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Experimental and Numerical Analysis of Using Thermoelectric Generator Modules on Hexagonal Exhaust Heat Exchanger

Altıgen Egzoz Eşanjöründe Termoelektrik Jeneratör Modüllerinin Kullanımının Deneysel ve Sayısal Analizi

Beytullah Erdogan*, Kağan Duran, İbrahim Zengin

Zonguldak Bülent Ecevit Üniversitesi, Mühendislik Fakültesi, Makine Mühendisliği Bölümü, Zonguldak, Türkiye

Abstract

Nowadays, many vehicles have internal combustion engines. In the cities, millions of vehicles affect badly the environment with their emissions due to fossil fuel. Besides of harmful pollution gases, a huge amount of energy is lost from the exhaust on internal combustion engines. It is possible to recover some part of the waste heat from the exhaust duct with advanced technological applications. Electricity generation from vehicle exhaust waste heat with thermoelectric generators is a highly attractive energy recovery application area in which many studies have been done recently. Thermoelectric generators are special semiconductor materials that produce electricity from the temperature difference between the surfaces by touching the hot source and heat sink. Recovering some part of the waste heat is extremely important in terms of contributing to reducing the pollution rate to unit energy production. In this study, the thermoelectric generator application was investigated experimentally with a hexagonal exhaust heat exchanger manufactured using aluminum material and 24 pieces TEG (Thermoelectric Generator) modules placed between liquid fluid copper cooling blocks and aluminum exchanger. The model was cooled by a cooling system similar to the engine cooling system. Pure water (100%) and ethylene glycol-pure water (50-50%) were used as a coolant fluid and the effect of fluid type was investigated. In cases which the fan is constantly running and Ethylene Glycol-Pure Water (50-50%) is used as the cooling fluid, 10.678W electricity was generated. In addition, it was determined that the energy-production increases with a deflector which was located to the exchanger's fluid volume center via the ANSYS CFD program on the manufactured model geometry. In the analyzes, it has been revealed that the deflector increases the temperatures on the surfaces that TEG modules are placed.

Keywords: TEG, ETEG, Waste heat recovery, Thermoelectric, Thermoelectric module, CFD

Öz

Günümüzde trafikteki şehirlerde içten yanmalı motorlar bulunan milyonlarca araç fosil yakıt kaynaklı emisyonlarıyla çevreyi kötü etkilemektedirler. Zararlı kirletici gazların yanı sıra, içten yanmalı motorlarda egzozdan büyük miktarda enerji de kaybedilir. İleri teknolojik uygulamalarla egzozdan gazlarla birlikte çıkan atık ısının bir kısmını geri kazanmak mümkündür. Termoelektrik jeneratörlerle (TEJ) egzoz atık ısısından elektrik üretimi, son zamanlarda birçok çalışmanın yapıldığı, popüler bir enerji geri kazanım uygulama alanıdır. TEJ'ler, sıcak kaynak ve bir soğutucuya dokunarak yüzeyler arasındaki sıcaklık farkından elektrik üreten özel yarı iletken malzemelerdir. Atık ısının bir kısmının geri kazanılması, birim enerji üretimine düşen kirlilik oranının azalmasına katkı sağladığından son derece önemlidir. Bu çalışmada, alüminyum malzemeden imal edilmiş altıgen egzoz eşanjörü ve sıvı soğutucu akışkan dolaştırılan bakır soğutma blokları arasına yerleştirilen 24 adet TEJ modülleri ile Termoelektrik jeneratör uygulaması deneysel olarak incelenmiştir. Model, motor soğutma sistemine benzer bir soğutma sistemi ile soğutulmuştur. Soğutucu akışkan olarak saf su (%100) ve etilen glikol-saf su (%50-50) kullanılmış ve akışkan etkisi araştırılmıştır. Fanın sürekli çalıştığı ve soğutma sıvısı olarak Etilen Glikol-Saf Su (%50-50) kullanıldığı durumlarda 10.678W elektrik üretilmiştir. Ayrıca imal edilen model geometrisi üzerinde CFD programı aracılığıyla eşanjörün akışkan hacminin merkezine yerleştirilen dağıtıcıların enerji üretiminin arttırılabileceği durumlar incelenmiştir. Dağıtıcılar TEJ'lerin yerleştirildiği yüzey sıcaklığını arttırmıştır.

