Design and simulation of heat sink for exhaust heat recovery system using thermoelectric generator

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Abstract: Heat sinks are a classification of heat exchangers ideally utilised in electronics to cool them. They can be simply fabricated, have low cost and are reliable for heat dissipation purpose. The protruding surfaces from them are called fins. They can be flat-plate or pin shaped. The aim of the present study is to investigate the performance characteristics of a heat sink. The materials and the fin design will be used as two major factors to increase the heat dissipation from the test apparatus. The project will show a three-dimensional analysis, using COMSOL 5.3a, which will verify with accessible exploratory information in the existing data for a continued finned heat sink. It will also identify the heat dissipation and mean temperature distribution of the heat sink for natural convection. Before moving on to design and simulation of heat sink, the first aim was to construct and simulate a leg of a thermoelectric generator model for obtaining the optimum working region of the thermoelectric generator taking into consideration the properties such as temperature difference and heat transfer coefficient. Therefore, available research techniques are briefed upon which enhance the heat removal from heat sinks.

Keywords: Heat Sink, thermoelectric generator, temperature difference, heat dissipation, three-dimensional analysis

1. Introduction

In the 21st century, with the continuous development in the field of electronics and automobile devices in the direction of increased performance while keeping the size small, heat dissipation problems and waste heat recovery becomes a big obstacle to its development [1]. The optimization of the thermal design of a heat sink dwells into minimizing the size as well as the mass of the heat sink while improving the heat removal capacity. Recovering waste heat through exhaust gas can be conducted through various recovery technologies [2]. The scope of this paper is to cover one such technology while aiming to optimize its efficiency.

Exhaust gas recovery using a heat sink can be typically utilised to increase the temperature or air in the combustion process thereby increasing the thermal efficiency of the combustion and decrease in consumption of fuel. With major concerns surrounding the efficiency of an Internal Combustion engine, various machineries and modernisations have been executed, one of which is the using a thermoelectric generator. In the late 20th century, many automotive manufacturers adopted
thermoelectric generators in their vehicles and from then on, the work on automotive exhaust system with thermoelectric generators has gained momentum. So, an important application of thermoelectric generators is waste heat recovery.

Much research has been done with respect to exhaust heat utilization from automobile engines. Shen Z et. al. [3] talks about the present status, roadblocks, and forthcoming prospects of automobile exhaust thermoelectric generator. At the same time Patowary et. al. [4] talks about the conversion of waste heat from IC engines, its applications, issues, and subsequent solutions. There are certain advantages of using thermoelectric generators such as low failure rate, noise free operation and stationary components. However, due to its energy conversion efficiency being low of around 5-7% and inability to produce higher power at lower temperature gradient, it is not an exceedingly popular option [5].

In this study, we are designing a heat sink that will effectively increase the efficiency of a thermoelectric generator by providing the optimum temperature region (\(\Delta T\)) and heat transfer coefficient for heat dissipation. In the novel work by Tuckerman and Pease [6], the optimization of the objective (heat sinks) was done subject to several constraints: the flow through the channels were developed fully as well as laminar in nature, the Nusselt number was fixed, and the design dimensions were varied. The works of Hamdi et.al. [7] is a review of the previous heat sink design and dwells into available research regarding active and passive practises for enhancing removal of heat from heat sinks.

On the other hand, Maha Ali et. al. [8] aims at the review of previous studies on heat sinks from a different approach i.e., providing help to understand the cooling ability of heat sinks based on specific geometries. Experimental results from Sheam-Chuyun et. al. [9] showed that the heat sink with oblique and planar fins exhibit better performance than typical vertical fins. At the same time numerical results from Ghanbarpour et. al. [10] displayed that the height and fin number were more effective than its thickness in reducing the temperature of the source.

