ISSN 2395-1621

Thermoelectric Power Generation Using Waste-Heat Energy from Internal Combustion Engine

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ABSTRACT

The efficiency in an internal combustion engine ranges from 25% to 35%. About 40% of the overall fuel energy losses in a combustion engine are waste heat which is blown out with the exhaust gases and 30% is cooled away by the vehicle's radiator. Even if a small fraction of the waste heat could be turned into useful energy again it would be a step in the right direction of improving fuel economy. Being one of the promising new device for an automotive waste heat recovery, thermoelectric generators will become one of the most important and outstanding device in the future. Thus this study involves generation of electrical energy with the help of thermoelectric power generator. Thermoelectric modules which are used as thermoelectric generators are solid state devices that are used to convert thermal energy from a temperature gradient to electrical energy and it works on basic principle of Seebeck effect. Hence the selection of thermoelectric materials plays very important role for energy conversion in thermoelectric applications. Thermoelectric modules will be selected according to the temperature difference between exhaust gases side and the engine coolant side. In order to achieve uniform temperature distribution and higher interface temperature, the thermal characteristics of heat exchangers with various heat transfer enhancement features such as internal structure, material and surface area is to be considered. After designing suitable heat exchanger the thermo electric modules will be incorporated on the heat exchanger for performance analysis. In order to observe the differential change in exhaust conditions due to the addition of thermoelectric generator to the exhaust system, experiments to be conducted on the test engine. Thus this project aims to analyze the performance of thermoelectric generator under various engine operating conditions like engine speed. It would be useful to update the potential of thermoelectric generation in the automobile industry nowadays.

Keywords- Seebeck Effect, Thermoelectric Module, Thermoelectric Generator, Waste Heat Recovery.

ARTICLE INFO

Article History

Received :18th November 2015

Received in revised form :

19th November 2015

Accepted : 21st November , 2015

Published online :

22nd November 2015

I INTRODUCTION

Most engines operate with an efficiency rate of about 30%, with most of the wasted energy lost as heat. There is an increased need to identify alternative energy sources and enhance the efficiency of engines in order to reduce the consumption of fuel. The purpose of this project is to examine whether lost energy can be recovered in the form of electricity to power the electrical components of a vehicle. Thermoelectric Power generator will be analyzed as possible solutions to recover this lost energy in order to improve the overall engine efficiency.

A. Problem statement

Study on automobiles gasoline powered internal combustion engine shows that only approximate 25% of the fuel energy is used to drive the engine, whereas 40% of the fuel energy is wasted in exhaust gas, 30% in engine coolant and 5% in friction and parasitic losses. For example, a full tank of vehicle capacity is 100 litre fuels, but only 25 litre of fuel is turn into useful mechanical energy to power vehicle, the remaining of 75 litre of fuel is dissipate as heat energy. This is not logic and non economical but this is what vehicle does every day. Therefore many studies had carried out to recover the waste heat dissipated by vehicle.

If the waste heat can recover, not only the every Ringgit spends for fuel is become more valuable, but also can reduce the fuel consumption due to less fuel require to generate electric for vehicle. As a conclusion, the increasing of oil prices in the world market and low utilization of gasoline powered engine makes it necessary to generate new sustainable sources of electric power in modern automobiles. Furthermore, vehicle nowadays requires more and more electricity energy in order to maintain the communication, navigation, engine control, and safety systems of the vehicle. Therefore TEG is the best solution to recover waste heat through converts the heat energy into electricity. The focus of this project is to design a TEG system which can integrate into the automobile vehicle to generate electricity.

B. Objectives

i. Use of thermoelectric power generator for recovering exhaust waste heat from engine exhaust.

ii. Study the performance of thermoelectric generators under various engine speeds.

C. Scope

The development of useful tools for the evaluation of power generating systems based on thermoelectric generators is the general topic of this work. The focus will be on general studies utilizing heat sources such as renewable energy sources and waste heat.

The scopes for thermoelectric power generator include:

i. Literature review on the working principle of the TEG based on Seeback effect in automotive industry.
ii. Design a mechanical assembly of TEG to produce electricity powers.
iii. Analysis the parameters of TEG performance such as the engine speed, mass flow.
iv. Tabulate the electricity power produce based on waste heat energy from I.C. engine by using TEG.
v. Discuss the TEG system and include recommendation for the future work.

