IDENTIFICATION OF A MODEL FOR MONITORING NITRIC OXIDE EMISSIONS IN A GAS TURBINE POWER PLANT

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The development and the identification of a model for the analysis of an aero-derivative gas turbine power plant employed in natural gas pipeline stations are presented. The purpose is establishing a method for prediction and remote monitoring of pollutant emissions, in particular nitric oxide, starting from the operating data provided by the usual gas turbine control unit.

Thermodynamic models of both plant and components are employed, including a chemical kinetics based simulation of NO formation. The full set of thermal cycle parameters is identified via proper optimisation techniques, starting from a limited set of operating data. A good agreement with experimental data is achieved. In addition, unreliable operating data can be interpreted and detection of either component or sensor fault is allowed. Continuous on-line prediction of both performance and emissions during the normal gas turbine operation, when only the normal control unit is active, can be then achieved. Some preliminary results obtained by use of components matching approach are also presented, and the potential advantages discussed.

The methodology can be also considered a basis for the definition of strategies for part-load operation planning and load sharing between several gas turbine units, with the objective of minimum pollutant emission.

1. Introduction

As it is known, an increasing attention is paid to the environmental impact of gas turbine (GT) power plants, and in particular to nitric oxides (NO_x) emissions, which greatly influence air and water quality. A relevant application of GT power plants is represented by natural gas pipeline stations, most of which are controlled with remote monitoring techniques [1,2,3,4,8,9]. It is therefore of primary importance the precise knowledge of NOx emissions of GT power plants, at the various operating and ambient conditions.

The results of a research work performed by the authors in co-operation with SNAM are presented. A model based approach combining the available theoretical and experimental information on the system is proposed, with the following purposes [15,20]:

- enhance the reliability of the measure provided by on-line emission sensors, also detecting their possible failures;
- check the physical consistency of the data measured by the GT control unit, providing information on components or sensor faults;
- in principle, eliminate the necessity of a continuous direct emission measure, which could be substituted for a periodic use of a mobile station to check model accuracy, with significant reduction of costs;
- develop a computational tool providing detailed information of power plant, allowing an effective control of the operating variables and a continuous monitoring of plant and component performance.

2. Power Plant Description

The scheme of the gas turbine power plant employed in a natural gas pipeline station is shown below (Figure 1). Three gas turbines PGT25 produced by "Nuovo Pignone" are actually used in the gas station. Their main technical characteristics referred to I.S.O. standard conditions are reported in Table 1. The gas turbine (T_{LP}) is employed to drive a centrifugal compressor (C_{NG}) for natural gas pumping in the pipeline. An amount of the natural gas is then supplied as fuel to the gas turbines. Detailed information on gas mixture composition and operating conditions of the centrifugal compressor are reported in previous papers[20.15].

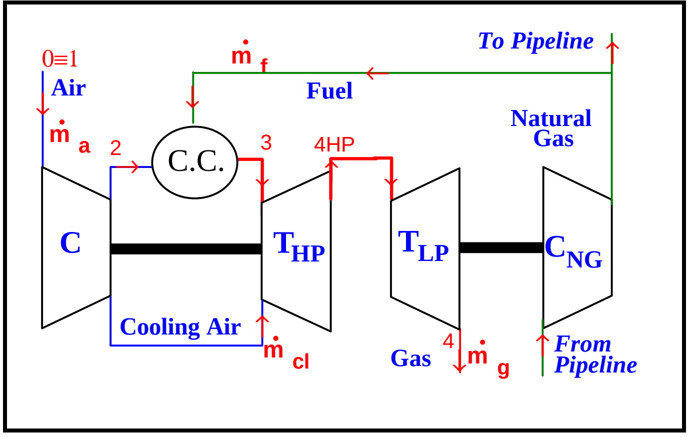

Figure 1 - Scheme of the gas turbine power plant for natural gas pipeline station

