

Study On Exhaust Heat Exchanger For Enhancement Of Thermoelectric Power Generation By CFD

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Abstract- In recent years with the advancement of thermo-electric materials, direct conversion of heat energy into electrical energy becomes possible. Thermoelectric technology is used for recovering heat energy losses from engine exhaust gases. The power generated by thermoelectric technology is called as thermoelectric power. In thermo-electric power generation an exhaust heat exchanger is used for recovering exhaust heat and a thermo-electric module is used for converting heat into electricity. The present research was aimed to optimize the design of exhaust heat exchanger by removing internal fins and changing the cross-sectional area of heat exchanger to overcome problem of pressure drop. The designs of exhaust heat exchangers considered in the previous research works recovered maximum heat from the exhaust of an engine. However problem of pressure drop or back pressure was observed affecting engine performance and working. Higher back pressure can deteriorate and damage engine resulting in stoppage of engine functioning. Computational fluid dynamics (CFD) was used in the simulation of the exhaust gases flowing inside the heat exchanger. The isothermal modelling technique was used in simulation process of the heat exchanger. The thermal simulation is done on heat exchanger to check the surface temperature, heat transfer rate, and pressure drop in three different test conditions (urban driving, suburban driving and max. power driving) of a vehicle with 1.2 L petrol engine. Rectangular shaped heat exchanger was used in exhaust manifold of internal combustion engine (ICE) is modelled numerically to recover the lost heat from engine exhaust. The study revealed that Rectangular shaped heat exchanger with gradually increasing cross sectional area minimized pressure drop and attains higher temperature and heat transfer rate at the surface. The mean surface temperatures obtained after CFD analysis are 458K, 556K, and 790K for the three test conditions. The pressure drop for the three test conditions are 24.14 Pa, 182.5 Pa and 5.413 Kpa and that is within the permissible limits.

Index Terms- Exhaust gases, waste heat recovery, Thermo-Electric power, Exhaust Heat Exchanger, Thermo-Electric module.

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I. Introduction

In today's world there are lots of problem regarding energy crisis and thermal management. The engine exhaust management is the major topic of discussion for automobile industries in recent years and in Internal combustion engines, lots of heat is wasted in the form of exhaust gases and out of the total heat energy supplied to the engine combustion chamber in the form of fuel approximately 30-40% is been converted into useful work and the remaining one is expelled in the form of exhaust gases and this exhaust gases contains a lot of heat that can be recovered by using a waste heat recovery system. The temperature of the exhaust gases after the catalytic converter is between 300-600°centigrade. Thermo-electric technology plays a vital role in generating electrical power from heat, temperature differences and temperature gradients. Thermo-electric power generators are small with no moving parts and they are relatively efficient at these temperatures so they are ideals in such applications.

In automobiles, big and heavy alternators are connected to the engines in order to meet the increasing electrical demands of different accessories. An alternator which operates at an efficiency of 50 to 62% consumes about 1 to 5% of the rated engine work output. About 40% of the thermal energy of the fuel injected to an IC engine is rejected in the form of exhaust gases as waste heat. If approximately 6% of waste heat can be utilized from the engines exhaust, it can fulfill the electrical requirements of our automobiles and it would have been possible to reduce the fuel consumptions about 10%. As compared to heat rejected through coolant and lubricating oil a lot of heat is expelled through exhaust gases at very high temperatures. Thus a thermo-electric

generator (TEG) can be used for converting energy from exhaust heat. TEG is similar to a heat engine which is used convert the heat energy into electrical energy and it basically works on the principle of Seebeck effect. Moreover TEGs are environmental friendly, highly reliable, operate smoothly and quietly, requires less maintenance.

II. Literature Survey

G. Murali , G. Vikram [1] - CFD models having solid field, fluid field and solid-fluid field coalesce are generated for different heat exchangers profile to stimulate turbulence and temperature contours operating at same condition. Comparing four different heat exchangers, the serial plate has high rate of heat transfer compared with other heat exchangers. Serial plate heat exchanger pushes the exhaust gases to flow backwards by passing through baffles increasing the rate of heat transfer at the surface of heat exchanger and increasing problem of pressure drop.

P M Meena et al [2] - An theoretical model of TEG will can be made based on thermodynamic theory, semiconductor thermoelectric theory, and law of conservation of energy, the equations of power output and current of thermoelectric generator (TEG). According to the analysis the power output per unit area is independent of the thermo legs and of their cross sectional area. The power output is max. at a certain thermocouple length and depends on other parameters. Hence to improve the performance of TEGs by modifying the parameters and design methodology.

Rohan mathai chandy et al [3] – In this work a circular heat exchanger with fins attached with the TEGs for recovering waste heat from an automobile exhaust pipe is analysed by performing CFD analysis. As the temperature increases voltage produced also increased as voltage is proportional to the temperature difference. It is analysed that the heat exchanger attached between muffler and catalytic converter gives more uniform flow distribution, lower back pressure, and higher surface temperature.

