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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 Seeback 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**

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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 Seeback 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 gradient is applied to a thermoelectric material, specifically metals or semiconductors, the heat passing through is conducted by the same particles that carry charge. The movement of charge produces a voltage. The junctions of the different conductors are kept at different temperatures which cause an open circuit electromotive force (e.m.f) to develop as follows:

$V_{oc}=\alpha\ (T_H - T_C)$

Where α is the difference in Seebeck coefficient of two leg materials and has the units of V/K, and TH and TC are the hot and cold side absolute temperatures both measured in Kelvin. A German Physicist, Thomas Johann Seebeck, discovered this effect in the early 1800s.

An important unit less constant to evaluate the performance of thermoelectric materials is the thermoelectric figure of merit, ZT. It describes the effectiveness of a specific thermoelectric material in terms of its electrical and thermal material properties. The figure of merit is expressed as:

$$ZT= T$$

ZT for materials has remained below 1 for decades, but in recent years, ZT of new materials has reached values greater than 2.

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,

$M_0 = \sqrt{(1+Z((T_1+T_0)/2)}$

T1 = temperature of the source (K)

T0 = temperature of the sink (K)

T1 = 400 K T0 = 315 K

M0 = 1.4396

The maximum thermal efficiency is given by,

$\eta_{th.max}= \sqrt{((T_1- T_0) / T_1) \times (M_0 - 1)M_0 + (T_0 / T_1)}$

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

Bi-Te is one of the available materials with highest value of α. Also the position of TEG system is just behind the catalyst converter. (400ºC and 200ºC) All the TEGs designed to be mounted in this position are based on bismuth telluride alloys, specifically Hi-Z commercial modules. 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.

III. HEAT EXCHANGER SELECTION AND DESIGN

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.

A. Heat Exchanger Internal Structure Optimization

In order to achieve uniform temperature distribution and higher interface temperature, the thermal characteristics of the heat exchanger with heat transfer enhancement, internal structures are studied. In order to attempt the above concerned objective, fishbone and Scattered heat exchanger gives uniform temperature difference and high interface temperature with low back pressure. Hence, we have selected this two internal structure for our plate shape heat exchanger.

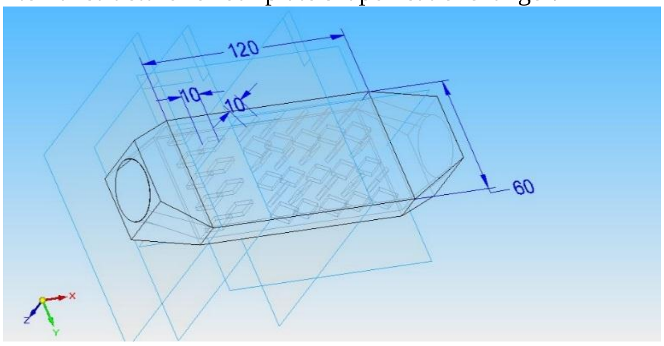


Fig. 1: Scattered Type Heat Exchanger.

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. $N_{mod,para}$ (no. of modules in parallel) and $N_{mod,ser}$ (no. of modules in series)exist to aid in developing the orientation of the modules in a zone.

Module size: 30x30x3 mm

$L_{mod,zone} = w_{mod} \times N_{mod,ser}$

$= 30 \times 2$

$= 60$ mm

$w_{mod,zone} = w_{mod} \times N_{mod,par}$

$= 30 \times 1$

$= 30$ mm

$A_{mod,zone}$ is the surface area of all the modules in the zone and β_{lw} is the ratio of the length of all the modules in the zone to the width of all the modules in the zone. These two parameters, in addition to a user input, can now be used to determine the dimensions of the zone. It is required that the user define the ratio of the total zone surface area to $A_{mod,zone}$.

$A_{mod,zone} = L_{mod,zone} \times w_{mod,zone}$

$= 60 \times 30$

= 1800 sq.mm

Blw = *Lmod,zone / wmod,zone*

= 60 / 30

= 2

Azone is the surface area of a zone and γ is the user defined ratio for zone area to modules in a zone area. γ is always greater than or equal to one by its definition. We take it as 4. *Ains* is the area of the insulation.

Azone = γ x *Amod,zone*

= 4 x 1800

= 7200 sq.mm

Ains = *Azone -Amod,zone*

= 7200 – 1800

= 5400 sq.mm

Lz is the length of an entire zone and *wz* 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.

Lz = √ Blw x *Azone* = *120* mm

Wz = √ (1/ Blw) x *Azone* = *60* 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.

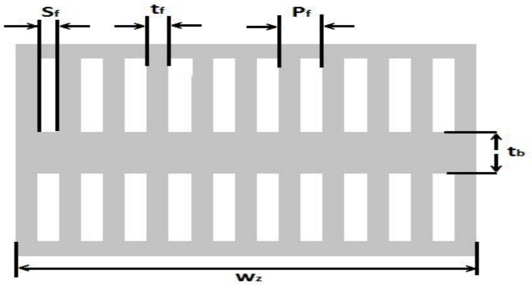


Fig. 2: Front View of Double Stacked Type Heat Sink For Cold Side.

