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Analytical and Numerical Approach for Performance Evaluation of Thermoelectric Generator

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Abstract

Growing demands in energy requirement need more efficient methods to recover waste energy from various energy conversion systems, among them generator set (Genset) run by diesel engines in construction and mining areas are commonly used to generate electrical energy and usually these systems work at an efficiency of around 30-35 %. A large part of energy loss in these systems is resulted from heat carried away by coolant and exhaust gases. The energy lost in the form of heat in the exhaust can be harvested using various heat recovery methods like Thermoelectric Generators [TEG]. Thermoelectric generators are used to convert thermal energy into electrical energy governed by the principle of Seebeck effect. Present work draws attention towards external factors that influence the output voltage of thermoelectric generators attached to a stationary waste heat source like Gensets. Here thermoelectric generator units were modelled by attaching them to the exhaust manifold of pipe of a diesel Genset and were analyzed both analytically and numerically to obtain their dependence of output voltage on thermal conductivity of exhaust pipe material, where TEGs can be mounted. From the analysis of obtained report it was observed that efficiency of waste heat recovery improved on using higher thermal conductive materials. In this preliminary analysis, an increase in thermal conductivity of 20% has resulted in an increase in power output of 11%.

Keywords: *Thermoelectric Generator, Thermal Conductivity, Waste Heat Recovery*

1.0 Introduction

The energy crisis has been a concern in modern times due to the growing demand of energy requirement. According to the 2018-2019 World energy outlook, nearly one billion people still have no access to electricity[1]. Also, burning fossil fuels will lead to increase of greenhouse gas emissions every year. Predictions suggest that energy demand would continue to grow at a rate of 1.3% every year[1] which will further increase emissions. To tackle this situation, there is a need to increase the use of renewable resources.

Further, apart from various renewable energy sources, a large fraction of heat in the exhaust gases is produced from small stationary Generators, Boilers, Kilns, Ovens, Furnaces etc. If a significant fraction of this waste heat is recovered, a reasonable amount of burning primary fuel could be saved. In this regard, Thermoelectric Energy Generation is one of the promising methods to generate energy from waste heat[2]. These thermoelectric energy systems work based on the principle of Seebeck effect which is the phenomena of direct conversion of heat energy to electrical energy. The literature review on thermoelectric energy has advocated being reliable, has

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low energy generation cost, and is one among the efficient ways to provide off-grid energy solutions[3].

A large proportion of greenhouse gas in the exhaust along with other pollutants can be attributed to diesel generators[4]. These constituents of a diesel engine coupled with an electric generator used for the generation of electricity in places that are off-grid specially construction and mining areas are of major concern. Typically, the efficiency of a diesel generator ranges between 30-35 %[5]. The significant energy loss is due to heat carried away by the coolant for the safe working of the engine. This energy loss can be harvested using waste heat recovery methods by use of a thermoelectric generator. This generator uses a group of Peltier Modules to convert heat energy into electrical energy using the Seebeck effect. Thermoelectric Generators being stationary provide an easy way of up-gradation on the diesel generators as space or dynamic constraints are not in place. The Indian diesel generator market estimated to be worth $1,039.7 million in 2018, is expected to reach $1518.1 millionby 2024[6]. The commonly used materials for manufacturing thermoelectric generators are bismuth telluride, lead telluride, silicon germanium.

A Peltier device is an active heat pump which transfers heat from one side to another by consuming electricity, correspondingly by maintaining a temperature difference between the two sides, electricity can be generated. Electric energy generation in Peltier Module takes place using the Seebeck effect. In this effect, the voltage generated is directly proportional to the temperature difference between the hot and cold side of the Peltier Module.

By improving the thermal conductivity of contact points at the hot and cold sides a higher interface temperature can be obtained. This increase in interface temperature would result in a greater temperature differential at the junction, resulting in a higher electrical output as shown in Figure 1. Seebeck observed the flow of electricity when the temperature gradient was maintained at a junction of two dissimilar metals, connected at two places[9]. Initially the electrical output was not suitable for power generation as shown in Figure 2, but with the discovery of semiconductors, the output can be magnified to use for practical applications.

