Efficient Turbine Vane Cooling Design: From 2D Concept to 3D CAD Modeling

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ABSTRACT

In order to improve the thermal efficiency of gas turbines, efficient cooling concepts for turbine vanes are becoming increasingly important. However, evaluating the performance of a cooling design is computationally intensive and usually requires a coupled CFD-CSM simulation. This approach is not practical in the early design phase when the cooling design is frequently changed. To overcome this limitation, a simplified yet physical approach is required to develop an initial cooling design.

This study presents a comprehensive approach for turbine vane cooling design that is integrated into an optimization tool chain. The model uses a vane geometry model, aerodynamic flow field, and coolant conditions from an internal turbine design tool chain. The cooling geometry is modeled in multiple radial sections using variable geometric parameters to account for variations in airfoil geometry and flow field. Both internal cooling, such as impingement or convective cooling, and external cooling, such as film cooling, are considered. This approach enables significant improvements in cooling design by reducing cooling air requirements as well as optimizing temperature distribution and thus minimizing thermal stresses during the early design phase. Consequently, a detailed 3D model of the vane is created with substantially reduced effort.

INTRODUCTION

During the early stages of turbine blade and vane cooling design, it is crucial to approximate the required coolant mass flow. Although empirical correlations found in the literature are commonly used for this task and allow for an early estimation of the cooling air mass flow, they do not provide information on the actual cooling geometry [1]. Therefore, a physically based approach is necessary to design efficient cooling concepts at an early design stage. While a 2D vane profile is suitable for this design stage, it is not sufficient as a base for a geometric 3D representation. Intermediate steps are required to bridge the gap between the 2D and 3D models.

This study presents such a process in the preliminary cooling design tool `PICCOOLO`, which enables the creation and evaluation of a cooling geometry and the derivation of a parameterization suitable for a 3D cooling geometry. To achieve this, the 2D cooling design model is extended to multiple radial sections, and a network model accounts for the connectivity between adjacent channels, resulting in a 2.5D model of the cooled airfoil. The final 3D cooling representation is generated by distribution functions based on the cooling geometry designs within the sections. The tool calculates the temperature distribution on various material layers for any number of radial sections of a turbine vane. The method can be applied to airfoil geometries with varying chord length, thickness distribution, and curvature. The capabilities of the cooling design tool are demonstrated using a first stage nozzle guide vane (NGV).

METHODS

The complex design of turbine blade cooling systems is divided into several sub-processes. The level of detail and computational complexity increases with each step, but the process is accelerated by building on the results of the previous step. The process starts with the generation of a simplified 2D design of the cooling geometry in the radial mid section of the vane. This step is repeated for several other radial sections to account for variations in geometry and flow parameters. Based on this 2.5D representation, a detailed 3D geometry of the vane can be modeled.

2D Design: `PICCOOLO`

`PICCOOLO` is a semi-empirical software tool developed for the preliminary design of cooling systems for turbine vanes and blades. It combines analytical and empirical methods to calculate the temperature distribution along an airfoil profile. It is based on the 1D form of Fourier's law of heat conduction, which is applied to the discretized pressure and suction side contours of a 2D turbine airfoil section. External and internal convection as well as conduction through the pressure and suction side walls are modeled as thermal resistances in series as outlined in Fig. 1.

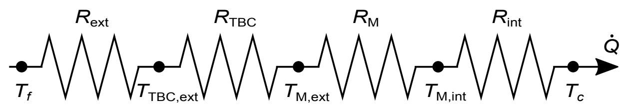

Fig.1 Thermal resistance model applied to a discrete point on the airfoil profile

The external and internal thermal resistances are calculated by

$$R_{\text{ext/int}} = \frac{1}{h_{\text{ext/int}} \cdot A}, \tag{1}$$

in which h_{ext} is the external and h_{int} is the internal heat transfer coefficient. The thermal resistances of the i-th material layer

$$R_i = \frac{\delta_i}{k_i \cdot A} \tag{2}$$

are determined based on its thickness δ_i and thermal conductivity k_i. The external Nusselt number

$$\text{Nu}_{\text{ext}} = f\left(\text{Re}_{\text{ext}}, \text{Pr}_g\right) \tag{3}$$

is calculated as a function of the hot gas Reynolds number Re_{ext}, which is evaluated along the vane profile, and Prandtl number Pr_g.

A distinction is made between laminar and turbulent boundary layers. We can then calculate the external heat transfer coefficient as

$$h_{\text{ext}} = \frac{k_{\text{ext}} \cdot \text{Nu}_{\text{ext}}}{C}, \tag{4}$$

with hot gas thermal conductivity k_{ext}, Nusselt number Nu_{ext} and chord length C [2].