Anahtar Kelimeler: TEJ, ETEJ, Atık ısı geri kazanımı, Termoelektrik, Termoelektrik modül, HAD

*Corresponding author: beytullaherdogan@hotmail.com

Beytullah Erdogan orcid.org/0000-0002-6120-9196
Kağan Duran orcid.org/0000-0002-3743-086X
İbrahim Zengin orcid.org/0000-0002-6261-7490

1. Introduction

Millions of vehicles in traffic are discharging harmful emissions from the exhaust to the environment everyday. Especially, one of the causes of air pollution is a car exhaust gases in the big cities (Bolatlı, 2019). There are so many studies to reduce exhaust pollution on combustion and exhaust systems (Ziolkowski, 2017). The main aim of all these studies is to improve the relation between engine efficiency and exhaust cleaning applications. Internal combustion engines discharge a huge amount of heat as well as harmful emissions (Jaziri et al., 2019). A conventional internal combustion engine uses only %25 of the energy generated by the fuel combustion but loses about %40 with exhaust gases (Hatami and Ganji, 2015). Some parts of the exhaust heat can be transformed into usable energy in the vehicle.

Thermoelectric generators are the most attractive applications that increase efficiency by recovering energy from exhaust waste heat. Thermoelectric material performance is determined by the thermoelectric figure of merit, defined as

$$ZT = a^2 \sigma / k \qquad (1)$$

where a, σ, k are the Seebeck coefficient, electrical conductivity, thermal conductivity of materials, respectively, and T is the absolute temperature (Zhang et al., 2015). Backpressure has a very important effect for the design of TEG heat exchanger (Ioffe et al., 1959). When backpressure has changed, engine conditions also can be changed negatively (Kumar et al, 2018). Choosing outer geometry for the exhaust heat exchanger is another key point for efficiency. Generally, TEG modules are located on the heat exchanger surfaces. Some of the applications for more space on surfaces need polygon geometry design. Also, the inner region of the exchanger can be arranged with baffle plates fins, or deflectors. Predesign and analysis via ANSYS FLUENT can be helpful to choose a more effective heat recovery model (Nour et al., 2019). Heat exchanger's different types of internal structures are possible to improve surface temperature and uniformity (Deng et al, 2013, and Cherkez, 2012). Thermoelectric generator application can be done without adding any parts to the vehicle's exhaust line. The muffler is a typical part of the exhaust line. it is possible to use a muffler as a thermoelectric generator heat exchanger. When a muffler is used in two ways, the inner structure should be proper a noise absorber as well as an effective heat exchanger (Deng et al., 2016).

Heat exchangers have importance in order to obtain a certain temperature difference for TEGs. The thermal characteristics of the fluid passing through the cooling blocks designed to cool a surface are also among the other important parameters for heat transfer. It is quite common in the literature to increase thermal properties by using various nanofluids. It is possible to further improve the thermal characteristics by applying a magnetic electric field in liquid metal flows as the working fluid. It has been stated that the increase in magnetic and electrical fields also increases the cooling process (Selimli et al., 2018). Yayla et al. have benefited from the vibrations occurring in the piezoelectric material for the alternative electricity generation method. They evaluated different vortex generator designs in the water channel in terms of turbulence kinetic energy generation as both experimental and numerical (Yayla et. al., 2020).

In this study, exhaust waste heat recovery is purposed with a TEG heat exchanger. A hexagonal aluminum exchanger model was used and the performance on the exhaust pipeline of a diesel internal combustion engine (ICE) was experimentally investigated. The temperature of TEG surfaces was investigated numerically via ANSYS FLUENT by adding the inner deflector to the center of the empty heat exchanger model. Also, the empty model was investigated on CFD, and it was compared the changing of surface temperature for three cases (Experimental, empty model numerical, and deflector model numerical). It was simulated at the engine maximum working conditions in all analysis.

