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Genetic algorithm optimization of film cooling effectiveness over a rotating blade

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ABSTRACT

Shape optimization of a laterally diffused hole has been performed to enhance the film cooling effectiveness under rotating conditions. The blade rotates at three different speeds of 0, 300 and 500 rpm. The shape of the hole is defined by three geometric design variables, namely, the injection angle of the hole, the lateral expansion angle and the ratio of the length to the diameter of the hole. The numerical results for the film-cooling effectiveness were validated by a comparison with the available experimental data. More than sixty designs within the design spaces are selected and numerically simulated to calculate the objective function at three rotational speeds. The objective function, which is defined as the area averaged film-cooling effectiveness, is approximated using curve fitting method (CFM) to search for the optimal point. The optimizations are carried out for three different rotational speed using genetic algorithm (GA) method. The film-cooling effectiveness has been successfully improved with the CFM-GA optimization at three rotational speeds as compared to the reference cylindrical hole.

1. Introduction

Modern gas turbines are designed to operate with high combustion temperature for better performance and power output [1]. Film cooling has been employed extensively in hot components of gas turbine engines for cooling combustor liners and turbine blades. In this method, the cooling air is injected through discrete holes on the hot surface to provide a coolant film that protects the turbine surface from the harmful effects of the hot combustion gases. Since the film coolant is extracted from the compressor of the gas turbine, the configuration of film cooling hole has to be properly designed and optimized to minimize the thermal efficiency loss [2]. Over the past decades, a considerable amount of studies have been performed in order to understand the fundamental physics of film cooling flow [3]. Enhanced film cooling configurations have been proposed to produce the most effective film cooling with a minimum amount of coolant air [4]. Since the film cooling performance is strongly influenced by the hole shape [5], the optimization of the hole geometry is necessary to achieve the higher cooling performance.

Several previous studies [6–9] have been indicated that the film cooling is affected by different factors, such as the blowing ratio, hole shape, position and direction of the injection.

Bogard and Thole have provided a detailed review on film cooling to investigate the effects of geometrical parameters on film cooling effectiveness [7]. Investigations on the film cooling effectiveness, have been performed for both stationary [10] and rotating blades [8]. The previous studies have focused on the effects of rotating speed on film cooling of blades with circular holes [8,11,12]. Many studies have devoted significant efforts for increasing cooling effective though shaped holes [13]. Lee et al. [14] investigated the effect of geometric variables of a fan-shaped hole on film cooling over a flat plate. They showed that increasing the angle of forward diffusion hole reduces the effectiveness of film cooling while increasing the angle of lateral diffusion hole will have the greatest effect on cooling performance. Film cooling performance and flow-field analyses of hybrid schemes and circular film hole on a flat plate are numerically investigated by Ghorab [15].

Montomoli proposes an innovative design which improves the lateral coverage and reduces the jet lift off [16]. Experimental and numerical investigation on Film cooling performances of the cylindrical film holes and the laid-back film holes on the stationary blade has been done by Liu et al. [17]. They showed that, the laid-back holes perform film coverage better than the cylindrical holes under large blowing ratio. Lakehal et al. [18] performed a numerical study to evaluate different turbulence models for predicting film cooling over a flat plate. They showed that the RNG k-ε is capable of predicting cooling effectiveness in good agreement with the experimental data.

Yao et al. [19] investigated the effects of major factors including the film hole location, blowing ratio and primary flow Reynolds number on

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the film cooling effectiveness and aerodynamic losses of a turbine blade at stationary mode. Yang et al. [20] conducted a numerical study on the effects of swirling coolant on film cooling performance. They performed cylindrical, clover shaped and compound angle holes on a flat plate. Al-Zurfi and Turan [21] studied the effects of rotation on film cooling effectiveness on the suction and pressure surfaces of a gas turbine blade by large eddy simulation. They showed that the rotation promotes an earlier boundary layer transition and increases the transition length on the suction surface. Ramesh et al. [22] evaluated the film cooling performance of a set of tripod hole designs, with and without shaped exits. Lee and Kim [23,24] reported the optimization studies on film-cooling with shaped holes. They performed optimization of a simple fan-shaped hole with various surrogate models on a flat plate. Experimental investigation on the effects of the near surface streamwise diffusion (NSSD) hole in a flat plate has been done by Bai-Tao et al. [25]. They compared this type of hole with a cylindrical hole and showed that using the NSSD hole is conducive to increase the cooling effectiveness. Optimization of a fan-shaped hole by RBF neural network and genetic algorithm has been done by Wang et al. [26]. Three geometric parameters, including incline angle, lateral expansion angle and hole length were selected as the design parameters. The optimum of these parameters was obtained by GA algorithm to improve film cooling performance. The effects of ellipse-shaped tabs at the location of the film hole on film cooling effectiveness and discharge coefficient have been experimentally and numerically investigated by Yang et al. [27]. They reported that the ellipse-shaped tabs at the film hole outlet have a great effect on the film cooling effectiveness.

Previous studies have focused on shape optimization of film cooling hole for flat surfaces or stationary blades. In the present study, optimization of the film cooling effectiveness has been performed for a rotating blade. Numerical simulation of flow and heat transfer over a rotating blade has been carried out, using the RNG k-ε turbulence model. The results obtained were compared with the available experimental data [8]. The genetic algorithm is employed to optimize the objective function, which is defined as the averaged film-cooling effectiveness over the rotating blade.

