Analysis of Thermoelectric materials for heating applications in Automobiles

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Abstract. In today’s world with the technological advancements, all that has been considered as slags and waste can be utilized to its maximum therefore attaining sustainability. Thermoelectric devices are now being used in various applications including cooling and heating processes in electronics and automobiles. The choice of materials for these thermoelectric devices are essential in order to determine the parameters such as temperature gradient, thermo emf and total heat dissipated with the help of Seebeck, Peltier and Thomson co-efficients. The elements for the thermoelectric device are arranged by their thermo emf produced in the thermoelectric series. This has been taken into account for the selection of materials for the heating device, analyzed in this article. In certain cold countries, temperature can drop below 10˚C, which is very much near its cloud point and pour point of petroleum fuels. Thermoelectric devices will thereby come to use in these places to maintain the temperature above the cloud point of the fuel. This study also focuses on another application of waste heat recovery in automobile engines to produce thermo emf, which can be utilized for small scale electronics in automobiles. In this study, materials are analyzed for the previously mentioned applications.

1. Introduction

The world which we live in has undergone so many changes in various perspectives. The earth has bestowed us with many resources that we could use it for our everyday life. Till 20th century, non-renewable resources have been majorly used for energy production. As a result of industrialization and urbanization, the earth is facing many environmental problems such as pollution, ozone depletion, and loss in diversity which leads to global warming, change in climatic patterns and many other adverse conditions. The only way to prevent the environmental degradation issues is to return to renewable resources, which is an eminent way but it needs to be sustainable for a sustainable future and pass on the resources for future generations to meet their energy needs [1].

With the unceasing demands on developing renewable energy technologies to resolve the global energy crisis, Thermo-electrics have interested many researchers and R&D’s of various companies to explore the usage of them in their applications due to their capability to recover waste heat and convert it to useful electricity [2]. They are used either as thermoelectric generators or thermoelectric coolers. The two foremost concepts deployed in thermo-electrics are Seebeck effect and Peltier effect. In Seebeck effect, when two junctions are maintained at a considerable temperature gradient, a thermo emf is produced in the system. The thermo emf produced in the system depends on the Seebeck co-efficient. The inverse to the Seebeck effect is the Peltier effect. When a voltage is given to the thermoelectric system, one junction gets heated up and the other junction gets cooled to form a temperature gradient. The voltage supplied also produces heat by the joule’s heating law which must not be confused with the temperature gradient produced by the Peltier effect. Thermoelectric generators make use of Seebeck effect and the coolers function in accordance with the Peltier effect.

The capability of thermoelectric system to convert waste heat into electricity, without emitting greenhouse gases, is an efficient tool to face today’s energy disputes. A lot of research in the field of
material science has been going on for advanced thermoelectric energy conversion applications [3]. Research has been done in recycling exhaust heat from the engine and converting it into electricity. Materials like Bi–Te, Half-Heusler compound materials and CoSb$_2$ has been advanced and tested for their efficiency in different engines [4]. Seebeck effect has been used in the management of temperature in battery packs of hybrid vehicles. Some of the critical electronics present in the cars are to be maintained at a lower temperature for their effective functioning. In this application, thermoelectric devices help to prevent damage that is caused due to elevated temperature conditions by producing the desired temperature [5].

Xiaoming Hu et al [6] investigated a thermoelectric generator of a nearly kilowatt class in a waste heat recovery application. The mode of heat transfer experimented in the study was radiation and it was observed that it gave better results than the convection and conduction-based heat transfer systems. The same study concluded that the conversion efficiency increased as the temperature at the hot junction increased while keeping the temperature at cold junction a constant at 308 K for that application. A review article by Hicham El Hage et al [7] discussed the techniques by which waste heat can be recovered from household applications. Exhaust gas from chimneys, waste heat from stove, drain water and electric generators. The waste heat recovered from the various systems mentioned above were used for reheating purposes and increasing the efficiency of other heating devices thereby minimizing the energy wastage.

The present study will mainly focus on the application of the thermoelectric devices in automobiles. A lot of heat energy is dissipated from the engine surface. By using a thermoelectric generator, the heat dissipated around the engine surface is converted into useful power. Another application discussed in this article is the prevention of fuel waxing. In this article, a study has been made on the heating capacity of thermoelectric devices with different type of semiconductor materials for the application of prevention of fuel waxing. The semiconductor materials are chosen from the different positions in the thermoelectric series and were analyzed for their performance in the thermoelectric devices. The individual analysis and combined working of the elements used in the thermoelectric device have been studied.