2. Materials and Methods

The heat exchanger for Thermoelectric Generator is located on a diesel engine exhaust pipe. Hot and cold sides of TEG modules have touched to waste gas heat source and fluid flow cooling block heat sink (Temizer, 2014). Figure 1 shows an aluminum heat exchanger model designed to use in the study (D_1=50 mm, D_2=97 mm, L_1=230 mm, L_2=510 mm). The hexagonal heat exchanger is made of aluminum with 2 mm thickness. For cold sides, cooling blocks are designed as 1.2 mm wall thickness copper rectangular tube. Cooling blocks should be fit and covered all TEG groups on surfaces (Topalcı, 2017).

Thermoelectric Generator modules convert directly heat into electricity. Commercial modules usually are made of some semiconductor special materials placed between two porcelain plates as shown in Fig. 2a. Porcelain is both

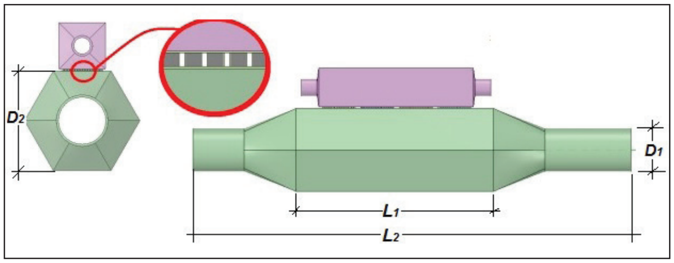

Figure 1. Heat exchanger model.

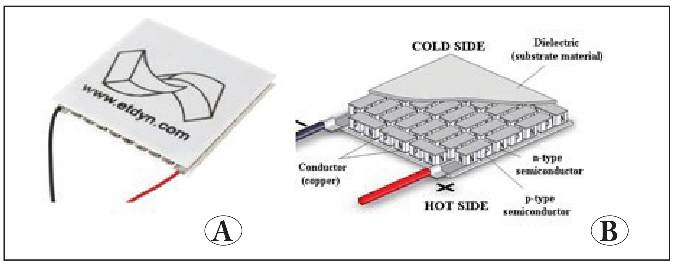

Figure 2. A) TEG module, **B)** TEG inner parts.

electrically and thermally non-conductive material. Two type p and n semiconductors (pellets) are inside of TEG. Pellets are connected electrically serial and thermally parallel. Fig. 2b. shows thermoelectric bridges (P-N), which should be made of a material with a high Seebeck coefficient, high electrical conductivity, and low thermal conductivity. Copper is used as due to effective conductivity between pellets. The thermoelectric module used for the experiments is made of Bi2Te3 semiconductor alloys. TEG modules produce continuously DC voltage due to the temperature difference across the heat exchanger (Orr et al., 2017).

The hexagonal exhaust pipe was placed to the nearest of the engine exhaust line for the highest temperature. In addition, the exhaust pipe between the engine and the heat exchanger was isolated to prevent the heat loss to improve TEG performance (Kim et al., 2018). Cooling system: pure water and ethylene glycol-water mixture passing through the copper blocks is cooled with a radiator fan set, same as on conventional internal combustion engine cooling system. TEG can produce electricity directly due to temperature difference ΔT with the Seebeck effect. Voltage can be calculated with Eq.2. V_{oc} shows open-circuit voltage, a_{pn} shows Seebeck coefficients difference n-p pairs of modules. Power (P_{elec}) can be calculated with Eq.3. I shows current, R_L shows load resistance (Lin, and Kiflemariam, 2019). Equations 3 and 4 are expressions representing the conversion of heat to electrical power. Max. Power generation of TEG is related to ΔT but ZT value is an important parameter determining the limited capacity of the module (Korotkov et al., 2017).

