

## ENCIT-2018-0118 EXERGOECONOMIC ANALYSIS OF A DIESEL ENGINE

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**Abstract.** Diesel engine is an important system to electricity production, however, with disadvantage of being a high source of pollutant emissions. This study, an engine operating with diesel oil containing 7% biodiesel, constant engine speed of 1800 rpm for different loads was studied. A combustion model based on the data of unburned hydrocarbon, CO and NO<sub>x</sub> was developed. The exergy and exergoeconomy analyses were carried out in order to calculate the parameters as thermal and exergetic efficiency, exergy destruction rate, cost rate of the exergy destruction, total cost rate, electricity cost rate per exergy unit, exergoeconomic factor and relative cost difference. The error of combustion model can be low when the chemical formula of fuel is known. The results reveal that the thermal and exergetic efficiency, total exergy loss and exergy destruction rate, fuel cost rate and total cost rate increase with load. On the other hand, the specific cost of electricity, exergoeconomic factor and relative cost difference decrease with load. The best performance of diesel engine is at high power load conditions according to exergetic and exergoeconomic point of view.

**Keywords:** diesel engine, pollutant emissions exergoeconomy, thermal performance, combustion.

### 1. INTRODUCTION

Internal combustion engines, powered with petroleum-derived fuels, emit a huge of harmful substances having negative, direct and indirect, influence on live organisms. The emissions produced by diesel engines have a serious impact on both the environment and human health. The substances produced by internal combustion engines of power units include: Significant amounts of hydrocarbons, nitrogen oxides, carbon oxides, carbon dioxides, sulphur oxides, particulates, aldehydes and heavy metals (Botwinska *et al.*, 2017). Such substances are toxic to the natural environment, and they are a serious cause of smog, ground-level ozone, acid rain and also human diseases, such as asthma, coughing, or nausea (Serio *et al.*, 2017). All of these problems have motivated the scientific society to seek new alternatives that have decreased global warming and pollution effects (Özener *et al.*, 2014).

Nowadays, diesel engines are part of the axis of world industry, providing high torque, durability and economical fuel usage under a variety of conditions (Özener *et al.*, 2014). These engines dominate sectors as such as road and train transport, agricultural, military, construction, mining, maritime, propulsion and stationary electricity production (Morón-Villarreyes *et al.*, 2007). Although the fuel demand of most diesel engines still has to be met by primitive petroleum products. Fossil fuel utilization is unsustainable and it causes greenhouse gases (Caliskan and mori, 2017a). As the diesel engine utilization increases air pollution increases. Therefore, it is extremely important that studies be conducted to predict the emissions of these kind of engines.

Thermodynamic analysis is well-known analysis tool for determining characteristics of engines. First and second laws of thermodynamics are generally used for analyzing engines. First law of thermodynamics is about energy analysis. Energy analysis alone is not enough to assess the best efficiencies of engines. The analysis of second law of thermodynamics is one of the recent tools utilized in energy conversion systems to measure its effectiveness (Hoseinpour, et al., 2017). Exergy analysis is used to understand and calculate the real efficiencies of engines by determining their losses and destructions. It bases on both first and second laws of thermodynamics. Exergy is also known as availability, potential or quality of energy. Due to the better efficiency comparison, the exergy analysis has been made in almost all types of thermodynamic cycles. For example, (Da costa, *et al.*, 2012), have been conducting studies related to exergetic analysis of a commercial diesel engine, with the purpose of investigating the performance characteristics when the engine is operated in dual form: natural gas and diesel. (Hoseinpour, et al., 2017), have presented studies about diesel engine fueled with diesel, biodiesel-diesel blends and gasoline fumigation to evaluate how these different fuels affect the energetics and exergetics balances. (Khoobbakht, et al., 2017), have analyzed the variation in balances of energy and exergy on a DI diesel engine fueled with different blends of Biodiesel, Ethanol and Diesel Fuel, investigating also operational changes in engine. (Pandiyarajan, et al., 2011), have used the exergy analysis as a tool to measure the quantity and quality of energy extracted from a diesel engine and stored in a combined sensible and latent heat storage system.