P. Mohamed Shameer et al [4]- In this research work TEG is fabricated for a two wheeler silencer. The performance of the engine will not be affected because only the surface heat of the silencer is drawn out. The main aim of this research is to transfer the surface exhaust heat to avoid the accidents (Burn-outs) caused by the overheated silencers, and to transfer the recovered heat to useful electric energy. The output could be increased by connecting TEGs in series, so that the voltage gets added up leading to increased power. The energy produced from this system is utilized in powering any auxiliary devices in a vehicle directly or it could be stored in a battery and then used later.

D. T. Kashid et al [5] - The research work is on design and analyze the effectiveness of heat exchanger for thermo-electric power generation using exhaust heat energy from IC engine. The heat exchangers are assembled in sandwich arrangement with TEGs between them. Thermal grease is spread on the surfaces where TEG modules are attached to increase the heat transfer. It was found that Double stacked type heat exchanger gives better temperature gradient across the TEG. Counter flow type arrangement enhances the effective heat transfer.

Shengqiang Bai et al [6]- Six types of exhaust heat exchangers are designed and their models are analyzed on CFD to compare rate of heat transfer and pressure drop in driving conditions for a car with a 1.2 L gasoline engine. The result showed that the serial plate HEx increased heat transfer by 7 baffles and transferred the maximum heat of 1737 W. It also has a maximum pressure drop of 9.7 kPa in a suburban driving cycle. The numerical results for the pipe structure and an empty cavity were verified by experiments. At maximum power driving condition, only the inclined plate and empty cavity structure undergoes a pressure drop less than 80 kPa, and the largest pressure drop exceeds 190 kPa.

Dipak Patil et al [7] – The study focus on different working condition i.e. rate of mass flow, fluid temperatures and correct place of thermoelectric module. The electric power produced from TEG is observed to be a strong function of mass flow rate and inlet exhaust temperature. The heat exchanger should be highly efficient which is necessary to enhance the amount of heat energy extracted from exhaust gas. It is observed that exhaust gas parameters and heat exchanger structure have a significant effect on the power output and the pressure drop. It is also identified that the potentials of the technologies when incorporated with other devices to maximize the performance of the vehicles.

Hazli Rafis et al [8]– A DC to DC voltage Booster for boosting voltage from Thermoelectric Cooler (TEC) with high temperature is demonstrated. Since voltage output by TEC is very low between 0.2 to 0.8 Volts, it cannot be utilized in vehicle. In this circuit design integrated circuit is introduced as DC-DC boost converter. The booster circuit can boost input voltage down to 0.7 V and produce a high adjustable output voltage ranging from 2.7 to 5.5 Volts. The booster circuit performance was checked at various operating conditions and voltage output is estimated.

Olle Hogblom et al [9] - A transient 3D CFD model for simulation of exhaust gas flow, rate of heat transfer and power output is developed. The model works under critical design parameters for TEG-EGR to be verified and design criteria for the TEG to be mentioned. Besides the theory of Seebeck effects, the thermal simulations of model gives detailed analysis of the temperature gradients in the gas phase and inside the TEGs. CFD model is a

valuable tool to identify bottlenecks, improve design and select optimal TE materials and operating conditions. CFD analysis shows that the greatest heat transfer resistance is in the gaseous phase and it is not possible to change this to get a larger temperature gradient over the thermo-electric elements without effecting on the maximum allowable pressure drop in the system.

C. Ramesh Kumar et al [10]– The study was conducted to measure performance of TEGs under various different types operating conditions. The thermo-electric modules on heat exchanger was tested in the engine test setup. Different designs of heat exchangers were modelled and CFD analysis is performed study the mass flow rate & rate of heat transfer characteristics. From the thermal simulation results it is observed that rectangular shaped heat exchanger satisfy our conditions. The study shoes that energy can be utilized from the exhaust gases and in future TEG can change the size of the alternator in automobiles.

Douglas Crane, Greg Jackson, and David Holloway [11] -The study is done on different working condition i.e. urban, suburban and high density traffic and correct place of TEG module. The electric power produced from TEG is observed to be a direct function of cross sectional area and inlet exhaust temperature. The heat exchanger should be highly efficient which is necessary to enhance the amount of heat energy extracted from exhaust gas. It is observed that exhaust gas parameters and heat exchanger structure have a significant effect on the power output and the pressure drop.

Ikoma, K., et al [12]]- In this research work TEG is fabricated for a four wheeler exhaust manifold. The heat exchangers are assembled in sandwich arrangement with TEGs between them. It was found that Double stacked type heat exchanger gives better temperature gradient across the TEG. Counter flow type arrangement enhances the effective heat transfer. It is also seen that the major of the technologies when incorporated with other devices to maximize the performance of the vehicles.

Anthony Joseph Tomarchio [13]-In this work a rectangular heat exchanger with fins attached with the TEGs for recovering waste heat from an automobile exhaust pipe is analysed by performing CFD analysis. As the temperature increases voltage produced also increased as voltage is proportional to the temperature difference. . The output could be increased by connecting TEGs in series, so that the voltage gets added up leading to increased power. The energy produced from this system is utilized in powering any auxiliary devices in a vehicle directly or it could be stored in a battery and then used later.

