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Analysis & Comparative Study on Different Cooling Systems of Motorbike Engines and Implementation of Thermoelectric Generator (TEG) on the Exhaust System.

B.Sc. Engineering (Mechanical) Thesis

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Research Certification

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Candidate's Declaration

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or professional qualification.

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1. Abstract

For a smooth running of the engine as well as to maintain an optimum performance, the engine needs to be cooled down. With the number of motorbikes increasing day by day in Bangladesh, finding an optimum cooling system for the motorbike engine is essential. Three different cooling systems are mostly used in the motorbikes engine of Bangladesh. With air cooling system being used broadly, oil cooling and liquid cooling are also applied. Comparing all the important features of the three cooling systems and their environmental impacts will help finding the most feasible cooling system for the motorbikes of Bangladesh.

On the other hand, around 30 to 35% of energy of an IC engine is used to run the vehicles and the rest is wasted as heat. This results in entropy rise and serious environmental pollution. In our study, a waste heat recovery system using a thermoelectric generator (TEG) designed for an I.C. engine is proposed & implemented. Specifically the system converts the waste heat from the exhaust manifold into electrical energy using a TEG. Our experimental data analysis & the result show that this setup can recover a considerable amount of heat.

Keywords – Cooling systems, motorbikes, comparison, environmental impact, waste heat, Thermo-electric generator, recover

2. Acknowledgements

We express our heartiest gratefulness to Almighty Allah for His divine blessings, without which it would not have been possible to complete this thesis successfully.

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3. Abbreviations

TEG- Thermo Electric Generator

TEM- Thermo Electric Module

IC- Internal Combustion

SOHC- Single Overhead Cam

AC- Air Conditioning

ECU- Electronic Control Unit

Pr- Prandtl Number

NO_x- Nitrogen Oxide

RPM- Revolutions per Minute

SFC- Specific Fuel Consumption

EGT – Exhaust Gas Temperature

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Chapter 1. Introduction

The motorbike cooling system plays an important role in the overall efficiency of the motorbike engine. a motorcycle engine burns the fuel in support of air and produces power to derive the motorcycle on the road. Therefore air & fuel mixture that compressed in the combustion chamber inside the motorcycle engine and then burns and produces power. That power drives the engine parts and finally delivered to the wheel and a motorcycle moves. Whatsoever in this combustion process, the engine also generates a huge amount of temperature besides producing power. Here actually a standard temperature condition is needed for efficient combustion therefore operating the motorcycle engine. But at the running the engine produces huge & access heat over the standard limit and that is wastage. And this access heat is unnecessary which harmful for an engine. Hence motorcycle engine cooling system works here to control the temperature within the standard limit cutting off the access heat. Commonly there are two basic cooling systems are very frequent in motorcycle engine cooling system. The air cooling and liquid cooling is a very well-known cooling feature for the motorcycle engine. Besides these two types of systems, there one more type of system also available which is an oil cooling system. Finding the optimum cooling system, keeping the environmental effect in mind, will benefit a great deal.

Now for the implementation of TEG, the idea is to recover some heat from the exhaust of a motorbike engine. If approximately 6% heat can be recovered from the engine exhaust, it can meet the electrical requirements of an automobile and thus it would be possible to reduce the fuel consumption by around 10% [1]. Heat is rejected through exhaust gases at a very high temperature when compared to heat rejected through coolant and lubricating oil. This shows the possibility of energy conversion using a thermoelectric generator (TEG) to utilize the exhaust heat energy. TEG is like a heat engine that converts the heat energy into electric energy and it works on the principle of the Seebeck effect. Moreover, TEG is highly reliable, operate quietly and are usually environmentally friendly [2]. Semi-conducting materials (in conjunction with copper inter-connecting pads), were found to offer the best combination of Seebeck coefficient, electrical resistivity, and thermal conductivity. Semi-conducting materials provide another benefit, the ability to use electrons or “holes” (the absence of an electron in a crystal matrix) to conduct current [3]. The thermoelectric module (TEM) has a cold side and a hot side. On the hot side, heat is absorbed by electrons as they pass from a high energy level in the n-type semiconductor element, to a lower energy level in the p-type semiconductor element. The power supply provides the energy to move the electrons through the system. At the cold side, energy is expelled to a heat sink as electrons move from a high energy level element (n-type) to a lower energy level element (p-type) [4]. By using the modules in reverse, where a temperature differential is applied across the faces of the module, it is possible to generate electrical power [5]. Although power output and generation efficiency are presently low, useful power often may be obtained where a source of heat is available.

1.1 Research Aims and Objectives

This paper identifies the optimum cooling system on a motorbike engine from the perspective of Bangladesh. It helps understand the importance of an ideal cooling system for motorbikes in various conditions. The second study identifies the problem of waste heat of an Internal Combustion motorbike engine. With these aspects in mind, below are the objectives and aims of our study.

- To find the most viable cooling system for various motorbikes in Bangladesh.
- To compare the economical feasibility of the existing cooling systems.
- To implement TEG on the exhaust system and analyze the capability of recovering waste heat.
- To present TEG as a possible solution to recover an amount of energy from the exhaust gas by implementing it on the exhaust system.

1.2 Cooling System

A system, which controls the engine temperature, is known as a cooling system. Internal combustion engine cooling uses either air or liquid to remove the waste heat from an internal combustion engine. For small or special purpose engines, cooling using air from the atmosphere makes for a lightweight and relatively simple system. Heat engines generate mechanical power by extracting energy from heat flows, much as a water wheel extracts mechanical power from a flow of mass falling through a distance. Engines are inefficient, so more heat energy enters the engine than comes out as mechanical power; the difference is waste heat which must be removed. Internal combustion engines remove waste heat through cool intake air, hot exhaust gases, and explicit engine cooling.

Engines with higher efficiency have more energy leave as mechanical motion and less as waste heat. Some waste heat is essential: it guides heat through the engine, much as a water wheel works only if there is some exit velocity (energy) in the wastewater to carry it away and make room for more water. Thus, all heat engines need cooling to operate.

There are three major cooling systems used in Motorbikes in Bangladesh.

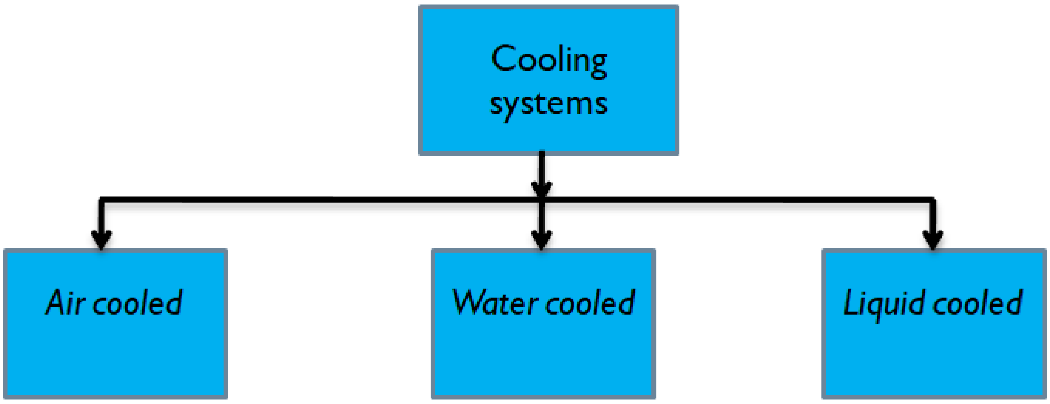

Figure 1.1 Major Cooling systems

1.3 Thermo-electric Generator (TEG)

TEGs are devices capable of converting residual thermal energy directly into electrical energy,

increasing the efficiency of the entire system. Thermoelectrics have involved around three phenomena, the Seebeck Effect, Thomson Effect, and the Peltier effect. TEGs have been successfully reported in several sectors, such as automotive, aerospace, industrial, and bioengineering. The Seebeck effect is the direct conversion of temperature differences to electric voltage and vice versa (Peltier Effect) via a thermocouple. A thermoelectric device creates a voltage when there is a different temperature on each side. Conversely, when a voltage is applied to it, heat is transferred from one side to the other, creating a temperature difference. At the atomic scale, an applied temperature gradient causes charge carriers in the material to diffuse from the hot side to the cold side.

This effect can be used to generate electricity, measure temperature or change the temperature of objects. Because the direction of heating and cooling is affected by the applied voltage, thermoelectric devices can be used as temperature controllers.

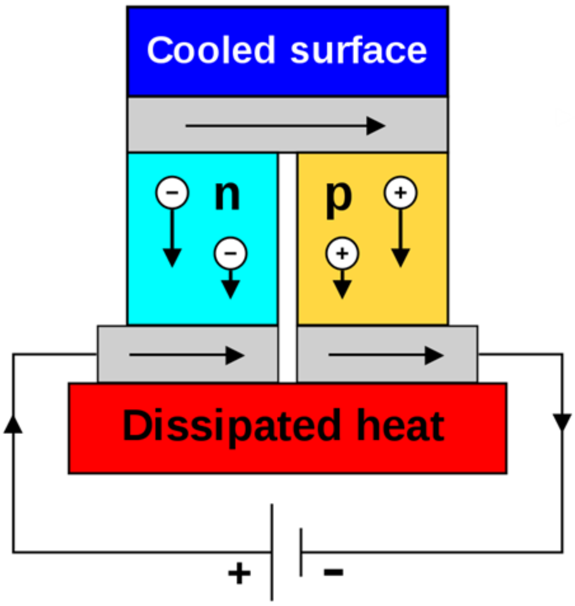

Figure 1.2 Simplified working principle of TEG

1.4 Thesis Organization

The thesis has been divided into seven chapters. The first chapter provides an introduction to the cooling systems and Thermo-electric generator along with research aims and objectives. Chapter 2 presents a literature review that examines the recent cooling systems of motorbikes used in Bangladesh and the performance of a TEG implemented on the exhaust system of IC engines. Chapter 3 demonstrates the structural, functional and analytical comparison of the cooling systems for the motorbikes of Bangladesh. The fundamentals and formulae related to the implementation of TEG will also be presented in this chapter. Chapter 4 reports the results found from the comparative analysis of the cooling systems from chapter 3 and further investigates the cooling system to find an optimum cooling system for the motorbikes of Bangladesh. Chapter 5 presents the design of a TEG model which will be implemented on the exhaust system of a 155 cc Liquid-cooled, 4-stroke, SOHC, 4-valve motorbike engine. The detailed demonstration of the design, as well as the logical explanations for the specific design, will be in this chapter as well. Chapter 6 represents the mathematical analysis of the designed TEG for various operating conditions of the 155 cc engine. Finally, conclusions and recommendations will be presented in Chapter 7.

