Energy 66 (2014) 839–848

Contents lists available at ScienceDirect

Energy

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

Optimal design of impinging jets in an impingement/effusion cooling system

Kyung Min Kim [a], Hokyu Moon [b], Jun Su Park [b], Hyung Hee Cho [b], *

[a] Korea District Heating Corporation, 781 Yangjae-daero, Gangnam-gu, Seoul 135-220, Republic of Korea
[b] Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul 120-749, Republic of Korea

ARTICLE INFO

Article history:
Received 9 July 2013
Received in revised form
21 November 2013
Accepted 13 December 2013
Available online 9 January 2014

Keywords:
Gas turbine components
Jet impingement cooling
Thermal stress
Optimization
Response surface method

ABSTRACT

To design an impingement/effusion cooling system that realizes the lowest thermal stress in an impingement/effusion cooling system, we conducted thermal analysis and optimization using a second-order response surface method. The optimal impinging jet system was based on four design variables: the spacing between the impinging jets and effusion holes ($1.0 \leq Sp \leq 5.0$), the channel height from impinging jet to effusion surface ($1.0 \leq Ht \leq 3.0$), the mass flux ratio of the crossflow to the impinging jet flow ($0.1 \leq G^* \leq 1.3$, $-1.3 \leq G^* \leq -0.1$), and the main flow temperature ($1100\ \text{K} \leq T_m \leq 1800\ \text{K}$). We considered several cases involving inlined and staggered jets, and two cooling flow direction: the same direction and reverse direction. Response surface functions were constructed to determine the impinging jet system with the lowest value among the maximum stresses calculated within the design ranges. In each case, the response surface function for determining the maximum stress was composed of combinations of the four design variables. These functions can be used to find the optimum design point that achieves the lowest stress around film cooling holes in hot components of a gas turbine.

1. Introduction

The energy efficiency of a gas turbine is improved by increasing the turbine inlet temperature. However, this also imposes greater thermal loads on the hot components of the turbine, such as combustor liners, transition pieces, and turbine vanes/blades. Hence, a number of cooling techniques have been developed to protect turbines from hot gas stream.

The latest gas turbine combustion liners are protected by a combination of film cooling on the exterior and jet impingement cooling in the interior [1]. Research on heat transfer distributions has been carried out for both interior surfaces [2] and exterior surfaces [3]. A number of studies [4–7] have noted that jet impingement cooling is characterized by a variety of design parameters, including the diameters of impinging jet (D_{imp}) and effusion hole (D_{eff}), the pitch in the spanwise direction (Ph), the ratio of the spacing between the jets and effusion holes to the hole diameter (Sp), the ratio of the height to the hole diameter (Ht), the mass flux ratio of the film cooling flow to the main flow ($G^{\#}$), and the mass flux ratio of the crossflow to the jet flow (G^*). All of these parameters greatly affect the enhancement of heat transfer. More recently, optimization techniques [8,9] have been developed to provide effective system designs. The general response surface method (RSM) for optimizing a cooling system is suitable for choosing the best geometry for heat transfer enhancement.

Inappropriate or excessive cooling methods can lead to thermal damage and failure of the main components, since a combination of thermal expansion and constraints induces high thermal stress. For example, thermal damage in film cooling systems occurs occasionally near the cooling holes because the thermal stress is concentrated by large temperature difference and material constraints [10]. Thus, the prediction of thermal stress as well as temperature has become increasingly important in the design of cooling systems [11–13]. Moreover, system failure [14–16] and lifespan [17,18] can be analyzed from these predicted temperatures and stresses. Computational results have proved to be useful for investigating the thermal problems of gas turbines, as well as for defining the factors that contribute to advanced maintenance and operation. Precise stress and lifespan predictions are required to improve engine durability and fuel efficiency.

A large number of simulations, experiments, and optimization techniques have focused on enhancing the heat transfer and thermal performance of impingement jet cooling and film cooling [1–7], but relatively little attention has been given to optimizing the reduction of thermal damage or failure. Accordingly, the objective of the present study is the design of an impinging jet to

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* Corresponding author. Tel.: +82 2 2123 2828; fax: +82 2 312 2159.
E-mail address: hhcho@yonsei.ac.kr (H.H. Cho).

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http://dx.doi.org/10.1016/j.energy.2013.12.024

