Memorias de SICEL 2023 | UNIVERSIDAD NACIONAL DE COLOMBIA

Análisis de Viabilidad Técnico-Económica de un Sistema Diesel/Ciclo Orgánico de Rankine para Generación Distribuida.

Techno-Economic Feasibility Analysis of a Diesel/ Organic Rankine cycle system for Distributed Generation

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Recibido: 08/07/2023. Aceptado: 22/08/2023. Versión final: 27/09/2023

Resumen

El uso del Ciclo Orgánico de Rankine (ORC) en la recuperación de calor de los gases de escape de los generadores diésel permite generar energía adicional en zonas aisladas. Se desarrolló un modelo energético del generador diésel para determinar parámetros como el calor específico, el caudal de masa y la temperatura de los gases de escape necesarios para el diseño del sistema. Utilizando el fluido R245fa en el ORC, se realizó un análisis comparativo entre los generadores diésel convencionales y el sistema diésel-ORC en una región no interconectada de Brasil. Los resultados muestran que se logra un consumo específico de combustible de 0.271 L/kWh con el sistema de generador diésel, mientras que con el sistema diésel-ORC es de 0.248 L/kWh. El costo de energía con el sistema diésel-ORC resultó ser un 15.56 % más económico en comparación con el sistema de generador diésel.
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Palabras clave: Ciclo Orgánico de Rankine (ORC), Consumo específico de combustible, Costo de energía, Eficiencia eléctrica, Generador diésel.

Abstract

The use of the Organic Rankine Cycle (ORC) for recovering exhaust gas heat from diesel generator sets allows for additional power generation in isolated locations. An energy model of the diesel generator was developed to determine parameters like specific heat, mass flow rate, and exhaust gas temperature required for system design. R245fa was used as the working fluid in the ORC. A comparative analysis was conducted between conventional diesel generators and the diesel-ORC system in a non-interconnected region in Brazil, considering energy cost, specific fuel consumption, and electrical efficiency. The results indicate a specific fuel consumption of 0.271 L/kWh for the diesel

Como citar: A.L. Galindo, L.S. Mendoza. “Techno-Economic Feasibility Analysis of a Diesel/ Organic Rankine cycle system for Distributed Generation” in XI Simposio Internacional de Calidad de la Energía Eléctrica, Valledupar: Universidad Nacional de Colombia, Nov. 2023. doi: https://doi.org/10.15446/sicel.v11.109039

generator system, compared to 0.248 L/kWh for the diesel-ORC system. The energy cost with the diesel-ORC system was 15.56% cheaper than that of the diesel generator system.

Keywords: Diesel generator, Electrical Efficiency, Energy cost, Organic Rankine Cycle (ORC), Specific fuel consumption,

