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COMPUTATIONAL TOOL FOR GE7FA THERMAL PERFORMANCE DIAGNOSIS

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Abstract. *A computational tool was developed for the thermal performance diagnosis of the GE7FA gas turbine. Gas turbine models in design and off-design conditions were developed in the GateCycle™ software for thermal schematics simulation from routine performance test data. A thermoeconomic model was defined; using an adaptation of the Structural Theory, for thermoeconomic calculations and the Fuel-Impact approach was implemented for thermal performance diagnosis. Parametric studies were done to validate the sensibility of the developed models. Variations of compressor isentropic efficiency, combustor efficiency, turbine isentropic efficiency, bleed valve leakage, among others malfunctions were studied to observe the deviation caused in the electricity cost. Some simple cases of intrinsic malfunctions in the components were introduced to show the potential of the computational tool for the thermal performance diagnosis. It was concluded that the models have satisfactory fuel-impact response when intrinsic and induced malfunctions are present, and that the computational tool that was developed is suitable for the thermal performance diagnosis of the GE7FA gas turbine.*

Keywords: *Thermoeconomic diagnosis, Thermal schematics simulation, Fuel-Impact, Gas turbine, Exergy.*

1. INTRODUCTION

Valero, *et al*., 2004a, understood that the general objective of thermoeconomic diagnosis is the detection of the efficiency deviation, its economic worth and location of its main cause. The efficiency deviation is caused by performance variations of a plant component, which in turn may have different causes, either external to the plant (variations of ambient conditions, plant production and fuel quality) or internal, which are presence of anomalies due to the component degradation (also called intrinsic malfunctions), efficiency variations induced by modifications of the component operation conditions, and control system intervention. In this sense, the aim of this paper is to show the computational tool that was developed for the thermal performance diagnosis of the GE7FA gas turbine as well as its theoretical fundamentals.

2. LITERATURE REVIEW

The thermoeconomics yields a particular approach to the problem of diagnosis of energy systems, of which a general definition might be proposed in an intuitive way as: how much every deviation in performance parameters affects the cost (Valero, *et al*., 2004b). Several approaches about thermoeconomics diagnosis could be found in the following literature (Lazzaretto, *et al*., 2006):

– The reconciliation of malfunction variables approach (Zaleta, *et al.*, 2004 and Zaleta, *et al.*, 2007). This approach evaluates the malfunction effect on the heat rate and power of the total plant and allocates these effects on a seat of free variables pre-selected on the basis of a detailed thermodynamic analysis;

ISSN 2176-5480

– The Fuel-Impact approach (Lozano and Valero, 1993; Reini, 1994; Reini, *et al.*, 1995 and Uson, *et al.*, 2009). This approach determines in analytical form the malfunction effect on the fuel consumption of the total plant and gets information from this effect on the causes of malfunction;
– The Fuel-Impact approach with filtration of induced effects (Verda, *et al.*, 2002 and Verda, 2006). The approach subdivides the effect of malfunction on total plant fuel consumption into different terms, in order to understand in what extent the behavior of each plant component and the control system contribute to the decreased plant performance; this information is then used to improve the knowledge on the causes of malfunction;
– The characteristic curve approach (Toffolo and Lazzaretto, 2003 and Toffolo and Lazzaretto, 2004). This approach measures the effect of malfunction through the variation of the component characteristic curves and primarily aims at the location of causes of malfunctions.
– The structural theory and symbolic thermoeconomics (Torres, *et al.*, 2002 and Valero, *et al.*, 2002). This approach integrates the thermoeconomics methodologies developed, such as Fuel-Impact and exergy technical saving, to compute the additional fuel consumption as the sum of both the irreversibilities and the malfunction cost of the plant components.

Among the methods mentioned above, the Fuel-Impact approach was selected for this work because of its following characteristics and advantages (Lazzaretto, *et al*., 2006):
– The local effect of malfunction is ‘translated’ into an effect for the total plant;
– The specific consumptions of resources are considered as performance parameters of the system, and base the evaluation on an analytical relationship (the ‘fuel impact’ formula) between the variation of the specific consumptions in the ‘i^{th}’ component and the total plant fuel variation. This is a unique tool to quantify the energy recovery (total plant fuel variation) obtained when design conditions are restored in a particular component;
– Demonstrates to be a reliable tool to quantify, and allocate in to the responsible components, the induced effects associated with variations of products only;
– The probable causes of malfunctions can then be detected with good approximation provided through a comparison driven by heuristic principles which are made between the malfunction costs calculated with the Fuel-Impact formula and those which are calculated using the variations of the specific consumptions in the components vs. variations of their products only because of the strong dependence of unit exergy consumptions from components’ products.

