Numerical Investigation of Rectangular Twisted Hole on Film Cooling for Gas Turbine Blades

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Abstract. This paper investigates a new method of film cooling using swirling coolant flow through a rectangular twisted film cooling holes with spirally corrugated tube. Two different air flows with different in temperatures were used in this study. Throughout the investigation, blowing ratio was varied from 0.5 to 2.0 with several configuration of rectangular twisted angle of 0°, 90°, 180°, 270° and 360°. The results of cooling effectiveness obtained were compared against a standard untwisted tube. Results show that the overall thermal effectiveness improved significantly when the temperature difference between the air flows is at 25 degrees. Such improvement is supported by heat transfer enhancement that obtained from 19% to 57%. Based on the findings, the study concludes that using a simple geometry of film cooling hole with specific twisted configuration may result to improve the convective heat transfer coefficient.

Introduction

The injection of a coolant or secondary fluid into one or more discrete points on a surface area exposed to an environment of high temperature in order to protect the surface at both the area of injection and downstream region is known as film cooling [1]. Film cooling in gas turbines results to aerodynamic assimilation losses and abridged temperatures of the flow of gas. Gas turbine thermal effectiveness enhancements could be attained by lowering the volume of the fluid and by creating a more equal dispersal of the cooling mixture on the exterior. There is general knowledge that the vortex mechanism in the cooling jets is the source of condensed film-cooling efficacy [2]. The procedure for film cooling is dependent on an array of parameters. The most important physical characteristics that impact on film cooling are a coolant to hot mainstream velocity ratio, blowing ratio, momentum ratio, pressure ratio, temperature ratio, density ratio and turbulence intensity. Furthermore, the geometrical characteristics have a bearing on film cooling. According to [3], a jet of fluid penetration into a traversal moving stream as used in many engineering applications, remains close to the surface of the wall thereby enhancing cooling at low blowing ratios as can be seen in applications such as turbine blade. [4] Shows that thermal and aerodynamics experimentations of various cooling holes with superficial holepositions play different roles in baseline test frameworks of segment cooling holes. According to [5], numerical simulation can be used for investigating film-cooling improvement by infusing moisture within the cooling air with an aim to find out the impact of different modelling approaches on outcomes of simulation. The impact of turbulence on flow inlet border circumstances with and without air supply plenum has in built simulation consequences on the near wall grid thickness [6]. This often leads to a renormalization of the k-□ modelframework, Reynolds stress framework, and the regular k-□ model turbulence replica with an improved wall action that generates regular and perfect outcome while the turbulence distribution has a substantial impact on mist film cooling through the stochastic trajectory estimation. [7,8] studied that detailed heat transfer dispersion formed within two pass coolant square tunnels and linked by two rows of holes on the separating walls can yield improved cooling attained by an integration of impingement and crossflow induced swirl. A similar study examined three mechanisms where the cross flow was produced from one coolant subway to the connecting coolant outlet through a group of directly opposite angled holes and a two dimensional slot positioned along the separating surface.According to [9], in order to get detailed measurement of the film cooling effectiveness for a scaled up film-cooling hole with multiple exits fed by a smooth and ribbed secondary flow channel, which is an arrangement typical of turbine blades, several kinds of bumps need to be installed downstream of the hole exits and the effects of the bumps on the film cooling investigated. The bump structures may include semi-circular, hemispherical, and/or cylindrical bumps. [10] Conducted a numerical simulation study to forecast the film cooling efficiency and heat transmission dispersal coefficient on oscillating blade stage with stator-rotor flow and downstream discrete film-hole flows in a turbine podium. Their findings based on Reynolds pressure commotion model coupled with a non-equilibrium wall occupation indicate that when the blowing ratio is comparatively low, the forward oriented ribs afford a higher film cooling effectiveness, thus suggesting that the rib orientation.

