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A vector optimization methodology applied to thermodynamic model calibration of a micro gas turbine CHP plant

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Abstract

This paper is focused on the validation of a cogeneration plant based on micro gas turbine. The experimental data related to design working point are compared to thermodynamic model results using a multi-variable multi-objective methodology depending on a genetic optimization algorithm (MOGA-II). The result with lowest Euclidean norm in objective functions space represents the operating conditions closest to experimental data, and it highlights at the same time the reliability of chain measurement. Finally, this preferred result is plotted on turbomachinery performance maps in order to validate indirectly the methodology outcomes.

Keywords: *Experimental validation; Micro gas turbine; Multi-objective optimization; Thermodynamic analysis; measurement reliability*

1. Introduction

The increasingly widespread adoption of cogeneration plants based on micro gas turbine is one of the keys to achieve the agreed energy saving target [1],[2]: since the last decades, micro gas turbine (MGT) as prime mover in

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CHP plants had a continuous development, because of several applications in energy markets, due to small dimensions and low pollutants emissions [3],[4]. Moreover, low noise and vibration production [5], in contrast to the internal combustion engines [6],[7], makes micro gas turbine adequate for combined heat and power generation in residential sector [8],[9].

Nomenclature

CC	Combustion chamber
$\dot{m}$	Mass flow rate [kg/s]
MGT	Micro gas turbine
N_S	Specific speed
P_E	Net electric power [kW]
p_{cc}	Combustion chamber pressure [bar]
T_1	Ambient air temperature [°C]
T_3	Turbine inlet temperature [°C]
T_4	Turbine outlet temperature [°C]
T_{4R}	Recuperator hot side outlet temperature [°C]
T_{STK}	Exhaust gas temperature at stack[°C]
Greek symbols	
ε_S	Heat exchanger efficiency
$\eta_{E,CHP}$	Overall electric efficiency of CHP plant
$\eta_{E,ref}$	Reference electric efficiency
η_b	Combustion efficiency of CHP plant
η_m	Mechanical efficiency of CHP plant
$\eta_{TH,ref}$	Reference thermal efficiency
ρ	Actual exploited thermal power ratio
Subscripts	
calc	Calculated value
exp	Experimental value

In order to design CHP plants that achieve significant energy savings, the Primary Energy Saving index must be defined (1):

$$\mathrm{PES} = \left(1 - \frac{1}{\frac{\eta_{E,CHP}}{\eta_{E,ref}} + \frac{\rho \cdot \varepsilon_S \cdot \left(1 - {\eta_{E,CHP}}/{(\eta_b \cdot \eta_m)}\right) \cdot \eta_b}{\eta_{TH,ref}}}\right) \tag{1}$$

$$\rho \cdot \varepsilon_s = \frac{T_{4R} - T_{STK}}{T_{4R} - T_1} \tag{2}$$

where the reference thermal and electric efficiency are $\eta_{TH,ref}$=0.90, $\eta_{E,ref}$=0.46 [10], respectively; ε_S is the heat exchanger efficiency and ρ is the ratio between exploited and available thermal energy. In equation (2), T_{4R} is the gas temperature at turbine recuperator outlet, T_{STK} is the exhaust gas temperature after the thermal exchange with heat transfer fluid addressed to the user, T_1 is the ambient air temperature. Plotting the PES as a function of MGT global electric efficiency (Fig. 1), it must be noted that the primary energy saving increases with both the electric efficiency ($\eta_{E,CHP}$) and thermal power exploitation ($\rho \cdot \varepsilon_S$). This second aspect is clearly depicted by the six lines, which represent the ratio between thermal power actually exploited and available. Thus, it is mandatory to design a cogeneration plant following two main features: achieving the highest electric efficiency, based on state-of-art, and maximizing the thermal power exploitation. As stated in authors' past works [11]-[12], this analysis can be performed through an accurate study of the interaction between user demand and CHP plant.