J. Vazquez, M. A. Sanz-Bobi, [14]-Two types of exhaust heat exchangers are designed and their models are analyzed on CFD to compare rate of heat transfer and pressure drop in driving conditions for a car with a 1.3 L gasoline engine. It also has a maximum pressure drop of 9.8 kPa in a urban driving cycle. The numerical results for the pipe structure and an empty cavity were verified by experiments. At maximum power driving condition, only the inclined plate and empty cavity structure undergoes a pressure drop less than 83 kPa, and the largest pressure drop exceeds 197 kPa.

Ghamaty, S. Quantum Well [15] - A transient CFD model for simulation of exhaust gas flow, rate of heat transfer and power output is developed. The model works under critical design parameters for TEG to be verified and design criteria for the TEG to be mentioned. Besides the theory of Seebeck effects. According to the analysis the power output per unit area is independent of the thermo legs and of their cross sectional area. The power output is max. at a certain thermocouple length and depends on other parameters. Hence to improve the performance of TEGs by modifying the parameters and design methodology.

III. Problems Formulation

Based on the work and results from these experiments and models, the following observations are made:

- There is a need of optimizing exhaust heat exchanger for increasing the efficiency of thermoelectric power generation.
- The Internal fins used in the exhaust heat exchanger increases heat transfer rate but simultaneously increases pressure drop which develops back pressure that can deteriorate engine performance.
- Due to high pressure drop there is a limitation of heat exchanger to work under high speed driving conditions.

IV. Reserch Objective

The main objectives of present research work are as follows:-

- To Optimise the design of rectangular exhaust heat to overcome the problem of pressure drop.
- To study the effect of optimising through CFD analysis.
- Calculation of power generated by Thermo-electric generator module.

V. Methodology

5.1 Design optimization of exhaust heat exchanger

The power generation using thermoelectric generator depends upon lots of factor like temperature gradient, correct size of heat exchanger, correct use of module and lots of other parameter .

So this project emphasizes the methodology that has been used for correct power generation by using systematic use of resources and sequence them in correct form to take maximum advantage of this technology for generating power. Based on the previously described TEG and optimization models, the governing parameters for a complete exhaust heat exchanger optimization problem are identified and the key input, design, and constraint variables are listed below:

Input Variables with Constraints

1. Heat source
2. Heat source characteristics
3. Exhaust gas composition
4. Exhaust Inlet temperature ($T_{e,i}$)
5. Mass flow rate (m_e)
6. Heat exchanger characteristics
7. Material data (ρ and k)
8. Heat sink

5.2 Procedure of design optimization for exhaust heat exchanger

1. Designing a new heat exchanger profile by modifying previous design on CREO PARAMETRICS V.1 PRO-ENGG. Software.
2. After designing the model it is transferred to ANSYS V.14 for CFD analysis, and then Meshing of model is done on CFD pre processor.
3. The boundary conditions are applied on the model and numerical solutions are calculated by using solver.
4. The finite volume method is used in solving the problem..
5. On the basis of the theories of thermal convection and turbulent flow, CFD analysis of the three-dimensional model of Rectangular heat exchanger is done on Fluent ANSYS V.14.
6. The thermal analysis of rectangular heat exchanger is done on different parameters such as energy equations, mass flow rate, inlet temperature, surrounding temperature, inlet pressure, convective heat transfer coefficient etc.
7. The computational fluid dynamics (CFD) is used to simulate the exhaust gas flow within the heat exchanger. The isothermal modeling approach is followed during simulation.

The Exhaust heat exchanger is designed on the basis of previous research paper design data. The heat exchanger has been modified by giving gradual increasing cross sectional area.

Table 5.1 Dimension specifications

S.NO	SPECIFICATIONS	DIMENSIONS (mm)
1.	Length	300 mm
2.	Thickness	5 mm
3.	Inlet Area	110 x 110 mm ²
4.	Outlet Area	165 x 165 mm ²
5.	Manifold Inlet Diameter	80 mm
6.	Manifold Outlet Diameter	80 mm

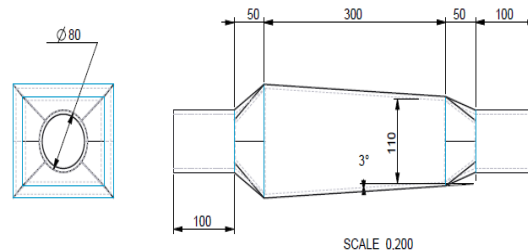


Fig.5.1 Two dimensional view of rectangular exhaust heat exchanger.

The most common materials used in the construction of the support structure of the Exhaust heat exchangers are steel, stainless steel, and in one case haste alloy, and aluminum. The thermal properties of these alloys are described in the Table below.

As the TEG has to be fabricated for a small car, aluminum was the only choice for the use of exhaust heat exchanger due to its high conductivity and light weight.

