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AEROTHERMAL SIMULATION OF THE EFFECT OF HOT-STREAK AND RESIDUAL SWIRL ON A HIGH PRESSURE TURBINE STAGE

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ABSTRACT

In new generation aero-engines, lean-burn combustors are equipped with swirl injectors in order to reduce pollutant emissions. At the exit of these combustors, the flow is dominated by temperature non-uniformity (hot-streak) and residual swirl. Available research has focused mainly on the isolated effects of the residual swirl only or the hot-streak only on the aerodynamic performance or thermal performance of the high-pressure turbine (HPT). Only few studies investigated the combined swirl and hot-streak on the aerothermal performance of the HPT using either idealized uniform or rounded hot-streak topologies. The present study investigates the effects of residual swirl and distorted hot-streak simultaneously on a first stage of a HPT. Other hot-streak types, uniform and rounded, have been also investigated with and without swirl to perform comparisons with the distorted hot-streak. Unsteady Reynolds-averaged Navier–Stokes (URANS) computations have been conducted to assess the aerothermal performance of a HPT under the influence of different hot-streaks. Results revealed that all hot-streaks without swirl were almost preserved as transported through the vane and altered as transported through the rotor due to the secondary flows. Under the residual swirl, all hot-streaks were remarkably altered at the vane exit and deformed more at the rotor exit. The uniform hot-streak was homogenised through the rotor and the rounded and distorted hot-streaks were dispersed. The distorted hot-streak showed the most complex transport behaviour through the stage. Results also revealed that the leakage flow through the rotor tip gap generated high heat transfer rates, in particular on the rotor blade suction side and tip surface.

1. INTRODUCTION

The new generation of aero-engines operate under a lean-burn combustion regime in order to reduce emissions threatening the environment (i.e. CO_2 and NOx). Lean-burn combustors generate highly swirled flows to attenuate combustion peak temperatures by enhancing the fuel-air mixing. The hot swirling flow attenuates as it propagates through the combustor and interacts with the coolant air from the combustor liner. However, a residual swirl persists at the turbine inlet and it features non-uniform temperature profile (hot-streak) that impacts the turbine aerothermal performance. The isolated effects of the residual swirl only, or the hot-streak only on the aerothermal performance of high-pressure turbines (HPT), are well studied in the literature, on either non-rotating vanes or rotating turbine stages [1-4]. In an early study, Shih and Lin [1] reported a computational investigation on a turbine vane that features a leading edge (LE) fillet with a modified shape under both inlet axial flow and residual swirl conditions. They mentioned that the modified LE fillet under inlet swirl can deliver both lower aerodynamic loss and heat transfer rate. The heat transfer coefficient was decreased by more than 30% on the endwalls and by more than 10% on the vane surface, with respect to the axial flow case. Qureshi et al. [2] carried out a combined detailed experimental and numerical investigations of the impact of aggressive residual swirl on both the aerodynamic and thermal characteristics of the stator vane of the MT1 turbine. A combustor swirl simulator was designed for this purpose. It was found that the residual swirl remarkably altered the endwall flow structures and vane aerodynamic load. The boundary layer exhibited streamline redistributions, where they were dissipated in certain regions and converged in other regions. Povey et al. [3] experimentally measured the heat transfer variation at the mid span (50%) of a HPT uncooled vane as well as on endwalls under hot-streak and uniform temperature. The clocking position of the hot-streak was also investigated. They reported that the vane facing a hot-streak has

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higher heat transfer rate on its suction side (SS) compared to the vane facing a uniform inlet temperature. Very recently Mansouri [4] performed an unsteady computational investigation on a HPT stage to examine the interaction between three different hot-streak maps and secondary structures from the rotor blades. Two simplified hot-streaks (radial and circular) from the literature and one distorted hot-streak at aero-engine representative conditions were evaluated. It was revealed that the hot-streak migration and its impingement onto the vane and rotor blades differed from one hot-streak map to another. The rotor secondary flows generated corrugated and wavy shapes on the temperature gradients, in particular near the hub and shroud.

