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Three-dimensional analysis of temperature field for various parameters affect the film cooling effectiveness

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ABSTRACT

In this paper, a lot of parameters that affect the film cooling performance have been investigated numerically in three-dimensional model. For this purpose, five different inclination angles (α = 30°, 45°, 60°, 75° and 90°), four blowing ratios (M = 0.2, 0.5, 1.0, 2.0) two different nozzle geometries, namely, circular and square shaped have been considered for multiple nozzles. Renormalized (RNG) k–ε turbulence model is used as turbulence closure. The performance of RNG k–ε turbulence model is tested by comparing with available experimental data found in the literature and it is observed that both results are in good agreement. Based on series of simulations it can be concluded that maximum cooling efficiency is obtained at inclination angle of 30° and the blowing ratio of 2.0. It should be noted that circular shaped nozzle provides more effective cooled surface than square shaped nozzles. Present paper shows also the dependence of the cooling efficiency to the one of the most important vortex structure of counter-rotating vortex pair.

1. Introduction

Film cooling is commonly used in modern gas turbines to protect turbine hot-section parts from the thermal loading of hot gas stream. Due its cheapness film cooling is the most investigated technique. In film cooling applications coolant fluid is injected from various different nozzles to form a thin thermal insulation layer on the blade surface to protect from the harmful hot gaseous. According to Arts and Bourguignon [1], film cooling efficiency is dependent mainly upon blade geometry, coolant injection geometry, free-stream flow velocity ratio and coolant to approaching gas temperature ratio. Over the last three decades a large amount of studies have been done on the transverse jet to better understand the fundamental physics of film cooling and to improve the cooling efficiency. Extensive knowledge can be obtained from the review of Bunker [2].

From the literature survey and paper of Gritsch et al. [21] it can be concluded that the length of the hole (L/D), the hole exit-to-inlet area ratio (AR), the hole pitch (P/D), the hole coverage (C/P), hole compound angle (γ), density ratio (DR) are suspect to have a vital impact on the film cooling performance.

A large and growing body of literature has been devoted to film cooling parameters. In 2004 Huiren et al. [3] published a paper in which they evaluated the effect of Reynolds number on round, dustpan-shaped and fan-shaped holes for different blowing ratios. After series of experiments, it was concluded that critical blowing ratio is 1.3 and 0.7 for the fan and dustpan-shaped and round shaped holes, respectively.

In other experimental studies, Schulz [4] and Lin et al. [5] reported different examples of film cooling configurations such as the cylindrical, fan-shaped and laidback fan-shaped holes. Although experiments have been done for various blowing ratios, very limited (α = 30° and 150°) inclination angles have been considered.

Jung and Lee [6] analyzed orientation angle effects for fixed inclination angle of 35° on the film cooling performance experimentally for three blowing ratios, 0.5, 1.0 and 2.0. It was concluded that increasing orientation angle enhances mixing between free-stream and coolant. Tough different orientation angles were considered, effect of the inclination angle is not taken into account.

Maiteh and Jubran [7] investigated the effects of pressure gradient on film cooling for simple and compound angle holes with the inclination angle of 35° only. One of the striking results reported is that staggered arrangement of compound angle injection holes provides better and uniform cooling protection than that of inline rows of compound angle holes.

Nowadays, in addition to the classical hole shapes, holes with new geometrical shapes such as console type has been considered. Sargison et al. [8] used converging slot–hole (console) film cooling geometry. For comparison, five different hole configurations were used for a fixed inclination angle, 35°. Parametric comparison on neither blowing ratio nor inclination angle was made.

For a cylindrical hole with a streamwise angle of 30°, 60° and 90°, Yuen and Martinez-Botas [9] published experimental results

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Nomenclature

C	constants
CFD	computational fluid dynamics
CVP	counter-rotating vortex pair
D	nozzle diameter
DNS	direct numerical simulation
G	generation of turbulence kinetic energy
H	channel height
JICF	jet in crossflow
k	turbulence kinetic energy
L	length of the nozzle
LDA	laser Doppler anemometer
LES	large eddy simulation
M	blowing ratio
p	pressure
RANS	Reynolds-averaged Navier–Stokes
Re	Reynolds number
RNG	renormalized
U, v, w	velocity components in streamwise, spanwise and normal direction
T	temperature
X, x	crossflow (streamwise) distance
Y, y	spanwise distance
Z, z	normal (vertical) distance

