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Research Article

Performance prediction of trailing-edge cooling system of gas turbine blade using detached eddy simulation

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ABSTRACT

This study evaluates the performance of the trailing-edge (TE) cooling system in a gas turbine blade. Eddy Simulation (DES), based on the turbulence model of Spallart-Almaras (SA), was used to simulate the TE cooling system. A TE configuration with a five-row staggered pin-fin arrangement was employed as a computational domain. Three parameters, i.e., the coefficient of heat transfer on the pin-fins surface (h_{pin}), the coefficient of discharge (C_D), and the effectiveness of adiabatic film cooling (η_{aw}) were used to assess the performances. The findings denoted that the heat transfer fluctuations occurred on the surface of the pin-fins in each row. The discharge coefficient increased with the rising of the blowing ratio. The trend predicted data of η_{aw} were in good agreement with realistic discrepancies compared to other researches, mainly for higher blowing ratio. The average effectiveness along the cut-off region was to be sensitive to the blowing ratio changes, which was attributed to the structures of turbulent flow along the mixing region.

1. INTRODUCTION

A blade cooling system of the gas turbine is necessary to ensure the lifetime of a turbine blade. The important part of the turbine blade that needed more attention is trailing-edge because it operates in extreme conditions such as high temperature, limited material strength, and very high pressure [1][2]. These extreme conditions cause serious aerothermodynamic problems for engine parts such as liners, blades, and vanes, i.e., melting, oxidation, crack, thermal fatigue, and buckling [3][4][5]. To address these problems, a cooling system is needed. This system works by utilising the fluid flow that passes through the turbine blade. Other manners widely used are by adding pin-fin arrangements, an extension of lands [6][7]. The purpose of adding this pin-fin is to produce a turbulent flow of cooling gas, so the heat transfer that occurred is higher. Another advantage of adding a pin-fin is to strengthen the construction of the turbine blade [8]. The turbulent flow is generated from the flow that passed through the pin-fin arrangement provides a further effect behind the slot-exit, and on the adiabatic wall, the intensity of turbulent flow made different patterns resulted from mixing the mainstream and cooling gas so that this mixing could reduce the mainstream with a higher temperature. On the other hand, pin fins in various configurations have been applied in many applications [9], for example, in-line [10] and staggered array [11][12][13]. The most widely used pin-fin shapes were circles [14][15], ellipses [16][17], two rows long rib arrays [18][19].

The research of TE cooling systems has been carried out both experimentally and numerically. Martini et al. [2][20][21] had conduct experiments on cooling systems of gas turbine blades for many years. Wall heat transfer and pressure loss in a TE cooling passage were also numerically simulated by Effendy et al. [22]. Another research has been carried out by Horbach et al. [23], whereas an investigation related to TE cooling is influenced by differences geometry and edge thickness. The findings indicated that the edge thickness strongly influences the predicted data of the discharge coefficient and effectiveness. Another method used to determine turbulent flow from mixing mainstream and coolant gas behind the slot-exit was a Pressure Sensitive Paint technique (PSP) like an experiment conducted by Yang et al. [4]. The results revealed that this technique could well capture a mixture of the mainstream with the cooling flow and the distribution of adiabatic film cooling effectiveness.

Furthermore, many previous researchers' research of the TE cooling system-based on simulations approach has been carried out using different methods [24][25]. Several turbulence models were widely used in investigating the cooling performance on gas turbine blades, such as steady RANS, unsteady RANS, DES, and Large Eddy Simulation (LES) [26][27][28]. Also, Effendy et al. [29] studied about TE cooling system, which was influenced by the thickness ratio of edge (t) to the height of the cooling slot (H). The results of the research found that cooling effectiveness increased with a rising t/H ratio. In contrast, Gao et al. [30] represented the study of DES turbulence model. It was found that the prediction of TE cooling by using DES gives better results as compared to the RANS method. In regards with the research conducted by Effendy, et al [29], the present research was to predict numerically a system of blade TE cooling in a gas turbine with DES based on the SA turbulence model. Three key parameters were investigated related to cooling performance of TE gas turbine i.e parameters, i.e., heat transfer on the pin-fins surface, C_D, and η_{aw}. The research focuses on the relationship between TE cooling and internal cooling due to the blowing ratios.

