Study of Potential for Energy Recovery in Low-Cylinder Diesel Engines and its Environmental Impact

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Abstract

This study of thermoelectric generators as an energy recovery system in exhaust gases is a constant research challenge. In this paper, the theoretical model that describes the behavior of the thermoelectric modules is exposed and the CFD simulation results across of ANSYS® software too, where the heat exchanger allows improving the efficiency of the modules increasing the transmitted heat and the surface temperature of hot focus, showing the temperature profile of heat exchanger in contact with exhaust gases and the electric potential of modules in the specific temperature. Also, the influence in the decrease of fuel consumption is evaluated and the environmental impact in the decrease of polluting emissions to the atmosphere.

Keywords: *Thermoelectric module, simulation, heat exchanger, fuel, polluting emissions.*

1. Introduction

The energy of the exhaust gases when they are driven out of the engine, it is lost in the totality to the atmosphere. That energy (only the 30%) can be recovered to be used in a system that needs energy for its functionality. Just in case of the diesel engines, that energy can be recovered across thermoelectrics devices [1].

One of the research carried out shows the possibility of directly exposing the thermoelectric device to the heat source (tube of the exhaust gases), while another of the surfaces is in contact with the cooling flow. For that analysis Negash [2] used a Diesel engine as a heat source, the cooling source was a mixture of water-ethylene glycol, which was pumped into the cooling canals for remove heat. Under the highest conditions of a load of the engine, the maximum output power of 43 W and conversion performance of 2% was obtained.

On the other hand, In et al. [3] affirm an increase in the performance of these when increasing the temperature of the hot side of module and that the difference temperature between the two extremes of thermoelectric module and differential pressure of the exhaust gas are the key factors in the performance of the energy generation of module.

The temperature that the cooling handle during the process of the engine to it contributes greatly to the maximum power that thermoelectric module will have. For this, Kim et al. [4] affirm that the decline of the cooling temperature from 293 to 283 K contributed an increase of 1.5% and 33.7% in the maximum power, obtaining a maximum power of 125.7 W under determined conditions of engine operation at 1500 rpm. However, according to He et al. [5] the parameters of the exhaust gases can fluctuate during the engine operation, for which is necessary to choose an optimal size from the thermoelectric and the direction of the flow achieving a high level of energy recuperation.

An alternative form has emerged due to the low conversion efficiency of the actual technology, and the relatively high costs of the semiconductors materials of thermoelectrics [6], is the combination of the thermoelectric devices with heat exchangers that it allows improving the efficiency of the thermoelectric generator. Lu et al. [7] studied the efficiency of heat exchanger when they use rectangular offset-strip fins and metallic foam with a certain porosity and ppi (pores per lines inch). With this type of fins, there is some improvement in the capacity of thermoelectric device changing the values, such as transverse separation of the fin and fin thickness, which must be selected according to the conditions of functionality. With respect a metallic foam, low porosity and a small ppi with these you will get greater efficiencies, nevertheless, this kind of porous media induce pressure drops so the power could decrease.

The use of thermoelectric generators requires the study of thermals parameters, also the geometry of heat exchanger that it will be implemented. The heat exchanger type sandwich plate was used for this study, with that heat exchanger the results show the great influence of parameters as the flow speed, the area of the thermoelectric module, changes in length, height and width of the heat exchanger in the capacity of energy recovery of the thermoelectric generation system [8].

To obtain a considerable energy use, have been studied thermals characteristics of the heat exchangers exposed to exhaust gases improving the heat transfer, such as the material, the internal structure, and surface. Su et al. [9] in the simulations and experiments results shows that a heat exchanger in the form of a brass plate with accordion form in its internal structure achieves a relative ideal performance, it can improve the global thermal performance of the thermoelectrics. Another kind of heat exchanger in these research is the kind EGR, showing that the electrical power of thermoelectric device increases when the temperature of exhaust gases increase, a decrease of cooling temperature or an increase in the exhaust flow rate [10].

