[in:] TECHNICAL, ECONOMIC, AND ENVIRONMENTAL ASPECTS OF COMBINED CYCLE POWER PLANTS
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NUMERICAL MODELING OF DEGRADATION EFFECTS IN A GAS TURBINE SILO-COMBUSTION CHAMBER

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Abstract
The modeling of gas turbine combustion chamber with thermal and chemical processes is considered in the paper. Due to the limitations of the state-of-the-art numerical codes and insufficient information about the boundary conditions required for modelling of gas turbine degradation processes an original approach has been formulated that coupled advantages of parametrical (0D), CFD (3D) and CSD (3D) analyses. The results of computations have been compared with the measurements.

1. Motivations

Conventional and hybrid combined cycles with gasification, high temperature fuel cells, humid air turbines, etc. will become a significant part of modern power system.
Then the gas turbines which are employed in these cycles are gaining steadily in importance. On the other hand extremely restrictive emission limits[1], particularly with respect to nitric oxides NO_x, makes the gas turbines and their combustion chamber a sophisticated construction.
Gas turbine combustion chamber is a complex device where a wide range of strongly coupled, interacting physical and chemical phenomena occur. Some of these phenomena are connected with turbulent transport of mass, momentum and energy, finite-rate chemistry, toxic substance emissions, radiation and particulate behaviour.
Two main types of combustion chamber are nowadays in use. First of them is a silo-combustion chamber where the hot gases leave the combustor perpendicularly to the turbine shaft via an innerliner. In the next step gas is directed axially by HGC to the first stage of the turbine. This kind of chamber are employed in turbines GT8C and GT11N2 of ALSTOM Power construction.
However a strong non-uniformity of temperature field at the turbine outlet is expected for silo-combustion chamber under partial load of gas turbine. This shortcoming was partly overcome by introducing an annular combustion chamber as it was reported by Baerfuss et al. (2000) for GT8C2 and GT26 turbines. They shown in the paper that the inhomogeneity of the exhaust temperature profile arise from some gas impurities that may block or erode the gas holes of the burners.

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[1] New design concepts of gas turbines assumes NO_x emissions below 15÷20 ppm (Moore, 1997; Gabler et al., 1998; Badur et al., 2003b; Andreini and Facchini, 2004).

Fast degradation of the gas turbine elements as combustion chamber, innerliner and HGC can be also connected with some gas composition variation. Even small differences in a chemical composition of the fuel gas strongly influence a turbine operation.

2. Main parameters and perfomance of GT8C

Main parameters of the gas turbine were estimated on the base of parametrical analysis by means of COM-GAS code (Badur et al., 2004). The simplified parametrical 0D analysis gave us some useful information about the GT8C operation with nominal and real gas.
Operation performance were computed for constant turbine power and mass flow rate (N_e=54.5 MW and m=182.3 kg/s respectively) under normal air conditions.
Let's suppose that fuel composition vary slightly even if its low heating value is keeping constant (LHV=19.8 MJ/kg) for both cases.

Table 1. Composition of nominal and real fuels

	Nominal gas	Real gas
Nitrogen N_2	48 %	54 %
Methane CH_4	46 %	38 %
Ethane C_2H_6	4 %	4 %
Propane C_3H_8	1 %	3 %
Other	1 %	1 %

As a result the effective combustion temperatures are different. It has been shown, that the combustion temperature of second fuel can be higher than 10K from designed temperature. It accelerates the degradation of combustion chamber material (Inconel alloy) that is very sensitive even to small changes of operation temperature.

3. Modeling of EV burner degradation

Burners of EV type (Fig.1) are typically mounted in silo as in annular combustion chambers with lean premixed technology. The fuel supplied the burner is injected through numerous holes across burner cone slots and mixed with air entering tangentially.

Fig. 1. Model of EV burner (Badur et al., 2004)

Polifke et al. (1995) described a computational model for combustion processes in double cone type of burners. Performance of EV burners in annular combustor were investigated also by Hirsch et al. (2002). These investigations confirm generally good operation of EV burners for the case of pure fuel.
Let's consider the situation when some impurities exists in the combustible gas entering the burners. The modeling of the small discrete particles which are brought with gas under nominal condition of the turbine operation, reveales that most of them are directed to the last gas holes as in Fig.2.

