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Evaluation of an experimental induced ignition engine under different gasoline

Evaluación experimental de un motor de encendido provocado bajo diferentes gasolinas

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Abstract

The internal combustion engine with provoked ignition is a thermal machine that enables obtaining mechanical power from the chemical energy of a fuel. The objective of this work was to evaluate the performance of an internal combustion engine through the balance of energy and exergy, under the individual use of the three types of gasoline sold in Ecuador (Super, Extra and Ecopais). The experimental methodology consisted of starting the engine with the individual use of gasoline until reaching its maximum power at engine speed, and taking measurements of temperature, specific fuel consumption and air-fuel ratio during 3 minutes. Results show an energy efficiency of 11.31% for the Super gasoline, 10.75% for the Extra gasoline and 10.39% for the Ecopais gasoline. Regarding exergy efficiency, 58.81% was established for the Super gasoline, 58.89% for the Extra gasoline and 59.19% for the Ecopais gasoline. Results enable us to conclude that there is an exergy potential for improvement that may be an opportunity to increase energy efficiency.

Keywords: energy balance, exergy, energy consumption, ignition motor induced.

Resumen

El motor de combustión interna de encendido provocado es una máquina térmica que permite obtener una potencia mecánica a partir de la energía química de un combustible. El presente trabajo tuvo como objetivo evaluar el desempeño de un motor de combustión interna mediante el balance de energía y exergía, bajo el uso individual de las tres gasolinas comercializadas en el Ecuador (Súper, Extra y Ecopaís). La metodología experimental consistió en la puesta en marcha bajo el uso individual de las gasolinas hasta alcanzar su máxima potencia a una velocidad de giro del motor, donde se tomaron mediciones de temperatura, consumo específico del combustible y la relación aire combustible para un tiempo de tres minutos. Los resultados muestran una eficiencia energética de 11,31 % para gasolina Súper, 10,75 % para gasolina Extra y 10,39 % para gasolina Ecopaís. En lo relacionado a la eficiencia exergética se estableció un 58,81 % para la gasolina Súper, 58,89 % para la gasolina Extra y un 59,19 % para la gasolina Ecopaís. Los resultados permiten concluir que existe un potencial exergético de mejoramiento que puede ser una oportunidad para aumentar la eficiencia energética.

Palabras clave: balance de energía, exergía, consumo energético, motor de encendido provocado.

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1. Introduction

Internal combustion engines (ICE) have great applications in energy generation and cogeneration systems, and in the automotive industry. Therefore, testing and studying the performance of these engines is very important to contribute to a larger growth of its scope of application and operation quality [1, 2].

In general, ICEs have a larger delivery and activity in the transportation sector, in which the use of fuels and the increase of emissions are related with industrial processes that drive a strong economic activity of marketing and insurance of goods and supplies [3, 4]. In Ecuador, the transport sector represents 49 % of the total energy consumption, where 98.3 % comes from diesel and gasolines, representing 25 % of the emission of greenhouse gases due to the combustion of gasolines [5].

The ICE is the most efficient and reliable energy plant in the transport (gasoline and diesel engines) and heavy machinery (diesel engine) sector. It is expected that ICEs are present until: (i) fuel shortage becomes a serious problem; (ii) less polluting and more efficient new technologies are developed as replacement; or (iii) emissions regulations, established by environmental agencies to improve quality of air, become unreachable for engine and vehicle manufacturers [6].

Since the last century, the automotive industry has been analyzing the design of engines with the purpose of reducing emissions of greenhouse gases –carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxide (CO)– and particulate matter (PM), main responsible for the degradation of the environment [7, 8]. In addition, ICEs are designed to guarantee a specific output power combined with the greatest possible efficiency [9]. The improvements have also increased through the use of fuels with better properties; one of the important factors that determine the quality of gasolines is the so-called octane rating [10]. It is defined as a quantification of the quality and antiknocking capability of gasolines; its main feature is identifying the combustion process within the engine: a high-octane rating represents a better antiknocking capability.

For example, in South America the gasolines with higher octane rating are Argentina and Peru with 98, followed by Brazil with 95 and Colombia with 92 [11]. Three types of gasolines are sold in Ecuador, which come from domestic refineries. According to the INEN 935 REGULATION, these are classified based on their octane-rating in two types:

- Super Gasoline, with a minimum octane rating of 92.
- Extra Gasoline and Ecopais, with a minimum octane rating of 87.

The Ecopais gasoline is defined as a biofuel which contains a mixture of 95 % of premixed naphtha and 5 % of ethanol [12].

The development of the automotive industry has an impact on the energy shortage [13], however, the increasing demand of biofuels as an alternative to mitigate the emission of gases and reduce the consumption of oil-based fuels is only a part of the solution [14], therefore, it is necessary to evaluate the performance of the engine through energy and exergy analyses.