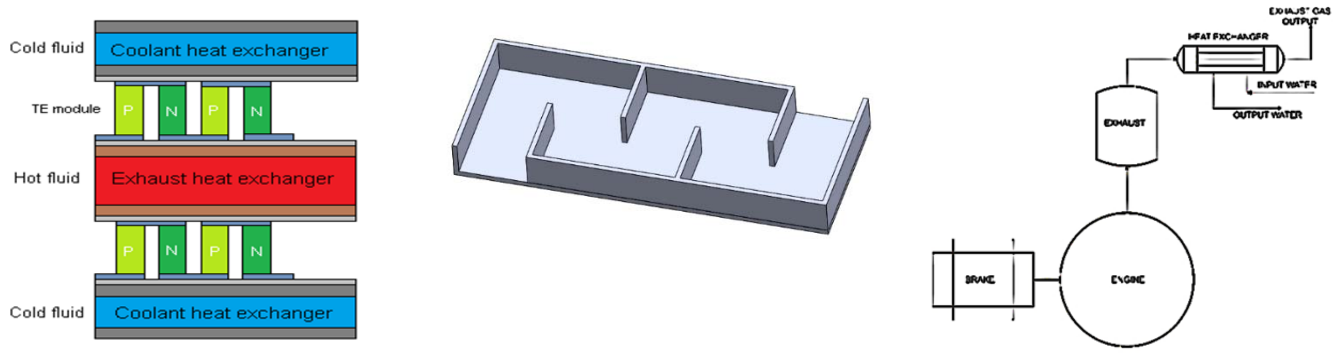
From the other hand, Cao et al. [11] showed an increase in output power and the density of output power of the TEG of 10.17% and 15.49% highest with the use of the heat tubes. The efficiency of maximum energy conversion achieved in that study was 2.58%.

In this paper, the influence of the implementation thermoelectrics generators as an energy conversion system in the exhaust of engine is exposed, generating a decrease in the fuel consumption and decreasing the pollutions emissions. Also, this analysis searches to maximize the capacity of the thermoelectric device in this kind of systems. Finally, this study focuses on measuring the percent of energy recuperation that it can be obtained of exhaust gases after you watch the temperature profile in the walls of the heat exchanger and electrical potential that is generated.

2. Model description

2.1. General configuration of TEG

The thermoelectric generating device is formed by two layers of thermoelectrics modules (TE), which are located between a heat exchanger and a cooling system. Each layer consists of 10 TE modules. This structure is shown in Figure 1.



(a) (b) (c)

Fig. 1. Schematic model of TEG: (a) structural scheme of TEG, (b) internal structure of heat exchanger, (c) schematic of the experimental test bench.

Each TE module is formed by a semiconductor type p and one type n, which are thermally connected in series by cooper plates. The TE modules are separated by the walls of the heat exchanger and cooling system by ceramics plates. As the exhaust gases circulate through of heat exchanger, it decreases the temperature when the TE modules absorb heat from these gases. Similarly, the flow (water) circulating by the cooling system, increases its temperature when it absorbs the heat transferred by the TE modules.

2.2. Electrical and thermal model of the TE module

The mathematical model of TE module considers the constant properties, ignores the radiation heat transfer and the Thompson effect is not taken into consideration.

The next equations describe the transfer of heat of each thermocouple [12,13]:

$$q_{f,i} = 0.5c_f m_f\left(T_{f,i} - T_{f,i+1}\right) = n_y(2l_2l_3)k_f\left[0.5\left(T_{f,i} + T_{f,i+1}\right) - T_{h5,i}\right] \quad 1\text{ (a)}$$

$$q_{w,i} = 0.5c_w m_w\left(T_{w.i+1} - T_{w,i}\right) = n_y(2l_2l_3)k_w\left[T_{c5,i} - 0.5\left(T_{w,i} + T_{w.i+1}\right)\right] \quad 1\text{ (b)}$$

The current present in a thermocouple is [12]:

$$I = \frac{\alpha_{pn}\left(T_{h5,i} - T_{c5,i}\right)}{R_L + R_{pn}} \quad (2)$$

Where R_L is the external electrical resistance.

