ENERGY AND EXERGY ANALYSIS OF AN MICRO-COGENERATION SYSTEM USING SEMI-CONDUCTIVE MODULE

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Abstract. *In the last decade, Brazil has been growing economically at a slower rate than other emerging countries. Any alternative to revert this scenario implies an increase in energy consumption that should be strategically associated with rationalization, reducing losses and applying cogeneration energy systems. The main alternatives for increasing the energy supply in the short term are thermoelectricity, small hydroelectric plants, in addition to solar and wind energy. This paper presents an experimental evaluation of a 1.5 kW generator operating in a cogeneration energy system. The system recovers losses in an exhaust collector, using a semi-conductive thermoelectric module and heat exchanger to heat the water. The tests were carried out at full load with constant rotation of the electric generator. The temperature curves of the flows were obtained using a data acquisition system and a PC. Mass, energy and exergy balance analysis were performed and the results obtained with the modifications and adaptations introduced were compared with those of the original version.*

Keywords: *Energy efficiency, Exergy, Cogeneration, Thermoelectric, Micro-generation.*

1. INTRODUCTION

One of the sectors that contributes most to greenhouse gas emissions is the generation of electric generation. A large portion of electric energy is generated in coal or gas burning thermoelectric plants. Global warming, a result of greenhouse gas emissions, has concerned governments worldwide, mainly in countries that ratified the Kyoto Accord, since they must reduce their 1990 emissions by 5.2% (BNDS, 1999).

One of the ways of reducing emissions is by increasing fuel efficiency. New technologies developed over the last 30 years have made it possible to implement or amplify, (as will be shown in this paper), distributed generation, using mainly microgeneration technology and combined cycle gas turbines. This has increased fuel efficiency considerably, when compared to conventional generation.

Cogeneration is beneficial to the industrial sector and is reflected in the more efficient use of primary energy, natural gas, coal and biomass. Moreover, it reduces contaminant emissions in the environment by burning less fuel per unit of energy generated. Other benefits are reduced production costs and increased competitiveness as well as self-sufficiency, continuity, diversity and an efficient supply of energy, which leads to confidence in the process and lower investments in installed power generating capacity. Cogeneration is also being used in major cities to generate electric energy to office buildings and thermal energy for air conditioning and heating. Countries such as Japan have several district heating systems in operation (D'Accadia, 2003).

A thermoelectric module is a rigid apparatus that directly converts thermal energy to electric energy, or vice versa, that is, it does not need moving mechanical components to perform the task (Vázques, 2002).

This technology has a number of interesting advantages in addition to reducing heat loss, such as energy generation with no moving generator parts. This means that there is no noise emission, mechanical wear or lubricant substitution. Operation and maintenance costs are low, and providing thermal limits are respected, no damage occurs to the semiconductors or to the ceramic plate. This equipment can operate for 6 years, with only yearly cleaning required (Leavitt, 2003). Another example of durability is the equipment installed on the unmanned voyager spacecraft, which uses generators that still produce electricity after 14 years (Vollstedt, 2001).

Despite its being old technology, it is only now being developed, thanks to solid state component technology, i.e.: microprocessors, transistors, and other technologies that depend on semiconductor components (Schroeder, 2000).

According to Borealis (2003), this new thermal electric/thermal ionic technology can reach between 20% and 30% efficiency for electric energy generation. In the near future, compact equipment will be able to generate $5We/cm^2$.

Kilgrow et al., (2003) also report that advances in the efficiency of heat exchangers will increase equipment performance.

The aim of this study is to present the results of mass, energy and exergy balance of a 1.5kW motor/generator operating at full load in its original configuration and using a semi conductive thermal electric cogenerator prototype.