Chapter 2. Literature Review

Several different studies were conducted on various applications of cooling systems and their effect on engine performance and cooling as well as the environmental impacts.

S. Palani and R. Irudhayaraj conducted tests on cooling systems to improve the performance with reduction of cost which demonstrated the various performance to cost ratio for the different cooling systems [9].

Masao Yoshida and Kohei Nakashima studied the effects of fins on a motorcycle engine. This study showed how the air cooling system works and what are the effects of the fins on engine cooling [10].

A.J Torregrosa n his paper of assessment of the influence of the different cooling system studied the various impacts of the cooling systems which indicated the performance difference of the cooling systems [11].

The Vienna researcher society studied the effect of various cooling system on the environment which is a key parameter for the comparative study of the cooling systems.

John Chastain in his study of internal combustion engine cooling strategies showed the impact of the major cooling systems on the performance of the engines.

Akbar and N Cahyono conducted studies on the cooling effectiveness of the v-Ixion motorcycle radiator using water coolant variation which showed how effective a cooling system with a radiator is. Their study also helped to understand the liquid cooling system [12].

On the other hand, recovering waste heat from the exhaust of an internal combustion engine has always been a vastly important field for researchers to study and practice the knowledge of thermodynamics and heat transfer mechanism. Among other ways of recovering waste heat, a thermo-electric generator has been studied thoroughly by many researchers.

Vasquez J in his study of the thermoelectric generators based on waste heat recovered from automobiles demonstrated how heat can be recovered from the exhaust of an IC engine of various automobiles. He also showed the use of that recovered heat energy by storing them on the battery [1].

Hank J. in his study of optimal design of a thermoelectric generator, designed the thermoelectric generator that can recover heat from the exhaust of an IC engine. He showed the materials and dimensions necessary to implement a thermoelectric generator which indicates the progressive study on this heat recovery system [2-3].

C. Ramesh Kumar and Ankit Sonthalia in their paper of experimental study on waste heat recovery from an internal combustion engine using thermoelectric technology showed the mathematical analysis of the thermoelectric generator and how it behaves under various conditions. Their experimental study established the relation between the thermoelectric generator's performance and the rpm of the engine and other factors that has an impact on the performance of the TEG [6].

J. S. Jadhao and D. G. Thombare further researched using a thermoelectric generator as a heat recovery system and reviewed the technology for future applications and mass production of this technology. Their study also indicated the positive impacts of implementing TEG as a heat recovery system [8].

Comparison of the Cooling Systems

3.1 Study of the cooling systems

A system, which controls the engine temperature, is known as a cooling system. A cooling system is needed mainly for preventing the materials of the cylinder and the components to not be damaged. If the heat is not dissipated properly it will greatly influence the performance of the engine and it would fail the cylinder material. Due to the high temperatures, the film of lubricating oil will get oxidized producing carbon deposits and it will result in piston seizure. Because overheating large temperature difference will lead to thermal stress buildup and low variation of thermal difference is recommended. On these points, it becomes necessary for a cooling system that will fulfil the requirements of the engine and work properly. The cooling system must remove about 30 per cent of the heat of the engine. Removing too much heat will result in lower thermal efficiency. There are Air cooling system, Oil cooling system, Water cooling system and Liquid cooling systems.

3.1.1 Air cooling

Air cooling is a method of dissipating heat. It works by expanding the surface area or increasing the flow of air over the object to be cooled, or both. An example of the former is to add cooling fins to the surface of the object, either by making them integral or by attaching them tightly to the object's surface (to ensure efficient heat transfer). In the case of the latter, it is done by using a fan blowing air into or onto the object one wants to cool. The addition of fins to a heat sink increases its total surface area, resulting in greater cooling effectiveness. There are two types of cooling pads are used in air cooling one is a honeycomb and another one is excelsior.

3.1.1.1 Structure

.The components that get the hottest, such as the cylinder and cylinder head, have fins, Figure 3.1, to direct the greatest amount of air into contact with the greatest amount of hot metal. When the engine is running, heat builds up in the cylinder head and cylinder. As the heat goes through the cylinder head and cylinder, it moves out into the cooling fins, as shown in Figure 3.2.

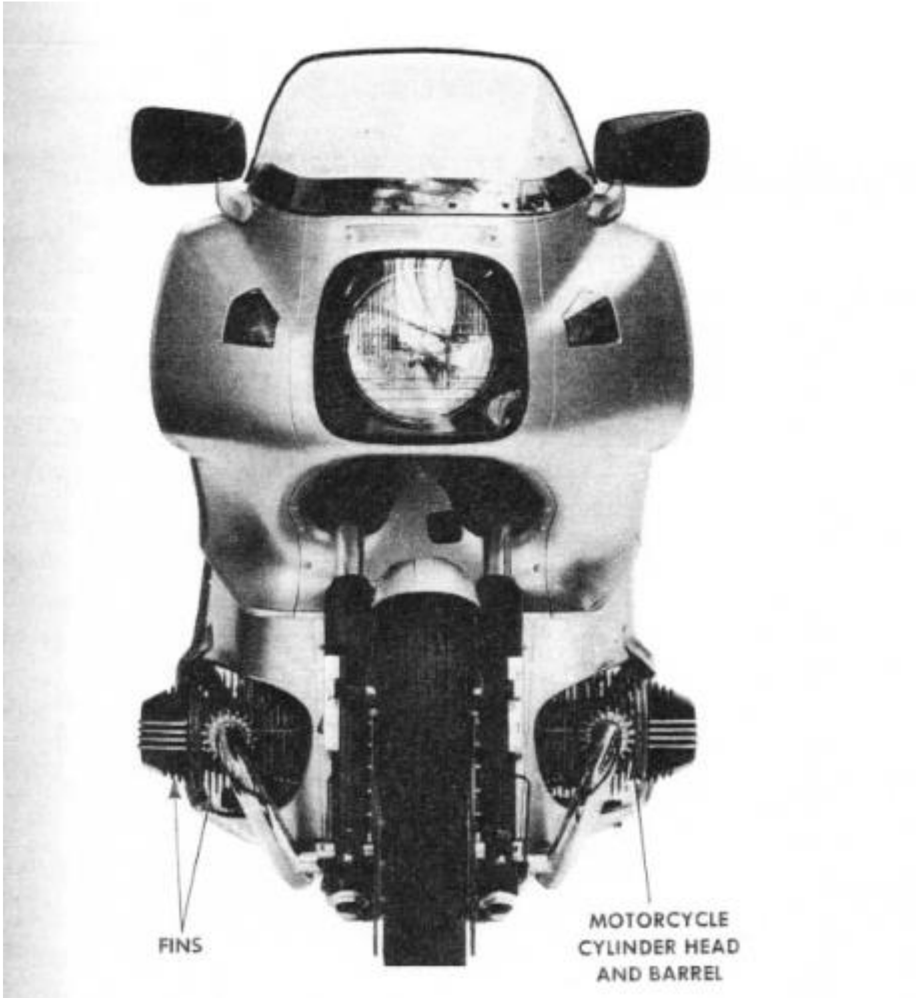

Figure 3.1 Air-cooled engines have cooling fins on cylinders and cylinder heads.

(B.M.W. of North America Inc.)

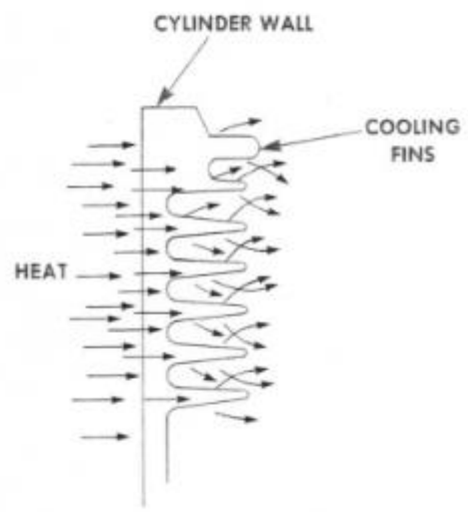

Figure 3.2 Heat goes through the engine parts and into the cooling fins.

When the vehicle is normally operated at a speed sufficient to provide enough air movement to transfer heat, the entire cooling system is merely the fins on the air-cooled engine. Many motorcycles are examples of this. But improved streamlining usually requires a smaller frontal area which demands narrower engines. In this case, cylinders have to be placed behind each other, and this requires ductwork (cowling) to ensure enough airflow to the rear cylinders of the engine. The shape of the cowling (Fig-3.3) guides the forced convection current around all the cylinders and provides a direct exist after the air has extracted and absorbed the heat from the engine. Some engine configurations, such as flat four-cylinder engines, employ baffles to improve the air distribution between cylinders and to direct additional air to critical components such as the oil-cooler. (Fig-3.4)

A fan or blower is installed in air-cooled engines, with little or slow movement of air, to sufficiently improve airflow past the fins. Most engines that use blower fans also use shrouds or ducts to ensure the flow of cooling air past the fins. Two classes of fan used with air-cooled engines are the radial flow type (Fig. 3.4C), where the air is flung outwards by centrifugal force, and the axial flow type (Fig. 3.4D), where the air is pushed along parallel to the axis of the fan spindle. The radial-flow fan is more compact for a given output but tends to be noisy. The axial-flow fan is more consistent, reliable and delivers large quantities of air. Hence, the former is used with small engines, while the latter is preferred for heavy duty high output engines.