Designing of TEG system for effective heat recovery from generator exhaust, depends on maximum temperature difference across the TEG and designing the effective heat exchangers that will have significant heat transfer with minimum losses. Therefore, the present study aims at increasing the temperature difference across the TEG, by employing different thermal conductivity materials to improve TEG Performance[16]. Also, the work aims to carryout analytical and numerical analysis to find output voltage of the thermoelectric generator using various heat exchanger materials having varied range of thermal conductivities and to determine percentage improvement in the thermoelectric generator efficiency with different thermal conductivity.

2.0 Methodology

2.1 Analytical Calculations using Energy Relations

The hot side of TEG gains heat from the waste heat of a diesel generator, the cold side rejects heat to environment[11]. The relation between these operating at hot side temperature T_H and cold side temperature T_C can be obtained by applying energy balance equations given below[10]. Here T_H is taken practically from the engine genset. Therefore, initially the power generated, and

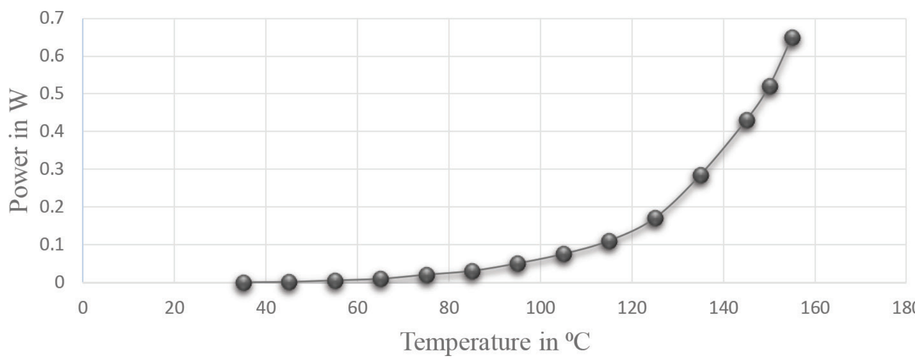

Figure 1. Variation of power output with temperature for thermoelectric generator.

efficiency was obtained analytically and then results of analytical and CFD results were compared.

$$Q_c = 2na_{teg}\alpha_{teg}\mathrm{T}_h I + 2n\frac{\alpha_{teg}k_{teg}}{I_{teg}}(T_h - T_c) + \frac{1}{2}\mathrm{I}^2 \times 2n\frac{r_{teg}I_{teg}}{A_{teg}} \quad (1)$$

$$Q_c = 2na_{teg}\alpha_{teg}\mathrm{T}_h I + 2n\frac{\alpha_{teg}k_{teg}}{I_{teg}}(T_h - T_c) + \frac{1}{2}\mathrm{I}^2 \times 2n\frac{r_{teg}I_{teg}}{A_{teg}} \quad (2)$$

The power output from a thermoelectric generator based on and can be written as

$$\mathrm{p}=\mathrm{Q}_h - \mathrm{Q}_c = \alpha_{teg} I(T_h - T_c) - I^2 \mathrm{r}_{teg} \quad (3)$$

When the current is zero, that is during open circuit condition, the voltage is

$$\mathrm{U}=\alpha_{teg}(T_h - T_c) \quad (4)$$

The maximum power output of a single TEG module is given by.

$$\mathrm{P}_{\max} = \frac{(\Delta T\alpha_{teg})^2}{4R_L} \quad (5)$$

Thermal energy conversion efficiency of TEG can be written as

$$\eta_{teg} = \frac{P}{Q_h} \quad (6)$$

2.2 Waste Heat Recovery from IC Engine Exhaust

Recovery of waste heat in IC engines can take place in the temperature limit of 400K to 1000K. Estimates show that 46 billion gallons of gasoline have been wasted in heat losses from the engines[12].

According to results published by Institute of Thermoelectricity of the National Academy of Sciences, and Ministry of Education and Sciences, Ukraine, the thermoelectric generator for a stationary diesel plant, produced extra electric power equivalent to 4.4% of the total electrical energy generated by the plant by employing TEGs[7].