2. EXPERIMENTAL DETAILS

2.1. Experimental Description

The experiment shown in Figure 1 consists of a 1.5 kW electric motor/generator unit, in which a cogeneration system was adapted and installed to recover exhaust gas heat. The system comprises a semi conductive thermal electric generator module installed on the flat surface of a cast aluminum block located on the muffler of the exhaust gas collector, with a conductive exchanger adapted to cool the cold face of the module. A second convective heat exchanger was installed at the gas outlet to maximize exhaust gas heat recovery. In addition, the experiment includes a measuring, acquisition and data monitoring system to control and record important parameters and variables such as temperatures, flows, and electric properties (De Araujo, 2005).

1. Hot source temperature- HST
2. Cold source temperature- CST
3. Conductive exchanger inlet temperature- CEIT
4. Conductive exchanger outlet temperature- CEOT
5. Convective exchanger inlet temperature- CEIT
6. Convective exchanger outlet temperature- CEOT
7. Escape gas inlet temperature- EGIT
8. Escape gas outlet temperature- EGOT

Figure 1- Thermoelectric Cogenerator Prototype

The trials were performed on a test bench composed of various measuring, acquisition and data monitoring systems, as shown in Figure 2.

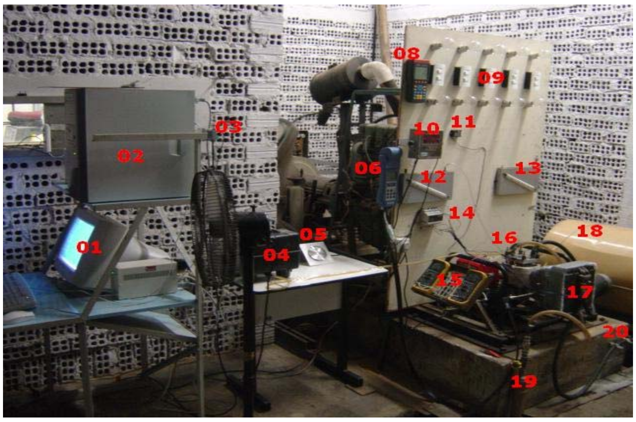

Figure 2- Experimental test bench.

1- Temperature sensor; 2- PC for temperature acquisition; 3- Field chart communicator between thermalcouplings/ PC; 4- Gravimetric fuel gauge (reservoir/ scale); 5- Barometer; 6- Gas analyzer; 7- Energy analyzer; 8- Fuel consumption indicator; 9- Panel with lights for generator power variation; 10- Tachometer; 11- Gauge to measure loss of gas flow through the convective heat exchanger (differential pressure gauge); 12- Air consumption gauge (differential pressure gauge); 13- Field Logger; 14- Thermalcoupling network; 15- Variable load panel for the semi-conductive thermal electric generator module; 16- Conductive heat exchanger (cold source); 17- Convective heat exchanger; 18- Air measuring system cylinder with orifice plate; 19- Water feed valve; 20- System water discharge.

2.2. Thermal Electric Module HZ-14

Figure 3 shows thermal electric module HZ-14 acquired from Hi-z technology Inc., used in this study (Leavitt, 2003). It recovers heat energy loss. The module uses bismuth-based alloys (Bi_2Te_3) and consists of 98 pairs, as shown in Figure 3. When installed, the module requires a heat flow of approximately 8Wcm2. With a temperature difference of

200ºC, the module converts 5% of the thermal energy that passes through it into electricity, generating a minimum of 14W of electric power. It has a 10.000-hour life when correctly installed. The application of this module requires certain precautions, both to reach expected output levels and to ensure proper operating conditions.

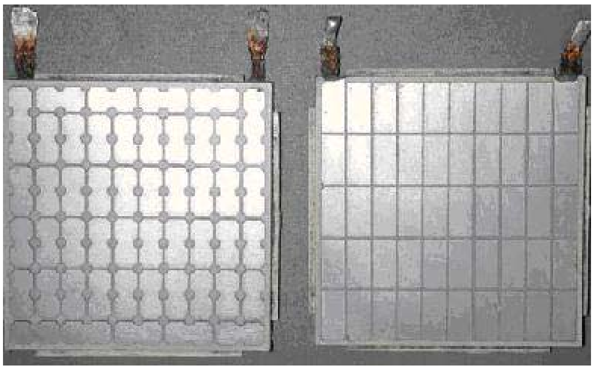

Figure 3 – Thermal electric module HZ-14:
cold face (right) and hot face (left).

