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Research Paper

Improvement on film cooling effectiveness by a combined slot-effusion scheme

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HIGHLIGHTS

- Exploring film cooling performance of combined slot injection/effusion array scheme.
- Comparing slot injection, effusion array and combined cooling scheme in details.
- Illustrating roles of combined scheme on overall and adiabatic cooling effectiveness.
- Combined cooling scheme produces more ideal cooling under the same coolant usage.
- Combined cooling scheme on film cooling improvement is dependent on blowing ratio.

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ABSTRACT

Experimental tests are performed in the current study to explore the overall cooling performance of a combined slot injection/effusion array cooling structure. The pure slot injection and pure effusion array cooling schemes are taken into consideration for the comparison purpose. In addition, numerical simulations on the adiabatic and overall cooling effectiveness are also performed to illustrate the conjugated effects, such as internal convective heat transfer inside the coolant flow channel, thermal conduction inside the perforated plate, and internal cooling in the multiple holes, on the film cooling performance. The combined cooling scheme overcomes respective drawback of slot injection cooling in its decayed stage and effusion array cooling in its developing stage, thus producing a more ideal cooling performance over the entire protected surface under the same coolant usage. Due to the conjugated effects, the influence of adding slot injection on improving overall cooling effectiveness is significantly weaker than that on the adiabatic cooling effectiveness. Related to the pure slot injection or effusion array cooling scheme, the benefit of combined cooling scheme on the film cooling improvement is dependent on the blowing ratio. Under a combination of M_{sl} = 0.5 and M_{eff} = 0.4, it produces more obvious improvement on overall cooling effectiveness. While under a combination of M_{sl} = 0.5 and M_{eff} = 1.2, the overall cooling effectiveness in the front zone of effusion array is a little less than the pure injection scheme.

1. Introduction

As a matter of fact, the turbine inlet temperature level is progressively getting higher while the usage of coolant becomes more limited in modern gas-turbine engines, which presents a great challenge for engineers to design highly effective cooling schemes for protecting the hot section components from overheating. Effusion cooling is regarded as an advanced scheme in the cooling applications of combustor liner and turbine blade as it is capable of producing fully coverage film coverage over the protected surface [1–4].

Vast efforts had been paid to reveal the film cooling performances of an effusion cooling scheme. Andrews et al. [5–7] made a series investigations on the full coverage discrete-hole film cooling. Their results showed that the film cooling effectiveness of an effusion cooling scheme was strongly dependent on the size and number of holes. Increasing the number of holes and simultaneously decreasing their diameter could lead to a substantial improvement in the film-cooling effectiveness. Martiny et al. [8,9] made experimental investigations to evaluate row-by-row adiabatic cooling effectiveness and overall cooling effectiveness

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Nomenclature

A	area (m^2)
Bi	Biot number
D_h	hydraulic diameter of flow channel (m)
d	diameter of film hole (m)
h	hight (m) or convective heat transfer coefficient (W/(m^2·K))
k	thermal conductivity (W/(m·K))
l_s	distance between slot outlet and first row of effusion array (m)
M	blowing ratio
m	mass flow rate (kg/s)
p	hole-to-hole spanwise pitch of effusion array (m)
Re	Reynolds number
s	hole-to-hole streamwise pitch of effusion array (m)
T	temperature (K)
u	velocity (m/s)
VR	velocity ratio
x	streamwise-direction
y	spanwise-direction
z	normal-direction

Greek letters

α	hole inclination angle (°)
δ	thickness of effusion wall (m)
η	film cooling effectiveness
μ	dynamic viscosity (Pa·s)
ρ	density (kg/m^3)
Θ	dimensionless temperature