The amount of blower air circulating between the cowling and the cylinders may be regulated by a throttle ring located on the inlet side of the fan. The function of this ring is to vary the effective inlet-passage exposed area of the fan to suit the operating conditions of the engine (Fig-3.5). This can be automatically achieved by incorporating a thermostat in a hot working region of the engine so that it senses the temperature change. When the engine is cold, the thermostat actuates either a linkage or a hydraulic servo connected to the throttle ring to restrict the air-flow to the fan. When the engine is hot, the restriction is removed, thus permitting more air to circulate. The thermostat provides the same benefits as those used on water-cooled engines and should always be in good working condition.

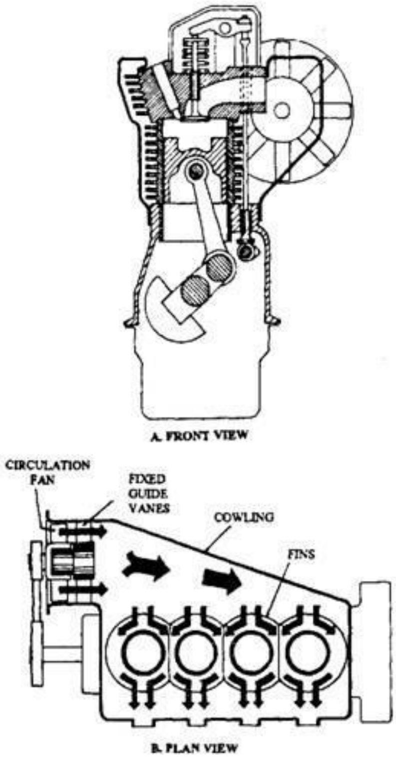

Figure 3.3 Air Cooling System

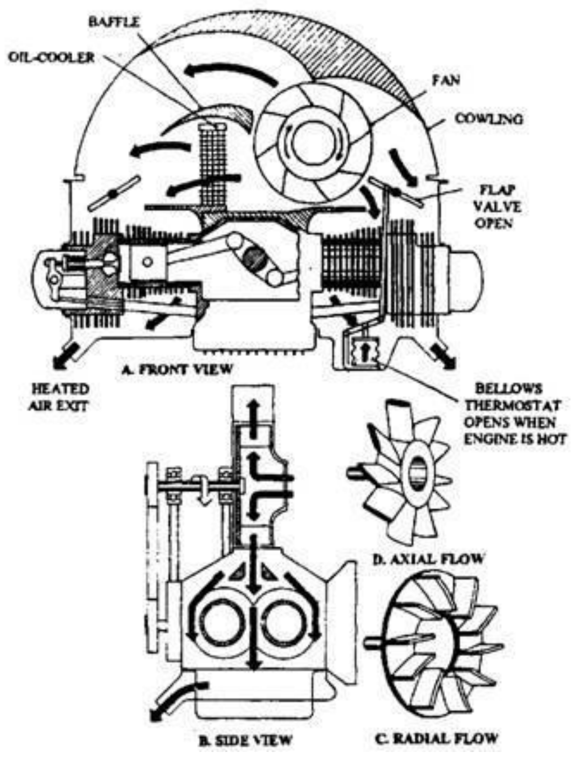

Figure 3.4 Air-cooling system for a horizontally opposed four-cylinder engine.

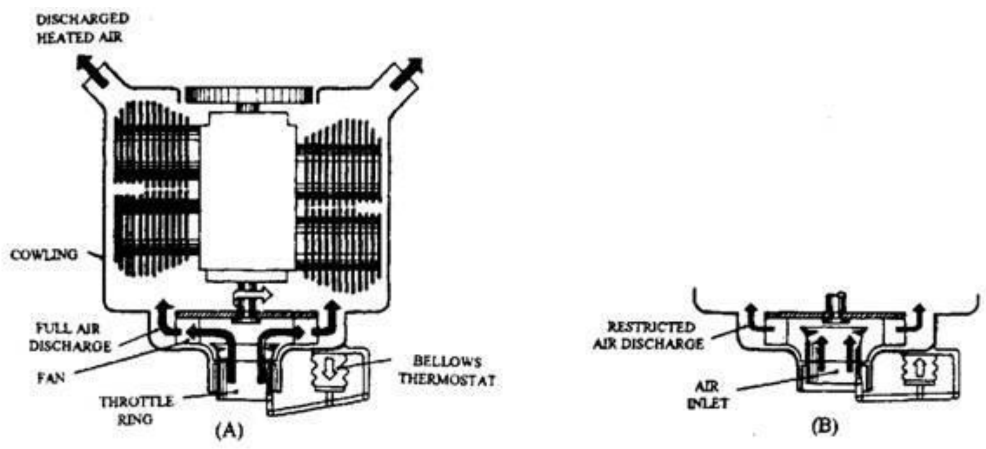

Figure 3.5 Air-cooled engine with fan discharge control. A. Thermostat opens the throttle ring. B. Thermostat closes the throttle ring.

3.1.1.2 Working Principle

In the air-cooling system, the heat is dissipated directly to the air after being conducted through the cylinder walls. Air cooling systems have fins and flanges on the outer surfaces of the cylinders. The heads serve to increase the area exposed to the cooling air, and so raise the rate of cooling. The basic principle involved in this method is to have a current of air flowing continuously over the heated surface of the engine from where the heat is to be removed. The amount of heat dissipated based on the following factors.

1. The surface area of metal into contact with air.
2. The rate of airflow.
3. A temperature difference between the heated surface and the air.
4. The conductivity of the metal.

For complete use of air-cooling, the surface area of the metal which comes in contact with air is improved by providing fins over the cylinder barrels. The more the surface area in a contact with air, the more the heat is dissipated. The higher the rate of airflow, the higher the heat is dissipated.

Similarly, the higher the temperature difference between the heated surface and the air, the higher will be the heat dissipation. A metal having conductivity dissipates more amount of heat.

3.1.2 Liquid Cooling

Liquid-cooled engines use a water-based liquid to cool the engine, but they do not use any regular water, be it hard, soft or tap water. They use a special coolant containing alcohol to prevent freezing and rusting/oxidation. This coolant is circulated through passages built into the engine. To ensure the coolant does its job efficiently, it passes through a radiator mounted to receive running airflow to lower its temperature and is then circulated again.

3.1.2.1 Structure

The liquid cooling system circulates liquid around hot engine parts to carry off the heat. Coolant passages called water jackets surround each cylinder in the block and the cylinder head very close to the valve area. The heat from the burning air-fuel mixture passes through the metal of the cylinder head and cylinder wall and enters the water jackets. The heat then goes into the liquid coolant circulating through the water jackets. Following are the main components used in a liquid cooling system.

- The Radiator
- Pressure Cap & Reserve Tank
- Pump
- Thermostat
- Bypass System
- Freeze Plugs
- Head Gaskets & Intake Manifold Gaskets
- Heater Core
- Hoses

The radiator core is usually made of flattened aluminium tubes with aluminium strips that zigzag between the tubes. These fins transfer the heat in the tubes into the air stream to be carried away from the vehicle. On each end of the radiator core is a tank, usually made of plastic that covers the ends of the radiator.

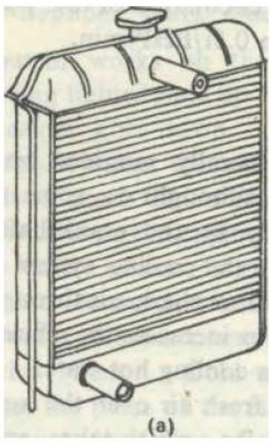

Figure 3.6 Radiator

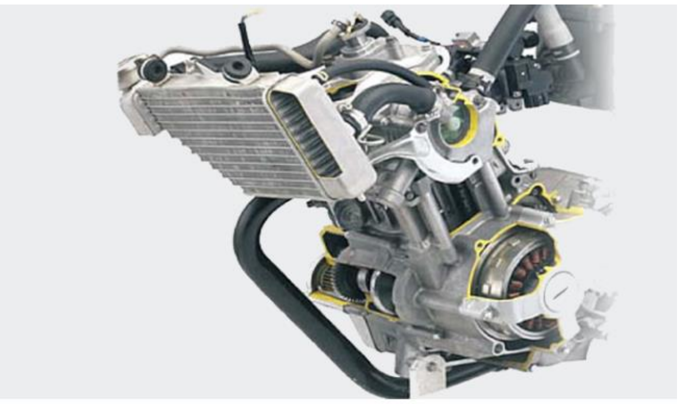

Figure 3.7 A radiator on the front of a liquid-cooled motorbike engine.

A water pump is a simple device that will keep the coolant moving as long as the engine is running. It is usually mounted on the front of the engine and turns whenever the engine is running. The water pump is driven by the engine through one of the following. A fan belt will also be responsible for driving an additional component like an alternator or power steering pump. A serpentine belt, which also drives the alternator, power steering pump and AC compressor among other things.

A liquid-cooled engine uses a thermostat to control the temperature effectively. When the engine is cold, the thermostat bypasses the radiator. It then circulates the coolant water within the engine; to quickly attain the engine's normal operating temperature. When the coolant temperature rises to certain degrees, (usually above 100 degrees Celsius); the thermostat opens and allows the coolant to enter the radiator to cool down.

3.1.2.2 Working principle

In the liquid-cooled motorcycle engine, there is a close loop of liquid coolant. They're also attached to a mechanical pump that circulates the liquid coolant within the loop.

The pump circulates the liquid toward the engine block, then to the cooling radiator and then the reservoir and ages toward the engine. Thus, the cycle continues.
Here in this system, the liquid coolant absorbs the access heat when flowing through the cylinder block or head and releases that heat when passing through the cooling radiator. Thus, it cools the engine and controls the temperature.

Here in case of an overheat situation the attached thermostat relays the signal to ECU. Accordingly, the coolant pump circulates the cooling liquid faster or if needed the radiator cooling fan starts to work to get the hot liquid of the radiator cool faster. So, you can see how precisely the liquid cooling system works.