Figure 3 shows the distribution of energy for a typical conventional IC engine. Nearly, around 25-38 % of energy is utilized for moving a vehicle. The efficiency further goes down for diesel generators used for producing electricity due to eddy current losses. Miscellaneous includes losses due to incomplete combustion[8].

2.3 Design Considerations of Heat Exchanger

The value of the over-all heat exchanger coefficient (UA) varies with heat exchanger geometry[13]. Efficient heat exchanger design requires increasing surface area in contact with the working fluid which also results in decreasing the thermal resistance and results in higher UA value.

Three geometries as shown in Figure 4 were studied by Esarte, *et al.* [14] and the value of UA for spiral, zigzag, and straight fins were found to be 2.07, 2.094 and 1.94 W/m$^{\circ}$C respectively. The highest UA value corresponds to Zig-Zag fins and will provide maximum maximum ΔT. Simillar experiments were conducted by Niu *et al.*,[15] for TEG at low temperature and observed that voltage linearly increases with increase in temperature difference..

Studies on differential pressure were also done by Esarte, *et al*[14]. Differential pressure (ΔP) is an important parameter to decide the amount of energy required by the pump to circulate fluid through the fins. A lower ΔP will result in a smaller pump power consumption and is always recommended. From Figure 5, the lowest value of ΔP is achieved in straight fins.

Optimum geometry while considering ΔT is obtained by using Zig-Zag fins while the least pump power consumption is obtained by straight fins. TEG should be designed by selecting the choice pair depending on operating conditions.

3.0 Proposed Design of TEG

The apparatus required for proposed TEG setup for Diesel Genset was aluminum heat sinks, copper plates, aluminum plates, stainless steel plates, thermal paste, Peltier modules as shown in Figure 6 and Figure 7.

During the experiments, measurement of parameters like output voltage generated by the thermoelectric

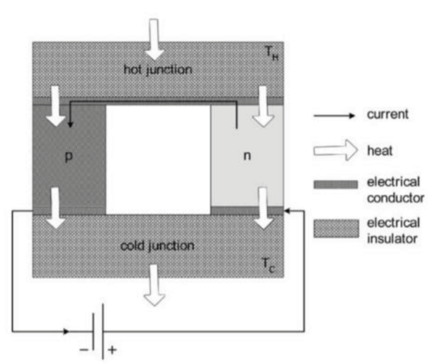

Figure 2. Thermoelectric couple schematic.

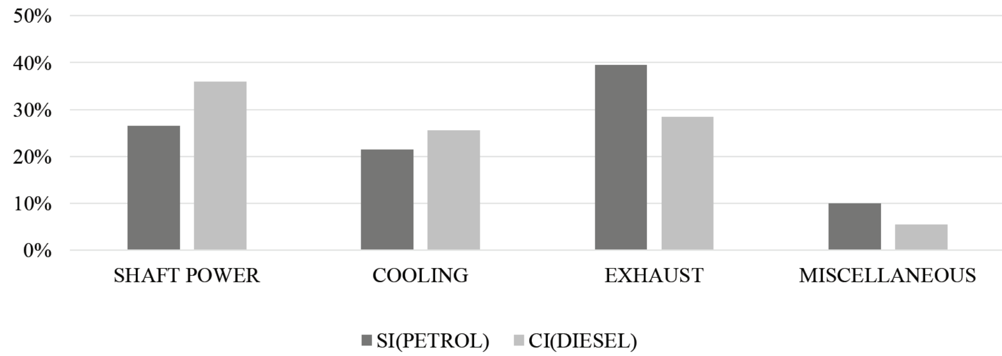

Figure 3. Waste energy in IC engines.