The energy analysis is based on the first law of thermodynamics, as an efficient way to know the energy distribution characteristics reflected in the conversion, transfer, usage and energy loss of the fuel in terms of quantity. With this characteristic as a guide, specific measures may be used to reduce energy loss. However, the energy analysis does not reflect the difference in energy quality, term which is indeed considered for the exergy analysis; the latter is based on the second law of thermodynamics, the exergy study may evaluate the energy quality to achieve a total reusability of the energy lost [15].

With respect to the energy analysis of the ICEs, up to 55 % of the input energy is yielded to the environment through exhaust gases and various heat exchange processes between the engine configuration of the engine, the refrigerant and the lube oil [16]. Figure 1 indicates the performance percentages of an ICE.

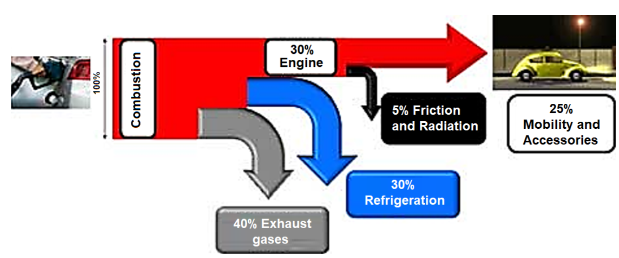


Figure 1. Sankey Diagram in ICE [17]

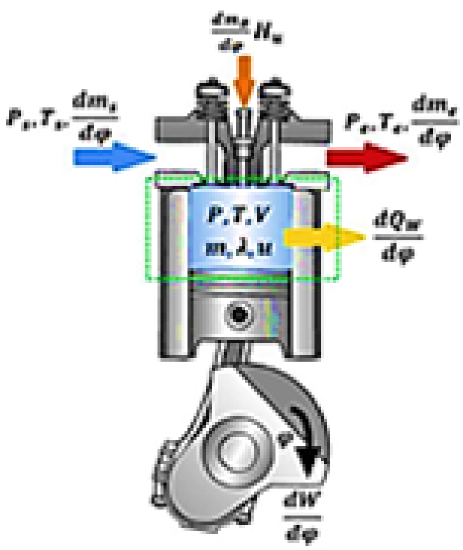
The ICE is a thermal engine that transforms chemical energy into mechanical energy, generally available in a turning output shaft. The chemical energy of the fuel is first transformed into thermal energy through the combustion or oxidation with the air within the engine, and after the combustion the reactants are transformed in products such as carbon dioxide (CO_2), water (H_2O) and carbon monoxide (CO). The thermal energy increases the pressure and temperature of the gases within the engine, the high-pressure gas expands against the mechanical mechanisms of the engine [18].

With the objective of reinforcing the knowledge and skills of the students of Automotive Engineering, the SEK International University acquired an experimental bench for ICEs, specifically engines with provoked ignition (EPI). It is unknown the energy performance of such engine when using the gasolines sold in Ecuador.

Based on the above, the general objective of this research study is to evaluate the performance of an experimental engine with provoked ignition, by means of the energy and exergy balance, with the individual use of the three gasolines sold in Ecuador, for assessing and evaluating its performance.

2. Materials and methods

Figure 2 indicates that the walls of the combustion chamber constitute the boundaries of the system. When using the first law of thermodynamics it is obtained the decomposition of the system energy, equation 1, which is equivalent to saying that «the change in the system energy (Esys), assuming that there are no energy losses in deformations of the control volume, reduces to the change in the internal energy of the system (U)» [19].



1. Energy of the system (*Esis*)
2. Energy supplied to the system by the fuel (*Qcomb*)
3. Inlet load (*madm*hadm*)
4. Mechanical work (*W*)
5. Heat dissipated through the refrigerant (*Qref*)
6. Heat of the exhaust gases (*mesc*hesc*)
7. Equivalent heat of the chamber gases that escape through the interstices between the segments (*mfug*hfug*)

Figure 2. Thermodynamic model of an ICE [20, 21]

$$\frac{dE_{sis}}{dt} = \frac{dU}{dt} = \frac{dQ_{comb}}{dt} + \frac{dQ_{refr}}{dt} + \frac{dW}{dt} + \\ + \frac{dm_{adm}}{dt}h_{adm} + \frac{dm_{esc}}{dt}h_{esc} + \frac{dm_{fug}}{dt}h_{fug} \quad (1)$$

For the practical purposes of calculating the energy balance of the engine, Equation (1) may be rewritten as shown in equation (2) [21]:

$$Q_{comb} + m_{adm}h_{adm} = W + Q_{refr}\frac{dU}{dt} + \\ + m_{esc}h_{esc} + m_{fug}h_{fug} \quad (2)$$

Regarding the scope, the present study is experimental, because it is based on the management of parameters that measure the performance of the engine, such as torque, rotational speed, engine power, volumetric flow and specific consumption of fuel under strictly controlled circumstances, with the objective of explaining how or why a particular situation or circumstance arises [22].