Greek symbols

α	inclination angle
ε	turbulence kinetic energy dissipation rate
η	adiabatic film cooling effectiveness
ρ	fluid density
μ	dynamic viscosity
δ	kronecker delta

Subscripts

aw	adiabatic wall
b	buoyancy
cf	crossflow
eff	effective
i	1, 2, 3
j	1, 2, 3
jet	jet
k	1, 2, 3
t	turbulence

at blowing ratios ranges from 0.33 to 2.0 for relatively low free-stream Reynolds number. It was concluded that inclination angle of 30° and blowing ratio of 0.33 provides highest cooling efficiency.

Effects of film cooling hole was analyzed numerically by Azzi and Jubran [10] by introduced console hole geometry. Comparisons were made for cylindrical, shaped and console type nozzles at two different blowing ratios, $M = 0.5$ and 1.0.

Miao and Ching [11] investigated effects of two different inclination angles, 40° and 42° for various blowing ratios ranging from 0.5 to 2.0 on concave plate and it was reported that coolant flow orientation governs both the trajectory and lateral spreading of the coolant jet. It was also concluded that blowing ratio has important effect on film cooling. For the similar blowing ratios, Koç et al. [12] performed a numerical study to deal with film cooling on a curved surface. It was showed that film cooling effectiveness depends on optimum selection of slope of the curved surface and blowing ratios as reported earlier by Jia et al. [13]. According to series of experimental and numerical cases it was claimed that depend on the blowing ratios, a recirculation region bubble downstream of the jet exists for jet angles larger than 40° but vanishes when the angle is 30° as expressed also by Bayraktar and Yilmaz [14]. Aforementioned works concerned very few numbers of blowing ratio and inclination angle.

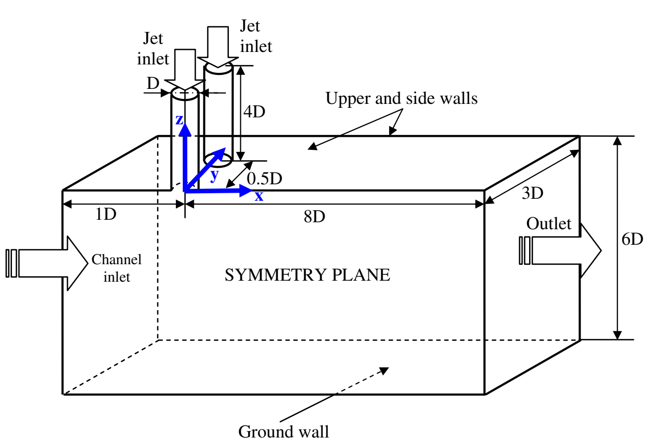

Fig. 1. Main dimensions of computational domain.

Blowing ratio effects on flow and film cooling effectiveness have investigated numerically by various researchers such as Rozati and Tafti [15], Lakehal et al. [16] and Islami et al. [17]. Because these researchers focused mainly on new type hole configurations, effects of inclination angle was not reported.

A recent experimental study of Colban et al. [18] reported two different hole geometries, cylindrical and fan-shaped holes for low and high free-stream turbulence level. It was noted that fan-shaped holes requires less cooling air for the same performance, thus increases the part lifetime. Fan-shaped holes showed increased film cooling effectiveness with increasing blowing ratio. Influence of hole shape and angle are also reported by Lu et al. [19] and Kanani et al. [20] for various blowing ratios.

It appears from the works that numerous experimental and/or numerical investigations have been made to deal with film cooling. However, no attempt was made to investigate the effects of blowing ratio and inclination angle for multiple circular and square shaped nozzles together. It was detected that due to some difficulties cited papers have investigated very limited numbers of parameters.

Table 1
Corresponding values used in the simulation.

Blowing ratio ($M = w_j/u_{cf}$)	Channel (crossflow)				Jet				
	u_{cf} (m/s)	Re_{cf}	L_{cf}/D	T_{cf} (K)	w_j (m/s)	Re_j	T_j (K)	D (mm)	L_j/D
0.2	10	16,780	9	353	2	960	293	7	4
0.5	10	16,780	9	353	5	2400	293	7	4
1.0	10	16,780	9	353	10	4800	293	7	4
2.0	5	8390	9	353	10	4800	293	7	4