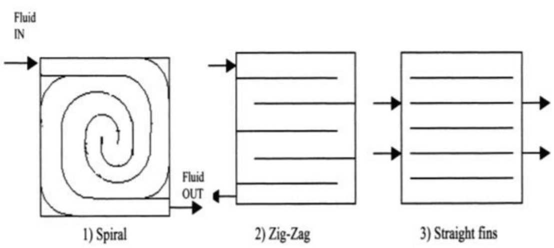

Figure 4. Heat exchanger design.

generator, the temperature of the hot and cold side of the thermoelectric generator has to be taken for different cases which involves a change of contact plates of the TEG.

4.0 Working of Proposed TEG Model

The proposed TEG model is operated by first switching on power supply, thereby forcing air through the fan at ambient temperature into the duct. The heater is switched on subsequently and as the air flows through the heater, heat transfer takes place from air to the heat sink at the hot side. Heat from the cold side of TEG is dissipated to the air which is at ambient temperature flowing over the heat sink. After the steady-state condition is reached the temperature difference is maintained constant between the two sides of TEG. The output voltage from Peltier modules is produced for given temperature differences. Variation in temperature difference can be achieved by changing the air temperature or by changing the metal contact plates. However, before conducting the experiments, the TEG system was analyzed analytically and through CFD methods to obtain initial results, which can assist in building effective TEG system for diesel genset.

5.0 Analytical Calculations

Heat transfer in the proposed design will occur by both convection and conduction and the schematic of it was shown in Figure 8.

For TEG module

The Seebeck coefficient can be calculated using the Fourier law of conduction[17]. The calculations are carried out considering room temperature at 27°C.

$$\alpha_{teg} = \frac{V_{opt}\{volts\}}{T_h\{kelvin\}} \quad \alpha_{teg} = \frac{16}{27+273} = 53mV/K \tag{1}$$

Determine the maximum performance of zero temperature difference . The electrical resistance is given by

$$R_0 = \frac{V_{opt}^{\ 2}}{2Q_c} = \frac{16^2}{2\times 61} = 2.1\Omega \tag{2}$$

To obtain the Quality factor for the maximum T value that is 70°C (from the graph)

$$X = R_q / R_0 \quad \frac{R_q}{R_0} = 2\frac{\Delta T}{V_{opt}^{\ 2}\times\left(1-\Delta T/T_h\right)^2} \tag{3}$$

$$\frac{R_q}{R_0} = 2\frac{70}{16^2\times\left(1-70/300\right)^2} = 0.93$$

The value of thermal resistance can be calculated using.

$$R_q = R_0 \times X$$

$$R_q = 2.10\times 0.94 = 1.97°K/W \tag{4}$$

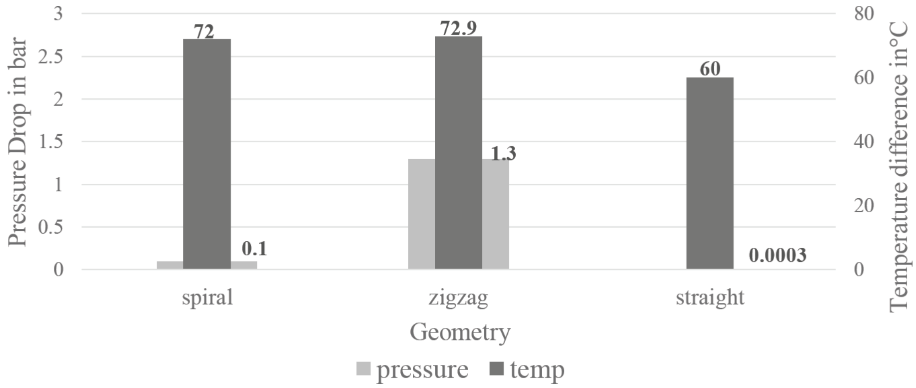

Figure 5. ΔT and ΔP vs flow geometry.

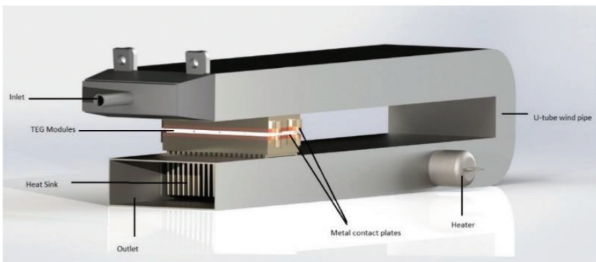

Figure 6. 3-D view of the proposed design of TEG.