3. METHODOLOGY

Thermoeconomic diagnosis procedures are based on a comparison between two working conditions: the real operating condition and a reference operating condition corresponding to plant operation without any deterioration or operation anomaly. The deviation between the real condition with respect to the reference conditions must be reconciliated into specific terms of malfunctions (Valero, *et al*., 2004b). At the beginning of the diagnosis both (real and reference) conditions are known, but it is not easy to locate the malfunctions and to state how they contributed to such deviation. So, the analyst criteria and the analytical model used to simulate a power system are the ‘‘key’’ to define the malfunctions associated with the process. This means that, from a simulator that commonly establishes a matrix [nxn] of dependent and independent variables, the malfunctions are those independent variables of the system affecting the plant performance and will mathematically reconcile real conditions with respect to reference conditions. The computational tool for GE7FA performance diagnosis was developed to run using data collected in routinely performance tests. This kind of performance test are realized using de ASME PTC 22 and assured the steady state condition of the gas turbine and reconciliated data for calculations. Ambient conditions (Pressure, temperature and relative humidity), fuel composition, and internal parameters of the gas turbine are collected like test data.

The GE7FA computational tool general algorithm is shown in Fig. 1 and will be used to explain the methodology that was implemented in the tool for the thermal performance diagnosis:
– File selection. The Excel file containing the routinely performance test data is selected;
– Checking the standard format. The file containing the routinely performance test data is verified aiming to guarantee that the test data are in the correct position and format to be read. If the data are not as expected, or wrong, then there is the possibility to open a file containing the correct format and position and paste the test data, save a new test data file to start the calculations and run the analysis;
– Import the test data. The test data for calculations are imported to Excel calculation book from the test data file;
– Store and process data. Once the data stored, the calculation are initiated. Firstly a performance ASME PTC 22 calculation procedure is executed. If the calculated performance indicators (Power, Heat Rate or Exhaust Gas Energy) have values better than the expected for the gas turbine operation hours, afterward it is concluded that the gas turbine thermal performance is in “good” condition, no thermoeconomic diagnosis is necessary and the calculations are stopped. On the other hand, if the results are worse than expected, the calculations continue in two steps as follow. Secondly the real operating condition and a reference operating condition are calculated using GateCycle™ simulation models. The GateCycle™ calculations results include the mass, energy, entropy, exergy

ISSN 2176-5480

balances, performance indicator values, etc. for both the real and the reference operating conditions. Thirdly the deviation between the real condition with respect to the reference condition are reconciliated into specific terms of malfunctions using the Fuel-Impact approach for the thermal performance diagnosis;
– Shown results. Tables and graphics are available for reports and further analyses.

Considering that the ASME PTC 22 is well-known thermal performance calculation procedure, the last two steps of the store and process data are explained in more details in the next topics.

