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Thermo-Electric Generator Design for Energy Harvesting From Exhaust Gases

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Abstract

Numerous campaigns on environmental and carbon emission issues has been going on for more than decades while researchers have lot of breakthrough to decrease carbon emission by enhancing the internal combustion engine of an automobile, however, none of this prove to decrease carbon emission due to major fact that the number of vehicles are increasing on daily basis. Therefore, this work provides a comprehensive review, design and development of an Enhanced Thermo-Electric Generator (ETEG) system that will generate power from the waste heat energy generated by an internal combustion engine through the exhaust gas channel. This research work provides an enhanced structural design of the system by introducing cooling fins accompanied with cooling fans on the cold side of the TEG, in order to maintain the temperature at a constant level. According to the output power generated from the proposed ETEG system, it is observed that when the temperature difference between the hot side and cold side of the TEG is maximum, the output power generated from the system reaches the maximum. Thereby resulting in useful low power generation from the fuel energy wasted in exhausted gases by the internal combustion engines.

Keywords: Waste heat energy, TEG, Power generation, green house effects, heat sink and Microcontroller.

INTRODUCTION

More than decades, public sectors and scientist are campaigning on environmental and carbon emission issues, and this has brought major interest of research on internal combustion engine, waste reduction and energy utilization. However, researchers have confirmed that internal combustion engine is considered as one of the major consumption fossil fuel which led to CO2 emission. In the world where 30% to 40% of heat supplied by fuel is converted into mechanical [14] while remaining heat energy is expelled through exhaust gas pipe to the environment resulting to serious environmental pollution claim to continue damaging our earth according to climate change campaign resolution. Therefore, reduction of waste heat requires utilization for useful work, the utilization and recovery of waste heat will not only reduce environmental pollution but would also conserve fuel consumption and reduce the total amount of waste heat generated by combustion engine.

Many researchers have carried out a lot of successful energy conversion for efficiency, however, most limit the scope of research for the improvement of thermal efficient for combustion engine, whereas, this paper focuses on potential solution to the usage of exhaust heat resulting from internal combustion engine, exhaust gas heat recovery system and energy utilization with increase in C02 emission yet, in cost effective way [6].

The intension of this work is to provide a comprehensive review, design and development of the Thermo-Electric Generator (TEG) system to generate power from waste heat energy resulting by internal combustion engine through the exhaust gas channel. [1] This is a possible solution to recover waste using thermoelectric generator, which will convert the temperature gradient [20] into usable voltage which can be used to power other appliances, such as auxiliary system and others.

Proposed System

This research has been implemented to study about heat loss at the exhaust the automobile engine. [21] The main objective of this research is observe the waste heat energy that has been thrown to the atmosphere as waste. A prototype of the TEG system has been built and the TEGs are placed on the four sides of the Aluminum pipe line. On the top of each TEG, the Aluminum heat sink has been placed to remove the excess heat from the cold side of the TEG. To obtain the faster rate of heat from Aluminum heat sink, the cooling fans are fixed that contributes to the heat removal and maintain the temperature on the cold side equivalent to the room temperature. All the four TEGs are connected in series and connected with load. The below block diagram (Figure 1) indicates the experiment setup.

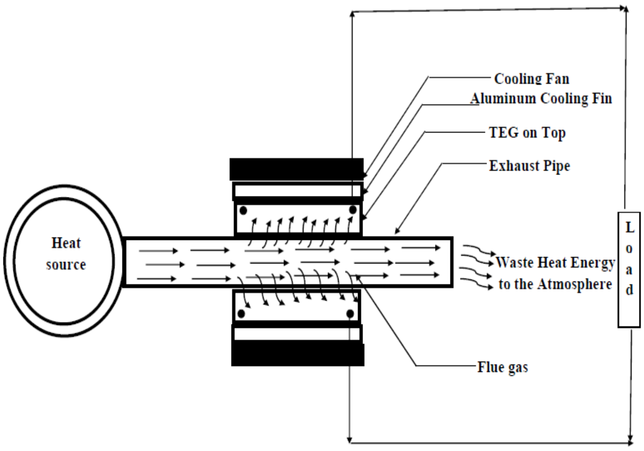

Figure 1: Block diagram of the thermoelectric generator system using heat sink and cooling fan

TEG Module

In this research Bismuth Telluride type of thermoelectric device has been used. Below is the rated power output and selected thermoelectric device dimension. [8] This device is placed in heat environment to generate a voltage output, and also to get the sum of a total voltage of two or more, which is connected in series and have the ability to withstand a continuous high temperature 260°C (500F).

