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# Experimental assessment of the aero-thermal performance of rib roughened trailing edge cooling channels for gas turbine blades

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## HIGHLIGHTS

- Combined aero-thermal analysis of cooling ducts for gas turbine blade trailing edge.
- Stereo-PIV and LCT experimental investigation.
- Performance comparison of different configurations (smooth and ribbed channels).
- Coupling of peculiar flow features with heat transfer augmentation.
- Assessment of the over-all performances and identification of the best configuration.

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## ABSTRACT

Based on the combined analysis of detailed flow field and heat transfer experimental data, the aero-thermal behaviour of different trailing edge cooling channels is reported.

The reference geometry (G0) is characterized by a trapezoidal cross section of high aspect-ratio, inlet radial flow, and coolant discharge at both model tip and trailing edge, where seven elongated pedestals are also installed. Two variations of the reference geometry have squared ribs installed inside the channel radial central portion (G1) or inside the trailing edge exit region (G2). The forced convection heat transfer coefficient has been measured by means of a steady state Liquid Crystal Thermography (LCT) technique, while reliable and detailed flow measurements have been performed by means of Particle Image Velocimetry (PIV) or Stereo-PIV techniques. The experimental Reynolds number has been fixed at 20,000.

The heat transfer data for the three configurations have been analyzed and compared considering both local and channel-averaged features of the heat transfer fields. In particular, the flow mechanisms responsible for the existence of high or low heat transfer regions have been identified and explained. The effects of the different turbulence promoters on both the flow and heat transfer fields have been put in evidence as well. With the aim to determine the most effective configuration, area averaged heat transfer data have been compared, together with information about the channels pressure losses. Configuration G1 turned out to be the most promising, giving rise to a significant heat transfer enhancement associated to a moderate increase in pressure losses.



## 1. Introduction

Nowadays, gas turbine engines see several applications, ranging from land based power plants to ship and aircraft propulsion. During the last decades, the research conducted on these devices led to the design of engines with the capability to sustain higher and higher combustion temperatures, hence obtaining a significant augmentation of performance and efficiency. These achievements have been possible mainly by the use of novel materials and through the development of more efficient blade cooling techniques.

The modern cooling techniques for high pressure gas turbine blades comprise a combination of internal (forced convention, impingement cooling) and external (film cooling) solutions [1]. Forced convection cooling requires ducts obtained inside the blade during the casting process, where a fraction of the feeding air coming from the compressor flows in to cool the blades with an open loop circuit. Commonly the cooling air is discharged in the expanding mainstream gas through holes at the blade tip, at the trailing edge or through film cooling holes at some specific

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**Nomenclature**

| | |
|---|---|
| AR | $B/H$, channel aspect ratio [−] |
| $B$ | channel width [m] |
| $C$ | mean velocity modulus [m/s] |
| $D_h$ | hydraulic diameter [m] |
| $h$, HCT | heat transfer coefficient, HTC [W/m$^2$K] |
| $H$ | channel height [m] |
| IR | inter rib module |
| Nu | $hD_h/\lambda$, Nusselt number [−] |
| PS | pressure side wall ($z > 0$) |
| $q$ | specific heat flux [W/m$^2$] |
| r.m.s. | root mean square value |
| Re | $U_bD_h/\upsilon$, Reynolds number [−] |
| SS | suction side wall ($z < 0$) |
| TE | trailing edge |
| $x, y, z$ | radial, axial and cross-wise coordinates [m] |
| $x'$ | direction parallel to the redirecting wall [m] |
| $y'$ | direction parallel to the inclined surface of SS at the TE [m] |
| $U, V, W$ | mean velocity components along $x$, $y$, and $z$ directions [m/s] |
| $u', v', w'$ | r.m.s. velocity fluctuations along $x$, $y$, and $z$ directions [m/s] |
| $-<v'w'>$ | Reynolds stress component referred to $V$ and $W$ [m$^2$/s$^2$] |
| $-<u_{\perp R}'v'>$ | Reynolds stress component referred to $U_{\perp R}$ and $W$ [m$^2$/s$^2$] |
| $U_b$ | bulk flow velocity [m/s] |
| // | parallel to |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | incidence angle [deg] |
| $\upsilon$ | kinematic viscosity [m$^2$/s] |
| $\Delta P$ | channel pressure loss [Pa] |
| $\lambda$ | thermal conductivity [W/mK] |
| $\rho$ | density [kg/m$^3$] |
| $\omega$ | vorticity [1/s] |
| $\xi$ | $2\Delta P/\rho U_b^2$, pressure loss coefficient |