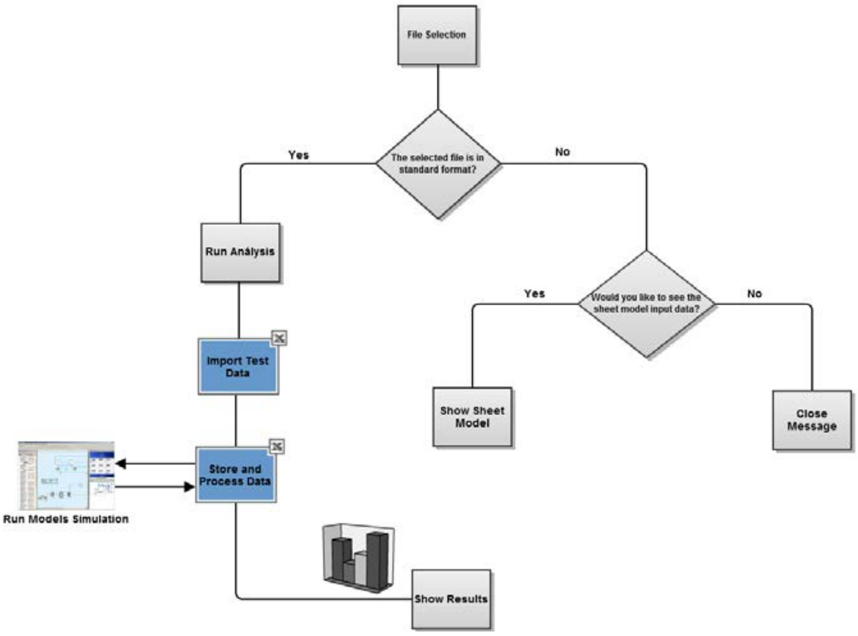

Figure 1. GE7FA Computational tool general algorithm

3.1 GateCycle™ simulation

In Tab. 1 the main data for GateCycle™ simulation are shown. In this table the data are separated by type and variable name, as well as by the model in question. Ambient and natural gas variables are external variables, in other words, are boundary conditions for both simulation models and the same values are assumed to run the calculations. The values that are shown for the ambient values are typical for the Belo Horizonte region in a winter day. The natural gas supply conditions are usually for GE7FA in power plants without fuel heating system. The natural gas composition has shown typical Gasmig (Natural Gas Company of Minas Gerais state) average values which provides the aforementioned region. The other variables in Tab. 1 refer to gas turbine internal component data. The values of these variables are collected by routinely performance tests. In some cases the collected data are used as input for the simulation, and in other cases are used to check or validate the results of the calculation. Figure 2 shows the thermal schematics of the GE7FA gas turbine that was modeling in the GateCycle™ software.

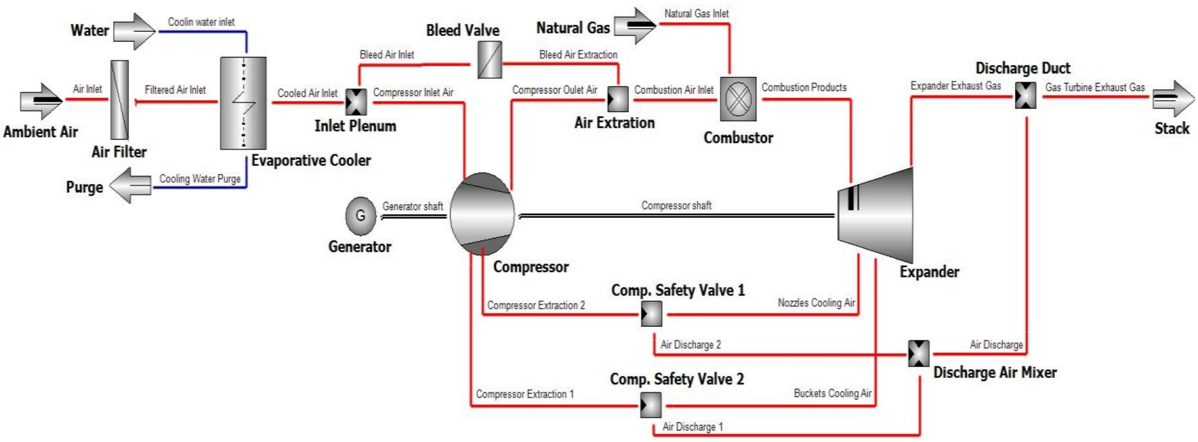

Figure 2. GE7FA thermal schematics in the GateCycle™ software

ISSN 2176-5480

The reference operating condition model is a simulation procedure that uses the maximum of gas turbine project data as available, and the idea is to run with the boundary conditions to obtain the results of gas turbine performance as new and clean, or other equivalent if desired, for example, after the gas turbine inspection. To run the GateCycle™ model compressor maps, isentropic efficiencies, pressure drops, cooling flow parameters, correction factors, etc. are used. The values of these variables are selected from the gas turbine project if available, or adopted from a calculated condition. For this paper was used the project data obtained from a calculated condition that was presented in Carvalho, *et al*., 2011.

The real operating condition model is a simulation procedure that uses the maximum of gas turbine routinely performance test collected as possible, and the idea is to run the model varying the isentropic efficiencies, pressure drops, leakage flows, etc., or other parameters that would be characterized as malfunction, or disfunction symptom. This model also runs with the boundary conditions and the variation in the aforementioned parameters are done in a predefined range using a GateCycle™ macro.

After run the GateCycle™ simulation the results of the characteristic parameters of the equipment (isentropic efficiencies, pressure drops, leakages, etc.), as well as the mass, pressure, temperature, enthalpy and chemical composition are available for all streams in the gas turbine. Using the methodology presented by Lozano and Valero (1986), the entropy and exergy were calculated for all streams. This way, the mass, energy, entropy and exergy balances are available for both the reference operating condition and the real operating condition. This information, together with the observed deviation in the different variables, is the input data for the thermal performance diagnosis using the thermoeconomic analysis and the Fuel-impact approach.