Rating: Umax (V): 15.4V, Imax (A): 6A, Voltage (V): 12V, QMax (W) : 92W.

Dimensions: 40mm x 40mm x 3.6mm.

Concept Designed derived from fundamental principles

In order to analyse and perform the computational data of the voltage generator module, some parameters have to be considered, which includes the coefficient of Seebeck and the total amount of thermoelectric module coupled together, and this results to [1].

$$N = \frac{\alpha}{(Seebeck Coefficent of \sin gle thermoelectric \sin gle couple)} \quad (1)$$

Where

α: Coefficient of Seebeck of a single thermoelectric module

N: Total number couples.

Therefore, based on parameters collected from TEC1-12706 datasheet,

Coefficient of Seebeck for p-type is 270µV/K

Coefficient of Seebeck for n-type is -270µV/K (- sign mean n-type)

Seebeck Coefficient of a thermoelectric single couple

$$= 270\ \mu V/K + 270\ \mu V/K \quad (2)$$

total number of couples used as generator, it will now be necessary to compute voltage produced by overall combination of thermoelectric device forming a single voltage generator module [7]

$$V = \alpha \times \Delta T \quad (3)$$

Where V is voltage

ΔT Is the temperature difference between T-hot and T-cold

$$T_{hot} = 60^0 c + 273 = 333^0 K \quad (4)$$

$$T_{cold} = 24°C + 273 = 297K \quad (5)$$

To calculate a multiple cascade voltage of thermoelectric module

$$V_{total} = V \times n \quad (6)$$

Where

V total is the total voltage produced, V is the produced voltage from each cascade module and thermoelectric module number is N.[22] Considering a situation where device is used for charging battery, this related to ampere hour per day, that is, the rate at which the current produced is to charge a battery.

Usage hours * Current flowing to the battery (7)

Finally, output power can calculate with $Output\,power = IV$ (8)

Where I and V are the total current and total voltage produced respectively.

To calculate the total power which is coming out from the car, the temperature at certain speed with specific car must be known. [4] [5] [25] the example that has been chosen here is 1996 Dodge Caravan Sport, at speed 34mph which releases the Exhaust gas (in manifold) at a temperature of 1134°F which is used to convert from Fahrenheit to Celsius using the following formula:

$$T(°C) = (T(°F) - 32) \times 59 \quad (9)$$

The temperature of the car exhaust is 1134 which is =(612)°C and it is assumed to be T(hot) and the temperature of the outside is assumed to be 35℃ which can called as T(cold). [15] The gas constants of the CO2 "R" is 0.1889 KJoule ⁄Kg*K taken from the table of ideal gas specific heats. The following formula is to calculate the internal energy:

$$H_{(hot)} = R \times T\,(K) \tag{10}$$

To calculate the volume flow, must chose a specific engine because each model of engine has a different volume flow, so according to "Continental Motors Continued" the engine model that has been chosen is M330 engine under 2400rpm which is equal to 497cfm (cubic feet per minute) and after converting from cubic foot per minute to meter cube per second the volume flow will be equal to 0.2346 m3⁄s .According to engine "Ti-AL 605 turbo" the pressure exhausted is 144.79kpa and this pressure has been taken as the average speed which is 3500rpm cross with 21psi according to the graph of the exhaust system pressure. [17]

The specific volume is obtained using the formula,

$$V_1 = \frac{RT}{P} \tag{11}$$

Further, the mass of flow of the gas can be calculated using the volumetric of flow rate over the specific volume and the volumetric flow rate can be obtained online for a chosen type of car as, [9]

$$m = \frac{V_1}{V} \tag{12}$$

Total power can be calculated by multiplying the mass of the gas flow with the difference of temperatures as mentioned below:

$$W = [m(h_{(hot)} - h_{(cold)}] \tag{13}$$

Experimental Set up

The TEG system is set such that the four TEG modules are attached on the flat surface of each side of a 5cm x 5cm square hollow aluminium. Then, a cylindrical pipe of 5cm is inserted through the hollow square pipe as shown in Figure 2. Further compression method is used in order to compress the TEG module between the heat sink and the aluminium plate, which is done with the help of stainless steel machine screws.

