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Direct numerical simulation of film cooling with a fan-shaped hole under low Reynolds number conditions

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ABSTRACT

Shaped film cooling holes have several features that can greatly improve film cooling effectiveness, and it has been studied and utilized in gas turbine engines for decades. Few studies, however, have reported the effects of low mainstream Reynolds number on shaped film cooling holes. In this study, the effects of mainstream Reynolds number on film cooling with a fan shaped hole are studied by utilizing direct numerical simulation (DNS). In addition, the compressibility and the viscosity of the working fluid are simultaneously considered, and the non-reflecting and absorbing boundary conditions are adopted at the exit of the main channel. The methods of the Roe scheme, preconditioning, and dual time stepping are employed together to solve the governing equations of a low-speed compressible flow problem. This study considers the mainstream Reynolds numbers of Re_D = 480 and 3200 with 0% and 5% turbulence intensity in the mainstream. Results reveal that the coolant jet penetrates into the mainstream with a mainstream Reynolds number of 480. However, at the higher Reynolds number, the coolant jet develops along the wall and results in better film cooling effectiveness. In addition, special attention is paid to the structures of the vortices developed from the crossflow. Hairpin vortices become smaller at higher mainstream Reynolds numbers. On the contrary, horseshoe vortices appear when the mainstream Reynolds number is increased. A detailed comparison of the vortices is presented in this study.

1. Introduction

Film cooling is considered as the most effective way to avoid turbine blade being damaged by high temperature working fluid. Nonetheless, the presence of film cooling obstructs turbine blades from receiving momentum from the working fluid, thus investigation of mechanisms of film cooling in a favorable trade off becomes an important issue.

Due to the complexity of film cooling, several parameters, such as blowing ratio, density ratio, shape and incline angle of the film cooling holes, mainstream turbulence intensity, etc., were usually used to investigate behavior of the film cooling. Goldstein [1] studied the effects of velocities, vortices, film cooling holes, density, blowing ratio, and temperature ratio on the interaction of the mainstream and coolant jets. Goldstein et al. [2] described the influences of the film cooling hole geometry and coolant jet density on three-dimensional film cooling, and obtained remarkable achievements for improving film cooling. Thole et al. [3], Kampe et al. [4], and Lee and Kim [5] also investigated and reviewed the effects of shaped film cooling holes on film cooling effectiveness, and recognized that the film cooling effectiveness of a fan-shaped film cooling hole is superior to that of a cylindrical film cooling hole under most conditions. Bunker [6] presented a review of shaped film cooling holes in turbine film cooling technology analyzing the effects of blowing ratio, compound angle injection, cooling hole entry flow character, and mainstream turbulence intensity on film cooling effectiveness. Saumweber and Schulz's [7] work analyzed the effects of geometry variations of fan-shaped holes on film cooling performance, in which the parameters of expansion angle, inclination angle, and length of the cylindrical part were considered to be the most important factors.

The film cooling mechanism is similar to a jet in crossflow. Several different vortices, such as counter-rotating vortex pair (CRVP), horseshoe vortex, hairpin vortex, and downstream spiral separation node (DSSN) vortices, are formed in the interaction region according to different piercing situations. Several studies, Fric, and Roshko [8], Camussi, Guji, and Stella [9], Baker [10], Gopalan and Abraham [11], Bagheri et al. [12], and Peterson and Plesniak [13], have been conducted to investigate the structures of vortices

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Nomenclature

D	width of the shaped film cooling hole (m)
e	internal energy $(\mathrm{J \cdot kg^{-1}})$
I^{+}	normalized momentum flux $I^{+} = \frac{(\rho U)_{Local}}{(\rho U)_{Max}}$
k	thermal conductivity $(\mathrm{W \cdot m^{-1} \cdot K^{-1}})$
L	length of the delivery channel (m)
M	blowing ratio $M = \frac{(\rho U)_{coolant}}{(\rho U)_{mainstream}}$
Ma_m	mainstream Mach number
N_x, N_y, N_z	number of grids in X, Y, Z directions
P	pressure (Pa)
Pr	Prandtl number
R	gas constant $(\mathrm{J \cdot kg^{-1} \cdot K^{-1}})$
Re_D	mainstream Reynolds number $Re_D = \frac{D(\rho U)_{Mainstream}}{\mu_{Mainstream}}$
T	temperature (K)
T_C	temperature of the coolant (K)
T_M	temperature of the main stream (K)
Tu	turbulence intensity
u, v, w	velocities in X, Y, and Z directions $(\mathrm{m \cdot s^{-1}})$
u_τ	friction velocity $(\mathrm{m \cdot s^{-1}})$ $u_\tau = \sqrt{\frac{\tau_w}{\rho}}$
U	velocity of the fluid $(\mathrm{m \cdot s^{-1}})$
x, y, z	Cartesian coordinates (m)
x/D	non-dimensional distance in X direction
z/D	non-dimensional distance in Z direction
x^+, y^+, z^+	non-dimensional wall distances in X, Y, and Z direction $\frac{\rho u_\tau x}{\mu}, \frac{\rho u_\tau y}{\mu}, \frac{\rho u_\tau z}{\mu}$
X, Y, Z	dimensionless Cartesian coordinates