The engine under study is a 1 cylinder four-stroke CT 150 air-cooled EPI, with carburetor. With an approximate weight of 15 kg, dimensions L × W × H (420 × 300 × 320 mm), approximate power of 2.2 kW, oil volume 0.6 L, magnetic ignition voltage, compression ratio 7:1, thermal probe for measuring the temperature of exhaust gases from 0 to 1000 °C, driven by a pulley of diameter 125 mm, and SPA 1250 v-belt (see Figure 3).

Figure 3. CT 150 engine

The following instruments and materials (integrated in the experimental bench as illustrated in Figure 4) were used for conducting the research:

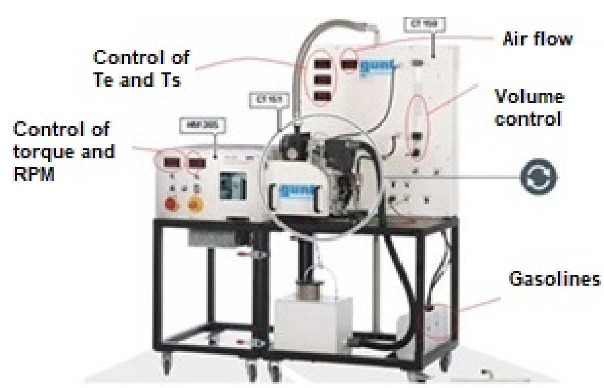


Figure 4. Experimental bench. Air-cooled gasoline engine with 1 cylinder, and HM 365 universal drive and brake unit

- Air-cooled gasoline engine with one cylinder.
- HM 365 universal drive and brake unit

- Asynchronous motor with frequency converter
  - power: 2200 W
  - maximum speed: 3000 $\min^{-1}$ approx.
  - maxumum torque: 12 Nm approx.
- Operation with v-belt
  - v-belt length: 1157 mm, 1180 mm, 1250 mm
  - type of v-belt: SPA
  - diameter of the v-belt pulley: 125 mm
- Resistive load: 72 Ω, 2400 W
- Measurement ranges
  - torque: ± 15 Nm
  - speed: 0… 5000 $\min^{-1}$
- 400 V, 50 Hz, 3 phases
- 400 V, 60 Hz, 3 phases
- 230 V, 60 Hz, 3 phases
- Super, Extra and Ecopais Gasolines (see Table 1, fundamental features)

Table 1. Properties of the fuels

Parameters	Super	Extra	Ecopais
Octane Rating (OR)	92	87	87
Sulphur content (%)	0,065	0,065	0,065
Gum content (mg/100 ml)	4	3	3
Aromatic content (% vol.)	35	30	30
Olefin content (% vol.)	18	18	18
Final point of evaporation (°C)	220	220	220
Density (kg/m^3)	722	723	749
LCV (kJ/kg)	48345	45124	44739

Note: Taken from the study conducted by Rocha-Hoyos, *et al.* [23]

The following steps were implemented to obtain the power curve:

- Start the engine at full load.
- Adjust the torque potentiometer (M) to progressively brake the engine (n) (reducing the rpm).
- Record the torque (M) and the number of revolutions (n) in a table (9 readings).
- Repeat the procedure for a second reading to be able to calculate the average.
- Apply Equation (3) for obtaining the power:

$$P = \frac{2\pi n M}{60}\ (W) \tag{3}$$

- Plot power (y axis) *vs.* rpm (x axis).

The following steps were implemented to obtain the consumption curve:

- The engine is adjusted to operate at constant revolutions (2500 rpm), and it is measured the time at which 5.1 cm^3 are consumed (which corresponds to a descent of 1 cm in the scale of the measuring tube, thus determining the volumetric flow Q) for a fixed torque in the equipment.
- Values are recorded for different engine torques (always maintaining the engine at 2500 rpm), the results are recorded in a table.
- Make a table that records the power, the mass flow $\dot{m} = Q\rho_{fluid}$ (where Q is the volumetric flow and ρ_{fluid} is the density of the fuel) and the specific consumption (b_e) obtained by means of Equation (4):

$$b_e = \frac{\dot{m}}{P} \tag{4}$$

- Plot b_e (y axis) and P (x axis).

