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FINITE ELEMENT SIMULATION OF THE GAS TURBINE COMBUSTION

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Abstract: *Gas turbines are one of the key energy producing devices of our generation. Improved designs of gas turbine components are necessary in order to address the increasing demands of high performance and reduced emissions. This paperwork addresses the key issue of automated optimization by presenting optimization algorithms that are implemented in realistic design processes of gas turbine components. The results include algorithmic advances and the development of efficient designs for turbine components.*

Keywords: *FEA, gas turbines, optimisation, combustion.*

1. Introduction

Finding optimal solutions to real world design applications is usually an iterative process limited by the available resources. These limits may be the maximal number of possible computational and experimental design evaluations or the limited labor time of the design engineers. The development of optimal designs can be achieved by human designers or by exploiting automated optimization techniques. Human designers exploit their accumulated domain knowledge while automated optimization algorithms search by analyzing design evaluations resulting from a systematic parameter variation.

The setup of an automated optimization requires three steps. The first step addresses the automation of the data flow. The different evaluation tools of a design process usually require input data in different formats. For an automated data flow, interfaces are necessary in order to convert formats and to execute the evaluation tools without user interaction. Then, a large number of designs can be evaluated with minimal user time, while performing simultaneously sensitivity analysis and optimization. In the second step, the design objectives and constraints are defined along with the free decision variables that are allowed to be modified in the optimization process. The objectives and constraints have to be formulated as a function of the design evaluation and optimization then may be formulated as the classical mathematical problem of finding the extreme values of functions. In the third step, an optimization algorithm has to be selected.

For combustion processes, numerical simulations are still rarely used, since combustion processes are difficult to handle with today's computational techniques and computer resources. The underlying chemical reactions are complex and the mixing of fuel and air has to be sufficiently resolved since mixing is mainly responsible for the flame properties. Thus, experimental test-rigs are widely used to analyze combustion processes.

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A multi-objective optimization problem can be described by a vector of decision variables x and the corresponding vector of objectives $f = f(x)$. Without loss of generality we restrict ourselves to the minimization of all objectives, since every maximization of a function f can be transformed into a minimization problem with:

$$\max(f(x)) = -\min(-f(x)) \quad (1)$$

The multi-objective optimization problem is defined as the search for the set of solutions *x* that minimizes:

$$\begin{aligned} f(x) &= (f_1(x), f2(x), ..., f_m(x)) \in F \\ x &= (x_1, x_2, ..., x_{1n}) \in X \end{aligned} \quad (2)$$

where $X \subseteq R^n$ is the n-dimensional decision space, $F \subseteq R^m$ is the m dimensional objective space. Both decision and objective space are real spaces, as they correspond to continuous variables and objectives for the proposed applications.

The evolutionary optimization starts by generating an initial population of individuals at a generation $g = 0$. An individual i in the population consists of a vector of decision variables $x_i \in X$ where $X \subseteq R^n$, is the n-dimensional decision space. The population consists of λ individuals and can be described by $P_\lambda^g = \{x_i\}_{i=1,...,\lambda}$. In the evolutionary optimization, the population evolves over several generations g. Within each generation, the selection, recombination, and mutation operators are applied for different aims. The selection operator increases the fitness in the population by selection on average fitter individuals. Thus, selection decreases on average the diversity in the population. The recombination operator exchanges information in the population in order to spread good properties of solutions. Finally, the mutation operator increases diversity in the population by adding random variations to the decision variables.

On the other hand, the Finite Element Analysis simulation is becoming a standard tool to study the dynamics of turbulent flows into the Gas Turbines, being a key tool for predicting and studying the processes encountered in many combustion devices as gas turbines but, also, rocket engines or industrial furnaces.

Up to now the reacting flows, combustor geometries, thermodynamic and transport properties were limited to fairly simple schemes for obvious purpose of cost and complexity reduction. This study presents the computation of a rather complex system as the burner of a Gas Turbine available on market.

2. Multi-Objective Optimization of Combustion Process

It is considered the multi-objective optimization of the combustion processes for a single burner of a stationary gas turbine. The burner combusts fuel (methane) by a vortex stabilized lean premixed flame. The burner is analyzed by an atmospheric test-rig. In the test-rig, the combustion can be passively controlled by a set of valves that control the fuel flow rates though different fuel injection holes along the burner axis. Two different setups are considered using either 8 proportional valves to adjust the fuel flow at each injection hole or 16 digital valves which just open or close certain injection holes. Noise-tolerant Strength Pareto Evolutionary Algorithm (NT-SPEA) is applied to the Pareto optimization of the combustion process. The optimization results in an approximation of the Pareto front for minimizing NOx emissions and reducing the pressure fluctuations (pulsation) of the flame. Both objectives are conflicting and affect the environment and the lifetime of the gas turbine, respectively.

