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Conjugate analysis and effective thermal conductivities of effusion-cooled multi-layer blade sections

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ABSTRACT

In order to predict the effective thermal conductivity along the chord of a typical turbine blade slice, different flat and curved – convex and concave – sections have been defined. Apart from the flat design, two different curvatures for both, the convex and concave plate, are identified. For these designs 3-D conjugate heat transfer and fluid flow analyses are performed for two blowing ratios. These analyses focus on the influence of the surface curvature on the vortex structures on the plate surface and on the cooling effectiveness on the TBC-surface as well as within the substrate layer. A multi-scale approach based on the homogenization technique is then linked to the conjugate analysis in order to predict the effective thermal conductivity of the blade sections. This method allows to calculate effective equivalent properties either for each layer or for the multilayer. The influence of the plate curvature and the blowing ratio on the effective orthotropic thermal conductivities is outlined.

1. Introduction

The reduction of CO_2 emissions required by the Kyoto protocol are presently the primary driving forces behind the technological innovations in power plant technology and the improvement of their thermal efficiency. Simulations show that it will be necessary to design gas turbines with combustion chamber outlet temperatures of 1520 °C [1] to achieve a total combined cycle efficiency of 65%. The temperature increase cannot be achieved by the development of new coated materials alone. Therefore, the components have to be cooled intensively. One method of doing this is the effusion cooling analyzed here. It consists of numerous smallest drilled holes and it brings the advantages of an open cooling system while minimizing the “loss” of compressor air to the cooling system.

Even though effusion cooling (also called full-coverage film cooling) has been investigated for decades, it was classified as one of ten remaining hot gas path challenges for increasing gas turbine efficiency some years ago [2]. Extensive experiments on a flat plate with numerous cylindrical effusion cooling holes have been performed by Gustafsson and Johansson [3]. The authors point out that a large number of holes is required for the investigations as otherwise the interaction of the different coolant jets cannot be properly captured. In a early study [4] full-coverage cooled blades were investigated experimentally. The coolant injection in the boundary layer is said to have an effect only in the region of the strongest curvature on the suction side. The importance of the thermal conductivity of the wall for the effusion cooling effectiveness has been discussed in detail in Ref. [5]. Yu and Ji [6] show that the inclination angle of 30° of cylindrical holes is slightly better than the other angles due to higher convective cooling within the holes. Furthermore, Bohn and Moritz [7] outline that a lateral widening of the cooling hole increases the lateral spread of the coolant and at the same time decreases the lift-off of the coolant jet. Conjugate calculations of curved effusion-cooled plates have to our knowledge so far only been performed in [8,9] for designs dotted with shaped holes without lateral opening, but with a fairly strong curvature and simple laid-back cooling holes. These analyses show that the required cooling effectiveness cannot be achieved by such simple shaped holes.

As the simulation of completely effusion-cooled blades will not be possible in the foreseeable future, an original multi-scale approach, combining the 3-D conjugate analysis with the asymptotic homogenization technique of heterogeneous, periodic materials [10] has been introduced in the past by the authors [11–13]. This technique allows to calculate equivalent thermophysical properties either for each layer separately or for the multi-layer. In a further step, it allows to calculate the aero-thermal behavior of complex gas turbine components by replacing the heterogeneous material by a continuous, equivalent one. For this purpose a reference unit cell with periodic boundary conditions is extracted from

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Nomenclature

C, H	indices for cooling or hot gas conditions
c_p	specific heat
D	diameter of the cooling channel
$\mathbf{e}^j$	unit vector
k_{ij}	thermal conductivity tensor
$\bar{k}^{\text{hom}}$	mean effective thermal conductivity
k_{ij}^{hom}	effective thermal conductivity tensor
k_{va}	volume averaged thermal conductivity
L	row spacing of cooling channels
$M = \frac{(\rho\mathbf{v})_C}{(\rho\mathbf{v})_H}$	blowing ratio
Ma	Mach number
p_{1t}	inlet total pressure of the main flow
p_{Cst}	inlet static pressure of the cooling fluid in the plenum
R	radius of curvature of the plates
S_l, S_w	shaping length and width of the diffusor
T^h	temperature of the porous material
T^0, T^1	order zero or one of the temperature serial development
T_{1t}	inlet temperature of the main flow
T_{Cst}	static inlet temperature of the cooling fluid
$\mathbf{x}$	macroscopic length scale variable
x, y, z	coordinates and components of $\mathbf{x}$
Y	volume of the unit cell
Y_f, Y_s	volume of the fluid or solid part of the unit cell
$\mathbf{y}$	periodic, microscopic length variable
y_1, y_2, y_3	coordinates at microscale
α	channel inclination
β_1	diffusion angles for shaped holes
Γ_{fs}	interface between solid/gas domains
$\varepsilon = \frac{\mathbf{x}}{\mathbf{y}}$	aspect ratio between micro- and macroscale
$\eta_c = \frac{T - T_H}{T_C - T_H}$	cooling effectiveness
χ^λ	microscopic periodic displacement field
Ω_0, Ω_1	structure of kidney vortices in cooling channel or in the main flow
LES	Large Eddy Simulation
PIV	Particle Image Velocimetry