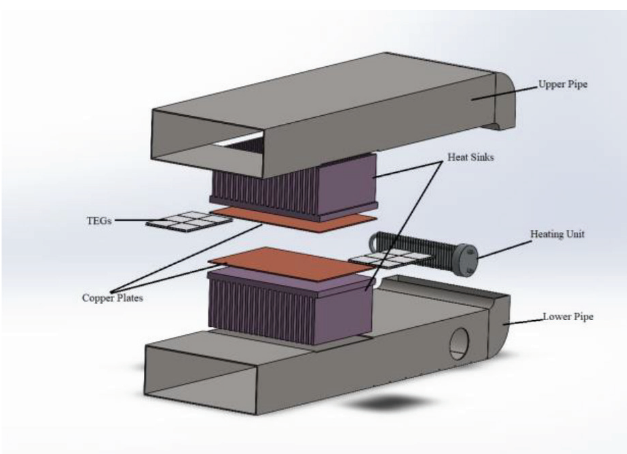

Figure 7. Exploded view of the proposed TEG model.

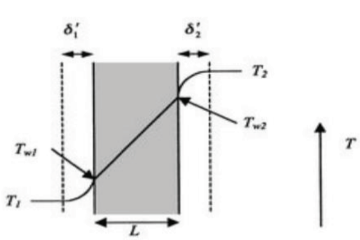

Figure 8. Conducting wall with convective heat transfer.

Thus, parameters of the Peltier module considered are.

- Seebeck coefficient - $54\text{mV}/\text{K}$
- Electrical resistivity - 2.10Ω
- Thermal resistivity - $1.97°\text{K}/\text{W}$

classical quality factor calculation,

$$Z=\frac{R_q}{R_0}\times\alpha_{teg}{}^2 \tag{5}$$

Example: $Z=0.93\times\left(53\times10^{-3}\right)^2$

$$=2.6\times10^{-3}/\text{K}$$

And $Z\bar{T}$

$$Z\bar{T}=2.6\times10^{-3}\times\frac{300+(300-70)}{2}=0.69$$

Figure $Z\bar{T}$ expresses the efficiency of thermoelectric generator material.

Maximum Efficiency of a thermoelectric module can be calculated by

$$\eta_{\max}=\frac{\Delta T}{T_h}\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+T_c/T_h} \tag{6}$$

Heat transfer co-efficient, h_c, can be calculated by using fundamental equation s of conduction.

$$\text{Nu}=0.23\ \text{Re}^{0.8}\text{Pr}^{0.4} \tag{7}$$

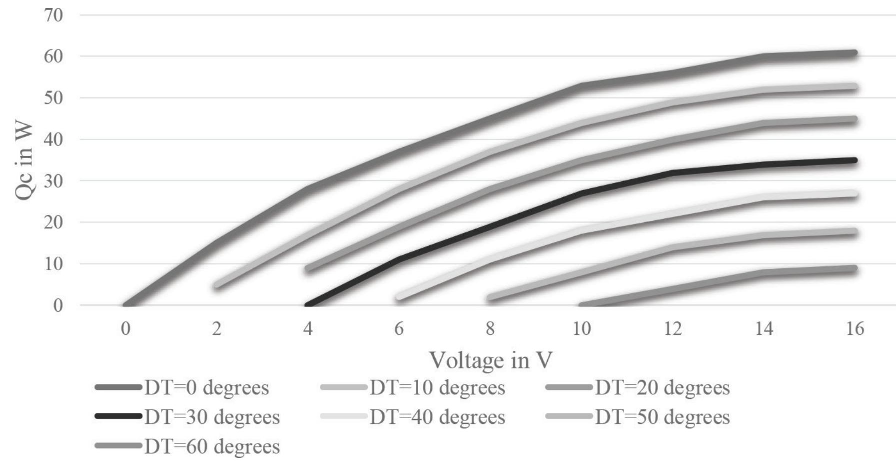

Figure 9. Standard performance graph V = f(ΔT). = 27°C (From Dymytrov, *et al*[18]).