2. Methodology

2.1. Geometry

The materials for this analysis are selected on the basis of their position in the thermoelectric series, availability, economic feasibility, and its sustainability. Considering these parameters, the materials taken for this study are namely Silicon, Graphite and Molybdenum. An experiment was initially conducted to find the thermo emf of the materials under the condition where two metals are soldered or welded with platinum as a reference point at 0°C and the material temperature at 100°C. The metals are heated to produce a thermoelectric voltage at the free, cold ends as shown in figure 1.

![Figure 1. Seebeck effect](image-url)
The major parameter of the thermo-electric system which is known to be the Seebeck coefficient was calculated using the formula

\[ \text{Emf}_{th} = (S \times \Delta T) \]  

Where, \( \text{Emf}_{th} \) is the Thermo emf, \( S \) is the Seebeck coefficient and \( \Delta T \) is the difference in temperature.

A Thermo-electric device is made by sandwiching a semiconductor and a metal in series between two ceramic plates held by a thermal paste as shown in figure 2.

![Figure 2. Thermoelectric device](image)

2.2. Pellet Dimensions

The dimension of the pellets in the thermo-electric device has to be decided in order to continue. So, considering the compactness of the device, the dimensions of the pellets are considered as 15mm x 5mm x 5mm as shown in the figure 3. The dimensions are kept constant for each of the materials in the analysis. The ceramic plate used in the application is of aluminium nitride due to the high thermal conductivity. The dimensions assumed for the ceramic plate is 120mm x 160mm according to number of pellets which is around 254.

![Figure 3. Semiconductor Pellet](image)

2.3. Design Parameters

Using the resistivity of the materials and the assumed dimensions, the electrical resistance has been calculated from,

\[ R_E = \rho \times (L/A) \]
Where, \( R_e \) is the total electrical resistance, \( \rho \) is the electrical resistivity, \( L \) and \( A \) are the length and area of the device, respectively. The absolute thermal resistance was also calculated using the thermal conductivity of the given dimensions.

\[
R_T = \frac{L}{\kappa A}
\]  

(3)

Where, \( R_T \) is the thermal resistance, \( \kappa \) is the thermal conductivity, \( L \) and \( A \) are the length and area of the device, respectively. A 2-ohm resistor is connected in the circuit to prevent the damage of the device. Using the electrical resistance and by varying the voltage supplied, the current was found in each case. Using the voltage and current found from the earlier steps, the Power dissipation is found by

\[
P_d = VI
\]  

(4)

Where, \( P_d \) is the power dissipated, \( V \) is the voltage and \( I \) is the current. The junction point temperature depends upon the above calculated parameters. So, the junction temperature is calculated with the help of

\[
T_j = T_A + (\theta_{JA}) \times (P_d)
\]  

(5)

Where, \( T_j \) is the junction temperature, \( T_A \) is the ambient temperature, \( \theta_{JA} \) is the junction-ambient thermal resistance, \( P_d \) is the power dissipated.

The variation of the junction point temperature or the highest temperature that the device can provide is plotted as a graph against the voltage supplied in figure 4. This could be useful to find the required voltage that is needed in different kind of applications. This could come in handy and avoid unwanted usage and wastage of power supply and would prove as a sustainable solution to use the resources properly. After analysing the materials, the values from the graph can be taken in account for the automobile applications.

![Figure 4. Voltage vs Junction point temperature](image)

2.4. Waste Heat recovery from Engines

The automobile engines produce a very high temperature during their operation. Hence, there is a lot of heat that gets dissipated on the outer surface of the engines. The average values of this temperature on the outer surface of the engines are calculated. On providing this temperature from the engines to the hot side of the thermo-electric device and keeping the cold side exposed to ambient temperature, assumed to be 300K and the hotter face is kept facing the engine walls. As per the Seebeck effect, when one side is provided with heat whilst the other one is maintained at a fixed lower temperature, a thermo emf is produced by the system. So, by this condition, a thermo emf from the waste heat that is dissipated from the surface of the engines. The thermo emf generated is calculated using the Seebeck formula.

\[
\text{Emf}_{\text{th}} = (S_B - S_A) \times \Delta T
\]  

(6)
Where, $\text{Emf}_{th}$ is the thermal emf, $S_B$ and $S_A$ are the Seebeck coefficient of the materials, $\Delta T$ is the temperature difference.