the 3-D conjugate model (see Fig. 1). In Laschet et al. [9] the steady state results of the conjugate calculations of curved plates have been homogenized in order to deduce the effective thermal conductivities and permeabilities of an equivalent porous material. Moreover, in [14] the authors predict for these curved cooled designs firstly the effective thermoelastic properties of each monolayer material and of the multilayer.

Since the blade curvature changes continuously, several blade sections with different curvatures have to be analyzed. Therefore, in the current numerical investigation, the developed multi-scale methodology is applied in order to quantify the influence of the curvature variation along a typical blade slice on its cooling film structures, its cooling effectiveness and on its effective thermal properties. In order to improve upon the previous studies [8,9], the holes are laterally widened now.

Effusion cooling is a boundary layer phenomenon and therefore the main goal of this study is to quantify the effect that the different curvatures have on the cooling effectiveness and on the effective thermal conductivity. This paper outlines numerical results and only gives a brief synthesis of the conjugate heat transfer and fluid flow model and of the implemented multi-scale technique. Besides the flat design, two different curvatures, $R = 180D$ and $R = 240D$ for the concave and $R = 180D$ and $R = 350D$ for the convex plates, are identified along a typical turbine blade slice (see Section 4). For these designs 3-D conjugate analyses are performed for two blowing ratios. After describing the geometry of the designs and the boundary conditions of the 3-D conjugate model, numerical results pertaining the cooling film structure, the temperature distribution and the local cooling effectiveness are discussed for the selected blade sections. In Section 6, the effective thermal conductivities of the multi-layer and each layer are compared for the same flow conditions and the influence of the blowing ratio on these conductivities is depicted.

2. Conjugate fluid flow and heat transfer solver

The numerical scheme of the CHTflow solver is based on an implicit finite volume method combined with a multi-block technique. The physical domain is divided into separate blocks and the full, compressible, 3-D Navier–Stokes equations are solved in the fluid blocks. The governing equations for the conservative variables are formulated in arbitrary, body-fitted coordinates to allow the simulation of complex geometries. For the closure of the conservation equations the algebraic eddy-viscosity turbulence model

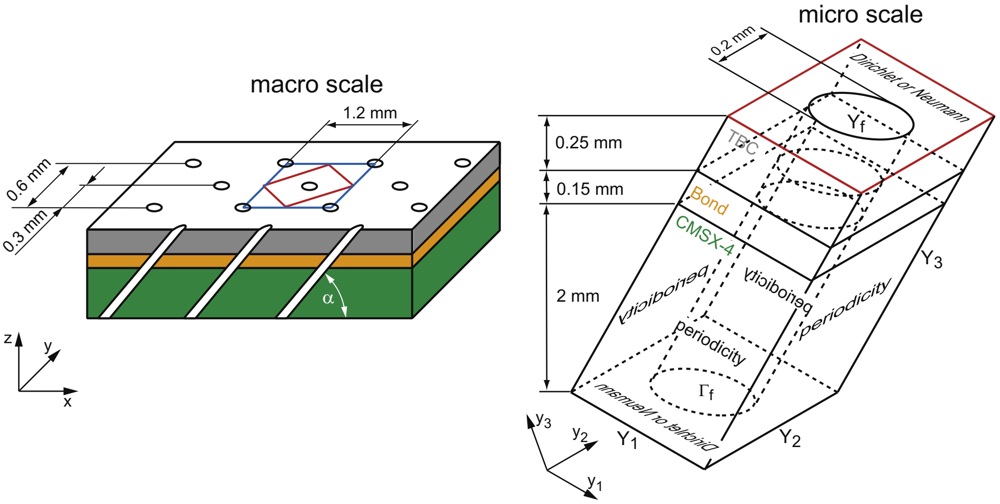

Fig. 1. Definition of a unit cell of periodicity Y_1, Y_2, Y_3 for the cooled multi-layer plate.