MODELLING OF THE HEAT TRANSFER IN A GAS TURBINE LINER COMBUSTOR

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Abstract

The combustion components of gas turbines (GT) are operating under high temperatures and stresses (due to combustion instabilities) and are therefore one of the critical parts in a gas turbine. As a result, they need regular monitoring or condition assessment in order to avoid failures that can compromise the integrity of the downstream hardware.

Integrated in a complete life-assessment methodology, the thermal analysis of one gas turbine combustion liner is presented in this paper. The goal is to investigate the effects of changes in the operational parameters on the temperature profile and heat flux distribution at the liner inner and outer interfaces.

A steady state CFD analysis is performed for a coupled combustion chamber-liner-casing domain. The numerical models used to describe the complete process are evaluated and results are commented.

Numerical calculations for different cases are performed and the results are compared and used to determine the most critical parameters for the combustor hardware. The benefit of the application of the TBC layer on the liner surface is also calculated in order to assess the reduction of the thermal load on the base material.

The results obtained are consistent with those found in literature and measured during the operations of GT.

Introduction

Modern gas turbines are very compact and have an extremely high energy conversion rate. Today's gas turbine can reach thermal efficiencies in excess of 40% as result of the increased thermodynamic parameters like pressure ratio and turbine inlet temperature. Both of the parameters have a direct impact on the thermal load and hence on the cooling system of the combustor hardware. The highest combustor exit temperatures are approximately 2000K and for the most widely used nickel or cobalt based alloys, the maximum temperature should not exceed 1200 K [3]. The mechanical strength of these materials declines rapidly at high temperatures and therefore protection systems such as Thermal Barrier Coating (TBC) and air cooling passages have been developed for protecting the liner and to keep the surface temperature below acceptable levels.

Many parameters play an important role on the characterization of the heat flux through the liner: hot gas temperature, flame temperature, radiation effects, cooling air temperature, material properties, pre-mixing of the mixture.

The biggest part of the thermal energy produced by the combustion process is transported with the exhaust gases to the first stage of the turbine but, a smaller segment is lost in the surroundings of the combustion chamber by different heat transfer mechanisms: radiation, forced convection and conduction.

The goal of this paper is to evaluate the impact of the changes in the operational parameters on the heat flux and temperature at the liner surface in order to determine the effect of a certain load profile on the overall lifetime of the combustion hardware, especially the combustion liner. Large amounts of data of operating engines are available to the end user as well as operational experience with heavy duty gas turbines; the geometry and the operational parameters used to define the Inlet Boundary Conditions (IBC) for the calculation are therefore related to commercial engines and data acquired from the field.

Integrated fluid structural analysis

The work described in this article is part of an integrated fluid-structural method for assessing the evolution of the condition (and damage) in a GT combustor.
Figure 1 describes the methodology flow used for the study.

The variation of GT control parameters for a fixed operational interval Δt are measured and stored by the Data Control System (DCS). For the most characteristic operating points a numerical thermal analysis is performed and pressure oscillation measurements are collected at the same time. Both thermal (temperature field) and dynamic (combustion instabilities) loads are given as input for the structural analysis where the characteristic stresses and strains for the considered cases are calculated. Finally, an interpolation of the stress calculated, on the base of the operational interval, results into a time-dependent stress curve that allows to estimate the cumulated damage on the structure.

The transitory behaviour of the GT Combustor is approximated by a number of steady state calculations. The values of the thermal loads on the chamber liner at intermediate operating conditions are interpolated between the values obtained for the calculated conditions avoiding extremely long transient CFD calculations. The advantage of the method is the limited computational effort needed for the numerical calculation as compared to a full transient simulation of the operation profile.