During the last few years, the effects of the residual swirl and hot-streak simultaneously on HPT vane aerothermodynamics has gained a particular attention. Many studies are now available in the literature [5-7]. However, works on combined residual swirl and hot-streak effects on rotating HPTs are rare in the literature [8-11]. Griffini et al. [5] performed a CFD investigation on the impact of combustor exit flow representative of aero-engine conditions on a film cooled HPT vane. They found that the case where the residual swirl is aligned with the vane LE had the harshest characteristics. This case presented high heat transfer rates accompanied with increased local and averaged surface temperature on both the vane SS and pressure side (PS) compared to the passage aligned swirl. The more recent numerical study by Mansouri [7] on the impact of three different distorted hot-streaks at engine representative conditions on a HPT vane was carried out under axial and swirl flow conditions. The results showed significant differences in the aerothermal field on the vane cascade under each distorted hot-streak. The presence of swirl induced aerothermal mixing and resulted in an increase of the heat transfer rate. Khanal et al. [8] reported a numerical study on the MT1 turbine to examine its aerothermal behaviour under combined swirl and hot-streak. They found a distinctive radial transport of the hot-streak across the vane and rotor passages with strong impact on the turbine performance. Very recently Adams et al. [11] conducted the first joined experimental and numerical investigation on the impact of combined realistic hot-streak and swirl on film-cooled turbine. They conducted the experimental measurements on the new generation aero-engine research turbine called LEMCOTEC. Both measurements and computations suggested that the hot-streak was relatively well preserved after crossing the turbine stage. The combined swirl and hot-streak induced changes in the rotor aerodynamics by causing local attenuations in blade loading near the hub and a reduction in tip leakage flow losses were decreased.

With the very remarkable advances in the present subject made through the investigations mentioned above and many others available in the literature, all investigated hot-streak shapes in rotating HPT stages were ideal, either circular [8, 9] or elliptical [10]. To date, there is only the very recent study by Adams et al. [11] that investigated the impact of representative aero-engine combustor exit conditions on a rotating HPT. Thus, the present investigation is mainly motivated by the need to further understand and examine the effects of aero-engine combustor exit conditions on the rotating blades of HPTs. This investigation presents the first computational study that compares and highlights the difference between the effects of lean burn combustor hot-streak and ideal hot-streaks from the literature under swirl conditions on the aerothermodynamics of a rotating HPT. To this purpose, numerical simulations using unsteady Reynolds-averaged Navier–Stokes (URANS) have been carried out on three hot-streak topologies (radial, rounded and distorted) under axial and swirl inlet flow conditions. Results of the different cases are compared and discussed.

2. TURBINE STAGE AND NUMERICAL METHOD

The configuration investigated in the present study is a first stage HPT uncooled model representative of a turbofan turbine composed of 36 NGVs and 70 rotor blades. A single passage geometry composed of one NGV and two rotor blades is shown in Figure 1(a). The NGV has an axial chord length of 38.23 mm, a height of 38.1 mm and an outflow angle of 67°. The rotor blade is a model similar to a turbofan HPT stage. At the mid-span, the rotor features a high turning angle of around 120° and an axial chord length of 29.46 mm. To investigate the effects of combined swirl and hot-streaks, three different hot-streak topologies were specified at the turbine inlet, which are “Radial”, “Rounded” and “Distorted” as shown in Figures 1(b-d), respectively. The residual swirl distribution used along with the hot-streaks is shown in Figure 1(e), it rotates in the clockwise direction. Circumferentially averaged radial profiles of the temperature ratio of each hot-streak are also plotted in Figure 1(f). The computational grid used in the present study is fully structured and was generated using ANSYS-TurboGrid. The stage has 4.68 million grid points that were selected after a detailed grid convergence study and validation with experimental measurements that can be found in our previous works [4, 7, 12]. Unsteady time accurate computations of the turbine stage were conducted using ANSYS-CFX. The turbulence was modelled using the well-established k-ω SST model with Gamma-Theta transition formulation. The transient rotor-stator technique is used at the interface of the stationary and rotational domains. The simulated exit isentropic Mach number is 1.013 and the rotational speed of the rotor blades is 7000 rpm. The rest of the used numerical parameters and boundary conditions can be found in [4].

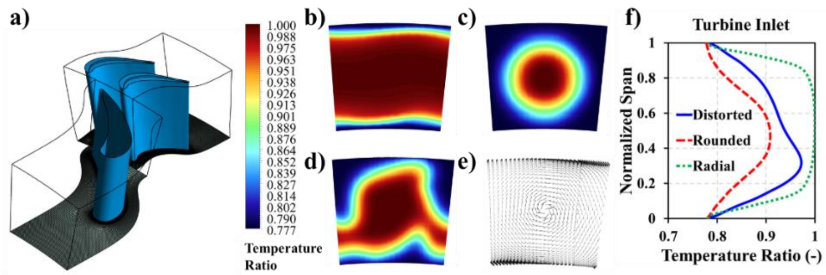

Figure 1: (a) single passage domain of the HPT, (b) radial hot-streak, (c) rounded hot-streak, (d) distorted hot-streak, (e) residual swirl and (f) hot-streak radial profiles.