2.3. Thermodynamic Analysis of the Cogeneration Plant with Thermoelectric Module

Figure 4 shows the temperature measuring points of flows that cross the system, that is, the inlet and outlet of each component involved in the global energy balance.

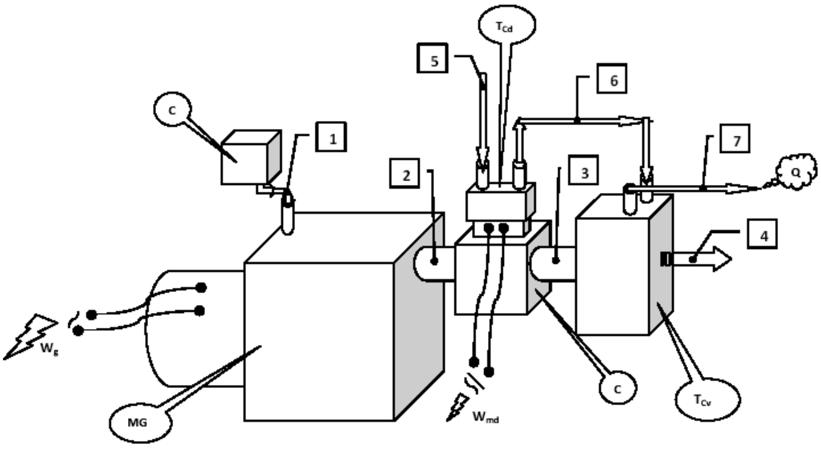

Figure 4 – System Flow Diagram

Motor/Generator:

Efficiency analysis of the motor/generator according to the first law of thermodynamics can be performed using equation 1:

$$\eta_{mg*} = \frac{\dot{W}_g}{\dot{m}_c \cdot PCI} \cdot 100 \qquad (1)$$

Where: η_{mg*} represents motor/generator efficiency, $\dot{W}_g$ electric power produced in the process, PCI is low calorific power and $\dot{m}_c$ is fuel flow.

Considering electric power $\dot{W}_{md}$ generated by the thermal electric module and the electric efficiency of the cogeneration motor/generation η_{mg} is obtained by equation 2:

$$\eta_{mg} = \frac{\dot{W}_g + \dot{W}_{md}}{\dot{m}_c \cdot PCI} \cdot 100 \qquad (2)$$

Exergy efficiency is a thermaldynamic measure recommended for thermal processes (Szargut, 1988). For the motor/generator in its original configuration and with the cogeneration prototype proposed we have equations 3 and 4, respectively:

$$\psi_{mg*} = \frac{\dot{W}_g}{\dot{m}_c \cdot PCI \cdot \varphi} \cdot 100 \quad (3)$$

$$\psi_{mg} = \frac{\dot{W}_g + \dot{W}_{md}}{\dot{m}_c \cdot PCI \cdot \varphi} \cdot 100 \quad (4)$$

Where: φ = 1.0401 + 0.1728 (h/c) + 0.0432(o/c)+ 0.2169(s/c)[1- 2.0628(h/c)] is the factor that corrects *PCI* to obtain liquid fuel exergy (Kotas, 1995); *PCI* = 44380 kJ/kg for isooctane (C_8H_{18}) liquid fuel (Taylor, 1988).