The value of the thermo emf is mostly of lower voltage. So, a buck boost converter is used to boost the voltage to a range of 4V to 12V. When the voltage is boost to this range, then this is enough to power a led or a series of LED. The led can now be used for any application in the automobiles such as side indicator lights or the light inside the cabins of the automobiles. This can be very useful in the usage of the waste heat from engines and usage of power from the batteries of the automobile is reduced.

| Materials   | Thermal conductivity $\kappa$ [W/m.K] | Electrical resistivity $\rho$ [ohm.m] | Thermo emf $\text{Emf}_{th}$ [mV] |
|-------------|----------------------------------------|--------------------------------------|-----------------------------------|
| Graphite    | 130                                    | 30e-08                               | 39.12                             |
| Silicon     | 390                                    | 5e-06                                | 0.15                              |
| Molybdenum  | 138                                    | 53.4e-09                             | 0.8                               |

### 2.5. Preventing Waxing in Cold countries

In cold countries where the ambient temperature drops below 273K or even below, the fuel inside the fuel tank loses its flow properties at very low temperatures. These temperatures below which the fuels forms wax and losses its flow and usability are called cloud point and pour point of the fuel, respectively. Normally petroleum fuels have cloud point in the range of $-13\, ^\circ$C to $-15\, ^\circ$C and pour point in the range $32\, ^\circ$C to below $-57\, ^\circ$C.

Conventional methods used to prevent the fuel reaching its cloud point is, to keep the vehicle in a closed environment like garage where the temperature to prevent the fuel waxing and cold start of the engine. Fuel additives like ethanol, xylene, toluene and n-heptane are also used to improve the cloud and pour points of the diesel fuel used in automobiles in cold regions.

In this study, the thermoelectric device is used for a heating application. This device which is kept outside the fuel tank will help to regulate and maintain the fuel temperature such that its flow properties remain intact.

The heat required to increase the temperature of the fuel below cloud point to a temperature of about 293K where the fuel has reasonable flow characteristics is calculated using

$$Q_C = m \times C_V \times \Delta T$$  \hspace{1cm} (7)

Where, $Q_C$ is the heat required, $m$ is the mass of the fuel, $C_V$ is the specific heat. So, by varying the amount of the fuel that is to be there in the fuel tank, the heat required in each case is calculated. Now, the heat required for this must be drawn from the thermoelectric device. So, from the results obtained using the analysis of the materials done before, the voltage and the junction point temperature for these conditions are easily calculated. The top ceramic plate will heat up the fuel tank by transferring the heat generated using the device through convection and that is calculated with the help of

$$Q = k \times A \times \Delta T / d$$  \hspace{1cm} (8)
Where, $k$ is the thermal conductivity, $A$ is area of the surface, $\Delta T$ is the temperature difference, $d$ is the thickness of the ceramic plate. This will come in very handy in countries such as Canada, Russia, Greenland, and Finland etc.

3. Result and Discussions

The absolute thermal resistance and electrical resistance of molybdenum, graphite, silicon are $(4.34\,\text{K/W}, 1.53\,\text{K/W}, 4.1615\,\text{K/W})$ and $(32.04\times10^{-6} \,\Omega, 3\times10^{-3} \,\Omega, 18\times10^{-5} \,\Omega)$ respectively. Using these values, junction point temperature was calculated using (5). The standard voltage value was taken as $12 \,\text{V}$ for all the systems. The voltage was varied from $0 \,\text{V}$ to $24 \,\text{V}$ incrementing it by $2 \,\text{V}$ every time and analysed the value of the junction point temperature. The trend of the junction point temperature is analysed and are tabulated as shown below.