$$Q_x = -k_x A_c \frac{dT}{dx} \text{ (Fourier's law)} \tag{8}$$

Heat is conducted through the fin element.

$$Q_x = Q_{x+dx} + Q_{convected} \tag{9}$$

$$Q_x = Q_x + \frac{\partial}{\partial x} Q_x dx + h_c A_{conv} (T - T_\infty) \tag{10}$$

$$0 = \frac{\partial}{\partial x}\left(-k_x A_c \frac{dT}{dx}\right) dx + h_c P dx (T - T_\infty) \tag{11}$$

Assuming k is constant

$$\frac{d^2 t}{dx^2} - \frac{h_c P}{k_x A_c}(T - T_\infty) = 0 \tag{12}$$

Put $(T - T_\infty) = \theta$, then

$$\frac{dT}{dx} = \frac{d\theta}{dx} \text{ and } \frac{d^2 t}{dx^2} = \frac{d^2\theta}{dx^2} \tag{13}$$

Put $\frac{h_c P}{k_x A_c} = m^2$, then

$$\frac{d^2\theta}{dx^2} - m^2\theta = 0 \tag{14}$$

This is in a standard second-order differential format equation, its general solution can be written as,

$$\theta = C_1 e^{-mx} + C_2 e^{mx} \tag{15}$$

Here C_1 and C_2 values are calculated by applying boundary conditions.

Now, to calculate the heat transfer through the aluminum base plate and the metal contact plate,

$$R = \frac{1}{A}\left[\frac{L_1}{k_x} + \frac{L_2}{k_2}\right] \tag{16}$$

$$Q_1 = \frac{\Delta T}{R} \tag{17}$$

The total heat transferred is given by

$$Q_h = Q_1 + Q_x \tag{18}$$

For this experiment, the properties of the thermoelectric module are calculated above

The Voltage generated by the couple is given by

$$V = \alpha_{teg} \times \Delta T \text{ (Seebeck Effect)} \tag{19}$$

$\Delta T = T_h - T_c$, this value varies for every metal contact plate used due to the different thermal conductivities.

The current through the load is:

$$I = \frac{\alpha_{teg}\Delta T}{R_0 + R_1} \tag{20}$$

Total Heat input to the couple (Q_h) is:

$$Q_h = (R_0 T_h I) - (0.5 I^2 R_c) + (K_q \Delta T) \tag{21}$$

$$K_q = \frac{1}{R_q} \tag{22}$$

The efficiency of the generator (η_{teg}) is:

$$\eta_{teg} = \frac{VI}{Q_h} \tag{23}$$

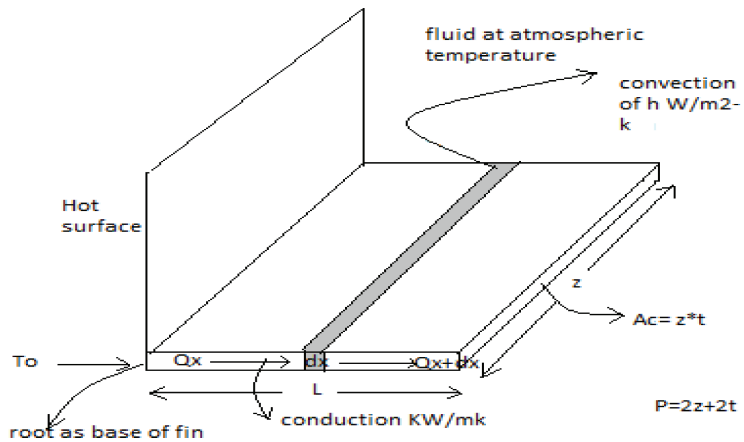

Figure 10. Rectangular fin.