Figure 1 shows a state-of-the-art mid-size gas turbine. Supporting systems like the secondary air systems are not show. In the figure, the gas flow through the machine is from left to right. Ambient air enters the compressor first. Then the compressed air is burned in the combustion chamber and finally expanded in the turbine. The difference in power between the turbine output and the compressor input is the net power to generate electricity.

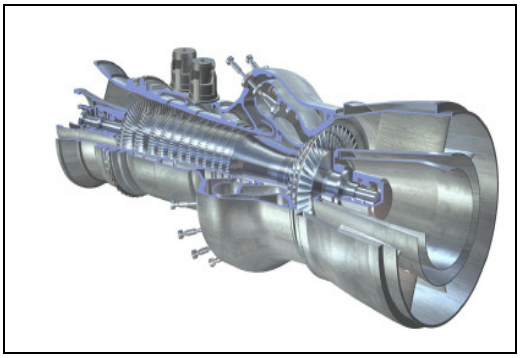

Fig.1. *Cut-away view of a gas turbine (Alstom Power).*

In today's machines, axial compressors generate pressure ratios between 1:15 and 1:30 and consist of about 20 to 30 stages. Each stage comprises a stator and rotor row. For the gas turbine in Fig. 1, the combustion chamber is annular around the turbine axis with a set of burners aligned in the annulus. The combustion products leave the combustor at temperatures of about 1200 – 1400^{0}C. The design of the turbine differs from the compressor. Since gaseous flow can be more easily expanded than compressed, only about 4 turbine stages are needed to expand the hot gas. Due to the high temperatures of the gas, the combustion chamber and the turbine rows need to be cooled.

A central component in the design of a gas turbine is the design of the burners in the combustion chamber as the burners are mainly responsible for the emissions of the machine and have a major impact on the thermodynamic inlet conditions of the turbine. The burners mix air and fuel and combust them continuously.

The design of a burner follows various objectives. The burner determines the position of the flame in the combustion chamber. The flame position should be well controlled, avoiding direct contact and thus damage on walls of the combustion chamber. Also, a uniform mixing of air and fuel is desired. Mixing is responsible for the emissions and the pressure pulsations of the combustion flame. For example, the presence of areas of rich combustion results in locally increased temperatures and NOx emissions. Local temperature peaks in the exhaust gas of the burner may damage the proximate turbine blades. Furthermore, the burner should produce a stable combustion flame, avoiding undesired pressure pulsations. Pulsations are thermo-acoustic waves, which occur in particular for very lean combustion when operating under part load condition. They can reduce the lifetime of the turbine, e.g., by fatigue and by local overheating the blades surface.

3. Atmospheric Test-rig for Gas Turbine Burners

The test-rig for a single burner under atmospheric pressure condition is illustrated in Fig. 2. Preheated air enters the test-rig from a plenum chamber. The air flows into the conical burner through two inlets as illustrated in Fig. 3. Along the inlets, fuel is injected and mixes with the air due to the difference in velocity.

The mixing is enhanced by the swirl in the burner that occurs due to its conical shape. A controlled vortex breakdown is caused by the difference in the cross-section between burner and combustion chamber. The flow re-circulates around the combustion zone. Recirculation stabilizes the combustion flame in a predefined combustion area. The fuel is methane and is injected through injection holes, which are uniformly distributed along the burner.

Gas analysis equipment and a microphone are used to measure all emissions and the pressure pulsations of the burner. Constant operating conditions are obtained by monitoring the airflow from the plenum chamber, the total fuel flow and the exhaust gas of the burner. The NOx emissions and the pulsation of the burner are the two objectives to be minimized in a Pareto optimization setup.