1. Introducción

Nowadays, in areas located far from the electricity distribution networks and therefore not interconnected, mini-distribution networks are used for the supply of electricity, where the most used generation source are diesel generator sets. These systems present higher energy costs compared to the interconnected system mainly due to the cost of acquiring and transporting diesel oil. To reduce fuel consumption, and hence the price of energy, the implementation of Organic Rankine cycle for diesel generator sets for the recovery of residual heat from the exhaust gases may be a viable option. According to Bianchi and Pascale [1] ORC is a promising and well-proven solution for the exploitation of low / medium temperature heat sources. The use of the organic Rankine cycle for to the recover the residual heat offers significant advantages over other recovery systems. Weerasinghe et al [2] the waste heat recovery from internal combustion engine by Rankine Cycle offers a fuel saving of up to 9% compared to 6.5% by using the turbo-compounding technique. Most research is limited to simple ORC configurations, noting that they perform well in ICE applications, improving the thermal efficiency and reducing of emissions [3]. According to Vaja and Gambarotta [4] and Wenzhi et al. [5] the energy produced by the integrated ICE-ORC system can increase up to 12%, using exhaust waste heat. YuG, et al.[6] examined the waste heat recovery potential from a diesel generator, increasing the thermal efficiency by approximately 6.1%, recovering about 66.7-81.6% of the exhaust energy. R. Cipollone et. [7] a made an experimental assessment of ORC unit for waste heat recovery from the ICE exhaust gases under various working conditions, their results showed that the thermodynamic efficiency is 10% and the overall plant efficiency is about 2-3%. The appropriately selecting the working fluid and the Rankine cycle operation conditions the overall plant efficiency was improved by 5.52% and fuel consumption was reduced by 12.69% [8]. The fluids R245fa, R245ca, R141b and R123 using in the ORC as working fluids have been referenced as a viable option for the waste heat recovery from internal combustion engines, since they present high thermal efficiency and the lowest cost of electricity production [9], [10]. Hajabdollahi et al. [11] presented a thermo-economical optimization of an MCI-ORC system, considering R123, R134a, R245fa and R22 as the cycle working fluids and concluded that the fluids R123 and R245fa present approximate results in terms of efficiency and annual costs. Shu et al. [12] evaluated the performance of 10 Alkanes as work fluids using various indicators, resulting in the fact that cyclohexane and cyclopentane fluids are best suited for ICE-ORC applications. Using cyclopentane as working fluid in ORC, it produces an increase of approximately 10% in the electrical power of the system. Jung et al.[13] considered R134a, R245fa, R1234yf, water and ethanol as working fluids for ORC for waste heat recovery from the ICE exhaust gases, concluded that R245fa is the most viable working fluid for this application. G. Shu et al. [14] presents the experimental comparison of R123 and R245fa as the working fluid of an ORC system for recovering engine waste heat, showing the advantages of each. Several authors have concluded that the R245fa shows high efficiency and is environmentally friendly and suggested it as an optimum working fluid in the application of waste heat recovery from internal combustion engines.

In this paper, an economic evaluation of the use of a diesel-ORC system for the supply of energy in isolated locations is presented, for this the R245fa was used as working fluid of the ORC cycle. In addition, a model for the diesel generator has been developed from data supplied by the manufacturers to obtain the fuel consumption of the generator for nominal and partial load conditions. From the study was determined the generation cost, the specific fuel consumption, the energy generated by the system, and was performed sensitivity analysis of change in energy cost when the price of diesel varies.

2. System modeling

The load curve for a typical isolated location exhibits a variable demand profile. The diesel generator is sized to power the load, considering the losses involved in the process. The optimum selection of the generator is carried out considering that it must cover the load, even in infrequent situations, where the entire installed load is used at the same time. Waste heat recovery from the generator diesel exhaust gases using organic Rankine cycle has the potential to yield more additional power without get up the consumption of fuel.

The configuration scheme of the diesel-ORC system is shown in figure 1. The components include the diesel generator, the ORC and an electric generator that is responsible for transforming mechanical energy into electrical energy. The diesel generator and ORC operate all the time together to power the load.

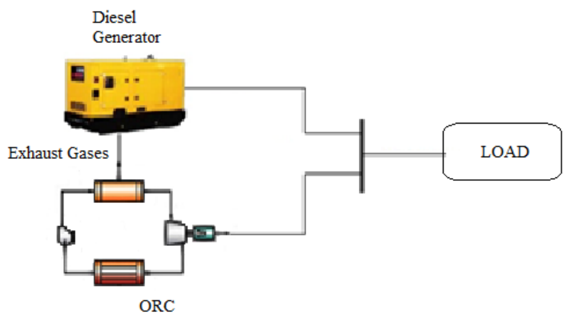

Figure 1. Configuration of Diesel-ORC system

2.1. Diesel Generator

To estimate the fuel consumption, mass flow rate, and exhaust gas temperature of the diesel generator, the following equations were used.[15]

Fuel consumption and the rated power of the generator is given by equation (1):

$$F_G = 0{,}395 * P_n^{0{,}945} \quad (1)$$

Where F_G is the fuel consumption at rated power (L/h) and P_n is the rated power (kW).
The fuel consumption at partial load is given by equation (2).

$$\frac{F_R}{F_G} = 0{,}9187 * P_L + 0{,}0784 \quad (2)$$

Where F_R is the fuel consumption at partial load (L/h); P_L is the partial load, which is defined as the ratio of the power out (P_{load}) and the rated power of the generator (P_n), equation (3):

$$P_L = \frac{P_{carga}}{P_n} \quad (3)$$

The combustion airflow rate in kg/s and the rated power in kW of the generator is given by equation (4).

