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Multiobjective Optimization of Micro-Gas Turbines Environmental Polluting Emissions Due to their Internal and External Thermal Losses

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Abstract: The ever-increasing demand for energy worldwide is hurting our environment, especially global warming. This is due to the significant use of fossil fuels. Faced with this situation, research and innovation actions are directed toward reducing these emissions by various scientific solutions including the multi-objective optimization of thermal machines. Among these thermal machines, one can mention the micro-gas turbines. Indeed, internal and external heat transfers are made in these machines because of their small size. These heat transfers contribute to degrading their performances in particular their environmental discharges that increase brutally. The present study aims at applying the eco-design methodology to these machines to evaluate their actual performances according to the heat transfers and to improve them. For this study, a thermodynamic model coupled with an environmental and economic model that describes the global behavior of micro-gas turbines has been performed. This model, operating in two modes adiabatic and polytropic to appreciate the deviations, gives good results that agree with those of the literature. The model was then optimized in a multi-objective way by Genetic Algorithms (NSGA IIb) giving a set of Pareto optimal solutions. The ideal solutions' selection was done by applying the TOPSIS multi-criteria decision-making technique and gave the following results in polytropic operation: net power: 858.4 kW; global warming potential: 0.9561 kg CO_2/kWh and the estimated production cost of US$4256/hr. This ideal solution was subsequently analyzed by OpenLCA software to evaluate the whole environmental impacts characterized mainly by HTP (kg C_6H_6/kWh): 0.356; EP (kg PO_4^{3-}/kWh): 0.525; PCOP (kg C_2H_4/kWh): 0.295; AP (kg SO_2/kWh): 0.356.

Keywords: Eco-design, Micro-Gas Turbines, Multiobjective Optimization, Genetic Algorithm

1. Introduction

More than ever, one of the interests of the rulers of this century is focused on the preservation of the environment and the framework of life. Indeed, usually in industrial, technological, and chemical processes, design, and optimization the attention of engineers has always been focused on their economic viability. This attention includes operational costs, investment, time of return on investment, etc. This design approach gives little importance to the environmental aspect of these industrial processes [1]. In terms of pollution, it should be noted that transport and energy production are the activity sectors that emit the most carbon dioxide (27%) [2] and depend on more than 98% of fossil fuels [3]. In addition, the use of these fossil fuels contributes to the steady increase in greenhouse gas emissions, in particular, carbon dioxide (70% of global greenhouse gas emissions) [2]. The consequences of these emissions are now well established (climate change) [4]. In this context of global warming, due to the important consumption of fossil fuels, it is imperative to optimize the exploitation of these thermal machines during their design stage. This aims to the reduction of their fossil energy consumption and thus slows down the degradation of the environment during their operating phase [5]. Among thermal machines, gas turbines are used for mechanical power energy production, air transport, and in gas-fired power plants. It should be noted that there are two types of these compressible fluid turbo-machines: large-size gas turbines called conventional turbines and small-size gas turbines said micro-gas turbines. Micro gas turbines operate on the same thermodynamic principles as large-size. These types of gas turbines are generally used for the production of electrical energy in gas-fired power plants. However, according to. Gong et al. [6] specific problems related to the small size of those micro-gas turbines affect their performances. Among these problems, the most important is the heat transfer between their different components. Indeed, in general, during the design phase of gas turbo-machines, performance estimation is generally made by admitting the adiabaticity of the gas flow in the various parts of this gas turbine. But, in reality, many studies have shown the negative influence of internal and external heat exchanges on the micro-gas turbines' performances (efficiency, power, pollutants.) while functioning at low loads and low speeds [7-10]. Therefore, the adiabaticity hypothesis is no longer acceptable for the current designs of these micro-gas turbines. But this theory of adiabaticity is still used to characterize thermal turbo-machines in general and micro-gas turbines in particular [5]. This consideration leads to often-erroneous results, particularly for the net performance of micro-gas turbines. In this work, a comparative study of the influence of adiabatic and non-adiabatic (polytropic) considerations on micro-gas turbines will be carried out. Subsequently, an analysis of the implications of these considerations on the performance and atmospheric emissions of these micro-gas machines will be conducted.

2. Gas Turbines

A turbo-machine is a set of mechanical parts allowing the exchange of energy between a fluid flow and a shaft provided with a wheel driven by a rotational movement [11]. Gas turbines are used for the production of electricity and transport [12].

Generally, a simple gas turbine consists of a centrifugal or axial air compressor (AC), a combustion chamber (CC), and a centripetal or axial gas turbine (GT) (Figure 1).

