Propulsion and Power Research 2013;2(2):148–161

http://ppr.buaa.edu.cn/

Propulsion and Power Research

www.sciencedirect.com

ORIGINAL ARTICLE

Turbine blade temperature calculation and life estimation - a sensitivity analysis

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Received 17 August 2012; accepted 16 January 2013
Available online 31 May 2013

KEYWORDS

Conjugate heat transfer;
Life assessment;
Sensitivity analysis;
Gas turbine;
Blade

Abstract The overall operating cost of the modern gas turbines is greatly influenced by the durability of hot section components operating at high temperatures. In turbine operating conditions, some defects may occur which can decrease hot section life. In the present paper, methods used for calculating blade temperature and life are demonstrated and validated. Using these methods, a set of sensitivity analyses on the parameters affecting temperature and life of a high pressure, high temperature turbine first stage blade is carried out. Investigated uncertainties are: (1) blade coating thickness, (2) coolant inlet pressure and temperature (as a result of secondary air system), and (3) gas turbine load variation. Results show that increasing thermal barrier coating thickness by 3 times, leads to rise in the blade life by 9 times. In addition, considering inlet cooling temperature and pressure, deviation in temperature has greater effect on blade life. One of the interesting points that can be realized from the results is that 300 hours operation at 70% load can be equal to one hour operation at base load.

1. Introduction

Increasing turbine inlet temperature is a means of improving efficiency, but this temperature exceeds allowable temperature of metal parts. In addition, the gas turbine hot parts operate in a harmful condition of centrifugal and gas pressure forces and thermal cycling. Subsequently, most

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Peer review under responsibility of National Laboratory for Aeronautics and Astronautics, China.

Production and hosting by Elsevier

2212-540X
http://dx.doi.org/10.1016/j.jppr.2013.04.004

Nomenclature

b	fatigue strength exponent
C	specific heat
c	fatigue ductility exponent
D	life fraction
E	modulus of elasticity
h	heat transfer coefficient
k	thermal conductivity
Ma	Mach number
N_f	number of cycles to failure
n	number of cycles
$\dot{m}$	mass flow rate
P	pressure
T	temperature
t_r	time to rupture

Greek letters

ε	strain
ε'	fatigue ductility coefficient
σ	stress
σ'	fatigue strength coefficient
ρ	density
δ	thickness

Subscripts

c	coolant
co	coating
in	inlet
me	metal
out	outlet
ref	reference
s	static condition
t	total condition

Abbreviations

CHT	conjugate heat transfer
LMP	Larson-Miller parameter
SAS	secondary air system
TBC	thermal barrier coating

of the life problems are encountered in this area. Blade metal temperature distribution and temperature gradients are the most important parameters determining blade life. Therefore, accurately predicting blade heat transfer parameters is essential for precisely predicting blade life.

As mentioned above, one of the most important loads for calculating blade life is temperature distribution. In cooled turbines, in order to calculate blade temperature precisely, internal coolant, external hot gas, and metal conduction should be simulated simultaneously by conjugate heat transfer (CHT) method. There have been increased research efforts in applying the CHT methodology to simulate gas turbine blade heat transfer. Some of them are on modeling C3X and MarkII vanes in a single solver [1–7]. Although three-dimensional (3-D) modeling of vanes and blades with complex cooling passages is time-consuming, there are some studies [8–11] which used 3-D solver and CHT method to calculate the temperature distribution of vanes and blades with more complex internal cooling passages.

In addition, there are some studies [12–16] in which blade simulated by conjugate (or coupled) heat transfer method using one-dimensional (1-D) simulation for internal cooling passages. Short calculation time is the most important reason that in these works, 1-D solver is used for simulation of internal cooling passages. Dewey and Hulshof [12] carried out aero-thermal analysis for combustion turbine F-Class life prediction. In order to get both temperatures and stresses right, they used combination of through-flow (BLADE-CT) and computational fluid dynamics (CFD) (FLOTRAN) to analyze the external gas flow, the Cooling Passage Flow (CPF) program to perform the cooling flow analysis and ANSYS program to analyze the heat conduction to calculate distribution of temperatures and stress. Zecchi et al. [13] presented a simulation tool to analyze cooling system of gas turbine. This tool couples energy, momentum and mass flow conservation equations together with experimental correlations for heat transfer and pressure losses. They validated this tool with experimental data using conjugate heat transfer methodology. In addition, they carried out sensitivity analysis to boundary conditions variation in order to show how uncertainty on data can affect metal temperature distribution. Takahashi et al. [14] performed a 3-D steady-state numerical analysis of thermal conjugation for inside and outside fields of the blade, which consists of convection heat transfer around the blade, thermal conduction in the blade material combined with a one-dimensional thermo-flow calculation for internal blade cooling rib-roughened passages. The 1-D calculation utilized correlations of friction and heat transfer in the rib-roughened cooling passages derived from large-eddy simulation in ribbed rectangular channels. In this study, effects of inlet temperature profiles, mass flow rate, and temperature of internal cooling air on the blade local temperature are also presented. Coutandin et al. [15] used iterative process involving external fluid dynamic simulations (CFD), internal flow network code and finite element conductive model (FEM) to design an advanced double wall cooling system and validated their results with experimental data. Amaral et al. [16] applied conjugate heat transfer method using 1-D aero-thermal model based on friction and heat transfer correlations for lifetime prediction of a high-pressure turbine blade operating at a very high inlet temperature. Their CHT method is validated on two test cases: a gas turbine rotor blade without cooling and one