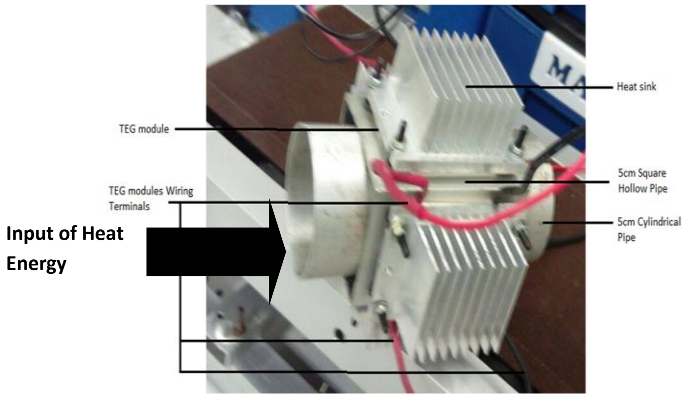

Figure 2: Experimental setup

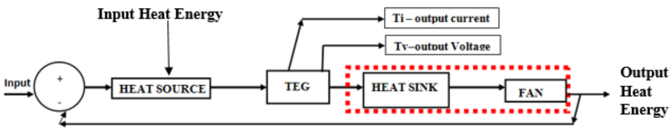

Figure 3: Block Diagram of the Experimental setup

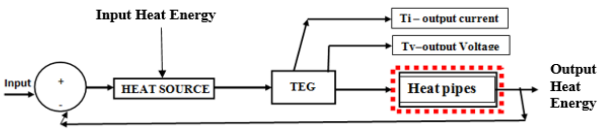

Figure 4: Block Diagram of the Experimental setup with heat pipes

The above block diagram indicates that heat pipes are used in order to reduce the power provided to the cooling fan and the excess temperature on the cold side is removed by attaching the heat pipes to it. Each TEG module has two terminals (i.e., red as positive and black as negative) as the generated power output. Figure 5 labelled each part of the TEG module.

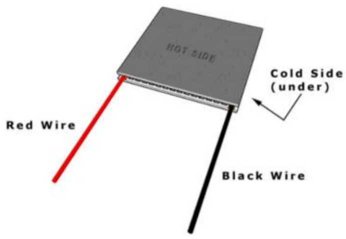

Figure 5: Fully labelled TEG module

The TEG module has two sides; one of them is the hot side. [24] Actually the hot side can deal till 300ºC (572ºF) as maximum temperature and the hot side of the TEG should connect to the heat source side to give the correct reading. The other side of the TEG module is the cold side, which can handle 60ºC (320ºF) as maximum temperature. [18] Thus, to avoid damaging the TEG module, it is important that the hot side and the cold side temperature does not exceed these limits. In addition, if the module has been reversed by changing the cold side and hot side positions, it will directly cause damage to the TEG module. [19]

Figure 6 shows the wiring diagram of the four TEG modules. [23] The four modules are connected in series to boost the overall output voltage. Then, this output is connected to a DC-DC converter to regulate the output voltage to a desired voltage for a load.

Figure 7 shows the snapshots of the constructed the final structure which consists of four TEG modules, four heat sink and four cooling FANs mounted each on the flat surface of every side of the square hollow aluminium attached with the cylindrical pipe.

