Experimental Analysis of Heat Exchangers in Thermoelectric Generator for Automotive Application

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ABSTRACT

In an internal combustion engine about 40% of fuel energy is wasted to surrounding. Efforts are made to catch 40% energy of exhaust gases. If this waste heat energy is tapped and converted into usable energy, the overall efficiency of an engine can be improved. In this work, an energy-harvesting system which remove heat from an automotive exhaust pipe and convert the heat into electricity by using thermoelectric power generators (TEGs) has to be built. Thermoelectric generators work on the principle of Seebeck effect. Experiments show that the temperature difference in automotive system is not constant, especially the heat exchanger, which cannot provide large amount of heat to the thermoelectric modules (TMs). Thus efficiency of this system is very low. The thermal performance of different heat exchangers with different internal structure in exhaust-based TEGs will be studied to obtain higher interface temperature, thermal uniformity and by using this efforts are made to get improved efficiency. Simulations, experiments and output power testing system will be carry out on a high-performance production engine with a dynamometer.

Keywords - Thermoelectric generator, Thermoelectric Module, Interface temperature

I. INTRODUCTION

In typical gasoline engine roughly 40% of the fuel energy is wasted in exhaust gases, and 30% in engine coolant. The motto is to utilize the heat energy of fuel which is discharge as waste heat through exhaust. Automotive Thermoelectric generator system is use to trap this heat energy and to produce electrical energy. This system consist of hot side heat exchanger, cold side heat exchanger and thermoelectric modules are placed in between this. This system is work on Seeback principle with advantage of being highly reliable, zero emission, and low noise and involving no moving parts. Thermoelectric modules (TEMs) made of semiconductor materials are sandwiched between the heat exchanger and heat sink in an exhaust based thermo-electric generation. Exhaust gas flow into the hot-side heat exchanger attached at end of exhaust pipe and cooling water is through heat sink. The electric power is generated as a result of the temperature difference based on the Seebeck effect. As the thermal energy of exhaust gas harvested, the temperature gradient will appear on the heat exchanger surface. In order to utilize the performance of each TEM, it is essential to have heat exchanger to get uniform temperature distribution as well as it should get maximum heat. The main disadvantage of this system is low efficiency. As different research on different component of ATEG system is carried out to increase the efficiency of system, as now the thermoelectric generator have 5–8% efficiency. In this work we have restricted our view to select the type of heat exchanger and study various internal structure of heat exchanger. During study we have designed new model to get high interface temperature with low back pressure, low temperature gradient and uniform temperature distribution and thus motto of increasing efficiency was achieved.

II. THERMOELECTRIC MODULE MATERIAL SELECTION

The driving principle behind thermoelectric generation is the known as the Seebeck effect. Whenever a temperature
For mounting of TEMs on heat exchanger flat surface is require. Concerning this requirement we have selected two type of heat exchanger one is plate shape heat exchanger and hexagonal prism shape heat exchanger. But for installation of ATEG system after exhaust system less space is available. As we know that Hexagonal prism shape heat exchanger required comparatively large space than Plate shape heat exchanger. Distance between chassis and ground is short and height of plate shaped heat exchanger is also short compare to Hexagonal prism shaped heat exchanger. The overall space requirement and height of ATEG system with plate shaped heat exchanger is less than that of ATEG with hexagonal prism shaped heat exchanger. Hence, we have selected Plate shaped heat exchanger for ATEG system. As a major factor, thermal capacity and heat transfer of the heat exchanger affect the performance of TEG effectively. With the thermal energy of exhaust gas harvested by thermoelectric modules, a temperature gradient appears on the heat exchanger surface, so as the inferior flow distribution of the heat exchanger.

### B. Hot Side Heat Exchanger Design

Sizing up the heat exchanger is based on the size, orientation, and number of modules. Instead of finding the whole heat exchanger size, the size of an individual zone is found and then extended to represent the entire heat exchanger. First, the length and width of all the modules combined within a zone is determined. 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. Nmod,para (no. of modules in parallel) and Nmod,ser (no. of modules in series) exist to aid in developing the orientation of the modules in a zone.