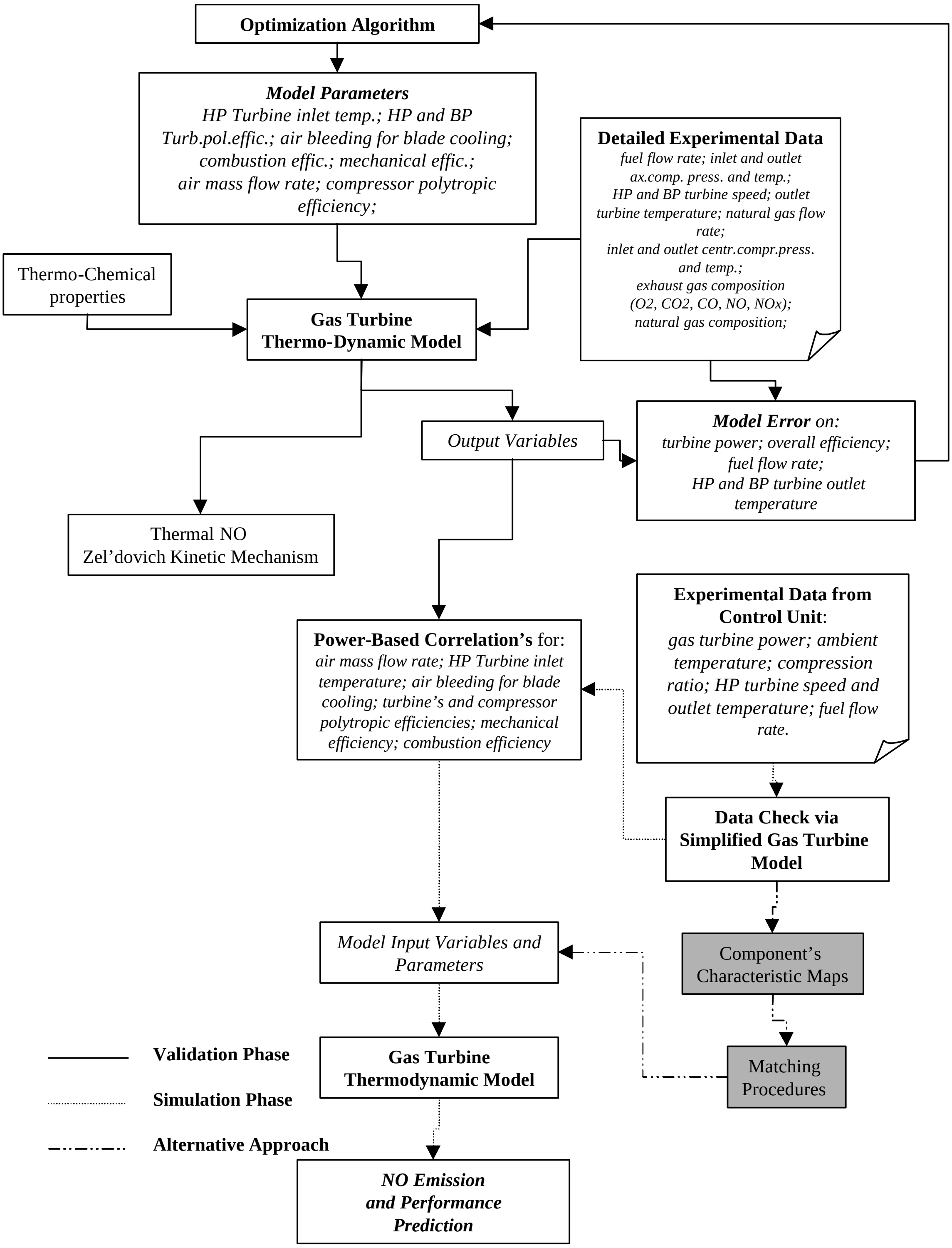

Figure 2 - Block Diagram of the Modelling Process

Mechanical Output	23266	kW
Heat Rate	9563	kJ/kW
Thermal Efficiency	0,3764	
Air flow rate	66,7	kg/s
Compressor Pressure Ratio	18.8	
HP Turbine Exhaust Temp.	813	°C
LP Turbine Exhaust Temp.	527	°C
HP Turbine Rotational Speed	9565	rpm
LP Turbine Rotational Speed	6500	rpm

Table 1 - Gas Turbine Nominal Conditions

The most important operating variables are measured by the power plant monitoring system. More detailed measurement, including the natural gas composition and GT exhaust analysis can be periodically performed by using a mobile monitoring station. A description of the measured variables is reported in Figure 2.

The results discussed in the paper have been obtained by analysing two different sets of data:

- A first complete set of experimental data measured by a mobile monitoring station over about two months, during winter season. This data set is related to 36 different operating conditions, with a mechanical power ranging from 8000 to 20000 kW and within the following ambient conditions: Pressure: 0.924 - 0.940 bar; Temperature: -2 - +12 °C; Relative Humidity 30-100 %.
- A second set of about 1000 data (*historical* data) provided by the usual power plant control unit.