$$\dot{m}_{ar} = 0{,}0021 * P_n^{0{,}9954} \quad (4)$$

From the mass balance of the engine, we can obtain the expression for the mass flow rate of exhaust gases in kg/s, equation (5).

$$\dot{m}_g = \dot{m}_{comb} + \dot{m}_{ar} \quad (5)$$

The fuel flow rate in kg/s can be calculated as:

$$\dot{m}_{comb} = \rho_{comb} * \frac{F_R}{1000} \quad (6)$$

Where, ρ_{comb} is the density of fuel (833 kg/m^3) e F_R is the fuel consumption (L/h).

To determine the energy from the exhaust gases at the partial load of engine, the figure 2 is used, which shows the behavior of the internal combustion engine at the partial load.

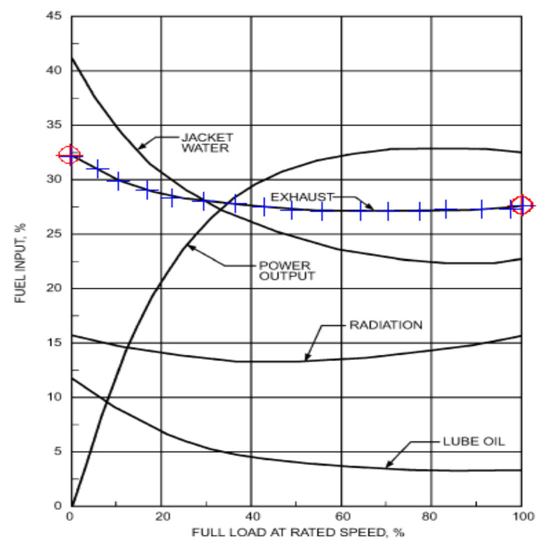

Figure 2. Power and heat losses of the diesel engine as a function of the partial load [16]

Can be modeled using the information in figure 5 the energy from exhaust gases at partial load (equation (7)) and obtained by regression as:

$$\frac{Q_G}{\dot{m}_{comb} * LHV_f} = 0{,}0003 * {P_L}^2 - 0{,}0453 * P_L + 0{,}3201 \quad (7)$$

Where LHV_f is the fuel lower heating value.

2.2. Organic Rankine Cycle

The scheme and the T-s diagram of the Organic Rankine Cycle (ORC) is shown in Figure 3.

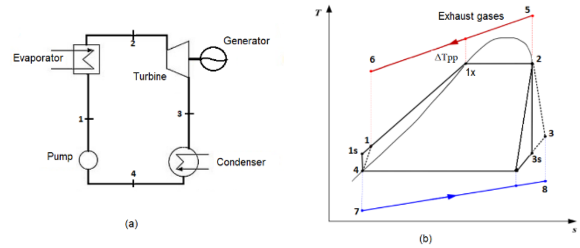

Figure 3. (a) Organic Rankine Cycle. (b) thermodynamics states [17]

For the cycle several assumptions were employed [15]:

- ✓ The system was operating under a permanent regime.
- ✓ The variations of kinetic and potential energy were neglected, as well as the heat losses of the equipment to the environment.
- ✓ Negligible pressure losses in the evaporator and pipes [18];
- ✓ Isentropic turbine efficiency: 80%
- ✓ Isentropic pump efficiency: 70%;
- ✓ Working fluid temperature at condensation: 35 ° C [4]
- ✓ Electric generator efficiency: 93%.
- ✓ The minimum pinch point (ΔTpp) allowed for the evaporator was 30 ° C and for the condenser, 5 ° C.