When considering that the external resistance is equal to the internal electrical resistance of the thermocouple, it has that the total external resistance is:

$$R_L = n_x n_y R_{pn} \quad (3)$$

The total current of one of the layers of the thermoelectric modules is [12]:

$$I = \frac{\left[\sum_{i=1}^{n_x} n_y \alpha_{pn}\left(T_{h5,i} - T_{c5,i}\right)\right]}{2 n_x n_y R_{pn}} \quad (4)$$

The total power of the device is:

$$P_{TE} = 2\sum_{i=1}^{n_x}\left(q_{f,i} - q_{w,i}\right) \quad (5)$$

2.3. Calculation of heat transfer and hydraulic resistance of the heat exchanger

Since the cross-section through which the exhaust gases circulate is not circular, it is required to calculate the hydraulic diameter [14]:

$$D_f = \frac{0.5wh}{w + h} \quad (6)$$

Where w y h is the width and height of internal canal of the exhaust exchanger respectively.

The coefficient of heat transfer by convection of the exhaust gases is calculated as follows [13]:

$$h_f = Nu_f k_f / D_f \quad (7)$$

where k_f is the thermal conductivity of the exhaust gases.

The pressure drop generated by the heat exchanger is [15]:

$$\Delta P = 4f(L/D_f)\left(d_f u_f^2/2\right) \quad (8)$$

Where L, d_f y u_f are the length of the heat exchanger, density, and speed of exhaust gases, respectively.

The power loss due to the pressure drop is [15]:

$$P_{loss} = \Delta P\left(\frac{m_f}{d_f}\right) \quad (9)$$

To the power obtained from the TE modules, the power lost due to the pressure drop must be subtracted to obtain the net power.

$$P_{net} = P_{TE} - P_{loss} \quad (10)$$

The conversion efficiency is defined as:

$$\eta = P_{net}/Q_h \quad (11)$$

3. Thermal simulation of the heat exchanger

The fluid dynamics software (CFD) is used to obtain the temperature profile that is formed on the wall of the heat exchanger by the flow of the exhaust gases inside it.

3.1. Configuration of mesh

The mesh structure is formed predominantly by elements of hexahedral geometry. Tetrahedral elements were used in the regions where curvatures appear on the surface of the heat exchanger. The number of nodes and elements of the mesh were 70986 and 71072 respectively. When the nodes and elements of the mesh increased above those values, the results of the outlet temperature of the simulation were not changed, then the mesh independence was achieved. Figure 2 shows the structure of the mesh.

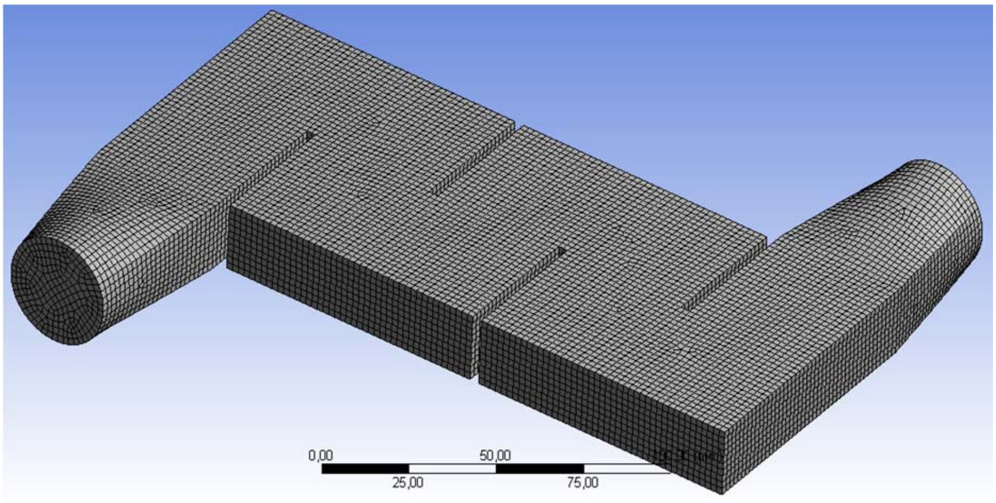


Fig. 2. Mesh structure implemented.