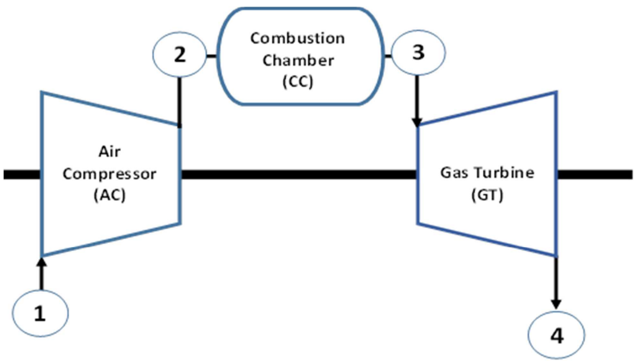

Figure 1. *Simplified diagram of a Simple-cycle, open flow, single-shaft gas turbine.*

Micro-gas turbine operates in an open-cycle thermodynamic machine [13]. The mechanical energy absorbed by the compressor is transferred to the fresh air sucked from the atmosphere at point (1) of Figure 1. At point (2) the pressure and the temperature of this air increased. In the combustion chamber, this compressed air oxidizes the fuel (in general natural gas) in a combustion process at constant pressure. Gases produced at high temperatures (3) expand in the turbine and transform their energy into mechanical energy on the turbine shaft. A part of this mechanical energy is used to operate the compressor. The rest of this energy is converted into mechanical power or electrical energy by an alternator. The exhaust gases (4) are either released into the atmosphere or used to produce superheated steam, which is used in a steam turbine to increase the thermal efficiency of the entire system. The gas turbine operates according to the Brayton cycle.

2.1. Thermal Transfers in Micro-Gas Turbines

A gas turbine is a turbo-machine, that is itself part of the large group of internal combustion engines. The thermodynamics of micro gas turbines are treated in the same way as large-size gas turbines. However, the mechanics of both types of machinery are different due to geometric considerations and manufacturing constraints. Considering several factors, including the high volume surface ratio, the hypothesis of adiabaticity is no longer accepted for micro-gas turbines. Important internal and external heat transfers must therefore be considered when designing these machines (Figure 2). Many authors have worked on the modeling of thermal exchanges in micro-gas turbines. The influence of heat transfers on the compressor results in a decrease in gas mass flow, a decrease in the compression ratio, and a drop in efficiency compared to the isentropic for a given operating point [14]. The high surface/volume ratio is the fundamental reason why the gas mass flow thermodynamic transformation in the micro-compressor cannot be considered adiabatic. The degradation of the compressor's performance associated with its heating by the heat coming from the turbine is the first factor in the degradation of micro-gas turbine performance [6]. The only indicator, invariant by similarity, which should be preferred in the dimensioning of adiabatic and non-adiabatic turbo-machines, is the polytropic efficiency [5].

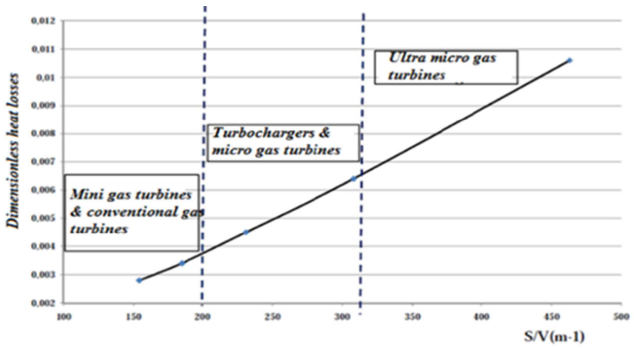

Figure 2. *Heat transfer in the volute versus the size of gas turbines [10].*

2.2. Micro Gas Turbine Modelling

A micro-gas turbine simulator was developed on Microsoft Excel in this work. This simulator operates in reversible adiabatic and polytropic modes. The simulator calculates each part and parameters of the micro-gas turbine (Figure 1) i.e. temperatures, pressures, heat capacities, adiabatic and polytropic works and powers, etc. The simulator which calculates the various parts of the micro-gas turbine was designed using Table 1 equations.

2.3. Micro Gas Turbine Exhaust Pollutants Modelling

Combustion in a micro-gas turbine is an incomplete process [13]. Gas turbine's exhaust combustion gas mainly consists of carbon dioxide (CO_2), water (H_2O), oxygen (O_2), and, nitrogen (N_2), carbon monoxide (CO), unburned hydrocarbons (UHC), nitrogen oxides (NO_x), soot, sulfur oxides (SOx). In general, carbon dioxide (CO_2) is not considered a pollutant because it is a normal consequence of hydrocarbon fuel's complete combustion. However, it contributes to overall heating (global warming) and can only be reduced by burning less fuel. The most common pollutants formed in the combustion chambers of micro-gas turbines are carbon monoxide (CO), unburned hydrocarbons (UHC), nitrogen oxides (NO_x), soot (VOCs), sulfur oxides (SOx), smoke, etc. [20]. Among these pollutants, only CO and NO_x are predominant in micro-gas turbines using gaseous fuels such as natural gas. Pollutants such as smoke and soot predominate when using liquid fuels [21-22]. Depending on the use of micro-gas turbines and inlet energy, the maximum NOx emissions must be limited to 15 ppm and CO emissions to 130 ppm [23]. Several correlations have been used in the literature to determine the quantities of CO and NO_x emitted by micro gas turbines in ppm [13].