A detailed analysis of the measured data can be found in previous papers [20].

3. The Modelling Approach

The methodology for remote monitoring of gas turbine power plant is based on combined use of thermodynamic models in both direct and inverse mode, as explained in the following, and of experimental data, at different levels of detail. A pictorial scheme of the modelling process and the connections between models, variables and experimental data is described in Figure 2. A discussion on the advantages of distributed and hierarchical modelling approach, with reference to similar physical systems, can be found in recent papers of the authors [21,22].

A comprehensive thermodynamic model, described in previous papers [16,17,18,19], has been used to perform these calculations.

In order to evaluate power plant emissions, the operating conditions of the gas turbine must be known, with particular regard to the following variables which affect the combustion process:

- the inlet gas temperature in HP Turbine or, more precisely, the final value of "firing temperature profile" in combustion chamber, which greatly influences power output and thermal NO_x formation;
- the local Air-Fuel ratio during combustion; in order to evaluate the actual air flow rate in this phase, it is therefore important to estimate the air bleeding rate for blade cooling (12).

Since a direct measure of these variables is not currently performed by the monitoring systems, they must be estimated starting from the available data, via inverse modelling approach.

In a second phase, performance and emissions are estimated starting from a more limited set of variables measured by the gas turbine control unit (historical data), by combined use of the thermodynamic model and of correlations obtained by the previous data. To reduce computational time, a simplified thermodynamic power plant model is also used to check the consistency of the historical data set.

3.1 Model Validation and Parameter Identification

In the first phase, the unknown operational parameters, not directly measured, are identified by combined use of an advanced thermodynamic model and optimisation techniques, using the detailed data provided by the mobile measuring laboratory.

The following model input parameters have been estimated:

- Inlet temperature in High Pressure Gas Turbine; HP and BP gas turbine polytropic efficiency; Cooling air mass flow rate for HP turbine blades (or, alternatively, the actual blade temperature); Combustion efficiency; Mechanical efficiency.

These variables have been determined by non-linear optimisation techniques [14], by minimising the error between the measured and computed values of the following variables:

- TG power; overall thermodynamic efficiency; fuel mass flow rate; outlet HP turbine temperature; outlet BP turbine temperature.

The resulting non-linear optimization problem has been solved by an augmented Lagrangian approach [14]:

$$(1.)\qquad f(\bar{x}) = \delta_{mq} + \sum_{j=1}^{4} \lambda_j \delta_j + \Pi \sum_{j=1}^{4} \delta_j^2$$

In order to enhance result reliability, both first and second order minimisation techniques have been used:

$$(2.)\qquad \min\left[f(\bar{x})\right] \Rightarrow \begin{cases} s(\bar{x}) = -t * \nabla\left[f(\bar{x})\right] \\ s(\bar{x}) = \nabla\left[f(\bar{x})\right] \cdot \mathbf{H}^{-1}\left[f(\bar{x})\right] \end{cases}$$

The second order technique was adopted in case that the Hessian matrix resulted positive definite. Otherwise, a first order gradient technique was selected to determine the optimal solution.

To reduce the computational effort, a simplified model has been used to evaluate gas properties, based on accurate thermo-chemical properties description for the given fuel provided by a detailed model. A good agreement between these two models has been achieved.

Different identification strategies have been adopted, in order to check possible errors in the experimental data. In particular, air flow rate and compressor polytropic efficiency should be considered as known, if reliable experimental data were available, but in some cases their values were affected by significant variations [20]. It is therefore important to check if these effects are due to a decay of compressor performance or, rather, to measurement inaccuracies or errors. Similar arguments can be drawn for air flow rate, whose variations cannot be completely explained by physical considerations.

Three different cases have been therefore defined:

1. Air flow rate and compressor efficiency are considered known;
2. Only air flow rate is estimated, while compressor efficiency is considered known;
3. Both air flow rate and compressor efficiency are estimated.

Some representative results are shown in Figure 3. The best results have been obtained by the third method, which leads not only to a lower value of mean quadratic error, but also to more regular trends for operating variables (20), and to overcome the discrepancies on compressor efficiency between the different tests.