D. Methodology

The basic theory and operation of thermoelectric based systems have been developed for many years. Thermoelectric power generation is based on a phenomenon called “Seebeck effect” discovered by Thomas Seebeck in 1821. When a temperature difference is established between the hot and cold junctions of two dissimilar materials (metals or semiconductors) a voltage is generated, i.e., Seebeck voltage. In fact, this phenomenon is applied to thermocouples that are extensively used for temperature measurements. Based on this Seebeck effect, thermoelectric devices can act as electrical power generators.

A schematic diagram of a simple thermoelectric power generator operating based on Seebeck effect is shown in Fig.1. As shown in fig. heat is transferred at a rate of Q_H from a high-temperature heat source maintained at T_H to the hot junction, and it is rejected at a rate of Q_L to a low-temperature sink maintained at T_L from the cold junction. Based on Seebeck effect, the heat supplied at the hot junction causes an electric current to flow in the circuit and electrical power is produced. Using the first-law of thermodynamics (energy conservation principle) the difference between Q_H and Q_L is the electrical power output We.

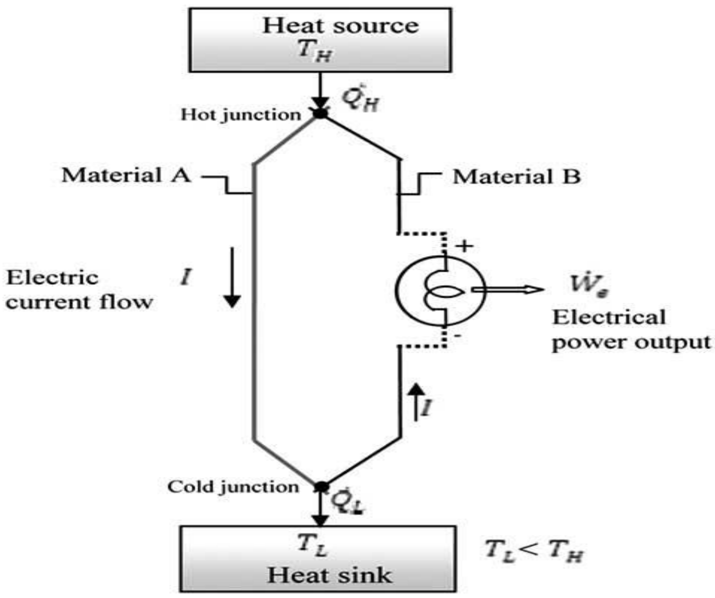

Figure 1. Basic concept of a simple thermoelectric power generator operating based on Seebeck effect

Fig.2 shows a schematic diagram illustrating components and arrangement of a conventional thermoelectric power generator. As shown in figure, it is composed of two ceramic plates (substrates) that serve as a foundation, providing mechanical integrity, and electrical insulation for n-type (heavily doped to create excess electrons) and p-type (heavily doped to create excess holes) semiconductor thermoelements. In thermoelectric materials, electrons and holes operate as both charge carriers and energy carriers. The ceramic plates are commonly made from alumina (Al2O3), but when large lateral heat transfer is required, materials with higher thermal conductivity (e.g. beryllium and aluminium nitride) are desired. The semiconductor thermoelements (e.g. silicon-germanium SiGe, lead-telluride PbTe based alloys) that are sandwiched between the ceramic plates are connected thermally in parallel and electrically in series to form a thermoelectric device (module). More than one pair of semiconductors are normally assembled together to form a thermoelectric module and within the module a pair of thermoelements is called a thermocouple. The junctions connecting the thermoelements between the hot and cold plates are interconnected using highly conducting metal (e.g. copper) strips as shown in figure.

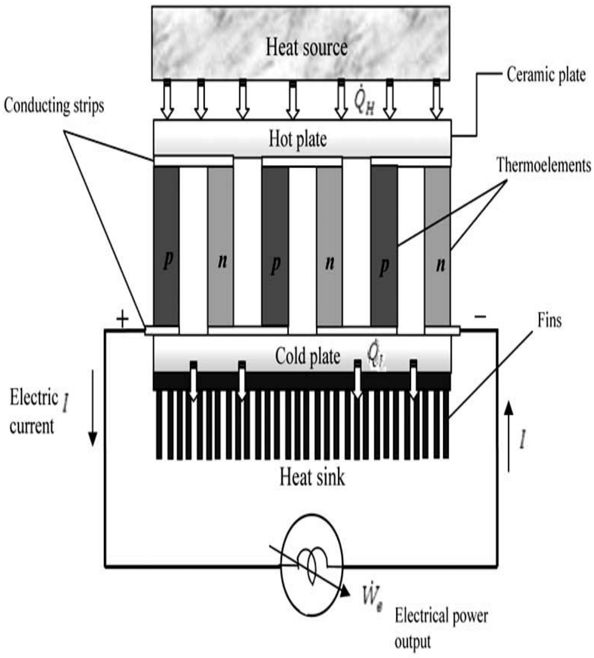

Figure 2. Components and arrangement of a typical single-stage thermoelectric power generator