Table 1. *Summary of micro-gas turbine simulator conception equations.*

Equipment	Gas turbine parts and references	Design Equations	N°
Compressor model	Compression work [15]:	$w_{Comp} = h_2 - h_1 = \int_{T_1}^{T_2} C_{pa}(\mathrm{T}) = \frac{\gamma_a\ r_a}{\gamma_a - 1}(T_2 - T_1)$	(1)
	Compressor thermal power [16]:	$\dot{W}_{Comp} = \dot{m}_a \int_{T_1}^{T_2} C_{pa}(\mathrm{T})\ dT$	(2)
	Constant pressure heat [16]:	$C_{pa}(\mathrm{T}) = 1.04841 - \left(\frac{3.8371\,T}{10^4}\right) + \left(\frac{9.4537T^2}{10^7}\right) - \left(\frac{5.49031T^3}{10^{10}}\right)$	(3)
Combustion chamber model	Combustion chamber energy balance [15]	$\dot{m}_a h_2 + \dot{m}_F PCI = \dot{m}_G h_3 + \dot{m}_F PCI(1 - \eta_{cc})$	(4)
	Combustion chamber heat [16]:	$q_{cc} = \int_{T_2}^{T_3} C_{pG}(\mathrm{T})$	(5)
	Heat constant pressure of combustion gas (flue gas): [16]:	$C_{pG}(\mathrm{T}) = 0.991615 + \left(\frac{6.99703\,T}{10^5}\right) + \left(\frac{2.7129T^2}{10^7}\right) - \left(\frac{1.22442T^3}{10^{10}}\right)$	(6)
	Pressure at the combustion chamber outlet [25].	$P_3 = P_2(1 - \Delta P_{cc})$ ΔP_{cc} = 0.03 bar [25].	(7)
	Combustion chamber power [17]:	$\dot{Q}_{cc} = \dot{m}_G\, q_{cc}$	(8)
	Combustion chamber efficiency is given by [17]:	$\eta_{cc,eff} = \eta_{cc} - \frac{\dot{Q}_{cc}}{\dot{m}_F\, PCI}$	(9)
Turbine model	Turbine expansion work [15]: (thermodynamic first principle)	$w_{Tur} = h_4 - h_3 = \int_{T_3}^{T_4} C_{pG}(\mathrm{T}) = \frac{\gamma_G\, r_G}{\gamma_G - 1}(T_4 - T_3)$	(10)
	Gas turbine exhaust [18]	$T_4 = T_3 + \left[\left(\frac{1}{\pi_T}\right)^{\frac{\gamma_G - 1}{\gamma_G}} - 1\right] T_3\, \eta_T$ With $\gamma_G = \frac{1}{1 - \frac{r_G}{C_{pG}}}$	(11)
	Expansion power [16]	$\dot{W}_{Tur} = \dot{m}_G \int_{T_3}^{T_4} C_{pG}(\mathrm{T})\ dT$	(12)
	Gas turbine net power [19]:	$\dot{W}_{Net} = \dot{m}_a * \int_{T_1}^{T_2} C_{pa}(\mathrm{T}) + (\dot{m}_a + \dot{m}_F) * \int_{T_3}^{T_4} C_{pG}(\mathrm{T})$	(13)
	Gas turbine efficiency [19]:	$\eta_{GT} = \frac{\dot{W}_{Net}}{\dot{m}_F * LHV}$	(14)
	Exhaust gas Heat discharged [10]	$q_E = \int_{T_4}^{T_1} C_{pG}(\mathrm{T})$	(15)

Table 2. *Environment Function Objective.*

Names	Equations	Units	N°
Nitrogen oxide mass flow rate [24]:	$\dot{m}_{NOx} = \frac{0.15\times 10^{16}\, \dot{m}_{fuel} \times \tau^{0.5}\ \mathrm{Exp}(\frac{-71100}{T_p})}{{P_2}^{0.05}\ {\Delta P_{cc}}^{0.5}}$	kg / s	(16)
Carbon monoxide mass flow rate [24]	$\dot{m}_{CO} = \frac{0.179 \times \dot{m}_{fuel} \times \mathrm{Exp}(\frac{7800}{T_p})}{{P_2}^2\, \tau\, {\Delta P_{cc}}^{0.5}}$	kg / s	(17)
Environmental criterion:	$F_{Ei} = \sum \dot{m}_N \times FP_{i,N}$ [26, 27]		(18)
Global Warming Potential	$GWP = \frac{3\times \dot{m}_{CO} + 40\times \dot{m}_{NOx}}{\dot{W}_{Net}}$	kg CO_2/kWh	(19)

Table 3. *Economic Function Objective.*

Names	Equations	Units	N°
Total cost rate [25]:	$Cost = \dot{C}_{fuel} + \sum \dot{Z}_k$	$/hr	(20)
Purchase cost [25]:	$\dot{Z}_k = Z_k\, .\, CRF.\, \frac{\phi}{3600\, N}$	$/hr	(21)
Fuel cost [25]:	$\dot{C}_{fuel} = 0.004\, \dot{m}_{fuel}.\, LHV$	$/hr	(22)
Capital recovery factor [25]:	$CRF = \frac{i\,(i+1)^n}{(i+1)^n - 1}$		(23)

According to Muhammad et al. [23], the principal pollutants emitted by gas turbines are listed in Table 4. The most significant of these pollutants are carbon monoxide and Oxides of nitrogen. The mass flow of CO and NOx are used in this work to model the Global Warming Potential (GWP) impact.

