International Journal of Thermal Sciences 133 (2018) 216–229

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Robust design optimization of a turbine blade film cooling hole affected by roughness and blockage

Sanga Lee[a], Wontae Hwang[b,c,*], Kwanjung Yee[a,c,*]

[a] Institute of Advanced Aerospace Technology, Seoul National University, 1 Gwanak-Ro, Gwanak-Gu, 08826, Seoul, Republic of Korea
[b] Institute of Advanced Machines and Design, Seoul National University, 1 Gwanak-Ro, Gwanak-Gu, 08826, Seoul, Republic of Korea
[c] Dept. of Mechanical and Aerospace Engineering, Seoul National University, 1 Gwanak-Ro, Gwanak-Gu, 08826, Seoul, Republic of Korea

ARTICLE INFO

Keywords:
Robust design optimization
Film cooling hole
Roughness
Hole blockage

ABSTRACT

High performance film cooling holes with complicated geometries have been regarded as impractical up to now because of manufacturability issues. However, recent advances in additive manufacturing (AM) technology have opened up new doors. Investigating characteristics of film holes built with AM, and finding the optimum shape considering these characteristics are now required to confirm their practical utility. In this paper, the performance of a high-efficiency film hole is numerically investigated. In-hole roughness and blade surface roughness are examined assuming an AM process, and contorted hole shape caused by partial blockage is also considered. A robust hole shape is obtained considering these uncertainties, utilizing a reference hole shape made by combining three cylindrical holes, which is meant to mitigate the detrimental effect of the counter-clockwise vortex pair. Main hole diameter, injection angle, and two angles for defining the two auxiliary holes are used as design variables to be optimized. For flow field and thermal analysis with roughness, compressible steady Reynolds averaged Navier-Stokes equations with a sand-grain roughness model are used. For the probabilistic assessment of each hole shape, Monte Carlo Simulations with the Kriging surrogate model is used, along with efficient global optimization (EGO) and a genetic algorithm. As a result, a high performance yet robust film cooling hole shape is obtained.

1. Introduction

Film cooling has been one of the main contributors to efficiency increase in modern gas turbines. Many studies have been carried out to improve film cooling performance, in particular regarding the hole shape [1–7]. These studies have introduced various intricate hole designs, but because of manufacturability limitations at small dimensions, the holes have had rather limited practical use. However, nowadays, new attention is being cast on these high-efficiency holes due to the rapid advancement in additive manufacturing (AM) technology.

New issues will inherently arise when these holes are built with AM. Compared to conventional methods such as electrical discharge machining (EDM) or laser drilling, surface roughness will likely be more of an issue. Stimpson at al. [8] reported that roughness varies substantially depending on the material, build speed, and especially on the build direction. This causes significant augmentation of friction factor on the hole inner surface, and implies that the characteristics of the coolant flow exiting the holes can have a wide deviation from those specified by the original design. This was recently supported again by the same research group [9] who experimentally showed the significant impact additive manufacturing had on the hole shape.

In addition to surface roughness owing to AM, partial hole blockage due to particle deposition or thermal barrier coating (TBC) is also becoming an issue. Many high-performance holes are made with the intention of mitigating the counter clockwise vortex pair so that the coolant better adheres to the surface. The ideal design requires a perfectly symmetric shape, but in practice there is no guarantee of this, due to issues such as hole blockage. Cardwell et al. [10] carried out experiments to measure the effect of blockage by sand at different flow conditions. A significant rise in blockage was observed as sand and metal temperatures increased. Sundaram et al. [11] investigated the endwall region film cooling effectiveness when there were deposits near the hole exit, partial hole blockage, and spallation. The maximum reduction in cooling effectiveness at the leading edge region occurred when there was film cooling hole blockage.

Despite the significance of these factors—roughness and hole blockage—they are hard to predict in the design stage. Therefore, a probabilistic approach is necessary and it would help the designer to be

* Corresponding authors. Dept. of Mechanical and Aerospace Engineering, Seoul National University, 1 Gwanak-Ro, Gwanak-Gu, 08826, Seoul, Republic of Korea.
E-mail addresses: wthwang@snu.ac.kr (W. Hwang), kjyee@snu.ac.kr (K. Yee).

https://doi.org/10.1016/j.ijthermalsci.2018.07.012
Received 19 February 2018; Received in revised form 28 May 2018; Accepted 10 July 2018
1290-0729/

Nomenclature

D	hole diameter	γ	branching angle for the auxiliary holes
E	expectation	ν	kinematic viscosity
h	sand grain roughness	u_τ	shear or friction velocity
h^+	dimensionless sand grain roughness	η	film cooling effectiveness
L	hole length	AM	additive manufacturing
$\dot{m}$	mass flow rate	DOE	design of experiment
α_a	injection angle for the auxiliary hole	EDM	electrical discharge machining
α_m	injection angle for the main hole	EGO	efficient global optimization
β	blockage ratio	MCS	Monte Carlo Simulation
		PDF	probability density function
		RDO	robust design optimization

aware of the probability of failure due to these factors. To date in gas turbine related research, many uncertainty factors such as blade shape imperfection arising from erosion [12], manufacturing tolerance of three dimensional blade shape [13] and film cooling hole arrangement [14], and uncertain operating condition of compressor rotor blades [15] have been considered through various probabilistic design optimization methods. Although the probabilistic design method has been actively adopted in many engineering fields, it has not been utilized in designing film hole shape so far.