Table 1. Data for GateCycle™ simulation

Variable Type and Name	Unit	Reference operating condition	Real operating condition
Ambient:			
Temperature	C	25.05	25.05
Pressure	kPa	92.36	92.36
Relative Humidity	%	41.36	41.36
Natural gas:			
Supply Temperature	C	29.71	29.71
Supply Pressure	kPa	3129.19	3129.19
Natural gas composition:			
Methane	% mol	93.11	93.11
Ethane	% mol	3.93	3.93
Propane	% mol	0.91	0.91
n-Butane	% mol	0.16	0.16
Iso-Butane	% mol	0.12	0.12
Iso-Pentane	% mol	0.03	0.03
n-Pentane	% mol	0.03	0.03
Nitrogen	% mol	0.92	0.92
Carbon Dioxide	% mol	0.77	0.77
Oxygen	% mol	0.04	0.04
Air filter and Evaporative cooler:			
Air filter pressure drop	kPa	To be calculated	0.98
Cooler outlet relative humidity	%	83.69	83.69
Compressor:			
Air inlet temperature	C	25.05	To be calculated
Air inlet pressure	kPa	92.36	To be calculated
Compressor speed	Rpm	3600	3600
Compressor pressure ratio		15.40	15.40
Air oulet temperature	C	To be calculated	376.78
Combustion chamber			
Fuel energy consumption	kJ/sec	388298.03	To be calculated
Oulet temperature	C	To be calculated	1296.58
Expander			
Exit pressure	kPa	94.349	To be calculated
Exit Temperature	C	603.31	603.31
Electric generator			
Power Factor		1.00	0.99
Power	MW	To be calculated	149.218

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3.2 Thermoeconomic model

To perform the thermoeconomic analysis, it is useful to define a productive or causal structure, the counterpart to the physical structure used to calculate the system energy and the exergy flows (Schwarcz, *et al*., 1997). For the thermal schematics of the GE7FA gas turbine presented in Fig. 2, the productive structure developed is shown in Fig. 3, which is a schematic representation of the plant based on the Fuel-Product concept. For calculation of the unit exergetic cost and the specific exergoeconomic cost, a model based on an application of the Structural Theory of Thermoeconomic analysis was developed (Valero, *et al*., 1993). The thermoeconomic model is a mathematical representation of the productive structure of a system (Serra and Cuadra, 2006). Exergy balances were applied to each system component shown in Fig. 3 aiming the calculatios of the unit exergetic cost and the specific exergoeconomic cost of each stream in the productive structure.