$$V_{OC} = a_{pn} \Delta T \quad (2)$$

$$P_{elec} = I^2 R_L \quad (3)$$

$$P_{elec} = P_{Heat} \eta \quad (4)$$

$$\eta = \frac{\Delta T}{T_h} \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+(T_c/T_h)} \quad (5)$$

2.1. Experimental study

The experiments were carried out by increasing the engine speed gradually, in four steps. The single-cylinder diesel engine was operated without load during all test stages. The exhaust gas temperature cannot be expected to be too high because a light diesel engine was used in the experiment. So, before a heat exchanger design, it was measured gas temperatures across the exhaust streamline. When the engine was worked without load maximum speed point, the exhaust gas pipe surface temperature was between 463-478 K. The European Thermodynamics company's GM250-127-14-10 TEG model was selected for high efficiency at low temperatures (Liu et al., 2014). TEG model parameters for the ideal maximum working condition can be seen in Table 1.

Table 1. GM250-127-14-10 TEG module parameters.

Parameters for hot side temp 523 K and cold side temp 303 K	
Matched load output power	9.9W
Matched load resistance	2.49Ω ± 15%
Open circuit voltage	9.93V
Matched load output	2A
Matched load output voltage	4.96V
Heat flow through the module	~198W
Maximum compress (non-destructive)	1.2MPa
Maximum operation temperature	Hot side ~523 K, Cold side ~448 K

During the experiment, temperatures were measured with k type thermocouples at inlet-outlet; for exhaust gas, cooling block surface, and exchanger surface. Also, the cooling fluid temperature was measured with an infrared thermometer. The engine speeds were recorded on the first experiments at four steps and these values were settled for the next repeats. In each step, the flow rate of the fluid passing through the coolant copper blocks was set at 1.5 l/min with an equal flow distributor. Fuel consumption was measured with a flow meter and determined mass flows. Electricity production values in the unit of Ampere, Volt were measured with a multimeter and recorded at engine speeds 1058 rpm, 1320 rpm, 1637 rpm, and 1929 rpm. The experimental system is shown in Fig. 3.

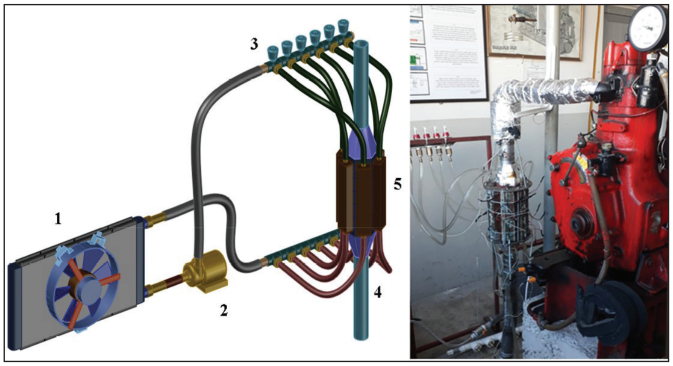

Figure 3. Experimental system, 1- radiator, 2- pump, 3- adjustable flow collector, 4- exhaust line, 5- cooling blocks.

2.2. Numerical Modelling

CFD approach was preferred to investigate the performance effect when the changed inner structure of the heat exchanger as seen in Fig. 4. The inner deflector was placed to the center of the heat exchanger model to increase surface temperature and it was investigated the effects of different deflector models via ANSYS FLUENT (Nozariasbmarz et al., 2019).

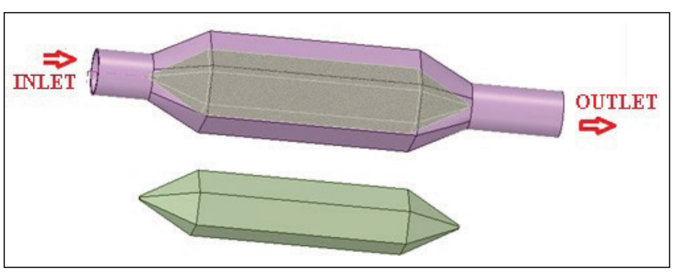

Figure 4. Heat exchanger deflector model.