Subscripts

ad	adiabatic
aw	adiabatic wall
ov	overall cooling
eff	effusion array
sl	slot injection
m	relative to primary flow
c	relative to coolant
w	relative to wall

on an effusion-cooled plate with a low injection angle of 17°. It was noticed that obvious jets lift-off the surface occurred in the starting region of an effusion-cooled plate under a high blowing ratio. However, even in cases of complete penetration, cooling benefits of an effusion cooling scheme were still illustrated due to the reduction of main flow temperature in the mixing zone ascribable to the massive coolant injection. Lin et al. [10] and Zhang et al. [11] conducted experimental studies to illustrate the influence of some factors on the effusion cooling performance, such as blowing ratio, multi-holes pattern, hole inclination angle and hole deflection angle, etc. Ligrani et al. [12,13] performed experimental investigations on the full coverage film cooling for dense and sparse multiple-hole arrays at different blowing ratios. Comparisons of adiabatic cooling effectiveness, heat transfer coefficient, and net heat flux reduction (NHFR) for sparse and dense multiple-hole arrays were presented, indicating that line-averaged values of NHFR from the dense array are generally higher than the values associated with sparse array at different streamwise locations. Facchini et al. [14] made an experimental investigation on the adiabatic and overall cooling effectiveness of a fifteen-row effusion cooling array in which the film holes were arranged in a staggered pattern. It was illustrated that the increase of blowing ratio leads to lower adiabatic cooling effectiveness, while it makes overall cooling effectiveness to grow. Andreini et al. [15] made an experimental and theoretical investigation on the film cooling effectiveness in multi-perforated plates simulating combustor liner effusion cooling. Seven multi-perforated planar plates, reproducing the effusion arrays of real combustor liners, were tested under six blowing ratios in the range 0.5–5. It was found that under a low blowing ratio the geometry with tilted holes shows the best wall protection. On the contrary, under high blowing ratios the normal-hole array provided a slightly better overall cooling effectiveness. Da Soghe et al. [16] performed a numerical study on the convective cooling over the cold side of effusion plates. An empirical correlation was proposed for predicting the heat transfer coefficient enhancement factor at the cold side of an effusion-cooled plate. Kakade et al. [17] performed an experimental study to quantify typical effusion-cooling performance at a range of combustor relevant free-stream conditions and also to assess the importance of modeling the coolant to free-stream density ratio. It was revealed that the free-stream turbulence impacts on both the adiabatic effectiveness and heat transfer coefficient, although this is dependent upon the blowing ratio, particularly the extent to which the coolant jets detach from the surface. Martin and Thorpe [18] conducted a set of experiments on combustor angled effusion cooling under conditions of very high free-stream turbulence. The results showed that the spatially averaged effectiveness is reduced at low blowing ratios when freestream turbulence is increased. However, as blowing ratio increases the spatially averaged effectiveness can be increased with elevated freestream turbulence. Jackowski et al. [19] performed a study to acquire discharge coefficients and the total cooling effectiveness of combustor liner tiles. Six effusion cooled combustor liner tiles with two innovative and four traditional cooling hole geometries were investigated. All specimens had the same cooling hole pattern with 16 rows. Their results showed a tremendous improvement of total cooling effectiveness for the innovative geometry with bent cooling holes compared to traditional geometries, both at reduced and realistic temperatures.

Although the effusion cooling has been well demonstrated to be a highly effective cooling scheme, the film layer coverage and cooling effectiveness in the front zone of an effusion-cooled plate still remain further improvement. Harrington et al. [20] conducted an experimental investigation on the full-coverage film cooling of short normal injection holes arranged in a staggered pattern with a row-to-row spacing of 7.14. It was pointed out that as many as eight rows are required to reach an asymptotic “fully developed” adiabatic cooling effectiveness level. Petre et al. [21] made a study on the influence of the row number on the convective heat transfer in the case of full coverage film cooling. Scrittore et al. [22] performed an experiment to measure the velocity profiles of effusion cooling with an injection angle of 30° and non-dimensional hole-to-hole pitch of 4.9 in both the streamwise and spanwise directions. It was proposed that a fully-developed velocity profile is established at a nominal location of the fifteenth row. The jet penetration in the front zone of an effusion-cooled plate was much higher than that in the fully-developed condition. Yang and Zhang [23] performed a numerical investigation on the developing process of the coolant jets injected from the front rows of an effusion array. A preliminary criterion evaluating the film development from developing stage to fully developed stage was brought forward. Krawciw et al. [24] made an investigation concerning on the influence of hole-to-hole interaction on the coolant at hole exit