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It may pointed that these holes are subjected to some degradation process. The potetntial change of the holes dimensions by an erossion process could significantly influence the conditions inside the combustion chamber and as a result the temperature distribution at the exhaust is more non-uniform (Badur et al., 2004).

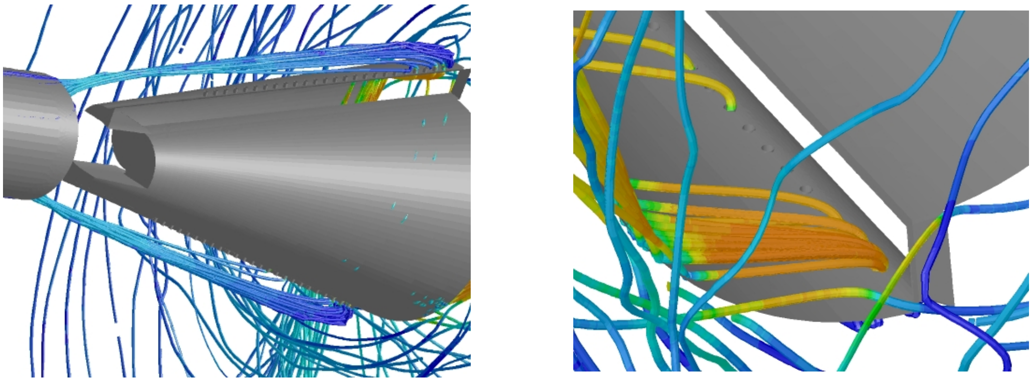


Fig. 2. Particle modeling in EV burner (Badur et al., 2004)

The same conclusions are draught when some of the gas holes are blocked by metal chips. In that case even annular combustion chamber gives the strong temperature differences at the turbine exhaust (Baerfuss et al., 2000).

4. Modeling of the temperature distribution at exhaust

Some interesting features are revealed during operation of turbines fitted with silo-combustion chambers. Especially part-load operation of these turbine leads to strong non-uniformity of the exhaust temperature fields. The temperature differences may reach even 150 as it was experimentally proved by Baerfuss et al. (2000).

The operation of the typical silo-combustion chamber fitted with EV burners at nominal and part loading conditions are investigated in the present study. The analysis involves three-dimensional EV burner modelling based on the external conditions computed by means of COM-GAS parametrical code 0D and its coupling with the three-dimensional silo-combustion chamber model via different profiles of velocity components, temperature and species distribution.

The set of burners and its position are presented in Fig.2 a) and b). A velocity vectors distribution at the chamber inlet could be seen in Fig. 2 c).

a) b) c)

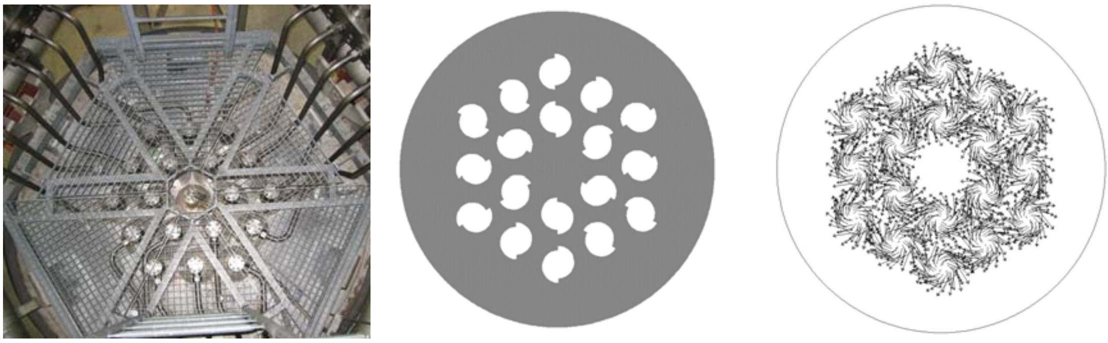


Fig.3. Set of EV burners in silo-combustion chamber (Badur et al., 2004): a) real turboset with three fuel-supply units, b) numerical model of chamber inlet, c) velocity vectors at the chamber inlet;

In Fig.4 one can find a visualisation of the silo-combustion chamber during a nominal operation when all of the eighteen burners are supplied by fuel gas.