Boundary conditions; the inlet flow was chosen as mass flow inlet 4.27 g/s measured at maximum experimental engine speed 1929 rpm. It was chosen carbon-oxide-nitride as exhaust gas in FLUENT. All outer surfaces exposed to air are subject to free heat convection with a free heat transfer coefficient taken as 10W/m^{2}K (Li et al. 2016). Also the standard κ–ε model and turbulent flow was chosen (Ravi et al., 2017). Pressure-based solution method was used in the analyzes. Other boundary conditions can be seen in Table 2.

Table 2. CFD boundary conditions

Boundary condition	Parameters
Inlet mass flow	4.27 g/s
Inlet temperature	504 K
Outer temperature	290 K
Heat transfer coefficient	10 W/m^{2}K
Turbulence intensity	10%

The model created for numerical analysis was analyzed in 5 different mesh numbers and the independence of the results was evaluated. The mesh independence study is given in Table 3. The average skewness value of the created mesh structures was determined as approximately 0.18, and the element quality value was determined as 0.48. The fact that the Skewness ideal value is close to 0 and the element quality ideal value is close to 1 does not pose a problem in terms of convergence. The mesh detail view of the model is given in Fig. 5. A special layer was applied to capture the boundary layer behavior of the flow.

Table 3. Mesh independence study

Analysis No.	Number of Nodes	Number of Elements	CFD Surface Temp. (K)
1	337504	305982	427
2	343143	311500	428
3	533352	487812	427.9
4	847666	726480	428
5	1648818	1449018	428

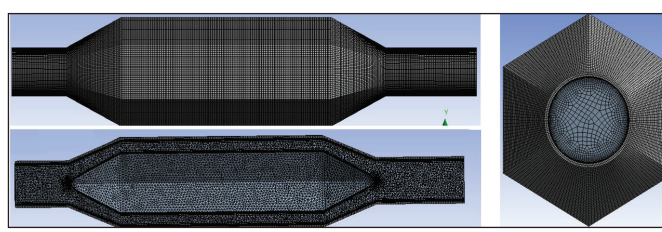

Figure 5. Mesh detail view.

3. Results and Discussion

For the first step, when used pure water as cooling fluid, the engine was run at 1058 rpm without load. In this case, the exhaust heat exchanger hot surface average temperature was 349 K, then engine speed was gradually increased. The maximum hot surface average temperature was measured as 419 K, and engine speed was measured as 1928 rpm. For maximum engine speed, 25V open-circuit voltage was produced and 10.298 W Power was obtained. Temperatures at all experimental steps can be seen in Fig. 6, and power values at experimental steps can be seen in Fig. 7.

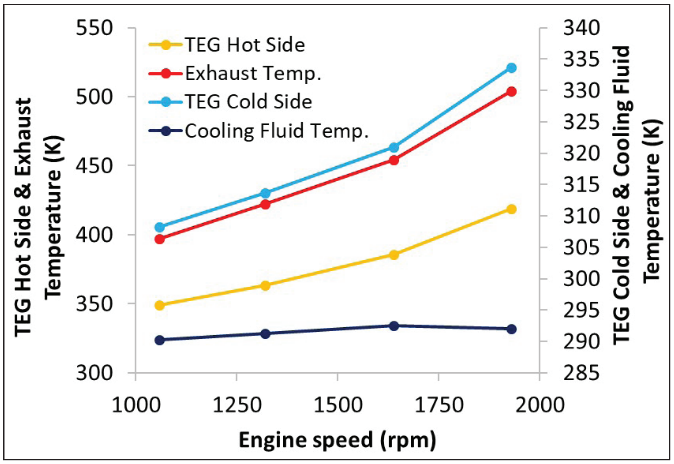

Figure 6. Temperatures at all experimental steps.

