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Numerical study of film cooling from converging slot-hole on a gas turbine blade suction side ☆

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ABSTRACT

A numerical research on the film cooling performance of a single row of converging slot-holes (console) on the blade suction side in an engine-simulated environment was carried out, in which the Reynolds number was arranged from 400,000 to 600,000 and the blowing ratio was arranged from 0.5 to 3. A comparison in contrast to a cylindrical hole was made and the effects of major factors on the film cooling effectiveness and aerodynamic loss were explored, including the film hole location, blowing ratio and primary flow Reynolds number. For the console cooling geometry, the interaction between the coolant jet from inclined console and the mainstream flow results in secondary vortices with a sense of rotation opposite to the kidney pair, which makes the coolant jet from the console be of the flow mechanism for suppressing normal penetration. Additional corner vortices are also observed in the intersection of two consoles on the convex surface. When the film holes are located upstream of the channel throat, the level of aerodynamic loss for the console is obviously less than the cylindrical holes. At higher blowing ratios, more coolant jet momentum is transferred to the tangent and lateral flow of the coolant jet issued from the consoles, resulting in a film cooling enhancement. The console row shows great potential in the blade film cooling application, especially favorable when it is located upstream of the channel throat.

1. Introduction

The development of gas turbine engines requires gas turbines to be operated at very high turbine inlet temperatures. This necessitates the innovative cooling techniques for gas turbine engines to protect the turbine components from overheating. One of the commonly used cooling techniques is film cooling, which involves bleeding cooling air from the compressor and routing it to the surface of the turbine vane through discrete holes or slots at several locations. This thin sheet of cooling air acts as a barrier and protects the airfoil surface from the hot gasses exiting the combustor and passing through the turbine. Since the film cooling air is bled from the compressor of the engine, vast amount use of the coolant for cooling blades can be otherwise detrimental to the engine overall efficiency. Therefore, film cooling configuration has to be properly designed and optimized to produce the most effective film cooling with a minimum amount of coolant.

Over the past thirty years, a considerable amount of investigations have been performed in order to understand the fundamental physics involved in the film cooling and assess the knowledge in the design of new film cooling systems. The studies on the film cooling from discrete film holes revealed that the film cooling effectiveness for gas turbine blades is very much dependent on the film hole shape, layout geometry, injection angle, etc. Goldstein et al. [1] carried out an experiment on the film cooling effectiveness comparison between straight round holes and axial shaped holes with lateral diffusion of 10°. A significant increase in the film-cooling effectiveness immediately downstream of the shaped holes as well as increased lateral coolant coverage was illustrated. They attributed this effect primarily to the reduced mean velocity of the coolant at the hole-exit, causing the jet to stay closer to the surface. Gritsch et al. [2,3] presented adiabatic effectiveness and heat transfer measurements, and Thole et al. [4] presented flow field measurements on fan shaped holes that expand laterally and forward near the hole-exit. The expansion of the fan shaped holes increases the lateral spread of the coolant film downstream of the holes and minimizes the penetration of the coolant flow into the mainstream. Investigations on the film cooling performance of compound angle diffuser shaped holes could be found in Bell et al. [5] and Yu et al. [6]. Generally, compound angle-shaped holes had a much improved lateral distribution of coolant over much wider ranges of blowing ratios and produced higher effectiveness and better protection than the axially oriented holes. Guo et al. [7] measured the cooling performance of fan-shaped hole on a nozzle vane model in a transonic annular cascade. They found that fan-shaped holes produced higher cooling effectiveness and lower heat transfer coefficient than cylindrical holes on both suction and pressure sides. Teng et al. [8] compared the cooling performances of three configurations of film holes (cylindrical hole, fan-shaped hole and laidback fan-shaped hole) at the gill part of the blade suction side. It was reported that the two shaped holes had a higher

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Nomenclature

b	slot height (mm)
c_d	pressure coefficient
c_p	specific heat (kJ/(kg K))
C	chord length of blade (mm)
C_x	axial chord length of blade (mm)
d	diameter of film hole (mm)
k	ratio of specific heats
I	momentum flux ratio
$\dot{m}$	mass flux (kg/s)
M	blowing ratio
p	hole pitch (mm)
P	cascade pitch (mm), pressure (Pa)
Re	Reynolds number
s	streamwise direction
T	temperature (K)
u	velocity (m/s)
w	slot width (mm)
x	x-direction
y	y-direction
z	z-direction