2. Numerical details

2.1. Problem descriptions

Fig. 1 illustrates the computational domain for film cooling over a rotating blade which is according to the experimental investigation of Tao et al. [8]. The computational domain of present study is composed of the main channel of the hot gas stream, blade surface and a film cooling hole. The x-axis is along the mainstream direction, y-axis is normal to the test surface and the z-axis conforms to the right-hand law. The origin is located at the downstream tip of the film hole. A flat blade parallel to the mainstream hot gas has been considered as a model gas turbine blade. The blade chord length and the height were 142 and 106 mm, respectively. The cooling hole diameter is 4 mm and the injection angle of the hole is 30°. The rotating radius at the center of the film hole was 450 mm.

The working fluid (air) is considered to be incompressible and Newtonian with temperature-dependent properties. At the inlet of main flow channel and at the cooling hole inlet, the mass flow boundary condition is applied.

Secondary stream (coolant air) is injected through the film cooling hole into the test section. In the present study, the cylindrical hole for cooling the rotating blade [8] is considered to be replaced with laterally-diffused hole (LDH) [28]. Geometric parameters of this hole is presented in Fig. 2. Hyams and Laylek [28] showed that for the laterally diffused hole, the coolant is effectively injected into the crossflow boundary layer and dissipated by diffusion mechanisms in downstream. The effectiveness of LDH is very high along the centerline and spanwise directions.

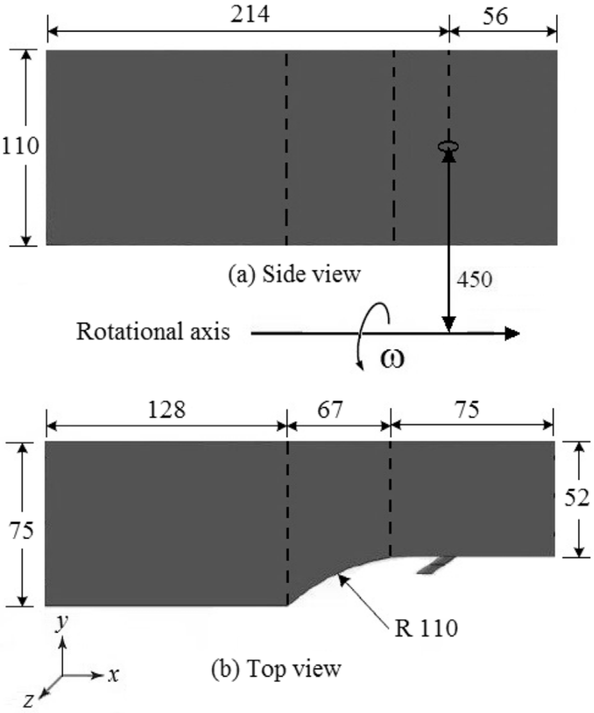

Fig. 1. Computational domain (dimensions are in mm).

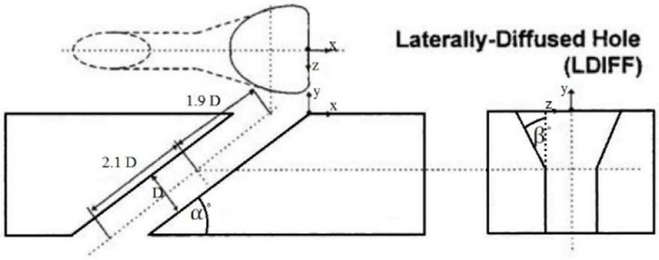

Fig. 2. Geometric Parameters of laterally diffused hole [28].

2.2. Governing equations and boundary conditions

The conservation form of three-dimensional incompressible, steady-state, turbulent flow under rotating frames can be written as:

$$\frac{\partial}{\partial x_i}(\rho\bar{u}_i)=0 \tag{1}$$

$$\frac{\partial}{\partial x_j}(\rho\bar{u}_i\bar{u}_j)=-\frac{\partial\bar{P}}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial\bar{u}_i}{\partial x_j}+\frac{\partial\bar{u}_j}{\partial x_i}\right)-\rho\overline{u'_i u'_j}\right]-2\rho\bar{I}_{ijk}\omega_k\bar{u}_j - \rho\bar{I}_{ijk}\bar{I}_{jlm}\omega_k\omega_l X_m \tag{2}$$

$$\frac{\partial}{\partial x_i}(\rho\bar{u}_i C_P\bar{T})=\frac{\partial}{\partial x_i}\left(k\frac{\partial\bar{T}}{\partial x_i}-\rho C_P\overline{u'_i T'}\right) \tag{3}$$

where the $\rho u'_i\overline{u'_j}$ is the Reynolds-stress tensor, the $\overline{u'_i T'}$ is the turbulence heat flux and $2\rho\bar{I}_{ijk}\omega_k\bar{u}_j$ is Coriolis force. The Coriolis force appears when the rotating coordinate system is used. It acts as a real force in rotating coordinates. In the present study, three different rotating speeds, i.e., 0, 300 and 500, rpm are considered for the blade.

To comply with the experiments [8], the following boundary conditions are employed:

The constant mass flow rates of 0.2 kg/s and $1.906*10^{-4}$ kg/s are applied for mainstream and coolant respectively. Hence the constant blowing ratio ($M = 0.3$) and momentum ratio ($I = 0.285$) have been achieved. Constant temperatures of 321.15 K and 311.15 K are applied