Table 4. *Micro-gas turbines principally emitted pollutants.*

Pollutants	Effects
Carbon monoxide (CO)	Toxic
Unburned hydrocarbon (UBC)	Toxic
Particulate matter (COVs)	Visible
Nitrogen oxides of (NOx)	Toxic, chemical precursor Smoke, stratospheric ozone depletion
Sulfur oxides (SOx)	Toxic, corrosive

The fuel used in the present study is methane. According to Yazdi, B. [24] the lower heating value for methane is equal to 50000 kJ/kg. Simple models of pollutant emissions from micro-gas turbines have been used. These models, based on semi-analytical correlations proposed by Barzegar et al. [12], have been used to determine CO and NOx emissions in kilograms per second. These models of pollutants depend on pressures, flame temperature, pressure drop allowed in the combustion chamber, and gas flows rate. All the parameters of these equations are given in Lazzaretto et al. [25]. Notice that the before mentioned pollutants models have been modified by Yazdi et al. [24] and are expressed now in kilograms per second (Table 2).

The environmental criterion for the first part of this study is the global warming potential (GWP). Its quantification is based on the methodology proposed by IChemE [26].

The potential impact factors used to calculate environmental criteria has given in Table 5. This GWP is sued for tri-criteria optimization.

Table 5. *Principal chemical's potential impact factors [26].*

Components	CO_2	CO	NOx
Potential impact factors	1	3	40

2.4. Micro Gas Turbine Economical Criterion Modelling

To determine the economic model, it is necessary to consider fuel used annual cost ($\dot{C}_{fuel}$), and each piece of the equipment purchase cost ($\dot{Z}_k$). The correlations used in this study are those of Lazzaretto et al. [25] and Silveira et al. [16] and are presented in Table 3.

3. Multi-Objective Optimization and Genetic Algorithm (GA)

Multi-objective optimization is a branch of combinatorial optimization whose particularity is to solve simultaneously the optimization of several objectives of the same problem. Most real optimization problems are described using several often-conflicting objectives or criteria that must be optimized simultaneously. The constraint set defines conditions on the state space that the variables must satisfy. Multi-objective problems have the particularity of being much more difficult to deal with than their mono-objective equivalent. The difficulty lies in the absence of an order total relationship between the solutions. Mathematically, a multi-objective problem is usually made up of a set of n criteria, f_k, with $k = 1$ to n, which must be maximized or minimized [29]. This type of problem presents a set of solutions known as the non-dominant solutions called Pareto's front, resulting in "no improvement can be made on an objective without degraded of at least another objective" [1]. Optimal individuals, non-dominated in the Pareto sense, represent a solution to the multi-objective problem [28]. Several methods are used to solve multi-objective optimization problems, including stochastic or evolutionary procedures, such as genetic algorithms [29]. The resolution of an optimization problem consists in examining a search space to maximize (or minimize) a given function [28, 30]. The Genetic Algorithm (GA) is a research algorithm based on the mechanisms of natural selection and genetics. Their operation is extremely simple [30]. A population of arbitrarily chosen potential solutions (initial population) is used, and their relative performance is then assessed. Based on these performances, a new population of potential solutions is created using simple evolutionary operators such as selection, crossover, and mutation. Repeat this cycle until a satisfactory solution is found.

The genetic algorithm has several variants, the most commonly used is NSGA II (Non-Dominated Sorting Genetic Algorithm II) developed by DEB. This version of the genetic algorithm is available in the Multigen library [1, 29] which is a macro implemented in VBA and interfaced with Microsoft Excel.

3.1. Problem Formulation of Multi-Objective Optimization

The use of the objective functions that are, power criteria, economic function, and environmental criteria, described above, allows to formulating of the multi-objective non-linear optimization problem as follows: determine the decision variables (operating conditions of the micro-gas turbine) to:

$$\text{Max gas turbine power: Max } \dot{W}_{Net} \tag{24}$$

$$\text{Min Total capital cost: Min } Cost \tag{25}$$

$$\text{Min Environmental Impact: Min } GWP \tag{26}$$

The decision variables in this study are compressor isentropic efficiency (η_{Comp}), Expansion isentropic efficiency (η_{Tur}), Turbine inlet temperature (T_3), Combustion efficiency (η_{CC}) compressor pressure ratio (π_{Comp}) [12]. Although the decision variables may be varied in the optimization procedure, each decision variable is normally required to be within a reasonable range. The list of these constraints is based on Sanaye's experience [31].

3.2. Genetic Algorithm Configuration

The Genetic Algorithm setting in this work is summarized in Table 6. It contains the generation number, the size of the population, the crossover, and mutation rates [27].

Table 6. *Genetic Algorithm setting parameters.*

Parameters	Values
Population size	200
Generations number	1000
Crossover rate	0.75
Mutation rate	0.02

The multi-objective problem consists in optimizing (minimizing or maximizing) several objectives simultaneously. In this study, three optimization problems were solved with the NSGA IIb version, included in the Multigen library. The optimization scenario is as follows:

Tri criterion Optimization: Environment, Net power, and Economy.

The determination of the decision variables that have a significant influence on the model of the micro-gas turbine is very important. Sensitivity analysis is used to determine these variables.

4. Sensitivity Analysis

Sensitivity analysis is used to analyze mathematical models by studying the effects of the variability of the model's input variables on the output variables [32]. The sensitivity analysis technic allows for the reduction of the output variations if it is synonymous with imprecision, and lightens the model by fixing the inputs whose variability does not influence the output variables [33].

For the sensitivity analysis study of the variables, Experimental Design (ED) technics are used because of their capacity to obtain the best precision of the variability of the variables on the results of the model [34].

Experimental Design is based on different models [35]. Among these models, one can find the Plackett-Burmann design, Factorial design, and Central composite design [36]. The design model adopted in this study is the full factorial design because of its simplest in technical terms and its efficiency in interaction management [37].

