International Journal of Thermal Sciences 111 (2017) 390–408

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Experimental and numerical studies on film cooling with reverse/backward coolant injection

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ARTICLE INFO

Article history:
Received 3 February 2016
Received in revised form
21 September 2016
Accepted 22 September 2016

Keywords:
Film cooling
Forward hole
Reverse hole
Injection angle
Discharge coefficient

ABSTRACT

The conventional forward injection for film cooling with cylindrical holes, where the axial component of the coolant velocity is aligned with mainstream flow direction creates kidney vortices. This results in quick mixing of the coolant with the mainstream. The conventional anti-kidney vortices cooling holes require shaping or branching which adds to the cost and complexity of the system. In this paper, reverse/backward injection is proposed to improve film cooling. In the case of reverse/backward injection the secondary air is injected such that its axial velocity component is in the reverse direction to that of the mainstream. Film cooling is studied experimentally and numerically on a flat plate with forward and reverse injection. The injection angle of the cooling hole is varied from 30° to 60° in both forward and reverse directions at five blowing ratios ranging from 0.25 to 3.0 at a fixed density ratio of 0.91. The length to diameter ratio of the cooling hole is kept at 5 and the mainstream Reynolds number is maintained at 3.75×10^5. Film cooling effectiveness obtained with the reverse holes is found to be much higher than that of the forward holes. Improvement in the area weighted average values of film cooling effectiveness for blowing ratio, $M = 1$ is 170%, 78% and 186% for injection angles 30°, 45° and 60° respectively. Coefficient of discharge obtained from reverse injection is found to be smaller than that of forward injection. The film cooling effectiveness in the case of reverse injection is found to be less sensitive to the injection angle.

1. Introduction

Film-cooling is used extensively in gas turbine engines for cooling of components exposed to hot gases. In film-cooling, relatively cold secondary fluid is injected into the hot flow through holes on the surface of the component. The injected cold fluid displaces the hot fluid and forms a layer between the surface to be protected and the hot gases. A coolant layer extends in the downstream direction for a distance determined by the mixing of coolant with the hot gases [1].

In film-cooling, the holes from which the secondary fluid or the coolant is injected are inclined with reference to the surface to be cooled. The flow separates from the wall fluid just downstream of the injection hole and splits into counter rotating vortices, popularly known as kidney vortices [2]. These vortices are influenced by the operating parameters and hole design. Operating parameters such as blowing ratio, density ratio and momentum flux ratio affect the generation and growth of kidney vortices [3]. Out of the design parameters, the hole inclination, orientation and shape influence the growth of kidney vortices [4]. The presence of kidney vortices increases the mixing of secondary fluid with the hot mainstream. Hence, kidney vortices must be minimized or eliminated to maintain maximum coverage of the surface with coolant film and hence better film cooling. In order to suppress the generation of kidney vortices, to avoid the lift off of secondary fluid jet and the associated undesirable effects, shaped holes are used in the film cooling.

The study of Goldstein et al. [5] is recognized as the first investigation of shaped holes in film cooling studies. The shaped holes have circular cross section which acts as throat or metering section, while the outlet end of the cooling hole is shaped as a diffuser with a divergence angle 10°–15° in the lateral direction as well as in the flow direction [6]. Based on the expansion of the hole, shaped holes are classified as: 'fan-shaped', if the expansion is in the lateral direction, 'laidback' if the expansion is in the direction of the surface. The purpose of expansion of the hole is to reduce the momentum of the secondary fluid which in turn decreases the penetration and hence mixing of the secondary fluid into

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http://dx.doi.org/10.1016/j.ijthermalsci.2016.09.027

Nomenclature

C_d	discharge coefficient non-dimensional
D	hole diameter, m
FH	forward hole
m	mass, kg
M	Blowing Ratio, $\frac{\rho_{sec}U_{sec}^2}{\rho_{ms}U_{ms}^2}$, non-dimensional
p	pressure, Pa
P	hole spacing(pitch) in lateral direction, m
Re	Reynolds number based on mainstream flow, $\frac{\rho U_{ms}\lambda}{\mu}$
RH	reverse hole
T	absolute temperature, K
TR	temperature ratio, $\frac{T_{sec}}{T_{ms}}$, non-dimensional
U	mainstream velocity, m/s
V	coolant hole velocity magnitude, m/s
X	streamwise coordinate, m
Z	spanwise coordinate, m

Greek symbols

α	injection angle, in degrees
η	Adiabatic effectiveness, $\frac{T_{ms}-T_w}{T_{ms}-T_{sec}}$
ρ	density, kg/m^3
μ	dynamic viscosity, Pa-s
λ	characteristic length of test section, m

Subscripts

c	coolant
cl	centerline
lat	lateral average
m	mainstream static
ms	mainstream
S	surface
sec	secondary
t	total

mainstream fluid.

