Thermal and Creep Analysis in a Gas Turbine Combustion Liner

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Abstract: - Numerical analyses are carried out in order to understand complex thermal characteristics of a gas turbine combustion liner such as combustion gas temperatures, wall adjacent temperatures and heat transfer distributions. Also, stress and creep analyses are performed using the commercial code, ANSYS. Creep life was predicted using the correlation between Larson Miller parameter and applied stress. The results show that wall adjacent temperatures and wall heat transfer coefficients in the combustion field are distributed differently throughout the combustion liner by the swirling flows. Outside the combustion liner, heat transfer is augmented largely due to the impinging jets of the coolant air. Metal temperature varies abruptly in the forward section by combustion characteristics. High creep stresses are locally induced in the inlet rib-roughened region due to high temperature gradients. The hot gas side of the inlet rib-roughened region appeared most vulnerable to creep damage.

Key-Words: - Gas Turbine, Combustor, Combustion Liner, Thermal Analysis, Creep, Life Prediction

1 Introduction

In modern gas turbine engines for aircraft propulsion and land-based power generation or industrial application, turbine inlet temperature has been increased steadily because of improvement of gas turbine performance. Accordingly, new material, thermal barrier coating (TBC) and advanced combined cooling methods have been developed for a few decades to improve reliability and durability of the hot component. In combustion liner cooling, various cooling methods like impingement cooling, film cooling and internal passage cooling are applied.

Recently, NOx is environmental problem and it has been attract attention of the world. High temperatures (above 1900K) of traditional gas turbine combustors result in relatively large NOx emissions. One approach to reducing NOx emissions has been to premix the maximum possible amount of compressor air with fuel. The result in lean premixed combustion produces cooler flame temperatures and lower NOx emissions. But, because the advanced combustors premix the maximum possible amount of air with the fuel for NOx reduction, little or no cooling air is available making film cooling of the combustion liner impossible. Therefore, impingement jet cooling and internal passage cooling tend to be adopted in combustion liner cooling instead of film cooling.

Another interest is creep. It is the tendency of a material to slowly move or deform permanently under the influence of stresses and the dominant failure mechanism for gas turbine hot components. The ability to perform a reliable life prediction is crucial for gas turbine component design and maintenance. Damages in the gas turbine components must be detected and repaired before it gets problematic. Therefore, the study on life assessment of a combustion liner which is one of the important gas turbine hot components should be performed.

The present study was performed for thermal analysis and life prediction of a gas turbine combustion liner (Fig. 1) with firing temperature of 1600K in operation. To accomplish this objective, numerical calculations of thermal and structural analyses using commercial codes and life prediction using reliable methods were conducted.

2 Research Methods

2.1 Numerical Calculation

In order to perform the life prediction, first of all, the information on heat and flow characteristics to calculate the distributions of wall adjacent temperatures and wall heat transfer coefficients are
required. It is difficult to experiment to obtain wall adjacent temperatures and wall heat transfer coefficients under high temperature and pressure environment. So, in the present study, in order to investigate flow and heat transfer characteristics of the objective combustion liner, numerical analyses (CFD, computation fluid dynamics) of heat and flow characteristics for hot combustion gas inside the combustion liner and coolant air outside the combustion liner were performed using CFD commercial codes, Fluent and CFX. From the CFD results, the distributions of temperatures and stresses for the life prediction were calculated using a finite element analysis (FEA) code, ANSYS.

2.1.1 Modeling for Analysis of Flow and Heat Transfer inside Combustion Liner
In order to analyze the combustion field, the combustion liner and 6 premixed nozzles were considered. Temperature distribution and flow characteristics of the hot combustion gas in the combustion liner were analyzed in 3-dimensions using commercial codes, GAMBIT and Fluent 6.3.

Fig. 2 shows the modeling for the analysis of the combustion field with 6 premixed nozzles. The domain for calculation ranges from the assembly of nozzle cap to the combustion liner end (908 mm). The inner diameter of the nozzle cap is 457.2 mm and that of the combustion liner connecting with the transition piece is 348.85 mm. The angle of the swirl vanes located at the outlet of the nozzles is 50° and the after section was treated as a simple shape as shown in Fig. 2. As for the base-load operation condition, the fuel gas is assumed to be CH₄ occupying most of the natural gas, mass flow rate of the fuel gas is 0.69 kg/s, the equivalence ratio is 0.38, average pressure in the combustion chamber is 15.2 atm and the fuel temperature at the inlet of the nozzles is 675.56K. The turbulence and species model are Realizable k-ε model and species transport, respectively. The mode 6 of the DLN 2.6 operation was applied to the analysis. The process of the combustion was considered as following equation for reaction.

\[
\text{CH}_4 + 2(\text{O}_2 + 3.76\text{N}_2) \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} + 7.52\text{N}_2
\]  (1)

2.1.2 Modeling for Analysis of Flow and Heat Transfer outside Combustion Liner
In order to analyze the flow and heat transfer characteristics outside the objective combustion liner,
3-dimensional analysis was performed using commercial codes, GAMBIT and CFX-11.