The potential of a material for thermoelectric applications is determined in large part to a measure of the material's dimensionless figure of merit (ZT). Semiconductors have been primarily the materials of choice for thermoelectric applications. There are challenges in choosing suitable materials with sufficiently higher ZT for the applications.

The performance of thermoelectric materials can be expressed as

$$Z = \frac{\alpha^2}{kR} \tag{1}$$

Z is the thermoelectric material figure-of-merit,
α is the Seebeck coefficient given by,

$$\alpha = \frac{\Delta V}{\Delta T} \tag{2}$$

R is the electric resistivity (inverse of electric conductivity) and
k is the total thermal conductivity.

The figure of merit depends on the properties of thermoelectric material used. A high value of Z is obtained by using materials of large seebeck coefficient, small thermal conductivity and small electrical resistivity.

This figure-of-merit may be made dimensionless by multiplying by $\bar{T}$ (average absolute temperature of hot and cold plates of the thermoelectric module, *K*), i.e,

$$Z\bar{T} = \frac{\alpha^2 \bar{T}}{kR} \tag{3}$$

$$\bar{T} = \frac{T_H + T_L}{2} \tag{4}$$

The term $\frac{\alpha^2}{kR}$ is referred to as the electrical power factor. In general, a thermoelectric power generator exhibits low efficiency due to the relatively small dimensionless figure-of-merit ($Z\bar{T} \le 1$) of currently available thermoelectric materials. The conversion efficiency of a thermoelectric power generator defined as the ratio of power delivered to the heat input at the hot junction of the thermoelectric device, is given by

$$n = \frac{W_e}{Q_H} \tag{5}$$

The maximum conversion efficiency of an irreversible thermoelectric power generator can be estimated using,

$$n_{ideal} = \left(1 - \frac{T_L}{T_H}\right)\left[\frac{M-1}{M+\frac{T_L}{T_H}}\right] \tag{6}$$

Where, $M = \left[1 + \frac{Z}{2}(T_H + T_L)\right]^{1/2}$ (7)

The value of the figure-of-merit is usually proportional to the conversion efficiency. The dimensionless term $Z\bar{T}$ is therefore a very convenient figure for comparing the potential conversion efficiency of modules using different thermoelectric materials.

2 LITERATURE REVIEW

Crane D. et al.[1] described a design concept that maximizes the performance for thermoelectric power generation systems in which the thermal power to be recovered is from a fluid stream (e.g., exhaust gas) subject to varying temperatures and a broad range of exhaust flow rates. The device is constructed in several parts, with each part optimized for a specific range of operating conditions. The thermoelectric system characteristics, inlet mass flow rates and fluid temperatures, and load and internal electrical resistances are monitored and generator operation is controlled to maximize performance. With this design, the system operates near optimal efficiency for a much wider range of operating conditions. Application of the design concept an automobile is used to show the benefits to overall system performance.

Basel I.I. et al.[2] presented a background on the basic concepts of thermoelectric power generation and recent patents of thermoelectric power generation with their important and relevant applications to waste-heat energy are reviewed and discussed.

Liang G. et al.[3] studied the performances of parallel thermoelectric generator (TEG) by theoretical analysis and experimental test. An analytical model of parallel TEG was developed by theoretical analysis and calculation, based on thermodynamics theory, semiconductor thermoelectric theory and law of conservation of energy. Approximate expressions of output power and current of parallel TEG were deduced by the analytical model. An experimental system was built to verify the model. The results indicate that only when all of the thermoelectric modules (TE modules) in the parallel TEG have the same inherent parameters and working conditions, the parallel properties of the TEG are the same as that of common DC power. The existence of contact resistance is just like the increase of the TE module's internal resistance, which leads to the deceases of output power. The thermal contact resistance reduces the output power by reducing the temperature difference between the two sides of the thermocouples. The results derived from the model are basically consistent with the experimental results.