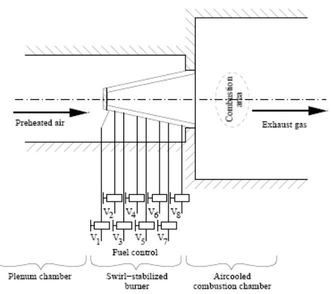

Fig.2. *Sketch of the atmospheric combustion test-rig with a low-emission swirl stabilized burner*

Pulsations are thermo-acoustic combustion instabilities, involving feedback cycles between pressure, velocity, and heat release fluctuations. The microphone measurements of the pulsation need to be time-averaged over several seconds. NOx emissions are exponentially dependent on the combustion temperature and occur especially in centers of rich combustion resulting from inhomogeneous mixing of fuel and air.

Figs. 3 and 4 show the valves that allow controlling the fuel flow distribution along the burner axis. The fuel injection is controlled with two different setups by either 8 proportional valves to individually adjust the fuel flow for the different fuel injectors or by 16 digital valves, which include or exclude fuel injectors along the distribution holes.

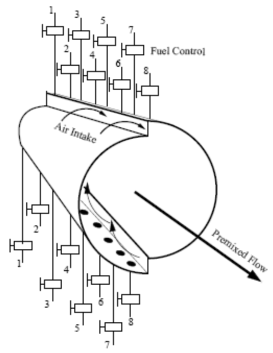

Fig.3. *Sketch of the EV burner. The burner consists of two half-cones with a certain offset, such that between the two half-cones two intakes emerge.*

4. The FEA Model

The FEA model of the Combustor of the Gas Turbine given in the Fig.1, is, somehow, complementary to the optimization model, allowing obtaining analytical results to completely describe the combustion process inside the Gas Turbine.

Up to now the reacting flows, combustor geometries, thermodynamic and transport properties were limited to fairly simple schemes for obvious purpose of cost and complexity reduction. This study presents the computation of a rather complex system as the burner of a Gas Turbine available on market (with main dimensions and input data changed),shown in Figure 1.

The second objectives of this study is to investigate the main thermodynamic parameters of the combustion process of the optimized Gas Turbine, as flows, velocities, temperatures and pressures, and supplementary, to investigate the main species mass fraction distribution and physical properties as enthalpies, entropies and so on.

The "negative" of the CAD simulation to simulate the flow paths of air and CH_4, is given in the Figure 4 and 5.

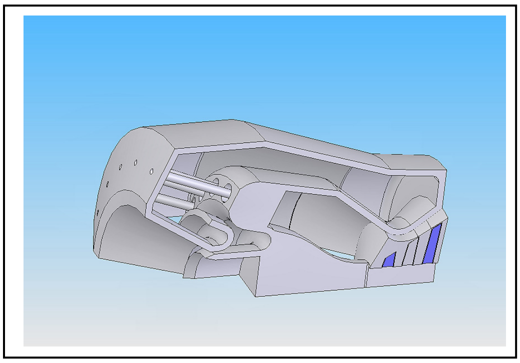

Fig.4.*The CAD geometry*

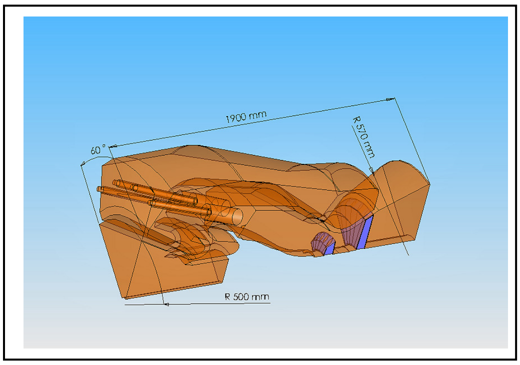

Fig.5. *The "negative" of the CAD geometry simulating the flow paths of Air, Fuel (methane) and combustion products*

On the above figures it may be identified the air inlet area having the diameter of *500 mm*, the fuel inlet in burners, having the diameter of *30 mm*, and the outlet area for the combustion chamber having the diameter of *570 mm*. The entire modeled assembly has the overall length of *1900 mm*. It was generated only a slice of 60^0 of the burner for computational purposes, the exit of the burning gases is passing through the two rows of blades of turbine, colored in blue on the figure.

5. The FEA Model for Flow Simulation

In simulating the flows in FEA models, the equations of mass, momentum and energy conservation has to be solved and additional transport equations should be considered when the flow is supposed to be turbulent, which is our case too.