Exergy is evaluated with a reference (dead) state. This reference state can be environment or restricted surroundings of the system (Caliskan and mori, 2017a).

The Exergy analysis can be applied using economic principles, called the exergoeconomic approach. Exergoeconomy (thermoeconomics) combines exergy analysis with conventional cost analysis in order to assess and improve the performance of energy systems (Abusoglu and Kanoglu, 2009). Several authors also have done the economics analysis. (Aghbashlo, et al., 2017), have used thermoeconomic analysis to evaluate the performance of a DI diesel engine operating with various diesel and biodiesel blends containing different amounts of polymer waste. (Caliskan and Mori, 2017b), have applied the exergoeconomic analysis to investigate the effects of use of Diesel Oxidation Catalyst (DOC) and Diesel Particulate Filter (DPF) after treatment systems, integrated a diesel engine fueled with biodiesel and diesel fuel. (Lee, et al., 2018), have been conducting studies evaluating in an exergetic and exergoeconomic way the combination of a solid oxide fuel cell (SOFC) and an internal combustion engine, to determine measures for improving its efficiency and the cost effectiveness. (Açikkalp, et al., 2014), have published works using an exergoeconomic analysis in a trigeneration system using a diesel-gas engine to suggest strategies for system optimization from the Exergoeconomic parameters. (Ahmadi and Dincer, 2011) have presented studies about thermodynamic and thermoeconomic analysis in a combined cycle power plant (CCPP) with a supplementary firing system aimed at system optimization. (Bolatturk, et al., 2015), have published works conducting exergetic and thermoeconomic analysis of Turkey-based Çayırhan thermal power plant. With the support of EES package program, they could calculate the thermal and second law efficiencies and the exergoeconomic factors and determined the highest amounts of exergy losses and the highest amount of exergy loss costs.

The present work aims to develop the exergetic and exergoeconomic analysis of stationary diesel engine with maximum power of 49-kW operating with diesel and biodiesel (B7) for different loads with constant speed. The specific contribution of this paper are following:

- To evaluate the heat transfer of engine.
- To develop the chemical species, energy, exergetic and exergoeconomic balance.
- To obtain the effect of engine lead on the performance and specific cost develop a balance specie and calculate the exergetic efficiency.

## 2. METHODOLOGY

The experiments were performance by Serio et al. (2017). The diesel engine was stabilized during 10 min under steady-state conditions. The engine speed was constant of 1800 min<sup>-1</sup> varying the load from 5 to 30 kW. The data acquisition measured the air and fuel mass flow rate and CO<sub>2</sub>, CO, THC and NO<sub>x</sub> emissions. Table 01 shown the engine feature.

Table 1. Diesel engine specifications. Source Serio et al. (2017).

Parameter	Type or value
Model	MWM D229-4
N° of cylinders	4
N° of strokes	4
Type of injection	Direct
Bore x stroke	102 mm x 120 mm
Total displacement	3.922L
Firing order	1-3-4-2
Maximum power at 1800rpm	44 kW
Aspiration	Natural
Compression ratio	17:1
Coolant	Water

The fuel mix used is a 93% volume of commercial N.2 diesel oil and 7% volume of biodiesel with etanol blends. The fuel properties are important in this analysis as the lower heat value (LHV) of 43.2 MJ/kg. The property of fuels are for commercial diesel (chemical formula C<sub>9.84</sub>H<sub>17.95</sub>, molar mass 136.3 kg/ kmol and relative density at 20°C 0.853) and for biodiesel (chemical formula C<sub>18.74</sub>H<sub>34.43</sub>O<sub>2</sub>, molar mass 291.8 kg/ kmol and relative density at 20°C 0.870) according to Santos et al. (2017).