2. NUMERICAL SIMULATION

2.1. Computational domain

The design, geometry, and meshing of specimens used in this study refer to Effendy's research [29]. Figure 1 provides the computational domain and flow boundary conditions. The cooling slot has a width of 12 mm with a pitch spacing (S) 12 mm, in the cooling channel (L_1 zone). There are five pin-fins arrangement with a slope of (α) 10 degrees. The pin-fins diameter (D) and the cooling-slot height (H) have the same dimensions, i.e., 4.8 mm. Pin-fins distance to spanwise (S) direction is 2.5D, and streamwise (Sx) direction is 2.167D, thus formed equilateral triangles. The meshing of the test specimen is given in Figure 2.

Dimension	L_1	L_2	L_3	S	S_x	t	H	D	α
mm	52	14.4	60	12	10.4	4.8	4.8	4.8	10°

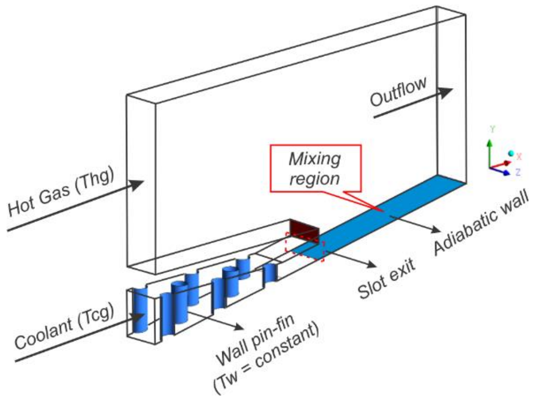


Figure 1. Computational domain.

2.2. Initial flow and boundary condition

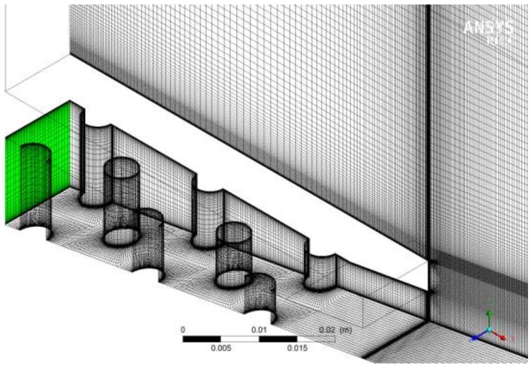
In the study, both flow conditions and constraints adopted the same experimental setup as used in Martini's experiments, as shown in Table 1.

Table 1. Experimental setup.

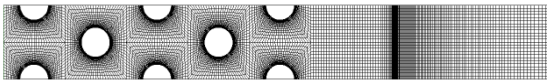
Mainstream flow	Coolant flow
Re_{hg} = 250,000	T_c, $L_{2\ exit}$ = 295 – 330 K
Ma_{hg} = 0,125	T_c, $L_{1\ inlet}$ = 293 K
u_{hg} = 56 m/s	Tu_c = 5%
Tu_{hg} = 7%	M = 0,2 – 1,25
T_{hg} = 500 K	
P_{hg} = 105 kPa	

2.3. Meshing and simulation

In this simulation, the mesh was kept at a high standard of grids up to $\Delta y^+ < 1$ for all surfaces. It is an attempt to make sure an adequate high spatial resolution of the unsteadiness in the mixing region, mainly along the adiabatic wall's surface. It was built in more exceptional quality mesh up to $\Delta y^+ < 0.5$ on average, as previously studied by Effendy et al. [31]. The 3-D domain spacing accuracy must be smooth enough to address the DES method to the blending factor (F) requirement.



(a)



(b)

Figure 2. Mesh. (a) 3D view. (b) Bottom view.

The finite-volume approach was used to resolve the governance equations of incompressible flow. Equations were spatially resolved by second-order precision on multi-block organised grids, while provisional computed using the 2nd order scheme was entirely implicit manner. The algorithm of SIMPLEC was employed by the 2nd order simulation scheme utilised to all equations of flow fields such as energy, momentum, and pressure of the non-steady RANS and DES calculations.

2.4. Film-cooling effectiveness

The film-cooling efficiency was calculated by formulation (1);

$$\eta_{aw} = \frac{T_{hg} - T_{aw}}{T_{hg} - T_{c'}}, \tag{1}$$

T_{hg} is the temperature of hot gas at the main flow, T_{aw} is the temperature of adiabatic wall surfaces, and $T_{c'}$ is the coolant gas's temperature among two adjacent pin-fin arrays that measured in the centrum of the coolant slot-exit.