The principal aim of this article is to study the effectiveness of twisted holes for rectangular cross section area corrugated tube under specific flow direction with boundary condition and to understand the impact of twisted angle characteristics on its effectiveness. Here, the effect of blowing ratio in the effectiveness is investigating where the blowing ratio represent ratio between density multiply velocity of hot flow and density multiply velocity of cool flow shown in Eq. 9.

Geometrical Configurations

Film hole geometry is one of the most influential parameters in film cooling performance as studied by M.G. Ghorab [11], so, five case by using five angle of twisted holes of film cooling (0°, 90°, 180°, 270° and 360°) have been simulated numerically, each has hydraulic diameter 8mm, at rectangular cross section area as shown in Figure 1.Configuration of geometry has been done by using solid works software. The fluid medium is air and the main flow velocity and injection film cooling velocity are relative low and steady, so the flow problem in hand can be considered as incompressible steady flow problem.

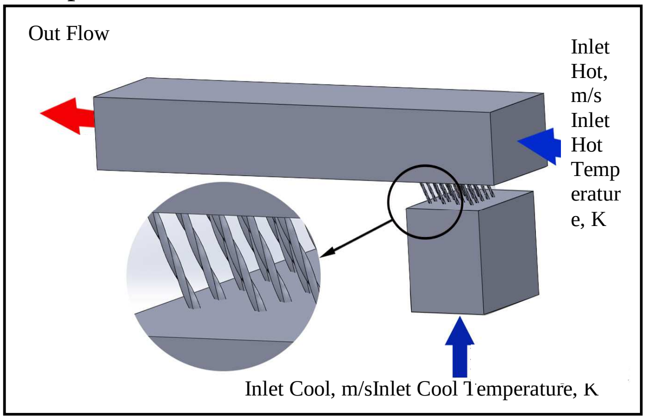
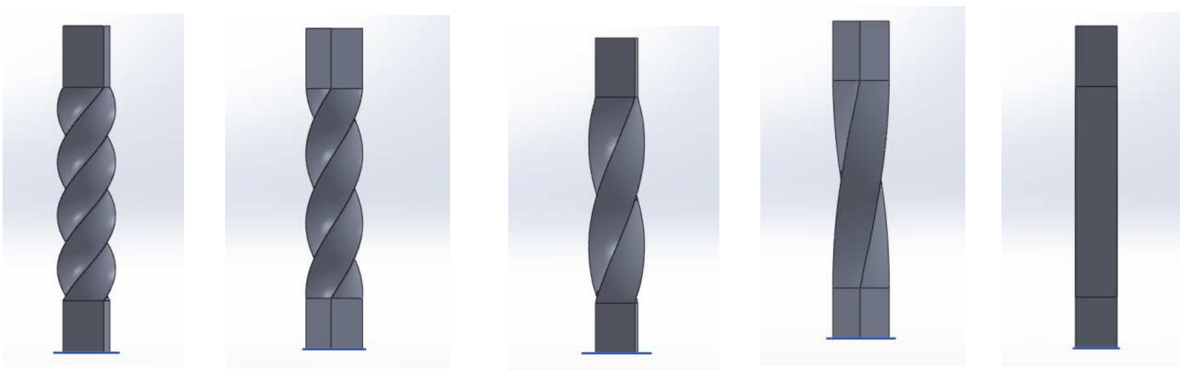


Figure1 Boundary condition configuration



(a) Case 1 (α =360°) (b) Case 2 (α =270°) (c) Case 3 (α =180°) (d) Case 4 (α =90°) (e) Case 5 (α =0°)

Figure 2 Rectangular Geometry varied

Governing Equations

The governing equation of the flow problem in the Cartesian coordinates system as follows Conservation of mass :

$$\nabla . \rho \vec{V} = 0 \quad (1)$$

Momentum equation:

$$\nabla . \left(\rho \vec{V} \vec{V}\right) = -\nabla P + \nabla . \left(\mu \nabla^2 \vec{V}\right) \quad (2)$$