In this work, a multi-variable multi-objective methodology has been applied to calibrate the thermodynamic model of a 100 kW micro gas turbine through the related experimental data: this cross validation methodology, widely described in [13]-[14], is characterized by thermodynamic and working parameters as decision variables and objective functions as detailed in the following. Based on the considerations made for PES index, the thermodynamic parameters of CHP turbine plant play a key role concerning the match between demanded and supplied thermal energy; in particular, the knowledge of mass flow and temperature at turbine outlet for a non-regenerative cycle, and at hot side recuperator outlet for a regenerative cycle, allows the qualitative and quantitative assessment of recoverable thermal power.

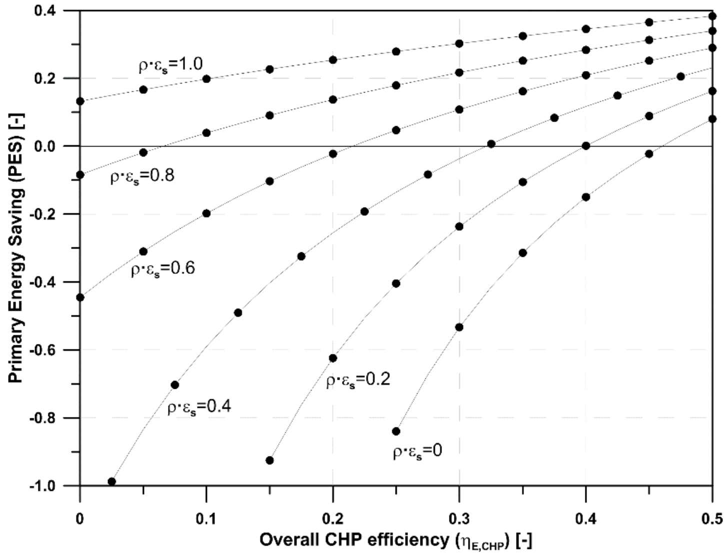

Fig. 1: Primary energy saving vs overall efficiency

Finally, one vector of working conditions has been chosen using the lowest Euclidean norm as criteria, and it was depicted on the performance maps of both turbomachinery, to meet the congruity of the operating points.

2. Methods and turbine model

The thermodynamic model of the studied micro gas turbine is one of the two main constituting elements of the methodology, along with an optimization driven by genetic algorithm MOGA-II [15]; both of them are schematized in Fig. 2. The plant model executes energy balances for regenerative Brayton cycle, determining thermodynamic quantities for each stream and electric and thermal power. Concerning the methodology, the flowchart is shown in same Fig. 2, with a focus on MOGA-II: the solution to a multi-variable multi-objective optimization problem, unlike the single-objective one, is not a single vector, but a group of vectors, which constitute the Pareto front. Each vector belonging to this front is *non-dominated*, meaning that there is not any vector that achieves lower values for all the objective functions at the same time, in a minimizing problem. Moreover, in a multi-objective optimization problem, a decision-making task must be outlined in order to define one single solution, named *preferred* [15]: in this paper, the preferred result is determined as the point in objective functions space with lowest Euclidean norm, as formulated in (3):

$$\text{Preferred result} = \min\left(\sqrt{\left(\frac{\Delta P}{P}\right)^2 + \left(\frac{\Delta\eta_G}{\eta_G}\right)^2 + \left(\frac{\Delta T_3}{T_3}\right)^2 + \left(\frac{\Delta T_4}{T_4}\right)^2 + \left(\frac{\Delta p_{CC}}{p_{CC}}\right)^2}\right) \tag{3}$$