Haven and Korosaka [4] investigated film cooling over a flat plate with cylindrical and shaped holes. They showed that kidney vortices are formed when the secondary fluid is injected through cylindrical holes which diminish film cooling performance. This study also revealed that the effect of kidney vortex can be decreased by using shaped holes. In shaped holes anti-kidney vortices were formed which suppress the jet lift-off [4].

The study of Gritsch et al. [7] provided a comparative analysis of cylindrical holes, fan-shaped holes and laidback fan-shaped holes. The laidback fan-shaped holes are the combination of both fan-shaped and laidback holes. This study highlighted that the film-cooling performance of fan-shaped holes is better than cylindrical holes and the performance of laidback fan-shaped holes is the best among all investigated hole shapes. Bell et al. [8] investigated shaped holes in combination with compound angle holes. Five hole configuration viz. (i) cylindrical round simple angle holes, (ii) laterally diffused simple angle holes (iii) laterally diffused compound angle holes, (iv) forward diffused simple angle holes, and (v) forward diffused compound angle holes were investigated. The simple cooling holes were inclined at an angle with the flow direction. In case of compound angle holes, the cooling holes were given some inclination in lateral direction as well. All the shaped holes were found to be better in terms of spread of the cooling film over the surface to be cooled, as compared to cylindrical holes. The best film cooling performance was found for the case of laterally diffused compound angle holes followed by forward diffused compound angle holes. They claimed that the improvement in film cooling effectiveness is partly due to film diffusion from expanded hole shapes and partially due to increased lateral spreading of injectant from compound angles.

Saumweber et al. [9] studied the effects of free-stream turbulence on film cooling with shaped holes over a flat plate at a fixed density ratio of 1.7. They concluded that at low turbulence levels, the shaped holes do not show any detachment from the surface even at the highest investigated blowing ratio i.e. $M = 2.5$. The momentum of the coolant decreases because of the expanded exit and hence the penetration of secondary fluid into the mainstream decreases. Silieti et al. [10] studied numerically film cooling over 3D gas turbine endwall with one fan-shaped cooling hole. A comparison of film cooling effectiveness in adiabatic and conjugate heat transfer mode was done for blowing ratio, $M = 1$ and coolant to mainstream temperature ratio of 0.54. The studies of Cho and Rhee [11], Yu et al. [12], Taslim and Khanicheh [13], Colban et al. [14], Lee and Kim [15], Wright et al. [16] on shaped hole re-iterate that the hole shaping improves the film cooling performance.

Shaped holes increase the complexity and cost of the system. In order to simplify the design of cooling holes, Dhungel et al. [17] proposed branched cooling holes. These holes are cylindrical in shape and after a certain distance from the inlet side, two symmetrical holes branch out from the main holes. Because of the branching of the holes, the momentum of the coolant decreases at the outlet of cooling holes. They claimed that the branched holes act as anti-vortex holes and reduce the effect of kidney pair vortices, which leads to better film coverage in both downstream and lateral directions compared to conventional cylindrical holes. A recent numerical study by Khajehhasani and Jubran [18] on branched holes also showed a significant reduction in the jet liftoff effect in comparison with the cylindrical and forward-diffused shaped holes.

In the quest of reducing the jet lift off and kidney vortices Lu et al. [19] investigated cylindrical holes with trenches. They studied the effect of the trench width and depth on film cooling from cylindrical holes embedded in trenches using a transient IR thermography technique to measure the heat transfer coefficient and the film effectiveness. They concluded that trenching the holes in a slot reduces the jet momentum at the exit, spreads the jet and provides 2D jet coverage compared to 3D nature of individual jets, providing better overall film cooling effectiveness.

The walls of gas turbine blades are usually thick and it is feasible to make shaped holes in the geometry of this kind. However, the combustion chamber liner and the wall of afterburner section of fighter planes, which also make use of film cooling, are very thin. Hence, it is not feasible to make shaped holes in these geometries. The shaped holes also add to the cost and complexity of manufacturing. Yang and Zhang [20] investigated a row of holes with ridge-shaped tabs. They found that the presence of the ridge-shaped tabs in the nearby region of the primary film cooling holes mitigates the primary vortices. The ridge-shaped tabs provide enhancement in cooling effectiveness but at the expense of larger pressure drop. They admitted that such holes are difficult to manufacture not practical for use in practical applications.

Cooling of combustion chamber and the afterburner section of a gas turbine engines is still a challenge because of their thin cross section. The operating blowing ratio and density ratio is also high for these components compared to that for turbine blade cooling.