2.1. Calculation of the thermal balance

The energy balance of the ICEs is basically a study of the first law of thermodynamics, which is also called energy balance, heat balance or thermal balance [20]. The analysis of the thermal balance is an efficient way to know the energy flow, enables the designer to evaluate the variation of internal energy as a function of the energy transfers as heat or work through the boundaries, and the enthalpies associated with the mass flow that crosses these boundaries, and then presenting a highly potential method which reduces fuel consumption in the engines [24]. The thermal balance enables carrying out the following equality: Energy that enters the system = Energy that exits the system.

From another point of view, Equation (5) is fulfilled for a process with flow and steady state.

$$\sum Q = \sum H_{input} - \sum H_{output} \tag{5}$$

Where:

$\sum Q$: sum of heat evacuated to the environment

$\sum H_{output}$: sum of enthalpies that exit the system

$\sum H_{input}$: sum of enthalpies that enter the system

In the light of the above, the sum of heats that cross the system is equal to the difference between the sum of enthalpies that enter the system and the sum of enthalpies that exit the system [19]. On the other hand, the change of enthalpy is a measure of the amount of energy absorbed or delivered in a thermodynamic system, i.e., is the change produced by a transformation in which it is possible to receive or provide energy (such as in the present case study, mechanical energy), and thus the enthalpy may be considered as numerically equal to the heat exchanged with the environment. In order to solve the thermal balance, the following general calculations are taken into account.

2.1.1. Mass flow of fuel (Equation 6)

$$\dot{m}_c = \rho \frac{v}{\Delta t} \tag{6}$$

Where:

$\dot{m}_c$ = mass flow of fuel (kg/s)

ρ = fuel specific density (kg/m^3)

V = fuel volume (m^3)

Δt = flow time (180 s)

2.1.2. Heat released by the fuel (Equation (7))

$$\dot{Q}_c = \dot{m}_c \cdot PCI \tag{7}$$

Where:

$\dot{Q}_c$ = Heat released by the fuel (kW)

PCI = lower calorific value of the fuel (kJ/kg)

2.1.3. Flow of exhaust gases (Equation (8))

$$\dot{m}_g = \dot{m}_{air} + \dot{m}_{fuel} \tag{8}$$

Where:

$\dot{m}_{air}$ = flow of air (kg/s)

$\dot{m}_{fuel}$ = mass flow of fuel (kg/s)

The energy efficiency of the system is determined according to Equation (9).

$$\eta_{energy} = \frac{P_{max}}{\dot{Q}_c} \tag{9}$$

Where:

P_{max}= Maximum power of the engine

$\dot{Q}_c$= heat released by the fuel

2.2. Exergy balance

The exergy is established as the analysis of the performance of the system based on the second law of thermodynamics. The exergy is the amount of «energy available» in the system. The exergy analysis is used to define the type, location and extent of the energy losses in different parts of an ICE [25]. The exergy is defined as the maximum amount of useful theoretical work, which may be obtained when a system reaches thermodynamic equilibrium with the environment. The destruction of exergy or the irreversibilities are accompanied by the generation of entropy. The main objective of an exergy analysis is to conceptualize the optimal design for a system, the design parameters and operation have considerable effects in the exergy balance during the operation of engine [26].

Three main sources of destruction of exergy may be identified: irreversibilities in the cylinder, mechanical irreversibilities and other forms of irreversibility. The effects of the heat transfer of the gases to the cylinder wall, the combustion and the viscosity are explained in the cylinder. Mechanical irreversibilities are caused by friction, which may be calculated by the difference between the indicated braking power. Other irreversibilities explain the sum of various irreversible processes, such as the pumping losses, the mixing process of air and fuel, the choking and the heat transfer from the wall to the cooling system [27].

The exergy balance is determined according to the following methodology:

Exergy associated to the fuel heat (Equation (10)):

$$E\chi_c = \dot{m}_c LCV \tag{10}$$

Where:

$E\chi_c$= Exergy of the fuel (kW)

LCV = lower calorific value of the fuel (kJ/kg)

Another very fundamental section of the exergy balance is the flow of exhaust gases from the engine. The specific heat used is determined based on a mean of the specific heat values, at the corresponding input and output operating temperatures of the engine (Equation 11):

$$\dot{E}\chi_g = \dot{m}_g \left\{ C_P T_0 \left[\left(\frac{T}{T_0} - 1 \right) - ln \left(\frac{T}{T_0} \right) \right] \right\} \tag{11}$$

Where:

$\dot{E}\chi_g$= Exergy associated to the flow of gas (kW)

$\dot{m}_g$= Flow of gas (kg/s)

C_P= Specific heat at constant pressure (kJ/kg K)

T_0= Reference temperature (K)

T= Temperature of the exhaust gases (K)

The exergy efficiency is determined from Equation (12):

$$\eta_{exergy} = \frac{\sum E_{inputflows} - \sum E_{outputflows}}{\sum E_{inputflows}} \quad (12)$$

The specific heat of air at a temperature T (K), is given by Equation (13):

$$c_{par,T} = C_0 + C_1T + C_2T^2 + C_3T^3 + C_4T^4 \ (J/kgK) \quad (13)$$

For a temperature between 200 and 800 K.