Table 5.2 Thermal properties of the alloys

PROPERTIES	HASTELLOY	STEEL	STAINLESS STEEL	COPPER	DURALUMIN
TYPE	-----	AISI 1010	AISI 302	99.9Cu+Ag	-----
MELT POINT(K)	1533	1670	1670	1293	923
DENSITY(Kg/m ³)	8300	7830	8055	8950	2770

5.3 Modelling of exhaust heat exchanger

By applying theories of thermal convection and turbulent flow, the three-dimensional model of rectangular heat exchanger is modified by providing a new design.

The heat exchangers made up of aluminum have inlet and outlet manifold diameters as 80mm, the area at inlet as 110x110mm and at the outlet 165x165mm. The wall thickness is about 5mm. From inlet of the heat exchanger the cross section is found to be increasing gradually to the outlet.

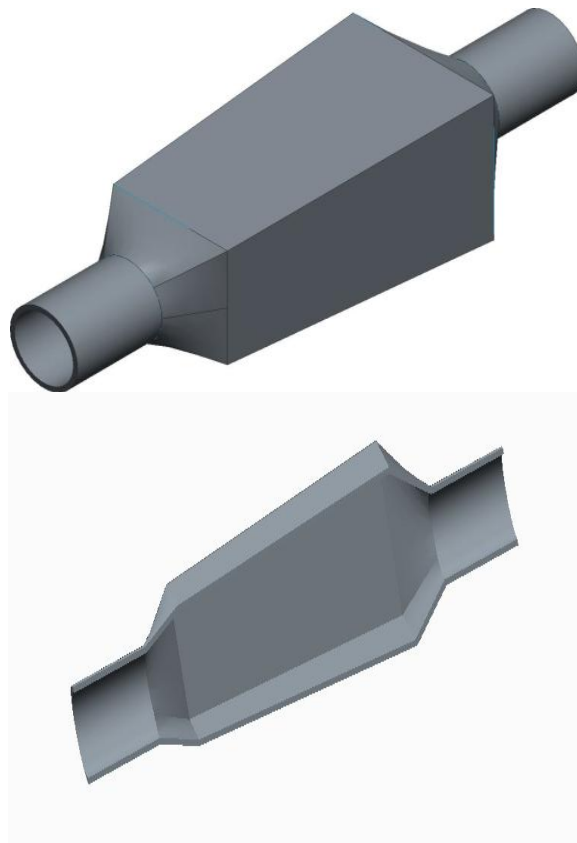


Fig.5.2 Three dimensional view and cross sectional view of rectangular heat exchanger.

5.4 Boundary conditions & mesh convergence

In Simulation of the model it is assured that the flow of exhaust gases in the heat exchanger is fully turbulent and molecular viscosity is neglected, so the standard κ - ϵ model is adopted in the CFD simulation.

At near wall area the standard wall function, the natural convective heat transfer coefficient and the environmental temperature are set.

The mass flow rates for different operating conditions are as follows: Urban: 5.7 g/sec, Suburban: 14.4 g/sec, Maximum power: 80.1 g/sec.

The Inlet temperature: 573.15 K, 673.15 K, 873.5 K for the three driving conditions, Inlet pressure is 300Kpa and outlet with gauge pressure.

The heat exchanger is approximately symmetrical about axis in geometry, so the velocity, pressure and temperature contours also show axis symmetric characteristics in the presence of ambient winds.