Applying the energy balance related to the heat required for the phase change of the working fluid within the evaporator (between 1x and 2, see Fig.6), the mass flow rate of the working fluid was calculated by Equation 8.

$$m_f = \frac{m_g * C_{pg} * (T_{gin} - T_{gpp})}{h_2 - h_{1x}} \quad (8)$$

where $T_{gpp} = \mathrm{T_{1X}} + \Delta\mathrm{T_{pp,min}}$, m_f is the working fluid mass flow rate (kg/s); T_{gin} is the exhaust gases temperature (K); T_{gpp} is the temperature of the exhaust gases at the pinch point and C_{pg} is the specific heat of the exhaust gases. For the analysis it was used the multi-platform "CoolProp" free software library was used to provide the thermodynamic properties of the working fluid [19].

The temperature of gases at engine exhaust at the evaporator outlet was calculated by Equation 9.

$$T_{g,out} = T_{g,pp} - \dot{m}_f \frac{h_{2x} - h_2}{\dot{m}_g * \bar{C}_{pg}} \quad (9)$$

The outlet temperature of the exhaust gases must be greater than 120 ° C ($T_{g,out} > 120\,°C$,) to avoid corrosion damage in the evaporator.
Applying the 1st and 2nd Law of Thermodynamics in the turbine (see Fig.6), equation 10 provides the enthalpy at point 3 (turbine output) as a function of the isentropic efficiency ($\eta_{is,t}$). Similarly, in the pump, equation 11 provides the enthalpy at point 1 (pump output).

$$h_3 = h_2 - \eta_{is,t}(h_2 - h_{3,s}) \quad (10)$$

Where h_{3s} is the enthalpy of the fluid for an isentropic condition at the turbine outlet and h_3 is the enthalpy of the fluid at the turbine inlet.

$$h_1 = h_4 + \frac{h_{1S} - h_4}{\eta_b} \quad (11)$$

By means of equations 12 to 16, the mechanical power generated in the turbine ($\dot{W}t$), the heat transfer rate in the condenser ($\dot{Q}cond$) and the evaporator ($\dot{Q}evap$), the power consumed in the pump (Wb), the net power of the system ($\dot{W}liq$), and the thermal efficiency of the cycle.

$$\dot{W}_t = \dot{m}_f(h_2 - h_3) \quad (122)$$

$$\dot{Q}_{con} = \dot{m}_f(h_3 - h_4) \quad (133)$$

$$\dot{Q}_{evap} = \dot{m}_f(h_2 - h_1) \quad (144)$$

$$W_b = \dot{m}_f(h_1 - h_2) \quad (155)$$

$$W_{liq} = (W_t - W_b) \cdot \eta_{gen} \quad (166)$$

Where η_{gen}, the efficiency of the electric generator.

$$\eta_{ciclo} = \frac{W_t - W_b}{\dot{Q}_{evap}} \quad (177)$$

3. Economic Analysis

The economic assessment considers Levelized Cost of Energy – LCOE. This cost depends of the annualized investment cost and the operation and maintenance costs expenses throughout the system's useful life [20]. The Levelized Cost of Energy is calculated as:

$$LCOE = \frac{C_{AI} + CO\&M_A}{E_{anual}} \quad (18)$$

Where E_{anual} is the electric energy consumed in kWh in a period of one year (Δt = 8.760 h), since it is the energy consumed that comes the revenues for the payment of the system costs; C_{AI} annualized investment costs, $CO\&M_A$ the annualized operation and maintenance costs.

The annualized investment cost (C_{AI}), based on the total cost of the system(C_I), is calculated as:

$$C_{AI} = \frac{d*(1+d)^n}{(1+d)^n - 1} C_I \quad (18)$$

Where n is the project lifetime and d is annual real interest rate, d given by:

$$d = \frac{i_{an} - f}{1+f} \quad (19)$$

Where i_{an} nominal interest rate and f is is the annual inflation rate.

4. CO2eq emissions

The emissions of each greenhouse gas from diesel fuel combustion are calculated according to the methodology of the Brazilian program GHG Protocol, which has 3 steps:
Step 1. Estimate of energy consumption

$$EC = FC * Fconv \quad (201)$$

Where EC is the energy consumption (TJ); FC is the Fuel Consumption (l) and Fconv is a Conversion factor (TJ/l).
Step 2. Estimate emissions of CO_2, CH_4, and N_2O

$$EGEE = EC * Femiss \quad (212)$$

Where EGEE is emissions of a given Greenhouse gas (kg) and Femiss is an emission factor (kg/TJ).
Emission factors for Diesel Oil according to IPCC Guidelines for National Greenhouse Gas Inventories is given on table 1.