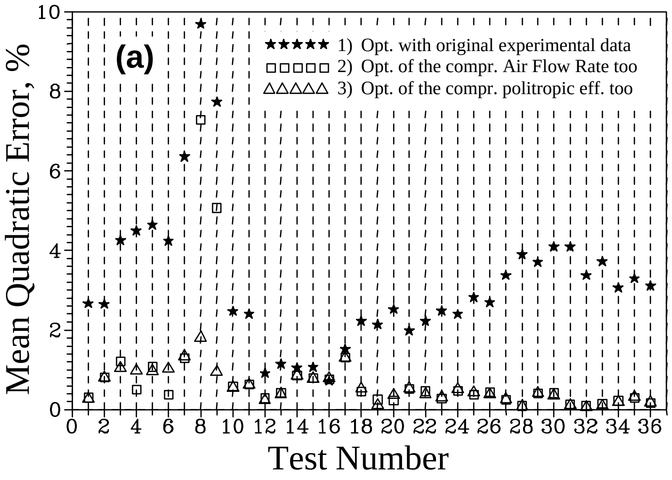

Figure 3 - Effect of the Optimization Strategy

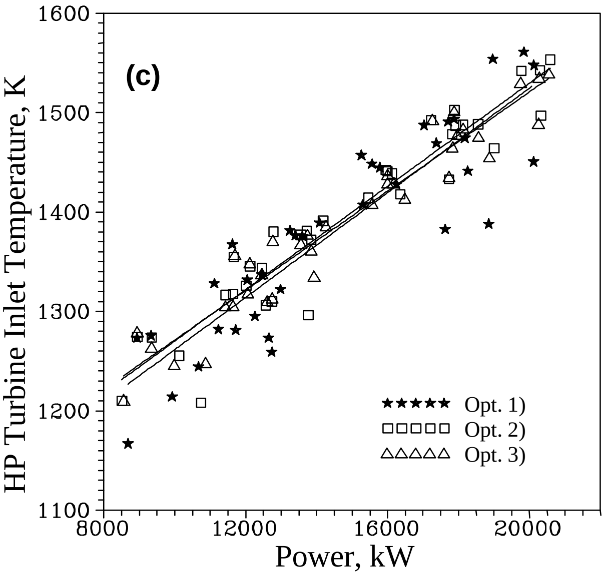

Figure 4 - HP Turbine Inlet Temperature.

The third method has allowed a more reliable estimation of both HP turbine inlet (Figure 4) and blade temperatures (Figure 5), as well as of air bleeding rate, which determines a variation in the local gas composition inside combustion chamber and exerts a relevant and non-linear influence on the kinetics of NO_x formation processes.

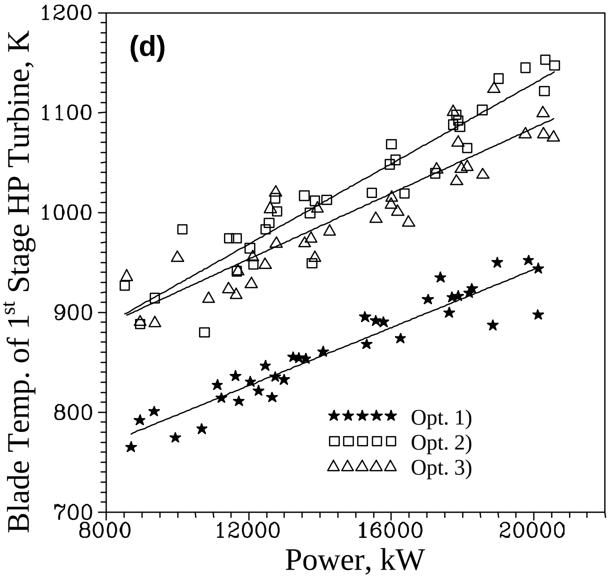

Figure 5 - 1st Stage HP Turbine Blade Temperature

3.2 Post-processing of the model validation results

The results of the previous computations, obtained by the third identification method, were then processed.

The NO emission have been computed using a thermo-chemical model based on Zel'dovich mechanism (13). Acceptable accuracy has been achieved (Figure 6) (20,15).

In order to provide a complete input data set for the subsequent use of the model in predictive mode, suitable correlations with turbine power have been derived for the following variables:

- mass air flow rate; HP turbine inlet temperature; cooling flow rate; polytropic efficiencies of turbines and compressor; mechanical efficiency; combustion efficiency.