The emissions of exhausted gases change with lead. The diesel engine was drive an electrical generator, And, thus, the lead was measured in electrical power. Its values are presented at table 02.

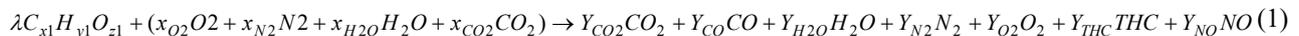
Table 2. Variation of emissions with load. Source Serio et al. (2017).

Load (kW)	CO <sub>2</sub> (g/kWh)	CO (g/kWh)	THC (g/kWh)	NO <sub>x</sub> (g/kWh)
5	1108.0	12.20	5.49	5.050
10	755.0	5.26	2.70	4.060
15	620.0	2.86	1.68	4.000
20	580.0	2.00	1.23	4.350
25	565.0	1.42	0.92	4.365
30	572.5	1.30	0.77	4.225

In order to evaluate the performance of system, some analyzes were carried out as following.

## 2.1. Chemical specie analysis

The combustion reaction was evaluated according to chemical species. Some reaction model has been proposed by (Ganjehkaviri et al., 2014 and Ahmadi et al., 2011). However, it do not consider the unburned hydrocarbon (THC). Due that a combustion reaction was proposed to considered THC. Its species coefficients can be expressed according to as follows:



Normally the combustion reaction is carried out for one fuel mole, however the unburned THC reduces the value to lower than one.

$$\text{Where: } \lambda = \frac{(\dot{m}_f - \dot{m}_{THC}) / M_f}{\dot{n}_f} \quad \text{and } M_f \text{ is the molecular mass of fuel} \quad (2)$$

The parameter below were evaluated according to chemical species

$$y_{CO2} = \lambda \cdot x_1 - y_{CO} + x_{CO2} \quad (3)$$

$$y_{N2} = x_{N2} - \frac{1}{2} \cdot y_{NO} \quad (4)$$

$$y_{H2O} = \frac{1}{2} \cdot y_1 + x_{H2O} \quad (5)$$

The thermodynamic model proposed is complex to solve, due to many emissions rate as CO, NO and THC. And, thus, these emissions were used as input data.

## 2.2. Energy analysis

Energy analysis is associated with the first law of thermodynamics. The first law of thermodynamics is used to determine the heat transfer involved in the analysis of the engine (Da Costa et al, 2012). The first law of thermodynamics for reacting system at steady-state system is given as follows according to (Borgnakke and Sonntag, 2009; Moran and Shapiro, 2009).

$$\dot{Q}_{CV} + \sum_R n_{in} \left( \bar{h}_f^0 + \Delta \bar{h} \right)_{in} = \sum_P n_{out} \left( \bar{h}_f^0 + \Delta \bar{h} \right)_{out} + \dot{W}_{CV} \quad (6)$$

Where  $n$  is the number of moles of the combustion reaction;  $\bar{h}_f^0$  is the enthalpy of formation and  $\Delta \bar{h}$  is the variation of enthalpy of formation. The subscript R and P are Reagent and product, respectively. The enthalpy of formation of T-T-diesel is 34661 kJ/kmol according (Borgnakke and Sonntag, 2009).

The thermal efficiency of the diesel engine is determined based on the Low heat value (LHV) by:

$$\eta_{DE} = \frac{\dot{W}_{net}}{\dot{m}_f \cdot LHV} \quad (7)$$

Figure 1 represented the schematic diagram of diesel engine with its flow rate, work and heat.