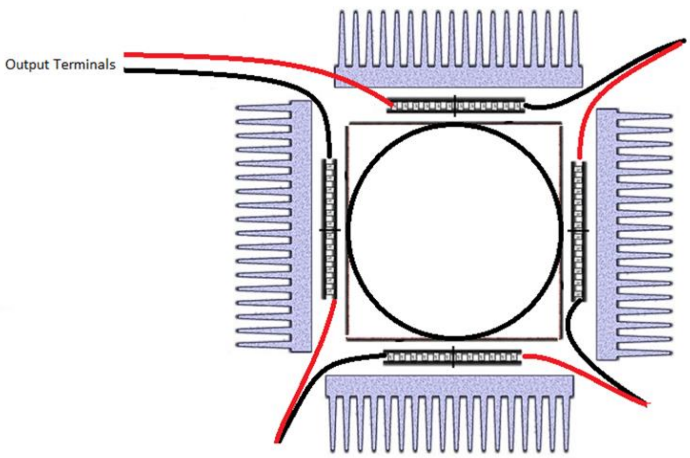

Figure 6: TEG Module Wiring

The constructed circuit consists of Arduino Nano soldered on the strip board below the LCD with the ACS712 current sensor module at the right side of the module and finally the DC-DC converter module at the upper side of the LCD. The generated voltage and current are displayed on the LCD along with the temperature.

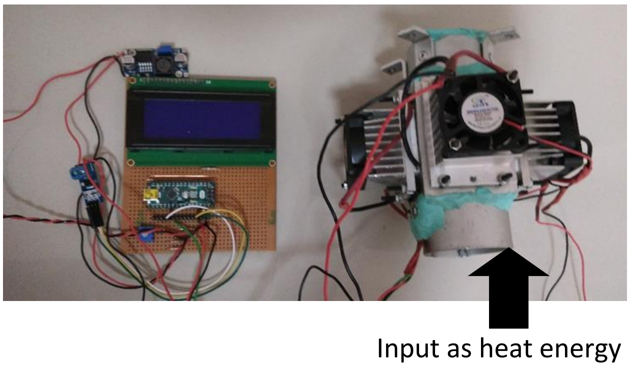

Figure 7: Snapshot of the Constructed Circuit together with the Cylindrical TEG System

Working Principle

Figure 8 presents the flowchart of the system working principle. First the system heated is applied through the cylindrical pipe. Then, the generated current and voltage together with the applied heating temperature are measured through the 10-bit analog channels 0, 1 and 2, respectively. Then, the measured value from the 10-bit analog channel ranging between 0 – 1023 are converted to the actual reading of current between 0 – 600mA, voltage between 0 – 18V and temperature between -50°C – 150°C, respectively. These converted readings are then changed to string in order to display on the LCD.

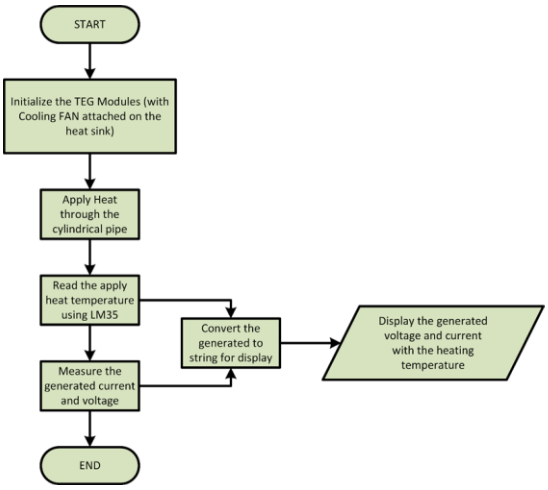

Figure 8: Flowchart of the System Working Principle.

Further the Arduino IDE v1.6.9 microcontroller is programmed using the C language, which initializes the analog channel 0, 1, and 2 as input channels for current, voltage and temperature sensors. Then, initializes the LCD control signals RS and EN using pin D13, D12 and LCD data line D4, D5, D6 and D7 using pin D11, D10, D9 and D8 of the Arduino Nano. The current, voltage and temperature sensor readings are converted using the Equations (13), (14) and (15).

$$I\_TEG = (((I_{\_sensor} - 5000)/1023) - 2500)/1000 \quad (13)$$

$$V\_TEG = (V_{\_sensor} - (5/1023)) \times 5.3 \quad (14)$$

$$T\ heating = T_{\_sensor} \times 0.48828125 \quad (15)$$

RESULTS AND DISCUSSION

Experiment setup with heat sink , without cooling fan, with cooling fan under no load condition at constant interval of temperature at every 10°C interval ranging from 40°C Figure 8 shows the graph drawn between temperature difference and voltage at no load condition with heat sink, cooling fan and without the cooling fan. It is observed that the theoretically calculated TEG $(V = \alpha \times \Delta T)$ output voltage linearly increases as the temperature difference between the hot side and the cold side of the TEG increases. Further, it is observed that the experimentally measured TEG output voltage linearly increases until 70 degree celcius of the temperature difference between the hot side and the cold side, while the TEG output voltage remains almost saturated with 3.7 v as the maximum output volatge from 80 degree celcius. The experimentally obtained result is varied slightly as compared to the theoretical result, which is due to the heat lost into the sorrounding atmosphere, during the conversion of the heat energy into power at the TEG system. Theoretical and experimental current is zero due to the no load condition.

