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Thermo-mechanical life prediction for material lifetime improvement of an internal cooling system in a combustion liner

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ABSTRACT

This paper is concerned with heat transfer analysis and life prediction in the after shell section of a gas turbine combustion liner with internal cooling passage. The method in the present study is the process to design cooling systems which enhance the material lifetime as well as the cooling performance. Using this method, we found the major causes of lifetime-affecting thermal damage induced by heat transfer distributions in the internal cooling system of the after shell section. From startup to shutdown, high thermal deformation occurred between the hot and coolant side walls in the welding region, the nearby cooling hole, and above the divider of the C-channel. Three regions were therefore very weak in relation to the thermal cycle. Moreover, these locations were in close agreement with the locations of thermal cracks in an actual gas turbine combustor currently in service.

1. Introduction

The thermal efficiency and the material lifetime of gas turbine systems are strongly affected by increases in turbine inlet temperature, which are accompanied by excessive thermal loads in the hot components of the turbine. [1,2] Thus various cooling techniques [3] have been used to protect the major hot components of gas turbines. If an unsuitable cooling method is used, local hot spots and structural failure may occur due to thermal stress and reduction of material lifetime at high temperatures. Moreover, the temperature differences in the hot parts increase with turbine inlet temperature, resulting in high thermal stresses. Hence it is necessary to calculate the temperature and stress distributions of these systems (in an appropriate environment) in order to predict the safety of hot components such as combustors, vanes, and blades.

A number of investigators [4–8] have recently attempted thermal analyses of the hot components, and thermal stresses have been predicted. These computational results have proved useful methods for studying the thermal environment of an actual gas turbine, and defining the factors that contribute to advanced maintenance and operation. In the design of a gas turbine, correct heat transfer analysis is particularly important for obtaining first process data. The heat transfer data are used in various applications, such as thermal analyses and failure analyses. In other words, heat transfer data obtained from CFD (computational fluid dynamics) analysis facilitate the effective thermal design and lifetime prediction of the hot components.

Furthermore, in order to apply an ideal cooling system (summarized by Goldstein [9] and Han et al. [3]) and improve the cooling performance (reported by Lee et al. [10], Kim et al. [11], and Hwang et al. [12]) to an actual gas turbine component, heat transfer analysis, thermal analysis, and failure analysis are required. However, many researchers have approached failure analysis from a purely material point of view, and thermal analysis is seldom included [13–15]. In the previous studies, we found the heat transfer and the material characteristics in the overall combustion liner during steady state operation [16,17], and in the after shell section of the combustion liner [18,19]. In addition, we obtained the minimum creep lifetime in the section pertaining to the distributions of heat transfer, temperature, and thermal stress. The locations with minimum creep lifetime were in close agreement with the locations of thermal cracks in actual gas turbine combustors currently in service.

However, the flow temperature in a gas turbine changes over a normal startup and shutdown cycle [20], as shown in Fig. 1. Light-off, acceleration, loading, unloading and shutdown in all produce, gas temperature changes, resulting in corresponding metal temperature changes. The high temperature components undergo induced thermal strains and stresses during gas turbine startup and shutdown operations. Repeated operations of this type cause TMF

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Nomenclature

c_p	specific heat
d	Hole diameter
E	Young's modulus
h	Heat transfer coefficients, $q''/(T_w - T_m)$
k	Thermal conductivity
N_f	Fatigue life (lifecycle)
p	Pressure
Re	Reynolds number, $\rho\ U\ d/\mu$
t_c	Creep lifetime in hours
T	Temperature
U	Average velocity

Greek symbols

q'' Heat flux per unit area

β	Thermal expansion coefficient
ε	Thermal and mechanical strains
μ	Dynamic viscosity
v	Poisson's ratio
θ	Range ratio, $(X_w - X_{\min})/(X_{\max} - X_{\min})$
ρ	Mass density
σ	Thermal and mechanical stresses

Subscripts

2	Coolant flow
m	Main flow
max	Maximum
min	Minimum
w	Wall

(thermo-mechanical fatigue) damage. TMF behaves like LCF (low cycle fatigue), but leads to a limited lifetime compared to isothermal LCF, due to additional deformation and damage resulting from varying temperature conditions. Despite its importance, it has received relatively little attention on account of its time consuming, labor intensive and expansive features. Data from isothermal LCF tests are traditionally used to predict the lifecycle of the components exposed to TMF. Fatigue life is expressed as the number of operational cycles required for crack initiation, and it is strongly influenced by the total strain range and the maximum metal temperature experienced during a transient period.