The choice of design variables and their range of functioning have been made by taking into account the design and experimental limits of operation, and data from the literature. These data from the literature are based on the conditions for optimizing the micro-gas turbine operation [12, 31].

5. Multi-Criteria Decision-Making Strategies

The determination of the "best" action (the optimal, the best compromise, etc.) is a perpetual intellectual challenge in science and engineering [38]. Multi-criteria decision support was then developed to offer both an approach and tools for solutions to complex decision-making problems. Technically, it deals with several classes of decision problems (choice, sorting, description, arrangement, etc.) while considering several criteria (attributes), often conflicting, while seeking to best model the preferences and values of the decision-maker(s). [39]. Many methods have been proposed to enable decision-makers to make a good "choice" [40]. After the analysis of more recent studies carried out on the comparison of several types of methods [41], the TOPSIS method has been choired for this study. The TOPSIS method is a multi-criteria decision-making method developed by HWANG et al. [38]. The basic concept of this method is that the chosen alternative must have the shortest distance to the ideal alternative (the best of all criteria), and the greatest distance to the ideal negative alternative (which degrades all criteria) [42].

6. Life Cycle Assessment (LCA)

The Life Cycle Assessment base on norm ISO 14040 and 14044 2006, is a tool for evaluating the Potential Impacts on the environment of a system. This system comprises all the activities associated with a product or service, from the extraction of raw materials to waste disposal [43]. Life Cycle Assessment is an eco-design decision support tool for assessing the environmental impact of a product (good or service) from the extraction of raw materials to the end of its life [44].

Life Cycle Assessment (LCA) is based on the notion of sustainable development. In an LCA study, the life cycle of a product is modeled as a system of products that provides one or more well-defined functions [45]. Product systems are subdivided into elementary processes, which are linked together by flows consumed (incoming flows) and rejected (outgoing flows) by these processes.

The objective of the LCA is to present a global vision of the impacts generated by the products (goods, services, or processes), consequently providing elements of decision-making.

The LCA implementation phases are presented by A. Demetrious et al. [46]:

1) Definition of objectives and field of study
   a) System Function, Functional Unit
   b) Definition of study boundaries
2) Life Cycle Inventory (LCI)
   a) Collection of the necessary data
   b) Assignment issues
3) Impact assessment (LCIA)
   Characterization in the form of indicators
4) Interpretation

The environmental impacts are classified into mid-point and end-point categories. In this study, only the mid-point category is analyzed.

Software is used to facilitate life cycle assessments (LCAs). Among these software one can cite SimaPro, GaBi, EcoPro, etc. [47]. In the present work, the OpenLCA software is used as LCA Software. The results obtained after the phases of optimization and decision-making strategy are analyzed by OpenLCA software. OpenLCA software is an LCA solution. It models each process of a system over its life cycle. This makes it possible to establish the best-oriented strategies [48]. It offers an accessible and constantly updated database.

7. Results and Discussions

7.1. Simulator Validation

The micro-gas turbine simulator design in this study has been implemented under the MS Excel environment interface by integrating the above thermodynamic models into a coherent system. In this simulation process, the air temperature at the compressor inlet is equal to 298 K and the pressure is fixed to atmospheric pressure. Pressure drop in the combustion chamber has been fixed at 5% of the admission pressure [16]. Thereafter, the simulator has been validated by comparing its results obtained from realized simulations with two other results.

The micro-gas turbine simulator was validated by performing a simulation, under the operating point proposed by Diango et al. [10]. This operating point is shown in Table 7.

The results obtained with the simulator were compared with those of Diango et al. [10] (Table 8) and the DWSIN Simulator in Table 9. Note that the DWSIM simulator is an engineering software that allows the simulation of many internal combustion engines and processes. This software is suitable for multiple uses such as combustion, acoustic intake, exhaust, supercharging engines, thermal analysis, transmission dynamics, and injection systems [49].

Table 7. *Gas turbine nominal operating point [10].*

T_3 (K)	$\dot{m}_A$(kg/s)	π_{Comp}	π_{Tur}	η_{Comp} (%)	η_{Tur} (%)
1042	19.8	7.17	6.57	0.8	0.855

Table 8. *Comparaison values: MS Excel simulator with Diango et al. [10].*

Parameters	MS Excel simulator	Diango et al. [10]	Relative Difference (%)
$\dot{W}_{Net}$ (kW)	1515	1514	0.07
$\dot{Q}_{cc}$ (kW)	9786	9560	2.34
η_{GT} (%)	15.50	15.80	2.05

Table 9. *Comparison values: MS Excel simulator with DWSIM simulators.*

Parameters	MS Excel simulator	DWSIM simulator	Relative Difference (%)
$\dot{W}_{Net}$ (kW)	2004.77	2099.52	4.62
$\dot{Q}_{cc}$ (kW)	10516.39	10876.00	3.36
η_{GT} (%)	19.06	19.30	1.25

In both cases, the MS Excel simulator is validated because the Relative Difference % is very small. The differences remain very acceptable. One can notice that the results obtained with the MS Excel simulator are slightly different from those of Diango et al. [10] and the DWSIM simulator. These differences are certainly due to the specific heat at constant pressure temperature variation in the gas turbine modeled under MS Excel. But this is not the case for Diango et al. [10] and the DWSIM simulator.