Module size: 30x30x3 mm

\[
\text{Lmod,zone} = \text{wmod} \times N\text{mod,ser} \\
= 30 \times 2 \\
= 60 \text{ mm}
\]

\[
\text{wmod,zone} = \text{wmod} \times N\text{mod,par} \\
= 30 \times 1 \\
= 30 \text{ mm}
\]

\[
\text{Amod,zone} = \text{Lmod,zone} \times \text{wmod,zone} \\
= 60 \times 30
\]
Blw = L_{mod, zone} / w_{mod, zone}  \\
= 60 / 30  \\
= 2  \\

A_{zone} is the surface area of a zone and \( \gamma \) is the user defined ratio for zone area to modules in a zone area. \( \gamma \) is always greater than or equal to one by its definition. We take it as 4.  

A_{ins} = A_{zone} - A_{mod, zone}  \\
= 7200  \\

L_{z} is the length of an entire zone and \( w_{z} \) is the width of a zone. These are used throughout the calculations of the finned heat exchangers and are necessary for defining various fin dimensions.

\[ L_{z} = \sqrt{B_{lw} \times A_{zone}} = 120 \text{ mm} \]  
\[ W_{z} = \sqrt{(1 / B_{lw}) \times A_{zone}} = 60 \text{ mm} \]  

Therefore final dimension of Hot side heat sink = 120 x 60 mm.  

C. Cold Side Heat Exchanger Design  

The basic requirement of cold side heat sink was 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. From various permutations and combinations, we selected stacked type heat sink for cold side.

Number of fins \( (Nf) = 11 \)  
Number of channels \( (Nch) = Nf-1 = 10 \)  
Thickness of an individual fin \( (t_f) = 2 \text{ mm} \)  

The length of heat sink = \( K \times (\text{length of hot side heat exchanger}) = 1.5 \times 120 = 180 \text{ mm} \)  

The width of heat sink = \( 62 \text{ mm} \)  

The length of an individual fin protrudes from its base \( (L_f) = 14 \text{ mm} \)  
Thickness of the base \( (t_b) = 5 \text{ mm} \)  
Number of stacks = 2  

IV. DESIGN OF FINS  

By applying fundamental formula of heat transfer \( \Phi = hA\Delta T \), heat convection can be greatly strengthened by the increase of the heat transfer area \( A \). This target can be approached by changing the structure of the conduction surface by fitting baffles i.e. fins. Another approach is to increase the heat transfer coefficient \( h \). According to the fluid dynamics theories, under the condition of Reynolds number \( Re > 4000 \), turbulent fluid flow is a significant impact factor on improving the heat transfer. Moreover, the greater the heat transfer coefficient \( h \), the better the heat transfer quantity. The thermal resistance of turbulent fluid convective mostly exist in the boundary layer. The field synergy principle was proposed as another indication of the synergy degree between velocity and temperature field for the entire flow and heat transfer domain, the better the synergy was between the temperature and velocity field, the better the heat transfer. According to both theories above, the strengthening of the heat transfer can be approached by adding turbulence device to enhance the fluid disturbance and damage the boundary. Hence, dimensions of fins for fishbone and scattered is set on trial and error bases keeping in mind to have low back pressure and simplicity in manufacturing with low material cost and having better optimum turbulence, with arrangement of fins in symmetry.  

A. Design of Fins For Fishbone Type Plate Heat Exchanger:  
Number of fins = 14,  
Length of fins = 25mm,  
Thickness of fins = 2mm,  
Height of fins = 11mm.  

Orientation of fins are kept concerning increase in time period of exhaust gases in heat exchanger to utilize more heat and add additional heat by turbulence, to increase the interface temperature as shown in figure 5.