Figure 3.8 Liquid cooled engine

3.1.3 Oil Cooling

Oil cooling is commonly used to cool high-performance motorcycle engines that are not liquid-cooled. Typically, the cylinder barrel remains air-cooled in the traditional motorcycle fashion, but the cylinder head benefits from additional cooling. As there is already an oil circulation system available for lubrication, this oil is also piped to the cylinder head and used as a liquid coolant. Compared to an oil system used solely for lubrication, oil cooling requires additional oil capacity, a greater flow rate through the oil pump, and an oil cooler (or a larger cooler than normal. This type of tech was marketed and made popular in India by Bajaj when they introduced it on their bigger Pulsars.

3.1.3.1 Structure

The structure of the oil-cooled engines quite similar to the structure of air-cooled engines. The oil that is used to lubricate the engine is also used to cool the engine in this cooling system. An additional oil cooler is used compared to an air-cooled engine. The purpose of the cooler is to circulate engine oil before it flows into the rest of the bike to lubricate various moving parts**.** Without any type of cooler, the oil used in your bike will likely overheat from the amount of friction the engine produces while operating. The oil serves a dual purpose for both lubricating the moving parts and keeping the bike cool enough to use. Some oil-cooled engine uses a radiator and some have a fin design like the air-cooled engine around the block to cool the engine.

If an engine is running at a higher temperature the oil becomes thinner and with the reduction in lubrication, friction between engine parts increases. To avoid this, and to make sure that oil maintains an optimal operating temperature; the oil is circulated between an ‘oil cooler’ shown in figure 3.8. This oil cooler is cooled by the flowing air and it cools down the engine oil.

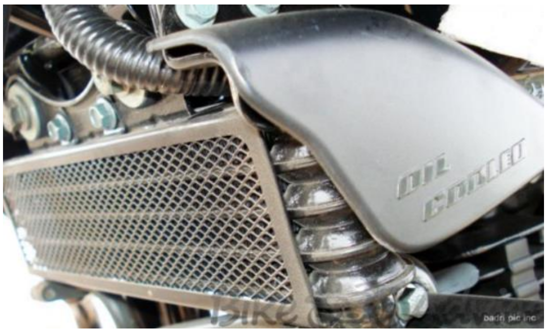

Figure 3.9 A radiator-like system used to cool the oil

3.1.3.2 Working principle

In the oil-cooled engine, the oil circulating in a wider range inside the engine. It absorbs the access heat and releases the same through the cooling radiator. So it also derived through quite the same type of cooling radiator and oil pump. Here the engine sump serves as an oil reservoir. Hence for the cooling system and channel circulation, it needs an additional volume of oil.

Typically in an oil-cooled motorcycle engine, the cylinder block and cylinder head assembly remain air-cooled and it constructed quite the same as an air-cooled engine. Therefore the cylinder block & head constructed with quite the same type of thin metal fins for the air cooling feature.

Figure 3.10 Passages on the engine for the oil to circulate

The oil goes through the engine block cooling and lubricating the engine cylinders and comes down to an oil collector which is called a sump. Then the oil is pumped directly to the crankshaft, connecting rod, piston pin, timing gears and camshaft of the engine through suitable paths of oil. Usually, the oil first enters the main gallery, which may be a pipe or a channel in the crankcase casting. From this pipe, it goes to each of the main bearings through

holes. From main bearings, it goes to big end bearings of connecting rod through drilled holes in the crankshaft. From there, it goes to lubricate the walls, pistons and rings. There is a separate oil gallery to lubricate timing gears. The lubricating oil pump is a positive displacement pump, usually gear type or vane type. The oil also goes to the valve stem and rocker arm shaft under pressure through an oil gallery.

Besides there also a cooling radiator is attached outside the engine like the liquid-cooled engine. But here the radiator size and dimension is different. The radiator set here the same way facing the high airflow line and it cools the hot oil by the flow of air.

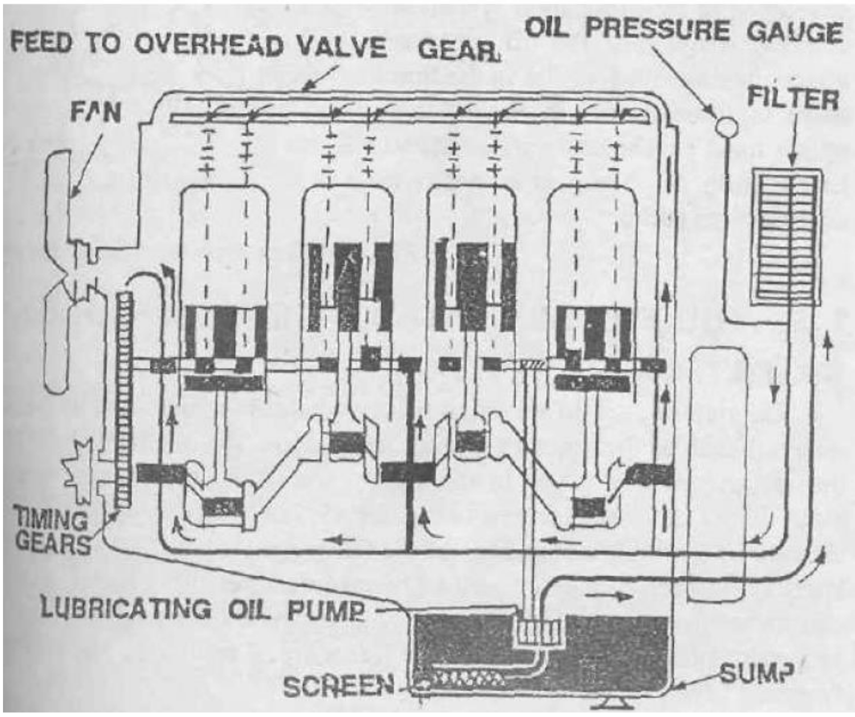

Figure 3.11 General Lubricating system of an IC engine where the oil works as a coolant

1.

3.2 Comparative Analysis

3.2.1 Structural Comparison

The main structural difference between the three cooling systems is their size and how they operate. The air cooling system is the most compact one while liquid cooling is the biggest of the three. Oil cooling is similar to air cooling but it has two main components which air cooling does not have. One of the components is a passage for the oil to go through the engine blocks which is shown in figure 3.9 and the other component is a separate cooler for the oil. The oil is mainly the part of the lubrication system used to reduce the friction of the engine cylinders, pistons and other moving parts. On the other hand on the liquid cooling system, there are more components in the system which are not used in the other two systems. In the liquid cooling system, there is a cycle through which the liquid goes from its reservoir to the engine block and comes back to the reservoir. There are a dedicated pump, thermostat and a radiator for the liquid cooling system which are not seen on the air and oil cooling system.