PICCOOLO determines the internal heat transfer coefficients resulting from several cooling techniques such as impingement cooling, rib and pin-fin enhanced cooling. Literature research has shown that impingement and pin-fin enhanced cooling are suitable for the cooling design of a first stage HPT NGV and are therefore discussed further [3]. Impingement cooling is a cooling method in which jets of cooling air are directed at a surface with high momentum, resulting in high heat transfer coefficients. It is used in areas subject to high thermal loads. This includes the leading edge of rotor blades or the entire surface of vanes. The correlation published by Florschuetz [4] is used to calculate the internal Nusselt number resulting from an array of impingement jets:

$$\text{Nu}_{\text{int}} = f\left(\text{Re}_{\text{jet}}, \frac{x}{D}, \frac{y}{D}, \frac{z}{D}, \frac{G_c}{G_j}, \text{Pr}_c\right). \tag{5}$$

Re_{jet} is the jet Reynolds number, $\frac{x}{D}$ and $\frac{y}{D}$ are the normalized distances in circumferential and radial direction, respectively. $\frac{z}{D}$ is the jet-to-target-plate distance, $\frac{G_c}{G_j}$ is the cross-flow ratio, and Pr_c is the coolant Prandtl number.

Pin-fins are cylindrical turbulators that connect the pressure and suction side of a turbine blade or vane and narrow the flow cross-section. Convective heat transfer is increased by disturbing the boundary layer and increasing the surface area. Pin-fins are primarily used in areas where impingement cooling cannot be used such as in the trailing edge region. The correlation for a staggered array of cylindrical pin-fins from Metzger [5] is used to calculate the resulting internal Nusselt number

$$\text{Nu}_{\text{int}} = f\left(\text{Re}_{\text{pin}}, \frac{x}{D}\right), \tag{6}$$

with Re_{pin} the pin Reynolds number and $\frac{x}{D}$ the dimensionless downstream distance. The internal heat transfer for impingement cooling and pin-fin enhanced cooling is calculated as

$$h_{\text{int}} = \frac{k_c \cdot \text{Nu}_{\text{int}}}{D}, \tag{7}$$

where k_c is the thermal conductivity of the coolant and D is the characteristic length that corresponds to the diameter for both impingement and pin-fin enhanced cooling.

Film cooling is used to create a protective layer of cooling air on the thermally highly loaded vane surface. This reduces the hot gas temperature at the surface and thus the temperature gradient driving the heat flow through. Various correlations are used, depending on the film cooling row position and geometry, to calculate the adiabatic film cooling effectiveness. At the leading edge, the effect of showerhead film cooling holes is an approximation based on the data published by Lakehal et al. [6]. The film cooling rows located further downstream are typically laidback fan-shaped, which are approximated with the correlation of Colban et al. [7]. The adiabatic film cooling effectiveness is calculated as

$$\bar{\eta}_f = f\left(\text{AR}, D, M, P, t, x\right), \tag{8}$$

where AR is the area ratio between hole outlet and inlet, D is the hole diameter, M is the blowing ratio, P is the pitch between adjacent holes, t is the lateral width of the hole outlet and x is the downstream distance from the hole outlet. The superposition approach published by Sellers [8] is used to calculate the effect of multiple rows of film cooling holes as

$$\bar{\eta}_f = \sum_{i=1}^{n} \bar{\eta}_{f_i} \prod_{j=0}^{i-1} (1 - \bar{\eta}_{f_j}). \tag{9}$$

Based on the adiabatic film cooling effectiveness, the gas temperature can be updated in order to take the coolant film into account as

$$T_g = (1 - \bar{\eta}_f) \cdot T_{\text{ext}} + \bar{\eta}_f \cdot T_{c_{\text{exit}}}. \tag{10}$$

The resulting heat flow rate into the vane

$$\dot{Q} = \frac{T_g - T_c}{\sum_{i=1}^{n} R_i}, \tag{11}$$

based on the hot gas T_g and the cooling air temperature T_c, is calculated for each discrete pressure and suction side node until energy conservation is preserved. The cooling air mass flow is estimated based on pressure loss correlations and the ratio between internal and external pressure. The coolant mass flow rate is iterated until mass balance is satisfied. The temperature distribution is calculated along the mid section airfoil contour.