Table 2. Variation of Junction point temperature with voltage for Molybdenum-Silicon system.

| Voltage [V] | Junction temperature for Molybdenum Silicon [K] |
|-------------|-----------------------------------------------|
| 0           | 258                                           |
| 2           | 265.72                                        |
| 4           | 288.91                                        |
| 6           | 327.54                                        |
| 8           | 381.63                                        |
| 10          | 451.18                                        |
| 12          | 536.21                                        |
| 14          | 636.21                                        |
| 16          | 752.54                                        |
| 18          | 883.91                                        |
| 20          | 1.03e+03                                      |
| 22          | 1.19e+03                                      |
| 24          | 1.97e+03                                      |

Table 3. Variation of Junction point temperature with voltage for Graphite-Silicon system.

| Voltage [V] | Junction temperature for Graphite Silicon [K] |
|-------------|-----------------------------------------------|
| 0           | 258                                           |
| 2           | 264.63                                        |
| 4           | 284.52                                        |
| 6           | 317.66                                        |
| 8           | 364.06                                        |
| 10          | 423.73                                        |
| 12          | 493.65                                        |
| 14          | 582.83                                        |
| 16          | 682.27                                        |
| 18          | 794.97                                        |
| 20          | 920.92                                        |
| 22          | 1.06e+03                                      |
Table 4. Variation of Junction point temperature with voltage for Graphite-Molybdenum system.

| Voltage [V] | Junction temperature for Graphite Molybdenum [K] |
|------------|-----------------------------------------------|
| 0          | 258                                           |
| 2          | 264.29                                         |
| 4          | 283.15                                         |
| 6          | 314.59                                         |
| 8          | 358.6                                          |
| 10         | 415.18                                         |
| 12         | 484.34                                         |
| 14         | 566.08                                         |
| 16         | 660.39                                         |
| 18         | 767.277                                        |
| 20         | 887.00                                         |
| 22         | 1.02e+03                                       |
| 24         | 1.16e+03                                       |

For the application of preventing fuel waxing, the calculation of the heat required for the increasing the temperature of the fuel of mass 1 kg was found to be 77.70 J. So, it was found that the system required a temperature of 293K to raise from the ambient temperature of 258K from the equations above.

This table can be used to find the voltage for providing the required temperature for any application in that considered ambient environment. So, when the required temperature or the heat required for any process or application is known then the required voltage or optimum power requirements can be calculated. The calculated voltage from the system can be compared with pre-existing systems and can be used to decide whether this system is feasible for the application or not.

So, from Table 2, the voltage of 4.3 has to be given to the thermo-electric device which could provide the required temperature and heat for the system by using molybdenum-silicon system. This value has been interpolated from the data obtained from the Table 2. Among the three systems this proves to be consuming less power to run this process.

For the application of waste heat recovery from engines, the Seebeck coefficients of the materials were calculated. The inference from these values is that the combination of materials which has a better Seebeck coefficient will provide better thermo emf.

The system with the molybdenum-silicon combination or the graphite-silicon combination can be suitably used for the generation of thermo emf efficiently by providing emfs of about 38.32mv and 38.97mv respectively which is mentioned in table 5. This emf is used to power the lights of the automobiles as the minimum voltage required for a LED light is about 3.3 V and a buck boost converter will provide voltage in the range of 4V to 12V.
Table 5. Seebeck co-efficient and thermo emf obtained from the calculation.

| Thermoelectric system          | Seebeck co-efficient of the system [μV/K] | Thermo emf obtained from the system [mV] |
|--------------------------------|------------------------------------------|----------------------------------------|
| Molybdenum-Graphite            | 436.4                                    | 38.32                                  |
| Graphite-Silicon               | 445.8                                    | 38.97                                  |
| Graphite-Molybdenum            | 9.4                                      | 0.65                                   |

4. Conclusions
The probability of revolutionizing the automotive heating, ventilation, and air-conditioning (HVAC) systems by thermoelectric materials is remarkably high. Advanced thermoelectric materials have the potential to be used in commercial HVAC systems which can provide many desired and exclusive features.

In the application of the cloud point and pour point of the fuels in cold countries, the thermo-electric device will be of significant use. Unlike using the garage heater for hours, the usage of the thermoelectric device just few minutes before the starting of the automobiles will help in taking the fuel temperature above the cloud point and making it ready to be burnt in the engine cylinder and thus prevent engine failure.

In the application of generating thermo emf from the waste heat of the automobile engines, the thermo-electric device can provide the power for the operation of lights and can also be a source of supply for mobile phone chargers. From the calculations made from the values in table 5, the device can give voltage in the range of 4V to 12V which is enough to power up LED and mobile chargers which requires 3.3V and 5V, respectively.

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