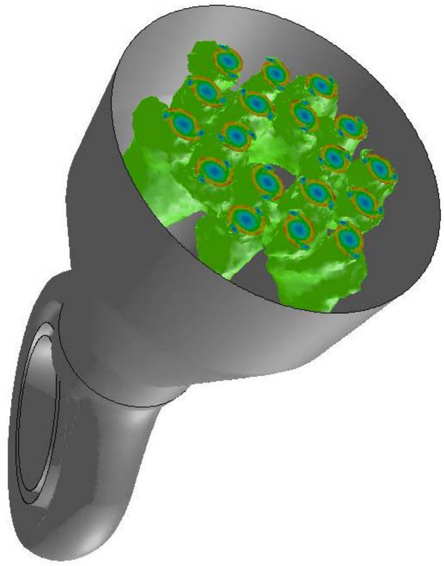


Fig. 4. Silo-combustion chamber during nominal operation (Badur et al., 2004)

For nominal state of operation only small differences of temperature are noticed at the turbine inlet (so respectively at turbine outlet). On the other hand, in the case of the part loading, which is here represented simply by blocking a particular burners the temperature fields at the exhaust are no more uniform.
Some normalized temperature[2] changes at measurements point at the outlet are presented in Fig.45 for operation with closed burners in sequence from 2 to18. The strong coupling between numerical results and the experimental data exists in this diagram.

[2] In the present study only the combustion chamber with innerliner and HGC were considered. The computational domain was then constrained by chamber inlet, walls of innerliner and HGC and the inlet to the gas turbine. On the other hand experimental data presented in this paper were obtained at the turbine exhaust (Lewandowski, 2003). Some normalisation of the results should be performed then to allow a directly comparison between numerical and experimental data sets (Badur et al., 2004).

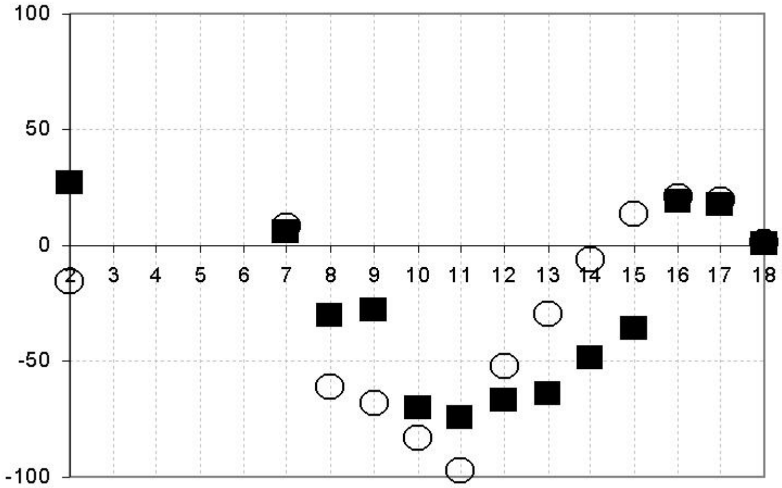


Fig. 5. Normalized temperature changes at turbine outlet for operation with closed burners from 2 to18 (○ measurements, ■ computations) (Badur et al., 2004)

The circumferential profile of normalized temperature at outlet in the case of single burner closing is presented in Fig.6. The computed temperature changes are rather similar with experimental data for this case.