Fig. 3 shows the modeling for flow and heat transfer analysis outside the combustion liner. The outer surface of the liner is cooled by impinging jets through the cooling holes of the flow sleeve and internal passage with rib roughened surface. The array of the cooling holes is twenty-four rows on the circumference of the flow sleeve, and each row is composed of four holes as shown in the Fig. 3. Therefore, the analysis was performed for one twenty-fourth of the channel formed between the flow sleeve and the liner because the shape has a symmetric behavior. The mass flow rate of the coolant air per cooling hole is assumed at 0.1 kg/s. For the cross flow from the transition piece, the Reynolds number based on the hydraulic diameter of the channel is assumed at 552,142 in consideration of the operation data under the base load. Grids were generated using GAMBIT and the grid consists of approximately 1.15 million cells. The turbulence model used in CFX is k-ε model.

2.2 Creep Life Prediction Method
Creep is known as the dominant life limiter of the gas turbine hot components during base load state. At this operation, high temperature and stress are imposed to them and accordingly the creep resistance of the materials decreases and the creep life (lifetime) of them becomes shortened. The life is generally extrapolated from accelerated high stress and high temperature data using widely accepted technique proposed by Larson and Miller (1952), since testing under the operation conditions are obviously impractical.

The Larson-Miller parameter has been shown to give reliable predictions so long as no micro-structural changes occur in the hot components under prolonged exposure in high temperature environment. The Larson-Miller parameter, \( P \) is given as follows.

\[
P = T (\log t_r + 20)
\]

where \( T \) is the applied temperature (K) and \( t_r \) is the time (Hr.) to rupture.

After creep tests for various combinations of stress and temperature (\( \sigma, T \)) are carried out, one usually finds a strong correlation between Larson Miller parameter \( (P) \) and log \( \sigma \). The polynomial function, \( f(\sigma) \) is induced from Larson-Miller rupture curves. Then, from the Larson-Miller parameter \( (P) \) and the correlation \( (P = f(\sigma)) \), the lifetime \( (t_r) \) is induced as following equation.

\[
\log(t_r) = f(\sigma)/T_w - 20
\]

where \( T_w \) is temperature in Kelvins, \( t_r \) is time in hours, and \( \sigma \) is stress in mega-pascals.

When the applied stress and temperature \( (\sigma, T) \) are known, the creep life of the material can be calculated by Equations (2) and (3). The present study has used this method to predict creep lifetime of a combustion liner.

3 Results

3.1 Analysis of Flow and Heat Transfer inside Combustion Liner Analysis
Fig. 4 shows the results of the flow analysis at the horizontal plane to the axial direction for base load operation. The velocity distribution of the incoming fuel-air mixed gas flow having the swirling velocity components generated by the swirl vanes increases abruptly due to the combustion reaction. The flow of
the combustion gas shows complex flow pattern. As the flow approaches the after section of the combustion liner, the velocity is more increased and shows uniform distribution throughout the cross-section due to the reduction of the flow area.

Fig. 5 shows the temperature distribution at the horizontal plane to the axial direction. The flame of the combustion gas is shown to be stable and the maximum temperature of the flame is calculated to be 1760K.

Fig. 6 shows the distribution of the swirling velocity and temperatures of the flow at the cross section. It is shown that 6 swirls are formed and high temperature region appears inside each swirl because of initial stage of ignition. The swirls and temperature distributions of the combustion gas along the combustion liner are gradually weakened and the temperature distribution becomes uniform as the flow approaches the end of the combustion liner. At the outer side of the cross section the five swirls appear to form clockwise rotating flows and at the inner side swirl, counter clockwise rotating flow appears. Due to the increased turbulence intensity by the interaction of the 6 swirl flows, uniform combustion field is formed in the combustion chamber.

The wall adjacent temperatures distributed differently throughout the combustion liner and high temperatures appear near the region greatly affected by the swirl flows from the nozzles. The distribution of averaged values along the axial direction appears low at the inlet of the forward section and keeps high from the middle of the section by the combustion reaction.