Conductive (E_{Cd}) and Convective (E_{Cv}) Exchangers:

The energy efficiencies of the Conductive (E_{cd}) and Convective (E_{cv}) exchangers were obtained using equations 5 and 6, respectively:

$$\eta_{Tcd} = \frac{\dot{Q}_{cd}}{\dot{Q}_{g2/3}} \cdot 100 \quad (5)$$

Where: η_{Tcd} is energy efficiency, $\dot{Q}_{cd}$ is the heat flow transfer to water and $Q_{g2/3}$ is the heat flow transfer of exhaust gases between points 2 and 3 of the process flowchart of the conductive heat exchanger:

$$\eta_{Tcv} = \frac{\dot{Q}_{cv}}{\dot{Q}_{g3/4}} \cdot 100 \quad (6)$$

Where: η_{Tcv} is energy efficiency, $\dot{Q}_{cv}$ is heat flow transfer to water and $Q_{g3/4}$ is the heat flow transfer of exhaust gases between points 3 and 4 of the process flowchart of the convective heat exchanger:

The exergy efficiencies of the Conductive (E_{cd}) and Convective (E_{cv}) exchangers were obtained using equations 7 and 8, respectively:

$$\psi_{Tcd} = \frac{\Delta\dot{E}x_{cd}}{\Delta\dot{E}x_{g2/3}} \cdot 100 \quad (7)$$

Where: ψ_{Tcd} is the exergy efficiency, $\Delta\dot{E}x_{cd}$ is the exergy flow transfer to water and $\Delta\dot{E}x_{g2/3}$ is the exergy flow transfer of exhaust gases between points 2 and 3 of the process flowchart of the conductive heat exchanger:

$$\psi_{Tcv} = \frac{\Delta\dot{E}x_{cv}}{\Delta\dot{E}x_{g3/4}} \cdot 100 \quad (8)$$

Where: ψ_{Tcv} is exergy efficiency, $\Delta\dot{E}x_{cv}$ is exergy flow transfer to water and $\Delta\dot{E}x_{g3/4}$ is energy flow transfer of exhaust gases between points 3 and 4 of the process flowchart of the convective heat exchanger.

The parameters to calculate energy and exergy efficiencies from equation 3 and 4 are shown for each piece of equipment in table 1.

Table 1 – Parameters used for the thermodynamic analysis of the cogeneration configuration.

Parameter	Heat Exchangers
$\dot{Q}_{cd}$	$\dot{m}_a(h_6 - h_5)$
$\dot{Q}_{g2/3}$	$\dot{m}_g(h_2 - h_3)$
$\dot{Q}_{cv}$	$\dot{m}_a(h_7 - h_6)$
$\dot{Q}_{g3/4}$	$\dot{m}_g(h_3 - h_4)$
$\Delta\dot{E}x_{cd}$	$\dot{m}_a(ex_6 - ex_5)$
$\Delta\dot{E}x_{g2/3}$	$\dot{m}_g(ex_2 - ex_3)$
$\Delta\dot{E}x_{cv}$	$\dot{m}_a(ex_7 - ex_6)$
$\Delta\dot{E}x_{g3/4}$	$\dot{m}_g(ex_3 - ex_4)$

2.4 Thermal, Electric and Global efficiency of the cogeneration system

The relations used to calculate thermal, electric and global efficiency are shown in table 2.

Table 2- Thermal, electric and global efficiency of the cogeneration system.

Efficiency	η (1st law of thermodynamics)	ψ (2nd law of thermodynamics)
Total thermal	$\frac{\dot{Q}_{cd}+\dot{Q}_{cv}}{\dot{m}_c \cdot PCI}\cdot 100$	$\frac{\Delta\dot{E}x_{cd}+\Delta\dot{E}x_{cv}}{\dot{m}_c \cdot PCI \cdot \varphi}\cdot 100$
Total electric	$\frac{\dot{W}_g+\dot{W}_{md}}{\dot{m}_c \cdot PCI}\cdot 100$	$\frac{\dot{W}_g+\dot{W}_{md}}{\dot{m}_c \cdot PCI \cdot \varphi}\cdot 100$
Global	$\frac{\dot{W}_g+\dot{W}_{md}+\dot{Q}_{cd}+\dot{Q}_{cv}}{\dot{m}_c \cdot PCI}\cdot 100$	$\frac{\dot{W}_g+\dot{W}_{md}+\Delta\dot{E}x_{cd}+\Delta\dot{E}x_{cv}}{\dot{m}_c \cdot PCI \cdot \varphi}\cdot 100$

The thermodynamic properties of the flows used in thermodynamic analysis are shown in table 3 and water and exhaust gas exergy was calculated from the following expression: $ex = (h - h_0) - T_0(s - s_0)$.