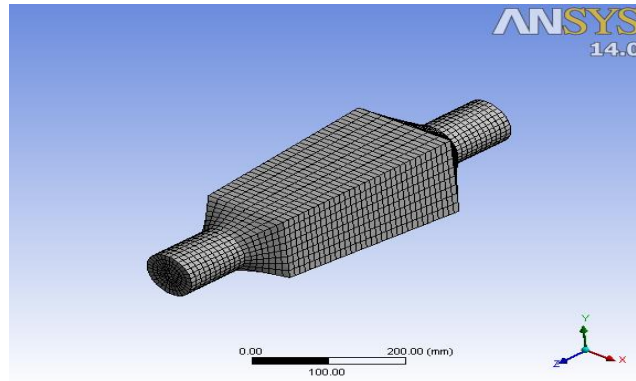


Fig.5.4 Meshing of rectangular heat exchanger

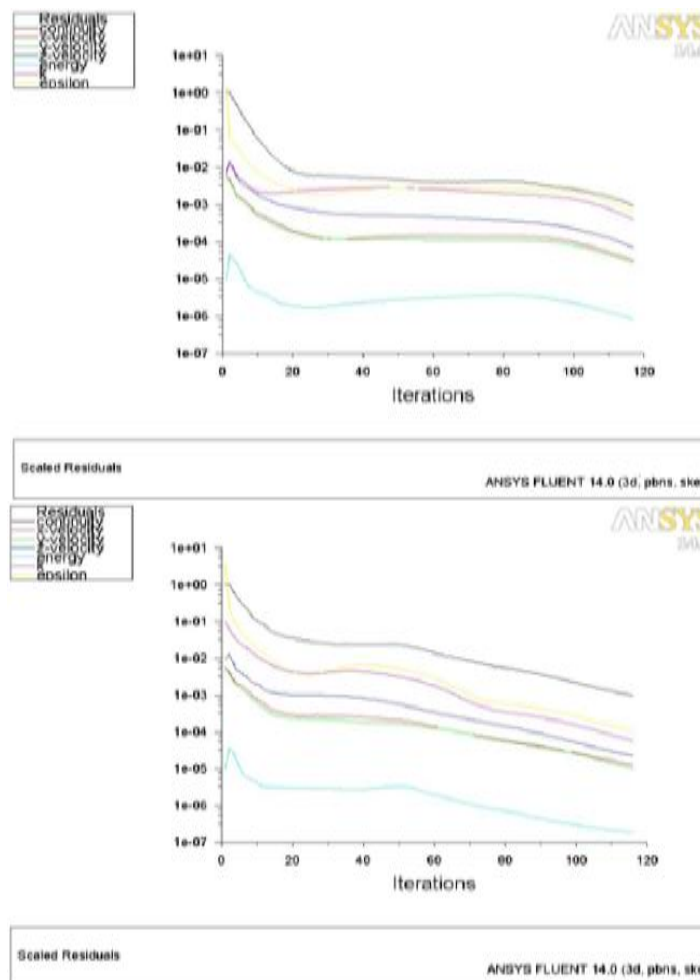
VI. Results

6.1 Convergence graphs

The Figures below shows the mesh convergence for the rectangular heat exchanger for the three driving conditions.

The iteration value is given in the solver for solving the boundary conditions and equations applied on the meshed model.

The mesh convergence graph shows that meshing is fine and solutions are obtained within given number of iterations. The No. of Nodes are 9520 and total No. of Elements are 8280



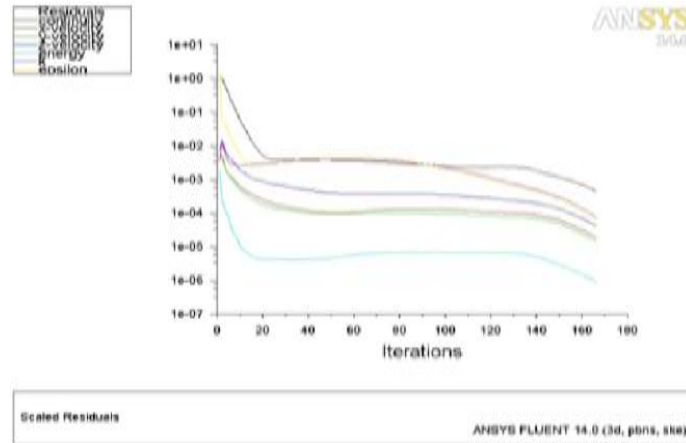


Fig.6.1 Mesh convergence graph for rectangular heat exchanger for urban,suburban & maximum power driving conditions

6.2 CFD analysis of exhaust heat exchanger

The computational fluid dynamics (CFD) is used to simulate the exhaust gas flow within the heat exchanger. The isothermal modeling approach is followed during simulation.

6.3 Thermal simulation results

The simulations are done in three engine loads such as; urban, suburban driving and maximum power and the results were plotted below.

6.4 Temperature distribution inside exhaust heat exchanger

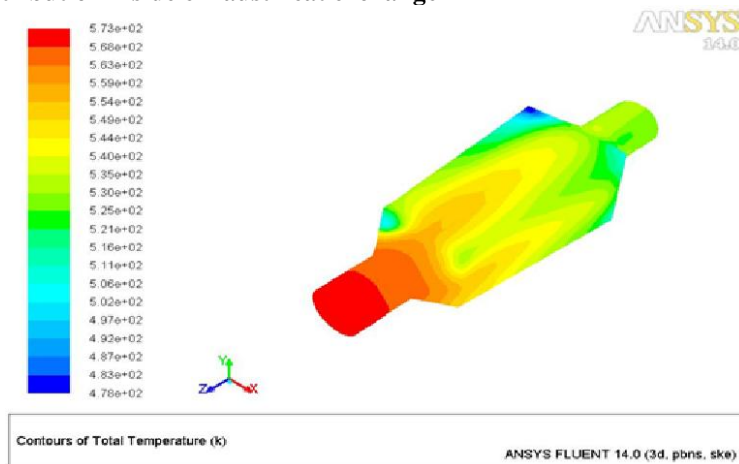


Fig.6.2 Total Temperature contour of rectangular heat exchanger for urban driving cycle condition.

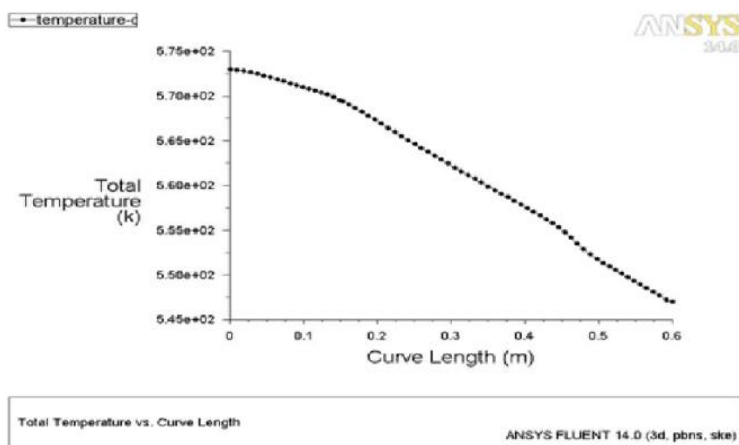


Fig.6.3 Total Temperature graph of rectangular heat exchanger for urban driving cycle condition