3. RESULTS AND DISCUSSIONS

3.1. Hot-streak transport

Figure 2(a) shows the radial profiles of static temperature ratio at the rotor inlet (NGV outlet), with uniform (no swirl) and swirl inlet conditions for each hot-streak case. With uniform flow conditions, all profiles keep their initial radial distributions (from the turbine inlet) with maximum values at around 30% span, 50% span and 30-70% span for the “Distorted”, “Rounded” and “Radial” cases, respectively. However, a reduction in temperature between turbine inlet and rotor inlet is found as expected and this is due to the compressibility effects as the flow crosses the vane passage since as the Mach number increases and the static temperature decreases. With inlet swirl condition, temperature profiles of all the hot-streak cases exhibit almost the same flattened distribution. The introduction of swirl enhances the aerothermal mixing and reduces the levels of temperature peaks. Figure 2(b) presents the same profiles at the rotor outlet. The profiles of the uniform flow condition are redistributed again after traveling through the rotor passages. This redistribution is mainly caused by the interaction with secondary flows (i.e. tip leakage and passage vortices). With inlet swirl condition, temperature profiles of all hot-streak cases kept almost flattened distributions, since the effects of swirl mixing persist within the rotor passage and may be also intensified by the secondary flows.

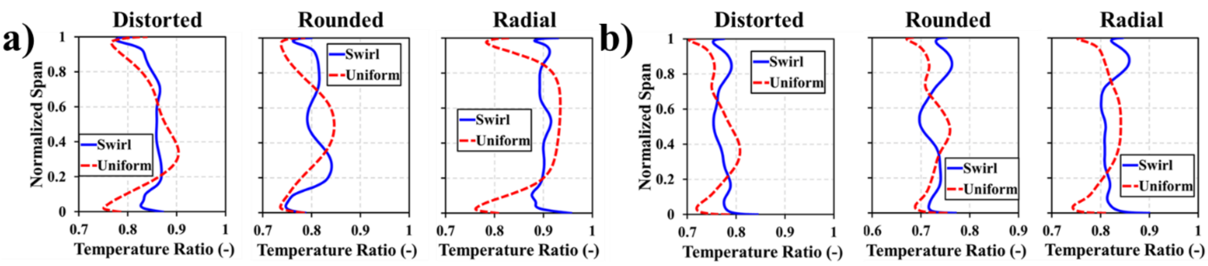

Figure 2: Radial profiles of the circumferentially averaged static temperature for the different investigated hot-streaks under uniform and swirl conditions: (a) profiles at rotor inlet and (b) profiles at rotor exit.

3.2. Rotor surface temperature

Figure 3 shows surface temperature distributions on one rotor blade at the tip and SS. With uniform conditions (Figure 3(a)), the temperature map from each hot-streak is transported axially as expected, where the highest temperature levels are located around the mid span region. The effects of the secondary flow vortices are clearly visible on the SS as the dashed line shows for the “Radial” case. The vortices cool down the near hub and tip regions on the SS since they radially transport the cool air from the endwall regions. The “Radial” case has the largest hot surface temperature zone, followed by the “Distorted” case and next the “Rounded” case. On the tip, the LE region has the lowest temperature compared to the mid chord region and this suggests that the leakage flow transports the cold flow from the shroud towards the LE and the hot flow from the passage towards the mid chord region. As the inlet swirl is introduced (Figure 3(b)), a complex change in the rotor thermal loading takes place. The effects of the secondary flows are attenuated and the temperature distribution on the blade surfaces does not reflect any more the initial temperature non-uniformity imposed on the turbine inlet. The “Radial” case has almost a uniform surface temperature distribution of low levels compared to the uniform case due to flow mixing, except a cold spot near the hub of the SS. In the “Rounded” and “Distorted” cases, the hot-streak is no longer printed on the mid span region but it is spread almost all over the span near the trailing edge region. On the tip surface, the mid chord region suffers from higher temperature levels compared to the uniform case due to the radial transport of the hot-streak. It can be said that the swirl has a significant impact on modifying the hot-streak distribution and simplified hot-streaks should not be used to represent engine operating condition. The “Radial” case generates excess of high temperatures and the “Rounded” case a simpler predicted temperature distribution.