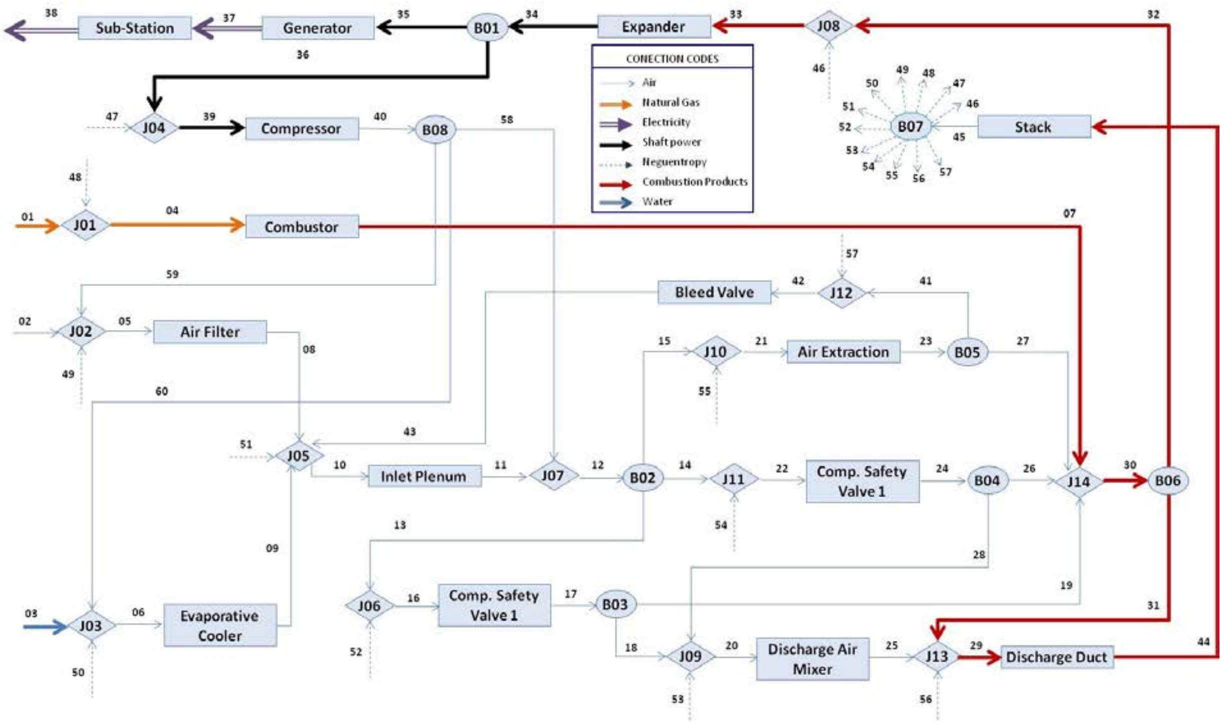

Figure 3. GE7FA productive structure

3.3 Fuel-Impact aproach

Figure 4 is an illustrative representation of the general idea of the thermoeconomic diagnosis using the Fuel-Impact approach. By means of this interpretation, detection, quantification and localization of the malfunction as well as their impact of fuel are carried out. In this picture the matrix ***DF*** contents the exogenous irreversibilities or dysfunctions, the matrix ***MF*** contents the endogenous irreversibilities or malfunction, the matrix ***MF**** contents the unit exergetic costs of malfunctions, the matrix ΔI contents the increment in irreversibilities, the matrix ΔR contents the increment in residues and the matrix ΔF_T contents the variation of the total resources or the Fuel-Impact.

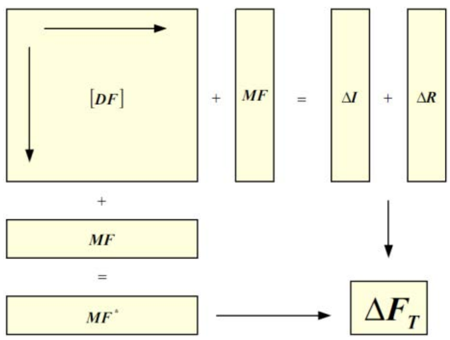

Figure 4. The Fuel-Impact approach for thermoeconomic diagnosis (Rangel, 2005)

ISSN 2176-5480

The expression for the calculation of the Fuel-Impact assuming the production of the plant as invariant is:

$$\Delta F_T = \sum_{i=1}^{n}\left[\sum_{j=0}^{n} k^*_{P,j}\cdot\left(\Delta\kappa_{ji} + \Delta\rho_{ji}\right)\right]\cdot P^0_i \tag{1}$$

Where:

$k^*_{P,j}$	Variation of the unit exergetic cost of the '*j*' component product;
$\Delta\kappa_{ji}$	Variation of the unit exergetic consumption of the product '*i*' related to the component '*j*';
$\Delta\rho_{ji}$	Entropy ratio coefficient of the fuel '*i*' related to the component '*j*';
P^0_i	Product '*i*' at the reference conditions.

In the equation above are include the endogenous irreversibilities or malfunctions. The internal malfunction is:

$$MF^{\kappa}_{ji} = \sum_{j=0}^{n}\Delta\kappa_{ji}\cdot P^0_i \tag{2}$$

The external malfunction is

$$MF^{r}_{ji} = \sum_{j=0}^{n}\Delta\rho_{ji}\cdot P^0_i \tag{3}$$

The exogenous irreversibility or disfunction is:

$$DF_{ji} = \sum_{h=1}^{n}\left[\sum_{h=0}^{n}\left(\Phi_{hj} + \Psi_{hj}\right)\cdot\left(MF^k_{ji} + MF^r_{ji}\right)\right] \tag{4}$$

Where:

Φ_{hj}	Coefficients of the irreversibility operator;
Ψ_{hj}	Coefficients of the residue operator.

Can be inferred from Eq. (1) that the cost of the malfunctions can be evaluated simply by multiplying the malfunction of the '*i*' component by the unit exergy cost of the resources utilized by the component, that is, for the case of internal malfunction:

$$MF^*_i = \sum_{j=0}^{n} k^*_{P,j}\cdot MF^{\kappa}_{ji} = MF^{\kappa}_i + \sum_{h=1}^{n}\left(\Phi_{hj} + \Psi_{hj}\right)\cdot\left(MF^k_{ji}\right) \tag{5}$$

While for an external malfunction:

$$MR^*_i = \sum_{j=0}^{n} k^*_{P,j}\cdot MF^{r}_{ji} = MF^{r}_i + \sum_{h=1}^{n}\left(\Phi_{hj} + \Psi_{hj}\right)\cdot\left(MF^r_{ji}\right) \tag{6}$$

Therewith, the Fuel-Impact can also be written in terms of the cost of malfunctions as:

$$\Delta F_T = \sum_{i=1}^{n}\left(MF^*_i + MR^*_i\right) \tag{7}$$

Or directly in terms of the malfunctions and disfunctions as:

$$\Delta F_T = \sum_{i=1}^{n}\left[MF^k_i + MF^r_i + \sum_{h=1}^{n}\left(\Phi_{hj} + \Psi_{hj}\right)\cdot\left(MF^k_{ji} + MF^r_{ji}\right)\right] \tag{8}$$

Where the first and the second terms in the right side of the equation refers to the malfunctions caused by internal and external endogenous irreversibilities respectively, while the last term refers to the exogenous irreversibilities.

