efficiency and high power output in gas turbine renders the need for increase in turbine entry temperature. However the engine operating temperature is beyond the permissible metal temperature hence reduces the life of turbine blade. In order to maintain an acceptable temperature level of gas turbine blade, cooling is an inevitable issue to provide safe operation under extreme heat load conditions. Film cooling is widely used as a cooling method where the coolant (usually air) is injected onto the surface of the turbine blade to produce a thin protective film so that the adjacent surface temperature is maintained at an acceptable temperature level. This method will consequently rescue the turbine blade from failure.

The heat-mass transfer analogy was used to measure the adiabatic film cooling effectiveness on the blade surface. The adiabatic film cooling effectiveness (η) is an excellent indicator of film cooling performance and defined as:

$$\eta = \frac{T_g - T_{aw}}{T_g - T_c}. \tag{1}$$

The heat flux ratio (q''/q''_0) according to the recent study by Wang and Zhao [2] defined as:

$$\frac{q''}{q''_0} = \frac{h_{af}}{h_o}\left(1 - \frac{\eta}{\varphi_o}\right) + \frac{h_{af}}{h_o} \cdot \frac{\varphi - \varphi_o}{\varphi_o}. \tag{2}$$

The study of the turbine blade film cooling requires investigation of various flow and geometrical parameters. Wright et al. [3] studied the effect of density ratio on flat plate film cooling. Three separate flat plates containing cylindrical holes, fan shaped holes and laidback fan shaped holes have been employed. The effect of density ratio on the film cooling effectiveness is coupled with varying blowing ratio, freestream turbulence intensity and film hole geometry. The main finding of their study is that in all cases as the freestream turbulence intensity increases the film cooling effectiveness decreases; this effect is reduced as the blowing ratio increases for all three film cooling hole configurations.

Recent study performed by Soe et al. [4] found that antivortex cooling holes have better effectiveness than cylindrical hole because the interaction of side hole vortices leads to reduce the main hole vorticity. Lee and Kim [5] numerically optimized a laidback fan-shaped hole film cooling. Their work has been performed to evaluate the effects of geometric variables of laidback fan-shape hole on film cooling. They evaluated the effects of injection angle of the hole, the

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[*] Corresponding author.
E-mail address: amirss_3000@yahoo.com (A.H. Ali).

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Nomenclature

C_2 and $C_{1\epsilon}$	constants
D	injection hole diameter (cm)
G_b	the generation of turbulence kinetic energy due to buoyancy
G_k	the generation of turbulence kinetic energy due to the mean velocity gradient
h_{af}	adiabatic film heat transfer coefficient, $h_{af}=q''/(T_{aw}-T_w)$ (W/m^2 K)
$\vec{J_j}$	the diffusion flux of species j
k_{eff}	the effective conductivity
M	blowing ratio
q''	heat flux (W/m^2)
q''/q''_0	heat flux ratio
r	radius of curvature of convex surface (cm)
S_h	includes the heat of chemical reaction and any other volumetric heat sources that could be defined
S_k and S_ϵ	user defined source terms
T_{aw}	adiabatic wall temperature (K)
T_c	coolant temperature (K)
T_g	main gas temperature (K)
T_w	wall surface temperature in contact with gas (K)
V_c	coolant velocity (m/s)
V_g	main gas velocity (m/s)
Y_M	the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate

Greek letters

α	cylinder inclination angle
η	adiabatic film cooling effectiveness, $\eta=(T_g-T_{aw})/(T_g-T_c)$
φ	film cooling effectiveness, $\varphi=(T_g-T_w)/(T_g-T_c)$, $\varphi_o=(T_g-T_{wo})/(T_g-T_c)$
σ_k and σ_ϵ	turbulent Prandtl number for κ and ϵ respectively.

Subscripts

aw	adiabatic wall
c	coolant flow
g	main gas
f	with film cooling
o	without film cooling
w	wall

lateral expansion angle of the diffuser, the forward expansion angle of the hole and the ratio of the length to the diameter of the hole on the film cooling. They found that an increase of the forward expansion angle makes a reduction of film cooling effectiveness and the lateral expansion angle has the biggest impact among the four geometrical variables on the spatially averaged film cooling effectiveness.