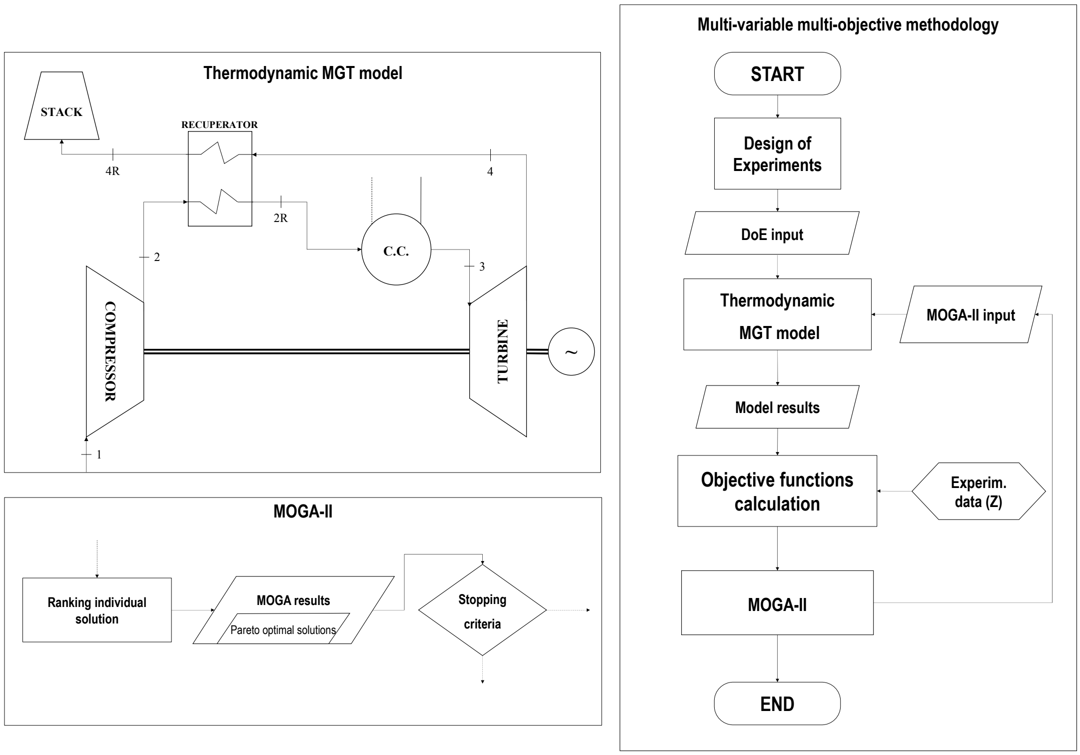

Fig. 2: Methodology and gas turbine model schematics

Table 1: decision variables ranges and objectives target values

DECISION VARIABLES					
	RANGE	UNIT		RANGE	UNIT
COMPRESSOR			FUEL COMPOSITION		
Air flow	0.7900–0.7935	kg/s	Methane	87.0–96.0	%vol
Pressure ratio at compressor	4.0–5.0	-	Ethane	1.8–5.1	%vol
Polytropic efficiency	0.77–0.886	-	Propane	0.1–1.5	%vol
Mechanical efficiency	0.85–0.98	-	Butane	0.02–0.6	%vol
RECUPERATOR			Carbon dioxide	0.1–1.0	%vol
Pressure drop hot side	0.001–0.2	bar	Nitrogenous	1.3–5.6	%vol
Pressure drop cold side	0.001–0.2	bar	Oxygen	0.01–0.1	%vol
TURBINE			COMBUSTOR		
Isentropic efficiency	0.77–0.91	-	Fuel flow	0.0065–0.0100	kg/s
Mechanical efficiency	0.85–0.98	-	Thermal power losses	0.01–6	kW
			Pressure drop	0.01–0.2	bar
OBJECTIVES					
	VALUE	UNIT		VALUE	UNIT
Net electric power	100	kW	Turbine outlet temperature	650	°C
Overall efficiency	0.30	-	Combustion chamber pressure	4.5	bar
Turbine inlet temperature	950	°C			

Following the flowchart in Fig. 2, the processing of the methodology starts with the definition of an initial population of decision variables, the so-called Design of Experiments (DoE), using a deterministic (*Sobol*, [16]) and an augmenting algorithm [17]: these variables are grouped into vectors, which represent the first input to be used by the thermodynamic model. Thus, the results generated by model are managed and ranked in order to determine new generations of decision variables vectors able to minimize the objective functions.

