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Research Paper

Computational investigation of heat load and secondary flows near tip region in a transonic turbine rotor with moving shroud

Zakaria Mansouri[a,*], Abdelhakim Settar[b], Hamza Khamane[c]

[a] Institut de Combustion Aérothermique Réactivité et Environnement, UPR3021-CNRS, 1C Avenue de la Recherche Scientifique, 45071 Orléans Cedex 2, France
[b] Institut Interdisciplinaire Carnot de Bourgogne, UMR 6303 CNRS, UTBM, site de Sévenans, Cedex, 90010 Belfort, France
[c] Laboratoire Aéro-Hydrodynamique Navale, Faculté de Génie Mécanique, Université des Sciences et de la Technologie, B.P 1505 El-Mnaouar Oran, Algeria

HIGHLIGHTS

- The effect of shroud motion on the aerothermal properties onto turbine blade tip is investigated.
- 3D numerical simulations using CFD code are done.
- Good agreement between numerical and experimental results.
- Important physical insights of transonic blade tip flow mechanisms are reported.
- Overall aerothermal performances of the blade with and without movement are clarified.

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ABSTRACT

The purpose of this paper is to investigate numerically the effect of the relative shroud motion on both the heat transfer and secondary flows near the tip of a transonic turbine blade. The simulations are done by solving the compressible Reynolds averaged Navier–Stokes (RANS) equations using the finite volume method implemented in the Fluent CFD software. The investigated rotor blade geometry was designed by SNECMA for modern aero-engines. The computational grid is created using multi-block topology and each block support a structured mesh. Calculations are done under a transonic flow regime for both stationary and moving shroud cases. The aero-thermal properties and flow topology at the blade tip, the shroud and the blade suction surface are compared with and without shroud movement. The relative motion has significantly changed the distribution and the level of the heat transfer coefficient, the pressure coefficient, the isentropic Mach number and the flow topology.

1. Introduction

In modern gas turbines, the first stages of the high-pressure turbine face simultaneous challenges related to the aerodynamics, heat transfer, and material capabilities. This is due to the recent trend of increased combustion temperatures to achieve higher thermal efficiency and higher power output. In shroudless axial flow turbines, there is undoubtedly a gap between the rotor tip and the adjacent casing (stationary shroud). This gap (clearance) allows the fluid to flow from the pressure side to the suction one of the rotor's blade, owing to the pressure difference. The over tip flow accelerates through the clearance and exits on the suction side where it mixes with oncoming passage flow as it rolls up into the tip leakage vortex (TLV). This tip leakage flow is responsible of high thermal loading and aerodynamic losses near the tip region. The tip loss is the most significant loss associated with the rotor, which on average accounts for 30% of the total stage loss. Also, it represents about 4% of stage efficiency, which is a very large amount [1]. This explains why the rotors are one of the most often inspected parts of the turbine, and the tip is the most inspected and repaired part of the rotor.

In current experiments on turbine rotor tip, many strategies for reducing the experimental costs and efforts are based on using stationary experiments. Dong-Ho and Hyung [2] investigated the effect of vane/blade relative position on heat transfer at the tip and shroud in a stationary turbine blade. They used a single stage stationary annular turbine cascade made up of sixteen guide plates and sixteen blades. They reported that different blade positions result in different heat/mass patterns at both the tip and shroud. The relative position of the blade changes the incoming flow condition significantly because the opening area varies with the relative position. Therefore, the heat/mass

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* Corresponding author at: ICARE CNRS-UPR3021, 1C, Avenue de la Recherche Scientifique, 45071 Orléans Cedex 2, France.
E-mail address: zakaria.mansouri@cnrs-orleans.fr (Z. Mansouri).

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transfer pattern is significantly varied, especially at the tip where the variation reaches up to ± 25% of the average value. In a second study, Dong-Ho and Hyung [3] investigated the blade position effect on heat transfer at the blade surface. They used the same earlier experimental facilities. They reported that the heat/mass transfer characteristics on the blade surface are affected strongly by the local flow characteristics, such as laminarization after flow acceleration, flow transition, separation bubble and tip leakage flow. The change in blade position, which causes a different interaction between vane and blade, changes significantly the heat/mass transfer patterns on the blade surface, especially near the blade tip.

The stationary turbine rotor experiments are much simpler than rotational experiments. They argue this by the heat transfer at the blade tip, which is not significantly affected by rotation. Since most of the experiments are stationary, this fact alters most of computational investigations which are necessarily dealing with stationary configurations. In an early study, Mayle and Metzger [4] examined the effect of a rotating shroud on heat transfer in rectangular profiled stationary tip model. The shroud was a motor-driven rotating disk. They found that heat transfer at the blade tip was not significantly affected by rotation, over a range of parameters tested. Metzger et al. [5] studied experimentally and numerically the heat transfer on flat and grooved blade tips while introducing a moving shroud surface. Their results show that, within the range of parameters considered, heat transfer characteristics on the tip are virtually unaffected by the shroud movement. Srinivasan and Goldstein [6] explored experimentally the effect of shroud motion on the heat transfer around a flat tip blade at different tip clearances. They used a moving belt as a shroud made of neoprene mounted on the top of the wind tunnel. The authors proved that for a small tip gap there is a small global reduction of the heat transfer. The authors also noticed that for high gaps there is no measurable effect of the moving belt. Bunker [7] confirmed also the neglected effect of the moving shroud on the tip heat transfer.