In some IC engines, ideally diesel fuelled ones, a fraction of the exhaust gas is cooled down and then mixed with air in an Exhaust Gas Recirculation (EGR) system to lower the Nitrogen Oxide(s) emissions. This gives better efficiency to the engine. Another technology which utilises the heat from exhaust gas is turbocharging as it improves the engine power. The problem occurs when we realise that only a tiny fraction of the energy can be converted into useful work while the remaining is expelled [11].

This is where a thermoelectric generator steps in, wherein the electricity that is produced can be stored as well as utilised for numerous inputs of a vehicle thereby improving fuel efficiency. Such a system was first developed by Neild [12] and Serksnis [13]. It was much later when in 1990 Bass et. al. [14] depicted a thermoelectric generator module which was made of Bismuth Telluride material. There has been an exponential increase over the past 15 years in the research output on Bismuth Telluride based thermoelectric generators. Therefore, the thermoelectric generator used for our simulation was the same as above mentioned material. Figure 1 shows a typical thermoelectric generator.

![Figure 1 – A simple diagram of a thermoelectric generator][23]
Heat sinks have great heat transfer capabilities and have a variety of applications in industries [17]. They come in various shapes such as cylindrical, rectangular, etc., all aimed at increasing the efficiency [18]. Figure 2 shows a standard pin fin heat sink.

![Figure 2 - A Standard pin fin heat sink [24]](image)

Flat plate heat sinks are more popular heat sink designs and many researchers have tried to enhance the heat transfer performance of a flat plate heat sink by making holes and creating rough surfaces. This was covered by Singh P et. al. [19]. Figure 3 shows a standard flat plate heat sink.

![Figure 3 - Flat plate aluminium heat sinks [25]](image)

One of the most extensive works which numerically and experimentally examined the rate of heat transfer for a pin fin under natural convection were by Mao Yu et. al. [20]. The study found out that the base plate, fin height and holes in the base plate were major influences on the heat transfer coefficient. The major influence of work by Singh G et. al. [21] who analysed the performance of a heat sink by designing and simulating a model with Ansys software. An experimental work was presented by Shitole et.al. [22] to calculate the transfer rate of the heat by using a vertical perforated plate in natural convection condition. It was inferred from the results that heat transfer increases by increasing the heat input supply as well as the perforation area.

In brief, the heat sink for TEG is of great importance for the exhaust heat recovery system for IC engines and motivates for research interests. The larger temperature difference makes great impact on electrical output for TEG. To achieve this, the research work was compared between the two predominant heat sink designs- a flat plate fin and a pin fin heat sink. In our work we created a model of heat sink of 40*40*4 mm³ base plate on which different flat plate and pin fin configurations were simulated. The heat dissipation and temperature difference of the heat sink under natural convection was simulated using COMSOL 5.3a software. The results obtained will contribute to enhance the performance of TEG with proper design of heat sink.
2. Theoretical model

For our study there were two items that required parameters for an output. For the thermoelectric generator leg, the parameters taken were Heat Transfer Coefficient (h) (W/m²K) and Temperature Difference (∆T) (K). The parameters for the design and subsequent simulation of the heat sink were Type of fins, number of fins and fin configuration for the design and thermal gradient, heat flux and temperature distribution for evaluating the output characteristics of the design at hand.

First, a leg of a thermoelectric generator model was created using COMSOL 5.3a. The purpose of this was to study the characteristics of the model by varying the temperature difference and the heat transfer coefficient between the hot and cold sides of the leg of thermoelectric generator. The leg of the thermoelectric generator consisted of the semiconductor region and the contact plates. The semiconductor was made of Bismuth Telluride (Bi2Te3) and the contact plate was made of Copper (UNS C10500). After the materials of the TEG leg were given, it was then fine meshed using the mesh option available in the software as shown in Figure 4.

![Figure 4 – Fine meshed picture of the TEG leg](image)

Then the hot and cold side of the leg of the thermoelectric generator was determined and subsequently the temperature input was given to it. For the simulation, the cold side of the thermoelectric generator was kept at 300K and the hot side temperature varied in increments of 100K. This helped us better understand the optimum working region of the thermoelectric generator where it works best and produces the best possible output.

