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# Geometrical optimization of nonuniform impingement cooling structure with variable-diameter jet holes

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ABSTRACT

In this paper, a novel impingement cooling structure with variable-diameter jet holes was developed for the internal cooling of turbine vanes to ensure a heterogeneous wall temperature distribution under nonuniform thermal load, and the corresponding optimization methodology was investigated. Using both single-objective and multi-objective genetic algorithms (GA), the location of the jet holes and the diameter of each hole were optimized based on conjugate heat transfer (CHT) CFD. The generation of 3D model and CHT mesh was realized using an in-house code developed specifically for turbine cooling optimization. To make the optimization computationally faster, a metamodel which can predict the detailed distribution of metal temperature on the vane was used in the optimization search coupled with GA.

Through single-objective GA search, an optimal nonuniform impingement cooling design was automatically found costing only dozens of CFD runs. The optimal design provided a more uniform temperature distribution on the vane surface while using equivalent coolant amount compared with the prototype. It was also demonstrated that multiple-objective optimization search could efficiently found a series of optimal cooling designs at various coolant amounts (Pareto front) with quite uniform wall temperature distributions on the vane surfaces cooled by impingement jets. Meanwhile the relationship between overall cooling performance and total coolant amount was investigated. In sum, it is anticipated that the nonuniform impingement structure together with its design optimization methods should be a beneficial extension of internal cooling technology of gas turbine.

## 1. Introduction

Among the forced convective cooling methods commonly used, jet impingement cooling has high convective heat transfer coefficient and also large flow resistance [1,2]. In industrial applications, the impingement jets are often used in arrays for thermal load management of hot components. Former studies on impingement cooling array have well demonstrated that jet Reynolds number, Mach number [3,4], jet-to-target distance and jet pitch [5] are the essential parameters, while the target curvature, rotation, and jet angle are also influential.

In the past decades, researchers much focused on improving the uniformity of convective heat transfer coefficient (HTC) of impingement jet arrays. Florschuetz et al. [6] and Rao et al. [7] studied the distribution of the Nusselt number of a jet array with crossflows. It is found that the crossflows leads to pressure drop on streamwise between the jet plane and target plane, resulting in a nonuniform cooling intensity on streamwise. These negative effects of crossflow is a limiting factor in the length of jet impingement arrays. Consequently, Esposito et al. [8] investigated a novel impingement geometry for backside cooling of combustor liners. A corrugated jet plane changes the impingement distance of jet flows, which can weaken the negative effects of crossflows. The author of this paper [9] also developed a multi-row impingement cooling structure, named Anti-Crossflows (ACF) impingement cooling structure, for the internal cooling of turbine vanes. The ACF impingement cooling uses a corrugated impingement tube to reduce the pressure drop caused by the outflow of crossflows. And the HTC uniformity in the streamwise direction was improved.

On the other hand, impingement cooling designs under nonuniform thermal load are required in many situations, especially in the backside cooling of turbine components when a homogeneous wall temperature with minimal thermal stress is required. Here the impingement cooling arrangement should be decided accommodating the detailed distribution of heat flux on the hot side. In other words, the impingement jet array should provide a desired distribution of HTC. For instance, impingement jets are deliberately arranged at the leading edge of turbine airfoils, where the jet-to-target distance and pitch-to-diameter ratio could much influence

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**Nomenclature**

| | |
|---|---|
| $A$ | area of vane surface |
| $a, b, c$ | parameter of linear/quadratic functions |
| $D$ | diameter |
| $H$ | impingement distance |
| $h$ | heat transfer coefficient (HTC) |
| $k$ | nodes (metamodel) |
| $m$ | coolant mass flow |
| $n$ | number of nodes (metamodel) |
| $Nu$ | Nusselt number (= $hD/\lambda$) |
| $P$ | pitch of jet array |
| $PR$ | pressure ratio |
| $p$ | pressure |
| $p^*$ | total pressure |
| $Re$ | reynolds number |
| $R$ | radius of revolution |
| $T$ | temperature |
| $T^*$ | total temperature |
| $Tu$ | turbulence intensity |
| $\alpha$ | inlet flow angle of cascade |
| $\lambda$ | thermal conductivity |
| $\varphi$ | optimization objective |
| $\omega$ | rotation speed |

