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Effects of flow incidence on aerothermal performance of transonic blade tip clearance flows

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ABSTRACT

This paper is a continuation of the previous work and aims to understand how the inlet incidence flows influence the transonic tip leakage loss-generation processes and overtip heat-transfer. Five incidences ranged from −15 to 15°, and two tip gaps of 0.4% and 1.0% of blade span are investigated. Numerical calculations have been carried out by means of the ANSYS-CFX calculation tool, using the k-ε SST turbulence model to study the sensitivities of transonic blade tip aerothermal performance to flow incidences in an RT27a linear turbine-cascade. Flow patterns over the transonic blade tip at design incidence, overtip flow fields and aerodynamics sensitivity to flow incidence, and transonic tip heat transfer characteristics at different incidences are investigated. The computed results show a fair agreement with the rig data and show that the effects of flow incidence on aerodynamics and heat transfer in the front part of blade tips are bigger than that in the rear part of blade tips, and flow incidence effects at 0.4% tip gap is smaller than that at 1.0% tip gap. At various incidences, as the tip gap height increases, the shockwave reflections become more obvious, and it hence reduces the leakage flow. However, the large tip clearance height induces elliptical TLV core structure, and leads to strong mixing with the mainflow. For the blade-tip trailing-edge flow regions, at two blade tip gaps the overtip heat transfer decreases normally as the incidence increases.

1. Introduction

Overtip leakage flows in high-pressure turbines lead to significant aerodynamic losses, induce large thermal-loads and lead to great blade tip thermal-stresses. Since the optimal transonic blade tip designs should be low leakage losses, low heat-fluxes and a more “plain” heat-flux contour, it is a major challenge to obtain a great blade tip aerothermal performance for gas turbine designers.

Lots of investigations in the last few decades have been performed for clarifying the tip leakage flow physics in various environments, so as to obtain innovative blade-tip design concepts. Studies in this research field have gone on from empirical model analysis, to linear- or sector-cascades, and to rotating test turbine devices, for various blade-tip structures and tip gap heights. Sjolander [1] showed a review of the overtip clearance flows, and summed up its effects on axial turbine performances. Later on, Bunker [2] gave a concise review, mainly carried out in low-speed cascade-flow environments, about the overall performance of turbine blade tips in a high-pressure transonic turbine flow environment.

The turbine blade rows in a modern gas turbine engine operate at different flow incidences, because of the variations in the rotational speed of rotors and the overall massflow rate. Nonetheless, only a few recent investigations have checked the effects of off-design flow incidence on turbine overtip clearance flows. Yamamoto [3] investigated the mechanisms of three-dimensional (3D) flows and of the induced losses happening near the overtip endwall regions of a linear turbine cascade with different tip clearances and incidences. The results indicated that for three tip gaps, at flow incidences of 0 and 7.2°, both tip leakage and passage vortices have been seen, which rotate in an opposite direction and interact with each other. At flow incidences of −8.3° and even lower, the tip passage vortex (TPV) vanishes. Nonetheless, the variation of the inflow angle varies the blade loading and hence the tip leakage flow driving force (and consequently also of the tip leakage vortex (TLV)). Willinger and Haselbacher [4] proposed a tip leakage loss model that can consider effects of off-design incidences, and the loss model is applicable to the turbine cascade used in this work and to Yamamoto's.

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Having clarified the mechanisms of overtip clearance flows, some turbine blade tip design methods have been put forward to reduce tip leakage influences [5,6] and then to improve the thermal performance of blade tips [7]. Squealer tips that adopt rims are proven to raise the aerothermal performance of turbine blade tips compared with flat tips. With the aim of further improving the overall aerodynamics of turbines and to decrease the blade-tip thermal-loads, winglet tips [8] could be taken into account as an alternative.

To achieve a higher turbine efficiency, the turbine rotational speeds and stage loadings are steadily increased, and therefore the blade overtip clearance flow might pass the transonic flow regime, which suddenly alters the flow physics in the blade tip regions. Since the supersonic tip flows has been indicated by Moore and Tilton [9] in 1988 and then clarified by means of water table experiments [10,11], only few recent investigations revealed the complicated shock wave flow physics. Zhang et al. [12] presented the results of high-temperature stripes induced by the shockwave flows within the tip gaps. Lately, the blockage effects of shockwaves were investigated by Zhang et al. [13,14] and O'Dowd et al. [15]. Wheeler et al. [16] indicated that at high Mach numbers, the pressure-side separation bubble halves the bubble length when the tip suction side Mach number increases from 0.1 to 1.0. In addition, CFD investigations carried out by Wheeler et al. [17] indicated that overtip clearance flows in transonic and subsonic blade rows are different obviously. Arisi et al. [18] investigated computationally the effects of outlet Mach number variation on the overtip heat transfer, and it is increased with increasing exit Mach number. In addition, O'Dowd et al. [19] indicated a decrease in tip clearance height causes decreased clearance leakage velocities within the blade tip regions, causing a reduced tip leakage flow density, and the TLV core further close to the suction side (SS) of turbine blades.