Further the cold side was given a heat transfer coefficient (h) value and the hot side was kept at 400K. The heat transfer coefficient was varied in increments of 10 W/m²K for each simulation and the results were obtained. This helped us better understand the optimum heat transfer coefficient of the heat sink that it is supposed to have for best heat dissipation which further leads to increased temperature difference and hence the thermoelectric generator will work better.

For heat sink simulation, a base of 40*40*4 mm³ was created using Fusion 360 software and flat plate fins and pin fins were arranged on top surface of the base and the results were simulated.
For flat plate fin, 10 fins of 40*1*8 mm³ was modelled on the heat sink base (Figure 5) and a heat source of 100W was applied on the bottom of the heat sink base. The top of the fins was kept constant at 298K, and the simulation was done.

![Figure 5](image)

**Figure 5** – Flat plate heat sink used for simulation using Autodesk Fusion 360

For pin fin, 16 pin fins of cylindrical shape of 5 mm diameter and 8mm height (Figure 6), were arranged on the sides of the heat sink base and bottom of the heat sink base was given a heat source of 100W and top of the fins were kept constant at 298K, and the simulation was done.

![Figure 6](image)

**Figure 6** - Pin fin heat sink used for simulation using Autodesk Fusion 360
3. Results and Discussion

3.1 Temperature distribution

For different ∆T values the cold side was kept at 300K and the hot side was kept at 400K, 500K, 600K, 700K and 800K respectively, and the results were obtained. This determined the temperature distribution inside the thermoelectric generator at the above-mentioned temperatures. Figures 7 - 11 shows the results for temperature distribution at different ∆T values.

Figure 7. Temperature distribution at ∆T 100K  Figure 8. Temperature distribution at ∆T 200K  Figure 9. Temperature distribution at ∆T 300K  Figure 10. Temperature distribution at ∆T 400K
For different heat transfer coefficient (h) values the hot side was kept at 400K and the cold was given the heat transfer coefficient of 40, 50, 60, 70, 80 and 90 (W/m²K) and the results were obtained. This showed the temperature distribution with respect to the heat transfer from the cold side where the heat sink will be attached. Figures 12-17 shows the temperature distribution for different h values.

**Figure 11.** Temperature distribution at ∆T 500K  
**Figure 12.** Temp. distribution at h 40 = W/m²K

**Figure 13 –** Temp. distribution at h = 50 W/m²K  
**Figure 14 –** Temp. distribution at h = 60 W/m²K
3.2 Isothermal Contour

For different $\Delta T$ values and the heat transfer coefficient ($h$) values, the isothermal contours were obtained which gave us a very elaborate idea as to how the thermoelectric generator behaves in the above-mentioned temperature regions and it showed the step wise temperature distribution within the
thermoelectric generator. Figures 18 - 22 are the plots for the isothermal contours at different $\Delta T$ values.

**Figure 19** - Isothermal contour for $\Delta T=200K$

**Figure 20** - Isothermal contour for $\Delta T=300K$

**Figure 21** - Isothermal contour for $\Delta T=400K$

**Figure 22** - Isothermal contour for $\Delta T=500K$

Figures 22 - 28 shows the isothermal contour distribution for the different heat transfer co-efficient (h) values.
Figure 23 - Isothermal contour for $h=40 \text{ W/m}^2\text{K}$

Figure 24 - Isothermal contour for $h=50 \text{ W/m}^2\text{K}$

Figure 25 - Isothermal contour for $h=60 \text{ W/m}^2\text{K}$

Figure 26 - Isothermal contour for $h=70 \text{ W/m}^2\text{K}$
3.3 Electric Potential