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The straightforward application of the Fuel-Impact formula is to determine the ''Impact'' (i.e. the variation) in fuel consumption of the total plant originated by a malfunction in one or more plant components at constant plant production. The Fuel-Impact is evaluated as sum of Fuel-Impact terms associated with each plant component. Each term supplies the contribution of the single component to the fuel variation of the total plant. In other words, it quantifies the ''effects'' of the malfunctions in terms of fuel variation for the total plant. A similar result can be obtained by the exergetic analysis and exergy losses can be evaluated in each component in the actual and reference state. The difference between these losses can be evaluated component by component and the sum of these differences corresponds to the total plant exergetic loss that is equal to the total fuel variation (the product being constant). However, the two approaches supply a different allocation of the total fuel variation among plant components. The reason to develop a fuel impact formula lies in the need of transforming the fuel variation within a component undergoing a malfunction into a fuel variation for the total plant: this is practically achieved through the exergetic costs. In other words, the Fuel-Impact formula takes account of the irreversible productive chain upstream the component in hand.

4. RESULTS AND DISCUSIONS

Parametric studies were realized aiming to validate the sensibility of the GateCycle™ simulation models and the thermoeconomic model. The impact on the electricity cost of the deviation of some malfunctions was used for the sensibility validation of these models. The data for parametric studies are presented in Tab. 2. In this table the malfunctions considered for the validation are shown, as well as the deviation induced for the validation. The impact on the electricity cost of the malfunctions can be seen in Fig. 5 plotted as function for the relative variation. Figure 5 shows the satisfactory sensibility of the models, which are able to detect small deviations in the selected malfunctions. It is important to remark that the rise in the malfunctions increases the electricity cost. It is possible to note that in the evaluated range the bleed leakage malfunction causes the highest impact on the electricity cost, while the compressor isentropic efficiency causes the smallest. The others malfunctions considered also cause a similar impact on the electricity cost.

Table 2. Data for parametric studies

Variable name	Value									
Malfunction ↓ / Relative variation →	0.000	0.110	0.220	0.330	0.440	0.560	0.670	0.780	0.890	1.000
Bleed Leakage (kg/s)	0.000	1.111	2.222	3.333	4.444	5.556	6.667	7.778	8.889	10.000
CSV[1] Leakage (kg/s)	0.000	1.111	2.222	3.333	4.444	5.556	6.667	7.778	8.889	10.000
Fall in Compressor Isent.[2] Efficiency	0.931	0.929	0.928	0.927	0.926	0.925	0.924	0.923	0.922	0.921
Fall in Expander Isent. [2] Efficiency	0.893	0.892	0.891	0.890	0.889	0.888	0.886	0.885	0.884	0.883
Fall in Combustion Efficiency	0.999	0.997	0.995	0.992	0.990	0.988	0.986	0.983	0.981	0.979

[1] Compressor Safety Valve. [2] Isentropic.

