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ORIGINAL ARTICLE

Numerical investigation on heat transfer in an advanced new leading edge impingement cooling configuration

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Abstract It is known that the leading edge has the most critical heat transfer area of a gas turbine blade. The highest heat transfer rates on the airfoil can always be found on the stagnation region of the leading edge. In order to further improve the gas turbine thermal efficiency the development of more advanced internal cooling configurations at leading edge is very necessary. As the state of the art leading edge cooling configuration a concave channel with multi inline jets has been widely used in most of the blades. However, this kind of configuration also generates strong spent flow, which shifts the impingement off the stagnation point and weakens the impingement heat transfer. In order to solve this problem a new internal cooling configuration using double swirl chambers in gas turbine leading edge has been developed and introduced in this paper. The double swirl chambers cooling (DSC) technology is introduced by the authors and contributes a significant enhancement of heat transfer due to the generation of two anti-rotated swirls. In DSC-cooling, the reattachment of the swirl flows always occurs in the middle of the chamber, which results in a linear impingement effect. Compared with the reference standard impingement cooling configuration this new cooling system provides a much more uniform heat transfer distribution in the chamber axial direction and also provides a much higher heat transfer rate. In this study, the influences of different geometrical parameters e.g. merging ratio of two cylinder channels, the jet inlet hole

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configurations and radius of blunt protuberances in DSC have been investigated numerically. The results show that in the DSC cooling system the jet inlet hole configurations have large influences on the thermal performance. The rectangular inlet holes, especially those with higher aspect ratios, show much better heat transfer enhancement than the round inlet holes. However, as the price for it the total pressure drop is increased. Using blunt protuberances instead of sharp edges in the DSC cooling can improve the heat transfer enhancement and reduce the total pressure drop.

1. Introduction

In order to achieve high process efficiencies during the operation of stationary gas turbines and aero engines, extremely high turbine inlet temperatures at adjusted pressure ratios are applied. The maximum hot gas temperature is limited by the allowable material temperature of the hot path components, in particular the vanes and blades of the turbine. Thus, intensive cooling is required to guarantee an acceptable life span of these components.

A large number of techniques have been developed in recent years to enhance the convective heat transfer ratio for internal cooling of turbine airfoils, e.g. rib turbulators, pin fins, dimpled surfaces, impingement cooing and swirl chambers. According to Ligrani et al. [1,2], the common points of all these techniques are that they all can increase secondary flows and turbulence levels to enhance the mixing of the flows. In all these cooling techniques, jet impingement has the most significant potential to increase the local heat transfer coefficient. It has been widely used in gas turbine blade leading edge area, where extremely high thermal load exists.

Over the past 50 years, numerous experimental and numerical investigations on flow and heat transfer characteristics of impinging jets have been carried out. Several good reviews have been published by Martin [3], Han and Goldstein [4], Zuckerman and Lior [5], which summarized the most important results of investigations on impinging jets before 2006. Baughn and Shimizu [6] and Cooper et al. [7] experimentally studied a single circular turbulent air jet impinging on a flat stationary surface. Lee and Lee [8] experimentally studied the effect of nozzle configuration on heat transfer of a single jet on flat surface. Since the impinging jets have been widely used in a variety of engineering applications with a curved surface like gas turbine blade leading edge, Lee et al. [9] investigated the effect of concave surface curvature on heat transfer of a fully developed round impinging jet in their experiment. Jordan et al. [10] investigated the influences of different jet geometries on impinging jet on a cylindrical concave surface. The measurement results show that the square edge racetrack holes provide the highest stagnation region Nusselt numbers for a given jet mass flow rate. Many of the previous works found in the literature have also dealt with numerical studies on single jet impingement. Abdon and Sunden [11] and Jia et al. [12] numerically investigated single jet impinging on flat and concave surfaces. In both studies the secondary peak of heat flux for impinging on a flat surface with a small nozzle-to-plate distance, which is related to the wall jet boundary layer transition, cannot be predicted. In the numerical study by Ibrahim et al. [13], single jet impinging on flat, concave and convex surfaces and multiple jets impinging on flat surfaces have all been investigated. The results of the calculation with turbulence model V2F showed overall the best agreement with experimental data compared with other turbulence models used for single jet impinging on different surfaces. The second peak for Nu cannot be found using k-ε, k-ω or V2F turbulence models in Reynolds-averaged Navier-Stokes (RANS) calculations. For multiple jets in three rows k-ω turbulence model presents the best agreement with experimental data. For impingement cooling on gas turbine blade leading edge, intensively experimental and numerical investigations have been carried out by Taslim et al. [14,15], Taslim and Khanicheh [16], Elebiay and Taslim [17] and Yang et al. [18].

Facing the challenge of continuously growing turbine inlet temperature, the development of some new cooling configurations that can provide higher heat transfer rates has become necessary. Recently, an alternative internal cooling configuration in the family of swirl chambers named double swirl chambers has been developed by Kusterer et al. [19]. Swirl chamber is a kind of internal flow passage, in which large-scale swirling of the flow circling under most circumstances around the main axis is generated by internal inserts or outlets configurations [1]. The swirl can significantly enhance the heat transfer rate. Double swirl cooling configuration can be generated by merging two swirl chambers. The numerical result by Kusterer et al. [19] showed that this cooling concept presented much higher local and globally averaged heat transfer rate than the values in a standard swirl chamber. The major physical phenomena in the DSC-cooling and the main reason for the improvement of heat transfer are: (1) Heat exchange can be enhanced between the two swirl flows in the shared section of two chambers; (2) Cross effect between two swirl flows can generate a