Fig. 7 shows that the distribution of inside wall heat transfer coefficients is affected by the swirling flows. And it shows that the wall heat transfer coefficients are varied largely at the forward section of the combustion liner like the wall adjacent temperature distribution and gradually approach constant values near the after section.

3.2 Analysis of Flow and Heat Transfer outside Combustion Liner

Fig. 8 shows the heat transfer characteristics outside the combustion liner. High heat transfer due to the impinging jets of the coolant air appeared on the outside surface of the combustion liner. The impinging flows are deflected by the effect of the cross flow from the transition piece. Therefore, high heat transfer region is moved toward the forward section rather than immediately below the cooling holes. The impinged coolant air added with the cross flow streams toward the forward section, augmenting heat transfer by the rib tabulators formed on the outside surface of the liner.
3.3 Creep Analysis

3.3.1 Temperature Distribution and Structural Results
From the distributions of the calculated wall adjacent temperatures and wall heat transfer coefficients in the combustion field and outside the combustion liner, thermal and structural analyses were conducted using a finite element analysis (FEA) code, ANSYS v11.

Fig. 9 and Fig. 10 show the distributions of temperatures of the combustion liner. Fig. 9 shows the distribution of temperatures on TBC, where the combustion gas is directly contacted. The temperatures range from 403ºC to 996ºC and the maximum temperature appears at the inlet rib-roughened region of the forward section. This maximum temperature is thought to appear due to the high heat transfer from the hot combustion gas as shown in Fig. 7. Fig. 10 shows the distribution of temperatures on the outside surface of the liner. The temperatures range from 402ºC to 831ºC and the maximum temperature also appears at the inlet rib-roughened region. It is shown that the inlet rib-roughened region of the forward section locally suffer higher temperature than other regions. Metal temperature varies abruptly in the forward section by the combustion characteristics.

Using these calculated temperature distribution, structural analysis was conducted. In the present study, the creep stress distribution is obtained from the calculated equivalent stress distribution excluding the portion of thermal strain. Therefore, the stress distribution corresponds to the applied stresses in the correlation between Larson-Miller parameter and stress. To calculate the stress distribution, constraints are applied at the inlet side. The combustion liner is constrained by the stopper attached on the inlet region. A finite element mesh was created with SOLID 5. The stress for structural materials is proportional to the material properties, thermal expansion coefficient ($\alpha$) and temperature difference ($\Delta T$) as presented in equation ($\sigma = E\alpha\Delta T$). In the calculated results, the equivalent or von-Mises stress ($\sigma_v$) and strain ($\varepsilon_v$) are used, and the stress is a part of the maximum stress in failure theory used to predict yielding in a ductile material.

In the creep stress analysis of the combustion liner without TBC, high stresses are locally induced in the inlet rib-roughened region of the forward section. This is because high temperature gradients resulting from the large temperature differences between the hot spots and the surrounding low temperature regions are imposed in this region. It is shown that the stress distribution is within the allowable stress range and higher stresses appear in the forward section than those in other sections. The stresses range from 0.18 MPa to 27.1 MPa.
The maximum stress and temperature (857°C, 27.1 MPa) are imposed on the hot gas side of the inlet rib-roughened region. And, the distribution of creep stresses and temperatures is used for creep life prediction.

3.3.2 Creep Life Prediction
Fig. 11 presents the distribution of the predicted lifetime at each element of the combustion liner. The lifetime distribution widely ranges from the hours of $10^4$ to $10^{22}$ orders. The minimum lifetime among the elements is estimated at 26,922 hours on the hot combustion gas side of the inlet rib-roughened region which has the maximum temperature and creep stress. From the result of lifetime prediction, the forward section appears more vulnerable to creep damage than other sections.

4 Conclusion
In the combustion field, wall adjacent temperatures and wall heat transfer coefficients are distributed differently throughout the combustion chamber by the swirling flows. Outside the combustion liner, heat transfer is augmented largely due to the impinging jets of the coolant air. The impinging flows are deflected by the effect of the cross flow from the transition piece.

The inlet rib-roughened region of the forward section suffers higher temperature than other regions. Metal temperature varies abruptly in the forward section by combustion characteristics. In addition, high creep stresses are locally induced in the inlet rib-roughened due to high temperature gradients resulting from the large temperature differences between the hot spots and the surrounding low temperature regions. The maximum stress and temperature are imposed on the hot gas side of the inlet rib-roughened region and the maximum strain and temperature are imposed on the same region as that of the stress temperature distribution.

The lifetime distribution widely ranges from the hours of $10^4$ to $10^{22}$ orders. The minimum lifetime is estimated at 26,922 hours on the hot combustion gas side of the inlet rib-roughen region.

References: