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EXERGY AS A USEFUL TOOL FOR THE PERFORMANCE EVALUATION OF INTERNAL COMBUSTION ENGINES IN A THERMOELECTRIC POWER PLANT

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Abstract
This article presents an exergetic analyzer, deployed within the MatLab/Simulink environment. As a practical evaluation of this tool, it shall be used to assess the performance, in terms of exergetic efficiency, of the PERKINS 20806A-E18TAG3 engine, in two different operating modes: the first is the original, Diesel fueled, operation and the second is with said engine operating uniquely on natural gas, equipped with a novel engine management system developed by DSofer Ltda. (DSofer) which enables a particularly attractive and efficient conversion. This engine was chosen for it is the one used by EPESA.

Keywords: *Diesel, Natural Gas, Non-destructive changes , exergy efficiency*

1. INTRODUCTION

DSofer Ltda. (DSofer) is a technology company, specializing in the research and development of highly engineered engine management systems, with great focus in alternative fuels. Developing its systems for each particular engine type/model, DSofer offers systems with an unprecedented level of integration into the original/base engine. The DSofer System used in the present work is named DDR2 and allows for the quick, easy and fully reversible conversion of the original Perkins 2806 Diesel engine to 100% alternative fuel operation (natural gas for the present work, but other fuels are equally feasible). This conversion consists of merely a few simple, quick part changes and can be performed in the field in a matter of hours. No major engine disassemblies are required. This is only possible due to the highly integrated design of the new parts, along with DSofer's own research and development for said parts/system, which are the direct result of thousands of hours of applied engineering. Further technical details on this novel System cannot be provided within this work.

Worldwide, about 55% of the overall energy sources come from oil and its derivatives along with natural gas, while in Brazil this percentage is circa 49.4%. When it comes to energy sources converted into electricity (electric matrix), Natural Gas is the second most used source, only behind hydropower in Brazil. As observed worldwide and reflected in Brazil, natural gas has become an attractive resource to produce electric power, increasing its participation by 18.1% as diesel has suffered a 7% drop in demand for this purpose, according to the International Energy Agency (2018). This can be explained by logistical reasons or even fuel cost.

The First Law of Thermodynamics states the conservation of energy in isolated systems and has been widely used to evaluate the efficiency of internal combustion engines (Li Yaopeng 2016). However, according to the second law of thermodynamics, in irreversible processes thermal energy cannot be fully converted to work. In this context, exergy is defined as the maximum useful work obtainable in a specific environment (Razmara 2016). Since it enables to find locations, types and magnitudes of losses in a process, exergy is a meaningful and useful tool to provide insights in efficiency assessments (Yaning Zhang 2019).

This article intends to show the development of an exergetic analyzer created in the MatLab/Simulink platform and its application to study the performance of engines modified by the DSofer DDR2 System.

The exergetic analysis was based on PERKINS engine model 20806A-E18TAG3, equivalent to the ones used by EPESA. Efficiency was evaluated in different modes of operation, fueled with 100% Diesel and 100% Natural Gas alternately.

2. CONCEPT OF EXERGY'S ANALISER MODEL

In general terms, the stoichiometric amount of oxidant in any given combustion is simply the amount of oxidant needed to react with the exact amount of fuel present. If the amount of oxidant is greater than the stoichiometric, the mixture is called a lean mixture (Φ <1), whereas if the amount of oxidant is smaller than the stoichiometric, it is called a rich mixture (Φ> 1). The stoichiometric oxidizing-fuel or air-fuel ratio is determined by a simple atomic balance assuming that the fuel reacts to form an ideal set of products. For a hydrocarbon fuels given by the generic chemical formula CxHy, the stoichiometric ratio can be expressed in equation 1. (Turns, 2000)

$$C_xH_Y + a(O_2 + 3{,}76N_2) \rightarrow xCO_2 + (y/2)H_2O + 3{,}76aN_2 \quad (1)$$

In order to obtain Fuel-air equivalence ratio, equation 2 can be used, which states the relation between the air-fuel ratio (AFR) of a given process at its molar base and the stoichiometric Air-fuel ratio based on equation 1.

$$\Phi = \frac{\left(n_{Fuel}/n_{air}\right)}{\left(n_{Fuel}/n_{air}\right)_{stoich}} \quad (2)$$

In each case there will be an exergetic potential that will come from the fuels. This potential shows how much energy is available to be converted in useful work and is defined in equation (3), where PCI is the lower heating value on molar base, *s* is the entropy associated with each element to be analyzed on molar base and *h* is the enthalpy associated with each element to be analyzed. (Moran and Shapiro, 2009).

$$e^{che} = \overline{PCI} - T_0(\bar{s}_F + \left(x + \frac{y}{4}\right)\bar{s}_{O_2} - x\bar{s}_{CO_2} - \frac{y}{2}\bar{s}_{H_2O_{(v)}} + a\bar{e}^{che}_{CO_2} + \left(\frac{y}{2}\right)\bar{e}^{che}_{H_2O_{(v)}} - \left(x + \frac{y}{4}\right)\bar{e}^{che}_{O_2} \quad (3)$$

Exergy is also related to work transfer, which is the effective power of the internal combustion engine for the generation of energy, associated with heat transfer and the constant mass transfer as shown in equation (4). The flux is brought from its initial potential to its referential, which in this case study is the environment, and it is associated with exhaust gas as in Eq (5).

$$E_q = \dot{Q}_t(1 - T_0/T_t) \quad (4)$$

$$E_f = h - h_0 - T_0(s - s_0) + \frac{V^2}{2} + gz + RT_0 ln\left(\frac{y_i}{y_i^{amb}}\right) \quad (5)$$

Equation 6 is used to obtain the exergetic efficiency of each mode of operation. Wc represents the energy generated by the motor generator in the operation per unit mass per second and Etotal is the chemical potential of the fuel.

$$\varepsilon = \frac{\dot{W}_{VC}/\dot{m}}{E_{total}} \quad (6)$$

2.1 Exergy Analyzer

In order to enhance the agility of the exergetic analysis, a computational model was created based on Perkins Engine model 2806A-E18TAG3 and taking into account not only its original condition using diesel as fuel, but also its generation characteristics after modification with the novel DSofer DDR2 System that enabled the use Natural Gas as fuel.

The Analyzer modeling was divided into 5 (five) main blocks, as shown in the flowchart in Figure 1. The first block corresponds to the operational data of the motor and the second block contains functions responsible for converting the data into molar flows so that the third block can read and locate the enthalpies and entropies. Finally, the fourth block is responsible for the exergy calculations and the last one shows exergy related to heat transfer, exhaust gas and the exergetic efficiency.

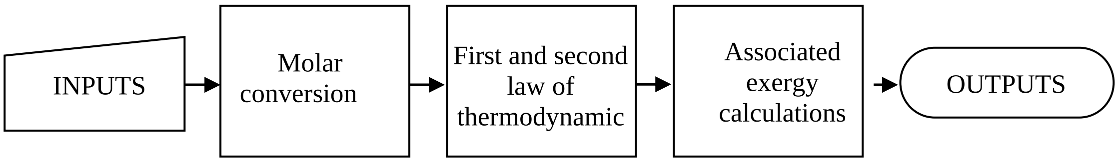


Figure 1- Exergy calculation flowchart

2.2 Input data

The genset used for this work is the FG Wilson model P750-1 (Fig. 1), which includes a PERKINS model 20806A-E18TAG3 Diesel cycle combustion engine. The data of its operation fueled with Diesel was provided by Silva (2017), whereas the operational data when running on natural gas as fuel was provided by DSofer Ltda. The considered input values are shown in Tables 1, 2 and 3.

Figure 1 - FG Wilson Generator Engine Model P750-1 using PERKINS Engine Model 20806A-E18TAG3
Available from: Silva 2017

Table 1 - Diesel consumption according to the operating speed

Operating mode	g/kWh	liters/h	g/kWh	liters/h
	1500 rpm		1800 rpm	
Standby	197	129	208	157
Prime + 10%	198	129	208	157
Prime	198	120	209	144
75% da Prime	204	93	202	104
50% da Prime	204	62	210	72

Table 2 – Perkins 2806 DDR2's Natural Gas consumption according to the operating speed

Operating mode	Nm^3/kWh	Nm^3/h
	1800 rpm	
75% da Prime	202	97
50% da Prime	210	63

Table 3 - Engine operating data according to operating speed.

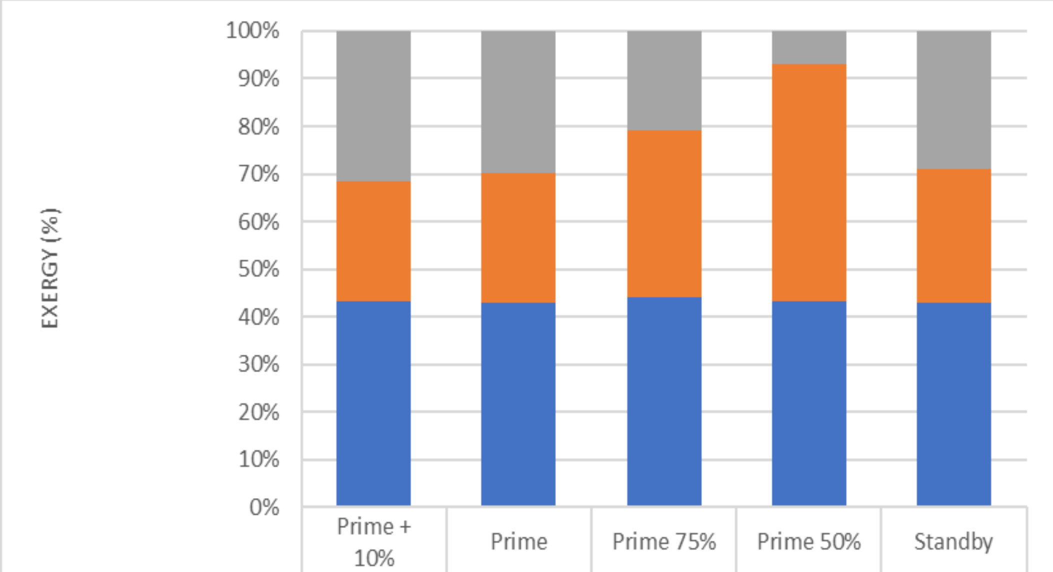
Designation	Unit	Type of operation and application	
		Prime	Standby
		60 Hz 1800 rev/min	
Flue air flow	m^3/min	47,2	50,5
Exhaust gas temperature (after turbocharger)	ºC	517,6	542,8
Generator output power (power factor = 0.8)	kWe	545	600
	kVA	681	750

2.3 OUTPUT DATA

In real operation, power output is kept within certain limits. This has roots in a number of operational reasons which are beyond the scope of this work.

In the following, some numeric examples shall be presented to demonstrate the operation of the computational tool and, mostly, for academic purposes, as some of them are based on power figures which are above the practical operating envelope of EPESA.

Considering the operation regime being the nominal load of the genset (545KWe for Prime Mode and 600 KWe for Stand by), the Figure 2 shows the analyzer output for the exergetic efficiency along with each exergy associated of diesel chemical potential. For this scenario the engine shows greater efficiency at 75% of Prime load but at 50% of Prime load much of the diesel potential is transformed into heat as shown in the graph in the exergy associated with heat transfer.



	Prime + 10%	Prime	Prime 75%	Prime 50%	Standby
Exergy - heat transfer	31,43%	29,68%	20,62%	6,97%	29,02%
Exergy Exhaust Gas	25,15%	27,07%	35,00%	49,30%	27,84%
Exergy Efficiency	43,09%	42,89%	43,82%	42,85%	42,80%

Figure 2 - Exergy associated with each PERKINS model 20806A-E18TAG3 engine operating mode with Diesel as Fuel

Similarly, the analyzer was used to study the engine operating with natural gas as fuel, equipped with the DSofer DDR2 System. In this scenario, the highest exergy efficiency was observed when the engine was operating with 50% of its nominal load whereas in the Diesel cycle it happened while operating with 75% of its nominal load

3. PERKINS 2809 ENGINE OPERATING MODE SETTINGS SET

A second analysis using the analyzer was run to search for the number of motors, operating in the best conditions in terms of exergetic efficiency, needed to meet the demand requested by National Operator of Electric System (237.12 MW, as granted by ANEEL (BIG, 2019). The flowchart in Figure 4 shows how the calculation proceeded to return the best configurations and with the minimum deviation possible.

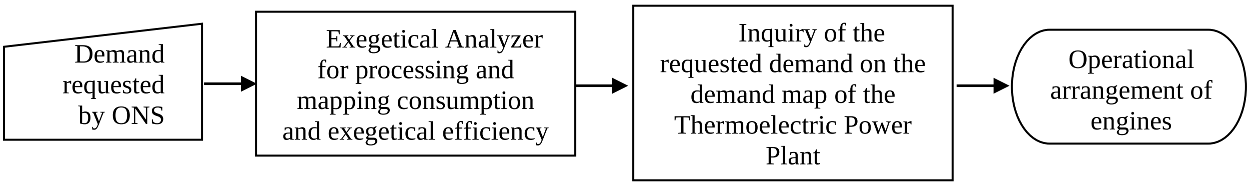


Figure 4 -Flowchart of the exergetic analyzer to obtain the configuration of engines that can meet the requested demand with more efficiency

Then, two graphs were generated showing all possible configurations of engines operating at 75% and 50% of the nominal load to meet the requested demand of 237.12MW. The horizontal axis varies according to the exergetic efficiency and the vertical axis shows the consumption of fuel on the right as the number of motors operating at the 75% and 50% of the nominal load is shown on left.

In Figure 5 it is observed fifteen different configurations to meet the demand with the engines running in the Diesel cycle. Due to the fact that the highest exergetic efficiency for engines in this condition is achieved with 75% of the nominal load, it is possible to observe that the higher the more engines in that condition are used, the higher the exergetic efficiency of the configuration is. All configurations shown could generate 237,075 MW, which represents a deviation under 0.019%.

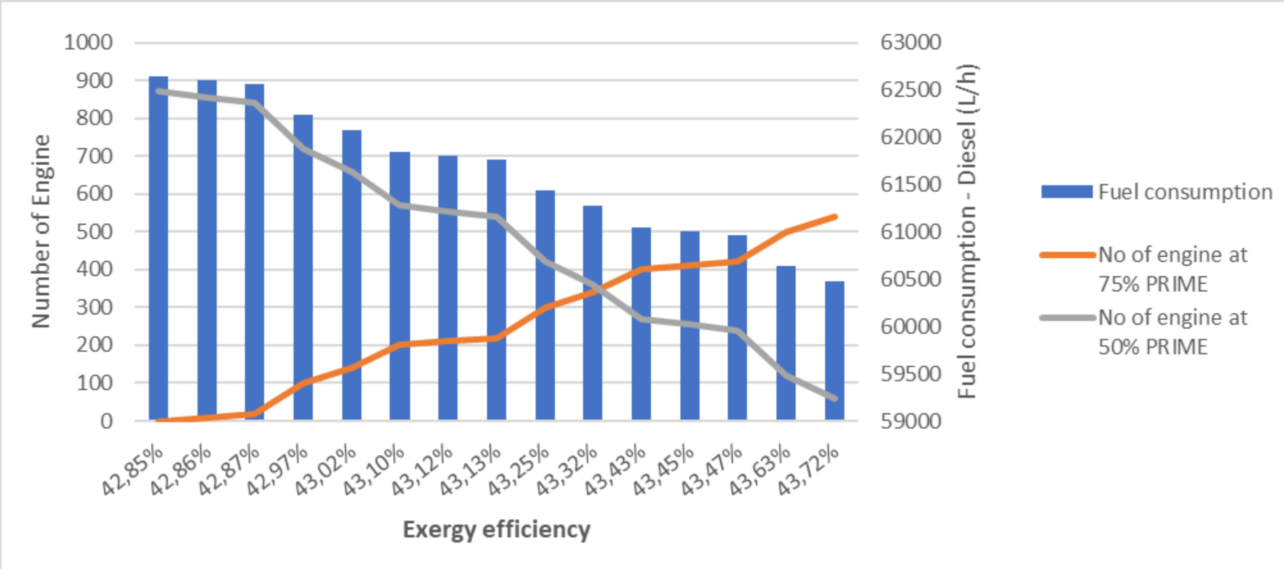


Figure 5 - Configuration chart to comply with 237.12MW demand with Perkins 2809 engine using Diesel as fuel (Standard)

In Figure 6 it is observed 12 possible configurations to meet the same demand of 237.12 MW, but in this case with engines running on natural gas at 50% of the nominal load the highest exergetic efficiency is achieved by engines with the DSofer DDR2 system installed. These configurations deliver an average power output of 237,16 MW, with an average deviation of 0,016%.

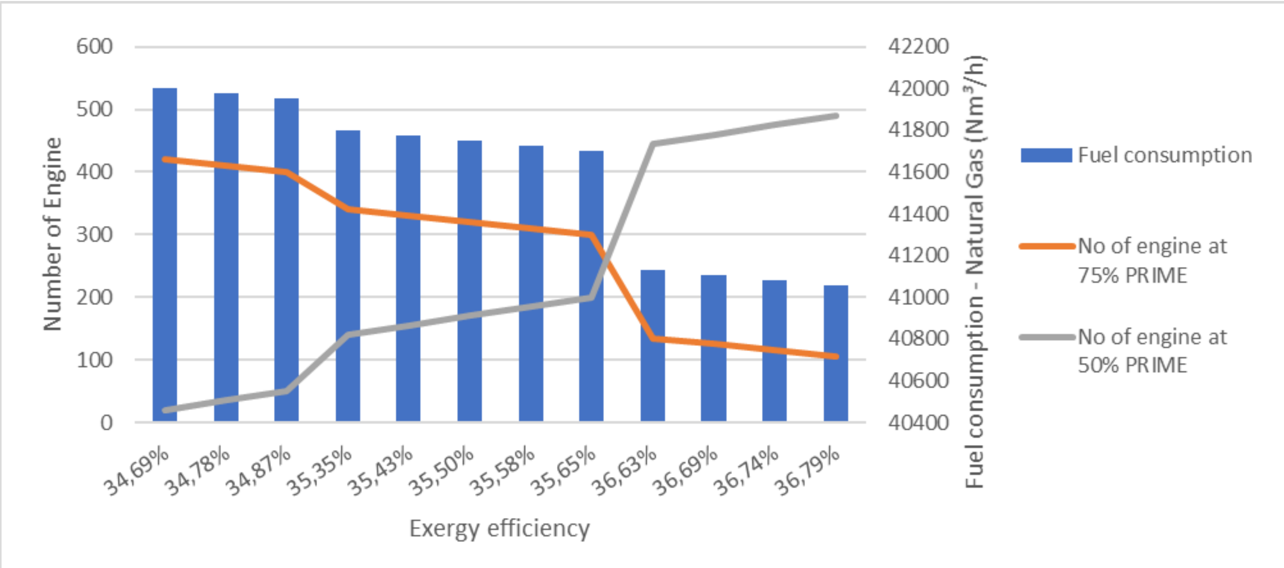


Figure 6 - Configuration chart to comply with 237.12MW demand with Perkins 2809 engine using DDR2 to operate with Natural Gas as fuel

The DSofer DDR2 System is capable not only of allowing for the Perkins 20806A-E18TAG3 engine, originally fueled exclusively on Diesel, to run successfully on natural gas, but, also, to lower the overall energy consumption by 7.81%. This reduction in energy consumption to achieve the same power output comes in addition to the gains obtainable through the lower cost of fuel.

It can be, therefore, deduced that the use of the DSofer DDR2 System can be of great value for any power plant, especially for EPESA.

4. CONCLUSIONS

The present work presented a computational tool created to help analyze engine data and was used to calculate the performance of the Perkins 20806A-E18TAG3 engine equipped with the novel DSofer DDR2 System, which enabled said engine to operate entirely with natural gas as its only fuel.

Different computations were performed with the tool, thus demonstrating its use as an analysis tool in the realm of initial evaluations of possible options to any given power plant.

Within the results obtained, a very clear operating advantage was identified for the engines when equipped with the DSofer DDR2 System and running on natural gas. This System proved to allow a considerably more efficient operation of the engines as well as its full operation on alternative fuels.

5. ACKNOWLEDGEMENTS

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