After the validation step, Table 10 displays the characteristics of the micro-gas turbine obtained with the MS Excel simulator. These results are achieved after a simulation with the operating point of Table 7.

Table 10. *Gas turbine energetic and environmental balance on MS Excel simulator.*

Technical Performances and Environmental Characteristics		Values
$\dot{W}_{Comp}$	(kW)	5583.115
$\dot{W}_{Tur}$	(kW)	7587.886
$\dot{W}_{Net}$	(kW)	2004.771
$\dot{Q}_{cc}$	(kW)	10516.385
η_{GT}	(%)	19.060
NOx	(kg/s)	14.820
CO	(kg/s)	20.340
GWP	(kg CO_2/kWh)	0.654
Cost	($US/hr.)	1437.980

Heat exchanges in micro-gas turbines contribute to degrading their performance, specifically environmental performance. These thermal losses are mainly due to the overheating of the compressor by the heat coming from the turbine through the axis and the losses to the outside. This heat transfer reduces considerably the compression and rebound rates thus reducing the powers of the compressor and the turbine. It is, therefore, necessary to take these losses into account in the design of these small machines.

7.2. Sensitivity Analysis

A sensitivity analysis is realized to determine the real variables that have a significant influence on the micro-gas turbine simulator.

The results obtained with the experience matrix were processed in multiple linear regression using Microsoft Excel with the level of confidence set at 95% to determine the coefficients of the variables. A variable *Xi* is said to be significant if its absolute coefficient value is greater than twice the standard error.

Experimental design results obtained showed that significant variables are compressor efficiency (η_{Comp}), Turbine expansion efficiency (η_{Tur}), and turbine inlet temperature (T_3). Figure 3 shows the effects of variables and their percentage contribution to the variation of the response studied (Net power). One can notice that the net power of the micro-gas turbine varies strongly with the turbine inlet temperature.

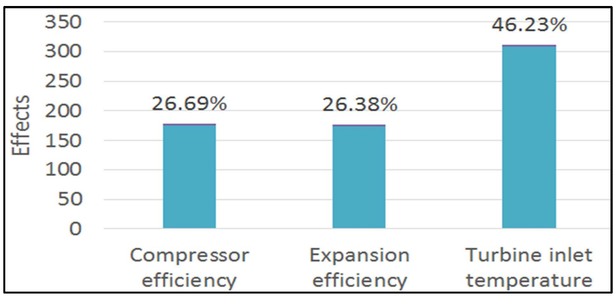

Figure 3. *Effects of factors and percentages contribution.*

7.3. Optimization and Multi-Criteria Decision Results

To improve the performance of the gas turbine, the simulator is now integrated into a multi-objective optimization loop by Genetic Algorithms (NSGA IIb) to optimize its performance.

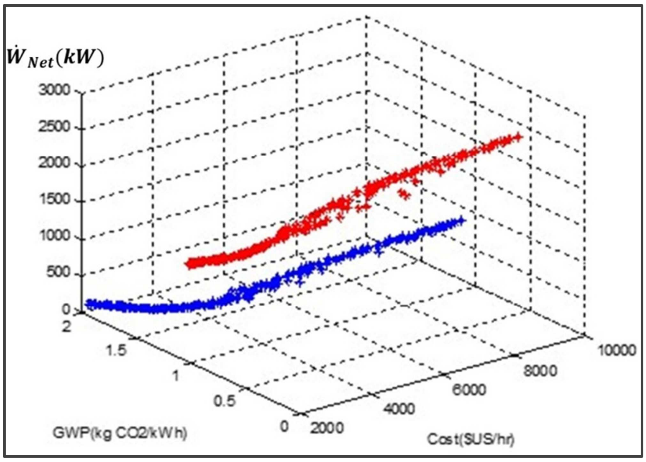

Figure 4. *Pareto's front: tri-objective optimization ($\dot{W}_{Net}$ – GWP –Cost).*

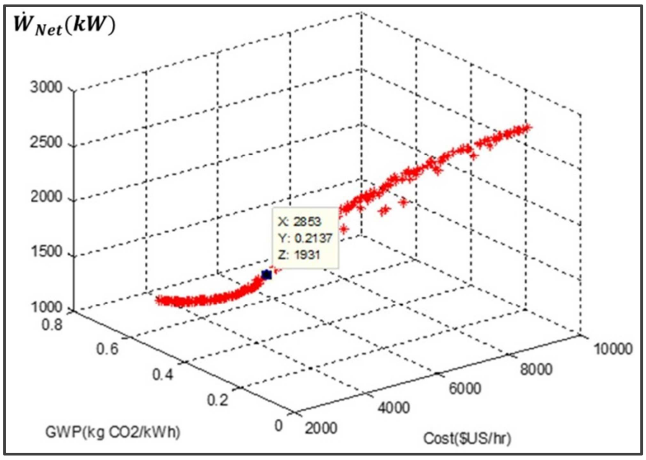

Figure 5. *TOPSIS solution for tri-objective optimization (Adiabatic).*

The tri-criteria optimizations led to the Pareto fronts represented in Figure 4. In this figure 4, it is remarkable that the two objectives (Net power and pollution) present antagonistic behaviors. The improvement in discharges is proportional to the deterioration in the power of the micro-gas turbine. It is noted that at equal power the adiabatic operation underestimates the pollution, which is lower than that of the polytropic micro-gas turbine.

The TOPSIS strategy made it possible to have the best compromise for the adiabatic functioning (Figure 5) represented by the point of coordinates (Cost = 2853 $US/hr.; GWP = 0.2137 kg$CO_2$/kWh; $\dot{W}_{Net}$ = 1931 kW) and polytropic (Figure 6) represented at the point of coordinates (Cost = 4256 $US/hr.; GWP = 0.9561 kg$CO_2$/kWh; $\dot{W}_{Net}$ = 858.4 kW). The values of all objectives correspond to the optimal point and the starting point are in tables 11 and 12. The comparison between the initial and the optimal solutions is made by calculating the following gain:

$$Gain = 100.\frac{Initial\ solution - optimal\ solution}{Initial\ solution} \quad (27)$$

The analyses of Tables 11 and 12 shows that the cost criterion is greatly increased due to the rise of the Net power and the decrease of environmental objective.

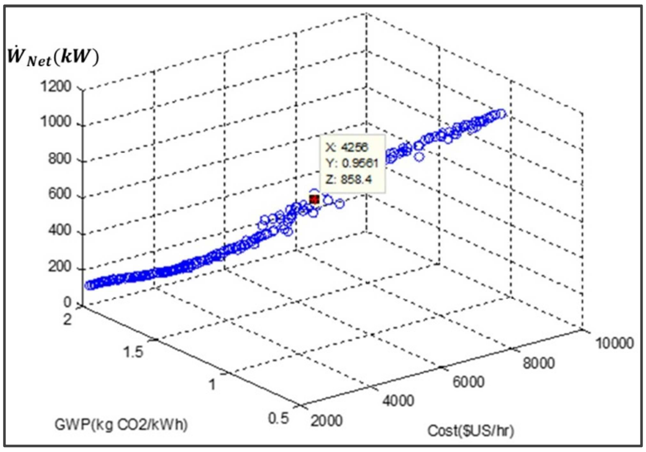

Figure 6. *TOPSIS solution for tri-objective optimization (Polytropic).*

Table 11. *Gain realized with the optimal adiabatic solution operation.*

Objective	$\dot{W}_{Net}$ (kW)	GWP (kg CO_2/kWh)	Cost ($US/hr)
Initial Solution	1724	0.6871	3012
Optimal Solution	1931	0.2137	2853
Gain (%)	- 12.00	68.90	05.28

Table 12. *Gain realized with the optimal polytropic solution operation.*

Objective	$\dot{W}_{Net}$ (kW)	GWP (kg CO_2/ kWh)	Cost ($US/hr)
Initial Solution	589.41	1.4540	3786
Optimal Solution	858.4	0.9561	4256
Gain (%)	- 32.60	82.17	-12.41

7.4. Life Cycle Assessment

The tri-optimization optimal solutions obtained in the previous study are used now for the life cycle assessment strategy. In this study, the best compromise for the tri-criteria optimization in adiabatic and polytropic operation given by the TOPSIS method is presented in Table 13.

Table 13. *Results tri-criteria optimization (TOPSIS).*

Impacts	Adiabatic values	Polytropic values
$\dot{W}_{Net}$ (kW)	1931.0	858.4
Cost ($US/hr)	2853	4256
GWP (kgCO_2/kWh)	0.2137	0.9561

The values mentioned in Table 13 were obtained by the following variables and parameters:

a) Turbine inlet temperature: 1487K

b) Compression efficiency: 0.868

c) Expansion efficiency: 0.869

Significant pollutants inventory:

a) Nitrogen oxides (No_x)

b) Carbon monoxide (CO)

Data processing with OpenLCA software provided the results presented in Table 14.

Table 14 gives different impact category values in the cases of micro-gas turbine adiabatic and polytropic operation. Significant differences between the two operations can be observed. The polytropic case gives the real operating values. This is why it is always necessary to consider the polytropic evolution during the design and sizing of micro-gas turbines to appreciate their real performances.

The life cycle assessment shows that the operation of the micro-gas turbine has a great influence on the different categories of impacts such as Global Warming Potential (GWP), Tropospheric Ozone Formation Potential (PCOP), Acidification Potential (AP), Eutrophication Potential (EP), and Human toxicity Potential (HTP) (Figure 7). Categories such as Human Toxicity, Eutrophication, and Acidification are generated solely by the nitrogen oxides (NOx) released by the combustion in these machines. On the other hand, global warming Potential and Photochemical Oxidation Potential are caused by both carbon monoxide (CO) and nitrogen oxides. In addition, pollution by the release of nitrogen oxides during the operation of these machines is felt more in the categories compared to that of carbon monoxide (Figure 8).