Table 1. Emission factors

CO_2(kg/TJ)	CH_4(kg/TJ)	N_2O(kg/TJ)
74100	3	0.6

Step 3. Estimate emission of carbon dioxide equivalent

$$ECO_{2eq} = ECO_2 + (ECH_4 * 25) + (EN_2O * 298) \quad (223)$$

Where ECO_{2eq} is the emission of CO_{2eq} (kgCO_{2eq})

5. Proposed solution

Figure 4 shows the flowchart of the system simulation process. The input data required for the simulation are the initial investment costs and operation and maintenance costs, as well as the project life, technical specifications of the system components; in addition, the hourly power demand in the period of one year is required.

The system is evaluated over a period of 8760 hours at one-hour intervals, allowing the determination of organic Rankine cycle size and annual fuel consumption. During the simulation, the system is considered semi-stationary, so that in each time interval the different system variables will remain constant.

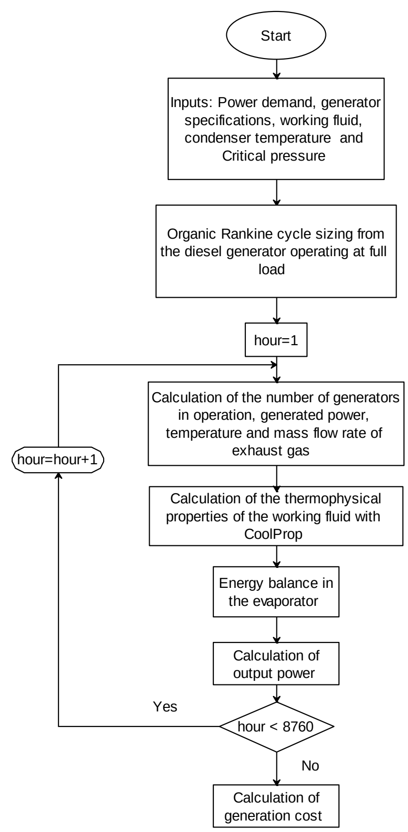

Figure 4 Flowchart of system simulation

6. Case Study

To simulate the proposed Diesel-ORC system, the load profiles of a medium sized population located in the state of Rondônia, Brazil, which is not connected to the National Interconnected System (SIN), were used. Figure 5 shows hourly variation of demand, with a maximum consumption of 7550 kWh.

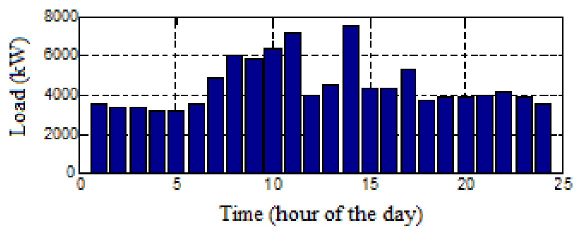

Figure 5 Load curve

For the present work the organic fluid R245fa was used, whose temperature and critical pressure are 427 K and 3639 kPa. To simulate the system was used MATLAB and the CoolProp program, to obtain the thermodynamic properties of the fluid.

Table 2 presents the data used for the economic evaluation of the system.

Table 2 Data for Simulation

Parameters	
Project life (years)	20
Discount rate (% a.a)	14.25
Inflation (%)	9.321
Fuel cost ($/L)	1.0
Size of Diesel generator (kW)	846 - 1250
Diesel generator cost ($)	6028.46 – 980837.69
Operations and maintenance cost of diesel ($/MWh)	23.51– 37.56
ORC cost ($/kW)	4166.09 – 6576.52
Operations and maintenance cost of ORC	1% of investment [21]

7. Results and discussion

7.1. Diesel generator set only.

The simulation of the system was performed, for this case when the diesel generator is the only source of electricity generation. The thermal power plant has 10 generating units with nominal power of 846 kWe, 1050 kWe and 1250 kWe (see table 3).