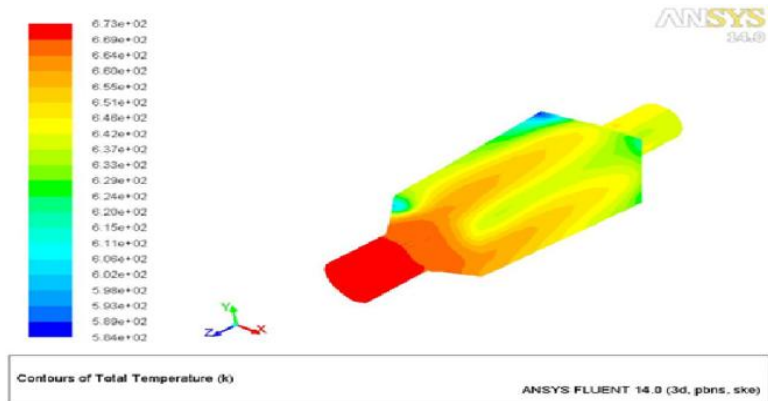


Fig.6.4 Total Temperature contour of rectangular heat exchanger for Sub urban driving cycle condition.

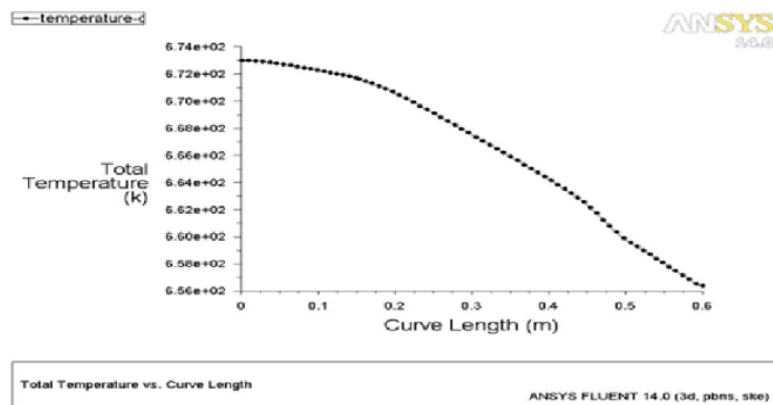


Fig.6.5 Total temperature graph of rectangular heat exchanger for Sub urban driving cycle condition.

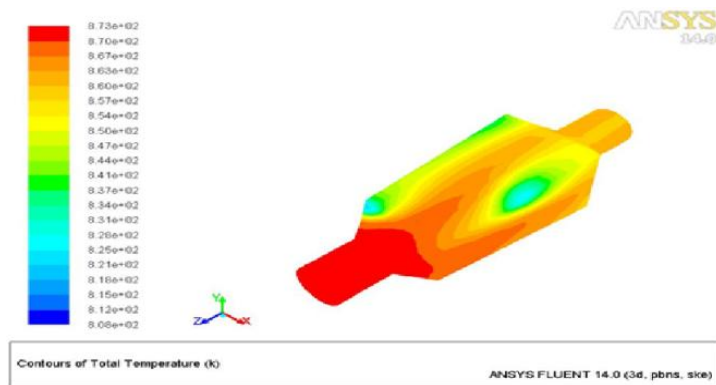


Fig.6.6 Total temperature contour of rectangular heat exchanger for max. power driving cycle condition.

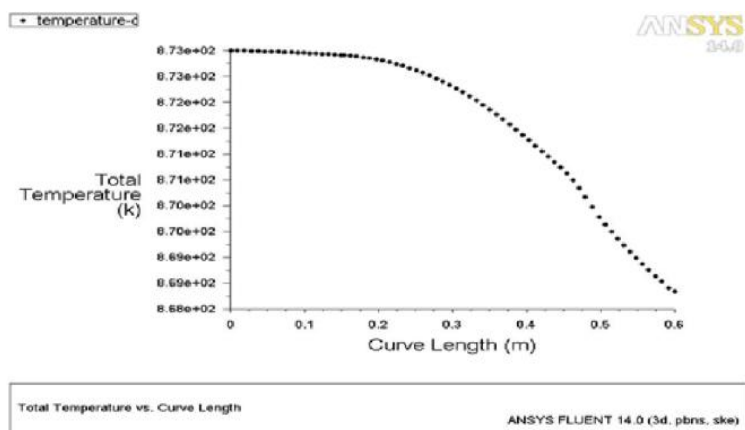


Fig.6.7 Total temperature graph of rectangular heat exchanger for max. power driving cycle condition.

