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Analysis of swirling flow effects on the characteristics of unsteady hot-streak migration

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Abstract The temperature of flow at the combustor exit is inherently non-uniform and the hot fluid is called hot-streak. An in-house CFD software, NUAA-Turbo, was used to carry out 3D unsteady simulations on the PW-E^3 single-stage high-pressure turbine. The hot-streak effect based on real stator and combustor counts was approximately evaluated by the contraction/dilatation method on the interface. The unsteady attenuation and migration process of hot-streaks in the turbine passage were well captured. The general performance parameters for different circumferential positions of hot-streaks were relatively consistent. Then, the influences of hot-streaks on blade surface temperature were investigated by comparing results under hot-streak and uniform inflow conditions. Unsteady simulations with combined inlet hot-streak and swirling flow show that the core of a hot-streak migrates to the tip under the influence of a positive swirl, while the phenomenon is just opposite with a negative swirl. Therefore, the heat transfer environment of rotor blades shows great differences with different directions of inlet swirl.

1. Introduction

In an attempt to increase the engine performance, it is common nowadays for a combustor to be designed with a concept of high exit temperature and relatively low end walls temperature for cooling needed. Therefore, there exists an apparent temperature non-uniformity region at the combustor outlet, and the local hot fluid is called hot-streak. For the improvement of combustion performance, the swirl design method is adopted to enhance the fuel-air mixing and to aid the flame stability, which leads to the inlet velocity distortion. Hence, an incoming flow consisting of both hot-streak and swirl at the turbine inlet will affect its performance accordingly. In view of the above, taking into consideration the effects of both hot-streak and swirl at the primary design stage will assuredly increase the accuracy of aerodynamic and cooling design.

Numerous works focusing on hot-streak only have been investigated from the 1980s. In the experimental aspect, with an adjustable distortion generator, Barringer et al.[1] studied the effects of temperature non-uniformity and pressure distor-

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tion on the secondary flow and heat transfer, respectively. Their unsteady flow measurements showed that the radial migration of the hot-streak along the pressure surface increased the thermal loading in the clearance region, and that the interaction between the hot-streak and the secondary flow made the mechanism of heat transfer and the flow field near the end walls complicated sufficiently, which have been verified by Jenny[2] who used fast response probes to investigate the hot-streak in an axial flow turbomachinery. In the computational aspect, most of works with three-dimensional (3D) unsteady numerical simulations concentrated on the effect of the non-uniform inlet temperature distribution on the flow field and heat transfer problems in a single-stage turbine. Zilli et al.[3] concluded that the turbine performance was not sensitive to non-uniform inlet temperature profiles though a small reduction in efficiency, whereas this drop in efficiency could be reduced by clocking the hot streaks toward the stators. Simone et al.[4] noted that the impact of the hot-streak on heat transfer for blades and casing depended on the circumferential position of the hot-streak, the ratio of hot-streak/stator count, and the ratio of cool/hot flow temperature. In another study, Basol et al.[5] used a particle tracking tool inconjunction with time resolved simulations to investigate the hot streak migration pattern to the tip leakage flow. Their results showed that hot streak induced secondary flows increased the radial spread of hot gas on the rotor pressure side without affecting the radial temperature distribution on the suction side. More recently, Liu et al.[6] studied the effect of the clearance height on the characteristics of hot-streak migration in that region, and the analysis indicated that a higher clearance height meant more leakage flows, which enhanced the migration of hot-streak and heat transfer as well. Rahim et al.[7] firstly investigated the effect of nozzle guide vane (NGV) lean on high-pressure turbine (HPT) aerothermal performance by comparing a nominal vane with a compound leaned vane under uniform and hot-streak inlet conditions. Rahim et al.[7] found that when a hot-streak was introduced, a leaned NGV resulted in a beneficial heat transfer characteristics, particularly at the tip region, as the hot fluid movement toward the tip was blocked by the radial pressure gradient on the pressure surface. Their results also highlighted the significance of an inflow temperature profile when considering the HPT blade shape design optimization.

Compared with hot-streak research, the amount of research related to the impact of swirling flow on turbine performance appears to be rather limited. In fact, both experimental and computational studies mainly focus on the influence of swirl on a combustor and its emission characteristics. For example, Li et al.[8] investigated the effects of different swirl configurations on the recirculation zone, velocity field, temperature distribution, flame structure, and emission characteristics. Huang et al.[9] numerically studied the inlet swirl effect on the flow development and combustion dynamics with a large-eddy-simulation (LES) technique, and more details were achieved. The swirling flow emanating from a combustor affects many important flow parameters, such as the flow incidence angle of downstream adjacent turbine stage; the loading distribution on the nozzle guide vanes; the inlet velocity; total pressure and boundary layer profiles; the free-stream turbulence; and the secondary flow characteristics.[8]

The importance of the combined effects of hot-streak and swirl on turbine aerothermal performance has been realized, but their definite influences and mechanisms still need to be researched. Khanal et al.[10] carried out a 3D unsteady simulation on the MT1 single-stage HPT in terms of combined hot-streak and swirl. Their results indicated that with the swirl's effect, the hot-streak moved downstream and was distorted synchronously. Moreover, the cores of hot-streaks were twisted clockwise by a positive swirl and counter-clockwise by a negative swirl, respectively. Hence the effect of swirling flow on the transmission characteristics of the hot-streak was significant. It should be noted that the effect of combined hot-streak and swirl was nonlinear, and thus could not be linearly superimposed. Another more recent study on the aerothermal performance of the MT1 single-stage HPT under non-uniform temperature and velocity inlet profiles was performed by Rahim et al.[11] A qualitative shift in the roles played by two aerodynamic parameters, i.e., heat transfer coefficient and adiabatic wall temperature, was shown in their results. They also considered the effect of NGV shaping on controlling the impacts of non-uniform inlet traverses. The rotor heat transfer characteristics under combined hot-streak and swirl were found to be dependent on the NGV shaping. They finally noted that research on the differences under different NGV shapes and inlet conditions would contribute to combined aerodynamic and heat transfer optimizations during a design process.

In this paper, an in-house CFD software, NUAA-Turbo, was used to perform 3D unsteady simulations on the PW-E^3 single-stage HPT. The sinusoidal correction method for a spanwise total temperature profile was adopted to obtain an approximately actual total temperature profile. A novel method of simulating a real flow field in the inter-space between the combustor and the HPT stator was also proposed. Effects of the hot-streak migration on the rotor blade surface temperature distribution and the turbine performance were then studied by comparing the results between hot-streak and uniform inflow at different instantaneous positions. The present work finally concentrated on the combined effects of hot-streak and swirl, including the hot-streak migration process in turbine passage and its effects on the heat transfer environment.

2. Computational procedures

The NUAA-Turbo solver, which is based on a structural grid, was employed in all the computational results presented in this paper. The solver is also based on a time marching of the 3D unsteady compressible Reynolds-averaged Navier-Stokes (URANS) equations. The equations were discretized in space using a second or third order Van Leer's MUSCL scheme[12] based on a finite volume method with an implicit Newton iteration scheme. The inviscid and viscid fluxes were computed with the Roe scheme and the second-order central discretization, respectively. A turbulence model has been achieved by using the standard one-equation turbulence model of Spalart-Allmaras.[13] The unsteady second-order accurate dual time-stepping method[14] has been adopted in all runs and the phase-lag method[15] has been used for a periodic boundary condition and the interface between rotors and stators.