3.2. The boundary condition of the simulation model

In the simulation model, the exhaust gas flow inside the heat exchanger is assumed completely turbulent, and molecular viscosity can be neglected, so the $k-\varepsilon$ model is used in the CFD simulation. As near wall area processing with standard wall function, the natural convection heat transfer coefficient and the environment temperature are set [16]. The approximate temperature in the exhaust engine is 310°C. This temperature is taken as the inlet temperature in the heat exchanger. Based on the operating characteristics of the motor, the flow rate is assumed to be 10 m/s. At the output of the heat exchanger, the pressure limit condition is used, taking the outlet pressure as the atmospheric pressure.

4. Results and discussions

4.1. Experimental validation

In each of the positions where a thermoelectric module is located, the temperature in the wall of the heat exchanger is measured. The measurements are in the geometrical center of the TE modules. These temperatures are assumed as the average temperatures of the faces of the TE modules (hot side). Figure 3 shows the locations of these measurement points.

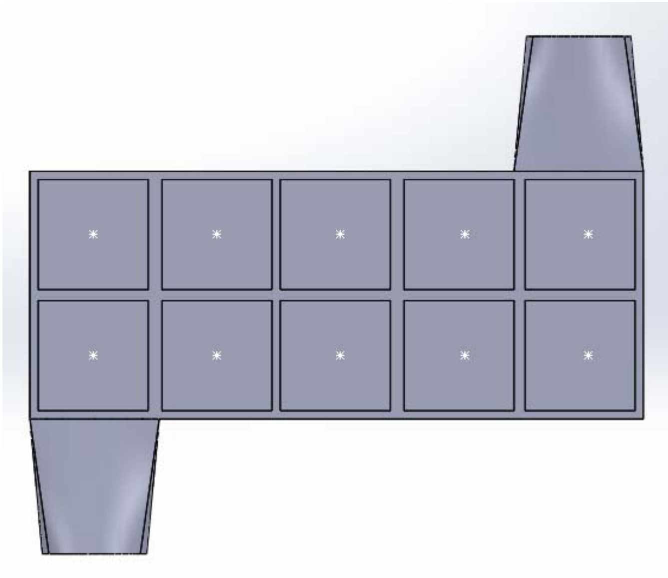


Fig.3. Location of temperature measurement points on the wall of the heat exchanger (upper part).

It is observed at the moment of taking the measurements that, the two faces of the TE modules present approximately equal measurements, this is due to the symmetry that the TEG device presents. Therefore, only the measurement values of one of the faces are displayed. The data obtained from the temperature sensors (type K thermocouple) are recorded in table 1. Due to the cooling system, the cold side of the TE modules is maintained at a temperature of 50 ° C.

During the operation of the test bench, the current of each of the thermoelectric modules is measured. These have an approximate current flow of 3 amps. With this information and the results of the temperatures mentioned above, the characteristic curve of the thermoelectric module shown in Figure 4 is used to obtain the voltage of each one of them.

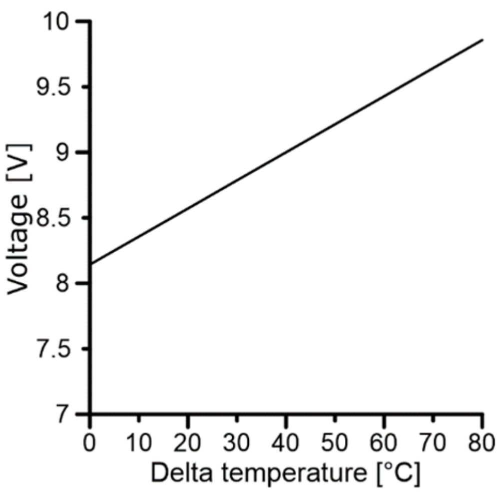


Fig.4. Caracteristic curve of TE from a current of 3 amps.

