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Effects of the laidback fan-shaped hole geometry on film cooling performance using large eddy simulation

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ABSTRACT

The higher temperature of the combustion chamber of a gas turbine yield higher efficiencies for the turbines but can affect the blade's life. As a preventative method, Film-cooling is a useful technique to enhance the performance of it by injecting coolant jets that the metal surfaces can be protected against the hot main flow. To improve cooling efficiency and increase the life of these components, several cooling strategies have been introduced. In the present study, the effects of the laidback fan-shaped hole geometry, in particular, are examined against the conventional cylindrical hole geometry using Computational Fluid Dynamic simulations. Computations are carried out based on three-dimensional Large Eddy Simulation. The open-source software OpenFOAM was utilized to solve the filtered governing equations for mass, momentum, energy conservation, and heat transfer. The mixing mechanism between hot and coolant fluids, nondimensional adiabatic film cooling effectiveness, and dynamics of vortices are presented and discussed.

KEY WORDS: Large Eddy Simulation, Film Cooling, Laidback Fan-Shaped Hole, Heat Transfer, Computational Fluid Dynamics, Finite Volume Method, OpenFOAM

1. INTRODUCTION

Film cooling strategy is firstly introduced in early 1970's with the simple inclined cylindrical hole. As the hole design is advanced, new types of hole geometry including ridge-shaped, laidback fan-shaped, curp-shaped, console holes and so on are introduced and extensively investigated in both physical experiments and numerical simulations.

For numerical studies, comprehensive investigations of the effect of hole geometry have mostly been carried out based on Reynolds-Averaged Navier-Stokes equations(RANS) with two-equation turbulence models by commercial software [1-3]. RANS simulation is the time-averaged steady approach which is hard to identify the mixing process and evolution of vortices. By taking an advantage of resolving the more influential turbulent scales, a number of research [4-7] has employed Large Eddy Simulations (LES) to examine the film cooling effectiveness and coherent vortex structures. However, these studies are limited to the cylindrical hole shape, and very little research of the fan-shaped hole has been performed using LES.

In the present study, we validate and predict the heat transfer and mixing behaviour between hot gas and coolant in crossflow as well as the film cooling effectiveness using the open source computational fluid dynamics C++ library, OpenFOAM version 7. Two types of laidback fan-shaped and cylindrical cooling holes are compared and evaluated.

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2. PROBLEM DESCRIPTION

A geometry of the system is depicted in Fig. 1 and parameters used in this study are tabulated in Table 1, respectively. The design of the laidback fan-shaped hole is directly adopted from [8] and the cylindrical hole is designed equivalent to the laidback fan-shaped hole for comparison. The length of the cooling hole is 7.5 times the hole diameter d = 0.01 m, and the crossflow channel size is 40d long, 6d wide, and 9d high. The injection hole angle is 35 degrees. The mainstream and coolant velocities are set to 20 m/s with the temperature of 510 K and 300 K, respectively. The desired blowing ratio, $M = \rho_c u_c / \rho_\infty u_\infty$, is 1.