Table 14. *LCA result from tri-criteria optimization.*

Impacts	Adiabatic values	Polytropic values
HTP (kg C_6H_6/kWh)	0.163	0.356
EP (kgPO_4^{3-}/kWh)	0.241	0.525
GWP (kgCO_2/kWh)	0.2137	0.9561
ODP (kgCFC11/kWh)	0	0
PCOP (kgC_2H_4/kWh)	0.135	0.295
AP (kgSO_2/kWh)	0.163	0.356

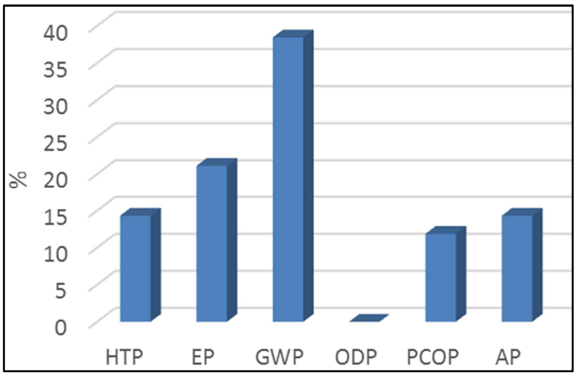

Figure 7. *Contribution of impact factors.*

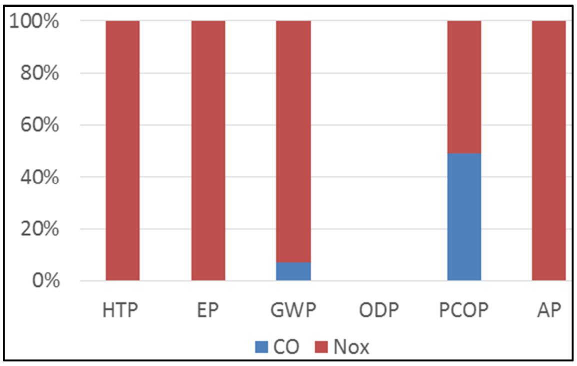

Figure 8. *Characterization of pollutants by impact.*

8. Conclusion

The problems of energy systems multi-objective optimization are complex since they are generally very constrained multi-variable problems. These problems involve and imply, most of the time, multiple and contradictory objectives that must be solved simultaneously. Several works have been devoted to the optimization of gas turbine operation, with a high number of design variables that affects optimization results. The present study's contribution was to determine the different environmental impacts caused during the actual design of micro-gas turbines by carrying out their life cycle assessment. For this purpose, a thermodynamic model was developed and coupled with an environmental and economic model that describes the overall operation of the micro-gas turbine (MS Excel simulator). The model has been optimized by Genetic Algorithms (NSGA IIb). A tri-criteria optimization has been performed. In this study, a sensitivity analysis was realized, thus giving real optimization variables (η_{Comp}, η_{Tur}, and T_3). This strategy gave better results than those of the literature that used several variables.

Two micro-gas turbines (adiabatic and polytropic) were compared during this work with the preview optimization variables. The analysis of the results achieved shows an overestimation of the adiabatic micro-gas turbine performances. Subsequently, the optimal solution obtained from the tri-criterion optimization was submitted to the decision-making strategy TOPSIS. For each case (Adiabatic and Polytropic), the TOPSIS strategy gives one ideal functioning point. The results obtained after this decision-making strategy are firstly in the adiabatic functioning (Cost=2853 $US/hr.; GWP = 0.2137 kg$CO_2$/kWh; $\dot{W}_{Net}$ =1931 kW) and secondly in the polytropic functioning (Cost = 4256 $US/hr.; GWP = 0.9561 kg$CO_2$/kWh; $\dot{W}_{Net}$ = 858.4 kW).

At that point, the previous two ideal functioning points' results were used in a life cycle assessment methodology to determine the environmental impacts using OpenLCA software. The results found after the OpenLCA investigation show that for both micro-gas turbines the higher contributions to the environmental impact are GWP, EP, HTP, and AP. For the Adiabatic micro-gas turbine: GWP = 0.2137 kgCO_2/kWh, EP =0.241 kgPO_4^{3-}/kWh, HTP =0.163 kg C_6H_6/kWh, AP = 0.163 kgSO_2/kWh. Concerning the Polytropic micro-gas turbine: GWP = 0.9561 kgCO_2/kWh, EP = 0.525kgPO_4^{3-}/kWh, HTP = 0.356 kg C_6H_6/kWh, AP = 0.356 kgSO_2/kWh. The analyses of these results show that the Polytropic micro-gas turbine emitted higher pollutants than the adiabatic micro-gas turbine. This is due to the heat exchange between the different components of the Polytropic micro-gas turbine. These results confirm the effect of heat transfer on micro-gas turbine environmental pollutant emissions. Future research will focus on a strategy that reduces the heat transfer between the polytropic micro-gas turbine components to reduce its pollutant emissions.

Symbols, Subscripts, and Superscripts

T: Temperature (K)
P: Pressure (Bar)
$\dot{W}$: Power (kW)
W: Specific work (kJ/kg)

$\dot{m}$: Mass flow rate (kg/s)
q: Specific heat transfer (kJ/kg)
$\dot{Q}_{cc}$: Combustion chamber power (kW)
C_p: Specific heat constant pressure (kJ/kg. K)
GT: Gas turbine
r: Gas constant (kJ/kg. K)
$\dot{C}_{fuel}$: Fuel cost per unit of energy ($US/kJ)
η: Efficiency
π: Dimensionless pressure
γ: Specific heat ratio
τ: Combustor residence time (s)
LHV: Lower heating value (kJ/kg)
a: Air
GT: Gas Turbine
CC: Combustion chamber
Comp: Compressor
Tur: Turbine
F: Fuel
K: Component GT
G: Gas
η_{cc}: Adiabatic efficiency of the combustion chamber
ΔP_{cc}: Pressure drop in the combustion chamber (0.03 bar).

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