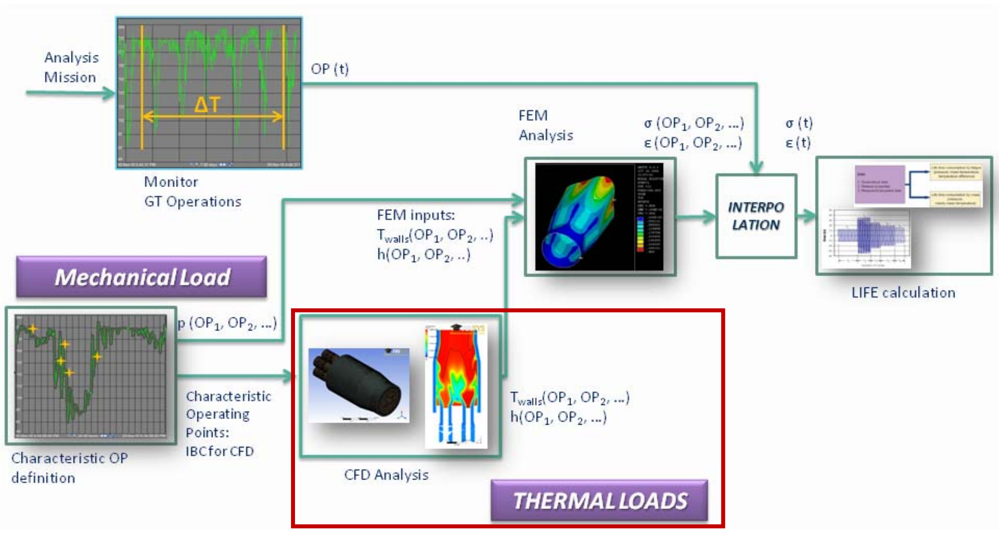

Figure 1. Methodology flow chart; the red box highlights the work described in the article.

Geometry

Figure 2 shows the geometry of the combustion system used for the calculation. It is a cannular combustor equipped with five premix burners with air swirlers and gas injectors. Thanks to the spin given by the air swirlers, the premixed mixture recirculates into the chamber increasing the residence time and completing the combustion process (reducing CO formation).

The liner is cooled at the outer side by the compressor discharge air which, before entering the combustion chamber, circulates counterflow externally with the twofold effect of cooling the liner walls and being pre-heated (to increase the combustion efficiency).

Four different fuel lines feed the chamber with natural gas: the primary line brings the fuel at the tip of the nozzle and acts on the pilot flame, the quaternary line delivers a percentage of the total feed gas to the air inlet upstream the premix swirlers; secondary and tertiary lines bring the fuel to, respectively, 4 and 1 burners with premix gas injectors. The opening of the split valve changes according to the power output and the start-up or turn-down procedure.

The asymmetry in the temperature field generates different temperature gradients across the wall and different heat flux for the structure. These effects are investigated in more detail and the possible damage on the structure are presented in the following sections.

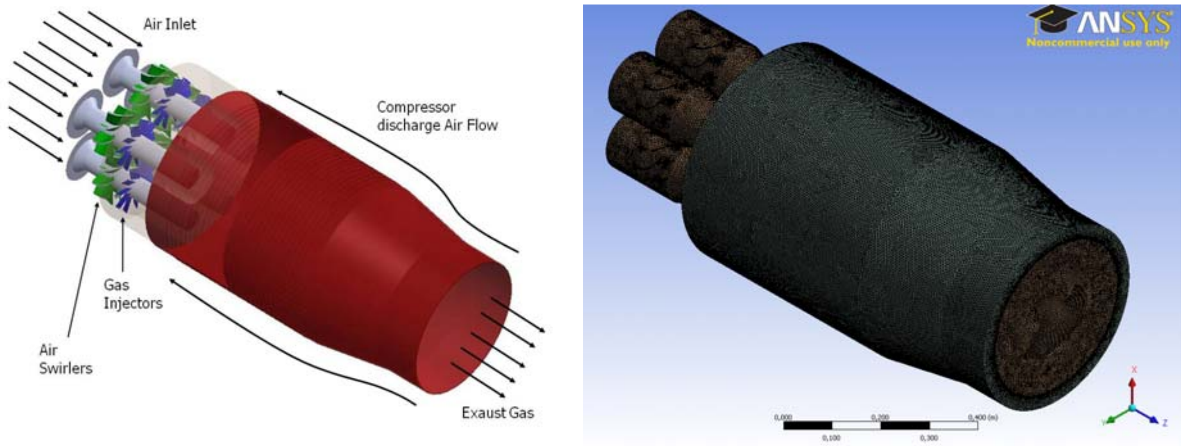

Figure 2. (a) CAD drawings and Air Flow for the cannular combustion system; (b) element grid for the three domains.

