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Research Paper

Analysis of transient radiation-convection coupled effects on the HP turbine blade heat load with hot streak inlet

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HIGHLIGHTS

- Unsteady convection-radiation coupled simulations were carried out in HP turbine.
- The evolution mechanism of radiative heat flux in entire HP turbine stage was found.
- The combined effects of hot streak and radiation were investigated in detail.
- The impacts of three dominant radiative factors on blades heat load were analyzed.

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ABSTRACT

Hot Streak (HS) and thermal radiation are the two important factors affecting the heat transfer process in High Pressure (HP) turbine stage, while the previous investigations were limited in studying either of them independently. In order to investigate the combined effects of the HS and radiation, the present study is aimed at unsteady convection-radiation coupled simulations with regards to HS and uniform inlet conditions. Three dominant radiative factors were analyzed in details. Compared with the uniform cases, it is found that there are two high temperature regions in the rotor passages of HS cases. The maximum temperature increase of the vane surface is about 40 K caused by radiation. As the HS changes the temperature distribution, the radiative heat flux is redistributed and a portion of radiative heat flux transfer from the stator passage to the rotor passage. The turbine inlet radiation mainly affects on the guide vane, whereas the gas radiation has a more significant influence on the rotor blade heat load.

1. Introduction

In order to achieve high engine efficiency, a general aim of the modern gas turbine manufacturer is to increase the turbine inlet temperature, which is severely limited by the blade material temperature tolerance. It is generally accepted that a 25 K under-prediction of the blade metal temperature can lead to a halving of its life span [1]. Consequently, it is of great importance to determine the blade heat load accurately. In the modern turbine engine, there are many factors limiting the prediction accuracy of the turbine heat transfer: combustor exit total temperature distortion (i.e. hot streak), residual swirl, turbulence intensity, radiation, rotational effects, and blade row interactions and so on. Those factors interact with each other and further lead to the complexity of the flow and heat transfer environment in the HP turbine. In the present paper, we focus on two main factors of them: HS and the thermal radiation. One is the combustor-turbine interaction factor, and the other is an important energy transfer approach for high temperature turbine operating state. It is supposed that HS and thermal radiation could affect the blade passage heat transfer characteristics significantly, and lead to complex heat load distribution on the turbine blade surfaces.

Until now, there are very few relevant experimental or numerical studies performed on the combined effects of HS and thermal radiation on the turbine flow and heat transfer under the rotor-stator interaction conditions. There are many factors limiting the study of HS-radiation coupled effects. For the experimental study, heat radiation studies generally have the requirement of high temperature environment of the test rigs, only a few experimental platforms can reach the high temperature level for the study of thermal radiation on the turbine [2–8]. HS studies usually require a whole turbine stage. Both of those factor lead to the challenging difficulty of HS and radiation experimental research. For numerical studies, the factors such as the computation load, the complex geometric structure and the matching error caused by the various models will augment the complexity of radiation-HS interaction

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Nomenclature

Symbol

a	absorption coefficient [1/(bar m)]
b	emissivity weighting factor
Ca	axial chord [m]
D	thickness [m]
F_1	blending function [–]
I	radiation intensity [W/(m^2·sr)]
L	optical path length [m]
P	pressure [Pa]
R	radius [m]
T	temperature [K]
TI_u	turbulence intensity [–]
s	unit direction vector for RTE [–]
$\mathbf{s}'$	unit scattering direction vector [–]
w	weighting factor [–]
y+	normalized distance from the solid wall [–]

Greek letters

Ω	solid angle [rad]
ψ	turbine circumferential angle [rad]
ε	total emittance [–]
ρ	reflectivity, [–]
σ	Stefan–Boltzmann constant,
σ_s	scattering coefficient [–]

Abbreviations

DTRM	discrete transfer ray-tracing method
DOM	discrete ordinate method
FVM	finite volume method
HP	high pressure
HS	hot streak
HV	horse vortex
PNM	spherical harmonics method
PS	pressure surface
PV	passage vortex
Rad	radiation
Re	Reynolds
RTE	radiative transfer equation
SS	suction surface
WSGG	weighted sum of gray gases

Subscripts

b	blackbody
i, j	dummy counter
norad	no radiation
nowsgg	no WSGGM
rad	radiation
w	wall surface
η	wave number
λ	wave length

research.