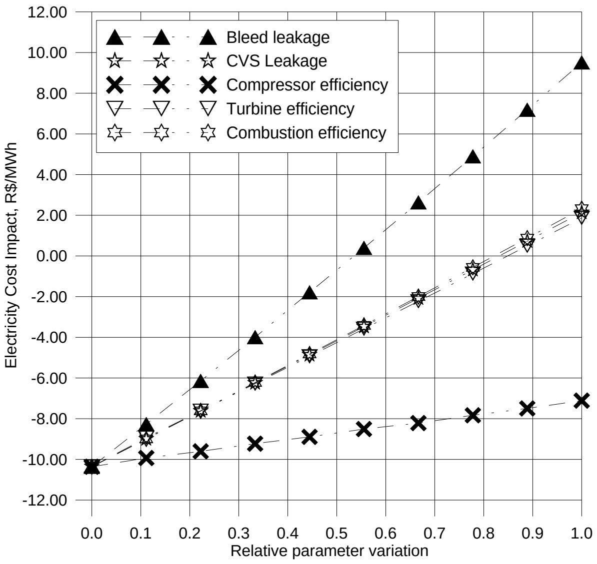

Figure 5. Results of GateCycle™ models validation

The results of thermal performance calculations are presented in Fig. 6 using the results interface of the developed computational tool for the GE7FA thermal performance diagnosis. The stages “File selection”, “Checking the standard format”, “Import test data” and “Store and process data” were executed using the icons “*Selecionar*”, “*Importar*” and “*Analisar*” shown at the top of the windows. In the center part of the windows several tabs access are used to show the results for all system (see the left side picture in Fig. 6) or the results for an individual component of the gas turbine, see, for example, the results for the combustor in the right side of the Fig. 6. In the last case detailed results are shown for both models the real operating condition and the reference operating condition, and include the energy, entropy, exergy and the gas composition values by stream, as well as the values of the characteristic parameters of the combustor. In the inferior part of the windows the values of temperature, pressure and mass flow can be visualized for each stream and for different situations like test data, reference operation condition and real operation condition. The deviation respect to the reference operation condition or test data could be displayed too.

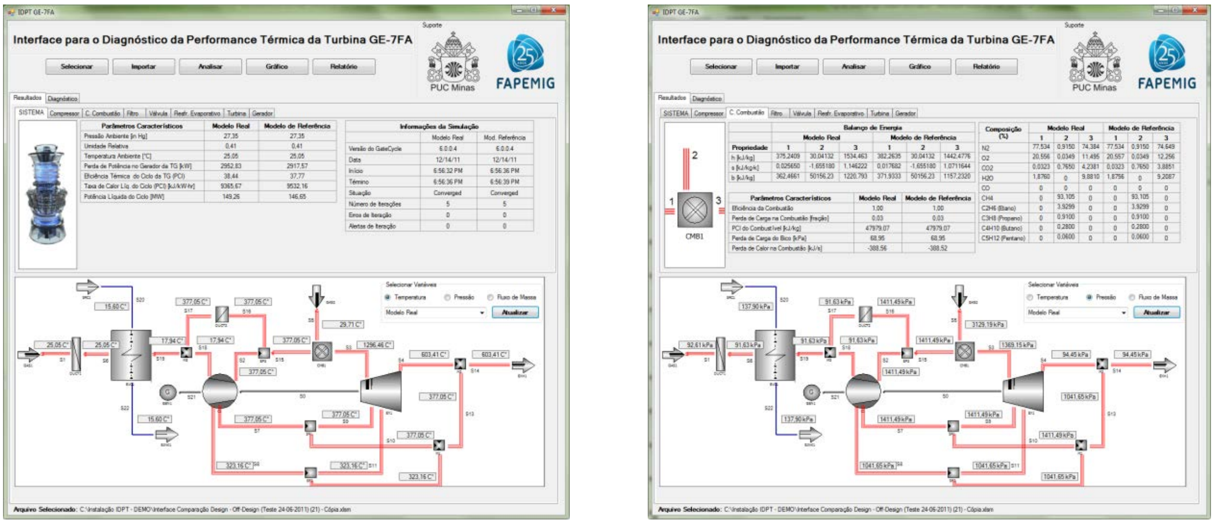

Figure 6. Results of thermal performance calculations

For the GE7FA thermal performance diagnosis the electricity cost is calculated using the thermoeconomic model. Figure 7 shows, in its left side, the economic entry data interface of the computational tool for the electricity cost calculations. It is possible to vary these data as desired or in dependence of the economic scenario of the analysis. The economic data include natural gas and water price, change rate, interest rate, operation hours per year between other. In the right side of the Fig. 7 tabs permit to show the results of the electricity cost calculations for the reference operating conditions and for the real operating conditions. Monetary cost flow, Fuel, Product, Irreversibility, Exergetic cost of Fuel and Exergetic cost of Product are presented for each gas turbine component.