Number of fins (*Nf*) =11

Number of channels (*Nch*) =Nf-1 =10

Thickness of an individual fin (tf) =2mm

The length of heat sink = K × (length of hot side heat exchanger)

= 1.5 × 120 = 180mm

The width of heat sink = 62mm

The length of an individual fin protrudes from its base (L_f) =14mm

Thickness of the base (t_b) =5mm

Number of stacks = 2

IV. DESIGN OF FINS

By applying fundamental formula of heat transfer *Φ=hAΔT*, 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 flow 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.

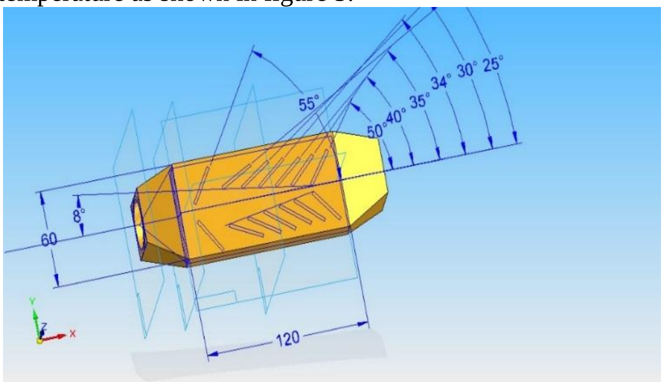


Fig. 3: Design And Orientation of Fins In Fishbone Type Plate Heat Exchanger.

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.

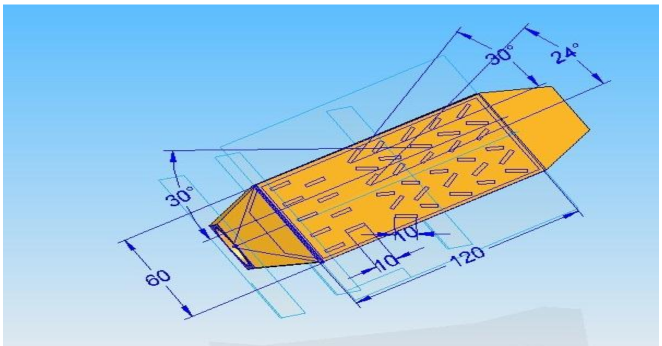


Fig. 4: Design and Orientation of Fins in Scattered Type Plate Heat Exchanger.

V- EXPERIMENTAL SETUP

We assembled the heat exchangers with the sandwich arrangement of TEG modules between them as shown in fig. 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 Digitalmultimeter.

Fig: Maruti 800 Engine for AETEG System Trials

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 TMs placing 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 Temprature 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.

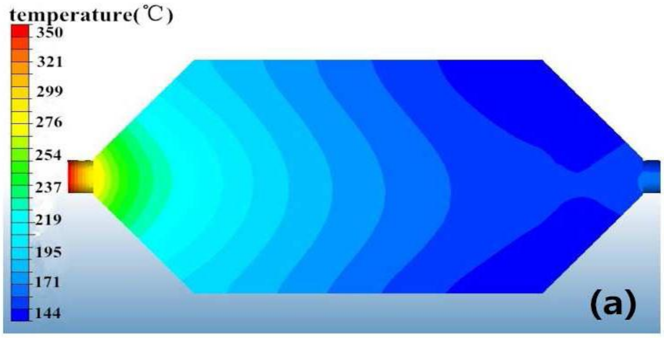


Fig. 5:Simulation of the heat exchanger with no internal structure.