For exhaust gases $\Delta h = \int c_p\, dT$, $\Delta s = \int \frac{dT}{T}$ and $c_p = \sum_j x_i . cp_i$.

Where: $cp_i = A_i + B_i.T + C_i.T^2$ represents the calorific capacity of composite $\boldsymbol{i}$ present in the exhaust gases, calculated from the composition and mass of the air and fuel, considering stiochiometric combustion (Callen, 1985).
The mass flow of exhaust gases $\dot{m}_g$ was obtained considering air/fuel ratio $r_{A/C} = 15$ for gasoline (isooctane) and excess air measured $\lambda = 1.23$ using equation 9 (Heywood,1988).

$$\dot{m}_g = \dot{m}_c . r_{A/C} . \lambda \tag{9}$$

Table 3 – Thermodynamic properties of the flows (Points correspond to figure 4).

Points	Description	Temperat.(°C)	$\dot{m}$ (kg/s)	*h – (kJ/kg)*	*s – (kJ/kg.K)*	*ex –(kJ/kg)*
1	fuel	28	0.00030	44,380.00	-	54,481.00
2	gas	680	0.00554	824.68	1.45	398.6
3	gas	260	0.00554	285.94	0.71	74.32
4	gas	35	0.00554	11.94	0.04	0.02
5	water	32	0.06412	134.2	0.4643	0.32
6	water	34	0.06412	142.6	0.4916	0.79
7	water	40	0.06412	167.6	0.5724	1.65

Reference conditions: T_0 = 25°C, P_0 = 101.3kPa, relative humidity = 62.47 %, absolute humidity = 0.018804 kg water/kg dry air; water: T_0= 25°C, h_0= 104.89 kJ/kg, s_0= 0.3674 kJ/kg.K (Incropera, 1998).

3. RESULTS

3.1. Performance Analysis

The experimental result with the original configuration had thermodynamic performance: energy efficiency $\eta_{mg*} = 10.3$ % and exergy efficiency $\psi_{mg*} = 9.6$ %.

Table 4 shows thermal, electric and global efficiency results with cogeneration configuration. The cogeneration configuration had better thermodynamic performance, both for the 1st and 2nd law of thermodynamics.

Table 4 – Thermal, electric and global efficiency results (cogeneration).

Efficiency	η (1st law of thermodynamics)	ψ (2nd law of thermodynamics)
Total thermal	15.8	0.6
Electric total	10.5	9.8
Global	26.3	10.4

The experimental results with the thermoelectric module were obtained with the empty trial, taking into account that under this condition thermal dissipation in the motor exhaust already met the thermal requisites of the module (temperature gradient and dissipated thermal flow). The power provided by the thermoelectric module was compatible with that provided by the manufacturer.

Figure 5 shows the variations in electric properties measured versus those provided by the manufacturer.