*Subscripts*

| | |
|---|---|
| $\perp R$ | rib normal direction |
| fc | forced convection |
| rad | radiative heat transfer rate |
| env | environmental conditions |
| $w$ | surface value |
| ext | lost through external surfaces |

positions on the blade surface. The surfaces of the internal cooling channels are often provided with turbulence promoters [2]: riblets and dimples cause a periodic boundary layer tripping while pin-fins generate horseshoe vortices. These solutions allow to enhance the Heat Transfer Coefficient (HTC) and to increase the total surface involved in the heat transfer process. Unfortunately, the drawback is an increase of the channel pressure drop, hence a trade off between the need of high HTC and the request to keep the pressure drop as lowest as possible must be achieved. A measure of the importance and difficulty in achieving such a task is provided by the results of recent studies that apply complex multi-disciplinary optimization techniques to analyze the conjugate heat transfer problem in simple cooling systems of vane blades. As an example, even if in the work of Verstraete et al. [3] the cooling system is composed of only five straight circular cooling channels, the optimal solution in terms of channels' diameter and position resulted in a considerable increase of blade lifetime coupled with a minimal increase of cooling mass flow. Similarly, in the work of Nowak et al. [4] the determination of the optimal position of five straight channels whose shape could also be varied, resulted in a relevant reduction of maximum material temperature, relative stress, and cooling mass flow.

One of the most challenging issues of blade cooling is to guarantee an adequate thermal protection of the trailing edge (TE) of high pressure turbine blades, where the geometrical constraints are very severe (very thin airfoils) and oblige for the adoption of internal channels with sizes and shapes strongly different with respect to those employed in the other portions of the blade [5] and well documented in literature. A complete review of classical cooling channel configurations (square or rectangular rib-roughened passages, in which the coolant flows along the main blade axis, i.e. along the radial direction, eventually in multiple passages configurations) and the related achievable performances can be found in Ref. [6]. Detailed descriptions of the highly three dimensional behaviour of the flow field and its impact on the thermal performances in ribbed, single pass channels can be found in Ref. [7], where detailed flow velocity measurements are used to define an inter rib model for the averaged flow field. The main features of the latter are than linked to the heat transfer distribution on the channel wall. A similar analysis is performed for a ribbed two pass channel by Ref. [8].

By contrast, a limited number of works consider TE cooling cavities and very few are those where the aero-thermal behaviour is described with combined flow and heat transfer field measurements or numerical simulations. Concerning investigations devoted essentially to the thermal aspects, Choi et al. [9] investigated the thermal field developing in a 3-cavities channel equipped with slot and lands at the TE outlet showing the influence of Reynolds number, blowing ratio, and three different geometric configurations on pressure drop, HTC, and film cooling effectiveness. Experimental investigations inside a channel with trapezoidal cross section and flow ejection at the TE through holes can be found in Ref. [10] where rotational effects on the thermal field were also considered. The analysis has also been extended to geometries provided with pin fins for heat transfer augmentation [11]. However, even if these works provide ready-to-use correlations applicable even to models with complex geometries, it should be noted that the flow patterns hypothesised by the researches to justify the heat transfer performances still need an experimental confirmation. After the forerunner thermal investigation carried out by Taslim et al. [12], Armellini et al. [13] and Coletti et al. [14] provided a complete aero-thermal analysis of a TE ribbed channel arranged with multiple cavities and jet impingement. In these latter works the cooling air from an adjacent passage was impinged on a rib-roughened surface at the Pressure Side (PS) or at the Suction Side (SS) wall via a series of race-track shape openings. Through Particle Image Velocimetry (PIV) measurements these authors obtained a deep insight on the flow, characterized by multiple primary and secondary impingements caused by the mutual arrangement of tilted crossing jets and angled ribs [13]. Liquid Crystal Thermography (LCT) measurements showed the great impact of this complex flow field on the heat transfer coefficient (HTC) distribution, on both channel sides [14]. The same authors provided also a comparison with the numerical predictions obtained by a Reynolds Averaged Navier Stokes simulation, which highlights the difficulties they encountered in achieving accurate numerical solutions of both