B. Design Of Fins For Scattered Type Plate Heat Exchanger:  
Number of fins = 39,  
Length of fins = 10mm,  
Thickness of fins = 2mm,  
Height of fins = 11 mm,  

Orientation of fins are kept concerning increase in time period of exhaust gases in heat exchanger to utilize more heat and add additional heat by turbulence, to increase the interface temperature. Fins in this type of internal structure are in regular pattern in symmetry shown in figure 3.
V- EXPERIMENTAL SETUP

We assembled the heat exchangers with the sandwich arrangement of TEG modules between them as shown in Fig. 4. Before assembly we applied the thermal grease on both the surfaces of TEG modules to enhance the heat transfer. Insulation of glass wool with POP for binding is provided on hot side except on mounting surface of modules as shown in figure. We made use of four scales of iron with holes drill at ends for fitting of nut bolts for clamping of heat exchangers. Thermocouples (K-Type) are connected along with the display for temperature measurement. After successful assembly, sets of trials are taken on the AETEG System retrofitted on a 4 stroke, 3 cylinder, MARUTI 800 SI Engine at different RPMs. As a load on system, LED load bank is used. Using the thermocouples; temperatures at 4 sections are measured on Digital temperature indicator. Then voltage & current at various engine speeds are measured on Digital multimeter.

VI - SIMULATION OF THERMAL FIELD OF THE HEAT EXCHANGER

A. Simulation Model:

The plate-shaped heat exchanger of TEG is connected to the exhaust pipe of diameter 36 mm on both sides. The section of the plate-shaped exchanger of 5 mm thickness is a 120-mm-long by 60-mm-wide rectangle. There are 2 TM placed on plate shape heat exchanger. The no-slip boundary conditions are imposed at all the solid walls. The inlet boundary condition is a uniform flow of velocity 15.2 m/s and temperature is 350°C. The exit of the exchanger is connected to the entrance of the rear muffler, whose exit is connected to atmosphere. Imposed at the outlet boundary are zero gradients for velocity and temperature. Additionally, brass has good performance of heat conductivity and heat convection. The heat exchangers are made of brass, so the coefficient of convective heat transfer between the outer surface of the exchanger and the air is set to 15 W/ (m² • K). For convenience, we adopt a fixed value of convection heat transfer coefficient h = 15 W/ (m² • K) in all the simulations. Finally, the exhaust gas was modelled as air whose properties vary with temperature.

B. Interface Temperature Distribution On Heat Exchangers With Different Internal Structures:

When heat exchanger was just an empty box with no internal structure, and the TEG system obtained little output power, only modules in the middle of heat exchanger produced electricity. Considering the fixed cooling water temperature, the results showed that most of the heat sources were concentrated in the middle part of heat exchanger while only a small part of heat passed through the both sides, so it is worth noting that the simulation of heat exchanger would enhance the further design, and obtain higher and more uniform temperature. The simulation of the heat exchanger with no internal structures was shown in Fig. 5 in this case study, the diameter of vehicle exhaust pipe is 36 mm but the heat exchanger of TEG system into the system, which leads to an uneven thermal distribution inside the heat exchanger, so the high-temperature region is mainly concentrated in the front of the heat exchanger. The general temperature distribution is not even, with low temperature at the middle and the end. Moreover, the temperature of part of the heat is only 140 °C. It is obvious that the heat exchanger cannot meet the requirement. Based on the theories of thermal convection, heat conduction and turbulent flow as mentioned earlier, two three-dimensional models of heat exchangers with different internal structures were designed by arranging internal baffles. Fig. 3 and Fig. 4 shows the block diagram of two heat exchangers with different internal structures which extracts waste heat energy. There are called fishbone-shaped and scattered-shaped heat exchangers. The CFD simulation results are shown in Fig. 5-7. Two heat exchangers have some internal structure in common: there are both two small fins set at the entrance for diverting the flow, so that the high-temperature exhaust gas is diffused in the entire lateral area rather than concentrating in the central region; some fins are disorderly set in the internal structure for disturbing the flow, so that the exhaust gas can be fully in contact with the metal walls of the heat exchanger and stays longer in the cavity of the heat exchanger, which can increase the heat that airflow transfers to the fins. There are also some differences: the fishbone-shaped heat exchanger uses 14 fins of 25 mm in length while scattered-shaped uses a lot of small fins of 10 mm in length. As indicated by the simulation results, the scattered-shape has slightly higher interface temperature at the inlet, and much higher at the outlet and middle. The temperature of outlet of the scattered-shaped heat at the outlet is expected to get
improved. Moreover, from simulation the scattered design shows better uniformity. During simulations, the ambient temperature is assigned for 25 °C. However, heat may accumulate in the system and the ambient temperature would increase for a short period of time. Regardless of this transient phenomenon, Fig. 5-7 is captured in steady state operational results. Thus, the heat exchanger with scattered internal shape is more ideal for TEG application.