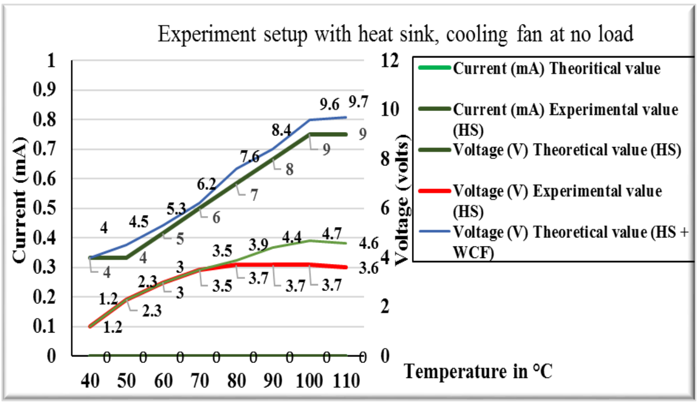

Figure 9: Graph between Temperature Vs Voltage (V) & Current (A).

Figure 9 shows the graph drawn between temperature difference and voltage under no load condition and with the cooling fan. The cooling fan is placed on the colling fins, which is done in order to remove the excess heat that contributes to the temperature at the cold side of the TEG. Thus, from the figure iIt is observed that the theoretically calculated TEG output voltage linearly increases as the temperature difference between the hot side and the cold side of the TEG increases. Further, it is observed that the experimentally measured TEG output voltage gradually increases slowly until 110 degree celcius of the temperature difference between the hot side and the cold side, and reaches a maximum output voltage of 4.7 v at 100 degree celcius. The experimentally obtained result is varied slightly as compared to the theoretical result, which is due to the heat lost into the sorrounding atmosphere, during the conversion of the heat energy into power at the TEG system. . Theoretical and experimental current is zero due to the no load condition.

Experiment setup: with heat sink and without cooling fan but DC – DC converter

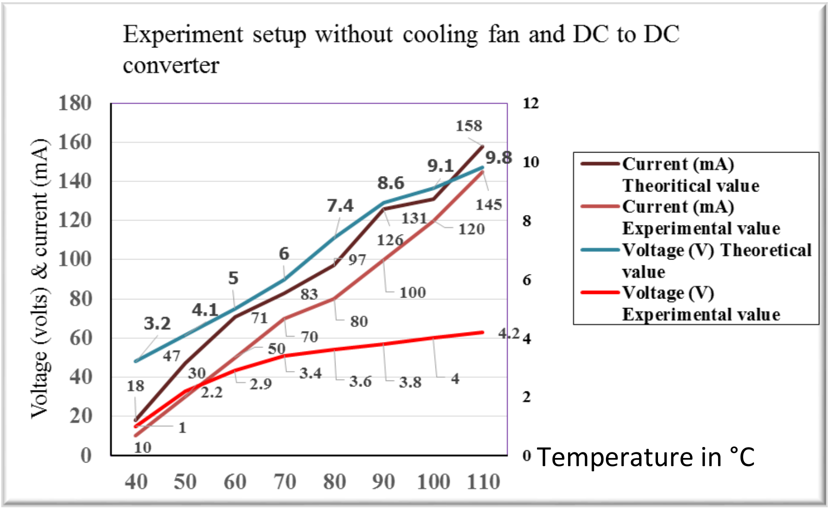

Figure 10: Graph between Temperature Vs Voltage (V) & Current (A).