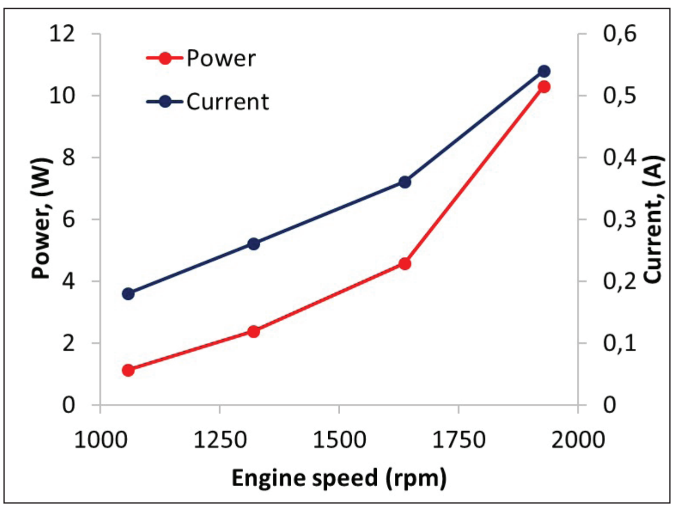

Figure 7. Experimental power.

The experimental setup was tested one more time at the same engine speeds under no-load with ethylene glycol-water mixture. The maximum hot surface average temperature was measured as 417 K, and engine speed was measured as 1928 rpm. Also at this operating conditions, 25.1 V open-circuit-voltage and 10.6 W power was produced.

The heat exchanger model inlet gas temperature was chosen as the highest temperature 504 K obtained from experiments for CFD analysis. For the heat exchanger with the inner deflector model and empty model, the changing of surface temperature was compared to each other and experimental results. When the numerical results and the experimental results are compared; at the experimental results, the highest temperature value was recorded as 437 K for the inlet surface of the hexagonal heat exchanger. As a result of the analysis, the inlet temperature of 427.1 K was reached on the surface. A deviation value of 9.9 K was reached. It can be seen temperature analysis for the empty model and with the deflector model in Figure 8.

The deflector model was placed at the center of the hexagonal heat exchanger and maximum surface temperature was measured as 439 K. In the analysis performed, the average highest measured temperature value has increased by about 11.9 K compared to the empty model. It is shown in Fig. 8 (b) the change of temperature across the exchanger surface.

A vortex pattern was observed at the result of empty heat exchanger model flow analysis but the heat exchanger deflector model flow was smooth at the same flow condition. The model with inner structure and empty model can be seen in Fig. 9. In all cases inlet surface temperatures are shown in Fig. 10.

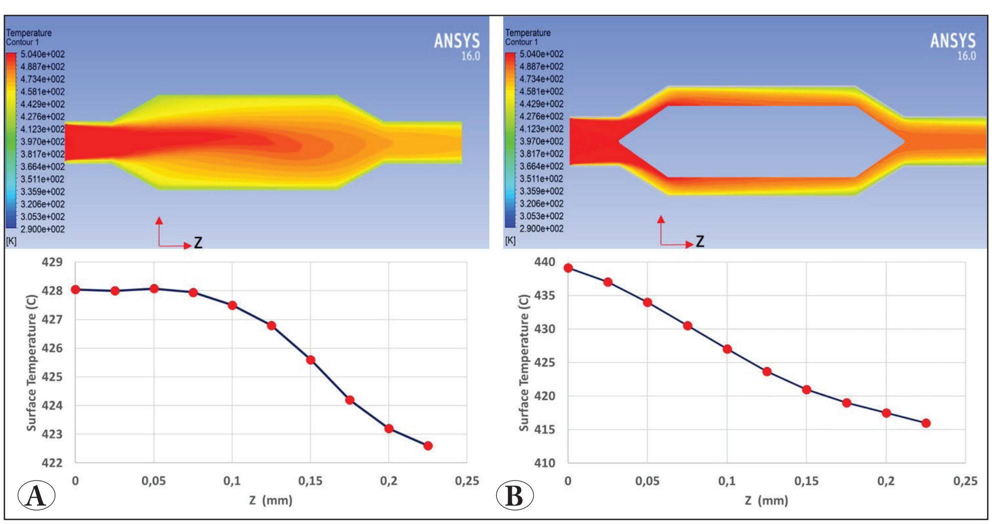

Figure 8. Temperature contour and surface temperature change for **(A)** empty model, **(B)** model with deflector.