Energy equation:

$$\nabla . \left(\rho \, \vec{V} C_p \, T\right) = \nabla . \left(K \, \nabla T\right) \quad (3)$$

The Theory Of Transient Heat Transfer

Figure3 shows the movement of transient heat across a flat surface. Looking at this situation, the experimental tool is firstly placed at a standardized heat T_i, while the convective borderline situation is abruptly used on the plate at period t >0. Let us view that the temperature is transmitted just in x-direction and their exist a balance of energy on the surface of the plate, we derive.
The 1-D transient conduction equation, also Fig. 4 to explain heat transfer across a flat surface with hole to injection coolant air.

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (4)$$

The boundary conditions (BC) is at x=0, $-k \left.\frac{\partial T}{\partial x}\right|_{x=0} = h\left[T_m - T_{(0,t)}\right]$

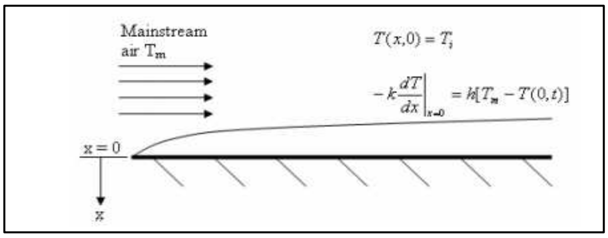


Figure 3 Flow over a flat plate

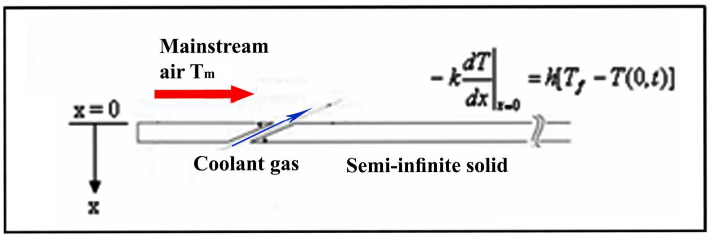


Figure 4 Flow over a flat plate

The initial condition (IC) isat t=0, T=T_i, and Eq. 4 is a second order partial differential equation; thus there is need for another BC to derive the solution to the problem.
The non-dimensional temperature at the convective boundary surface [12]:

$$\frac{T_W - T_i}{T_m - T_i} = 1 - \left[exp\left(\frac{h^2 \alpha t}{k^2}\right)\right] erfc\left[\frac{h\sqrt{\alpha t}}{k}\right] \quad (5)$$

The temperature of the film is dependent on the local mixture of both streams. Here, the surface heat flux is given as:$q'' = h_f\left(T_f - T_w\right)$
The film temperature equals the adiabatic wall temperature when an adiabatic surface exists in Eq. (6). Also, the film temperature (T_f) and the heat transfer coefficient (h_f) are unknown, as depicted in Figure 4.
Here, we define a non-dimensional temperature given as film-cooling effectiveness (η), so as to derive T_f in terms of known quantities T_m and T_c, as shown below:

$$\eta = \frac{T_f - T_m}{T_c - T_m} \quad (6)$$

Or$T_f = \eta(T_c - T_m) + T_m = \eta T_c + (1 - \eta) T_m$(7)

It should be noted however that the film-cooling effectiveness can only have values between 1 and 0 as its highest and lowest values respectively.We can now obtain the equations in terms of the two unknowns, h and η, by replacing T_m in Eq. (5) with T_f in Eq. (7), as:

$$T_w - T_i = 1 - \left[exp\left(\frac{h^2 \alpha t}{k^2}\right)\right] erfc\left[\frac{h\sqrt{\alpha t}}{k}\right] \times \left[\eta T_c + (1 - \eta) T_m - T_i\right] \quad (8)$$