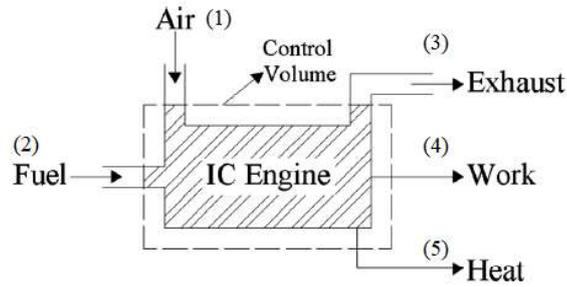


Figure 1. Control volume of diesel engine. Source: Caliskan et al. (2010)

### 2.3. Exergy analysis

Only the energy balance is not a completely effective method to measure how efficient the system is working. The concept of exergy was developed by J. Willard Gibbs in 1878. It was further developed by Zoran Rant in 1957. In 1965, H. D. Baehr termed the part of energy that is converted into all other forms of energy as exergy. Exergy is based on the second law of thermodynamics. It is the useful work potential of energy (Kumar, 2017). According to this, the exergetic balance was conducted in order to calculate a more approximate measure of the actual efficiency of the cycle.

The total exergy rate is composed by physical exergy rate plus chemical exergy rate, as equation below:

$$\dot{Ex}_T = \dot{Ex}_{ph} + \dot{Ex}_{ch} \quad (7)$$

And the physical and chemical exergy rate are evaluated by correlation below:

$$\dot{Ex}_{ph} = \sum m_i \cdot (h_i - h_0 - T_0 \cdot (s_i - s_0)) \quad (8)$$

$$\dot{Ex}_{ch} = \sum m_i \cdot (\sum y_i \cdot \bar{e}_i + \bar{R} \cdot T_0 \cdot \sum y_i \cdot \ln(y_i)) \quad (9)$$

where  $y_i$  and  $\bar{e}_i^{ch}$  are the molar fraction and the standard molar chemical exergy in the  $i$  th exhaust gas component.  $\bar{R}$  is the universal gas constant (8.314 kJ/kmol K). The unburned mass of THC is a mixed of gases. The specific enthalpy of THC was assumed to be methane.

In the ambient conditions (standard reference state), the thermodynamic exergy is null. Then, the total exergy for a fuel is exactly equal to the chemical exergy (Kumar, 2017). The exergy rate of fuel  $\dot{Ex}_{fuel}$  is found from:

$$\dot{Ex}_{fuel} = \dot{m}_{fuel} LHP_{fuel} \varphi \quad (10)$$

$$\varphi = 1,0401 + 0,1728 \frac{H}{C} \quad (11)$$

where  $\varphi$  is the chemical exergy factor of the fuel, and H and C are the mass ratios of hydrogen and carbon.

Different approaches for formulating efficiencies and auxiliary costing equations have been suggested in the literature. In this work the specific exergy costing approach (SPECO) was used. It works with the fuels and products definition. The two fundamental principles (F and P principles) are formulated according to (Lazzaretto and Tsatsaronis, 2006). In the view of exergy analysis, destruction exergy rate happens along the whole cycle due to irreversibility (Li et al, 2016). The exergy destruction rate is calculated considering the exergy rate of exhausted gases and the losses due to heat transfer from coolant:

$$\dot{Ex}_D = \dot{Ex}_F - \dot{Ex}_{loss} - \dot{Ex}_P \quad (12)$$

The main heat loss rate is the heat transfer to coolant (water). Its exergy rate is calculated considering the average water temperature:

$$\dot{E}x_{loss} = \dot{Q}_{out} \left( 1 - \frac{T_0}{T_{cw}} \right) \quad (13)$$

$T_0$  is the temperature of the standard reference state of 298.16 K, and  $T_{CW}$  is the average temperature of the cooling water of  $T_{CW} = 353.16$  K according to Caliskan and Mori (2017 b).

The exergetic efficiency at each component is the ratio between the product exergy and the fuel supplied exergy according to the equation:

$$\varepsilon = \frac{Ex_p}{Ex_f} \quad (14)$$

#### 2.4. Exergoeconomic analysis

The thermoeconomic analysis combines the exergetic analysis with the economic according to Bejan et al. (1996). The exergetic cost rate per exergy unit of each product is calculated in order to understand the cost formation process.