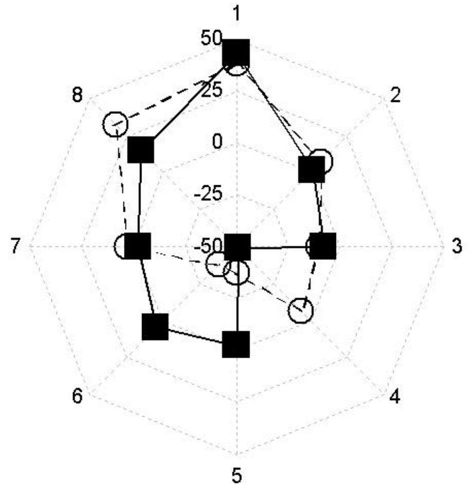
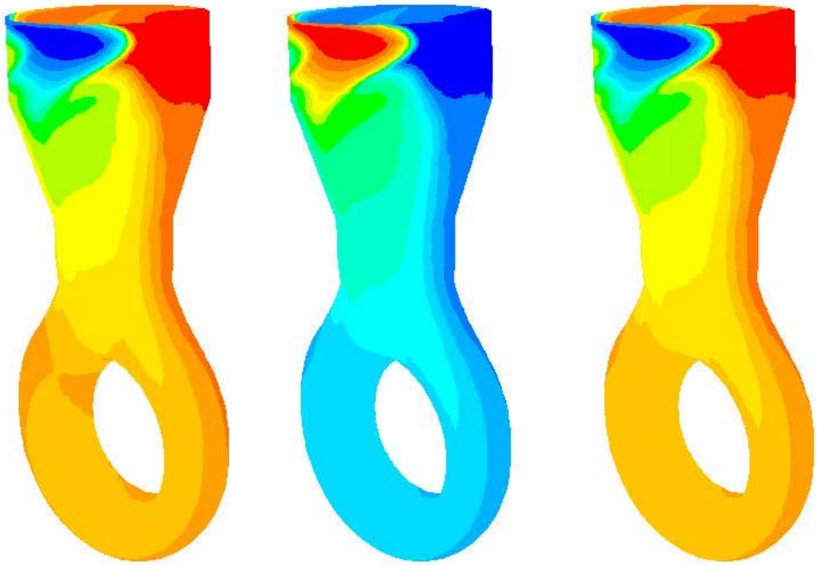


Fig. 6. Circumerential profile of normalized temperature at outlet for operation with closed one of burners (○ measurements, ■ computations) (Badur et al., 2004)

When a single burner is closed some nonuniformities of temperature and species distributions at the walls are expected as it is presented in Fig. 6. These nonuniformities are responisble for thermal and chemical loading of structure.



a) b) c)

Rys. 7. Case of single burner closing – examplery distribution of : a) temperature, b) O_2 and c) H_2O (Badur et al., 2004)

5. Modeling of the innerliner and HGC degradation

Proposed form of coupling (CFD+CSD) is based on simultaneous solving both sets of governing equations. The first one, describes the compressible hot flue gas after combustion process, the second one, describes a thermo-chemical loading on alloy of a chamber walls.

The thermo-mechanical coupling between the flow and deformation via energy equation was established and described earlier (Bielecki et al., 2001; Badur et al. 2003a). New procedure that beside of energy equation involves also a chemical species influence has been proposed (Kucharski, 2004). The results of flow and combustion in a silo chamber of typical gas turbine were directly prepared to damage analysis of the construction.

In this case degradation is caused mainly by high temperature connected with presence of gaseous hydrogen, oxygen and water that could migrate into material. High temperature leads to high stresses and material creep rates. Presence of hydrogen, oxygen and water in exhaust gas activate a chamber corrosion. Both proceses are running same time and they are conected with each other. Accelerated creep causes enlarged corrosion, and higher corrosion leads to faster creep. Modeling of these proceses are very difficult and needs some new looks at material degradation process.

Shortly we may write that model is based on two parts: mechanical and diffusive – reactive part which describes transport of chemical species in material as depence of local elastic and inelastic material strains. Both parts are conected through Gurson damage parameter. A simplified algorithm of degradation of GT8C combustion chamber is shown on Fig.8.