In the simulation the generating units operate with a load factor varying from 50% to 100%, to guarantee good system efficiency and low specific fuel consumption. The system was simulated for a period of 8760 hours, to obtain the generation cost (see table 3). The results indicate that the generation cost of 0.45 $ / KWh.

Table 3 Result of the diesel system simulation

Generating Unit	Operating time (h)	Generated Power (MW)	Energy from exhaust gases (MW)	Fuel consumption (L)
DGU-01 (1250 kW)	8369	7493.1	5927.1	2070700
DGU-02 (1250 kW)	8369	7493.1	5927.1	2070700
DGU-03 (846 kW)	7182	6414.6	4739.4	1748600
DGU-04 (846 kW)	4010	3628.5	2672.6	988200
DGU-05 (846 kW)	2636	2438.4	1796.6	663000
DGU-06 (1250 kW)	8046	7222.5	5710	1995400
DGU-07 (1250 kW)	640	604.4	427.7	166100
DGU-08 (1250 kW)	391	350.2	277	96800
DGU-09 (1250 kW)	391	350.2	277	96800
DGU-10 (1050 kW)	1746	1572.2	1206.6	430900
Total		**37567**	**28996**	**10327000**

DGU: Diesel generating unit.

The CO_{2eq} emission results of the generator diesel set was 27533.42 tCO_{2eq}/year.

7.2. Diesel-ORC system

For the case study, a diesel generator set consisting of seven generating units, 4 units of 1250 kW, 3 units of 846 kW and one-unit of 1050 kW was used, for 8585 kW. According to the results of the simulation, an organic Rankine cycle of 823.76 kW is necessary for waste heat recovery from the generator sets exhaust gases. The main results of the simulation are presented in Table 4.

Table 4 Result of the diesel-ORC system simulation

Parameters	
Diesel Generated Power (MWh/year)	35974
ORC Generated Power (MWh/year)	3347.7
Operating time (h)	
DGU -01 (1250 kW)	8392
DGU -02 (1250 kW)	8362
DGU -03 (846 kW)	7676
DGU -04 (846 kW)	4859
DGU -05 (1250 kW)	2349
DGU -06 (846 kW)	2256
DGU -07 (1250 kW)	381
DGU -08 (1050 kW)	695
Fuel consumption (L/year)	9742400

The simulation results show that the configuration provides 100% of the energy demanded by the load, in addition to having lower fuel consumption than the diesel system only and generation cost of 0.38 $ / kWh.
The CO_{2eq} emission results of the diesel-ORC system was 25723.01 tCO_{2eq}/year.

7.3. Comparative análisis

To determine the viability of the implementation of the Diesel-ORC system, a comparison is made with the 100% diesel system in terms of specific fuel consumption, generation cost, electrical efficiency, and excess energy.

Figure 6 below shows the differences in generation cost between the only diesel system and the Diesel-ORC system. It can be seen from figure 7 that the diesel-ORC system has a generation cost of 15.56% cheaper than only diesel system.

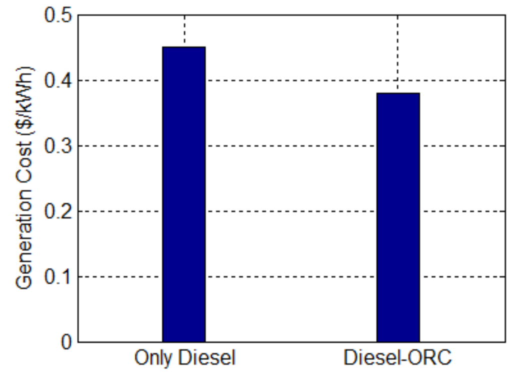

Figure 6 Generation Cost

One of the important indicators in the diesel power plants used in isolated systems is the specific fuel consumption. In Brazil, the National Electric Energy Agency (ANEEL) [22] establishes maximum fuel consumption specific values of 0.283 L / kWh for the power range of the systems presented in this study. In addition, ANEEL approve the reimbursement of up to 75% of the value of the investment for the generating company that is in operation and with proven total or partial reduction of fossil fuels. Figure 10 shows the specific fuel consumption of the systems.