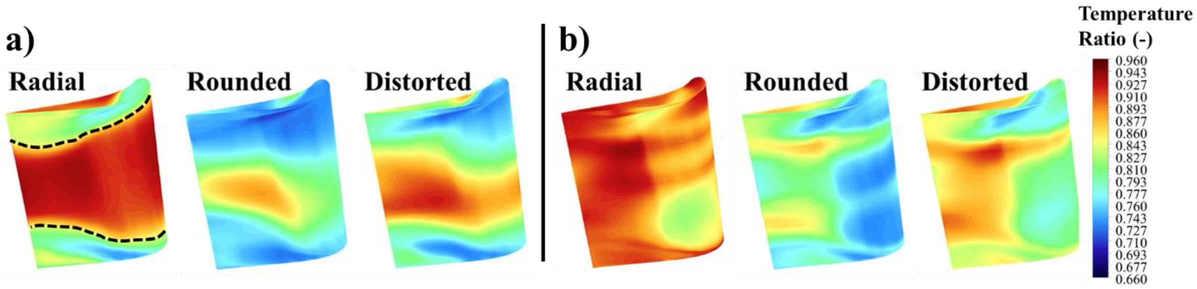

Figure 3: Surface temperature of the rotor blade tip and suction side for all the investigated hot-streaks: (a) with uniform inlet flow and (b) with inlet swirl condition.

3.3. Rotor surface heat transfer

Figure 4 shows heat transfer coefficient distributions on the first rotor blade surface at the tip and SS regions. It can be seen that the highest HTC regions are on the tip surface and rotor blade SS near the tip for all the investigated hot-streaks. This is obvious due to the leakage flow when it crosses the tip gap region and then forms the LV. To explain this interesting thermal behaviour, it is better to recall the definition of the HTC in the near wall region as:

$$HTC = \frac{\rho c_p v^*}{T^+} \tag{1}$$

where ρ is the density of the air, c_p is the heat capacity of the air, $v*$ is the velocity scale in the logarithmic part of the boundary layer and T^+ is a normalized temperature near the wall. The velocity scale is calculated based on the turbulent model constant (C_μ) and turbulence kinetic energy (k). The normalized temperature is calculated based on the Prandtl number (Pr) and dimensionless near wall grid distance (y^*). Thus, the upper term can be considered as a viscous term and the lower term as a thermal term. Hence, the leakage flow when it passes through the tip gap it generates high shear tress due to the tight space and high flow speed. The shear tress (τ) is proportional to the turbulence kinetic energy and it is known that higher τ leads to higher k. Consequently, the significant local rise of k impacts directly the viscous term to be much more significant than the thermal term and then the HTC increases. Regarding the effect of residual swirl, it can be seen that it contributes to the increase of the HTC on the rotor SS (red dashed line in Figure 4(b)) as expected. The flow rotation induces higher shear stress and this intensifies the LVs to have more kinetic energy and as a result higher HTC. Furthermore, the HTC near the hub is about 2.5 orders of magnitude lower than the HTC near the tip. This indicates that the hub secondary flow (i.e. passage vortex) has less turbulent kinetic energy that produces lower HTC.

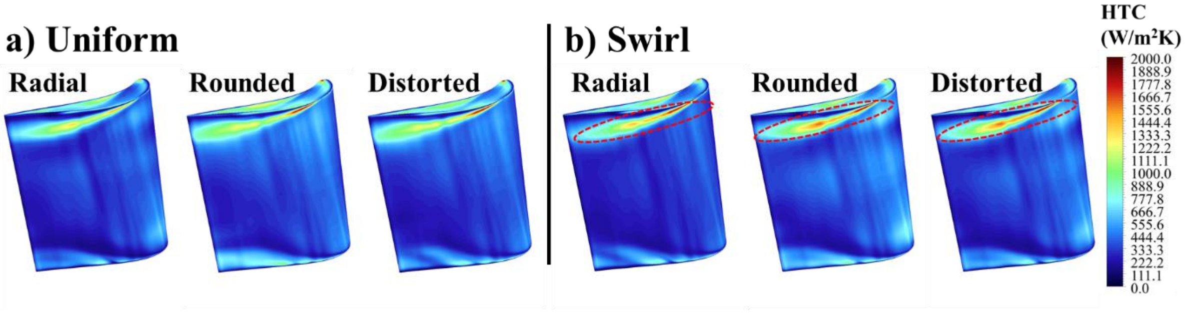

Figure 4: Surface heat transfer coefficient of the rotor blade tip and SS for all the investigated hot-streaks: (a) with uniform inlet flow and (b) with inlet swirl condition.