Thermal Analysis of the liner wall

During the combustion process, heat is transferred from the hot flame by radiation and by convection of the combustion gases. The radiative heat exchange depends on the distance between the flame and the walls and by the absorption of the colder combustion gases in between. In the modern GT the contribution of the radiative heat is lower because of the high bulk flow velocity and short residence times but it can have a significant impact on the chemical reactions and thus on the NO_x formation [3].

Figure 3 shows the heat flux through the liner: it is heated by convection and radiation from the exhaust gas inside and it is cooled by radiation to the outer casing and by convection to the casing air passage.

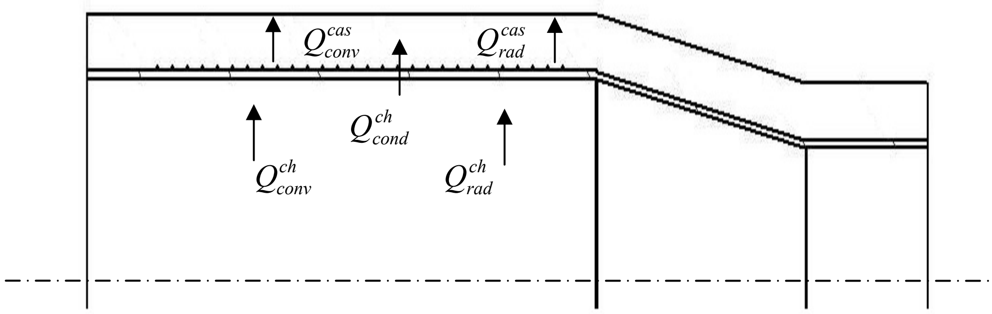

Figure 3. Heat fluxes through the liner walls.

Under steady-state condition, the heat transfer into the wall domain is balanced by the heat transfer out of it.

$$Q_{conv}^{ch} + Q_{rad}^{ch} + Q_{cond}^{w} = Q_{conv}^{cas} + Q_{rad}^{cas} \qquad (1)$$

For flame temperatures up to about 1700 K, forced convection is the dominant mechanism in flame heat transfer [8]. Loss of heat by conduction along the liner wall is very small compared to the other terms. The convective, radiative and conductive heat are calculated using the equations sotto:

$$Q_{conv} = h\left(T_{gas} - T_{wall}\right) \qquad (2)$$

$$Q_{rad} = \sigma_{SB}\varepsilon\left(T_{\max}^{4} - T_{wall}^{4}\right) \qquad (3)$$

$$Q_{cond}^{1-2} = \frac{k_w}{t_w}\left(T_{w1} - T_{w2}\right) \qquad (4)$$

where,

T_{gas}, T_{wall} and $T_{\max}$ [K]are respectively, the temperature of the exhaust gas near the wall (wall adjacent temperature), at the liner wall and the maximum flame temperature,

h [W/m² K] is the heat transfer coefficient;

ε is the emissivity of the wall;

k_w [W/m K] is the thermal conductivity of the liner wall (for the base material and TBC);

t_w [m] is the thickness of the liner wall;

σ_{SB} [W/m² K^4] is the Stefan-Boltzman constant.

Flame temperature, absorption, reflection and emission characteristics of the liner material, equivalence ratio of the mixture and wall thickness directly influence the heat flux while flue gas composition, mass flow velocity and cooling techniques have an indirect effect. Some of them are therefore used to assess the impact of their changes on the heat flux by the heat transfer coefficient. The heat transfer coefficient *h* is the amount of heat energy crossing a unit area per unit time per unit temperature.

The results are presented in the following paragraphs.

Computational Setup

Starting from an unique geometry file, three separate domains has been modelled and meshed using Ansys 12.1 Workbench: the fluid casing cavity walls, the solid liner and the fluid chamber domain (Figure 2,a).

The element grid has been prepared using unstructured tetrahedrons with an average skewness value of 0.28 (Figure 2, b). The sizing parameters are listed in the Table 1.

Table 1. Mesh size and elements characteristic dimensions for the three domains.

	Chamber Fluid Domain	Casing Fluid Domain	Liner Solid Domain
min edge length [mm]	2	3	2
max edge length [mm]	5	6	2
Elements	8.6M	3.8M	1.6M

The fluid-dynamic analysis was carried out using the commercial code ANSYS CFX v12.1.