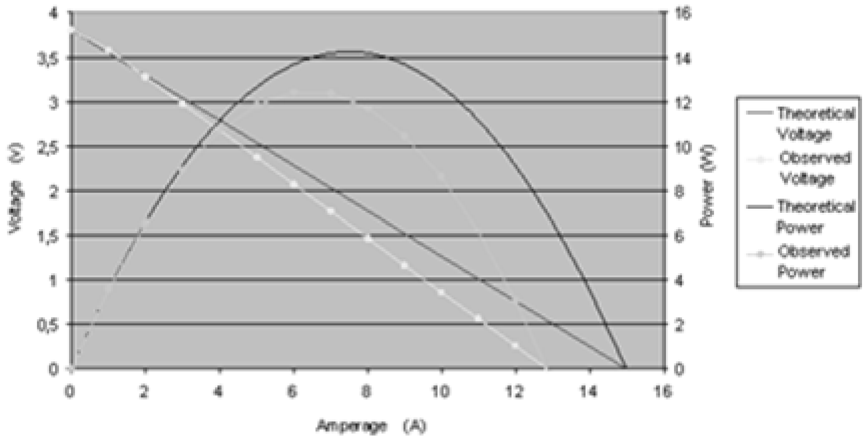

Figure 5- Thermoelectric curve supplied by the manufacturer and that experimentally obtained.

Quantitative data analysis shows good agreement in installation results when the ideal power recommended by the manufacturer is compared to the experimental values obtained. For the same temperature variation submitted, the ratio between effective electric power and ideal power was more than 90%.

Figure 6 shows electric power generation provided by the generator and thermoeçlectric module, whereas figure 7 shows thermal power obtained through heat exchangers at different load regimes.

In all the regimes, recovered thermal power was always greater than the amount of electric energy generated. The thermal power removed from the convective heat exchanger had a higher growth rate with the load than that of the conductive exchanger.

The energy provided by the adapted thermoelectric module was 3.4% of the energy provided by the electric generator at a partial load of 20% of maximum power. This recovery can be increased considerably by the installation of various thermoelectric modules in series or parallel and managed by an electronic control system, in detriment to thermal recovery by cogeneration in the convective exchanger.

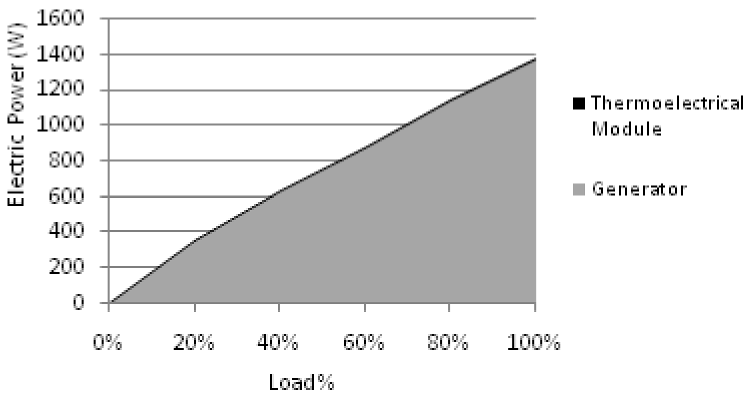

Figure 6 – Electric power

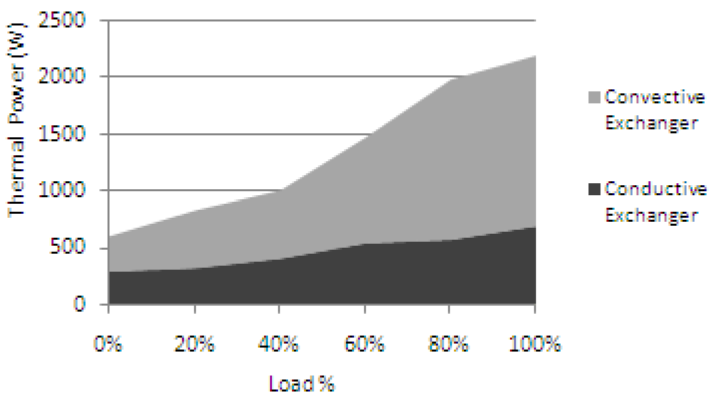

Figure 7– Thermal power

Figure 8 shows that the point at around 80% of maximum power had higher global system performance, both for the original configuration and for the proposed one, reaching approximate values of 10.5% and 26.3%, respectively.

