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Effect of ribbed and smooth coolant cross-flow channel on film cooling

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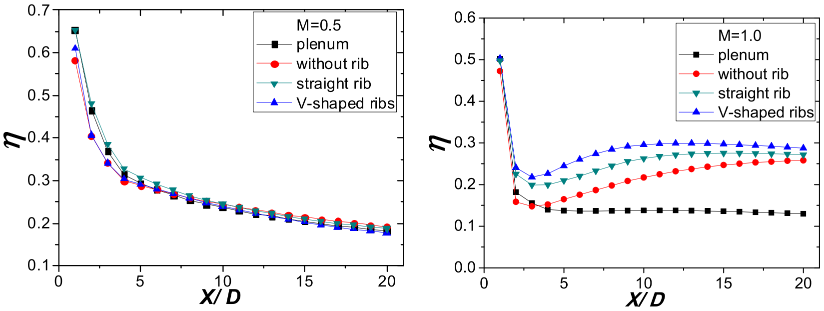
HIGHLIGHTS

- Little different for plenum model and the cross-flow model at M = 0.5.
- Crossflow model is much better than plenum model at M = 1.0, especially with ribs.
- Coolant flow channel with V-shaped ribs has the best adiabatic film cooling.
- Film cooling with the plenum model is better at M = 0.5 than at M = 1.0.
- Crossflow model is better at M = 0.5 near film hole and at M = 1.0 for downstream.

GRAPHICAL ABSTRACT



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ABSTRACT

The influence of ribbed and unribbed coolant cross-flow channel on film cooling was investigated with the coolant supply being either a plenum-coolant feed or a coolant cross-flow feed. Validation experiments were conducted with comparison to numerical results using different RANS turbulence models showed that the RNG k–ε turbulence model and the RSM model gave closer predictions to the experimental data than the other RANS models. The results indicate that at a low blowing ratio of M = 0.5, the coolant supply channel structure has little effect on the film cooling. However, at a high blowing ratio of M = 1.0, the adiabatic wall film cooling effectiveness is significantly lower with the plenum feed than with the cross-flow feed, especially for the cases with ribs. The film cooling with the plenum model is better at M = 0.5 than at M = 1.0. The film cooling with the cross-flow model is better at a blowing ratio of M = 0.5 in the near hole region, while further downstream, it is better at M = 1.0. The results also show that the coolant cross-flow channel with V-shaped ribs has the best adiabatic film cooling effectiveness.

1. Introduction

The very High Temperature Gas-cooled Reactor (HTGR) has unique inherent safety features and has been identified as one of the Generation IV nuclear systems. The modular high temperature gas-cooled reactor combined with a helium gas turbine is a very efficient design with favorable safety and economic characteristics. Helium gas turbine can also be used with space reactors to generate power. However, since the helium gas turbine inlet temperature is very high, the turbine blade must be cooled with film cooling being a very effective method.

Film cooling introduces coolant fluid through small holes or a slot along a surface exposed to a high-temperature environment to provide a thin, cool film along the external surface (Han et al., 2012). Film cooling has become the main cooling method in many designs, such as in modern gas turbines and combustion chambers.

Most previous studies of film cooling (Ammari et al., 1990; Sinha et al., 1991; Yu et al., 2002; Saumveber et al., 2003; Tao

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Nomenclature

D	hole diameter, mm
M	blowing ratio
L	hole length, mm
Pr	Prandtl number
S	hole distance, mm
T	temperature, K
T_{aw}	local adiabatic wall temperature, K
T_c	coolant flow temperature, K
T_∞	mainstream flow temperature, K
u_i	velocity component, m/s
x	streamwise distance downstream of film hole exit, m
y	coordinate normal to the surface, m
z	mainstream spanwise coordinate, m

Greek symbols

ρ	density, kg/m^3
η	adiabatic effectiveness
λ	thermal conductivity, W/(m·K)
k	turbulent kinetic energy, m^2/s^2
ε	dissipation of turbulent kinetic energy, m^2/s^3
μ	dynamic viscosity, Pa·s
μ_t	turbulent dynamic viscosity, Pa·s
v	kinematic viscosity, m^2/s

Subscripts

ad	adiabatic
c	cooling stream
∞	free stream

et al., 2008; Li and Hassan, 2015; Singh et al., 2017) have mainly focused on the plenum-coolant-feed model, which cannot accurately describe the coolant flow in the internal coolant channel because it simplifies the film cooling process. In turbine rotor blades, the coolant usually flows along the blade axial direction, which is perpendicular to the outer hot mainstream, so the coolant flows in the coolant channel cannot be treated as stagnation plenum flows. The coolant cross-flow condition is then more appropriate but the model must consider the coolant supply flow channel design.