For both of the fluid domains, the flow is turbulent. The standard k-ε turbulence model was chosen to predict the effect of the turbulence on the flow, on the heat transfer and on the combustion process itself. Because the value of Mach number is lower than 0.3 in the whole domain, the viscous effects can be neglected and the thermal energy heat transfer model is therefore used.

The combined eddy dissipation-finite rate chemistry model (EDM/FRC) is chosen to model the combustion reaction process. It uses a single-step reaction model and it describes the evolution of the combustion process through the calculation of the reaction rate. Other combustion models have been tested but EDM/FRC is the best option because of its capability of covering the whole range of Damkholer numbers, for both "turbulent mixing-dominated" and "chemistry-dominated" reaction rates.

Fuel composition has a big impact on the combustion reaction process. Natural gas is composed primarily of methane (CH_4) and between 0-20% of higher hydrocarbons. Laminar and turbulent burning velocities of the flame vary for different compositions causing an unstable behaviour of the flame. For this analysis, pure methane is used as fuel and a mixture O_2-N_2 as oxidizer (0.232-0.768 mass fractions).

The radiative effects on the heat transfer are modelled using the P1 thermal radiation model.

Chamber Domain

The complete burner geometry has been included in the chamber fluid domain to observe the effects of the fluid paths. The spin given by the burner swirling vanes and the gas injector location play an important role on the dynamics of the flame and its stabilization. The rate of mixing achieved affects the flame temperature, the recirculation zone (very important for the flame stabilization), the heat release and the maximum wall temperature.

Three different inlets have been defined: the air + quaternary fuel, the secondary gas inlet and the tertiary gas inlet. Measured mass flows and the species compositions (CH_4, O_2 and N_2 mass fractions) at the three different inlets for different openings of the fuel split line have been assigned as Inlet Boundary Condition (IBC) for the fluid domains.

Liner Solid Domain

Ansys CFX enables to create, through the conjugate heat transfer model, solid regions in which the equations for heat transfer are solved, but with no flow. Within the solid domains, the conservation of energy equation can account for heat transport due to solid motion, conduction, and volumetric heat sources:

$$\frac{\partial(\rho h)}{\partial t} + \nabla(\rho U_s h) = \nabla(\lambda \nabla T) + S_E \quad (5)$$

where h, ρ, and λ are the enthalpy, density, and thermal conductivity of the solid, respectively. U_s is the solid velocity, if specified, and S_E is an optional volumetric heat source. The solid motion advection term (the term including U_s) is also optional and is added only when a solid motion velocity is set. In the case considered, no solid velocity is set and the term is therefore neglected.

Nickel based alloys are generally used for combustion liners because of their high resistance to oxidation and corrosion and high temperature strength. The base material is internally covered by a thin layer of TBC (≈500 μm) which aims to reduce the metal surface temperature and protects the base material.

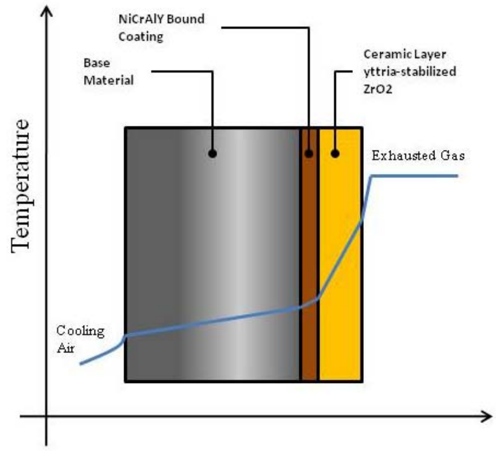

Figure 4. Composition of TBC Layers and typical temperature drop through the whole liner.

The TBC material is characterized by very low emissivity and low thermal conductivity. It is divided into two different layers: NiCrAlY bound coating (at the base material interface) and the ceramic layer composed by yttria-stabilized ZrO_2 which provide the highest resistance to the heat flux from the chamber wall to the GT casing (Figure 4).

The reduction of temperature at the interface with the base material achievable with this technique is about 100 °C.[1]

The material properties adopted for the calculation are listed in the Table 2.

Table 2. Material properties of the liner base material for the solid domain. Source: Haynes International, Inc.