Non linear regression techniques have been used in this phase [14].

An alternative approach would consist in the use of the characteristic maps of compressors and turbines, with suitable matching procedures (grey boxes in Figure 2). A description of this technique, with preliminary results, is in course of publication.

3.3 Use of the model in predictive mode

Once that the model has been validated over the first set of more detailed data, it has been applied to predict the emissions corresponding to a larger set of about 1000 operating conditions (historical data set), where only more limited set of experimental information, provided by the turbine control unit, were available (Figure 2). The missing input data have been provided by the power-based correlations.

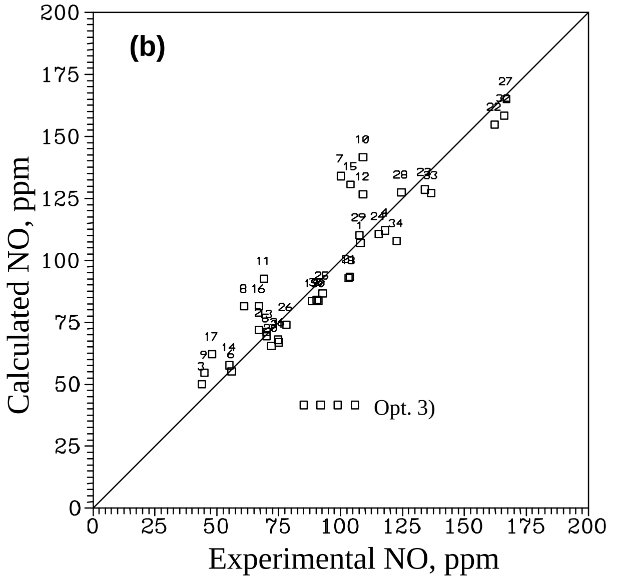

Figure 6 - Comparison of computed and measured NO emissions

Some comparisons between the variables in the historical data set and those of the previous detailed data sets are reported in Figure 7. It can be noticed that the historical data covered the range from 3000 and 19000 kW, wider than the range analysed in the previous set. Therefore, some uncertainty due to extrapolations can be expected at part loads, where, however, temperatures and NO emissions are lower.

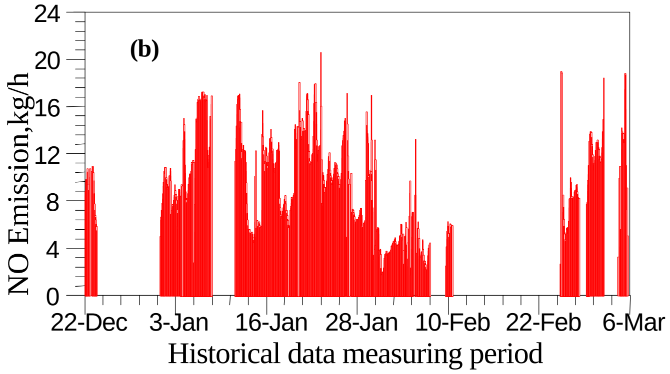

Figure 7 - Estimated NO Emission during the Monitoring Period

4. Conclusions

A technique for the thermodynamic analysis of gas turbine power plants oriented to the monitoring of a natural gas pipeline station has been presented. The proper combined use of experimental data and mathematical models, at various level of detail, allows to predict performance and emissions on the basis of a limited set of measured data, detecting also possible errors and failures in measuring system. An inverse modelling approach, with use of optimisation techniques, has been then adopted, with various strategies. Suitable correlations between the power plant load conditions and the model input data have also been derived.

A combined use of physical and regression based models has been subsequently adopted for rapid monitoring purposes, in order to estimate, on-line, performance and emissions for any load condition. The results have been proved to be robust with respect to ambient condition variations and component defections, due to the fact that it has been validated starting from an accurate thermodynamic model rather than only from statistical analysis of measured data.

Further work is in progress to include systematic evaluation of statistical significance in the identification process, and to develop component's matching procedures, in order to overcome some intrinsic limitations of the thermodynamic approach and to extend the capabilities of the plant monitoring tool.

5. Nomenclature

λ	Lagrange multiplier
Π	Penalty factor
δ	Mean quadratic error
f	Objective function
H	Hessian matrix
s	Research step
x	Independent variable vector

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