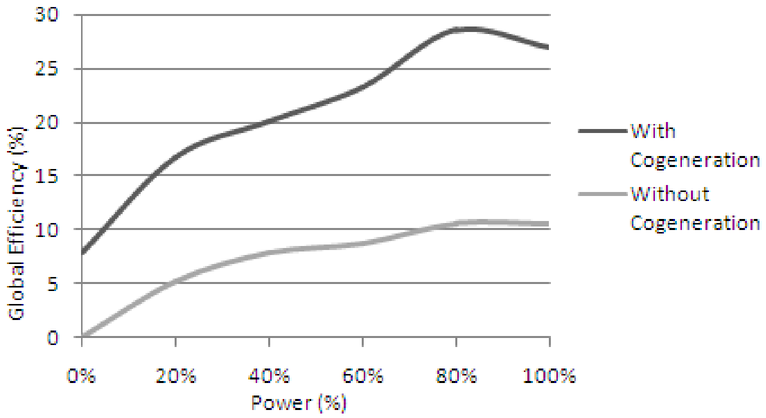

Figure 8 - Global efficiency of the system

3.2. Emission Analysis

Table 6 shows the emission values of the system under different power regimes, obtained in a series of tests using a UNIGAS-3000 gas analyzer.

Table 6 – Gas emission values produced by combustion.

Emissions	O_2 [%vol]	CO_2 [%vol]	CO [%vol]	HC [ppm vol]	NOx [ppm vol]	λ
Empty	7,7	9,6	0,0194	490,5	51,3	1,54
20%	7,0	10,1	0,0201	367,9	77,0	1,47
40%	6,8	10,2	0,0202	333,3	85,0	1,45
60%	5,7	11,1	0,0212	163,5	105,5	1,35
80%	4,3	12,1	0,0211	16,7	118,3	1,24
Full load	4,1	12,2	0,0211	1,7	150,0	1,23

Overall analysis of the values shows an expected variation for O_2 and CO_2 emissions because of the decreasing tendency of the CO and HC lambda (λ) factor. The values found were in agreement with the carburation and ignition patterns of the motor/generator under study.

The CO values are low for any load regime and are explained by the excess of air for any load submitted, a design most likely created by the Honda engineering team, given that this gas might be lethal, depending on the concentration.

With respect to hydrocarbons (HC), we found high emission levels at low partial loads; these levels fell abruptly with a decrease in the lambda factor.

Finally, the increase in nitrogen oxide gases when the submitted load is increased reflects this tendency by an increase in combustion chamber temperature of the motor.

4. CONCLUSION

The results show that the modifications and adaptations introduced for exhaust gas recovery of the microgenerator investigated in this study met the objectives proposed quite satisfactorily.

The global output of the cogeneration system increased from 10.3% to 26.3%, which reinforces the importance of cogenerating whenever possible in small units, since their conversion performance is low. Cogeneration makes the distribution of microgenerated energy more feasible, mainly for remote and adverse applications, reducing fuel storage capacity as well.

The configuration proposed increased considerably the amount of raw product that enters the system, as shown by the analysis of the first and second laws of thermodynamics.

The thermoelectric module had maximum performance of more than 90%, very near to the value provided by the manufacturer.

The energy lost by the escape of hot gases was significantly reduced, since up to half of the 33 % normally wasted in internal combustion engines was recovered (Taylor, 1988; Heywood, 1988).

The equipment had satisfactory emission levels of combustion subproducts, considering the type of ignition and fuel feed system used in the motor/generator investigated.

As further research, we suggest a study regarding increasing capacity using thermoelectric modules, the optimization of thermal insulation and the development of low-cost semiconductor modules for thermoelectric applications.

5. ACKNOWLEDGEMENTS

To PPGEM (Postgraduate Program in Mechanical Engineering) and to the Energy Laboratory at UFRN (Federal University of Rio Grande do Norte) and CT-GAS for their support and to the technicians Arivaldo and Frazão for their invaluable assistance during the experiments.

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