The decision variables ranges and the objective functions targets for the studied case have been inferred from [18] and they are summarized In Table 1: Each of the five objectives is handled by MOGA-II through a related function: for a general variable y, the objective function is defined as (4), and is set to minimize in the optimization.

$$\Delta y = |y_{calc} - y_{exp}| \tag{4}$$

In this way, the algorithm seeks for input thermodynamic variables that give rise to calculated output parameters closest to the experimental data.

Formerly, this methodology was applied by authors in other thermodynamic model validations ([13],[14]), and also to find the optimal trade-off solutions between primary energy savings and simple payback period of the investment ([11],[12],[19]-[21]).

3. Results and discussion

Among 25,000 computed results, the preferred one is chosen using lowest Euclidean norm and its parameters are listed in Table 2.

Table 2: preferred result summary

DECISION VARIABLES					
	VALUE	UNIT		VALUE	UNIT
COMPRESSOR			FUEL COMPOSITION		
Air flow	0.7928	kg/s	Methane	90.36	%vol
Pressure ratio at compressor	4.65	-	Ethane	4.50	%vol
Polytropic efficiency	0.812	-	Propane	1.34	%vol
Mechanical efficiency	0.963	-	Butane	0.28	%vol
RECUPERATOR			Carbon dioxide	0.95	%vol
Pressure drop hot side	0.259.3	bar	Nitrogenous	2.49	%vol
Pressure drop cold side	0.093.5	bar	Oxygen	0.08	%vol
TURBINE			COMBUSTOR		
Isentropic efficiency	0.873	-	Fuel flow	0.0072	kg/s
Mechanical efficiency	0.98	-	Thermal power losses	0.6876	kW
			Pressure drop	0.1709	bar
OBJECTIVES					
	VALUE	UNIT		VALUE	UNIT
Net electric power	100.1022	kW	Turbine outlet temperature	650.71	°C
Overall efficiency	0.2994	-	Combustion chamber pressure	4.28	bar
Turbine inlet temperature	951.87	°C			

Fig. 3 depicts the optimization methodology results on electric power versus overall efficiency objective functions plane, while Fig. 4 shows the results on another objective functions plane, defined by turbine inlet temperature versus turbine outlet temperature. In both figures, the blue points depict the results belonging the Pareto front, and the red point highlights the preferred one: it must be noted the thickening of Pareto optimal points near the axes origin, which suggests the effectiveness of the adopted methodology.