The results of the calculations of theoretical, experimental and simulated difference of temperature and power are shown in Table 1.

Table 1. Calculation of difference of temperature and power of each TE modules (theoretical, experimental and simulated).

Thermal module N°	ΔT[°C] Theoretical	ΔT[°C] Experimental	ΔT[°C] Simulated	Theoretical power [W]	Experimental power [W]	Simulated power [W]
1	79	77	75	2.95	2.61	2.81
2	76	74	72	2.86	2.52	2.72
3	73	72	70	2.77	2.43	2.63
4	69	67	68	2.68	2.33	2.53
5	67	66	66	2.59	2.24	2.44
6	66	65	64	2.50	2.15	2.35
7	63	61	62	2.41	2.06	2.26
8	61	62	60	2.31	1.97	2.17
9	59	57	58	2.22	1.88	2.08
10	56	54	55	2.13	1.78	1.99

When adding the individual powers of each TE module, the electrical power generated by the TE modules located on the upper face of the TEG is obtained. This value is 21.97 W. The total electrical power of the TEG is 43.94 W. Figure 5 shows the comparison of the values of electrical power of each thermoelectric module from the theoretical analysis, experimental and simulation results.

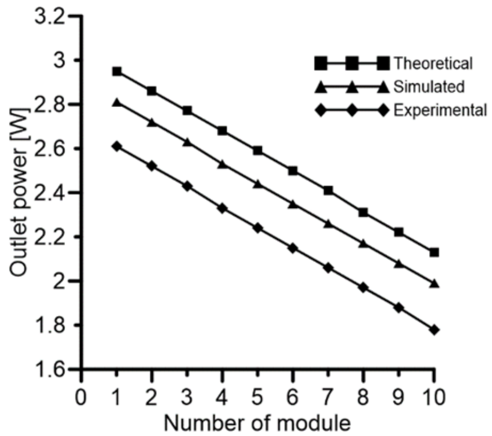


Fig.5. Values of electrical power of each module (theoretical, simulated and experimental).

4.2. Simulation results

With the temperature profile obtains in the simulation, the values of the temperatures in the same locations that were physically measured in the experimental assembly are observed. The temperature profile of the simulation is shown in Figure 6.

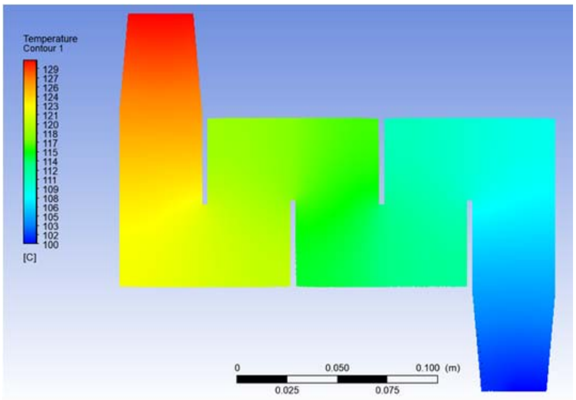


Fig.6. Simulated temperature profile.

The values of difference of simulated temperature are compared with the values of difference of physically temperature to verify the prediction capacity of ANSYS®. This comparison is shown in table 2.

Table 2. Comparison between the experimental and simulation measures.

Thermal module N°	ΔT [°C] physical measurement	ΔT [°C] Simulated measurement	Error [%]
1	77	75	1.57
2	74	72	1.61
3	72	70	1.64
4	67	68	0.85
5	68	66	1.69
6	65	64	0.87
7	61	62	0.90
8	62	60	1.79
9	57	58	0.93
10	54	55	0.96

Table 2 shows that the percentage error remained below 2%, which verifies the feasibility of using the ANSYS software as a tool to study the efficiency of the heat exchanger.