Figure 10 shows the graph drawn between temperature difference and voltage with DC-DC converter in series as the load and without the cooling fan. It is observed that the theoretically calculated TEG output voltage linearly increases as the temperature difference between the hot side and the cold side of the TEG increases. Further, it is observed that the experimentally measured TEG output voltage linearly increases until 80 degree celcius of the temperature difference between the hot side and the cold side, while the TEG output voltage remains almost saturated with 3.6 v as the maximum output volatge from 80 degree celcius. The experimentally obtained result is varied slightly as compared to the theoretical result, which is due to the heat lost into the sorrounding atmosphere, during the conversion of the heat energy into power at the TEG system. Theoretical and experimental current are initially the same but deviates a bit as the temperature difference is increased from 60 degree celcius to 110 degree celcius.

Experiment setup: with heat sink, cooling fan and DC – DC converter connected under load condition

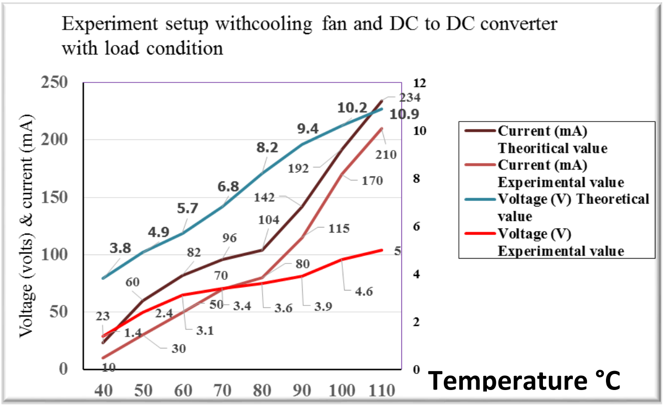

Figure 11: Graph between Temperature Vs Voltage (V) & Current (A).

The graph in Figure 10 shows the temperature difference and voltage with DC-DC Conveter connected in series as the load and with the Aluminum fins, cooling fan. The cooling fan is placed on the cooling fins, which is done in order to remove the excess heat that contributes to the temperature at the cold side of the TEG. Thus, from the figure it is observed that the theoretically calculated TEG output voltage linearly increases as the temperature difference between the hot side and the cold side of the TEG increases. Further, it is observed that the experimentally measured TEG output voltage gradually increases slowly until 110 degree celcius of the temperature difference between the hot side and the cold side, and reaches a maximum output voltage of 4.2 v at 110 degree celcius. The experimentally obtained result is varied slightly as compared to the theoretical result, which is due to the heat lost into the sorrounding atmosphere, during the conversion of the heat energy into power at the TEG system. . Theoretical and experimental current are almost follow the same as the temperature difference is increased from 40 degree celcius to 110 degree celcius.

HEAT PIPE cooling of TEG

Cooling TEG with fan is counter productive as the harvested output of TEG would be wasted in running the cooling fan. For further study a passive cooling device such as heat pipe is proposed to cool the TEG without any power consumption.[11]. A heat pipe is a closed evaporator-condenser system consisting of a sealed, hollow tube whose inside walls are lined with a capillary structure or wick. Thermodynamic working fluid, with substantial vapor pressure at the desired operating temperature, saturates the pores of the wick in a state of equilibrium between liquid and vapor.[12]

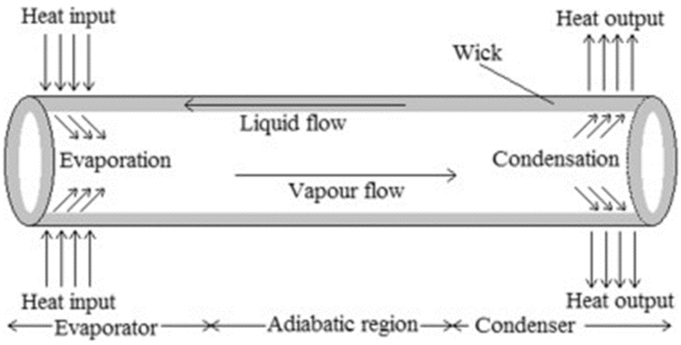

Figure 12: Fully labelled Heat Pipes module

When heat is applied to the heat pipe, the liquid in the wick heats and evaporates. As the evaporating fluid fills the heat pipe hollow center, it diffuses throughout its length. Condensation of the vapor occurs wherever the temperature is even slightly below that of the evaporation area. [13] As it condenses, the vapor gives up the heat it acquired during evaporation. This effective high thermal conductance helps maintain near constant temperatures along the entire length of the pipe. Attaching a heat sink to a portion of the heat pipe makes condensation take place at this point of heat transfer and establishes a vapor flow pattern. Capillary action within the wick returns the condensate to the evaporator (heat source) and completes the operating cycle.