6.5 Pressure gradient on heat exchanger

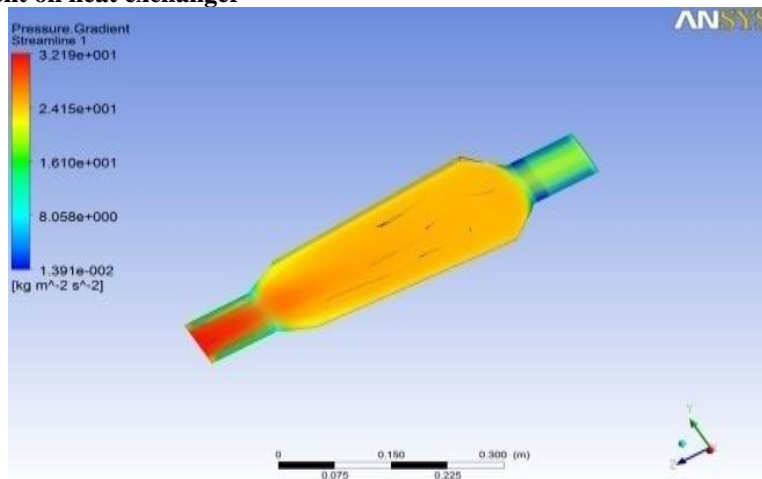


Fig.6.8 Pressure gradient contour for urban driving condition.