	Values *
Molar Mass [kg/kmol]	60.25
Density [kg/m³]	8220
Specific heat capacity [J/(kg K)]	486
Thermal conductivity [W/(m K)]	9.1

* reference state: 25°C

Casing Cavity Fluid Domain

To account for the cooling effects of the compressor discharge air passing counterflow on the liner outer surface, the Casing Cavity fluid domain has been created. The mass flow and temperature of the fluid at the casing cavity inlet are obtained from the DCS system. The presence of a number of ribs on the outer side of the liner reduces the velocity field of the air, increase the residence time and enhance the heat transfer improving the cooling effect on the liner wall (forced convection). The mesh at the liner-casing interface has been refined in order to capture these effects. The calculated temperature at the outlet of the casing domain (pre-heated air) is used as input value for the air IBC at the chamber domain.

Selection of the Operation Points (OP)

Gas turbines are very flexible in operation, and depending upon market and grid conditions, their load settings can vary over the day, ranging between minimum load and base load

[1] Data on TBC materials and reduction of temperatures achieved at the BM-TBC interface has been estimated based on other modeling studies at the Structural Integrity Assessment and Monitoring (SIAM) department of Laborelec.

operation. Moreover, frequent start/stop operation of gas turbines is also widespread in order to deliver peak power. Six cases are selected in order to assess the weight of the changes in the operation variables on the thermal loads.

Table 3. Characteristic OP selected.

	OP 1	OP2	OP3	OP4	OP5	OP6
Power [MW]	243	177	117	243	243	243
Air Flow [kg/s]	30.9	21.43	20.05	24.7	30.9	30.9
Gas Mass Flow [kg/s]	0.72	0.5	0.47	0.72	0.72	0.72
Quaternary Fuel [%]	11	11	11	11	0	11
Tertiary/Secondary Fuel Split [%]	81.7	82.73	83.4	81.7	81.7	81.7
Compressor Air discharge Temp. [°C]	373	337	331	373	373	373
Compressor Air Discharge Press. [bar]	14.95	10.3	9.5	14.95	14.95	14.95
Equivalence ratio Φ	0.4	0.4	0.4	0.5	0.4	0.4
Liner material	BM	BM	BM	BM	BM	BM+TBC

The power output of the GT influences the flame temperature and the mass flow velocity. The fuel split modifies the temperature distribution inside the chamber generating non uniform gradients of temperatures at the liner surface.

OP1, OP2 and OP3 compare the behaviour at base load, intermediate and minimum load for premix steady state operation.

OP4 shows the dependency of changes in the Equivalence ratio Φ and their impact on the flame temperature [9].

OP5 is the scenario where the quaternary valve is closed. The quaternary line of the fuel system line delivers part of the total gas mass flow at the air inlet where a preliminary premixing is achieved. It helps to stabilize the flame and uniforms the gas mixture fraction.

Last case OP6, models the effect of the application of a 500 μm TBC layer on the inner surface of the liner wall. The calculation domain is composed by liner solid domain and casing cavity fluid domain. The boundary condition at the inner side of the liner is the temperature field exported from case OP1 reduced by 100 K in order to model the effect of the temperature reduction at the base material interface obtained. The goal is to look at the temperature profiles at the inner and outer surface of the liner.

The parameters describing the selected cases are listed in Table 3.

Results

The results of the thermal analysis performed for the six cases are presented in this section. The temperature profile are shown in Figure 5 while Table 4 and Figure 7 compare some of the calculated parameters.

The steady-state results of the model show the different distribution of temperature along the liner cross section plane passing through two of the burners mid-lines, one belonging to the four secondary burners and the other one belonging to the tertiary line. Differences in the temperature are calculated because of the reduced fuel concentration for the tertiary line.

The hot regions of the chamber are highlighted in the Figure 5. They are located at the recirculation zone over the top of the burner and at the outlet of the combustor liner where the temperature tend to be uniform.

The average value of temperature calculated at the outlet of the chamber is compared with the corrected exhaust temperature estimated by the DCS system at the first stage of the turbine nozzles (Figure 6). We observe a very good consistency between the temperature calculated by the CFD model and the estimated values from the DCS system at high and base loads (relative error ≈1.5%) and a small deviation at partial load (relative error 2.7%).

