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Analysis of film cooling performance of advanced tripod hole geometries with and without manufacturing features

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ABSTRACT

The present study evaluates the film cooling performance of a set of manufacturable tripod hole designs, with and without shaped exits. The tripod holes with realistic manufacturing features included rounded corners at the hole inlet and outlet, as well as a webbing between the tripod holes. Standard cylindrical and shaped cylindrical (10° fan + laidback) holes were also studied for comparative analysis. Transient heat transfer experiments with a mainstream $Re_d \approx 3200$ were conducted on a flat plate test rig. Different hole geometries were tested at equal mass flow rates, corresponding to a range of blowing ratios equal to 0.5, 1.0, and 2.0 for the cylindrical hole. IR (Infrared) thermography was used to evaluate adiabatic film cooling effectiveness, heat transfer coefficient, and the normalized heat flux on the flat surface. Results showed that the presence of rounded corners or webbing did not lower the performance of the tripod cooling holes. Both tripod hole geometries, with and without manufacturing features, yielded higher film cooling effectiveness compared to the cylindrical holes and slightly higher effectiveness than the shaped holes, while consuming 50% less coolant when operating at the same blowing ratio. The heat transfer coefficient measurements and the overall heat flux ratios further corroborated the thermal advantages of the tripod hole design over traditional cylindrical and shaped holes.

1. Introduction

Increasing turbine inlet temperatures lead to thermal efficiency improvements for gas turbines. The ever growing demand for energy and the progressive advances in the field of gas turbines have enabled higher turbine inlet temperatures. The material strength of the blades and vanes however, often imposes limits on the thermal load these components can bear. This is where gas turbine cooling becomes critical. Better cooling designs have the potential to extend the blade life span, enable higher rotor inlet temperatures, and conserve compressor bleed air. Film cooling is extensively used to protect hot gas path components in the gas turbine. Innovative film cooling hole designs have the potential to further enhance the durability of these components.

Ideal coolant coverage over a surface can be achieved via cooling slots. Fabrication of slots on the blade results in excessive material removal and a corresponding decrease in strength. For this reason, discrete hole film cooling came into existence wherein the coolant is ejected through discrete holes that are located along the span of the blade in critical hot spot regions that are affected by the combustion exhaust gases [1]. However, increasing power demand has added thermal load on the components, which brought forth a need for a better cooling design, resulting in the development of innovative discrete hole cooling techniques including cylindrical and shaped hole geometries. One of the drawbacks of cylindrical holes is that the exiting coolant jet interaction with the mainstream forms counter rotating vortex pairs (CRVPs). These vortices have the tendency to prevent the coolant mainstream mixture from staying close to the surface, thus lowering the cooling effectiveness. This jet lift-off can be mitigated to a certain extent by reducing the exit momentum of the coolant jet, achieved by increasing the exit area of the hole. Even though several shapes for the hole have been proposed in the past [2], only shaped exits have had the biggest impact in the industry [1].

Early work to maximize the potential of cylindrical holes was carried out by Goldstein [3–5]. Since then, numerous factors affecting film cooling performance have been thoroughly studied. Bogard and Thole [6] provided a recent summary on the technology of gas turbine film cooling. Bunker [1] did a thorough review on shaped holes. A comprehensive survey on gas turbine cooling literature has been compiled by Han et al. [7]. Relevant to this study is the work conducted by Baldauf et al. [8], [9] where the authors examined local adiabatic effectiveness and heat transfer

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Nomenclature

a	circular cross sectional area of the cylindrical hole
AV	anti-vortex hole (tripod hole)
BR	blowing ratio
CY	cylindrical hole
d	hole diameter (m)
DR	density ratio
h	heat transfer coefficient, laterally averaged (W m^{-2} K^{-1})
ho	heat transfer coefficient, baseline, laterally averaged (W m^{-2} K^{-1})
I	momentum flux ratio
IR	infrared
k	thermal conductivity (W m^{-1} K^{-1})
l	hole length (m)
L	thickness of the test plate (m)
$\dot{m}$	mass flow rate (g/s)
N	number of film cooling holes
p	hole pitch (m)
q	heat flux due to film cooling (W m^{-2})
q_0	heat flux for the baseline case (W m^{-2})
Re_d	Reynolds number of the mainstream based on hole diameter
SH	shaped hole
SHAV	shaped anti-vortex hole
t	time (s)
T	temperature (K)
V	velocity (m/s)
α	thermal diffusivity (m^2/s)
δ	boundary layer thickness (m)
η	adiabatic film-cooling effectiveness
ρ	fluid density (kg/m^3)