C.Ramesh Kumar et al.[4] experimentally studied the performance of thermoelectric generators under various engine operating conditions. A heat exchanger with 18 thermoelectric generator modules was designed and tested in the engine test rig. Various designs of the heat exchangers were modelled using computer aided design and analysis was done using a computational fluid dynamics code. From the simulated results it was found that rectangular shaped heat exchanger met our requirements and also satisfied the space and weight constraint. Hence fabricated and the thermoelectric modules were incorporated on the heat exchanger for performance analysis. Also revealed that energy can be tapped efficiently from the engine exhaust and in near future thermoelectric generators can reduce the size of the alternator or eliminate them in automobiles.

Hsu C. et al.[5] constructed a system to recover waste heat comprised 24 thermoelectric generators. Simulations and experiments for the thermoelectric module in this system are undertaken to assess the feasibility of these applications. A slopping block is designed on the basis of simulation results to uniform the interior thermal field that improves the performance of TEG modules. Besides simulations, the system is designed and assembled. Measurements followed the connection of the system to the middle of an exhaust pipe. Open circuit voltage and maximum power output of the system are characterized as a function of temperature difference. Through simulations and experiments, the power generated with a commercial TEG module is presented.

Dai D. et al.[6] proposed a new type of thermoelectric generator (TEG) system based on liquid metal which serves to harvest and transport waste heat. To demonstrate the experimental prototype which combined commercially available thermoelectric (TE) modules with the electromagnetic pump was set up. Output voltage from TE modules and temperature changes of the main parts of the liquid based TEG system were experimentally measured, as well as the flow rate of cooling water and the load resistance. It was shown that the maximum open-circuit voltage of 34.7 V was obtained when the temperature of the waste heat source was 195.9^{o}C and the temperature gap between liquid metal heating plate and cooling-water plates was nearly 100^{o}C. TEG system performance is discussed and a calculated efficiency of 2% in the whole TEG system is obtained.

Love N.D. et al.[7] experimentally investigated a thermoelectric which is in the contact with clean and fouled heat exchangers of different materials. The thermoelectric devices are tested on a bench-scale thermoelectric heat recovery apparatus that simulates automotive exhaust. It is observed that for higher exhaust gas flow rate, thermoelectric power output increases from 2 to 3.8W while overall system efficiency decreases from 0.95% to 0.6%. Degradation of the effectiveness of the EGR-type heat exchangers over a period of driving is also simulated by exposing the heat exchangers to diesel engine exhaust under thermophoretic conditions to form a deposit layer. For the fouled EGR-type heat exchangers, power output and system efficiency is observed to be 5–10% lower for all conditions tested.

S. R. Jumade et al.[8] demonstrated the potential of thermoelectric generation. The use and evolution of different kinds of thermoelectric materials presented. Also, several main characteristics of the different structures proposed for the thermoelectric generators (TEGs) compared. The results presented can be considered as references of the minimum goals to be reached.

Weng C.et al.[9] explored influences of the number and the coverage rate on the heat-exchanger of the TEGs via simulations. It was found that implementing more TE couples does not necessarily generate more power in total, and most of all the average power per TE couple decreases rapidly. Furthermore, it was also found that for a given total number of TE couples, it is better to retain a portion of the heat exchanger uncovered with TE couples at the downstream side so that the downstream wall of the exhaust pipe uncovered with TE couples becomes even hotter than the upstream wall covered with TE couples. Heat is consequently conducted from the downstream wall to the upstream wall and successively to the attached TEGs; a larger total power can be thus obtained..

Patil D. et al.[10] reviewed thermoelectric concepts and explains briefly the challenges in enhancing the figure of merits. Also focused on various operating condition i.e. flow rate, temperatures of fluids and position of thermoelectric module. Comparison of Thermoelectric generator technology with other technologies such as PV, turbocharger or even Rankine bottoming cycle technique to maximize energy efficiency, reduce fuel consumption and greenhouse gas (GHG) emissions is explained.