The equation for mass conservation is:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{v}) = S_m \tag{3}$$

For the inertial reference frame, the momentum conservation equation is:

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla(\rho \vec{v}\vec{v}) = -\nabla p + \nabla \tilde{\tau} + \rho \vec{g} + \vec{F} \tag{4}$$

where the stress tensor is given by:

$$\tilde{r} = \mu\left[\left(\nabla \vec{v} + \nabla \vec{v}^T\right) - \frac{2}{3}\nabla \vec{v} I\right] \tag{5}$$

6. Input Data for the FEA Model of the Combustor Area and the Outlet

The Finite Element Grid comprises 763.892 tetrahedral cells, as it's seen in figure 6.

Species Properties Table 1

	CO_2	CH_4	N_2	O_2	H_2O
Weight [kg/kgmol]	44.009	16.043	28.013	31.998	18.015
Enthalpy [J/kgmol]	-3.93e8	-7.48e7	0	0	-2.41e8
Entropy [J/kgmolK]	213715	186040	191494	205026	188696

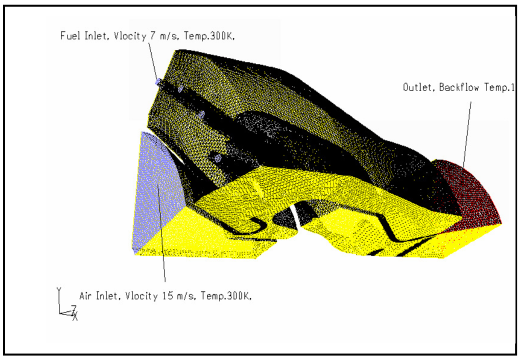

Fig.6. *The finite element's grid*

There were defined the boundary conditions as follows:

-The air-inlet zone having a hydraulic diameter of *0.25 m*, the temperature of 300^0 *K* and the velocity magnitude of the air coming from compressor, *15 m/s*.

- The fuel-inlet (CH_4) zone modeling the inlet into the burners, having a hydraulic diameter of *0.03 m*, the temperature of 300^0 *K* and the velocity magnitude, *7 m/s*.
- The outlet zone modeling the outlet from the blades row, having a hydraulic diameter of *0.27 m*, the backflow total temperature of 1000^0 *K* .
- The walls have been set to have the temperature of 900^0 *K*.

The mixture material is methane-air, and the defined species are CO_2, CH_4, N_2, O_2, H_2O, with the properties given in Table 1.

The specific heat for the mixture was taken accordingly a mixture law and for each species this was deemed non-constant, obeying a piecewise-polynomial function.

7. Numerical Predictions and Discussion

The program, after 500 iterations, provided the results discussed below:

Pressure

The maximum pressure (Fig.7) was found to be $34.2e^6$ *Pa* in the burner zone and right before the blades row, in the outlet zone decreasing sharply, being identified some portions with cavitations conditions (min. pressure $1.1e^5$ *Pa*).

Velocity

Starting from the burner's zone, the velocity of the fluid (Fig.8) sharply augment to *119 m/s,* the maximum being calculated in the blades row and outlet zone where, on very thin areas, it reaches the staggering value of *2380 m/s*, about *7* times the speed of sound.

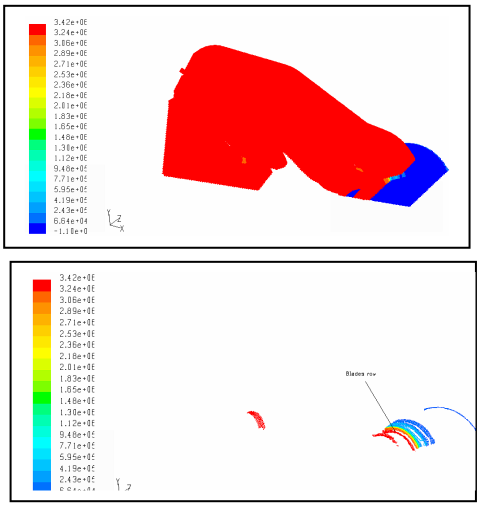

Fig.7. *The pressure distribution*

Species Properties Table 1

	CO_2	CH_4	N_2	O_2	H_2O
Weight [kg/kgmol]	44.009	16.043	28.013	31.998	18.015
Enthalpy [J/kgmol]	-3.93e8	-7.48e7	0	0	-2.41e8
Entropy [J/kgmolK]	213715	186040	191494	205026	188696

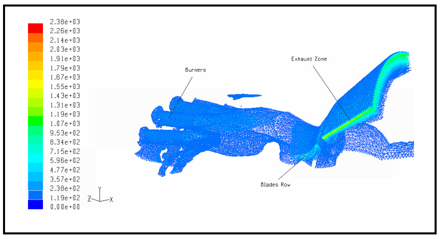

Fig. 8. *The velocity distribution*

Temperature

The highest temperature, as is expected, was calculated in the burner's zone, where it achieves the maximum value of *1870* ^{0}K, in the exhaust zone being *926* ^{0}K.