Greek symbols

α	inclination angle (°)
β	diffuser angle (°)
θ	non-dimensional temperature $\theta = \frac{T_M - T_{local}}{T_M - T_C}$
γ	specific heat ratios
η	film cooling effectiveness $\eta = \frac{T_M - T_{Local}}{T_M - T_C}$
μ	viscosity $(\mathrm{kg \cdot m^{-1} \cdot s^{-1}})$
ρ	density $(\mathrm{kg \cdot m^{-3}})$
τ_w	wall shear stress (Pa)

for further validation of the mechanism. Besides, the variation of vertical momentum of coolant jets is mainly affected by the inclination angle of the delivery coolant channel. The smaller the inclination angle is, the less vertical momentum the coolant obtains. The coolant jet then flows more easily along the downstream blade surface, which is advantageous to film cooling effectiveness and has been validated by Abdullah et al. [14–16]. Zhong et al. [17] studied the effects of an approaching boundary layer on film cooling effectiveness and vortex structure. Results showed that when the approaching boundary layer was laminar, a small recirculation zone formed in the upstream area of the film-cooling hole and transported downstream. This recirculation zone increased film cooling effectiveness by expanding the distribution of coolant in a spanwise direction.

Goldstein and Yoshida [18] studied the difference between laminar coolant jets and turbulent coolant jets. The results indicated that the velocity distribution became more flat as the coolant jet is turbulent. As a result, the effectiveness of the case with a turbulent coolant jet was superior to that of the case with a laminar jet. Saumweber and Schulz [19] studied the effect of free stream Mach number on film cooling with fan-shaped holes. In this study, results showed that increasing the free stream Mach number is not always having a good effect on film cooling effectiveness. At high blowing ratio (M = 2.5), the increase of the free stream Mach number resulted in one-sided separation, thus the film cooling effectiveness is reduced about 40%. Anderson et al. [20] studied the effects of approaching mainstream boundary thickness, mainstream turbulence intensity, and Reynolds number on shaped hole film cooling. In this study, results showed that thicker boundary layer thickness produced higher film cooling effectiveness. Schroeder and Thole [21] studied the effects of a mainstream with high turbulence intensity on film cooling effectiveness under shaped film cooling hole conditions. Results showed that, with a moderate turbulence intensity, area-averaged film cooling effectiveness decreased at low blowing ratio, and slightly varied at high blowing ratio. Schroeder and Thole [22] conducted an extension study of [21], and results pointed out that the effect of high turbulence intensity on film cooling effectiveness was not apparent at high blowing ratio.

Harrison and Bogard [23] used FLUENT code to simulate film cooling mechanisms using three turbulent models of Realizable $k-\varepsilon$ (RKE), Standard $k-\omega$ (SKW), and Reynolds stress model (RSM). Models of SKW and RKE, respectively gained the best lateral average and central line effectiveness. The lateral distributions of coolant stream simulated were smaller than the lateral distributions obtained by experimental results. Tyagi and Acharya [24] adopted the Large Eddy Simulation model (LES) to investigate variations of eddy structure in the cross-flow and the fluid used was regarded as compressible. Relative to the Reynolds averaged Navier-Stokes (RANS) model, results simulated by the LES model were more similar to empirical results. Renze, Schroder, and Meinke [25] also used the LES model to investigate the effects of velocity and density ratios on film cooling mechanisms. Results revealed that the mass flux ratio was an important factor for investigating film cooling effectiveness. Muppidi and Mahesh [26] used direct numerical simulation (DNS) to study a normal cylindrical jet in a crossflow, and important flow features such as horseshoe vortex and hovering vortex were presented in this study.

In the existing literature, investigations into the effects of the shaped film cooling hole and low Reynolds number on film cooling are relatively few. Thus, the aim of this study is to investigate the film cooling mechanism with a shaped film cooling hole under low Reynolds number condition with DNS. A physical model, which is composed of a main channel, coolant channel, and delivery channel, is designed for the current DNS calculation. Fluid viscosity, compressibility, and the limitation of CFL number [27] are taken into consideration. Three channels are separately constructed with structured girds. Bilinear and trilinear interpolations matching Jacobi transformation are applied to connect different structured grids. The numerical method used in this study follows the procedures of the numerical method used in Li et al. [28]. Several methods are applied in this numerical method, such as nonreflecting boundary conditions developed by previous works [29,30], the schemes of Roe [31] matching preconditioning method [32] for resolving the governing equations used in this study, dual time stepping [33] for calculating transient states, the method of MUSCL (Monotone Upwind-centered Schemes for Conservation Laws) [34] which is used to solve the turbulent structure accurately, and the method of LUSGS (Lower–Upper Symmetric-Gauss–Seidel) [35] modified by Xu, Lee and Pletcher [33] which makes the iterative method used in this study more suitable for solving low Mach number flow. In order to economize calculation time further, two parallel computing methods, open multi-processing (open MP)