The analysis reveals which equipment should be possible and economically feasible invest in order to improve the system. The basic thermoeconomic equation is shown as follows:

$$c_p \cdot \dot{E}x_p + c_{loss} \cdot \dot{E}x_{loss} = c_f \cdot \dot{E}x_f + \dot{Z} \quad (15)$$

$C_p$  and  $C_f$  represent the average costs per exergy unit of product and fuel, respectively. This equation states that the cost rate associated with the product of the system is equal to the sum of cost rate of fuel and capital cost. The purchase cost function of the component ( $Z_i$ ) is determined by [5, 14, 15, 16]. The capital investment of a component is converted into the cost rate considering the capital recovery factor (CRF):

$$\dot{Z}_i = Z_i \cdot CRF \cdot \varphi \quad [$/s] \quad (16)$$

Where  $\varphi$  represents the maintenance factor 1,06

The cost rate of the exergy destruction rate is defined as:

$$\dot{C}_D = c_f \cdot \dot{E}_D \quad [$/s] \quad (17)$$

The total cost rate was determined as follows:

$$\dot{C}_{TOT} = \dot{Z}_i + c_f \left( \dot{E}x_D + \dot{E}x_{lost} \right) \quad [$/s] \quad (18)$$

The exergoeconomic factor is defined as:

$$f = \left( \frac{\dot{Z}_i}{\dot{Z}_i + c_f \left( \dot{E}x_D + \dot{E}x_{lost} \right)} \right) \cdot 100 \quad [\%] \quad (19)$$

The relative cost difference was calculated as follows:

$$r_k = \left( \frac{c_p - c_f}{c_f} \right) \quad (20)$$

As the purpose of engine is to generate power, all cost associated with its ownership and operation must be charged to power. The exergy losses are covered by the supply of additional fuel to the engine. The auxiliary equations of the cost balance are formulated using the fundamental principles (F and P principles) as discussed by Lazzaretto and Tsatsaronis (2006) as follows.

Table 3 – Auxiliary equations in Exergoeconomic Analysis

Auxiliar equation	Principle
$\frac{\dot{C}_1 + \dot{C}_2}{\dot{E}_1 + \dot{E}_2} = c_3$ ,	Fuel
$\dot{C}_1 = 0$	Fuel
$C_{\text{loss}} = c_2$	Fuel

The approach of the cost rate associated of exergy loss stream is used to understand the cost formation process to evaluated the performance of a single component according to Bejan at al., (1996).

### 3. RESULTS

In order to validate the model of combustion reaction which consider the unburned hydrocarbon some texts were carried out. The work of Caliskan and Mori (2017) has the chemical formula of fuel ( $C_{14.01}H_{25.00}$ ), mass flow rate of air and exhaust gases, air and fuel temperatures and its emissions mass flow. The diesel engine was experimentally analyzed at three loads for diesel JIS#2 and constant speed of 1800 rpm. The input data were chemical formula of fuel, emissions rate of CO, THC and  $NO_x$ . The output data was the  $CO_2$  mass flow rate. The results are shown at table 03.

Table 3. Validation of combustion model with work of Caliskan and Mori (2017).

Torque [N.M]	$\lambda$	$W_{\text{Net}}$ [kW]	$CO_2$ model [g/h]	$CO_2$ mesured [g/h]	Error [%]
106.1	0.9996	20	16505	16455	-0.30
198.9	0.9997	37.49	27270	27221	-0.18
254.9 full	0.9998	48.06	33188	33146	-0.13

The error between the model and measured data of  $CO_2$  is very low. The model of the combustion reaction at equation 1 can predict the chemical species with low error.

In the present work, the chemical composition of fuel at this work was assumed similar of Santos et al. (2017). The fuel mix has 7% volume of biodiesel and 93% of diesel. The diesel engine was experimentally analyzed at six loads and constant speed of 1800 rpm. The results of  $CO_2$  modeled and error are shown at table 04.

Table 4. Validation of combustion model with the work (Serio, *et al.*, 2017).