Result and Discussions

The results show that the overall thermal performance improved significantly when we have two different air flows with different in temperatures were used in this article, with a heat transfer enhancement between19% to 57%. These findings show that the twisted angle increased effectiveness in the following ways;it limited the thermal stresses on the walls due to their differential corrugation, also when twisted angleincreased for a given vortices in jet flow, it increased the convection on the surfaces of the blade and it enabled the presence of secondary movements of the fluid.The numerical results obtained from Eq.8 were experiment work standard smooth holes [13]. Figure 5shows the comparison between numerical and experimental work at blowing ratio equal 2, y-axis is represent the effectiveness which depend on temperature of surface blade turbineas shown in Eq. 6 while x-axis represent the ratio of axial distance and hydraulic diameter of the hole. This ratio is also known as stream wise location as reported from previous work [11, 12]. From figure 5 there is a good agreement the deviation was found to be less than 2 %, hence, it is acceptable.

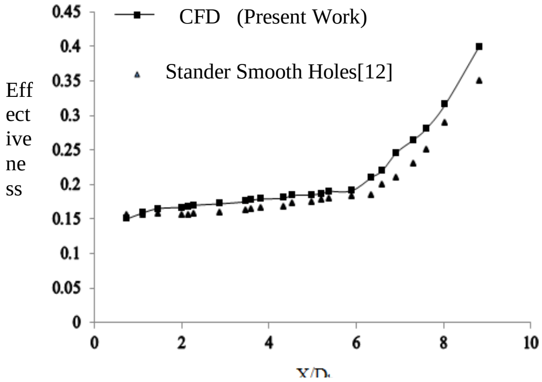
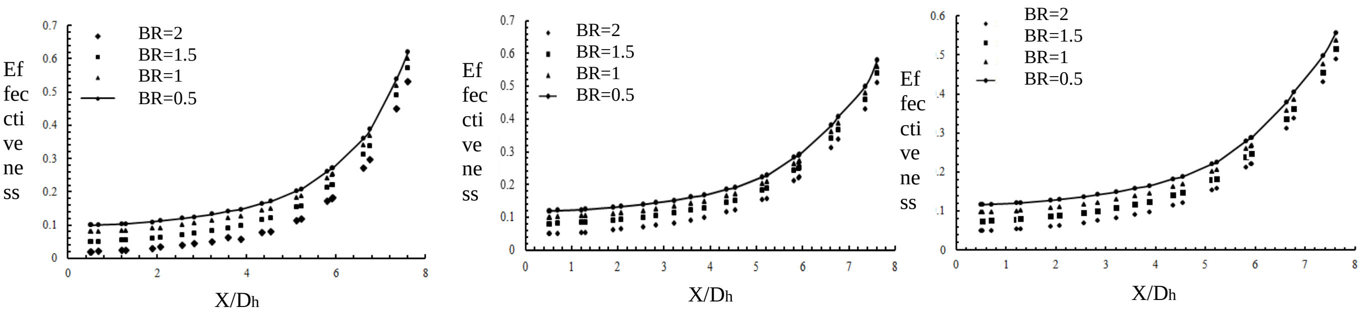


Figure 5 Results validation between standard smooth hole [12] and numerical results of Circular cross section area at BR=2

Figures 6 shows the effectiveness (η) against the axial distance X/D_h at blowing ratio at 0.5, 1, 1.5 and 2 at twisted angle of holeat180°, 270° and 360°. It can be seen that there is a twisted angle at 360° effect on effectiveness but it’s still better than smooth rectangular cross section area (α at 0) of hole due to low blowing ratio, also we note that the flow is turbulent and the secondary flow rejection from holes Re at 6200 which means that corrugations helps to mix the flow and break the boundary layer and create turbulence in the area adjacent to surface of blade turbine, hence, more corrugations means more vortices.