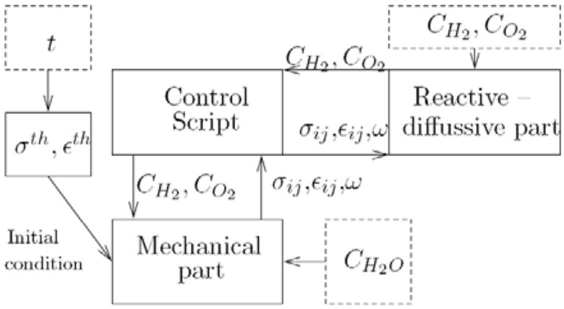


Fig.8. Algorithm of proposed corrosion model. Dashed line represents data obtained from CFD calculations; *t* – temperature, c^{χ} – concentration of chemical species, δ^{ter}, ε^{ter} – strains and stresses from thermal loads (Kucharski, 2004)

The evolution of Gurson damage parameter with two parts from local concentrations of hydrogen and oxygen is describes by an differential equation:

$$\frac{d}{dt}\omega = -\underbrace{\mathrm{div}\left(D_\omega \mathrm{grad}\omega\right)}_{\omega \quad diffusion} + \underbrace{\dot{\lambda}(1-\omega)N_{ii}}_{growth} + \underbrace{\mathcal{A}\frac{d}{dt}\bar{\epsilon}^p}_{nucleation}$$
$$+ \underbrace{A_5^{H_2}\frac{1}{2}C^{H_2}\exp\left(C^{H_2O}\right)}_{from \quad H_2} + \underbrace{A_5^{O_2}C^{O_2}\exp\left(C^{H_2O}\right)}_{from \quad O_2} ,$$

where, ω - damage parameter, C^{H_2O}, C^{H_2}, C^{O_2} – concentration of water, hydrogen and oxygen. A_5^x - calibration constants.

The results of computations are presented in Fig.8 for the case of 10000h operation of the gas turbine. The dark plumes represents places where damage processes are more intensive. They are strongly correlated with the temperature and hydrogen distributions at the surfaces.

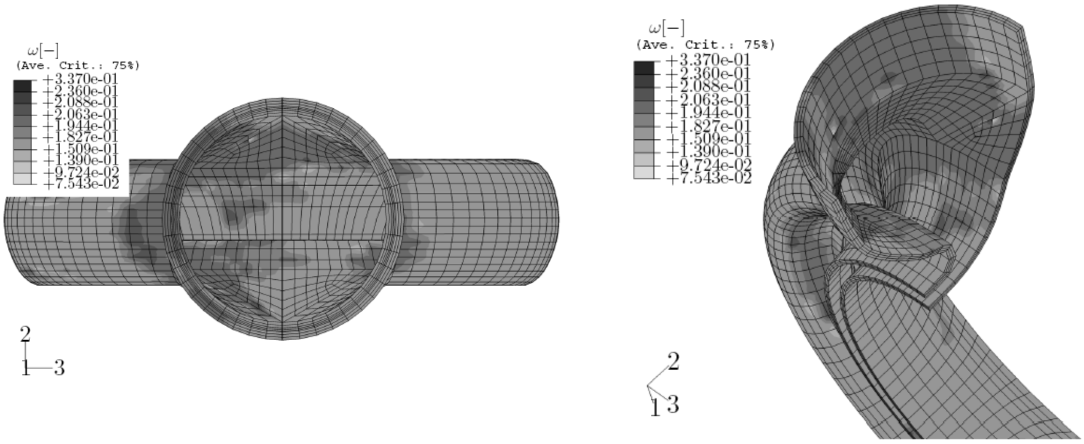


Fig. 9. Damage parameter of HGC after 10000h of operation (Kucharski, 2004)

6. Conclusions

Present analysis reveales some possible reasons that could be responsible for actual gas turbine combustion chamber degradation proces and their influence on overall turbine performance.

It is important to include all of the main processes from species transport and temperature distribution obtained from CFD analysis, to modeling a damage parameter by means of CSD. It should be pointed that the paramterical analysis is also important to estimate a boundary conditions for three-dimensional models.

It is possible to model such difficult processes by individual treatment of particular components and their coupling via an evolution equations. This approach gives us a possibilty of estimation of the actual degradation state, lifetime prognosis, toxic substance emission level with proper local distribution of different important parameters as the temperature, pressure, stresses, damage parameter, etc. even for strongly sophisticated devices.

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