Load (%)	$W$ (kW)	$CO_2$ model (g/kW.h)	$CO_2$ measured (g/kW.h)	Error (%)
10.20	5	1212	1108.0	8,58
20.41	10	756.3	755.0	0,17
30.61	15	652.5	620.0	4,98
40.82	20	583.0	580.0	0,52
51.02	25	554.6	565.0	-1,88
61.22	30	546.3	572.5	-4,80

The error to predict the chemical species of  $CO_2$  is higher. The lack of fuel chemical composition at work (Serio, *et al.*, 2017) reduced the model accuracy.

The input data of work Serio et al. (2017) were evaluated. The heat transfer was calculated by equations (6) considering the CO, NO and THC emissions and the thermal efficiency of engine was calculated by equation (7). Table 5 shows the ratio between the heat transfer and the power for different loads.

Table 5. Energy balance of diesel engine of maximum power of 49 kW

Load (%)	$W$ (kW)	$\dot{m}_{air}$ (kg/h)	$\dot{m}_{fuel}$ (kg/h)	$T_{exh}$ (C°)	$Q$ (kW)	$\eta$ (%)	$Q/W$ (%)
10.20	5	140.3	2.7234	220	10.07	15.30	201.4
20.41	10	140.4	3.3826	260	10.56	24.64	105.6
30.61	15	139.5	4.3596	310	11.13	28.67	74.19
40.82	20	140.0	5.1840	350	12.75	32.14	63.76
51.02	25	141.6	6.1560	405	14.55	33.83	58.2
61.22	30	141.9	7.2756	437	19.21	34.36	64.02

At low load the losses by heat transfer is higher than the power. As the load increases, the heat transfer and power increase. However, the increase of power is higher than to heat transfer. Therefore, the losses due to heat transfer is reduced and the thermal efficiency increases. The maximum power was not achieved due to high temperature of exhausted gases which passes through a valve of exhaust gas recirculation (EGR). However, the effect of EGR was not considered in this work. The thermal efficiency and exergetic efficiency are shown at figure 2.

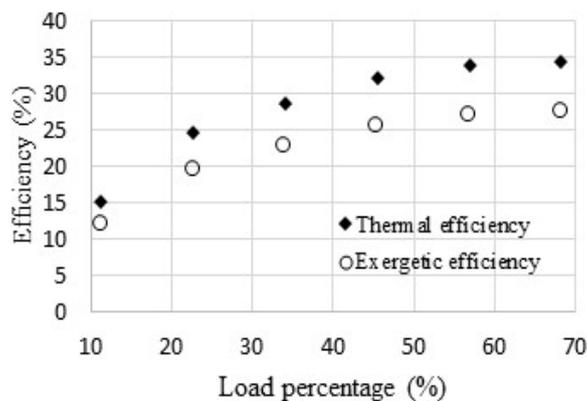


Figure 2. Effect of load on the thermal and exergetic efficiency.

The both efficiencies increase with the load. The maximum efficiency is around the full load. The reason for this is that engine was designed for full load. For larger loads, the power increasing is higher than to increasing exergy destruction and the thermal and exergetic efficiencies are better.

Figure 3 shows the effect of load on the total exergy loss rate and exergy destruction rate.