![Simulation of the heat exchanger with no internal structure.](image)

![Simulation of the heat exchanger with Fishbone internal structure.](image)

![Simulation of the heat exchanger with scattered internal structure.](image)

**Fig. 5:** Simulation of the heat exchanger with no internal structure.

**Fig. 6:** Simulation of the heat exchanger with Fishbone internal structure

**Fig. 7:** Simulation of the heat exchanger with scattered internal structure

**VII - RESULT ANALYSIS**

**TABLE I**

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Engine Speed (RPM)</th>
<th>Pin (W)</th>
<th>Pout (W)</th>
<th>AETEG Overall Efficiency $\eta = \frac{P_{\text{out}}}{P_{\text{in}}}$ (%)</th>
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**TABLE II**

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</table>

**Graph 1:** Temperature Difference Vs Engine Speed

The graph shows that the difference between exhaust gas temperature at hot side inlet and Outlet increase with increase in engine speed.
The graph shows that as the engine speed increases voltage generated also increases. Hence voltage is proportional to engine speed. With the engine speed of 3500 RPM, voltage generated was 13.78 V.

Graph 2: Voltage Vs Engine Speed

The graph explains that the current increases with the engine speed. It first increases gradually up to 2000 RPM then rapidly beyond that speed. At the speed of 3500 RPM the current was 1.54 A.

Graph 3: Current Vs Engine Speed

Scattered type plate heat exchanger is more desirable. It gives high interface temperature and uniform temperature distribution. Scattered type heat exchanger has low back pressure as like in fishbone. It is most effective to use scattered type plate heat exchanger for ATEG system which give high power output of module. As ATEG reduces the wastage of energy, it improves the overall efficiency of vehicle. ATEG system can be profitable in the automobile industry.

VIII. CONCLUSION

Scattered type plate heat exchanger is more desirable. It gives high interface temperature and uniform temperature distribution. Scattered type heat exchanger has low back pressure as like in fishbone. It is most effective to use scattered type plate heat exchanger for ATEG system which give high power output of module. As ATEG reduces the wastage of energy, it improves the overall efficiency of vehicle. ATEG system can be profitable in the automobile industry.

ACKNOWLEDGMENT

First and foremost, I would like to express my deep sense of gratitude and indebtedness to my guide Prof. Ghuge N.C. for his invaluable encouragement, suggestions and support from an early stage of this seminar and providing me extraordinary experiences throughout the work. Above all, his priceless and meticulous supervision at each and every phase of work inspired me in innumerable ways. I am highly grateful to Dr. G.K. Kharate, Principal, Matoshri College of Engineering and Research Center, Eklahare, Nashik, Prof. J.H. Bhangale, Head, Department of Mechanical Engineering and Prof. D.D. Palande PG coordinator, Department of Mechanical Engineering for their kind support and permission to use the facilities available in the Institute.

REFERENCES