The coefficient of discharge, C_D, was formulated as follow

$$C_D = \frac{\dot{m}_{c,real}}{\dot{m}_{c,ideal}}, \tag{2}$$

$$C_D = \frac{\dot{m}_{c,real}}{p_{1,t} \cdot \left(\frac{p_2}{p_{1,t}}\right)^{\frac{\kappa+1}{2\kappa}} \cdot A_{slot} \cdot \sqrt{\frac{2\kappa}{(\kappa-1)\cdot R \cdot T_{1,t}}\left[\left(\frac{p_{1,t}}{p_2}\right)^{\frac{\kappa-1}{\kappa}} - 1\right]}} \tag{3}$$

where $T_{1,t}$, and $p_{1,t}$ is total temperature and pressure at the coolant inflow, respectively, p_2 is static pressure at the coolant slot-exit, A_{slot} is the cross-section area of coolant slot- exit, κ is the capacity of specific heat and R is the constant of gas.

3. RESULTS AND DISCUSSION

Numerical simulation of the gas turbine's blade TE cooling system has been carried out by implementing the DES-SA turbulence model. It successfully identified three main parameters, i.e., the heat transfer on the pin-fins surface (h_{pin}), the coefficient of discharge, and the effectiveness of adiabatic film cooling. The results describe as follows.

3.1. Heat transfer coefficient

Figure 3 provides the heat-transfer (HTC) coefficient at the superficies of the pin-fin arrays on the various blowing ratios at the coolant slot-exit, called as throat section. It was found that the trends of the heat transfer have similarities in three blowing ratios. Effendy et al. [32] found that the average coefficient of heat transfer at the surface pin-fin within the cooling passage is marginally increased. The heat-transfer coefficient is decreased after the fourth row of the pin-fin array. The highest h_{pin} occurred on the fourth pin.

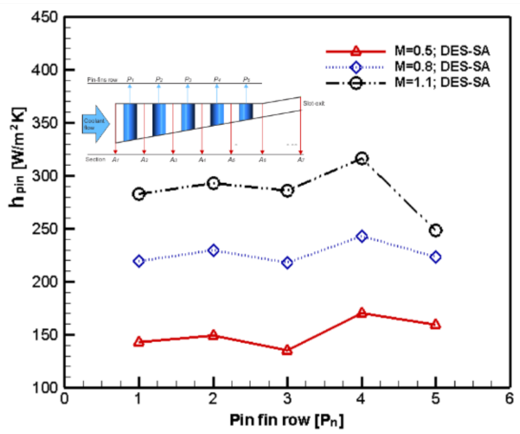


Figure 3. Pin-fin HTC.

Due to the turbulent flow effect of cooling gas that passed through the fin-pin arrangement, it caused different heat transfer on each pin. Effendy et al. [33] highlighted the combined impact of the pin-fin array and the converging passage influences the motion of the coolant air through the pin-fin, which affects the near-wall turbulent flow structures and their growth.

3.2. Discharge coefficient

The C_D reflects the discharge action of the trailing blade of the cooling opening. This formula exposes the real flow of coolant mass against the magnificent mass-flux due to isentropic development from the upstream area to the free-flow at the ejection in the slot-exit.

Figure 4 indicates the discharge coefficient (C_D) of the research results. The results are consistent with previous research conducted by Martini et al. [2][18], Horbach et al. [20], and Effendy et al. [26]. Hence, the current study is slightly under predictions compared to the others. It can be explained that the C_D value increases with a rising blowing ratio (M). It is due to ribs or pin-fins arrangement in the L1 zone, which causes the difference of main flow velocity distribution, which entered the L_3 section. The increase in the blowing ratio matches the changes of the real coolant mass flow inside the cooling slot.

This finding confirms the correct discovery of film-cooling effectiveness, which, as discussed above, also results in sound harmony. Therefore, three validation studies using the baseline are necessary for further research to be established.