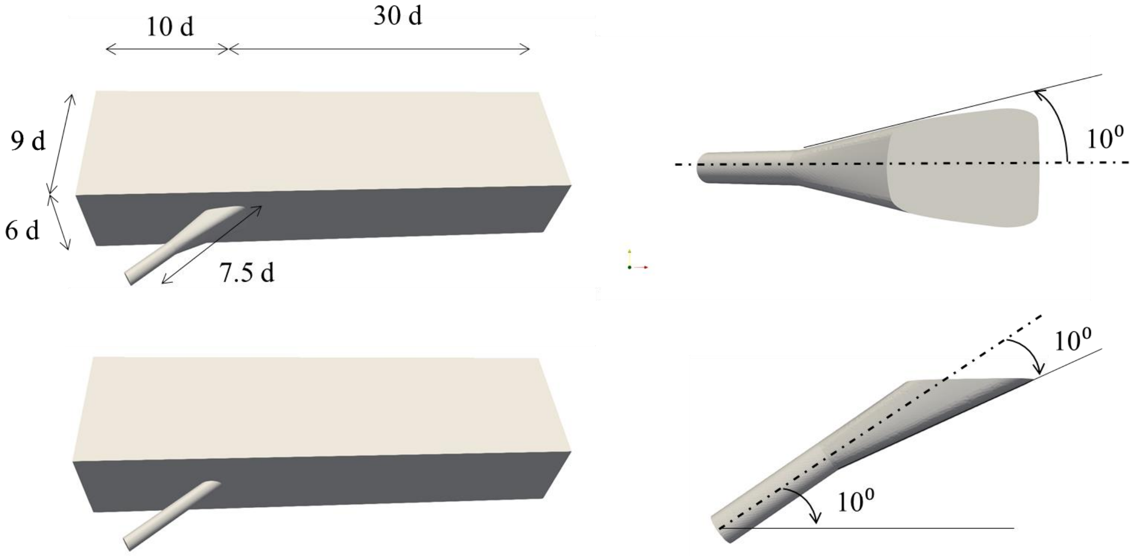

Fig. 1 Geometry of laidback fan-shaped and cylindrical holes and detailed.

Table 1 Parameters and test conditions

Hole diameter, d	Blowing ratio, M	Inclination Angle	Flow velocity (Main / Coolant)	Temperature (Main / Coolant)
10 mm	1	35 º	20 m/s / 20 m/s	510 K / 300 K

3. NUMERICAL SIMULATION

The LES here is conducted using the open-source CFD software, OpenFOAM v7. The fluid dynamics is evaluated by incompressible and Newtonian Navier-Stokes equations. For the turbulence closure, the conventional Smagorinsky sub-grid model is utilized. The passive scalar transport with turbulence eddy-diffusivity modeling is used for heat transfer with a constant Prandtl number of 0.7. Governing equations for the grid-filtered conservative equation, Navier-Stokes equation, and heat transport equation are as follow:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(2\left(\nu - \nu_{sgs}\right)\bar{S}_{ij}\right) \tag{2}$$

$$\frac{\partial T}{\partial t}+\bar{u}_j\frac{\partial T}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\left(\frac{\nu}{Pr}+\frac{\nu_t}{\sigma_t}\right)\frac{\partial T}{\partial x_i}\right) \quad (3)$$

where the bar represents the filtered quantity, and eddy viscosity is calculated as $\nu_{sgs}=C_s^2\Delta^2\bar{S}_{ij}$.

The unstructured tetrahedral topology grids of 5.4M and 6.8M are generated and used for cylindrical and laidback fan-shaped holes, respectively. The first grids near the wall are refined so that y+ is less than 1. Adiabatic and no-slip boundary conditions are imposed on the walls, and symmetry boundary conditions are used at the side walls of the crossflow channel.

For time-dependant governing equations, second-order backward discretization is employed in temporal derivatives, while spatial discretization scheme is the second-order Gauss linear method. PIMPLE solver algorithm is used for time advancement, and the maximum Courant number is limited to be less than 0.5 for reliable solutions. The averaging time step is around 1e-6 sec, and total simulation time is 1 sec. The statistical sampling is carried out after 0.1 sec.

4. RESULTS AND DISCUSSION

4. 1. Mean Quantities

The counter-rotating vortex pair(CRVP) is observed in both cases along the downstream of the jet hole. In Fig. 2, the development of CRVP is depicted in the x/d =3, and 10 planes with time-averaged in-plane velocity contours and vectors normalized by U_∞. Comparing to the cylindrical hole, the laidback fan-shaped hole shows more mixing process in the wide range due to the expanded jet exit area as well as the reduced exit velocity. At x/d = 10, the coolant jet in the cylindrical hole case is detached from the bottom adiabatic wall, whereas the jet in the laidback fan-shaped hole case is still attached to the surface.