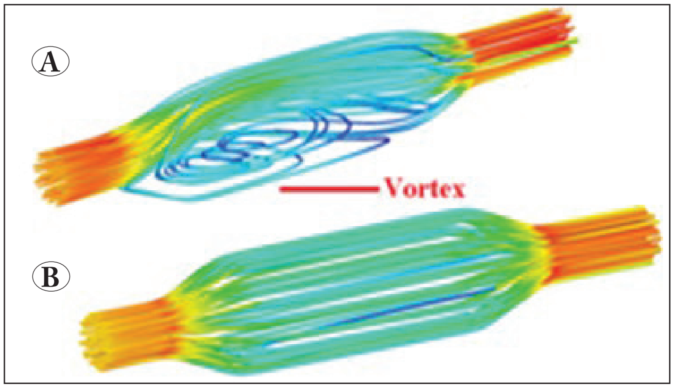

Figure 9. Streamlines for **A)** empty model, **B)** deflector model.

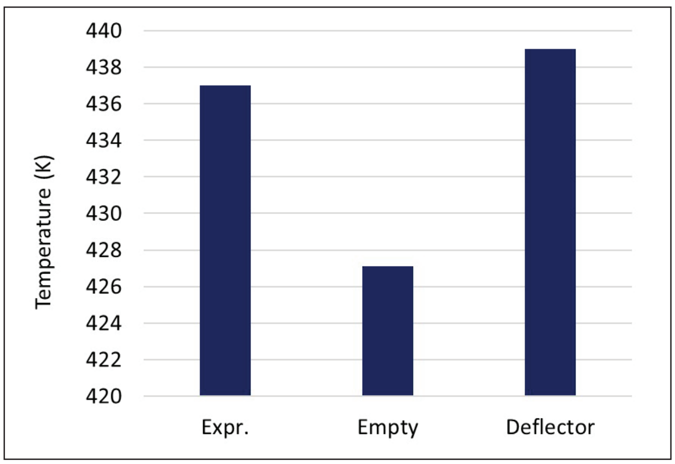

Figure 10. Inlet surface temperatures.

The difference of this study compared to other studies is that a 10.678W power increase was obtained by performing an experimental study at real temperature (437 K) and number of revolutions (1929 rpm) in a single cylinder tractor engine. In addition, it has been calculated that this increase can be increased by 3.3% by performing CFD analysis with different geometries. In other studies, generally, 1800-3000 number of revolutions and 350-400 K temperatures have been carried out, and 5-17 W power values have been obtained.

4. Conclusions

This study examines the efficiency of electricity generation using a heat exchanger and TEG modules on the exhaust line of a light diesel engine. At the same time, different models of the heat exchanger designed for the exhaust line were investigated to understand surface temperature change by using the CFD approach. When compared this study with other studies, it has been observed that as engine speed and inlet fluid temperature increases, the obtained power value increases, that is, it shows a similar trend. In order to increase these power values, even more, more fluid must contact the exhaust surface. Further power increases can be achieved by designing different exhaust geometries that direct the fluid towards the surface. Also, it can be alternative methods changing the inner structure of the heat exchanger, model with fins and baffle plates are worth further investigation. In addition, Waste heat recovery is considered to be one of the best solutions for energy efficiency because it can improve energy efficiency by converting heat exhausted from plants and machinery to electric power. This technology would also prevent atmospheric temperature increases caused by waste heat, and decrease fossil fuel consumption by recovering heat energy, thus also reducing CO2 emissions.

5. Acknowledgments

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