*Subscripts*

| | |
|---|---|
| ave | surface-average |
| c | coolant/coolant inlet |
| g | gas side |
| i | inlet |
| m | metamodel |
| max | maximum value |
| o | outlet/cascade stage outlet |
| opt | current optimal (during optimization) |
| span-ave | spanwise-average |
| w | wall |
| x | chord-wise |
| y | span-wise |
| 0 | prototype |
| 1–50 | first-level iterations of optimization |

*Abbreviations*

| | |
|---|---|
| ACF | Anti-Crossflows |
| CFD | computational fluid dynamics |
| CHT | conjugate heat transfer |
| GA | Genetic Algorithm |
| HTC | heat transfer coefficient (convective) |
| LE | leading edge |
| MO | Multi-Objective |
| PS | pressure side |
| RANS | Reynolds averaged Navier-Stokes equations |
| SO | Single-Objective |
| SS | suction side |
| TE | trailing edge |

both spanwise average value and spanwise gradient of HTC [10]. Parida et al. [11] studied several impingement cooling designs of an automotive power converter with two isolated heat sources, showing that optimizing jet arrangement, inclination angle and also jet-to-target structures could achieve a more favorable distribution of HTC. Though some specific impingement designs in industrial applications could provide the desired HTC distributions, these designs were mostly decided using empirical data and through costly experimental iterations.

For the possibility of finding optimum cooling designs with lower cost and less human interference, recent turbine cooling studies focused on the application of optimization methodology. Many earlier studies on turbine cooling optimization were based on 1D flow network models, empirical correlations, and 2D heat conduction models, as introduced by Martin et al. [12,13] and Talya et al. [14]. Though the computational costs were quite low, these simplified models could not give detailed designs with localized thermal load management. Therefore, some later optimization studies began to use 3D CFD approach instead of the empirical models. Verstraete et al. [15,16] studied the optimization of a U-bend of a internal cooling channel for minimal pressure loss and higher average HTC. Lee et al. [17,18] optimized a fan-shaped film hole to explore the effect of geometric variations on the film cooling effectiveness. Farahani et al. [20] optimized an impingement cooling structure with two slot jets in order to achieve a uniform HTC distribution. As many former studies pointed out that conjugate heat transfer (CHT) simulation can give more realistic and reliable predictions of the heat transfer of cooled blades [19,21], some recent optimization studies on turbine cooling began to use CHT CFD approach [22–24]. The author of this paper [25] reported an optimization study for the impingement cooling system of a turbine vane considering both coolant amount and cooling performance. Though the optimization method could effectively find the optimal cooling design, many hot zones still existed on metal surface of the optimized vane, which mainly due to the limited cooling capability of the traditional impingement array with uniform jet pitch and an identical hole diameter.

To improve the temperature homogeneity of object surface cooled by impingement jets, in this paper a nonuniform impingement cooling structure with variable-diameter jet holes is developed based on the ACF structure [9]. Moreover, the design optimization strategies of the nonuniform impingement cooling structure are built. Here optimization strategies based on both Single-Objective (SO) and Multi-Objective (MO) Genetic Algorithms (GA) are investigated. A metamodel is developed and implemented in order to increase the efficiency of the optimization process. It is hoped that the variable-diameter jet holes designed by the optimization method could ensure more homogeneous wall temperature distributions compared with those of the traditional impingement cooling array with identical- diameter jet holes. It is also hoped that relationship between cooling performance and total coolant amount could be explored simultaneously utilizing MOGA.

## 2. Geometry and parameterization

### 2.1. Prototype vane with traditional impingement array

The aerodynamic profile of the optimization study was from the 2nd stage turbine of General Electric Energy Efficient Engine (GE $E^3$), and the numbers of vanes and blades of the stage are 48 and 70. This paper focuses on the design optimization of the cooling system of the vane.

The prototype vane cooling system was designed by an optimization study presented in [25], as shown in Fig. 1. The vane is installed with internal cooling structure without film holes. The vane is separated into two cavities. An traditional impingement