The amount of electric potential that was being generated inside the thermoelectric generator for the different $\Delta T$ values is shown in figures 29 – 33. It can be clearly observed that more the temperature difference between the hot and cold side of the Thermoelectric generator, more is the electric potential that is produced.
Figures 34 - 39 shows the electric potential produced in the TEG when different heat co-efficient values were given to the cold side of the TEG leg. This also accounts for the heat transfer coefficient (h) values as high h values increases the temperature dissipation resulting in lowering of temperature of the cold side more drastically and hence the temperature difference increases, and more electric potential was produced in the simulated results obtained.
Figure 35 - Electric Potential at $h=50 \ W/m^2K$

Figure 36 - Electric Potential at $h=60 \ W/m^2K$

Figure 37 - Electric Potential at $h=70 \ W/m^2K$

Figure 38 - Electric Potential at $h=80 \ W/m^2K$
1-D plot shows the graph between the terminal voltage (V) and terminal current (A) that is produced by the thermoelectric generator for the various simulations that were carried out. Figures 40 – 44 shows the 1-D plot for the various ΔT values.

**Figure 39 - Electric Potential at h=90 W/m²K**

**3.4 1 Dimensional plot**

**Figure 40 - 1D Plot at ΔT=100K**

**Figure 41 - 1D Plot at ΔT=200K**
Figure 42 - 1D Plot at ΔT=300K

Figure 43 – 1D plot at ΔT=400K

Figure 44 - 1D Plot at ΔT=500K

Figure 45 - 1D plot for h=40 W/m²K

Figure 46 - 1D plot for h=50 W/m²K

Figure 47 - 1D plot for h=60 W/m²K

Figure - 45, 46, 47, 48, 49 and 50 show the 1-D plot for the various heat transfer co-efficient value given to the cold side of the TEG leg.
Figure 48 - 1D plot for \( h = 70 \, \text{W/m}^2\text{K} \)

Figure 49 - 1D plot for \( h = 80 \, \text{W/m}^2\text{K} \)

Figure 50 - 1D plot for \( h = 90 \, \text{W/m}^2\text{K} \)
3.5 Heat Flux

The results for flat plate fin (Figure 51) showed that the heat flux of 0.08887 W/mm² (maximum) and 0.03422 W/mm² (minimum) was obtained. For pin fin simulation (Figure 52) the heat flux obtained were 0.3466 W/mm² (maximum) and 0.009655 W/mm² (minimum).
3.6 Temperature distribution

The results for flat plate fin (Figure 53) showed the maximum temperature of 30.23°C (303.38K) and minimum temperature of 25°C (298K). For pin fin simulation (Figure 54) the maximum temperature obtained was 48°C (321.15K) and minimum temperature of 25°C (298K). The minimum temperature for both flat and pin fin heat sinks were 25°C (298K) as the top sides of the fins were given a constant value.
3.7 Thermal Gradient

For flat plate heat sinks (Figure 55), the thermal gradient of 0.5137°C/mm (maximum) and 0.1978°C/mm (minimum) was obtained. For the pin fin heat sink (Figure 56), the thermal gradient of 2.004°C/mm (maximum) and 0.05581°C/mm (minimum) was obtained. These results show that the temperature dissipation was more in the pin fin heat sink as the decrease in temperature per millimetre was more and hence more heat loss to the surroundings from the heat sink.

Figure 55 - Thermal gradient for flat plate heat sink

Figure 56 - Thermal gradient for pin fin heat sink
4. Conclusion

The TEG leg simulation using the two parameters, temperature difference (ΔT) and heat transfer coefficient (h) proved that higher the difference in temperature between hot and cold sides of the TEG, more electrical output is produced. As the h values correspond directly to the heat dissipation rate of the heat sink, it contributes to lower the cold side temperature.

From the heat sink simulation, it is evident that the pin fin heat sink provides maximum heat dissipation, as it has a heat flux of around 0.3466 W/mm$^2$ and thermal gradient of 2.004°C/mm. This maximum heat dissipation from the pin fin heat sink will provide more temperature difference and hence maximum output from the TEG.

Acknowledgment

We acknowledge IIT Delhi for carrying out the COMSOL 5.3a simulation work.

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