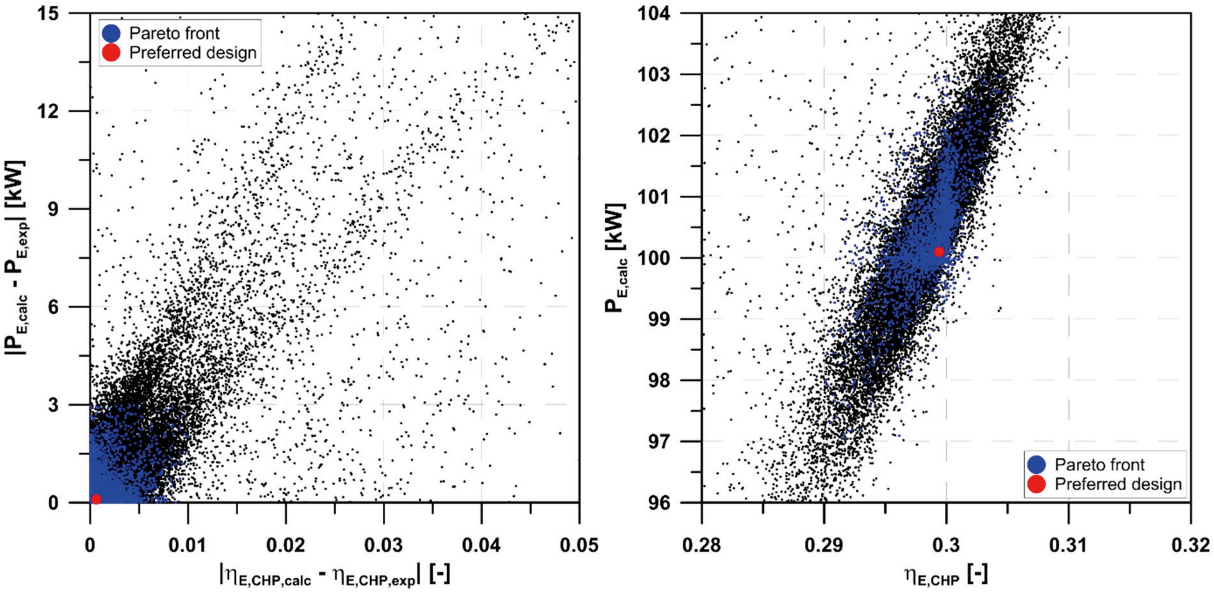

Fig. 3: Turbec T100 multi-variable multi-objective results (η_G, P)

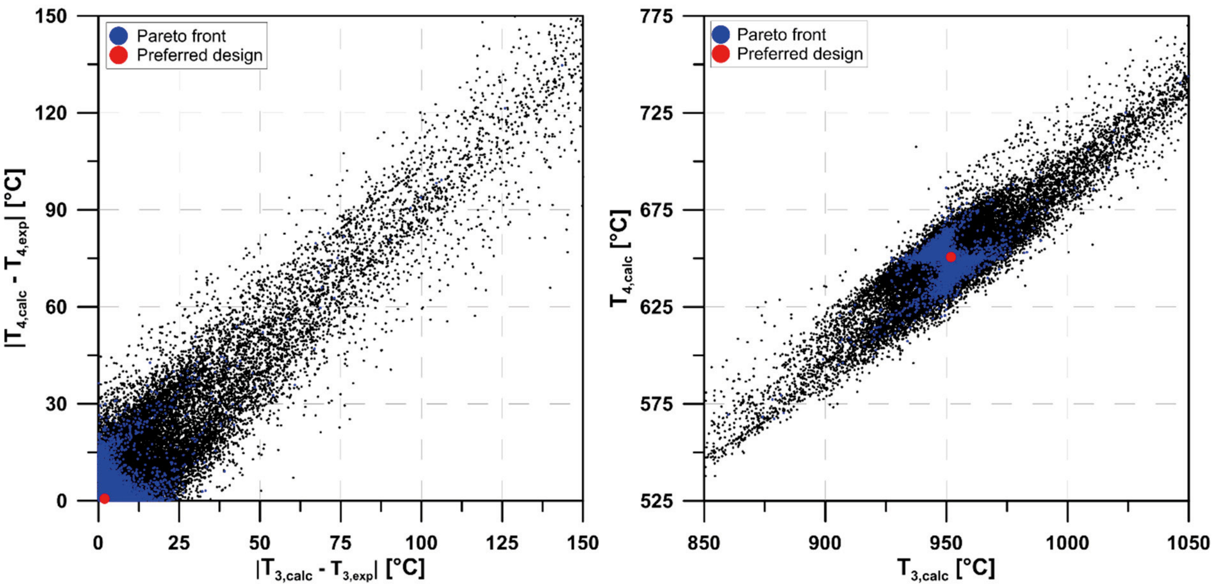

Fig. 4: Turbec T100 multi-variable multi-objective results (T_3, T_4)

Furthermore, the performance maps of Turbec T100 have been rearranged based on [22]-[23] and have been adapted to specified reference conditions (Fig. 5): the preferred design is again plotted with a red point, and it is specified by the mass flow rate and the compression or expansion ratio. Shaft speed related to preferred design is closer to experimental data, and since it was not included in optimization parameters, this can be assumed as an indirect validation of the proposed methodology; the same observation can be done about compressor and turbine efficiencies, whose values differ from the experimental data by +3% and -5%, respectively.