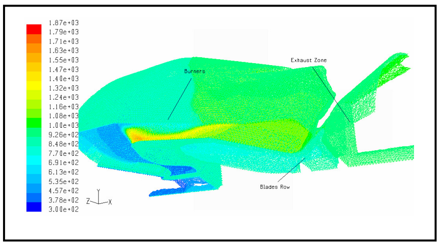

Fig.9. *The temperature distribution*

Specific Heat

As was stated above, the specific heat (Fig.10) for each species was deemed to obey a non-constant piecewise-polynomial function, the mixture being calculated considering a mixing law, therefore the specific heat varies within the domain, reaching a maximum of *4090 J/kg-K* in the burner's and outlet zone, in the rest of the domain being averaged on *1470 J/kg-K*.

Enthalpy

The maximum enthalpy (Fig.11) was calculated in the burner and blade's row zones, reaching a value of $2.35e^{6}$ *J/kg*, the rest of the domain having an average of $3.55e^{5}$ *J/kg*.

Entropy

The entropy distribution (Fig.12) follows the same pattern as enthalpy; the maximum was calculated in the burner and blade's row zones, reaching a value of $3.34e^{3}$, the rest of the domain having an average of *700*.

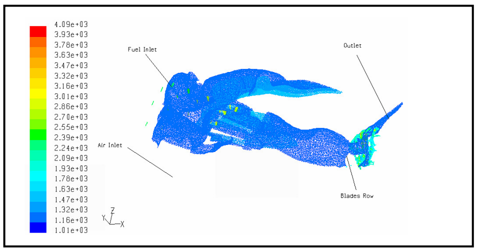

Fig. 10. *The specific heat distribution*

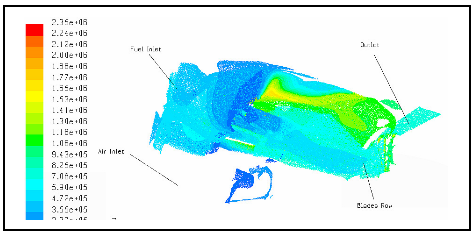

Fig.11. *The enthalpy distribution*

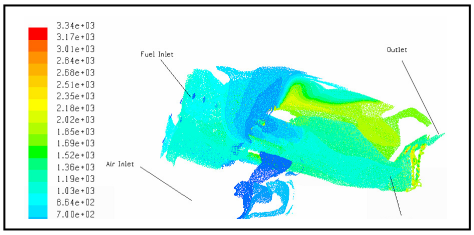

Fig.12 *The entropy distribution*

8. Conclusions

Optimization of engineering problems in an automated setup requires blending of domain knowledge with expertise in optimization techniques. Analysis of the problem specific requirements is always the first step in setting up an automated optimization. Then, an optimization algorithm is chosen with respect to the problem requirements. The characteristics and capabilities of efficient optimization algorithms can be identified by comparing different algorithms on test functions.

The test functions should be selected such that they reflect the assumed problem features. Improvements of existing algorithms are often necessary, when the performance of the different algorithms is not satisfying for these functions.

The proposed method of optimization is also highly suitable for other problems sharing key features with the design of gas turbine components such as noisy and conflicting objectives, expensive function evaluations and only point-wise information about the objective functions. Experimental test-rigs for gas turbine burners represent a noisy multi-objective problem. The goal is to obtain an approximation of the Pareto front for minimizing NOx emissions and for reducing thermo-acoustic pressure waves (pulsations). Both objectives are time averaged measurements and thus noisy.

This paperwork illustrates that automated optimization can find excellent solutions to complex engineering problems. However, a prerequisite is the careful setup of the optimization process with expertise in both optimization algorithms and the problem to optimize.

The numerical results are highly dependant of the input parameters and the geometry of the combustor, the optimization of this sensitive area of the gas turbine leading to the final results of the overall efficiency of the turbine and the noise/NOx effluents.

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