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ORIGINAL ARTICLE

Film cooling adiabatic effectiveness measurements of pressure side trailing edge cooling configurations

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Abstract Nowadays total inlet temperature of gas turbine is far above the permissible metal temperature; as a consequence, advanced cooling techniques must be applied to protect from thermal stresses, oxidation and corrosion the components located in the high pressure stages, such as the blade trailing edge. A suitable design of the cooling system for the trailing edge has to cope with geometric constraints and aerodynamic demands; state-of-the-art of cooling concepts often use film cooling on blade pressure side: the air taken from last compressor stages is ejected through discrete holes or slots to provide a cold layer between hot mainstream and the blade surface. With the goal of ensuring a satisfactory lifetime of blades, the design of efficient trailing edge film cooling schemes and, moreover, the possibility to check carefully their behavior, are hence necessary to guarantee an appropriate metal temperature distribution. For this purpose an experimental survey was carried out to investigate the film covering performance of different pressure side trailing edge cooling systems for turbine blades. The experimental test section consists of a scaled-up trailing edge model installed in an open loop suction type test rig. Measurements of adiabatic effectiveness distributions were carried out on three trailing edge cooling system configurations. The baseline geometry is composed by inclined slots separated by elongated pedestals; the second geometry shares the same cutback configuration, with an additional row of circular film cooling holes located upstream; the third model is equipped with three rows of in-line film cooling holes. Experiments have been performed at nearly ambient conditions imposing several blowing ratio values and using carbon dioxide as coolant in order to reproduce a density ratio close to the engine conditions ($DR=1.52$). To extend the validity of the survey a comparison between adiabatic effectiveness

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measurements and a prediction by correlative approach was performed to compare the experimental results with 1D methodologies.

1. Introduction

The engine cycle efficiency is directly linked to the peak temperature of the working fluid, that affect the gas path, currently above the maximum allowable metal temperature. Design of the trailing edge (TE) blade cooling system is nowadays challenging due to the geometric constraints in combination with aerodynamic demands and structural integrity.

For high thermally loaded blades, a combination of internal and external cooling systems are employed at blade trailing edge to guarantee wall temperatures within the limits prescribed by structural integrity. The current state of the art of trailing edge cooling systems often use schemes where cooling air, used to provide an internal convective cooling, is ejected onto the pressure side trough spanwise slots, also called cutback, or film holes. The unsteady interaction between coolant and main flow and its effect on cooling performance are difficult to be predicted; as a consequence, the adiabatic effectiveness distributions on the trailing edge pressure side are generally hard to estimate with sufficient accuracy using classical simplified correlations, which may lead to high overestimation of the cooling rates and, above all, makes difficult the optimization of the cooling system.

In the technical literature several works were presented regarding the characterization of trailing edge cooling devices at blade pressure side. An extensive survey was presented by Holloway et al. [1,2]: they combined both numerical computations and experiments to investigate pressure side bleed on the trailing edge of a turbine blade. The vortex shedding at the slots lip was identified as the key mechanism for the mixing of coolant and hot gas and the major responsible of effectiveness decay for cutback with high lip thickness. A follow-on to their study was conducted by Medic and Durbin [3] who analysed the primary role of natural and forced unsteadiness in trailing edge cooling flows by means of unsteady Reynolds averaged Navier-Stokes (RANS) computations. More recently, further numerical studies on trailing edge cooling performance were carried out by Schneider et al. [4] and Joo and Durbin [5] by employing respectively a large eddy simulation (LES) matched with an existing experimental set-up and an hybrid RANS/LES approach.

Concerning experimental works on film effectiveness at blade trailing edge, a pioneering study was conducted by Taslim et al. [6] testing different slot models varying the exit configuration. The results showed that film effectiveness is mainly affected by slot lip thickness to height ratio, while slot width to height ratio and density ratio represent less sensitive parameters. More recently, Martini et al. [7] evaluated, by means of an infra-red technique, heat transfer coefficients and the film effectiveness of a cutback trailing edge model for different internal cooling arrangements. Results suggested a dominant role of the mixing process generated at the ejection lip on film covering. In continuation of this work the same research group performed deepened investigations [8,9] on the effects of different slot lip geometries. In terms of adiabatic effectiveness, results highlighted a strong dependency on ejection lip thickness, while minor improvements are obtained with a rounded ejection lip profile. Film cooling efficiency on the surface of the pressure side trailing edge area for two TE configurations was determined by Dannhauer [10] using an infra-red thermography technique. Yang and Hu [11] carried out an experimental campaign to measure the adiabatic cooling effectiveness distribution over the protected surface in the breakout region of a turbine blade trailing edge model. Tests were performed by means of the pressure sensitive paint (PSP) technique, and were coupled with detailed flow field measurements in order to optimize design parameters for improved cooling performances.

Several works focused on both the aerodynamic and thermal issues associated with trailing edge cooling. An extensive analysis on two typical TE geometries was conducted by the University of North Dakota [12–15] in a large scale cascade composed by a four vane three full passage arrangement. For a gill slot configuration equipped with a pin fin array, authors found high adiabatic effectiveness levels at the slot exit, however up to 4 cm downstream the injection protection tends to dissipate toward the trailing edge, suggesting an interaction with the shedding. From an aerodynamic perspective, the gill slot produces a total pressure loss, at design and near design flow conditions, rather higher than a solid base reference vane. At design flow, this loss decreases with increasing Reynolds number. In the case of a letterbox trailing edge, obtained adding flow partitions to the previous geometry, film cooling protection is reduced with respect to gill slot. The letterbox configuration has achieved smaller total pressure losses compared with the gill slot. However, the letterbox needs an increased pressure drop for equal ejection flow. Barigozzi et al. [16] investigated a trailing edge cooling configuration featuring a pressure side cutback with film cooling slots and two rows of holes placed upstream of the cutback. Downstream of the cooling holes, the highest adiabatic effectiveness level can be reached for a mass flow ratio equal to 1.2%. Downstream