For turbulence influences on the heat transfer of turbine tips, Wheeler and Sandberg [20] and Zhang et al. [21] studied the turbulence intensity influences on the blade-tip heat transfer, and the results indicated that the effect on the blade tip heat transfer depends on the relative magnitude of turbulence intensities. In the meantime, for the impacts of casing relative motion, Zhou [22] and Zhang et al. [13] showed a circumferential viscous shear force produced by the casing motion, which alters the leakage flow structures, therefore altering the heat transfer distributions over a transonic flat tip.

Based on the above research work, tip-surface reshaped design concepts have been put forward to maintain the tip clearance flow passage to be choked, and in the meantime it is fully utilized to reduce the overtip heat transfer. Shyam and Ameri [23] gave a divergence pathway for the overtip leakage flow that may decrease the shock-wave intensity, and therefore alleviate the overtip heat transfer fluctuations. Nowadays, Zhang et al. [24] suggested accelerating the overtip clearance flow locally in the front part of the turbine blade by a convergent-divergent nozzle structure, with the purpose of decreasing the overtip heat transfer. In addition, an optimization strategy has been presented by Maesschalck et al. [25] to obtain several blade-tip airfoils with improved overall performances for lots of tip clearance flow velocities. The numerical results showed that the blade tip structures that present superior in subsonic tip flows are not optimal for supersonic tip flows. They also indicated that turbine designers can try to reduce the adverse influences of transonic blade tip clearance flows with operation at tight tip gaps (Maesschalck et al. [26]). Gao et al. [27] computationally investigated the sensitivity of transonic blade tip aerothermal performance to tip gap heights in a linear turbine cascade. The results indicated that the increased tip gap height delays the shockwave reflection but it is more obvious, which hence causes decreased leakage flowrate and blade-tip rear part thermal-loads. In addition, the blade tip aerothermal performance changes with tip gap heights has opposite trends in the different parts of blade tips, and the impact of tip gap heights on the former is slight.

Additionally, several investigations for squealer tips were performed at relatively high Mach numbers. Hofer and Arts [28] carried out a test investigation of the overtip leakage flows for squealer tips by means of oil flows and wall pressure measurements. The squealer tip obviously decreases the leakage jet velocity, which is not so sensitive to Reynolds number variations as the flat tip. Li et al. [29] numerically studied the clearance flow for a cavity tip design for high-pressure turbine blades, and the results showed that even with choked clearance flows the squealer blade tip design shows good performance. Additionally, the computational results of Wheeler's [30] indicated that the coolant injection as usual has the capacity of decreasing the leakage losses.

Generally, the turbine rotor blade rows are devised to obtain the optimum power extraction and blade tip aerothermal performance at engine-representative flow conditions. Nonetheless, frequently gas turbines work outside the design conditions that may cause unexpected rotor blade failures. So, it is important that the effects of off-design conditions should be fully clarified to reduce the danger of failure and then to maximize turbine blade-tip aerothermal performances. As analyzed above, off-design flow incidences happen when a gas turbine engine operates at conditions that are different from the design condition, and it therefore affects transonic overtip leakage flows and then blade tip aerothermal performances. However, to the authors' knowledge, only a few investigations concerning the effects of flow incidence on transonic blade tip clearance flow mechanism and its impact on the loss mechanisms and overtip heat transfer exist.

Based on the previous research work, the current work aims to clarify the transonic tip clearance flow mechanisms at various incidences. 3D computational methods were adopted to study the sensitivities of transonic blade tip aerothermal performance to flow incidences in an RT27a linear turbine cascade. Five incidences ranged from -15 to 15°, and two tip gaps of 0.4% and 1.0% span are investigated. Flow patterns over the transonic blade tip at the design incidence, overtip leakage flow fields and aerodynamics sensitivity to flow incidence, as well as the heat transfer characteristics of blade tips at different incidences are shown and discussed in the current paper.

2. Numerical methods and verification

2.1. Flow solver

The ANSYS CFX 14.5 software is adopted for the current numerical calculations, and solutions are performed by solving the Reynolds-averaged N-S (RANS) equations in conjunction with a finite volume method. The overall accuracy is of second order. Since the transonic tip clearance flow is as insensitive to the computational modeling as in subsonic blade tip flows (Wheeler et al. [16]), the two-equation SST turbulence model based on Wilcox k-ω model [31] is adopted, and no "wall function" is used in current investigations. In the meantime, the CFX "Gamma-Theta" transition model [32] is employed to model the turbine blade suction side flow transition.

2.2. Geometric model, grids and boundary conditions

A representative profile of high pressure turbine blades has been