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Research Paper

Pressure distribution effects due to chevron fences on film cooling effectiveness and flow structures

Antar M.M. Abdala [a,*], Fifi N.M. Elwekeel [b]

[a] Helwan University, Faculty of Engineering, Matareya Branch, Cairo, Egypt
[b] Helwan University, Faculty of Industrial Education, Cairo, Egypt

HIGHLIGHTS

- Chevron fence geometry was investigated as a potential alternative.
- Film cooling effectiveness, pressure patterns and flow structures were investigated.
- Three pressure coefficient peaks were identified as characterizing the fences.
- Main mechanism of the improvement is coolant lateral spreading via these peaks.
- Chevrons fences with rounding helped in enhancement the film cooling effectiveness.

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ABSTRACT

In the present study, film cooling effectiveness behavior for novel fence geometries were investigated depending on flow structures and related pressure patterns. Eleven fence geometries are evaluated. Generally, it can be described as upstream chevrons with sharp and rounded edges instead of straight shapes. The film cooling effectiveness was investigated and compared with experiments with and without fences, which are available in literature review. Velocity profiles, static pressure coefficient profiles and turbulence kinetic energy contours were discussed. Blowing ratios in the range of 0.5, 1, 1.5 and 2 were investigated. Results show that the fence cases are characterized by three pressure coefficient peaks that are responsible for generating useful higher pressure difference between the leading edge of a film hole and the midline region to improve coolant lateral spreading. Results indicate that the best novel fence is chevron with rounded edge “case (e)” with higher film cooling effectiveness levels compared with the experiments**.**

1. Introduction

Gas turbine blade cooling technologies play a vital role in an increasing the life of the turbine blades and vanes. In the advanced gas turbines, the turbine inlet temperature can be increased as high as 1500 °C to achieve the demands of increasing each of the power output and thermal efficiency [1]. However, this temperature exceeds the melting temperature of the metal airfoils. Therefore, it is necessary to use effective cooling methods. Gas turbine blades are cooled internally and externally. Internal cooling is achieved by passing the coolant through several enhanced serpentine passages inside the blades and the extracting the heat from the outside of the blades. Both jet impingement and pin-fin cooling are also used as a method of internal cooling. External cooling is also called film cooling. Internal coolant air is ejected out through discrete holes or slots to provide a coolant film to protect the outside surface of blade from hot combustion gases. Film cooling technology is considered in this study. Designers need information about the film cooling performance and local airfoil metal temperatures for the advanced applications. The film cooling performance is an important parameter depends on the film cooling geometry, the secondary flow and cross flow fields. From heat transfer point of view, the film cooling performance must increase over blade surface. This can be achieved by increasing film cooling effectiveness and decreasing heat transfer coefficient and for that reason; the net heat flux reduction over blade surface will increase.

By using discrete circular film holes, the secondary flow will penetrate deeply in the cross flow at higher blowing ratios. Therefore, film cooling performance will decrease over the blade surface [2].

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* Corresponding author.
E-mail address: antar451@yahoo.com (A.M.M. Abdala).

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Nomenclature

B	pitch (space between the injection holes) (m)
$\mathbf{C_P}$	pressure coefficient (-), $\mathbf{C_P} = \frac{\mathbf{P-P_\infty}}{\mathbf{0.5*\rho_\infty*u_\infty^2}}$
D_h	hydraulic hole diameter (m)
DR	density ratio of coolant to mainstream, ρ_c/ρ_∞ (-)
L	hole length (m)
M	blowing ratio of coolant to mainstream (-) $M = DR * U_c / U_\infty$
P	pressure of the fluid (Pa)
S	height of fence (m)
T	temperature (K)
Tu	mainstream turbulence intensity (%)
u	velocity (m s^{-1})
X	streamwise coordinate along model surface (m)
Y	vertical coordinate (m)
Yplus	non-dimensional wall distance

Greek symbols

α	coolant injection angle (deg.)
η	adiabatic effectiveness, $(T_\infty - T_{aw})/(T_\infty - T_c)$
θ	non-dimensional temperature ratio, $(T_\infty - T)/(T_\infty - T_c)$
ρ	density (kg m^{-3})

Subscripts

∞	mainstream
aw	adiabatic wall
c	coolant
w	wall

Many novel techniques were used to increase the cooling effectiveness such as embedded cylinder holes in craters [3–4]. They showed that the film cooling effectiveness can be enhanced than the cylindrical hole.