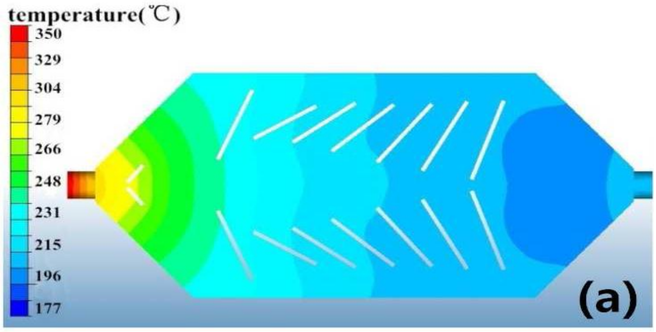


Fig. 6:Simulation of the heat exchanger with Fishbone internal structure

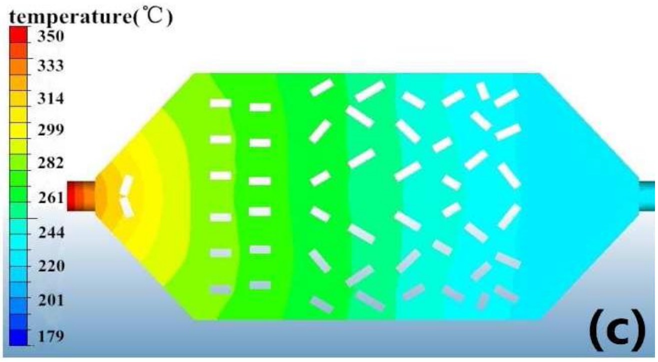


Fig. 7:Simulation of the heat exchanger with scattered internal structure

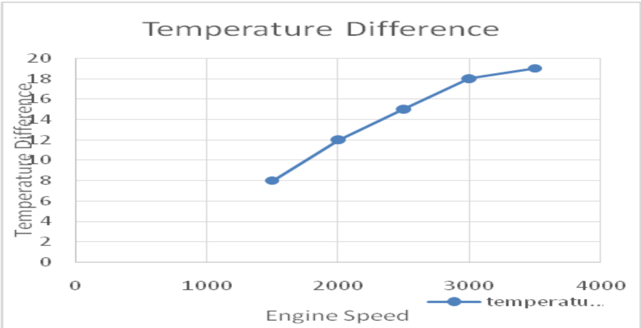
VII - RESULT ANALYSIS

TABLE I
RESULT TABLE of FISHBONE TYPE HE

Sr.No	Engine Speed (RPM)	Pin (W)	Pout (W)	AETEG Overall Efficiency η= Pout /Pin (%)
1	1500	108.108	1.26	1.165
2	2000	187.46	2.39	1.27
3	2500	263.075	5.96	2.265
4	3000	346.58	12.32	3.555
5	3500	397.08	21.22	5.344

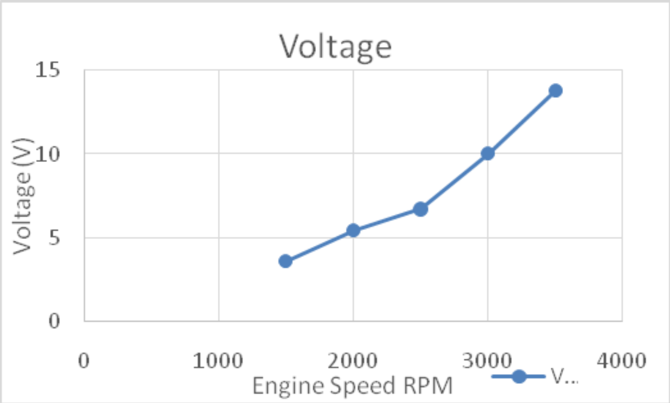
TABLE II
RESULT TABLE of SCATTERED TYPE HE

Sr.No	Engine Speed (RPM)	Pin (W)	Pout (W)	AETEG Overall Efficiency η= Pout /Pin (%)
1	1500	94.59	1.85	1.95
2	2000	171.83	4.20	2.44
3	2500	192.921	10	5.18
4	3000	250.31	15.59	6.22
5	3500	334.39	23.95	7.162



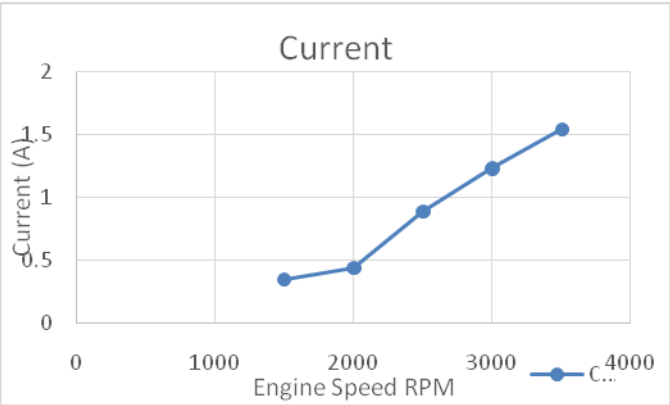
Graph 1: Temperature Difference Vs Engine Speed

The graph shows that the difference between exhaust gas temperature at hot side inlet and Outlet increase with increase in engine speed.



Graph 2: Voltage Vs 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 3: Current 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.

A. *Discussion On Result*

1. While taking result on engine setup it is necessary to confirm that engine maintenance is carried early. So that the efficiency required will be attend and setup will give accurate result of temperature and speed.
2. During experimentation it is observe that when temperature is measure at convergent zone of inlet and outlet it gives high temperature difference. Because, in Fishbone and Scattered Type HE, exhaust gases are accumulated in heat exchanger for considerable long period due to which only part of exhaust gases comes out which get cool due to surrounding air. Hence, we get less temperature at outlet.
3. To have high power output of TEG modules, it is necessary to have less temperature difference with uniform distribution of temperature. Hence, the temperature difference is measure between front and rear end of actual flat surface of heat exchanger where the modules are placed.
4. From experimental result ,the power output as well as the efficiency of scattered type heat exchanger is high that of fishbone type.
5. It has been observed from simulation result fig 5-7 that temperature is more uniformly distributed with high interface temperature in scattered type heat exchanger. From this we can conclude that we can get maximum power output and efficiency for scattered type heat exchanger.

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 AETEG reduces the wastage of energy, it improves the overall efficiency of vehicle. AETEG system can be profitable in the automobile industry.

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