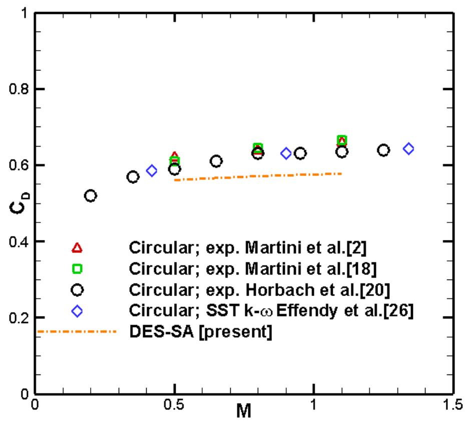
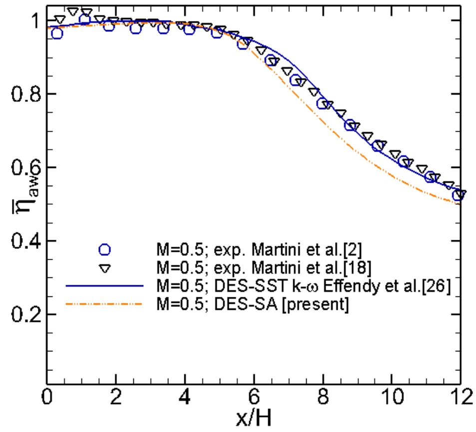


Figure 4. Discharge coefficient.

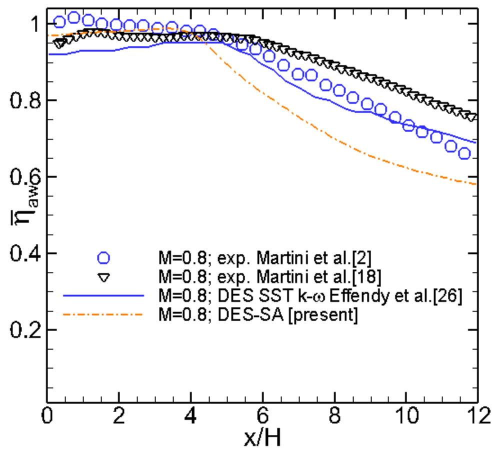
3.3. Film cooling effectiveness

The effectiveness of film cooling (η_{aw}) is an important parameter that needed to be analysed on the TE cutback section. It can be obtained by calculating the average value of η_{aw} on the adiabatic/protected wall surface.

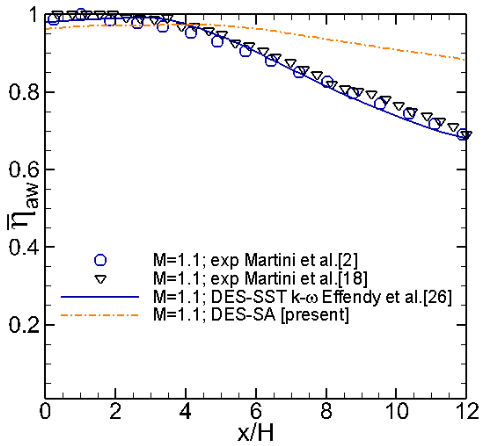
Figure 5(a), (b) and (c) indicate film cooling effectiveness (η_{aw}) that occurred at the adiabatic wall in three different blowing ratios (M) with non-dimensional length (x/H) (x denotes the length of L_3 zone, and H denotes the high of slot exit). Figure 5(a) presents the simulation results of η_{aw} at M = 0.5. The results agree well with measurements data carried out by Martini et al. [2] [18] and Effendy et al. [26], while the difference in simulation results with the other research was 4.7%. The result indicates that the mixture of hot and cold gas behind slot-exit made the significant cooling on an adiabatic wall surface.



(a) M=0.5



(b) M=0.8



(c) M=1.1

Figure 5. Film cooling effectiveness.

Figure 5 (b) shows the η_{aw} at M = 0.8, whereas there is an "under-prediction" at position x/H > 4. It is attributed to hot gas dominated the temperature distribution on the adiabatic wall surface.

Figure 5 (c) represents the η_{aw} at M = 1.1, whereby there is an over-prediction at position x/H > 4 which occurred opposite phenomenon at M = 0.8, the coolant gas is dominated the temperature distribution on the adiabatic wall surface, since η_{aw} higher generated as compared to M = 0.5 and 0.8.

This reduction is due to the increase in the vortex's discharge coefficient from the coolant ejection slot. It happens within a definite operational range of slot ejection, attributing to an escalating mixing phase amongst the mainstream and the coolant.

4. CONCLUSION

In conclusion, the numerical approach using DES-SA turbulence model has been worked out to identify three critical parameters of the blade TE cooling system of the gas turbine, i.e., heat transfer on the pin-fins surface (h_{pin}), discharge coefficient (C_D), and effectiveness of adiabatic film cooling (η_{aw}). Both η_{aw} and C_D agree well with all the different blowing ratios. The discharge coefficient increases with rising blowing ratios. A slight under-prediction has been found in the middle of the blowing ratio and over-prediction in high blowing ratios.

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