Table 1. Results obtained for 21 CFM flow at 0.6145m/s laminar flow in fluent

Plate Material	Hot Side Tempearture, (°C)	Cold side Temperature (°C)	Output Voltage (V)	Output current (A)	Net Power Output (10 TEGs) (W)
Brass	129.19	25	5.522	2.629	145.20
Copper	134.53	25	5.805	2.764	160.46
Silver	136.9	25	5.9307	2.824	167.49

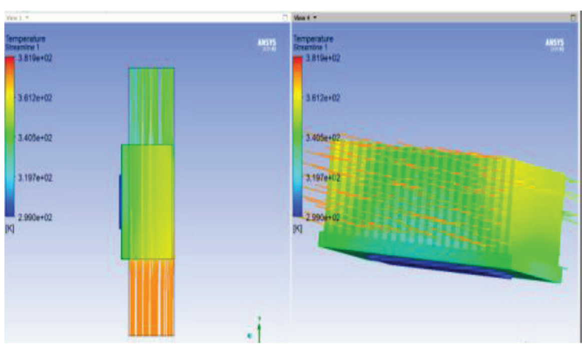

Figure 11. CFD Image in ANSYS Fluent for 21 CFM. Fluent Solver was used in finding the input and output heat from the pipe to calculate the heat absorbed by the fins.

6.0 CFD Analysis for TEG

Computer simulations performed with ANSYS to obtain heat absorbed by the fins. The surface temperatures using this heat absorbed were obtained from CFD analysis as shown in Figure 11 and Figure 12, which was used to find the power output from the thermoelectric generator.

From the analysis of the TEG, efficiency of waste heat recovery improved on using higher thermal conductivity materials. In this preliminary analysis, an increase in thermal conductivity by 20% has resulted in an increase in power output by 11% as it is evident from Table 2.

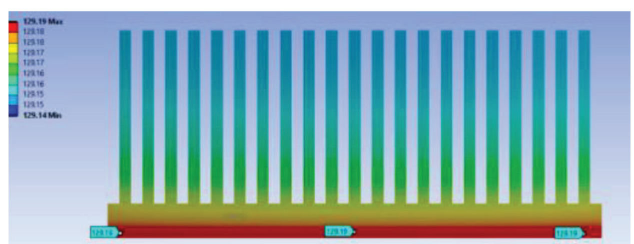

Figure 12. Steady-State analysis performed in ANSYS Workbench. The analysis is done to determine surface temperatures for different plate materials.

Table 2. Surface temperature of a few metals

Plate Material	Inlet Heat(W)	Outlet Heat(W)	Net Heat Absorbed (W)	Temperature at Surface (°C)
Brass	952.87	565.80 W	387.07	129.19
Copper	952.87	550.49 W	407.38	134.53
Silver	952.87	545.52 W	412.35	

7.0 Conclusions

A considerable fraction of heat energy loss carried away by coolant and exhaust gas in IC engine driven genset can be recovered from TEGs. The present work is a small effort to find the role of external factors affecting the performance of TEG. Among various external factors thermal conductivity of the contact material with TEG plays a significant role in waste heat recovery from it. In this regard following conclusions can be drawn from the present work:

- The performance of TEG can be significantly enhanced by using higher thermal conductivity materials along with the best heat exchanger designs.
- The simulation and analysis showed that with 20% in thermal conductivity there was about 11% increase in the output power with the help of TEG.

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Nomenclature:

α_{teg}	Seebeck coefficient of TEG
k	Thermal conductivity of wall
Q	Heat transfer through the wall
Q_c	The maximum performance for zero temperature difference
Q_h	Total heat transfer through one side of the TEG module
η_{teg}	Net efficiency of the complete TEG system
η	Air Kinematic viscosity, m^2/s
R_L	External load of circuit, Ω
R_0	Electric resistance in Ω
R_q	Thermal resistance of TEG
Re	Reynolds number
v	Velocity of air, m/s
Z	Classical Quality-factor
r_{teg}	Electrical resistivity of a P or N leg, Ω m
Pr	Prandtl number
Re	Reynolds number
R	Thermal resistance through the plates
Nu	Nusselt number