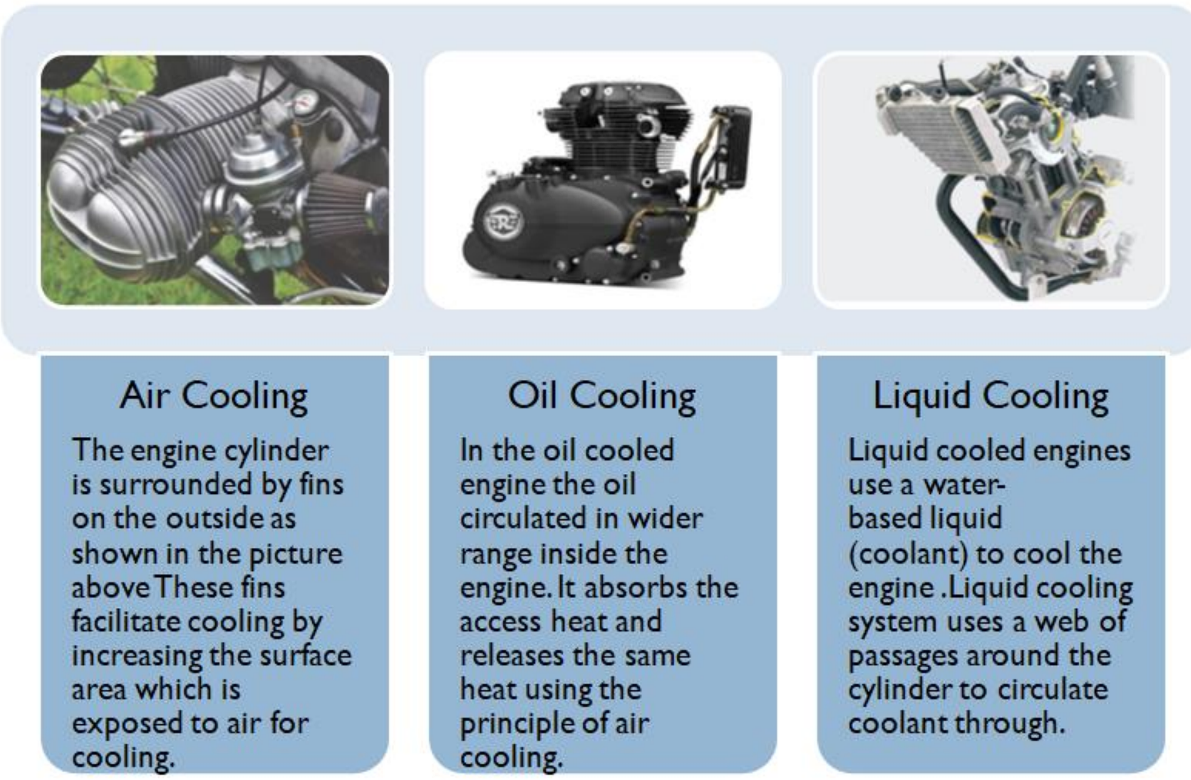

Figure 3.12 Comparison of the structures of the three systems

3.2.2 Performance Comparison

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Table 3.1

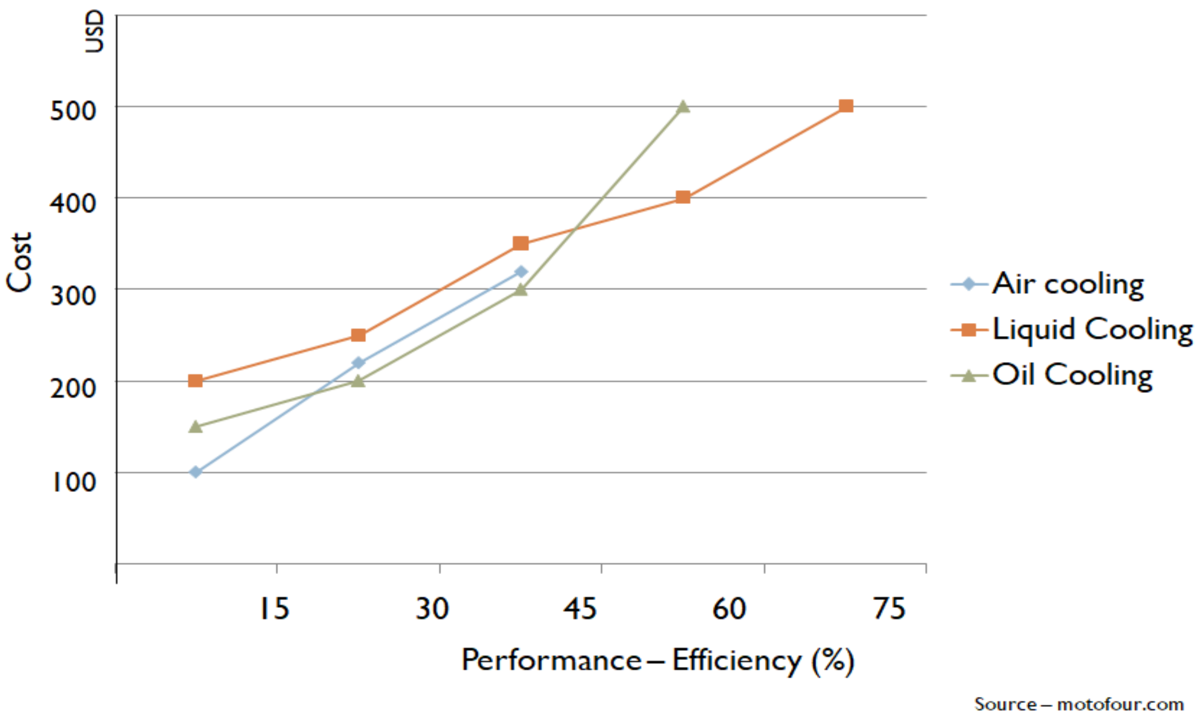
Subject	**Air Cooling**	**Oil Cooling**	**Liquid Cooling**
Average Heat Absorption (mostly convection which largely depends on Prandtl number)	0.7	1-10	50-2000 Pr is high, so it has the most heat absorption capability.
Temperature Rise or Effectiveness (decided by the specific heat capacity of the medium)	1.004 kJ/kgC	4.182 kJ/kgC As Cp is inversely proportional to temperature rise, it's better.	2.2 kJ/kgC
Noise	Air cooling system are the noisiest	Oil cooling runs comparatively subdued.	Liquid cooling is the least noisy.

Vibration	The air cooling system produces more vibration due to less cooling effect.	Oil cooling produces medium level vibration, close to liquid cooling.	Liquid cooling produces less vibration due to having embedded shock absorbers on the system.

3.2.3 Cost Comparison

Air cooling is the cheapest system of the three where liquid cooling is the most expensive one. Due to having no extra components other than the fin design on the shell of the engine, air cooling costs very little than the other two. Oil cooling is more expensive than air cooling but liquid cooling, because it has dedicated components, is the most expensive one. Analyzing different manufacturing of motorbikes using these cooling systems, it has been estimated that air cooling costs about 150-400 USD, Oil cooling costs about 300-800 USD where liquid cooling can cost starting from 350 to 1000 USD depending on the size and performance of the engine.

However, with the cost, the performance of the cooling system increases as well. Though air cooling is the cheapest, it has the least cooling performance as well. So striking a balance between these key parameters can be a challenge. But because Bangladesh being the least developed country, manufacturers use air cooling to keep the price of the motorbike within a reasonable range. A graph comparing the cost with performance has been demonstrated below to understand the cost vs performance ratio better.



3.2.4 Environmental Impacts

The air cooling system dissipates heat by expanding surface area or increasing the flow of air over the said object. The design of this system is fairly simple so the impact it has on the environment is the least among all the existing cooling systems. The air-cooling system uses fins to dissipate the heat and no extra chemicals or coolants are used. The amount of heat dissipated raises the temperature of the environment but it is negligible. The system needs richer fuel to air ratio which pollutes the environment. It also produces noise affecting the environment.

In Oil cooled engines, the circulating liquid evens-out hot spots in the cylinder head. This is better for detonation control and emissions. The combustion chamber surfaces can be kept hot enough to encourage more complete combustion, but not so hot to promote detonation or high NOx emissions. The passages for circulating oil might sometimes cause spillage. It is not good for the road and the burnt oil is harmful to the ecosystem. The oil harms animals and insects. It disrupts the natural food chain and takes a long time to recover.

The liquid cooling framework is considered to be the foremost effective and compelling way to cool off a cruiser motor and is comparable to the ones found on car motors. The concept includes a liquid-coolant liquid circulated through inner channels built inside the crankcase all around the motor. Similar to the oil-cooling setup, fluid cooling requires an externally mounted radiator but maybe a much bigger and complex one with a better number of channelling and extra cooling fans. The radiator pump permits the coolant to be circulated all through the engine and carry back the heat towards the radiator to be cooled down and re-circulated back into the engine. The fans give extra cooling for ideal motor execution amid all working conditions. Liquid-cooled motors are calmer, more effective, and environment-friendly in comparison to their air-cooled partners.

Table 3.2

	Air Cooling	Oil Cooling	Liquid cooling
Biological	High	Medium	Low
Thermal	High	Low	Low
Chemical	Low	Medium	High

3.3 Summary of the comparative Analysis

The different cooling systems are used for different scenarios. The air cooling is used for the smaller motorbikes and the bigger motorbikes, air cooling becomes insufficient. So, oil and liquid cooling are introduced. The air cooling system needs a richer mixture so the smoke is more harmful and the oil cooling and liquid cooling systems do not create as much noise as the air-cooled engines. The coolants used in the oil and liquid-cooled systems are harmful to the environment if they are leaked. In terms of cost, the air cooling system is the cheapest system available. All things considered, different cooling systems have different pros and cons and it will depend on the usage for the selection of a cooling system.

Table 3.3

Subject	**Air cooling**	**Oil Cooling**	**Liquid Cooling**
Size	Compact	Comparatively larger	Largest
Maintenance	Easy	Less easy	Difficult

Cost	Cheaper	Less cheap	Costly
Performance	Lowest	Medium	Highest
Applications	Most applied	Least applied	Applied on higher performance engines

4 Working Principle, Design, Implementation and Mathematical Analysis of TEG

4.1 Working Principle

To fully understand the function of TEG, we need to understand the physics behind Thermoelectricity. The conversion of thermal energy to electrical energy is based on a principle called the 'Seebeck Effect' which was invented by a German physicist named Thomas Johann German. The opposite of this conversion (Electrical energy to thermal energy) is called the ' Peltier Effect' invented by French physicist Jean Charles Athnase Peltier.

Seebeck Effect

The Seebeck effect is a phenomenon in which a temperature difference between two dissimilar electrical conductors or semiconductors produces a voltage difference between the two substances.

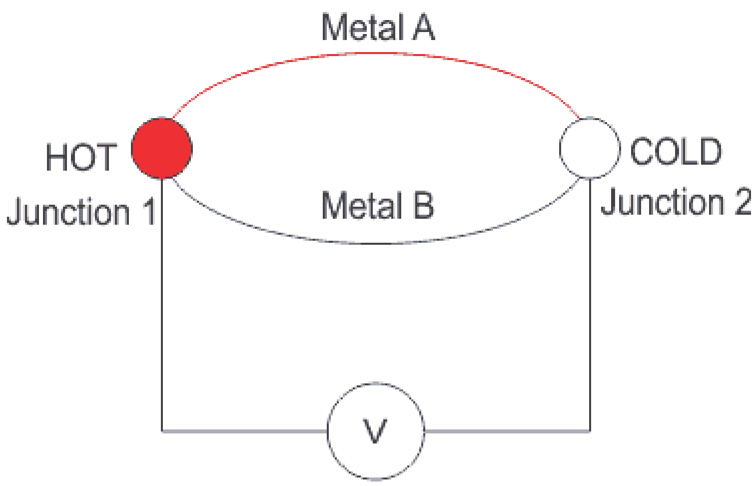


Figure 4.1 Basic structure of a TEG

Let, Metal A is Iron (Fe) & metal B is copper (Cu).

The temperatures of the two junctions are different from each other. Now,

We know that the electron configuration of Iron (Fe) is $[Ar]3d^{6}4s^{2}$& that of Copper (Cu) is $[Ar]3d^{10}4s^{1}$.

So . when junction 1 is being heated, electrons from both the materials will get kinetic energy & start to run rightwards. At junction 2, two sets of the electron will collide. As an atom of Copper has one odd electron at the outer shell & Iron doesn't have an odd electron, the electrical conductivity of Copper is higher. So the resultant momentum of electrons will be anticlockwise in the loop.

As the temperature at the hot junction increases, the kinetic energy of electrons will also increase. We know, every metal has its critical value of drift velocity of its electrons. In this case, electrons of Copper will reach their critical drift velocity faster than that of Iron. So, eventually, the anticlockwise resultant momentum will follow a parabolic path & will come to a value of zero when both the velocities are the same as

Copper's critical drift velocity. Then, as Iron has more free electrons, the Clockwise momentum will be increasing furthermore.

If we represent this phenomenon in a graph,

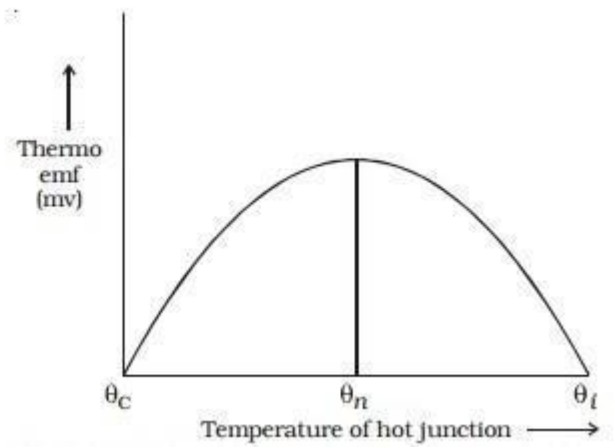


Figure 4.2 Relation of temperature to EMF

The equation of this parabola will be,

$y = ax^2 + bx$

here, we take EMF as Y-axis & Temperature of hot junction (θ) as X-axis,

the equation yields,

$E = A\theta + B\theta^2$

This equation is called the Seebeck equation.

