Applied Thermal Engineering 111 (2017) 537–549

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Aero-thermal optimization on multi-rows film cooling of a realistic marine high pressure turbine vane

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HIGHLIGHTS

- A full three-dimensional optimization platform is established.
- Aero-thermal optimizations on multi-rows film cooling are performed.
- Film cooling effectiveness and aerodynamic loss are taken into considerations.
- Bothe single objective and multi-objective optimization are adopted.

ARTICLE INFO

Article history:
Received 5 August 2016
Revised 19 September 2016
Accepted 24 September 2016
Available online 26 September 2016

Keywords:
Marine gas turbine
Film cooling
Optimization platform
Aero-thermal optimization

ABSTRACT

Aero-thermal optimizations on multi-rows film cooling of a realistic marine high pressure turbine vane are performed in this paper. Firstly, a full three-dimensional optimization platform for film-cooled turbines, which consists of the parametric modeling, automatic mesh generation, the CFD numerical calculation and the optimization strategy is established. The design variables are selected based on the considerations of hole-to-hole interactions and invalid coverage of cooling film. Two objective functions of aerodynamic efficiency and adiabatic film cooling effectiveness are adopted to evaluate the overall performance of film-cooled turbine vane. Bothe single objective and multi-objective optimization are adopted to optimize the configurations of multi rows film cooling holes, and the Multi-Island Genetic Algorithm and The response surface approximation with the Non-dominated Sorting Genetic Algorithm (NSGA-II) are selected to conduct the optimizations. The objective of the present study is to use a numerical optimization method to find the optimal cooling structure configurations that yields better cooling performance with an acceptable aerodynamic penalty. The results show that the film cooling effectiveness of multi-objective optimization is increased by 11.4%, and average temperature of the blade surface is reduced by 75 K.

1. Intruction

Higher turbine inlet temperature is a direct and effective means to improve gas turbine thermal efficiency and power output. Cooling of turbine blades becomes necessary to ensure a safe operation and reasonable lifetime, film cooling has been extensively used in turbine blade designs [1].

There are a variety of parameters affecting the efficiency of film cooling, such as hole arrangement and configuration, blade surface curvature, surface roughness, mass flux ratio, momentum flux ratio, mainstream turbulence and Reynolds numbers and blowing ratios [2,3]. Many experimental and numerical investigations have been performed to find the effects of these parameters on film cooling performance [4–7]. Design optimization techniques have developed rapidly in the last decade because of the less requirements on the design experience and human interference of a computer-automated optimization.

Film cooling optimization of turbine vanes has been addressed by some researchers. Some studies of shape optimization for film cooling have been given by Lee et al. [8–11] to enhance film-cooling effectiveness, indicating the cylindrical hole, fan-shaped hole and laidback fan-shaped hole. Optimization of film cooling hole has been performed by surrogate modeling approach, the spatially-averaged film cooling effectiveness is considered as the objective function. The results showed that film cooling effectiveness has been successfully improved with the optimization as compared to the reference geometry. Choi et al. [12] conducted a parametric analysis and optimization of double-jet film cooling holes. The results showed that cooling performance of double-jet

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http://dx.doi.org/10.1016/j.applthermaleng.2016.09.143
1359-4311/

Nomenclature

A	area of blade surface, mm^2
$c_{p\Gamma}$	specific pressure heat of mainflow, J kg^{-1} K^{-1}
c_{pB}	specific pressure heat of coolant, J kg^{-1} K^{-1}
C_1	average velocity of mixture, m/s
D	diameter of film hole, mm
G	mass flow rate, kg/s
H	available energy, kJ/kg
N_1	the number of film hole, –
N	the number of design variable, –
P	hole spacing, mm
p	pressure, Pa
T	temperature, K
y^+	non-dimensional distance
η_1	the cooling effectiveness, –
η_2	aerodynamic efficiency, –
α	injection angle, °
β	compound angle, °
ω_1	weight coefficient, –
ω_2	weight coefficient, –