Subscripts

c	coolant
i	initial
in	inlet
m	mainstream
w	wall/flat plate surface

coefficients for cylindrical holes using IR thermography. Effects of blowing angle, hole spacing, and density ratio were investigated. It was observed that cylindrical holes perform best when the blowing ratio is around 0.85–1.0 with a momentum flux ratio of 0.4 and 0.5 respectively. Sinha et al. [10] also conducted flat plate experiments with cylindrical holes to study the effect of density ratio and momentum flux ratio on laterally averaged film effectiveness. Measurements were taken using a series of thin ribbon thermocouples that were attached to the test plate. The effect of density ratio on film cooling effectiveness while maintaining constant velocity ratio, blowing ratio, and momentum flux ratio was studied. Using a similar test facility, Schmidt et al. [11] performed experiments to understand the effect of compound angle on round holes and holes with diffusing expanded exits. The authors concluded that the addition of a compound angle improves effectiveness at higher momentum flux ratios while a combination of forward expansion and compound angle yielded the best results. Gritsch et al. [12] investigated film cooling performance of shaped cylindrical holes at different blowing ratios. The holes that had laid-back fan-shaped exits performed better than cylindrical and fan-shaped holes.

In 2006, Heidmann and Ekkad [13] started working on a novel concept for film cooling holes referred to as anti-vortex design. In addition to a central cylindrical hole, the coolant was also ejected through two bifurcated cylindrical holes that branched out on either side of the central hole resulting in a tripod-like arrangement. Coolant from the side holes interacted with the mainstream and produced vortices that countered the main central rotating vortex pairs, weakening it and pushing the coolant jet towards the surface. Given the size of the tripod hole arrangement, there was one tripod hole set for every 2 cylindrical holes, which implied that tripod holes have coolant coming out at lower exit momentum for the same coolant mass flow rate. Tripod holes were investigated further by Dhungel et al. [14] where the side hole placement and branching angle were optimized. Leblanc et al. [15] further extended the work of Dhungel et al. [14] with a modified design where the side holes were of the same diameter as the main hole. With the new tripod design, Leblanc et al. [15] performed flat plate experiments that showed that a 65% increase in film cooling effectiveness over cylindrical holes with standard pitch was achievable while consuming 50% less coolant.

The development and transition of a film cooling hole concept from its design phase to its implementation in the industry is slow. Manufacturability, as well as the performance of the cooling hole with imperfections are concerns that must be fully addressed prior to incorporating a new technology in industrial designs. Johnson et al. [16] for instance, studied the impact of manufacturing techniques on film cooling effectiveness. The authors compared film cooling effectiveness of cylindrical holes which were fabricated using four different manufacturing methods, using temperature sensitive paints. The authors showed that the manufacturing technique had a noticeable impact in the performance of the cooling hole which was more pronounced at higher blowing ratios. Jovanovic et al. [17] also presented the effect on adiabatic film cooling effectiveness of hole imperfections in the form of a torus inside a cylindrical film cooling hole. The location of this torus was found to have an impact on the cooling effectiveness.

The anti-vortex hole design has proved to be a potential alternative to dramatically improve film cooling technologies. Manufacturability studies however are lacking and these are critical for the prompt adoption of the tripod hole technology in industry. Recently, an innovative method to manufacture tripod holes was discussed by Alvin et al. [18]. This realistic manufacturing process for the tripod hole geometry results in a modified design with chamfered corners at the hole inlet and outlet. Moreover, the region where the holes bifurcate into three individual units included a webbing. The original design studied computationally and experimentally in previous studies [15] featured sharp corners which are not possible to achieve from a manufacturability stand point. Fig. 1 shows an illustration that emphasizes these features. Additional details are provided in the "film hole geometries" section. The film cooling tripod hole with the realistic manufacturing features was termed "as manufactured". Coupons with as manufactured tripod holes, cylindrical holes, and no holes will be tested in a high temperature rig facility at NETL in the future. It is critical to estimate the performance of the as manufactured design prior to the experimental effort and hence the realistic design was fabricated using additive manufacturing for laboratory testing. Moreover, studying the gap between the design phase of a cooling hole and the implications of its manufacturability are critical for the prompt incorporation of the technology. Therefore the thermal performance of the realistic as manufactured tripod hole design, along with the idealized tripod design was studied in the present