The turbulence in the flow generated by the swirlers affects the temperature distribution in the inner region of the chamber [10]. Wider cold regions are present at lower loads and the temperatures are less uniform then at base load.

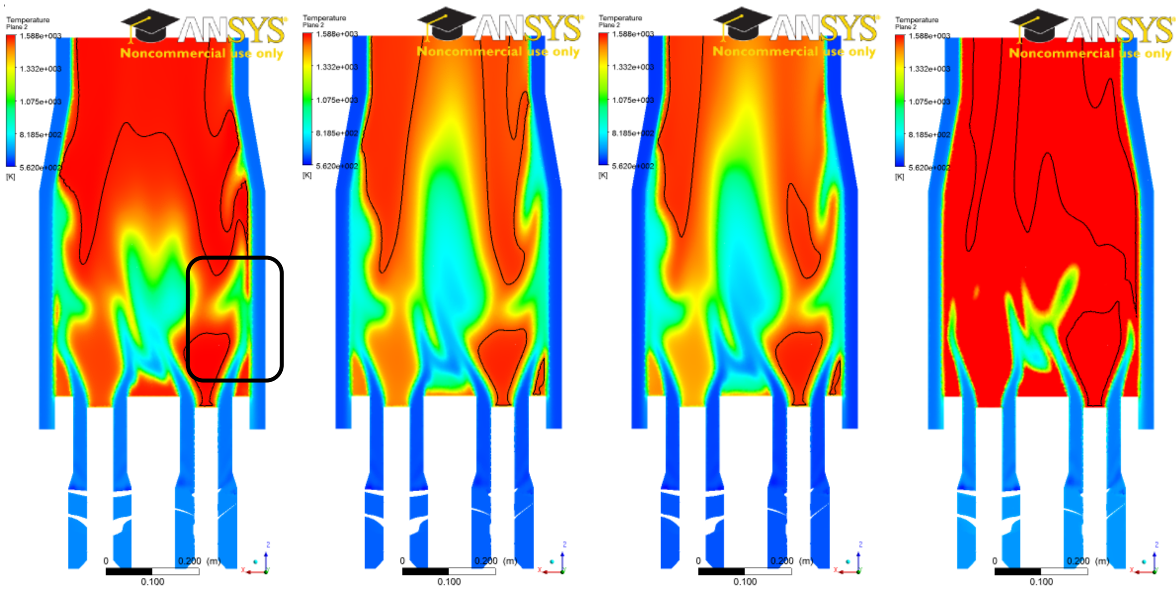

Figure 5. Temperature profile for the different operating points: OP1, OP2, OP3, OP4. The hot regions ($T > 0.95*T_{MAX}$) are highlighted with black lines. The location of the zoom-window from Figure 8 is indicated.

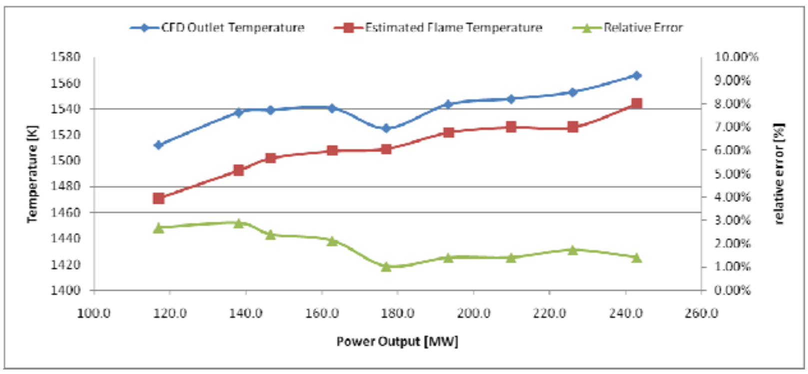

Figure 6. Comparison between the CFD calculated average temperatures at the chamber outlet with the estimated values from the DCS system.

Looking at the CH_4 mass fraction, the values for the average concentration calculated in a plane located at 1/8 of the combustor total length, show that the mixture is consumed faster at higher loads. Higher loads generates in fact higher flow velocity, the turbulence kinetic energy increase enhancing the mix between the gas and the air which benefit the combustion process itself.

Table 4. Calculated parameter for the cases selected.