Where:

$$c_0 = 1,0189 \times 10^3$$
$$c_1 = -1,3784 \times 10^{-1}$$
$$c_2 = 1,9843 \times 10^{-4}$$
$$c_3 = 4,2399 \times 10^{-7}$$
$$c_4 = -3,7632 \times 10^{-10}$$

The specific heat of the combustion gases at constant pressure is given by Equation (14):

$$c_{p\ g,T} = c_{par,T} + \frac{f}{1+f}\theta_{Cp,T} \ (J/kgK) \quad (14)$$

Where:

$$f = \frac{\dot{m}_{comb}}{\dot{m}_{ar}} \quad (15)$$

$$\theta_{Cp,T} = C_{P_0}T + C_{P_1}T^2 + C_{P_3}T^3 + C_{P_4}T^4 + C_{P_5}T^5 \quad (16)$$

For a temperature between 200 and 800 K.

$$c_{po} = -3,5949 \times 10^2$$
$$c_{p1} = 4,5164 \times 10^0$$
$$c_{p2} = 2,8116 \times 10^{-3}$$
$$c_{p3} = -2,1709 \times 10^{-5}$$
$$c_{p4} = 2,8689 \times 10^{-8}$$
$$c_{p5} = -1,2226 \times 10^{-11}$$

2.3. Experimental design

The software Statgraphics Centurion XVI is used for the analysis and comparison of results, performing a simple ANOVA for the different treatments (combinations) shown in Table 2. Three repetitions of each treatment were carried out, as established by the NTE INEN 2205 [28] regulation in its section 6 about testing methods, where item 6.1.5.4 states «Record and average a minimum of three readings in each test». The fuel with three levels (Extra, Super and Ecopais) is the independent variable, while energy and exergy efficiency are the dependent variables.

An ANOVA analysis was used to determine if there is a significant difference among the experimental groups, applying tests of multiple comparison of means, for this case the Least Significant Difference (LSD) in a 95 % of confidence [29, 30].

Table 2. Treatments for the analysis of significant

Number of treatments	Engine	Fuels
T1	Motor CT 150	Super
T2	Motor CT 150	Extra
T3	Motor CT 150	Ecopais

3. Results and discussion

Table 3 shows the results of the nine measurements of revolutions and torque, variables required for calculating power and for plotting P *vs.* n.

Figure 5 indicates the power as a function of the turning speed of the engine, it is observed that as the turning speed increases, the power generated also increases, but only up to reaching its maximum power. The maximum power generated with the use of the Super gasoline is 1174.17 W, which corresponds to an engine turning speed of 3199 rpm. The maximum power generated with the use of the Extra gasoline is 1142.46 W, which corresponds to an engine turning speed of 3121.5 rpm.

At last, the maximum power generated with the use of the Ecopais gasoline is 1183.35 W, which corresponds to an engine turning speed of 3224 rpm. In summary, it is obtained that for speeds under 3000 rpm there are no differences in the behavior of the power, as opposed to speeds between 3000 and 3600 rpm where the Super and Ecopais gasolines show the best results. These results are compatible with the works [31] and [32], where power tests with the Extra and Super gasolines were carried out, obtaining the same behavior trend as in the present study.