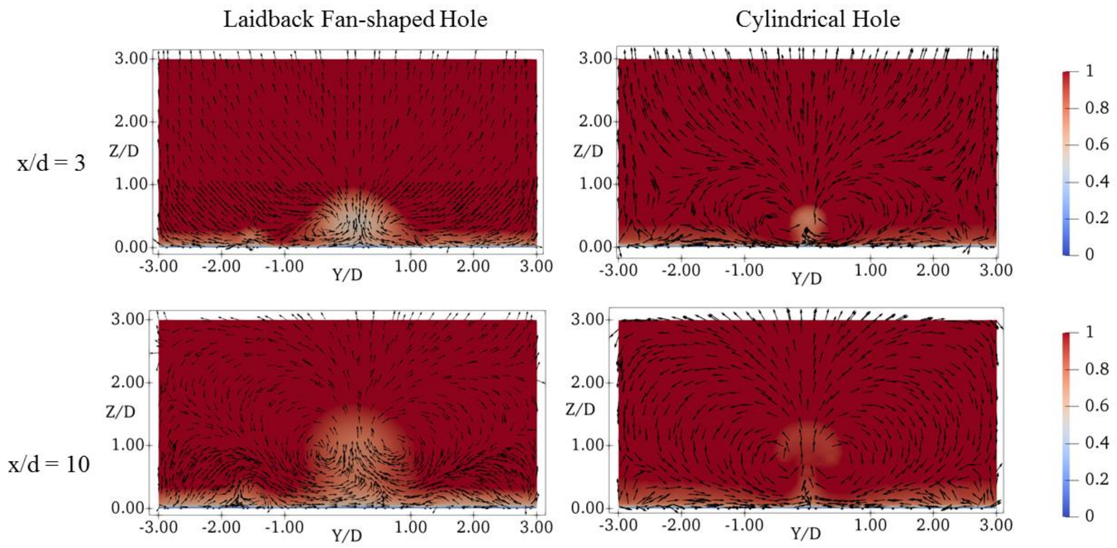

Fig. 2 Time-averaged mean velocity with spanwise velocity vectors

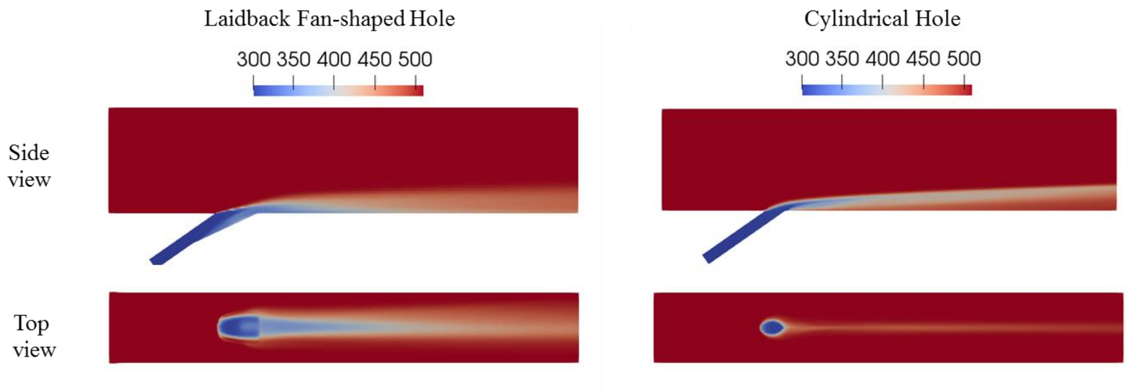

Fig. 3 Time-averaged mean temperature in side and top view

Fig. 3 shows the mean temperature field in the center-plane and z-plane at z=0. The temperature in laidback fan-shaped hole case starts to change from the inside of the hole due to the geometry, and the change spreads to the main channel with mixing process. In case of the cylindrical hole, due to the detachment from the surface, the temperature change is rarely observed at the adiabatic wall.

For validation, film cooling effectiveness, $\eta = (T_\infty - T_w)/(T_\infty - T_C)$, is compared with experimental measurements by [8] and [9]. Fig. 4 shows the film cooling effectiveness along the centerline in the streamwise direction. Numerical simulation results of the cylindrical hole are reasonably well matched with experimental data, while the film cooling effectiveness of the laidback fan-shaped hole is higher in numerical results. [8] conducted the experimental test with 8.2% turbulence intensity and 1.7 density ratio that may induce the discrepancy between numerical and experimental data.