Xue et al. [5], Laveau and Abhari [6] and Gao and Han [7] proved that the shaped film hole increases film cooling effectiveness levels than the other configurations.

Rhee et al. [8] investigated effects of changing the film hole shape for more cases on the film cooling performance. These film hole shapes are rectangular film hole with and without expanded exit, the basic circular film hole and the slot. They concluded that the film cooling performance will increase via the rectangular film hole with expanded exit due to decreasing the jet penetration in the cross flow and increasing the jet lateral distribution over the surface.

Compound angle injection improves the coolant spreading and provides higher film effectiveness especially at low blowing ratio. At higher blowing ratios the film effectiveness deteriorates due to the jet lift off but still higher than the base hole [9,10].

Ramesh et al. [11] studied the effect of antivortex hole on film cooling effectiveness by using advanced tripod hole. They showed that at any given blowing ratio, the tripod hole designs use 50% less coolant and provide overall averaged higher cooling effectiveness than the traditional cylindrical holes.

Ke and Wang [12] investigated a pulsed film cooling with square and sinusoidal waves on a modified NASA C3X vane. They showed that sinusoidal wave pulsed flow leads to less mainstream ingestion into film hole than square wave pulsed flow.

Abdala et al. [2], Na and Shih [13], Barigozzi et al. [14,15] and Rallabandi et al. [16] have proved that using fence can improve the film cooling effectiveness.

These fences can be manufactured in the thermal barrier coating systems as cooling scheme on endwall surfaces makes this solution particularly interesting also for platforms applications [14].

However, the mechanisms and the reasons to increase the film cooling effectiveness via the novel fences and related pressure patterns with flow structures need to explanation in detail, in literature.

In this paper, innovative fences were used with a circular and rectangular film holes. The adiabatic film cooling effectiveness and related pressure patterns compared with the experiment were investigated. The influence of the secondary flow velocity on film cooling effectiveness was discussed. The near flow-filled phenomena such as static pressure coefficients, turbulence kinetic energy, jet velocity components and velocity profiles for fence and without fence cases were investigated.

2. Governing equations

2.1. Reynolds Averaged Navier-Stokes (RANS) equations

Substituting the time-averaged into mass, momentum, and energy equations at steady state results in the Reynolds averaged equations given below. In the following equations, the bar is dropped for averaged quantities, except for products of fluctuating quantities [17].

$$\frac{\partial}{\partial x_j}(\rho U_j) = 0 \tag{1}$$

$$\frac{\partial}{\partial x_j}(\rho U_i U_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(\tau_{ij} - \rho\overline{u_i u_j}) + S_M \tag{2}$$

$$\frac{\partial}{\partial x_j}(\rho U_j h_{tot}) = \frac{\partial}{\partial x_j}\left(\lambda\frac{\partial T}{\partial x_j} - \rho\overline{u_j h}\right) + \frac{\partial}{\partial x_j}[U_i(\tau_{i\ j} - \rho\overline{u_i u_j})] + S_E \tag{3}$$

where ρ and u are density and velocity, respectively. p is the static pressure and τ is the molecular stress tensor (including both normal and shear components of the stress). The source term S_M represents Body forces.

h_{tot} is the mean total enthalpy, λ is the thermal conductivity and S_E is the heat source. The $\frac{\partial}{\partial x_j}[U_i(\tau_{i\ j} - \rho\overline{u_i u_j})]$ term in the equation is the viscous work term that can be included by enabling Viscous Work in CFX-Pre.

These equations contain an additional turbulence flux terms, $\rho\overline{u_i u_j}$ and $\rho\overline{u_j h}$ represent the Reynolds stresses and turbulent heat fluxes, which should be modeled properly for a turbulent flow.

2.2. Two equation turbulence models

Two-equation turbulence models are very widely used, as they offer a good compromise between numerical effort and computational accuracy. Two-equation models are much more sophisticated than the zero equation models. Both the velocity and length scale are solved using separate transport equations (hence the term ‘two-equation’).

The k-ε and k–ω two-equation models use the gradient diffusion hypothesis to relate the Reynolds stresses to the mean velocity gradients and the turbulent viscosity. The turbulent viscosity is