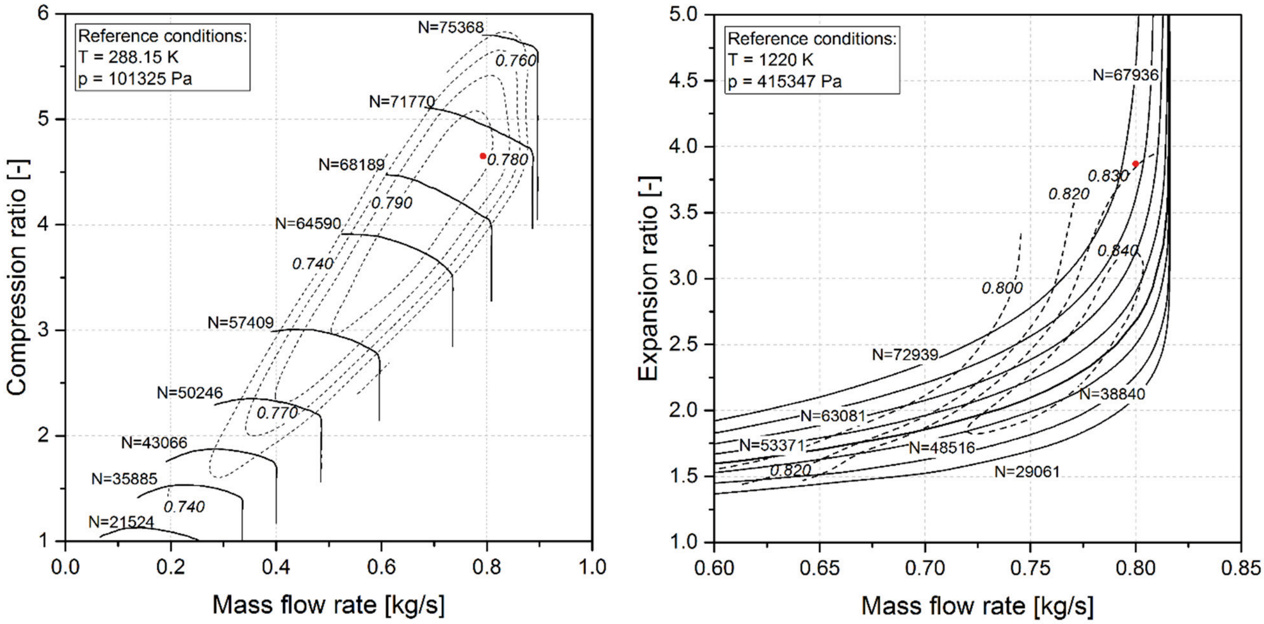

Fig. 5: Turbec T100 performance maps

Table 3 lists the objectives of the methodology and the related percentage variation: the maximum difference between calculated and experimental data is the combustion chamber pressure, which is specified in [18] as "approximately 4.5 bar", while the difference for other quantities is less than 0.3%.

Table 3: methodology results overview

	VALUE	UNIT	|Δ%|		VALUE	UNIT	|Δ%|
Net electric power	100.1022	kW	0.120%	Turbine outlet temperature	650.71	°C	0.263%
Overall efficiency	0.2994	-	0.200%	Combustion chamber pressure	4.28	bar	4.889%
Turbine inlet temperature	951.87	°C	0.198%				

The $\rho\varepsilon_s$ parameter, above defined in equation (2), can be characterized with the following values of temperature:

$$\rho\varepsilon_s = \frac{T_{4R} - T_{STK}}{T_{4R} - T_1} = \frac{270 - 110}{270 - 15} = 0.63 \tag{5}$$

Thus, the result of the matching between the plant overall efficiency and the value of $\rho\varepsilon_s$ in equation (5), involves an achievable theoretical primary energy saving around 10%, as pointed out in Fig. 1.

4. Conclusions

This study examined the validation of the thermodynamic model of Turbec T100 micro gas turbine through a multi-variable multi-objective methodology; the study was aimed to investigate both reliability of experimental data and congruence of the model. A large amount of calculations based on a vector optimization methodology has been carried out and it allowed the authors to identify one set of thermodynamic parameters that minimizes the difference between calculated and experimental data, using the lowest Euclidean norm criteria. The slight variations of thermodynamic parameters, directly (Table 3) and indirectly (Fig. 5) evaluated, confirm the methodology effectiveness, and create the conditions for future works, that will involve more complex models both of micro gas turbine and integrated power plants.

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