Greek letters

α	angle between blade chord and cascade inlet plane (°)
β	primary flow angle (°)
ρ	density (kg/m^3)
μ	dynamic viscosity (Ns/m^2)
θ	inclined angle of film hole (°)
η	film cooling effectiveness
ζ	enthalpy loss coefficient

Subscripts

av	laterally-averaged
aw	adiabatic wall
c	coolant or secondary flow
∞	primary flow

Superscripts

●	total

Abbreviation

KE	kinetic energy

cooling effectiveness and lower heat transfer coefficient than the cylindrical holes. Lee and Kim [9] made a study on a fan-shaped hole for film cooling to find the effect of geometric variations on the cooling performance and optimized it to enhance film-cooling effectiveness using three-dimensional Reynolds-averaged Navier–Stokes analysis and surrogate approximation methods. The injection angle, lateral expansion angle, and ratio of length-to-diameter of the hole were chosen as the design variables, and the effects of these variables on the cooling performance were evaluated. To optimize a fan-shaped hole, the spatially-averaged film-cooling effectiveness was considered as the objective function, which was to be maximized. A comprehensive review of shaped film cooling and its effects may be found in Bunker [10]. It was reported that the improvement in film cooling effectiveness using shaped holes was due to the increase of the separation of the kidney-vortices which delays the jet lift off and induces a counter-pair of vortices; hence the effect was more significance at high blowing

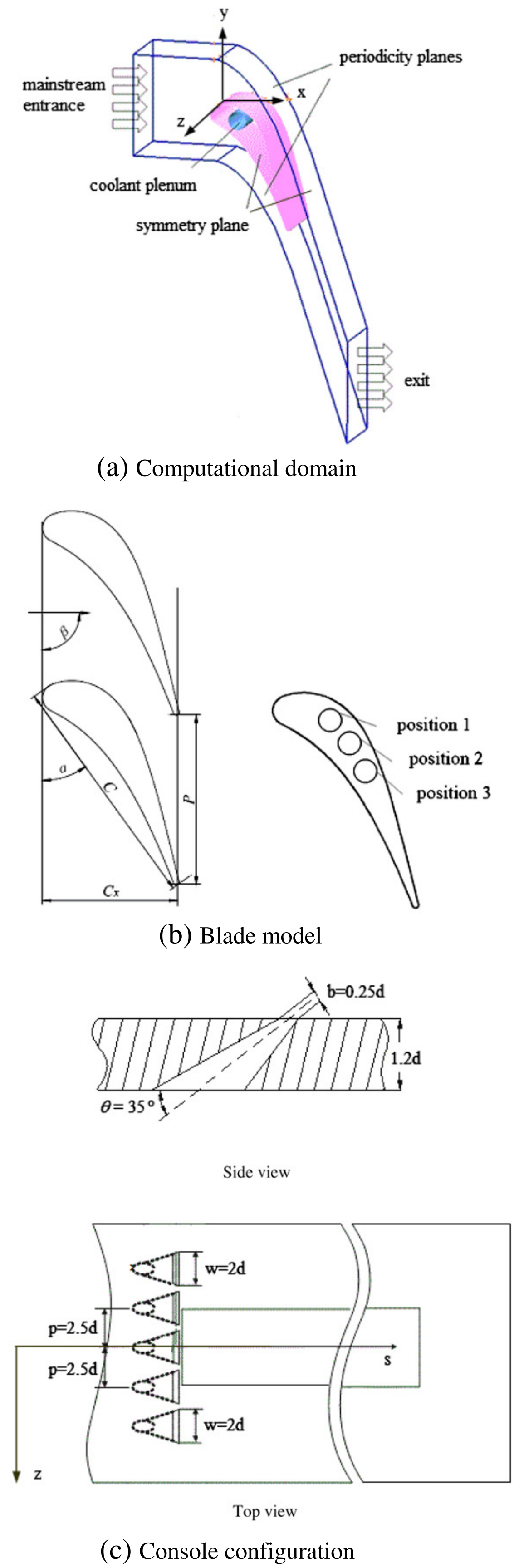

Fig. 1. Schematic diagram of computational model.