Nomenclature

C	polynomial coefficient
D	diameter of impinging jet and effusion hole (m)
E	Young's modulus
$G^{\#}$	mass flux ratio of film cooling flow to main flow, $\dot{m}_{\mathrm{f}}/\dot{m}_{\mathrm{m}}$
G^{*}	mass flux ratio of crossflow to impinging jet flow, $\dot{m}_{\mathrm{c}}/\dot{m}_{\mathrm{j}}$
h	heat transfer coefficient (W $\mathrm{m^{-2}\,K^{-1}}$)
H	channel height (m)
Ht	ratio of height to hole diameter, H/D
k_{c}	conductivity of air
$\dot{m}_{\mathrm{c}}$	mass flux of crossflow ($\mathrm{m^3\,s^{-1}}$)
$\dot{m}_{\mathrm{f}}$	mass flux of film cooling flow ($\mathrm{m^3\,s^{-1}}$)
$\dot{m}_{\mathrm{m}}$	mass flux of main flow ($\mathrm{m^3\,s^{-1}}$)
$\dot{m}_{\mathrm{j}}$	mass flux of impinging jet flow ($\mathrm{m^3\,s^{-1}}$)
Nu	Nusselt number, hD/k_{c}
Ph	pitch between impinging jet and effusion hole (m)
R^2	determined R squared
R^2_{adj}	adjusted determined R squared
$\mathrm{Re_j}$	Reynolds number of impinging jet, $D_{\mathrm{h}}u_{\mathrm{j}}/\upsilon$
S	spacing between impinging jet and effusion hole (m)
Sp	ratio of hole spacing to hole diameter, S/D
T_2	coolant flow temperature (K)
T_{aw}	adjacent flow temperature (K)
T_{m}	main flow temperature (K)
u_{j}	impinging jet average bulk velocity ($\mathrm{m\,s^{-1}}$)
α	thermal expansion coefficient
ε	strain
ν	Poisson's ratio
σ_{v}	von Mises stress
υ	kinematic viscosity ($\mathrm{m^2\,s^{-1}}$)

reduce the thermal stress in a film cooling system. We determine optimum design parameters for the impinging jet to minimize thermal stress, using an advanced response method based on functional design variables within the design variable ranges. In addition, we obtain a variety of correlations for the functional design variables, and identify impinging jet geometries that realize the minimum thermal stress around film cooling holes.

2. Research methods

2.1. Optimization technique

Determination of the optimum dimensions related to many design parameters is often very important in an engineering design. RSM is a well-known optimization technique that also provides correlations among the design variables, which can then be used to select design geometries with optimum values. Equations such as first- or second-order polynomials are generally used to represent the response surfaces, based on approximations. Using the first- or the second-order polynomials, we can search for local optimum values within the region of interest, using the method described by Myers and Montgomery [19]. However, a general RSM cannot be used with complex functions higher than second-order, and is hampered by low physical response (local sensitivity) and limited selection of design variable ranges, since the results are represented by quadratic curves. Kim [8,9] and Giunta [20] proposed an advanced problem-solving technique based on functional variables with the thermal characteristics of the design variables. This advanced RSM procedure incorporates the thermal characteristics of the design variables over a design range, and changes the variables x_i into functional design variables $f(x_i)$, as in the following polynomial:

$$\begin{aligned} y = {} & C_1f(x_1)^2 + C_2f(x_2)^2 + C_3f(x_3)^2 + C_4f(x_4)^2 + C_5f(x_1)f(x_2) \\ & + C_6f(x_1)f(x_3) + C_7f(x_1)f(x_4) + C_8f(x_2)f(x_3) \\ & + C_9f(x_2)f(x_4) + C_{10}f(x_3)f(x_4) + C_{11}f(x_1) + C_{12}f(x_2) \\ & + C_{13}f(x_3) + C_{14}f(x_4) + C_{15} \end{aligned} \tag{1}$$

where $f(x_i)$: $\sin(x_i)$, …, $\log(x_i)$, …, $\exp(x_i)$, etc., depending on the characteristics of the design variables. These characteristics are used to determine the trend of each variable from literature reviews and case-by-case studies. A best-fit function is then selected from among a variety of functions, using the least-mean-square method. Functional RSMs offer certain advantages, such as the selection of wide ranges and close physical approximation. The results of functional RSMs are closer to actual data than those of non-functional RSMs. The steps in the procedure are as follows: select the design variables and spaces from among the design parameters, investigate the thermal characteristics of the variables, construct design points using design of experiment (DOE) methodology, perform experiments or numerical analysis, perform regression analysis and analysis of variance (ANOVA), construct the approximate equations, and determine the optimum values.

An RSM was used in this study to obtain an optimal thermal design for impinging jets. In the RSM procedure, the unknown coefficients C_i of a second-order response surface polynomial in x_i and the functions $f(x_i)$ are determined using the least-squares method. The set of design points was selected via the D-optimal method, which provides an efficient technique for constructing a response surface model, as suggested by Mitchell [21]. This is a useful and reliable method for constructing a response surface with a small number of design points (in this case as few as 1.5–2.5 times the number of unknown coefficients in the polynomial). When the observed response values are accurately predicted from the ANOVA

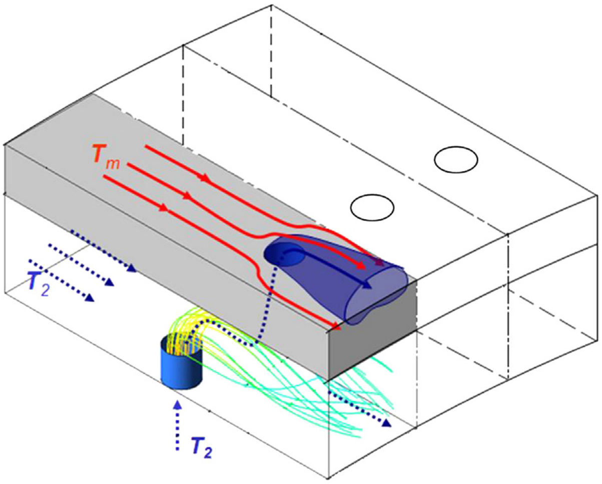

Fig. 1. Schematic flow pattern in an impingement/effusion cooling system.