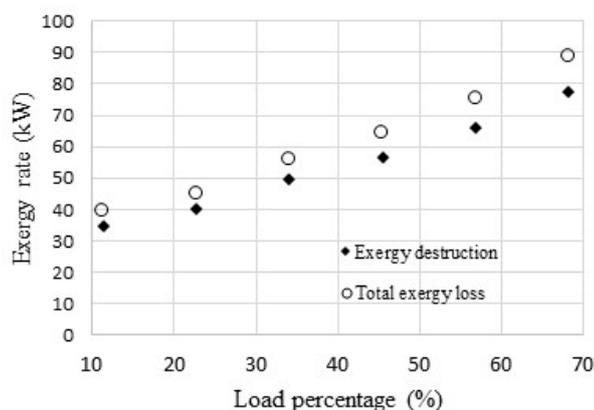


Figure 3. Total exergy loss and exergy destruction rate as affected by load

The total exergy loss is composed of the exergy destruction plus the exergy loss rate and the exergy rate of exhausted gases. The values of exergy destruction rate ranged from a minimum value of 34.93 kW to a maximum of 77.31 kW. The values of total exergy loss rate ranged from a minimum value of 39.35 kW to a maximum of 88.47 kW. The values of exergy loss rate and the exergy rate of exhausted gases are not significant in relation to exergy destruction rate. As the

load increases, the exergy destruction rate and total exergy loss rate increase. However, the exergetic efficiency is increasing due to higher power increasing.

The results of the thermoeconomic analysis of the system are shown following. Figure 4 is a relation between the fuel cost rate by load percentage.

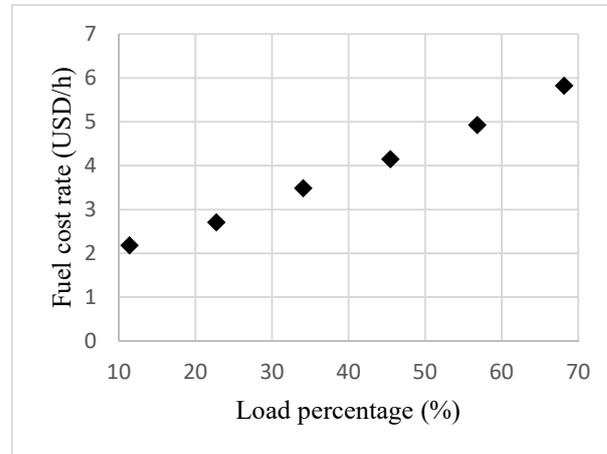


Figure 4. Effect of load on the fuel cost rate

The fuel cost rate varied from a minimum value of 2.179 US\$/h to a maximum value of 5.822 US\$/h. The fuel cost rate is proportional its mass flow rate. This occurred due to the load being directly proportional to the mass flow rate of fuel. As the load increases, the fuel cost rate increases due to higher fuel consume.

Figure 5 shows the effect of load on the electricity cost rate per exergy unit.

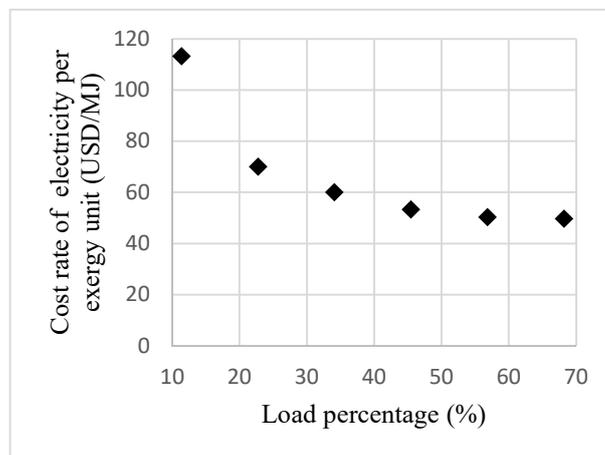


Figure 5. Effect of load on the specific cost of electrical power.

The cost rate of electricity per exergy unit was evaluated by relation 15, which is the average costs per exergy unit of fuel ( $C_p$ ). It ranged from a maximum of 113.3 USD/MJ to a minimum of 49.78 USD/MJ. This reduction in cost with increasing load occurs due to the fact that with increasing load, the exergetic efficiency increases. In this way, there is more energy being converted from the combustion, increasing the power.

The total cost rate per load is shown at figure 6.