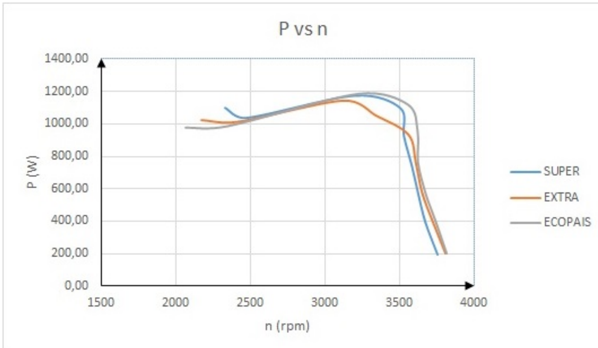


Figure 5. Curves of power *vs.* rpm

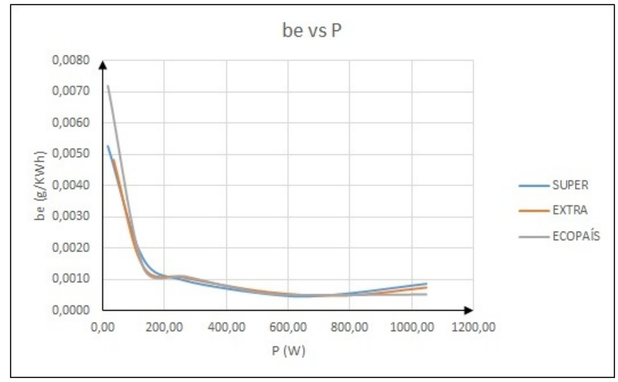


Figure 6. Curves of specific consumption *vs.* power

Table 3. Values of revolutions, torque and power

	Super			Extra			Ecopais	
n (rpm)	**M (Nm)**	**P(W)**	**n (rpm)**	**M (Nm)**	**P(W)**	**n (rpm)**	**M (Nm)**	**P(W)**
3753	0,5	196,51	3808,5	0,495	197,42	3815	0,5	199,75
3671	1,03	395,96	3724	1,005	391,93	3743	1,005	393,93
3624	1,5	569,26	3650,5	1,505	575,33	3671,5	1,5	576,72
3579,5	1,995	747,81	3609	2,005	757,76	3623	2,01	762,59
3528	2,505	925,48	3559,5	2,5	931,87	3621	2,5	947,98
3501,5	3	1100,03	3342	3	1049,92	3554	3,005	1118,38
3199	3,505	1174,17	3121,5	3,495	1142,46	3224	3,505	1183,35
2474,5	4,005	1037,81	2412,5	4,005	1011,81	2340	4,01	982,63
2333	4,5	1099,4	2169	4,5	1022,12	2067,5	4,505	975,37

Table 4 shows the results of the six power and mass flow measurements, parameters required for calculating specific consumption (b_e).

Figure 6 indicates the fuel specific consumption as a function of the power generated; as power increases the fuel specific consumption reduces to approximately 600 W, and then a slight increase starts to occur from this value with the greatest consumptions occurring at low revolutions. This result is compatible with the one obtained by Alzate and Agudelo [3], where tests were carried out in the operating regime from 1100 rpm to 3600 rpm; from 1100 rpm to 2000 rpm the fuel specific consumption diminished progressively down to its minimum value, a from then on it successively grew as a function of the increase in the engine turning speed. In summary, it may be concluded that the behavior of the specific consumption for the three gasolines is not significant, similar to the results obtained in the study by Quimbita and Guallichico [32], where it is observed a fuel specific consumption of 47.44 g/kWh for the Super gasoline, 43.17 g/kWh for the Extra gasoline and 49.96 g/kWh for the Ecopais gasoline.

Table 5 shows the results of the measurements required for calculating the thermal balance of the ICE at maximum power, carried for the Super, Extra and Ecopais gasolines; and Table 6 indicates the variables obtained when applying the methodology described in the section of the method.As indicated in Table 4, the energy efficiency for the Super gasoline is 11.31 %, and the exergy efficiency is 58.81 %, for the Extra gasoline 10.75 % and 58.89 %, and for the Ecopais gasoline 10.39 % and 59.19 %, respectively; this is due to the fact that there is an amount of exergy being destroyed in the exhaust gases that can be used to generate work.

Table 4. Tabulated values of power, mass flow and specific consumption for the different gasolines tested

Super			Extra			Ecopais		
P(W)	**m(kg/h)**	**be (g/kwh)**	**P(W)**	**m(kg/h)**	**be (g/kwh)**	**P(W)**	**m(kg/h)**	**be (g/kwh)**
18,33	0,096	0,0053	36,652	0,1777	0,0048	15,708	0,1132	0,0072
130,9	0,22	0,0017	130,9	0,1891	0,0014	130,8997	0,1817	0,0014
261,8	0,254	0,001	264,417	0,2824	0,0011	264,4174	0,2938	0,0011
562,87	0,277	0,0005	534,071	0,3222	0,0006	526,2168	0,3003	0,0006
748,75	0,373	0,0005	785,398	0,3836	0,0005	785,3982	0,4045	0,0005
1047,2	0,89	0,0008	1047,198	0,7808	0,0007	1047,1976	0,5567	0,0005

Table 5. Tabulated average values for calculating energy and exergy efficiency at maximum power

M_{max} (Nm)	P_{max} (W)	Consumption (m^3)	Q (m^3/s)	P_c (kg/m^3)	$\dot{m}_c$ (kg/s)	$\dot{m}_{aire}$ (kg/s)	$\dot{m}_{gas}$ (kg/s)	$\bar{T}_e$ (°C)	$\bar{T}_s$ (°C)	PCI (kJ/kg)
Gasolina Super										
3,505	1174,17	53,55	2,97 E-07	722	0,0002148	0,002071	0,002286	22,77	543	48345,66
Gasolina Extra										
3,495	1142,46	58,65	3,26 E-07	723	0,0002356	0,002046	0,002282	23,72	543,5	45124,76
Gasolina Ecopais										
3,505	1183,35	61,2	3,40 E-07	749	0,0002547	0,00206	0,002315	23,77	541,5	44739,17