Subscripts

Γ	mainstream flow
B	coolant flow
0	inlet
1	outlet

film-cooling holes was improved considerably by optimization in comparison with the reference geometry. Chi et al. [13] developed a two-level optimization methodology for the exit shaping of shaped holes using CFD methods. The optimization methodology can efficiently find the optimal geometries of shaped holes using only hundreds of CFD runs. They also studied a tripod cylindrical film hole with asymmetric side holes on a flat plate. The resulted showed that cooling performance of the optimized asymmetric tripod hole was significantly better than that of the simple cylindrical hole, especially at high blowing ratios [14]. Peter et al. [15] presented the numerical optimization of a narrow, swept trench geometry for film cooling applications. The infrared data indicated a maximum improvement of about 56% compared to the straight trench at the highest momentum ratios. Felipe et al. [16] conducted a temperature-based optimization of film cooling in gas turbine hot gas path components. Design of experiments and cheap-to-evaluate approximations were used to alleviate the computational burden, and the goal attainment method was used for optimizing of film cooling configuration. The results for a turbine blade design showed significant improvements in temperature distribution while maintaining/reducing the amount of used cooling flow. An aero-thermal optimization approach for film cooling of gas turbine airfoil was implemented for a typical gas turbine vane by Ayoubi et al. [17]. The optimization objectives were to improve the adiabatic film cooling effectiveness while reducing the aerodynamic losses. A purely thermal optimization resulted in almost 30% increase in surface averaged adiabatic film effectiveness and a 1.2% increase in aerodynamic loss. Müller et al. [18] presented results from the application of an improved parallel evolution strategy to the multi-objective optimization of parameters in a model of gas turbine blade film cooling. The results of the study suggested that evolution algorithms presented a robust, automated optimization tool offering a viable alternative to the optimization of engineering devices using gradient-based methods and engineering intuition. Johnson et al. [19] performed an in-depth investigation of the heat transfer characteristics and cooling effectiveness of a full-scale fully cooled modern high-pressure turbine vane as a result of genetic algorithm (GA) optimization. The optimized cooling array resulted in a reduction of average near-wall gas temperature of 2 K, a reduction in the maximum near-wall gas temperature of 3 K, a reduction in maximum heat flux of 2 kW/m^2 and a reduction in pressure loss over the vane. Yin and Fang [20] optimized the film cooled stator of the first high pressure stage of GE-E3. Source term method and multi-objective optimization method were employed to simulate the effect of overall film cooling and minimize the maximum temperature and average temperature of the blade. The loss of momentum near the wall caused by the injected coolant could be observed from the simulated results.

In the present study, a full three-dimensional optimization platform for film-cooled turbines, which consists of the parametric modeling, automatic mesh generation, the CFD numerical calculation and the optimization strategy is established at first. Aero-thermal optimizations on multi-rows film cooling of a realistic marine high pressure turbine vane considering the film cooling effectiveness and aerodynamic loss are performed using single objective and multi-objective optimization method. The objective of the present study is to use a numerical optimization method to find the optimal cooling structure configurations that yields better cooling performance with an acceptable amount of coolant consumptions.

2. Optimization platform for air-cooled turbines

The traditional cooling system design of the turbine is a simple combination of the finite design variables, which requires a lot of work force and the design cycle is long. With the development of optimization theory, the design of the complex cooling structure of the turbine is possible, which can reduce the consumption of human resources and shorten the design cycle. Based on the engineering background, an optimization platform for air-cooled turbines is developed, which mainly includes the parametric modeling, automatic mesh generation, the CFD numerical calculation and the selection of the optimization strategy.

2.1. Parametric modeling of film-cooled HPT vane

The parametric modeling for film-cooled HPT vane is a critical issue for the cooling design optimization of gas turbines, it could reduce the difficulty of designing complex structures, accelerate the design process.

For the parametric modeling of film cooling, the local coordinate system (m, r) is established along the blade surface from leading edge to trailing edge, the origin of coordinate system(0, 0)is located at the bottom of blade leading edge line, and other important points of coordinate system is shown in Fig. 1(a). The coordinate value m on pressure surface is positive. The center position of the film hole on blade surface can be represented by the local coordinate system (m_f, r_f), the jet direction of film hole jet is described in Fig. 1(b). Where n is normal direction, J stands for the radial direction, K is tangential direction at f point on blade surface. In general, the film hole configurations can be determined by several parameters, including the injection angle α, compound angle β, diameter of film hole D, hole spacing P and the number of film hole in each row N_1. The automatic reading of calculation model, the reconstruction of new geometry and the automatic processing of