3 PROPOSED WORK

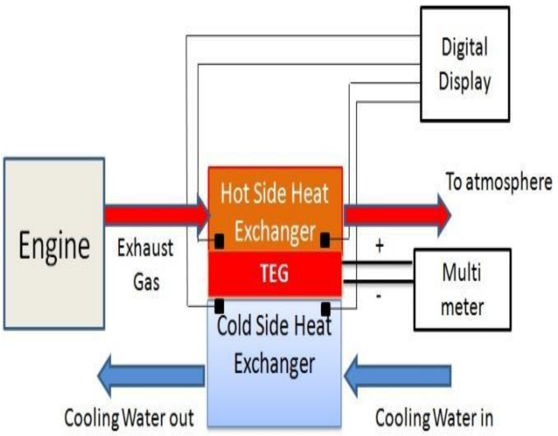

Figure 3. TEG System Layout

As shown in the fig. 3, the proposed system consists of one hot side heat exchanger and one cold side heat exchanger. Between the two heat exchangers the thermoelectric modules (TEG) are placed. The exhaust gas from engine passes through hot side heat exchanger and cooling water from radiator passes through cold side heat sink. According to the principle of Seebeck effect, thermoelectric modules convert the heat into useful electricity.

Thermoelectric power generator consists of three main components, they are:

i. Thermoelectric materials
ii. Hot-side heat exchanger
iii. Cold-side heat exchanger

Experimental set-up

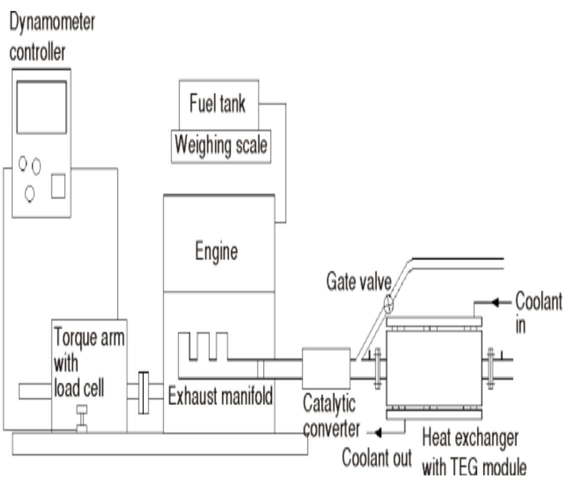

Figure 4. Schematic diagram of experimental set-up [4]

Thermoelectric material for module

Thermoelectric modules are selected according to the temperature difference between exhaust gases side and the engine coolant side. Thermoelectric materials are evaluated by figure of merit which is determined by three physical values -Seebeck coefficient (α), electrical resistivity (ρ), and thermal conductivity (κ). The larger the value of Z, the better is the thermoelectric material. The main focus is to investigate the possibility of a low-cost thermoelectric generator (TEG) to harvest the wasted heat of vehicles.

Hot-side Heat Exchanger

The function of hot-side heat exchanger is to extracting waste heat and delivering this heat to the surface of TEM. Sizing up the heat exchanger will be based on the size, orientation, and number of modules. Because the modules are assumed to be square as they often are, length and width differ by the number of modules defined by flow orientation. So that design of hot side heat exchanger will be done analytically.

Cold-side Heat Exchanger

The cold-side heat exchanger is responsible for dissipating heat from TEM to prevent damage on TEM due to high temperature. The basic requirement of cold side heat sink are heat sink should flow with full of water i.e. no air gap should get created and length of cold side heat sink should be larger than hot side heat exchanger as cooling should be effective. So that design of cold side heat sink will be done analytically.

Manufacturing and assembly

The heat exchangers will be assembled with the sandwich arrangement of TEG modules between them as shown in fig.3. Before assembly thermal insulation will be applied on both the surfaces of TEG modules to enhance the heat transfer. Thermocouples will be connected along with the display for temperature measurement.

Performance analysis of TEG

After successful assembly, sets of trials will be taken on the TEG System retrofitted on an I. C. engine at different RPMs. Using the thermocouples; temperatures at different sections will be measured on Digital temperature indicator. Then voltage & current at various engine speeds will be measured on Digital multimeter. Performance analysis will be done through the output power of TEG system.

4. EXPERIMENTAL WORK

A. Selection of Suitable Thermoelectric Material for TEM

Among the vast number of materials known to date, only a relatively few are identified as thermoelectric materials. Thermoelectric materials can be categorized into established (conventional) and new (novel) materials. Today's most thermoelectric materials, such as Bismuth Telluride (Bi_2Te_3)-based alloys and PbTe-based alloys, have a $Z\overline{T}$ value of around unity (at room temperature for Bi_2Te_3 and 500-700K for PbTe). However, at a $Z\overline{T}$ of 2-3 range, thermoelectric power generators would become competitive with other power generation systems. The figure-of merit of a number of thermoelectric materials together with potential power generating applications relevant to waste heat energy is shown in Figure.4.1. Effective thermoelectric materials should have a low thermal conductivity but a high electrical conductivity. A large amount of research in thermoelectric materials has focused on increasing the Seebeck coefficient and reducing the thermal conductivity, especially by manipulating the nanostructure of the thermoelectric materials. Because the thermal and electrical conductivity correlate with the charge carriers, new means must be introduced in order to conciliate the contradiction between high electrical conductivity and low thermal Conductivity.