In this study, we investigate how lifetime is affected by thermal-mechanical stresses during the transient operations, such as unit startup and shutdown. Thus the objective of the present research is to find the major causes of lifetime-affecting thermal damage induced by heat transfer distributions. As an example, we calculate the thermal-mechanical lifetime that often yields two axial cracks and one weld crack in actual combustion liners (as shown in Fig. 2 (a)), and then determine the major causes of these cracks from results of the analysis.

2. Research methods

The geometry of the overall combustion liner is explained in detail by Kim et al. [19] and Martling and Xiao [21]. The liner is divided into three parts; forward shell section, center shell section, and after shell section. Each section has a different cooling method.

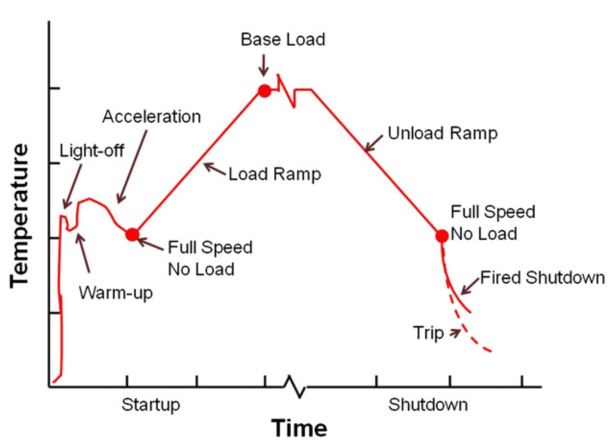

Fig. 1. Firing temperature changes during turbine start/stop cycle [20].

The forward shell section is cooled by rib-roughened passage, the center shell section by impingement jet, and the after shell section by C-channel. The after shell section is cooled via an internal passage cooling method because it is inserted into a transition piece. The C-channel was invented by Intile et al. [22], and consists of cooling holes, divider walls, hot side wall, coolant side wall, and spring seals, as illustrated in Fig. 2(b). The calculations and numerical modeling in the present study are the same as those in the previous study [19]. In other words, a segment containing one of the 88 cooling holes in this section is analyzed, since the shape is symmetric, as shown in Figs. 2(b) and 3(a).

The fluid flow and heat transfer calculations are carried out using the computational fluid dynamics (CFD) software CFX v11. The Reynolds-averaged Navier–Stokes equations, as well as the

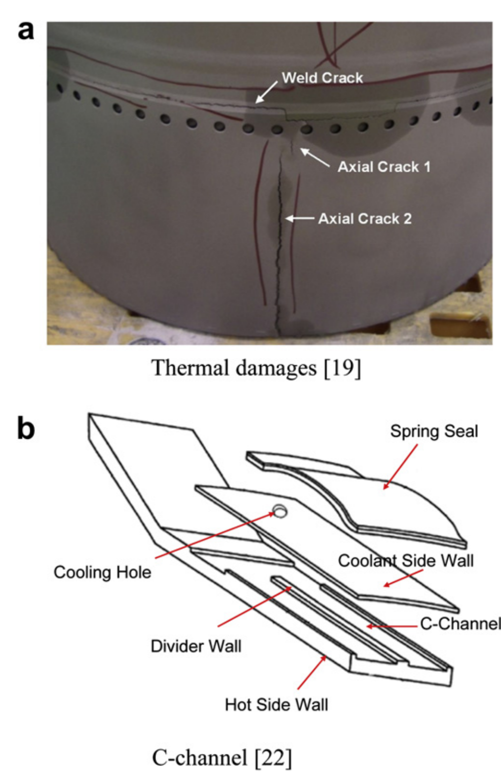

Fig. 2. Thermal damages observed in service and schematic of a C-channel in the after shell section.