2.5D Design: PICCOOLO

The 2D approach is based on the assumption that the radial mid section of the vane is representative of the entire airfoil surface. To account for the radial variation of airfoil profile geometry and flow parameters, the vane is split into several radial sections. PICCOOLO is used as a network model to calculate the temperature distribution on the profiles at the different sections. As noted by Chowdhury et al. [9], particularly the hub and tip areas must be considered in the cooling design because of their different heat transfer coefficients. Accordingly, the airfoil is usually divided into three sections, however, any number of radial sections is possible. Although the network model adds complexity to the iteration process, the increased computational effort is still negligible compared to a conjugate heat transfer approach, which is typically done by coupling CFD and CSM simulations. Based on the cooling design of each section, a radial distribution of cooling geometries is created. In terms of film cooling, a quadratic spline is fit through the relative positions of film cooling rows of each section. This interpolation is repeated similarly for impingement and pin-fin geometries.

3D Design: CoolingGen

CoolingGen is a parametric CAD tool, which creates cooling geometries for vanes and blades using non uniform rational b-spline (NURBS) surfaces. Based on the radial distribution of cooling geometries from the previous design stage, a 3D model of the cooled airfoil is created. Internal cooling is modeled as cooling channels, which are optionally designed in a multipass configuration or supplemented by pins to further enhance the internal heat transfer coefficient. Impingement cooling can be designed between two adjacent channels or by means of impingement baffles, as it's common in vane cooling designs. Trailing edge slots and film cooling holes can be added for external cooling, with typical hole shapes such as laidback fan-shaped. The resulting solid model of the blade can be used for detailed flow and structural simulations.

RESULTS AND DISCUSSION

The process chain was used to design the cooling geometry for the high-pressure turbine (HPT) nozzle guide vanes (NGV) of DLR's ultrahigh bypass ratio (UHBR) geared turbofan (GTF) engine concept [10]. The design process based on an optimized 2D design of the cooling system in the mid section, which was previously published [11]. In addition, the 2.5D design stage was executed in an optimization process to determine the radial distribution of the cooling geometry and to create a 3D model of the cooled vane. The material considered for the vane is a single crystal nickel-based superalloy (CMSX-4) [12], and a partially yttria stabilized zirconia thermal barrier coating (TBC) [13] is applied. It is assumed that the temperature dependent thermal conductivity remains constant throughout the profile at the specified operating temperature. Table 1 provides a summary of the material properties.

Table 1 Material parameters

	δ [mm]	k [W/mK]	T_{max} [K]
Metal	1.85	26.1	1 323
TBC	0.15	1.4	1 523

The multi-objective optimization process was carried out using the DLR's in-house optimizer `AutoOpti` [14]. An evolutionary algorithm was utilized to generate new members based on the specified parameter space. In this process, a total of approximately 100 cooling geometry parameters were varied, which allows for a detailed variation of film cooling, impingement cooling, as well as internal cooling channel geometry. The primary objectives of the optimization process were to minimize the demand of cooling air and the standard deviation of material temperature along the surface, thereby reducing thermal stresses. As constraint, the maximum tolerable material temperatures must not be exceeded. Furthermore, violations of the valid correlation ranges were penalized. The results of the optimization process are illustrated in Fig. 2. A total of 10,000 cooling configurations were evaluated in 10 hours. The members with a Pareto rank of 1 representing optimal solutions are marked in blue. It is evident from the figure that small changes in the standard deviation of the material temperature along the vane surface result in significant variations in the required cooling air mass flow rate. Therefore, a member with a balanced objective function was selected for further evaluation.

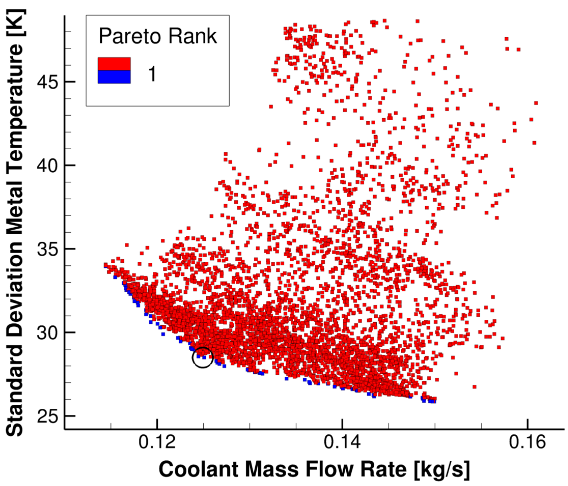

Fig.2 Pareto diagram of the 2.5D cooling design optimization

Upon comparison with the baseline case, it is observed that significant improvements in terms of coolant mass flow reduction can be achieved while simultaneously reducing the thermal stresses. The improvements are summarized in Table 2.