Note: The values of LCV were taken from the study by Rocha-Hoyos *et al.* [23]

Table 6. Average results of energy and exergy efficiency calculated at maximum power

P_{max} (W)	$\dot{Q}_c$ (kW)	η_{ener} %	$E\chi_g$ (kW)	$E\chi_c$ (kW)	$E\chi_k$ (kW)	η_{ener} %
Gasolina Super						
1174,17	10,38	11,31	0,64	10,38	3,63	58,81
Gasolina Extra						
1142,46	10,63	10,75	0,65	10,63	3,72	58,89
Gasolina Ecopais						
1183,35	11,39	10,39	0,66	11,39	3,99	59,19

Note: The exergy due to the conduction and convection heat transfers has been denoted as $E\chi_k$, estimated as 35 % of $E\chi_c$ according to Li *et al.* [7].

Having an exergy efficiency greater than an energy efficiency, implies that there is an exergy potential for improvement through which it is possible to take advantage of part of that exergy being destroyed and transform it into work, thus achieving an increase in the thermal efficiency [33].

The results obtained are compatible with the work by Gonzalez *et al.*, [33], where it was obtained an exergy efficiency of 14.77 % which is greater than the energy efficiency of 12.79 %, concluding that this difference is due to the increase of 43.19 % in the engine turning speeds.

On the other hand, according to Llerena [34], an energy efficiency of 39 % and an exergy efficiency of 79 % were obtained at the beginning of the study, and later a reduced exergy efficiency of 56 % was achieved due to the use of the exhaust gases that escape from the turbine to generate vapor (cogeneration), thus enabling an increase of 67 % in the energy efficiency.

Table 7 and Figure 7 represent the multiple range test and the box and whisker plot for the energy efficiency as dependent variable. It is concluded that there is a significant difference between the gasolines, and the Super gives the best result.

Table 7. Analysis of significant differences for the energy efficiency

Fuel	Cases	Mean	Homogeneous Groups		
T3 (Ecopais)	3	10,39	X		
T2 (Extra)	3	10,75		X	
T1 (Super)	3	11,31			X

Note: Method: 95.0 percentage of LSD

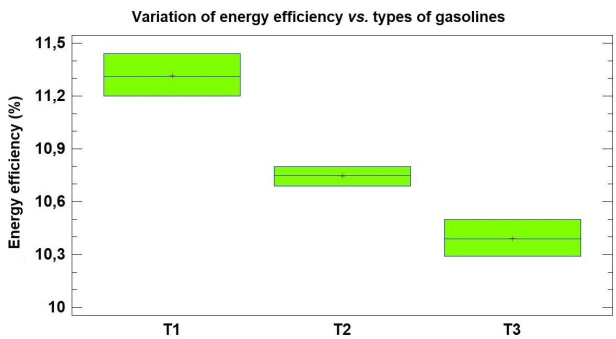


Figure 7. Comparative graph of the energy efficiency for the different types of gasoline

On the other hand, Table 8 and Figure 8 show the multiple range test and the box and whisker plot for the exergy efficiency as dependent variable, where it is concluded that there is a significant difference between the gasolines, with the Ecopais gasoline giving the best result; however, there is no significant difference between the Extra and the Super gasolines.

Table 8. Analysis of significant differences for the exergy efficiency

Fuel	Cases	Mean	Homogeneous Groups	
T1 (Super)	3	58,8	X	
T2 (Extra)	3	58,89	X	
T3 (Ecopais)	3	59,19		X

Note: Method: 95.0 percentage of LSD

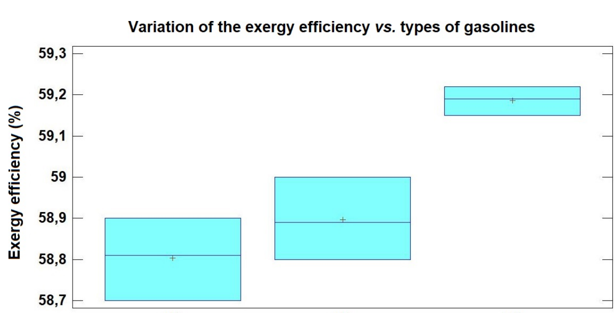


Figure 8. Comparative graph of the exergy efficiency for the different types of gasoline

For a better visualization of the results of the energy part, values of energy flow are presented in Table 9, as well as Figures 9, 10 and 11, which represent the Sankey diagrams for the three types of gasoline used. These diagrams represent the quantitative distribution of the energy flows that enter and exit the system, as well as the losses due to heat transfer and emission of exhaust gases.