Here A & B are called Thermocouple Constant.

In a TEG, the structure will be a bit modified for making it easy to collect electrons & extract a good amount of EMF.

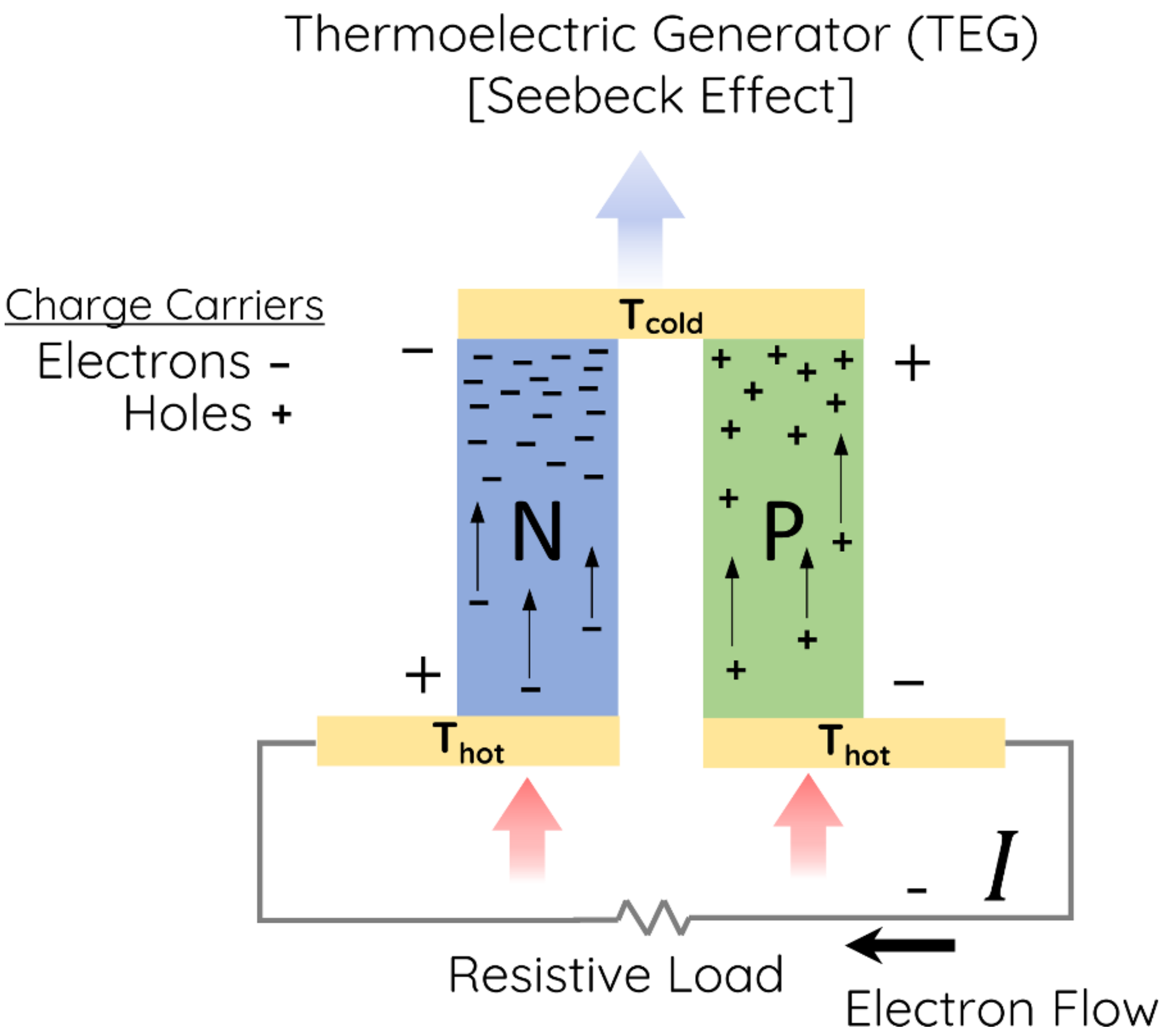


Figure 4.3 Working principle of TEG

A thermocouple is made up of one p-type semiconductor and one n-type semiconductor. The semiconductors are connected by a metal strip that connects them electrically in series. The semiconductors are also known as thermoelements, dice or pellets. The Seebeck effect occurs due to the movement of charge carriers within the semiconductors. In doped n-type semiconductors, charge carriers are electrons and in doped p-type semiconductors, charge carriers are holes. Charge carriers diffuse away from the hot side of the semiconductor. This diffusion leads to a buildup of charge carriers at one end. This buildup of charge creates a voltage potential that is directly proportional to the temperature difference across the semiconductor. Three materials are commonly used for thermoelectric generators. These materials are bismuth (Bi_2Te_3) telluride, lead telluride (PbTe) and Silicon germanium (SiGe). Which material is used depends on the characteristics of the heat source, cold sink and the design of the thermoelectric generator. Many thermoelectric generator materials are currently undergoing research but have not been commercialized.

To create a thermoelectric generator module, many p-type and n-type couples are connected electrically in series and/or parallel to create the desired electrical current and voltage. The couples are placed between two parallel ceramic plates. The plates provide structural rigidity, a flat surface for mounting and a dielectric layer to prevent electrical short circuits.

4.2 Design of the TEG

The Thermo Electric Generator is planned to implement on the exhaust system of a motorbike. It is to have a small and efficient design that can be easily implemented in the exhaust system. The efficiency and the conversion of the heat energy to electrical energy will depend on the design of the TEG. The TEM (Thermo Electric Module) will generate a voltage which will depend on the Temperature difference of the cold and hot side of the TEG.

The considered engine for the TEG has been designed is used on an R15 motorbike from Yamaha motor company. Here is the specification of the engine.

Considered Engine specification

Table 4.1

Engine type	Liquid-cooled, 4-stroke, SOHC, 4-valve
Displacement	155 cc
Bore & stroke	58.0 mm × 58.7 mm
Compression ratio	11.6 : 1
Maximum horsepower	13.7 kW (18.6PS) /10000 rpm
Starting system type	Electric starter
Transmission type	Constant-mesh, 6-speed
Clutch type	Wet, multiple-disc
Fuel system	Fuel injection
Maximum torque	14.1 Nm (1.4 kgf-m) @8,500 RPM

4.2.1 Materials

The TEG will have two copper plates on the hot side of the TEG and 6 Aluminum plates connected by a screw on the cold side of the TEG. The Aluminum plates will have a finned design to have a better cooling mechanism. The air will work as the cooling fluid. The reason to choose copper and Aluminum will be better understood from the table and discussion below –

Table 4.2

Properties		Hastelloy	Steel	Stainless steel	Copper	Duralumin
Type		–	AISI 1010	AISI 302	99.9 Cu + Ag	–
Melt point [K]		1533	1670	1670	1293	923
Density [kgm^{-3}]		8300	7830	8055	8950	2770
k [Wm^{-1}K^{-1}]	T = 294 K	9.1	–	–	–	–
	T = 300 K	-	64	15	386	174
	T = 473 K	14.1	–	–	–	–
	T = 500 K	–	54	19	–	188
k_p [Jkg^{-1}K^{-1}]	T = 294 K	486	–	–	–	–
	T = 300 K	–	434	480	385	875

Copper has a high melting point, more than thousand-degree Celsius which is significantly above the maximum temperature of the exhaust gas of the engine that has been chosen. And the conduction heat transfer co-efficient of copper is also very high which will make the copper plates as much hot as possible which will be attached to the exhaust line of the engine. Aluminium has been chosen due to its lightweight, economic feasibility and availability and good convective heat transfer co-efficient. Because the TEG will be implemented on a motorbike, the lightweight design is very crucial.

4.2.2 Dimensions and Assembly

The dimensions of the copper plates and Aluminum plates –

Table 4.3

Material	Number of plates	Length (cm)	Width (cm)	Height (cm)
Copper	2	12	8	2
Aluminium	9 5 Curved 4 Rectangular	13	Curved Upperside – 7 Lower side – 4 Rectangular - 3	1

The copper blocks will be on the hotter side attached to the exhaust pipe. Since copper has more heat conductive co-efficient, it will absorb the heat available on the exhaust pipe and get one side of the TEG hotter.