To provide an insightful qualitative analysis of the thermal characteristic near the rotor tip region, the profiles of HTC at 90% blade span are plotted in Figure 5. Negative values of the normalized axial chord distance (C_{ax}) indicate the blade PS and positive values of C_{ax} indicate the blade SS. In general, the HTC distribution at this location has almost the same trend for all the cases. It is important to note that the investigated rotor blade is a subject of boundary layer transition at both the SS and PS as reported in [4]. Boundary layer transition on the PS happens when the stagnating flow on the LE reaccelerates again and the highly cambered shape of the PS causes an over-acceleration that forms a laminar recirculation bubble across the whole span. At this location, HTC reaches its lowest values of around 59 ±6 W/m^2. Downstream the mid-chord region (C_{ax}< -0.5), the boundary layer is fully turbulent and the HTC increases progressively till its maximum value of around 669 ±26 W/m^2 at C_{ax}=-0.88 for all the cases. At the SS, the blade exhibits another boundary layer transition and this time is due to the presence of a shock that induces a separation and re-attachment of the boundary layer after forming a laminar bubble. This strong interaction reduces significantly the HTC, for example, for the “Radial” case at uniform flow the HTC decreased from 491 W/m^2 at C_{ax}=0.4 to 403 W/m^2 at C_{ax}=0.53. Downstream of the shock region (C_{ax} ~ 0.5), the boundary layer is subjected to relaxation and reacceleration to be fully turbulent and it interacts with the LV to generate higher heat transfer rates. Moreover, the introduction of the residual swirl intensifies the heat transfer on the SS region for all the hot-streaks. For example, the HTC peak around the location C_{ax}=0.75 is increased by 22.43% and 19.3% for the “Rounded” and “Distorted” cases, respectively with regard to the non-swirl condition.

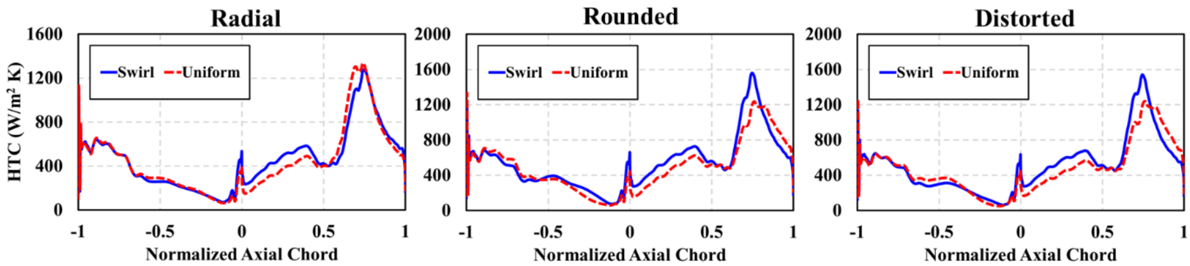

Figure 5: Surface heat transfer coefficient of the rotor blade tip and SS for all the investigated hot-streaks: (a) with uniform inlet flow and (b) with inlet swirl condition.

4. CONCLUSIONS

A high-pressure turbine stage has been evaluated using unsteady computations under combined residual swirl and three hot-streak topologies. Two of the hot-streaks are widely used in the literature with radial and rounded distributions respectively and the third type replicates engine representative conditions with a distorted distribution. Results revealed that all hot-streaks without swirl were almost preserved as transported through the vane and altered as transported through the rotor due to the secondary flows. Under the residual swirl, all hot-streaks were remarkably altered at the vane exit and deformed more at the rotor exit. The rotor blade surface temperature was highly affected by the hot-streak type and flow inlet conditions. Under "Radial" hot-streak, the whole rotor surfaces suffered from high levels of temperature because of the simplified topology of the hot-streak that contains 80% by surface of hot fluid. Under "Rounded" and "Distorted" hot-streaks with uniform flow, the rotor faced high levels of temperature around the mid span regions. When the inlet swirl is combined with the "Rounded" and "Distorted" hot-streak, the mid span regions no longer suffer from very hot temperatures but the hot-streaks are spread almost all over the span near the rotor trailing edge. Results of surface heat transfer coefficient on the rotor blades revealed that the tip surface and SS near tip region suffer from the highest heat transfer rates. It was found that the leakage flow induces high shear stress that contributes to intensifying the highest heat transfer rate around the tip region. The residual swirl was found to intensify the leakage flow and, in particular the leakage vortex and hence, the heat transfer rate increases around the tip region. As a general conclusion, the results of the present study revealed that over-simplified hot-streak topologies similar to the "Radial" case generate non-realistic thermal behaviour with an excess of high temperature levels. A "Rounded" topology could be an alternative to the previous case to overcome the excess of high temperature levels. However, its simplified circular shape may not provide the full picture of the complex thermal behaviour of a turbine stage. The "Distorted" hot-streak was found to generate a complex thermal behaviour through the turbine stage.

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