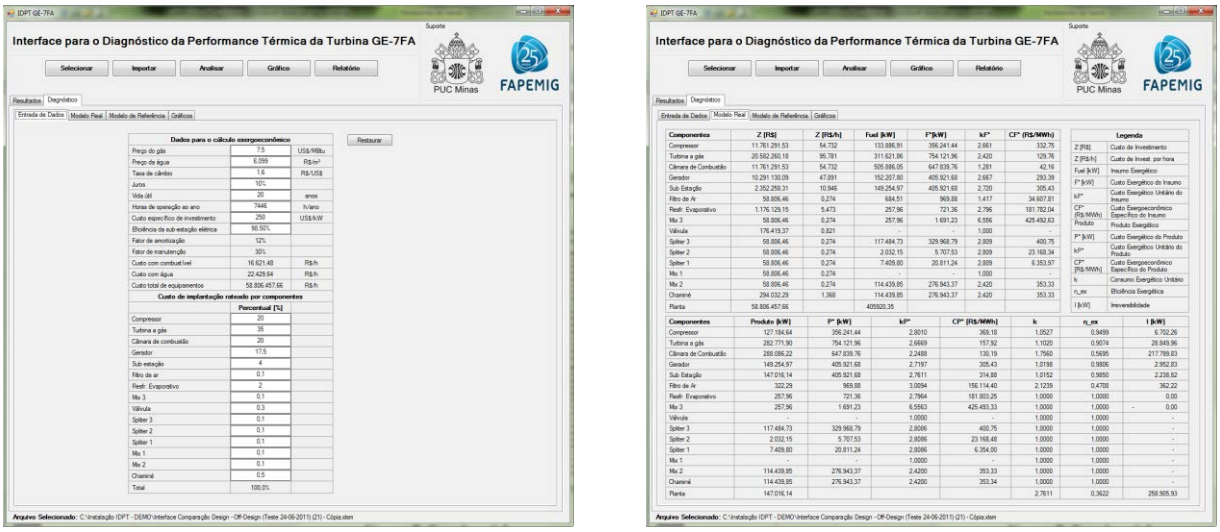

Figure 7. Results of thermoeconomic calculations

ISSN 2176-5480

Figure 8 shows results of thermal performance diagnosis that could be obtained with the computational tool that was developed. In the left side of the figure, preliminary diagnosis results are exposed. In this illustration, based on the simulated results for the real operation condition and for the reference operation condition, it is presented the deviation in the unit exergetic consumption (Δk), the deviation in the unit exergetic cost of the fuel (ΔkF*), the product (ΔkP*) and the deviation in the cost of product (ΔCP*) for the main gas turbine components. Like most of the deviations are negative or close to zero the results indicate the “good” condition of the gas turbine thermal performance. From this conditions the malfunctions mentioned were induced in Tab. 2 to observe the computational tool potential for diagnosis. As an example, in the right side of the Fig. 8, the results of the Fuel-Impact approach for a combustor malfunction when the combustion efficiency fall from 0.999 to 0.979. The fall in combustion efficiency implies to burn more natural gas in the combustor to keep the gas turbine power as invariant. Let’s go to analysis the results for the compressor. Like the expander operates in stall, burning more gas implies in less air in the compressor and a negative disfunction in this component (benefic impact), on the other hand, less air increases the pressure ration and the specific power consumption implying in a positive intrinsic malfunction. Due to the disfunction effects an economy potential (reduction in fuel consumption) is expected when the fall in the combustion efficiency will be fixed. A similar analysis could be realized for another component. It´s also possible to observe that no malfunctions are evidenced for secondary components, in which only disfunctions are observed if an exergetic product exists. As expected, the highest economy potential will be obtained when the fall in the combustion efficiency is fixed.

Fuel-Impact of combustor malfunction
Fall in combustion efficiency from 0.999 to 0.979
Sample of results of calculations

Component	MF	DF	Economy Potential
Compressor	1917.2	-7132.6	906.1
Expander	-5346.2	2749.8	-8084.8
Combustor	12094.2	1321.0	12951.9
Generator	-16.3	-6876.5	-16.6
Substation	0.0	-47.1	0.0
Air Filter	7.1	7.7	-11.1
Evaporative cooler	0.0	10.2	0.0
Inlet Plenum	0.0	-41.3	0.0
Bleed Valve	0.0	0.0	0.0
Air Extraction	0.0	5372.0	0.0
Comp. Safety Valve 2	0.0	91.0	0.0
Comp. Safety Valve 1	0.0	575.2	0.0
Discharge Air Mixer	0.0	0.0	0.0
Discharge Duct	0.0	1060.3	0.0
Stack	0.0	0.0	0.0

Figure 8. Sample of results of thermal performance diagnosis

5. CONCLUSIONS

The computational tool for GE7FA thermal performance diagnosis was presented as well as its theoretical fundamentals, functional algorithm and a sample of application. In this sense, it is possible to summarize the following conclusions:

– The computational tool was performed to realize the thermal performance diagnosis from routinely performance test data;

– The test data are used for simulation of the reference operation condition and the real operation condition;

– The simulation model of both, reference and real, operation conditions were developed in the GateCycle™ with a high disaggregation level;

– The developed thermoeconomic model was able to realize the exergetic analysis of the system component by component and compute the cost of the electricity based on market economic data;

– The application of the Fuel-Impact approach was capable to detect the malfunctions and disfunctions that were simulated and induced as examples;

– All models implemented in the computational tool have satisfactory sensibility and Fuel-Impact response when intrinsic and induced malfunctions are present;

– The computational tool that was developed is suitable for the thermal performance diagnosis of the GE7FA gas turbine.

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