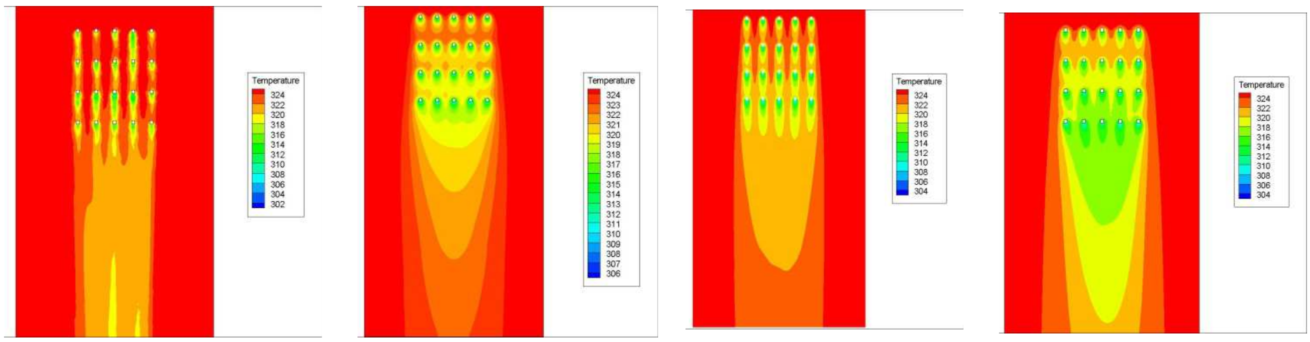


(a) (b) (c)

Figure6(a) Effectiveness vs Stream wise locationat twisted angle (α=360°) (b) Effectiveness vs Stream wise locationat twisted angle (α=270°)(c) Effectiveness vs Stream wise location at twisted angle (α=180°)

Figure 7 shows the distribution temperature on the surface of blade at blowing ratio (0.5, 1, 1.5 and 2), which is also the same reason why the knee of temperature distribution curves occurring on the surface of turbine blades, from this figure can be notes when blowing ratio increase the effectiveness decrease because at high blowing ratio happen separation between the coolant flow and surface of blade of turbine.

$$BR = \frac{U_j}{U_m} \qquad (9)$$



(a) (b) (c) (d)

Figure 7 Detailed temperature distribution at □=45°(a) Case 1 BR=2 (b) Case 2 BR=1.5 (c) Case 3 BR=1 (d) Case 4 BR=0.5

Conclusion

In this study, rectangular cross section area corrugated holes was numerically investigated to clarify the effect of twisted angle characteristics on heat transfer effectiveness. The results indicate that simple geometry configurations can improve the temperature distribution significantly at a blowing ratio of 0.5, and also yield a high value of heat transfer coefficient at a low blowing ratio. Furthermore, the results show a higher effectiveness with an increase in the twisted angle and a decrease in the film cooling hole angle, under a constant blowing ratio. The study therefore concludes that the blowing ratio and twisted angle height have a great effect on film temperature (effectiveness) because as twisted angle increased vortices increased and also as blowing ratio decreased effectiveness increased. The effectiveness range that was studied by simulation was between 19% to 57%. Thus implies that the tube geometry has a good cross section for producing higher effectiveness by using twisted holes.

Nomenclature

Symbol	Quantity	Units
Br	blowing ratio ($\rho_j u_j/\rho_m u_m$)	-
C_p	specific heat	W/kg.k
D	hydraulic diameter of film hole (m)	m
D_h	hydraulic diameter of the main duct	m
DR	density ratio (ρ_j/ρ_m)	-
h	heat transfer coefficient (W/m^2K)	W/m. K
K	thermal conductivity of plate	W/m K
L	length of film hole	m
Nu	Nusselt number	-
p	film hole pitch	m
q	Heat transfer flux	W/m^2
Re	Reynolds number	-
T	temperature	K

T	time	s
$\mathbf{T_w}$	average wall temperature	K
$\mathbf{U_m}$	normal main stream velocity in x-direction	m/s
x, y, z	coordinates	
$\boldsymbol{\alpha}$	thermal diffusivity	m^2/s
$\boldsymbol{\eta}$	local film cooling effectiveness	-
	non-dimension surface temperature	-

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