In this regard, high-efficiency film cooling hole shape is optimized in this study, through the probabilistic design method considering uncertainties for in-hole roughness, blade surface roughness, and partial hole blockage. Bons et al. [16] investigated surface roughness on in-service turbine blades from nearly 100 turbine components and concluded that the blade external surface is typically roughened more severely than the in-hole surface by fuel deposition, erosion, corrosion, and spallation. Thus, the blade surface roughness was regarded as a separate uncertainty factor in this study, in addition to in-hole roughness. The reference hole shape was the Nekomimi film hole, suggested by Kusterer et al. [17], and is made from three cylindrical holes. Main hole diameter, injection angle, and two angles for defining two auxiliary holes are the design variables to be optimized.

For flow field and thermal analysis with roughness, compressible steady Reynolds averaged Navier-Stokes (RANS) equations with sand-grain roughness model are used. For the probabilistic assessment of each hole shape, Monte Carlo Simulation (MCS) with the Kriging surrogate model is used. The Kriging model is necessary because MCS requires an infinitely large number of implementations and is impossible to use with direct CFD simulations. After the Kriging model is constructed, the optimized film hole shapes are sought by a genetic algorithm. Every population obtains a fitness function by implementing MCS combined with the Kriging model. As a result, high performance yet robust film cooling hole shapes are obtained.

The contents of this paper were presented at the American Society of Mechanical Engineers (ASME) 2018 Turbo Expo conference (GT2018-76424 [18]). Publication permission has been granted from ASME.

2. Methodology

2.1. Numerical approach

The reference model is composed of three cylindrical holes: one main hole and two auxiliary holes branched off from the center main hole. The baseline hole shape is shown in Fig. 1. This type of film hole is named Nekomimi (which means cat's ear in Japanese), because of its distinctive exit shape [17]. We chose Nekomimi as the reference, since it is a well-known high-efficiency film hole focusing on formation of anti-counter-rotating vortices.

For flow field and thermal analysis, the compressible steady Reynolds averaged Navier-Stokes (RANS) equations are chosen in ANSYS CFX 14.5, where the element-based finite volume method (FVM) and algebraic multi-grid (AMG) coupled solver are used. For turbulence closure, the k-ω based shear stress transport (SST) model is employed. The SST model is known to yield better predictions for near wall turbulent flow, especially when flow separation due to an adverse pressure gradient is present [19,20]. Lee et al. [5] and Ayoubi et al. [21] concluded that the SST model shows good performance for turbine heat transfer and film cooling problems. Fig. 2 and Table 1 show the computational domain and corresponding boundary conditions. These conditions are based on the work of Kusterer et al. [22]. The number of mesh points is approximately 8–10 million depending on the cases, and y^+ is less than 1 in the measuring region where the surface is smooth.

For roughness analysis, CFX provides a sand grain roughness model. This model expresses the roughness as an equivalent layer of sand grain of diameter h. This affects the skin friction losses and creates a downward shift in the logarithmic velocity profile near the wall, as shown in equation (1) [23,24].

$$u^+ = \frac{1}{k}\ln(y^+) + B - \Delta B \tag{1}$$

where the shift ΔB is a function of the dimensionless roughness height,

$$h^+ = \frac{hu_\tau}{\nu}. \tag{2}$$

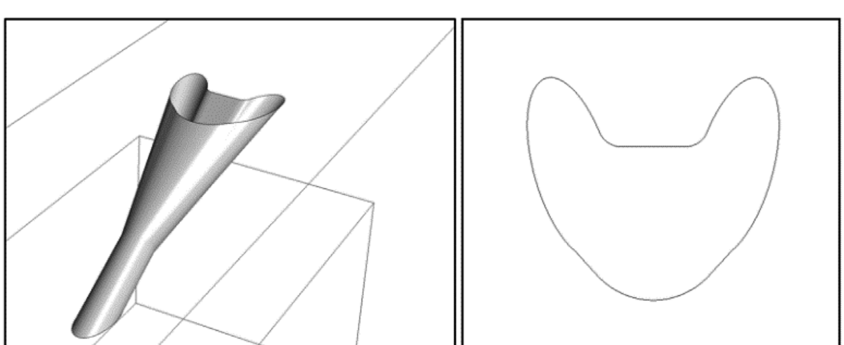

Fig. 1. Reference film hole shape (baseline).