Chen et al. [6] experimentally evaluated the efficiency of the concept of using an upstream ramp to enhance film cooling performance. They concluded that a large ramp angle with a high blowing ratio leads to better film cooling protection than other cases considered. Ghorab et al. [7] conducted an experimental investigation of film cooling performance of louver scheme. Their finding showed that the louver scheme has superior centerline and lateral film cooling effectiveness than other film cooling schemes referred in their study. Bayraktar and Yilmaz [8] numerically conducted a three dimensional model to study film cooling performance. Circular and square shaped multiple nozzle geometries have been considered. The main finding was that using circular multiple nozzles leads to higher thermal film cooling effectiveness than that of square shaped multiple nozzles. Islami et al. [9] conducted computational study for a row of coolant injection holes on each side of a symmetrical turbine blade model near the leading edge. Four different hole configurations, a cylindrical, a forward diffused, a cylindrical within a transverse slot and forward diffused within a transverse slot are employed. They found that the shape of the hole and the integration of the holes with a continuous slot, significantly affect the film cooling flow over the protected surface.

Ely and Jubran [10] numerically evaluated a novel sister hole cooling technique. Two sister holes bound the primary injection hole. Four blowing ratios were used, 0.2, 0.5, 1.0 and 1.5. The main result is that the sister hole technique significantly improves the effectiveness at all blowing ratios. Lee and Kim [11] conducted a study for optimization of a cylindrical film cooling hole by surrogate modeling approach using three-dimensional Reynolds-average Navier–Stokes analysis. Performances of three basic surrogate models and three weighted average surrogate models have been evaluated. They found that Kriging model predicts the optimum point with the highest objective function value, among the surrogate models tested. Zhang et al. [12] established physical and mathematical models for film cooling at high pressure. The solution of gas in liquid, real gas property and its variable thermophysical properties are taken into account. They found that the cooling mechanism of liquid film at high pressure is different from that at low pressure.

Theoretically, additional flow effects exist for the film cooling over the curve surfaces which are not existing in flow over flat surfaces. Centrifugal force and cross stream pressure gradient can greatly affect the trajectory of a jet along curved wall leading to improving or degrading film cooling effectiveness. Schwarz and Goldstein [13] experimentally studied film cooling on concave surface. Three different injection hole diameters, two density ratios and wide range of blowing rates were considered. They found that an increase in blowing rate yields an improvement in film cooling performance on a concave surface. Schwarz et al. [1] by using the same experimental apparatus in [13] investigated the effects of injection rate and strength of curvature on film cooling performance on convex surface. The more important result of their investigation is that the increased convex curvature enhances effectiveness at low injection rate.

Hung et al. [14] studied the effect of injection angle orientation on film cooling of concave and convex surfaces. They employed a transient liquid crystal thermography to measure film cooling performance. Four blowing ratios (0.5, 1.0, 1.5, and 2.0) have been used. In their study they examined four different injection configurations, one with simple and three with 8° forward-expanded holes. Three compound angles of 0, 45, and 90° are tested. They found that forward-expanded hole with simple angle injection provides the best film cooling performance. Berhe and Patankar [15] numerically studied curvature effect on discrete holes film cooling. Three surfaces were considered namely convex, concave, and flat surface. Computations were performed for blowing ratios of 0.5, 1.0 and 1.5 at a density ratio of 2.0. The main result is that the convex surface had higher film cooling effectiveness than the flat surface and the flat surface had higher film cooling effectiveness than the concave surface for the blowing ratios of 0.5 to 1.5.

Lutum et al. [16,17] experimentally investigated the influence of the streamwise pressure gradient on film cooling performance of a convex surface. Five different injection geometries, three with cylindrical and two with shaped holes were examined. They found that the effect of streamwise pressure gradient seems to be more pronounced on a curved surface than for flat plate film cooling. Jung and Hennecke [18] studied the curvature effects on film cooling. The adiabatic film cooling effectiveness on convex and concave surfaces with two staggered rows of film cooling holes is investigated. Two different radii of curvature and two streamwise distances of the rows are considered. Wide range of blowing rates from 0.25 to 2.0 has been employed. They found that at high blowing rates the effectiveness is not greatly influenced by surface curvature. Chen et al. [19] showed that the forward expanded hole injection ($\beta=0$)