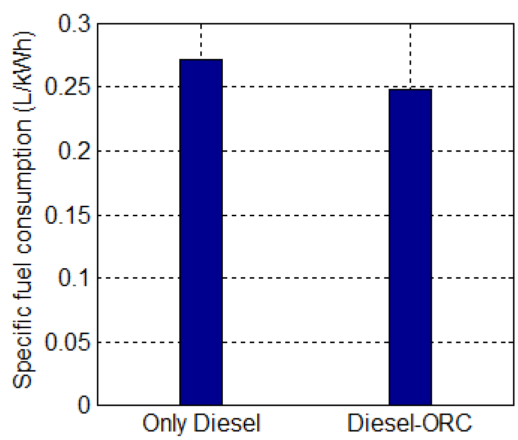

Figure 7. Specific fuel consumption

As can be seen, the using of the ORC cycle for waste heat recovery from the generator set exhaust gases allows a reduction of the specific fuel consumption of 8.85%, allowing a significant saving in fuel, thus lower operating cost of the system. In addition to reducing CO_2 emissions in 6.57%,

Another of the evaluated parameters is the electrical efficiency of the system, as it is possible to observe it in Figure 8, there is an increase in the efficiency by taking advantage of the energy contained in the exhaust gases of the generator by means of the addition of the organic Rankine cycle, obtaining an increase of 13% in the efficiency.

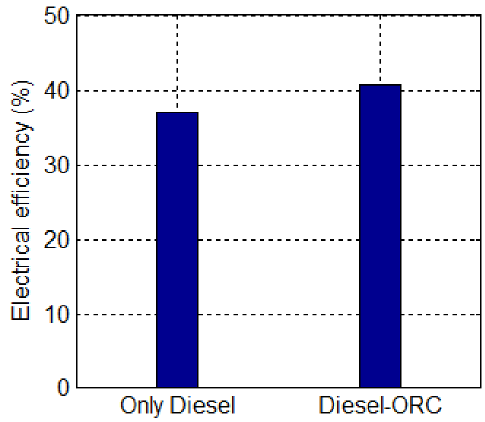

Figure 8. The electrical efficiency of the systems.

7.4. Sensitivity análisis

For this analysis, it was considered a 50% and 100% increase in the diesel price, allowing verifying the influence on the energy cost. It can be seen, from Figure 9, that the variation of the generation cost (GC) is linear with the price variation of the diesel oil. It is shown that the Diesel-ORC system is more advantageous than the conventional diesel system.

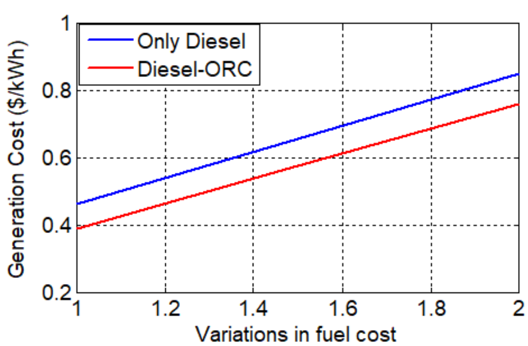

Figure 9. Variation in cost of energy due to fuel cost

8. Conclusions

The model developed for the internal combustion engine, based on a database of several engines with different power ranges, is useful for calculating engine consumption for different loading levels. They also allow determining the mass flow and temperature of the exhaust gases, data necessary for the application of the ORC.

The use of the organic Rankine cycle for the exhaust gas heat recovery from diesel generator sets, allows an increase of the energy generated in 9.6%, besides increasing the electrical efficiency about 13% and reduce the cost per kWh of energy by approximately 15.56%.

It has proven that with the use of the organic Rankine cycle CO_2 emission can be reduced in 6.57%, This is very important to estimate of their impact on the environment.

Acknowledgments

The authors would like to express their sincere gratitude to the Research Department of the Unidades Tecnologicas de Santander and Universidad Autónoma de Bucaramanga for their invaluable collaboration in the development of this work.

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