4.3. Study of the influence of TEG on polluting emissions

The following circular diagrams (Figure 7) show the emissions of diesel engine with a low displacement used in the present research and that has been used by other authors [17]. The reduction of these emissions when applying TEG proposed in same engines can be observed. The use of thermoelectric shows a reduction of 2.5% that can continue to be studied to increase this percentage, apart from achieving an increase in the overall efficiency of the thermal machine.

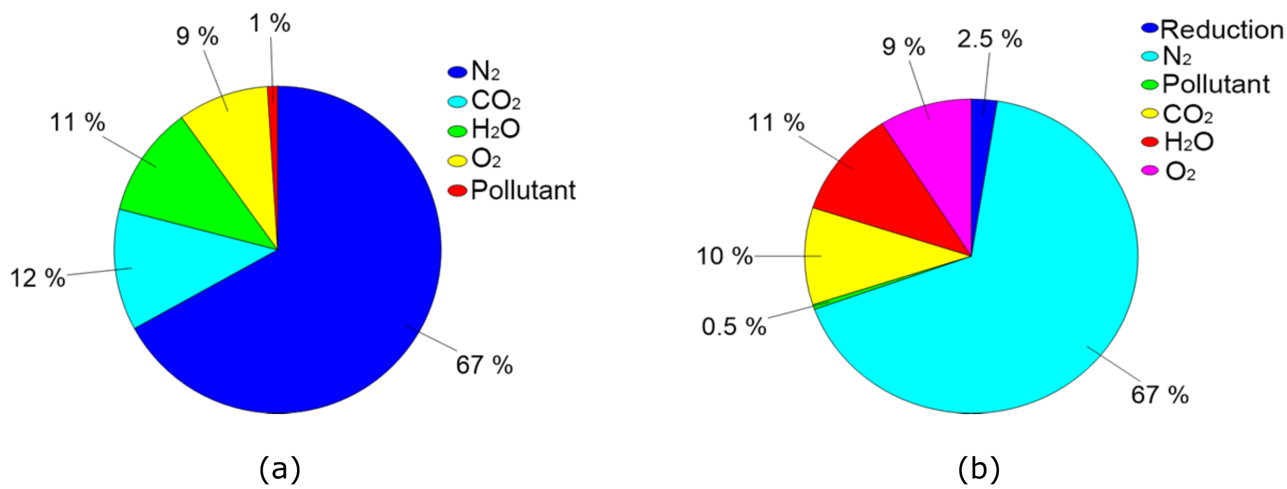


Fig.7. Emissions of a diesel engine. (a) Emissions percentages commonly of a diesel engine, (b) Emissions percentages of emissions from diesel engine applying thermoelectric.

5. Conclusion

Energy analysis for residual heat recovery in low displacement engines was carried out. Based on the results obtained, it is established that in the points closest to the exhaust gas inlet of the heat exchanger the temperature is higher in comparison to those located near the exit of the gases due to the heat losses they are generated by tracing the internal structure of this. Despite these losses (little considerable), a total TEG experimental power of 43.94 W is obtained, indicating that 3% of the engine power can be recovered. Just in case of the outlet power of each module, the value of theoretical power is greater than the value of the experimental and simulated power for a little error percentage. The value of power leads to a decrease in fuel consumption and too polluting emissions. Concerning the emissions of diesel engine exists an energy recovery of 2.5%, then the emission of CO_2 decreases a 2.0%, and the pollutant emissions (SO_2, NO_x, CO, HC, PM) decreases a 0.5%. At the same time, with the use of ANSYS® software as a prediction tool in the validation process, an error rate of 2% was obtained, which allows us to continue improving the internal geometry of the heat exchanger to achieve greater energy recovery without experimental costs unnecessary.

Nomenclature

c = specific heat capacity (KJ/KgK)

m = mass flow rate (Kg/s)

T = temperature (°C)

I = current (A)

D_h = hydraulic diameter (mm)

k = thermal conductivity (W/cm℃)

N_u = number of Nusselt

α = Seebeck coefficient (V/°C)

Greek Symbols

η = efficiency

Subscripts

f = exhaust gases

w = water

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