Given the above research studies, the relative motion effect of the shroud on the aerodynamic behavior of the tip leakage flow is not considered. The authors used the argument that tip leakage flow is governed by the pressure difference of the blade surfaces to justify theirs studies. This could be true for some specific cases related to some specific operating conditions (e.g., low speed) and rotor geometries. However, the secondary flows generated from tip leakage flows are governed by both the pressure difference and shroud motion/rotation. Yaras et al. [8] studied the effects of the shroud relative motion on the tip leakage flow of low turning angle turbine cascade. They employed a motor-driven belt with thin blades. The moving shroud has led to decrease the pressure difference across the tip gap. It strengthened and drew the passage vortex (PV) toward the gap flow outlet at the suction side. Consequently, a throttling effect on the leakage flow took place, which resulted in a 50% reduction of the mass flow rate through the gap. Krishnababu et al. [9] performed a numerical study to investigate the effect of shroud motion on the tip leakage flow and heat transfer in unshrouded turbine cascade. They observed the same effect as Yaras et al. [8] for the moving shroud and related it to decreasing pressure differences and driving the PV. In addition, the effect of the relative motion was to decrease the average heat transfer to the tip due to the decrease in leakage flow velocity caused by the drop of driving pressure difference. Palafox et al. [10] investigated the effects of moving shroud on tip leakage and secondary flow fields on a low-speed turbine blade. They used PIV experimental technique for velocity measurements. They found a separation bubble at the tip and the moving shroud had a clear influence on its shape and size. In addition, they reported that the relative blade shroud motion had a significant effect on both the TLV and the PV. The moving shroud distorted the TLV and moved both vortices closer to the suction surface. Virdi et al. [11] combined experimental measurements and numerical computations to investigate the aerothermal performance of turbine blade tips with relative shroud movement effects. High-speed linear cascade is used with two blade-tip configurations (squealer and flat) and three tip-gaps (0.5%, 1% and 1.5%). Validation shows a good agreement among the CFD computations and the experimental measurements for the stationary case. Supplementary CFD analyses are done to examine the effects of relative shroud motion. The results show that the relative movement affects considerably the detailed near-tip aerothermal field. In addition, as the tip gap reduces, there is a reduction of heat transfer and the highest heat load is localized near the trailing edge.

Very few studies have investigated the effect of relative motion on the shroud wall itself. Chana and Jones [12] investigated experimentally the heat transfer behavior and the static pressure distribution on the rotor tip and shroud wall of a gas turbine stage. They found that the shroud was shown to suffer the highest heat transfer compared to the rotor tip, where its rate was seen above the pressure side of the blade. Thorpe et al. [13] reported measurements of time-mean heat transfer and time-mean static pressure on the shroud of a transonic axial flow turbine operating at engine representative flow conditions. They found that the heat transfer rate and the adiabatic wall temperature of the shroud are strongly varied with the axial chord through the turbine rotor. The highest heat load on the shroud was seen above the leading edge of the rotor. In addition, the shroud static pressure measurements follow the trends of the thermal load, with maximum values at once above the rotor leading edge.

After a literature survey, many studies have tried to investigate the relative shroud movement effects on the aerothermal performance of turbine blade tips. Most of these studies was performed under low-speed conditions. Nevertheless, there are no studies that combine both heat transfer and secondary flows under the shroud movement effects at high speed conditions. Basing on the above literature review, contributions of the present work can be listed as follow:

(a) 3D simulations are performed with aero-engine representative flow conditions (transonic flow regime) to better understand the aerothermal characteristics compared to the low-speed (subsonic flow regime) studies [2–10].
(b) Heat transfer and secondary flows are investigated simultaneously with comparisons between stationary and moving shroud cases, to strengthen the understanding of the coupling of these two phenomena. Unlike previous studies where secondary flows [8,10] and heat transfer [12,13] are studied separately.
(c) The aerothermal characteristics of the transonic flow are investigated at the blade tip, the shroud and the blade suction surface, to cover all blade regions sensitive to the shroud movement. This gives better insight compared to the studies focusing on only one or two regions [2,3,11]

2. Cascade geometry, mesh and numerical details

Fig. 1a displays the investigated rotor cascade geometry. The rotor was designed by SNECMA for modern aero-engines [14–16]. It is characterized by a high turning angle of 119°, an axial chord of 35.906 mm, a stager angle of 58.38° and a pitch of 0.7607. The 2D airfoil of this rotor has been a subject of several experimental and numerical tests by Arts et al. [17]. They performed the investigations over ranges of exit isentropic Mach number (from 0.79 to 1.3), inlet turbulence intensity (from 1% to 6%) and inlet incidence angle (from −14° to 11°). After a detailed analysis of their results, they decided to set the nominal incidence angle at −5°. It was due to the position of the stagnation point, where an arrangement of cooling holes will be placed later in the same position. In the present study, 3D simulations are performed at the same nominal incidence angle with aero-engine representative flow conditions, as shown in Table 1. Note that the considered total-to-static pressure and the gas-to-wall temperature ratios are those of a real turbine environment [18]. Furthermore, a flat rotor tip geometry is considered with a clearance between the rotor tip and the shroud equal to 1% of the rotor height (H). In terms of the linear