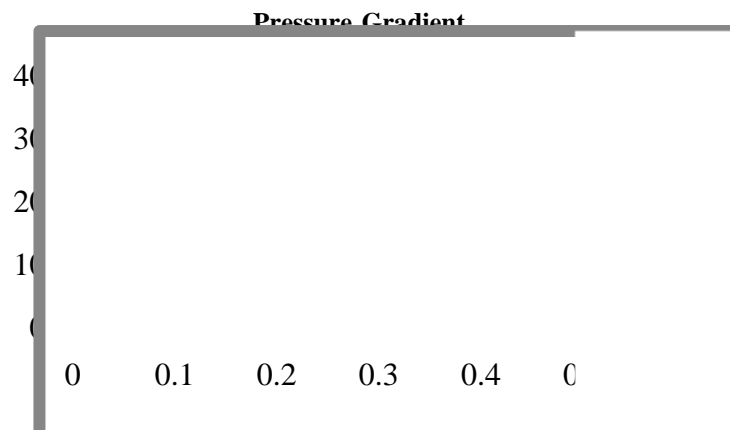


Fig.6.9 Pressure gradient curve for urban driving condition

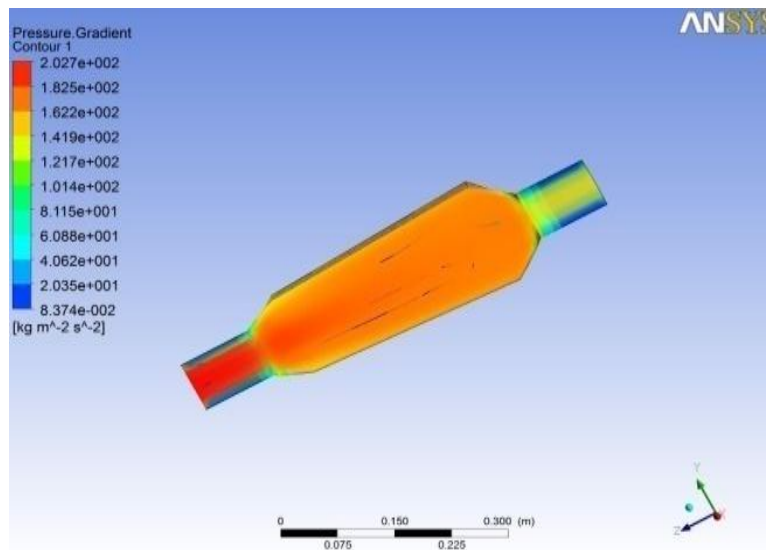


Fig. 6.10 Pressure gradient contour for sub urban driving condition

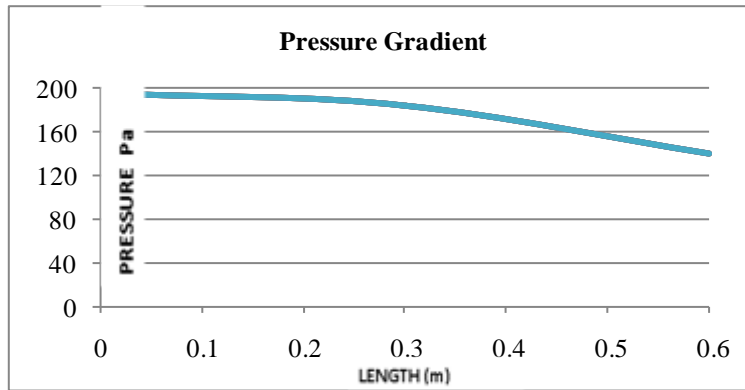


Fig 6.11 Pressure gradient curve for sub urban driving condition

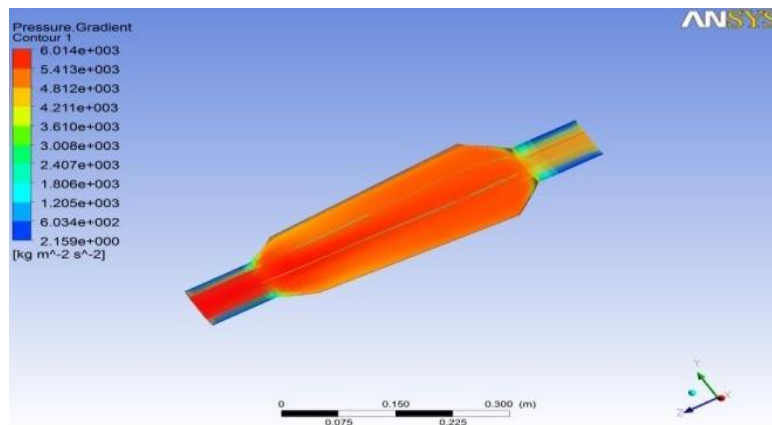


Fig. 6.12 Pressure gradient contour for max. power driving condition.

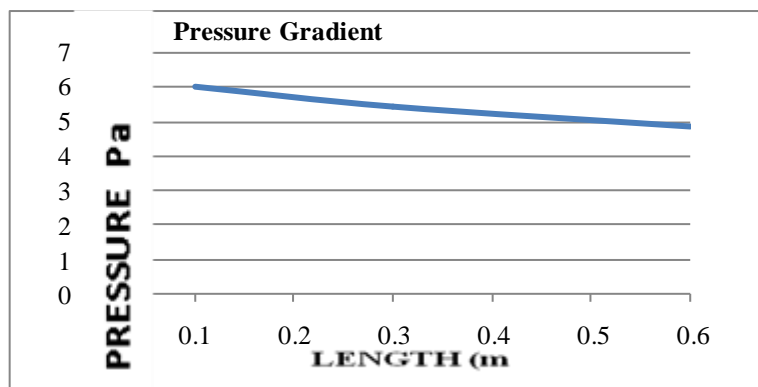


Fig.6.13 Pressure gradient curve for max. power driving condition

Table 6.1 summary of calculated power output for the three driving conditions by TEG

Mass flow rate (g/s)	5.7 g/s	14.4g/s	80.4 g/s
Inlet Temp. (K)	574 K	674 K	874 K
Inlet Pressure (KPa)	300 KPa	300 KPa	300 KPa
Hot side surface Temp	458K	556K	790K

(K)			
Cold side Temp (K)	304K	304K	304K
TEG Voltage (Volts)	0.0448Volts	0.0724Volts	0.1400Volts
Total voltage by 8 TEG modul (Volts)	0.359V	0.589V	1.120V
Voltage after Boosting Vout (Volts)	2.38 Volts	3.85 Volts	7.46 Volts
Current I(A)	0.25 Amp	0.4 Amp	0.75 Amp
Power P=VI Watt	0.596watt	1.55watt	5.7watt

Table 6.2 Effect of design optimization on surface temperature, heat transfer rate and pressure drop.

SR. NO.	PARAMETERS	PREVIOUS DESIGN	NEW DESIGN	EFFECT OF OPTIMIZATION
1.	SURFACE TEMPERATURE			
a)	URBAN DRIVING	423 K	458 K	INCREASED BY 8.51 %
b)	SUB URBAN DRIVING	583.5 K	556 K	REDUCED BY 4.88 %
c)	MAX. POWER DRIVING	-	790 K	-
2.	HEAT TRANSFER RATE			
a)	URBAN DRIVING	597 W	693 W	INCREASE BY 16.08 %
b)	SUB URBAN DRIVING	1737 W	1294 W	REDUCED BY 25.5 %
c)	MAX. POWER DRIVING	14971 W	2421 W	REDUCED BY 83.82 %
3.	PRESSURE DROP			
a)	URBAN DRIVING	1.3 Kpa	24.15 Pa	PRESURE DROP IS REDUCED BY 97 %
b)	SUB URBAN DRIVING	9.7 KPa	182.5 Pa	
c)	MAX. POWER DRIVING	190.7 KPa	5.413 KPa	

VII. Conclusions

Outcome of the investigation and Thermal analysis which is done in ANSYS FLUENT are as follows:

- The temperature contours shows that the surface temperature attained in rectangular shaped exhaust heat exchanger with gradually increasing cross sectional area is uniform and better as compared to the previous models.
- The optimized rectangular exhaust heat exchanger design gives mean surface temperature exchanger of 458K for urban driving cycle, 556K for sub urban driving cycle and 790 K for maximum power driving cycle.

- By removing the internal fins from the exhaust heat the pressure drop is reduced. The pressure gradient is uniform throughout with nominal pressure drop of 24.15 Pa for urban driving cycle, 182.5 Pa for sub urban driving cycle, 5.413 Kpa for maximum power driving cycle.
- From the velocity contour it is very clear that in rectangular shaped TEG the exhaust is distributed uniformly over the profile. The heat transfer rate has been increased as shown by wall heat flux contours.
- The calculated power generated by TEG module ranges from 0.5 watt to 5.6 watt.

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