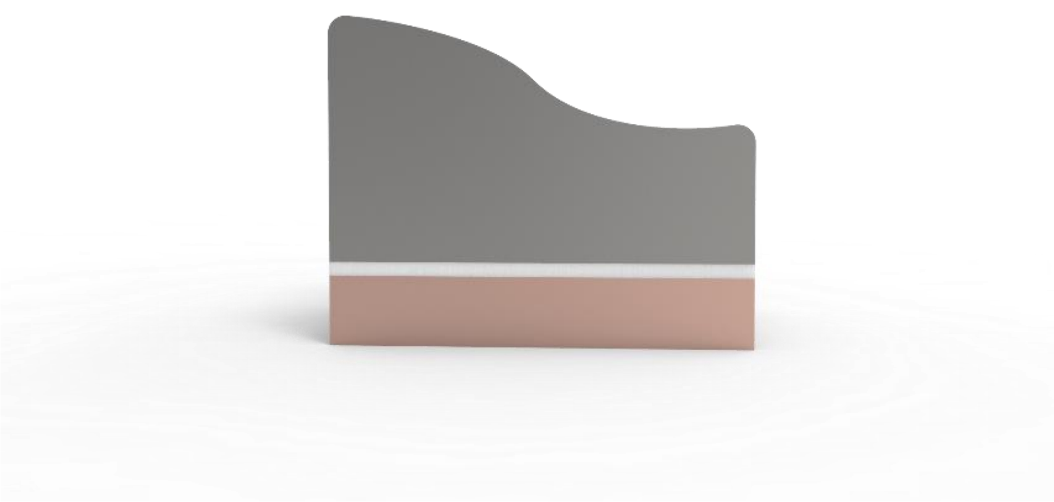


Figure 4.4 Side view of the designed TEG

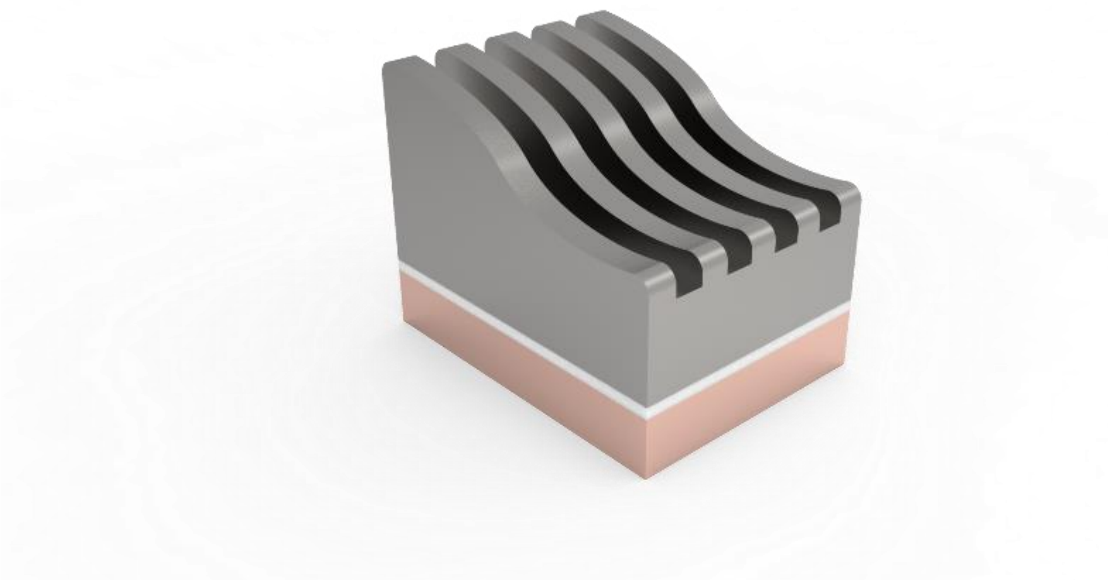


Figure 4.5 3D view of the designed TEG

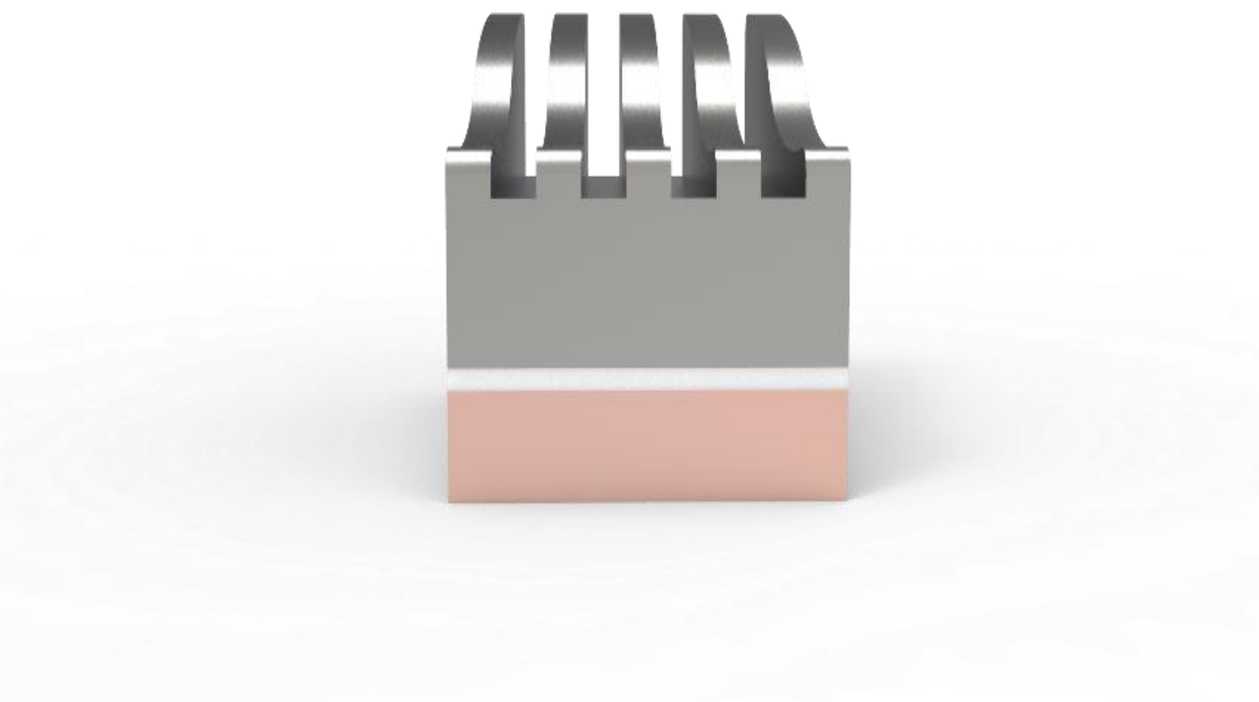


Figure 4.6 Fin design on the cold side of the designed TEG

TEM or Thermo-electric module will be in between the copper and aluminium block which will be connected with e battery or other electrical devices. Below is the basic construction of the Thermo-electric module.

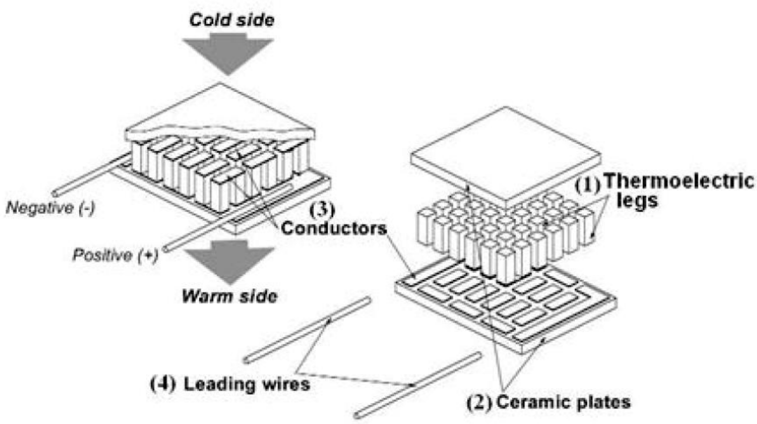


Figure 4.7 Schematic of TEG Module

4.3 Performance Analysis

4.3.1 Mathematical Analysis

Available Waste Heat from the considered Engine –

The amount of available waste heat is dependent on three factors. The mass flow rate of the exhaust gas (*m*), the specific heat of exhaust gas (*Cp*) and the Temperature difference of the exhaust gas and the copper side of the TEG.

$$Q = m*Cp*\Delta T$$

Q is in kJ/min ; m is in kg/min ; Cp is in kJ/kg°K

The approximate temperature of the exhaust gas of a 4 stroke IC petrol engine is 420°C or 693°K. This will be the temperature of the source. To find the maximum available temperature, the sink temperature will be considered as 298 K which will be the average operating temperature in most cases.

Assuming,

Volumetric efficiency (Vr) is 0.8 to 0.9

Density of petrol fuel is 0.748 gm/cc

Calorific value of petrol is 44 to 45 MJ/kg

Density air fuel is 1.167 kg/m^3

Specific Fuel Combustion – 55 gms/kW-hr

Specific heat of exhaust gas is 1.1-1.25 KJ/kg°K

Now the Compression Ratio –

$V_r = (V_c + V_s)/V_c$

V_s= capacity = 155 CC = 0.000155 m^3

V_r= compression ratio = 11.6

Therefore, $11.6V_c = V_c + .000155$

$V_c = 1.46*10^{-5}$

Total Volume $(V_T) = V_c + V_s$

$V_T = 1.46*10^{-5} + .000155$

$V_T = 1.696*10^{-4} m^3$

Mass flow rate of fuel (on the basis of specific fuel consumption)

s.f.c = m_f/ Power

m_f= s.f.c * Power

m_f= 55 * 13.7 = 753.5 gms/hr = 0.209 gms/sec

Now, Volume rate , v = swept volume * speed

$v = Vs * N = .000155 * 10000$

$v = 1.55\ m^3/min$

Volumetric efficiency, η_v = *volume of air / sweft volume*

$\eta_v = m_a / (\rho * N * Vs)$

$m_a = \eta_v * \rho * N * Vs = 0.9 * 1.167 * 10000 * .000155$

$m_a = 1.627\ gm/min = 0.027\ gm/sec$

Mass flow rate of exhaust gas, $m_g = m_f + m_a = 0.209 + 0.027$

$$m_g = 0.236\ gm/sec = 0.236*10^{-3}\ kg/sec$$

Heat loss in exhaust gas, $Q_E = m_g * Cp * \Delta T$

$$Q_E = 0.236*10^{-3} * 1.15 * (693 – 298)$$

$$Q_E = 0.107\ KJ/ sec\ or\ KW$$

Now an open circuit voltage will be measured across the negative and positive end of the module connection. The measured voltage without any load (R) will be,

$$V = \alpha*\Delta T$$

where $V$is the output voltage from the couple in volts (V), α (V°C^{-1}) – the average Seebeck coefficient, and, ΔT[°C] – the temperature difference across the couple.

The temperature difference is the difference between the hot side and cold side of TEG

$$\Delta T = T_h – T_c$$

where Th is the hot side of the couple and Tc is the cold side of the couple.

Assuming approximate values, considering the heat loss on the hot copper side and heat gain on the cold Aluminum side,

$$T_h = 280\ °C\ or\ 553K$$

$$T_c = 33\ °C\ or\ 306K$$

When a load is connected to the thermoelectric couple the output voltage (V) drops as a result of internal generator resistance. The current through the load is:

$$I_{load} = \alpha * \Delta T/(R_c + R_L)$$

where *I*load [A] is the generator output current, *R*c [W] – the average internal resistance of the thermoelectric couple, and *R*L [W] – the load resistance.