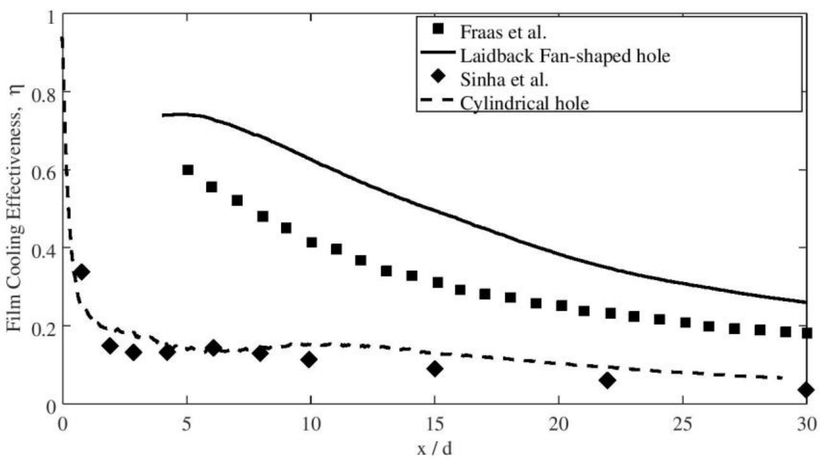

Fig. 4 Time-averaged film cooling effectiveness along the centerline

4. 2. Unsteady Dynamic Quantities

Fig 5. shows the instantaneous velocity contour in the center plane. In general, the laidback fan-shaped hole case shows much higher dynamic behavior than that of the cylindrical hole case, which results in the better mixing process with the mainstream. Near the downstream exit of the laidback fan-shaped hole, the circulation region of jet flow is observed, which causes better wall attachment by reducing the flow velocity in downstream and vice versa in upstream. The expanded hole exit of the laidback fan-shaped hole enhances the lateral spreading. Those are the benefits of the laidback fan-shaped hole over the cylindrical hole without diminishing the mass flow rate.

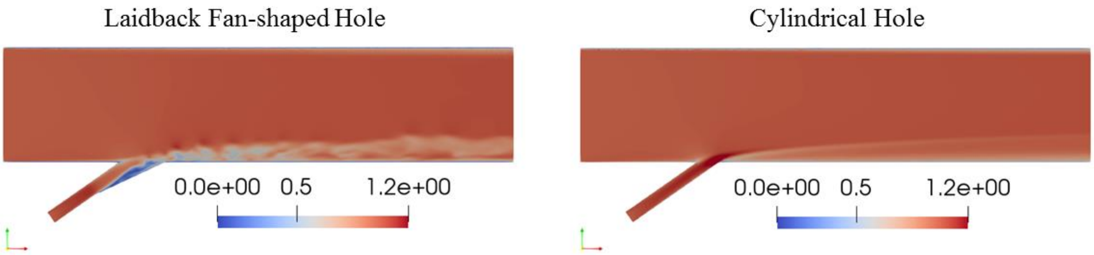

Fig. 5 Instantaneous velocity profiles normalized by U_∞.

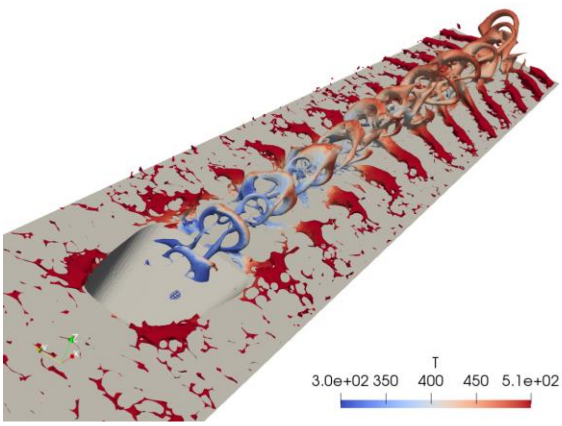

Fig. 6 Instantaneous vortex structures with Q-criterion colored by temperature

Fig. 6 presents vortex strictures near the adiabatic wall in the laidback fan-shaped hole case using Q-criterion method ($Q = 1 \times 10^4$). Hairpin-like vortex is formed along the downstream of the jet hole and becomes larger in further downstream. The secondary vortex beside the Hairpin-like vortex in the spanwise direction are also observed.

5. CONCLUSIONS

The film cooling problem for laidback fan-shaped and cylindrical hole geometries is numerically investigated using OpenFOAM. The numerical results by LES method are validated in predicting the cooling effectiveness at blowing ratio of 1. The influences of two geometries on velocity, temperature, and vortex structures are examined and discussed in terms of mean quantity and unsteady dynamic quantity. The results show that the laidback fan-shaped hole is overall beneficial against the cylindrical hole for mixing mechanism with mainstream and film cooling effectiveness for the current particular test setup.

NOMENCLATURE

C_s	Smagorinsky coefficient	
d	diameter of the hole	(m)
M	blowing ratio	
Pr	Prandtl number	
S	rate-of-strain tensor	
T	temperature	(K)
u	velocity	(m/s)
x	streamwise direction	
y	spanwise direction	
y+	non-dimensional distance normal to the walll	
z	surface normal direction	

Greek symbols

Δ	filter width
η	film cooling effectiveness
ν	viscosity

Subscripts

c	coolant
sgs	sub-grid scale
t	turbulence
w	adiabatic wall
∞	main flow

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