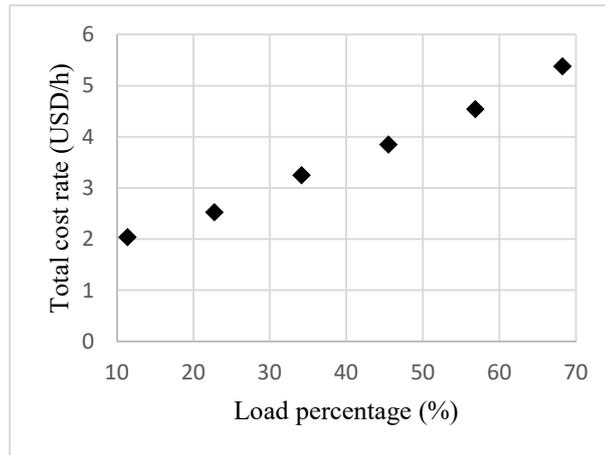


Figure 6. Effect of load on the total cost rate.

The total cost rate was calculated by equation 18, which is summarized of cost rate of component and the cost of the total exergy loss. Its values increase with enhancing engine load and varie from a minimum of 2.04 USD/h to a maximum of 5.38 USD/h. As load increases, total cost rate increases due to the increase of total exergy loss rate. Its behavior is similar to the total exergy loss rate.

Figure 7 shows the effect of load on the exergoeconomic factor.

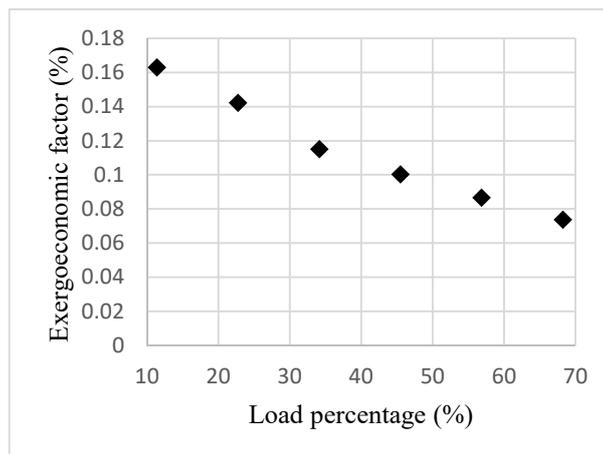


Figure 7. Effect of load on the exergoeconomic factor.

The exergoeconomic factor was calculated according to correlation 19. Their values ranged between 0.156% and 0.0717%, decreasing with the load. It compares the component costs with the total cost rate composed of exergy destruction and exergy loss. As the load increases, the total cost rate and the exergy destruction increase. The low value of exergoeconomic factor means that the total cost rate is higher than the component cost. The component cost is negligible in relation to total cost rate.

Figure 8 shows the relation of relative cost difference with load percentage.

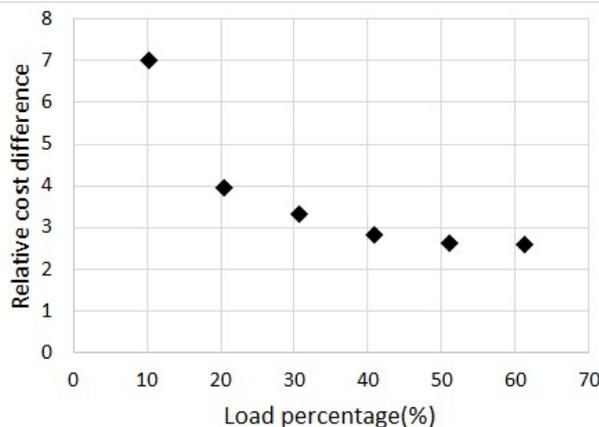


Figure 8. Effect of load on the relative cost difference.

The relative cost difference was calculated according to equation 20. Their values change from 6.998 to 2.579. This variable reveals the relative increase in the average cost per exergy unit between fuel and product of component. It is useful for optimizing a component indicating a potential of improvement. Its value should be minimized. The values reduction with load means that the engine is being optimized. In high loads, the exergetic efficiency is high and specific cost of electricity is low

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