	OP 1	OP2	OP3	OP4	OP5	OP6
T_{max} @Chamber [K]	1604	1568	1570	2011	1597	1604
T_{ave} @Chamber [K]	1300	1208	1189	1640	1291	1300
T_{ave} @Chamber Outlet [K]	1566	1525	1512	1955	1561	1566
Estimated T@Turbine Inlet [K] *	1543.95	1509.35	1471.11	-	-	1543.95
T_{max} Liner inner surface [K]	1398	1318	1293	1676	1393	1298**
T_{ave} Liner inner surface [K]	1116	955	920.4	1406	983.1	925.2
ΔT Liner [K]	215.4	147.1	120.2	302.6	206.8	170.6
Heat transfer coefficient [W/m²K]	2047.42	1808,25	1473,68	1333,24	2080,78	-
V_{ave} @Chamber [m/s]	80.38	75.91	74.23	78.14	79.57	80.38
Residence time [s]	0.019	0.021	0.021	0.019	0.019	0.019
CH_4 average mass fraction@h_section_plane	0.00584	0.00701	0.00727	0.00508	0.00596	0.00584
ΔT between casing cavity outlet and inlet [K]	30.22	24.94	25.38	49.48	28.94	23.20

* estimated values from DCS
**values at the base material-TBC interface

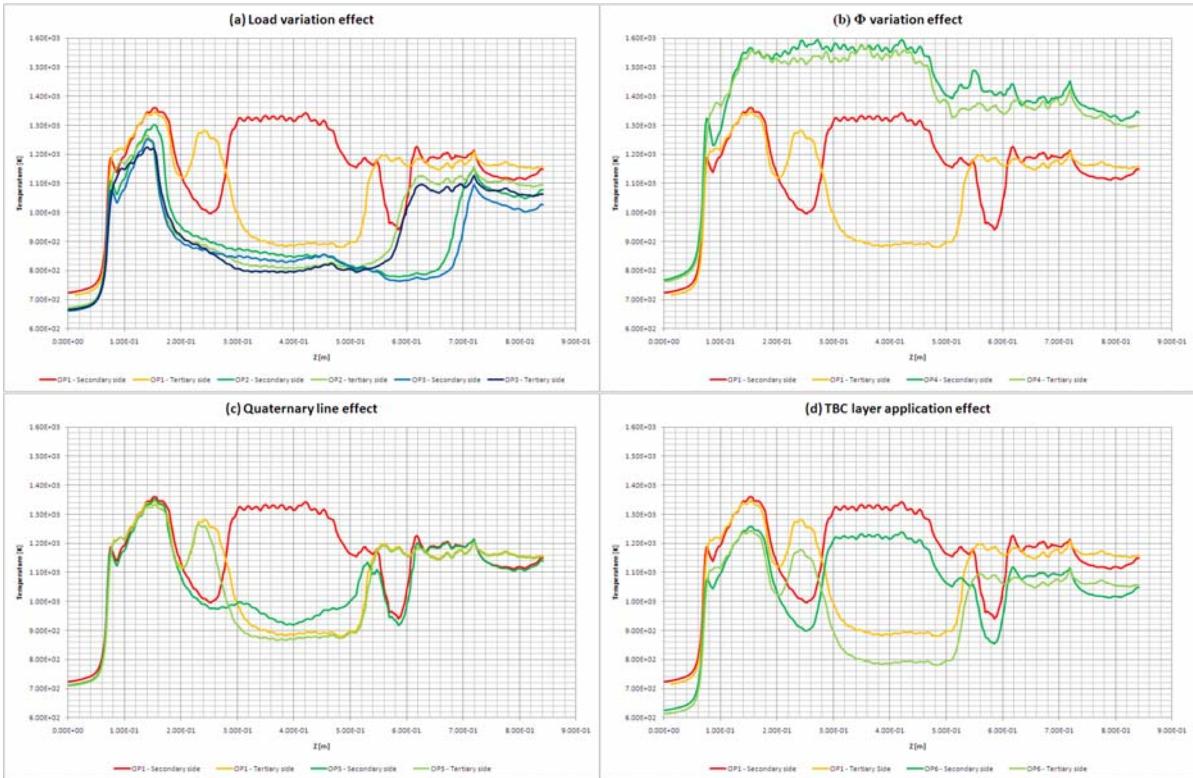

Figure 7. Comparison charts. Reference case: OP1. Values plotted along the axial line at the liner interface. (a) Load variation effects; (b) equivalence ratio variation effects; (c) quaternary line closure effects; (d) TBC layer application effects.