Table 2 Comparison of optimization objectives

	Coolant MFR [kg/s]	$\bar{T}_{metal}$ [K]	$\sigma_{T_{metal}}$ [K]
Baseline	0.1512	1 270.1	41.1
Optimized	0.1256	1 246.7	28.1

The temperature distributions along the hub, mid and tip vane sections with optimized cooling geometry are shown in Fig. 3. The position of the film cooling rows varies slightly between the sections to compensate for the deviation in thermal load that results from differences in temperatures and heat transfer coefficients along the profile.

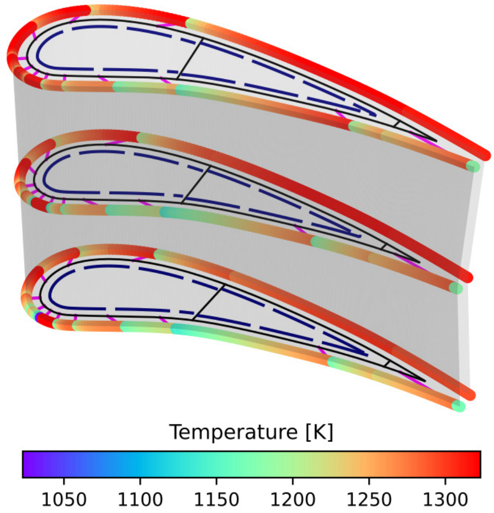

Fig.3 2.5D temperature distribution at the external metal surface

Based on these section designs, a 3D distribution of the cooling geometries, in particular of the film cooling holes, was derived. Therefore, a quadratic spline was fitted to the known positions of the film cooling holes in the three radial sections. The resulting 3D distribution is shown in Fig. 4.

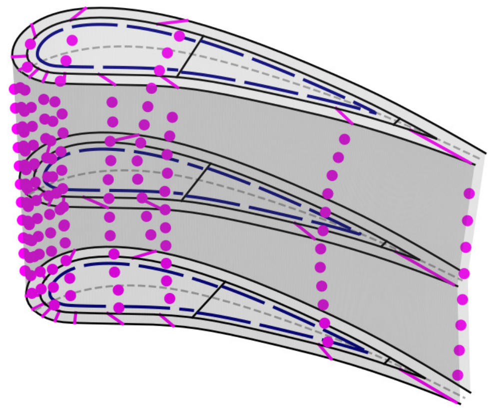

Fig.4 3D film cooling hole distribution

The radial distribution of the cooling geometries completes the parameterization of the 3D vane geometry. By using `CoolingGen`, a surface model of the vane was generated, as demonstrated in Fig. 5. This CAD model can be utilized to conduct more comprehensive analyses of the flow field and structural evaluations, as it can be seen in the turbine design overview of Grunwitz et al. [10].

CONCLUSIONS

The development of efficient cooling concepts for turbine vanes is crucial to enhance the thermal efficiency of gas turbines. However, conventional approaches to evaluate the performance of a cooling design using coupled CFD-FEM simulation are computationally intensive and not practical during the early design phase. To address this issue, a simplified yet physical approach is presented in this study. By incorporating `PICCOOLO` in an optimization process,

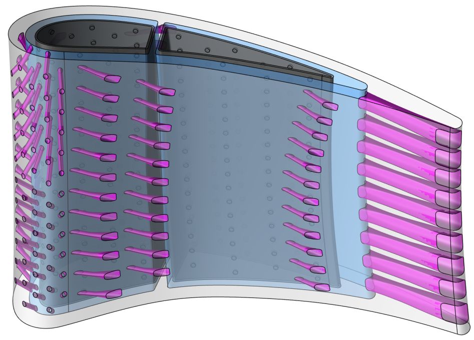

Fig.5 3D turbine vane surface CAD model

a detailed and efficient cooling design can be generated in approximately 10 hours, significantly reducing the time and computational effort required. Even at this early phase, significant variations in the efficiency of cooling systems based on the same cooling methods can be observed. The optimization of the cooling design at this level, therefore, minimizes the computation time of subsequent, more detailed, and computationally intensive calculations. Based on the optimized cooling design, a detailed 3D model of the vane is generated with `CoolingGen`, which can be used for further investigations. Overall, this study provides an effective and practical solution for the design and geometric modeling of efficient cooling systems for turbine vanes in gas turbines.

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