Table 9. Values of energy flow

Energy flow (kW)			
Gasoline	**Super**	**Extra**	**Ecopais**
Fuel	10,38	10,63	11,39
Exhaust Gases	5,58	5,77	6,22
Losses due to convection	3,63	3,72	3,99
Shaft power	1,17	1,14	1,18

With the results obtained it may be concluded that the amount of energy loss in the engine under study when using the Super gasoline is 9.21 kW (88.73 %) as indicated in Figure 9, whereby it was determined that the engine has an energy efficiency of 11.31 % and an exergy efficiency of 58.81 %.

On the other hand, the amount of energy loss in the engine under study when using the Extra gasoline is 9.49 kW (89.28 %) as indicated in Figure 10, whereby it was determined that the engine has an energy efficiency of 10.75 % and an exergy efficiency of 58.89 %.

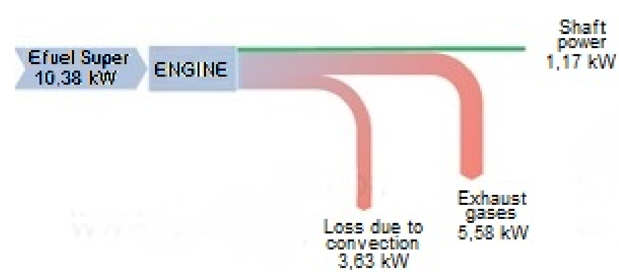


Figure 9. Sankey Diagram-Super Gasoline

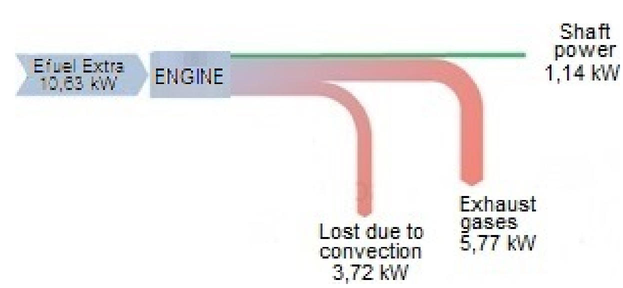


Figure 10. Sankey Diagram-Extra Gasoline

At last, the amount of energy loss in the engine under study when using the Ecopais gasoline is 10.21 kW (89.64 %) as indicated in Figure 11, whereby it was determined that the engine has an energy efficiency of 10.39 % and an exergy efficiency of 59.19 %.

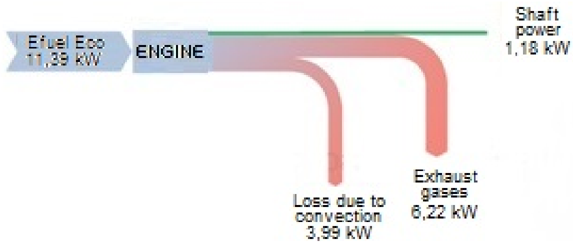


Figure 11. Sankey Diagram-Ecopais Gasoline

With the results presented it may be concluded that there are variations in the energy and exergy efficiency in the motor under study when using the three gasolines, the best efficiency of 11.31 % is obtained for the Super gasoline. It is also observed that the largest energy loss of 10.21 kW (89.64 %) exists in the engine for the Ecopais gasoline, this energy loss occurs in the emission of exhaust gases and in the conduction and convection heat transfers, consistent with the results of Llanes-Cedeño, Carguachi-Caizatoa, and Rocha-Hoyos [19], and at the same time this represents a high exergy potential for improvement which may be used to generate work and simultaneously achieve an increase in the energy efficiency of the engine when using the Ecopais gasoline, these results are compatible with the ones obtained by Valle *et al.* [35], where energy losses of 8.57 kW (66.35 %) of a total of 12.92 kW (100 %) were obtained.

4. Conclusions

The static engine which was studied when using different gasolines, shows an energy efficiency of 11.31 % for the Super gasoline, 10.75 % for the Extra gasoline and 10.39 % for the Ecopais gasoline. Regarding exergy efficiency, it was determined as 58.81 % for the Super gasoline, 58.89 % for the Extra gasoline and 59.19 % for the Ecopais gasoline. The exergy efficiency is much greater than the energy efficiency in each of the cases, thus existing an exergy potential for improvement that may take advantage of the exergy being destroyed to transform it into work, and thus achieve an increase in the energy efficiency.

The maximum power of the engine is directly proportional to the energy efficiency, therefore, it may be concluded that the best energy efficiency of the engine was obtained when consuming the Super gasoline, with a maximum power generated of 1183.35 W at 3224 rpm and an energy efficiency of 11.31 %.

Based on the methodology applied, energy efficiencies in the range from 10.39 % to 11.31 % were determined, which are very low compared to the real thermal efficiencies of an internal combustion engine which oscillate between 25 % and 30 %.

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