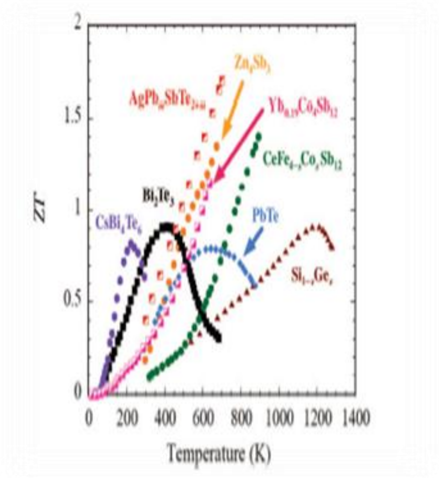

Figure 5. Figure of merit ZT shown as a function of temperature for several bulk thermoelectric materials [2]

Thermoelectric materials (those which are employed in commercial applications) can be conveniently divided into three groupings based on the temperature range of operation, as shown in table 4.1. Although the above mentioned materials still remain the cornerstone for commercial and practical applications in thermoelectric power generation, significant advances have been made in synthesising new materials and fabricating material structures with improved thermoelectric performance. However the proportion of heat supplied that is converted into electrical energy is only about 5 to 7 percent. Efforts have focused primarily on improving the material's figure-of-merit, and hence the conversion efficiency.

Table1. Temperature range for thermoelectric materials

Temperature range	Thermoelectric material
up to around 450K.	Alloys based on Bismuth (Bi) in combinations with Antimony (Sn), Tellurium (Te) or Selenium (Se)
up to around 850K	based on alloys of Lead (Pb)
up to 1300K.	SiGe alloys

B. Performance analysis of selected thermoelectric material

Bismuth Telluride (Bi_2Te_3):

The maximum value of figure of merit,

$Z_{max} = 3 \times 10^{-3} K^{-1}$

The optimum value of the resistance ratio,

$$M = \left[1 + \frac{Z}{2}(T_H + T_L)\right]^{1/2}$$

Where,

T_H = temperature of the source (K)

T_L = temperature of the sink (K)

T_H = 400 K T_L= 315 K

By putting above values in equation,

$$M = \left[1 + \frac{3 \times 10^{-3}}{2}(400 + 315)\right]^{1/2}$$

We get, M= 1.4396

We know that, the maximum or ideal thermal efficiency of a thermoelectric convertor is given by,

$$\eta_{th\,max} = \left(1 - \frac{T_L}{T_H}\right)\left[\frac{M-1}{M+\frac{T_L}{T_H}}\right]$$

by putting above values in given equation,

$$\eta_{th\,max} = \left(1 - \frac{315}{400}\right)\left[\frac{1.4396-1}{1.4396+\frac{315}{400}}\right]$$

We get, maximum thermal efficiency is

$\eta_{th\,max}$= 0.083130= 8.313%

Bi-Te is one of the easy available materials with highest value of α, low cost. Also the position of TEG system is just behind the catalyst converter. All the TEGs designed to be mounted in this position are based on bismuth telluride alloys. It minimizes the amount of heat transfer surface required. This decreases the pressure drop across the generator and results in a lower back pressure. Hence we have selected Bismuth Telluride as TEG material.

Acknowledgment

I have a great pleasure to express my deep sense of gratitude and sincere regards to my project guide Prof. S.H.Barhatte for his guidance and friendly discussion which helped me immensely in selecting this topic. His generous encouragement helped me in completing this project work. I would like to thank Dr. B. S. Kothawale, Head of Mechanical Engineering Department for allowing me for to do this project. He has immensely helped in providing all opportunities and facilities for this work. I would also like to thank our Principal, for providing all facilities at right period of time. I am thankful to all the faculty members of Mechanical Engineering and library staff for helping me in this work. Finally, I would like to thank to all those who directly or indirectly helped me during my work.

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