The heat transfer coefficient calculated at the liner interface for the different cases highlights the importance of the distribution of the temperature inside the chamber. OP1, OP2 and OP3 show a similar and proportional temperature distribution (Figure 7a) and therefore the calculated HTC is decreasing proportionally to the load output of the combustor. Figure 7b shows the effect of the Φ variation. For a higher value of the equivalence ratio, the difference in temperature between the solid surface and surrounding fluid area increases and therefore, the HTC decreases.

The OP5 results show the effect of the elimination of the fuel in the quaternary line on the thermal behaviour of the combustor. The technique is useful for the stabilization of the flame nevertheless, closing the quaternary valve could be beneficial for the liner walls because it lowers the temperatures at the liner interface as shown in the Figure 7(c).

Figure 8 presents a zoom of the chamber-liner-casing interface. The temperature gradients generated by the fuel splits and by the turbulent flow as well as the cooling effect on the outer liner surface are visible. The compressor discharge air passing through the cavity walls cools the liner and therefore the temperature of the discharge air increases (see Table 4). Because of the non-uniformity of the temperature gradients both in intensity and direction, the material reacts with different thermal expansion rates causing the bulging of the liner and degradation of the material.

Experimental data gathered estimates the reduction of the temperature at the BM-TBC interface. The results obtained by the CFD model indicate a reduction of the temperature gradient through the liner section to 309.4 K instead of the 394.9 K calculated for the BM without TBC layer (OP1).

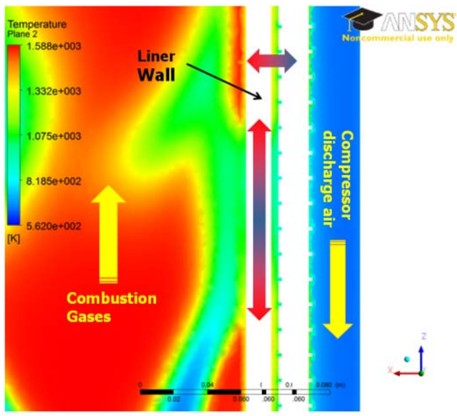

Figure 8. Temperatures gradient zoom at the chamber-liner-casing interfaces.

Conclusion

The energy released by the combustion reaction process inside the combustion chamber is transferred to the surroundings causing temperature gradients and heat flux oscillations in the liner solid domain that depletes the base material and coating and that damages the chamber walls. Degradation of the material properties, bulging of the chamber, crack development and release of damaged pieces downstream are some of the most common failures of the combustion liners.

Object of the study is to define the thermo-pressure conditions and their dependency from the OP at the liner wall surfaces (external and internal) for the development of an integrated fluid-structural model used for life time assessment of the combustor hardware.

The following conclusion can be drawn from this work:

- the fluid analysis performed on the complete combustion hardware shows its potential in the identification of the most dangerous operating condition for a GT combustor liner; the effect of certain parameters (operating conditions, liner materials, geometries, cooling flow) on the liner boundaries has been investigated;
- the models used for the simulation of the process are suitable for the purpose although the quality of the results needs to be further evaluated;
- the calculated values are consistent with those found in literature and measured during the operation of the GT. However, the model needs to be validated with measurement campaigns;
- detailed information on the temperature profile and heat flux can be obtained at the liner boundaries but, a more specific structural analysis needs to be implemented to investigate the effects of the thermal loads on the structure itself;
- a first approach in calculating the effect of the TBC on the temperature profile at the boundaries of the liner is feasible with fluid analysis calculations but it is not enough to investigate the heat flux and the thermal conditions at the base material-TBC interface unless a separate TBC domain is used for the calculation.

Nomenclature

CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
FEM	Finite Element Method
GT	Gas Turbine
IBC	Inlet Boundary Condition
DCS	Data Control System
BM	Base Material
TBC	Thermal Barrier Coating
HTC	Heat Transfer Coefficient
OP	Operation Points

Superscripts

cas	casing
ch	chamber
w	liner wall
conv	convective
cond	conductive
rad	radiative

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