In most high pressure turbine experiments and numerical calculations, the thermal radiation is generally ignored due to the change of working gas (from absorbing combustion gas to air), relatively low temperature level and the complexity of the radiation evaluation itself. However, with the development of engine technology, the turbine inlet temperature of the next generation aero-engine will even reach to 2200 K–2400 K. Under such high temperature conditions, thermal radiation, as an important heat transfer method under high temperature environments, will play an important role in the whole heat transfer system. According to previous study, when the gas temperature in the turbine stage is about 2000 K, the radiation heat flux of the combustion products to the blades could reach over 10% of the convective heat flux [9]. Thus it is necessary to consider the thermal radiation effects during the analysis of HP turbine thermodynamics and aerodynamics.

Even though there are a large number of investigations on radiative heat transfer [10–12] and the effects of thermal radiation in the turbine has raised concerns since 1970s [9,13], there are few studies aiming at thermal radiation in the gas turbine passages. Full coverage film cooling plate experiments were selected [14] for two groups of hot and cold fluid temperature, i.e. 750 K/293 K and 2100 K/770 K. It is found that the cooling efficiency is about 9% higher in the first group than the latter, and the researchers proposed that the thermal radiation is one possible reason that resulted in the decrease of the cooling effectiveness in the second group. Mazzotta [15] used a two-dimensional blade model to calculate the heat flux with different gas composition. The results suggest that the radiation heat flux of the high temperature gas occupies 3%-5% of the total heat flux at 1700 K. Multi-physics simulations have been performed in a helicopter gas turbine by Amaya [1], and the results showed that radiation had a non-negligible impact on the fluid and the blade temperature. Mick [16] studied a kind of internal convection cooling blade by experimental and numerical methods to analyze the influence of gas radiation. It was found that when considering the effect of gas radiation in 1273 K, the calculation results were closer to the experimental data. The blade surface temperature rise about 6%. Hong Yin [17] proposed a coupled heat transfer simulation including radiative heat transfer for the HP turbine vane. Those studies mainly pay attentions on the effect of radiation on the HP turbine guide vanes, which are exposed to the combustor exit. However, with the increase of the turbine inlet temperature, the effects of gas radiation will cover the entire turbine stage, including the rotor blades. Because of the difficulty in arranging the cooling structure on the turbine rotor blades, the additional heat load caused by the radiation will severely deteriorate the blades working conditions. Accordingly, it is necessary to study the radiative heat transfer in the entire turbine stage, including the turbine rotor blades.

Another unfortunate factor deteriorates the blade temperature distribution is the hot streak (HS) [18,19]. Bulter [20] proposed a circular HS introduced from a tube upstream of the stator in a single stage turbine rig. The results revealed that the rotor flow field is significantly affected by the introduction of the hot streaks. A flow separation effect was observed in the rotor passage that results from the migration of hotter gas to the pressure side and colder gas to the suction side, which is called "Kerrebrock and Mikolajczak effect" [21]. Shang [22] utilized three dimensional unsteady numerical simulation to calculate the migration mechanism in a Rolls-Royce transonic turbine. They proposed that the turbine inlet HS migration characteristics are mainly affected by buoyancy, flow separation and the rotor-stator relative motion. Jenny [23] carried out an experiment to study the influence of unsteady blade row interaction on the migration of HS. A hot streak simulator was designed and implemented in a turbine test facility by Povey [24]. To investigate the impact of HS on HP turbine efficiency and aerodynamics, the HS effect on the turbine vanes [25], turbine blades [26] and the intermediate pressure vanes [27] had been investigated in their subsequent studies. Zhao [28] investigated the effect of the HS temperature ratio of a low pressure stage in a counter-rotating turbine. Under the real working state of the turbine, HS is found to be combined with other key factors to influence the aerodynamic performance and heat transfer of the HP turbine. There are many researchers further studied the interactions between HS and swirling flow [29], HS and