Some studies have investigated the effect of the coolant supply flow on film cooling. Hale et al. (2000) experimentally investigated the flow structures associated with injection through short length-to-diameter holes into a mainstream flowing from different directions with the results showing that the different coolant inlet directions strongly influenced the short-hole injection flow. The results of Gritsch et al. (2000, 2001) and Hay et al. (1983) showed that the coolant crossflow strong influences the film cooling. Gritsch et al. (2003) experimentally investigated the effect of three different crossflow hole geometries on the film cooling with the results showing that the film cooling in the near hole region can be more than 100% higher for the crossflow cases compared to the plenum flow case. The multiple narrow-band Thermochromic liquid crystal technique was used by Gunter and Stefan (2000) to investigate the effects of the internal flow conditions and plenum geometry on the film cooling effectiveness with the results showing a higher film cooling effectiveness than with a standard plenum configuration. Thole et al. (1997) experimentally investigated the effects of different velocities in the crossflow channel at the cooling hole entrance with the results showing that in the separation region, the cooling jets exit in a skewed manner with very high turbulence. The CFD results of Kohli and Thole (1997) demonstrated how different coolant flow directions at the inlet can affect the overall cooling performance. Wang and Jiang (2006) numerically investigated the adiabatic film cooling effectiveness for plenum flow, flow parallel in the same or opposite direction of the mainstream at the hole exit, and flow perpendicular to the mainstream at the hole exit. Peng and Jiang (2012a) experimentally and numerically analyzed the effect of coolant cross-flow on the film cooling effectiveness with cylindrical, fan-shaped and trenched holes. The results showed that the counter-rotating vortex pairs (CVP) are broken up by the internal coolant flow, which has a large effect on the film cooling. Peng and Jiang (2012b) also investigated the effect of coolant cross-flow on the film cooling effectiveness using the Large-eddy simulation (LES) method with the results showing that the coolant cross-flow greatly increases the laterally averaged film cooling effectiveness, especially for M equal to 1.0. Silieti et al. (2009) numerically investigated the film cooling effectiveness with one fan-shaped hole for adiabatic and conjugate heat transfer models using both the plenum model and the internal coolant flow model, with the results showing that the conjugate heat transfer models predict significantly different temperatures than the adiabatic models.

However, most previous studies have focused on smooth coolant channels. In fact, most coolant supply channels are stiffened with ribs which affect the coolant flow and heat transfer mechanisms. Peng and Jiang (2009) numerically investigated the influence of film cooling channels with and without ribs to show that the ribs strongly affected the film cooling. Luo et al. (2014) numerically studied the influence of internal flow structures on the film cooling for the plenum model and cross-flow models with a smooth channel and ribbed channels with the angled ribs and a high coolant inlet Reynolds number of 100,000.

Only a few studies have focused on ribbed coolant channels with a high coolant inlet Reynolds numbers. However, few studies have investigated the effects of the ribs in the coolant channel, especially for low coolant inlet Reynolds numbers which may occur in helium turbine blade. Therefore, this study presents an analysis of the effects of ribs in the cross-flow channel on the film cooling for a constant coolant inlet Reynolds number of 18,500.

2. Physical model

The physical models shown in Fig. 1 include the plenum model (a) and the cross-flow model (b). For the plenum model, the coolant flow inlet was simplified in the gas plenum where the cooling gas is almost stagnated. For the cross-flow model, the coolant flows in the perpendicular channel to the mainstream with fluid injected into the mainstream through the film cooling holes.

The film cooling holes with the inclination angle to the mainstream at 20–40 degrees, the length-to-diameter ratio L/D of 2–6 and the distance between holes S/D of 3–6 were well documented in the literature (Bunker, 2005). In the present study, the film cooling holes were cylindrical with a diameter of 5 mm, an inclination angle of 30° to the mainstream, a length-to-diameter ratio of $L/D = 3$ with five holes in one row and a distance between holes of $S/D = 3$. The mainstream channel cross-section was 100 mm (width) × 50 mm (height) with a length of 200 mm. The film cooling holes were located 75 mm from the mainstream inlet. For the cross-flow model, the coolant channel inlet cross-section was 20 mm × 15 mm while the outlet was 10 mm × 15 mm. The coolant channel flows was analyzed with and without ribs with either straight ribs or 60° V-shaped ribs with the ribs having a width of 1 mm and height of 1.5 mm, as shown in Fig. 2.