The wick structure provides a path for liquid to travel from condenser to the evaporator using capillary action. [3] Wick structures have performance advantages and disadvantages depending on the desired characteristics of the heat sink design. Some structure have low capillary limits making them unsuitable for applications where they must work without gravity assist. The heat pipes are fixed on the cold surface of TEG to remove the excess heat energy travelling from hot side to cold side of TEG. The analysis on heat energy transferred by using Nano fluids as the working fluid in Heat pipes.

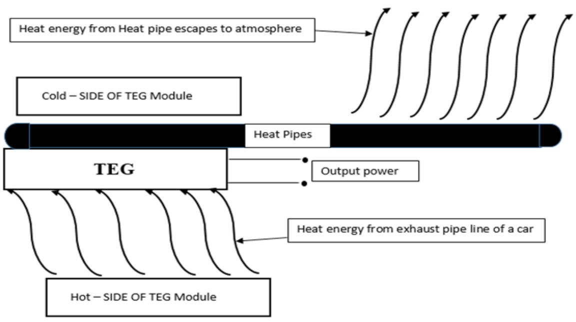

Figure 13: Assembly of TEG with Heat Pipes module

This proposed system is designed to conserve fuel consumption and utilize some part of waste heat generated by combustion engine in our society. From the literture, it is observed that the researchers have used the cooling fins to the TEG system on the cold side in order to control the temperature raise due to the power generated which is observed to be low. Hence, in order to improve this existing system, cooling fins along with the cooling fan, has been introduced to increase the output power generated and to maintain constant temperature at the cold side. Experimental results of different testing shows the performance of the proposed TEG system. The first test examines the performance of the prototype without load with cooling fan OFF. Second test examines the performance of the prototype without load but with cooling fan ON. Third test examines the performance of the prototype with load but the cooling fan is OFF. Finally, Fourth test examines the performance of the prototype with load and cooling fan ON.

The results of the first test highlight that the voltage increases linearly from 40°C to 80°C. The output voltage is maintained at 3.7V from 80°C to 100°C, then a sudden drop to 3.6 at 110°C. These results suggest that heating temperature of both heating and cooling side of the TEG modules increases at the same time. This is mainly because in this setup, the heat sink is the only cooling components at the cold side of the TEG. The results of the second test highlight that the generated voltage at the corresponding temperature. The generated voltage increases in similar to the first test, i.e., from 40°C to 70°C. While, from 80°C to 100°C the voltage increases exponentially from 3.9V to 4.7V, respectively. Then, a slight drop of voltage from 4.7V down to 4.6V at 110°C was observed. Thus, this suggests that the cooling setup has reached its maximum point and therefore not cooling anymore the results of the third test highlight that the generated voltage at the corresponding temperature. The voltage increases linearly from 0.8V to 3.6V at 40°C to 90°C, respectively. Then the voltage drops to 3.5V at 100°C and 110°C.

Results presented for the fourth test show that the current drawn by the DC-DC converter is around 10mA with 0.8V at 40°C, and 145mA with 4.52V at 110°C. As observed here, the overall performance of the system is improved as the generated voltage is 4.2V at, which is higher than the 3.6V from Test 3. Thus, this concludes that higher cooling power improves the temperature difference between the heat and cold surfaces. While the results of the last test show that the current drawn at 40°C by the DC-DC converter is 10mA at 1.4V, while at 110°C is 210mA at 5.0V. As observed here, the overall performance of the system is further improved by increasing the load. Thus, this suggests that the power efficiency can be improved by applying correct amount of load to the generated power.

Moreover, the theoretical performance of the TEG module used in this researchhas been compared with the experimental performance using the proposed system. These results are based on loadconnected at the TEG output terminals. These results highlight that the expected voltage of the SP1848 at 20°C temperature difference is 0.9V at 225mA, while the actual experimental results exhibit slightly lower. Instead, the experiment shows the generated voltage at 20°C temperature difference is 0.8V with current drawn by the load of about 190mA.

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