Considered TEG = TEC1-12706 TEC Thermoelectric Cooler Peltier Module CPU – 12V, 5.8 A(available in the market)

Now, $R_c = V/A = 12/5.8 = 2.06\ \Omega$ for one module

So, for six modules = 6*2.06 = 12.36 Ω

considering a load resistance of 2.96 Ω (ref - Analytical and Numerical Study for the Determination of a Thermoelectric Generator's Internal Resistance)

Average Seebeck coefficient for a typical 12V thermoelectric module = 0.05 V°C–1

Now,

$$V = \alpha * \Delta T$$

$$V = 0.05*(553-306)\ V$$

$$V = 12.35V$$

And

$$I_{load} = \alpha * \Delta T/(R_c + R_L)$$

$$I_{load} = 0.05*(553-306)/(12.36+2.96)$$

$$I_{load} = 0.806\ A$$

Now the total power output of TEG

$$P_o = V * I / 1000 \text{ KW}$$

$$P_o = 12.35 * 0.806 / 1000 \text{ KW}$$

$$P_o = 0.00995 \text{ KW}$$

The efficiency of the TEG is calculated from

$$\eta = (P/Q_E)*100\%$$

$$\eta = (0.00995/0.107) *100 \%$$

$$\eta = 9.30\%$$

4.3.2 Performance and implementation analysis

To analyze the performance of a TEG, it is necessary to know the effects of mass flow rate, temperature difference, exhaust gas temperature. Experimental results obtained indicate that the heat loss increases with higher temperature but the percentage of heat loss react oppositely.

Effect of mass flow rate:

Mass flow rate has a direct impact on the performance of TEG. From the mathematical analysis, we have seen that the amount of waste heat or available heat depends on the mass flow rate. And the mass flow rate determines how much waste energy is there to be recovered. The more the mass flow rate, the more energy will be available. It also indicates that the engine rpm is also a big factor in the performance of the TEG. As the engine rpm increases the mass flow rate of fuel into the cylinders because more fuel is required for higher engine rpm. So, the mass flow rate is directly proportional to the amount of energy that can be recovered by the TEG. However, the efficiency may not vary that much with the mass flow rate.

Effect of temperature difference:

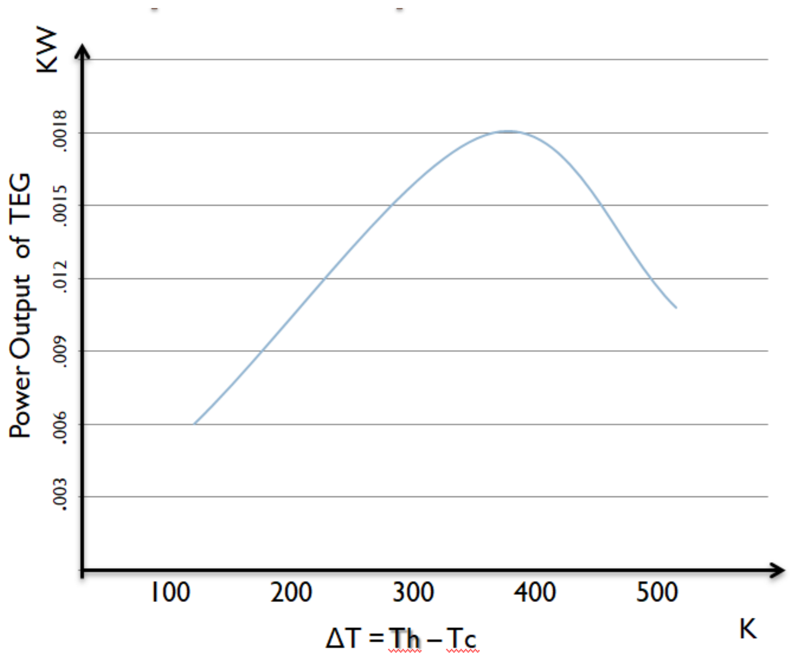


Figure 4.8 Effect of temperature difference on power

Fig 5.2 shows the amount of power obtained from TEG. The power output increases with the increase of temperature difference. The increase in exhaust gas temperature happens because of the increase in engine power output. The mass flow rate is also connected with this increment of power. A thermoelectric generator's power increases with the square of the temperature difference applied across it [7]

Effect of Exhaust Gas Temperature:

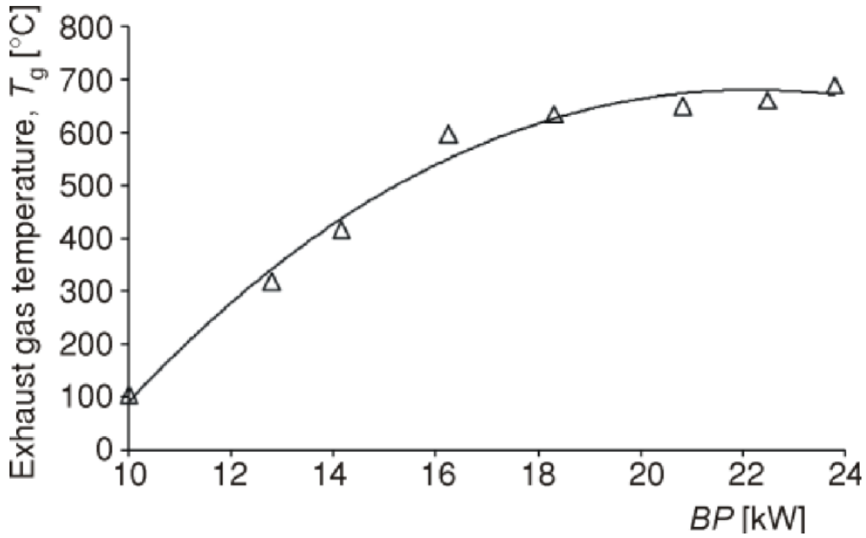


Figure 4.9 Variation of EGT with Brake Power

Fig 5.3 shows the effect Exhaust Gas Temperature (EGT) has on the brake power of the vehicle. The power produced can be increased by increasing the size of the TEG or by increasing the number of modules.

The making cost of this TEG will not be very high. For a continuous heat source, TEGs can produce power 24 hours a day. Unlike fossil fuel generators, TEGs have few moving parts, other than cooling fans or water-cooling pumps, and can be rated to last for more than 100,000 hours of continuous operation. There is no pumps or fans but designed fins, so it is expected to last more.

5 Discussion and Recommendations

5.1 Cooling Systems

Air cooling, being the cheapest system, has been the most used and preferred system in Bangladesh despite having a less cooling effect. As per our research, it has been found that air cooling has less cooling effectiveness with an average value of 1.004 kJ/kgK which is less than both the oil cooling system and liquid cooling system. Motorbikes with lesser performance and engine capability manage to keep the engine temperature down to operating temperature but the efficiency of the engine drops due to not having the most effective cooling system as air cooling only relies on the fin design on the engine shell for cooling. Though air cooling is the cheapest system, it is not the most reliable one for engines operating on higher rpm. The study demonstrates that the oil cooling system and liquid cooling system, both have better cooling performance than the air-cooling system. Also keeping the environmental impact in mind, oil cooling and liquid cooling have less impact on global warming than the air-cooling system.

But we cannot straightaway select oil cooling or liquid cooling over air cooling. The cost does play an important role in the motorbikes used in Bangladesh. So for lower performance engines, an air cooling system may still be a viable option. However, for engines having volumes over 150 cc, oil cooling might be a good option. But oil cooling too struggles to keep the engine temperature down while engines over 200 cc running on higher rpm. Then the high-performance engines shall have a liquid cooling system. But, from the perspective of Bangladesh, the number of motorbikes having over 200 cc engine volume is very low. Therefore, liquid cooling can be used for special types of engine only, not for mass production in Bangladesh.

Recommendations

With a better cooling effect and less impact on the environment, the oil cooling system may have enough potential to be used efficiently in the motorbikes of Bangladesh. More research and application of an oil cooling system is suggested.

5.2 Thermoelectric Generator

This research has established the fundamental analysis of thermoelectric modules of TEG on an automobile. By increasing the number of modules and by using them on array formation more power can be generated and more waste heat can be saved.

But there is an undisputed fact of space constraints, weight constraints, cost, module interface and the constantly high demand for temperature difference that makes it quite difficult for practical uses. Practical problems exist in using thermoelectric devices in certain types of applications resulting from a relatively high electrical output resistance, which increases self-heating, and a relatively low thermal conductivity, which makes them unsuitable for applications where heat removal is critical, as with heat removal from an electrical device such as microprocessors. From the making cost and life of TEG, it can be said to be justified.

From the experimental data obtained, the temperature difference between the hot and cold junctions of TEG increased as the engine speed or the coolant temperature increase. The output voltage, according to the Seebeck effect, also increased as the temperature difference increase. Therefore, the output power and thermal efficiency can be improved. The temperature of atmospheric air is much lower than the exhaust gas, which caused a smaller hot temperature on the TEG hence induced poor performance. Different materials suitable for lower temperature operation are needed for the radiator module.

It was found that rectangular-shaped TEG gave better results. The power produced by the TEG increased with the increase in the power output of the engine. The temperature drop between the hot plate and the cold plate plays a major role in the working of the TEM. The maximum temperature on the exhaust side is limited due to the maximum operating temperature of TEM. The total power that could be extracted from the exhaust gases was limited due to space and cost constraints and due to which the output of the present design is small, a much larger unit with improved heat exchanger design would be required to fully utilize the exhaust energy. However, with the current design maximum allowable hot junction temperature for the module was readily reached during testing. A higher temperature resistant thermoelectric module along with a better heat exchanger can improve the exhaust energy recovery.

To understand the significance of TEG implementation on IC engines, here are the main advantages of the device listed below –

1. **Reliability** - Thermoelectric generators are solid-state devices. Having no moving parts to break or wear out makes them very reliable. Thermoelectric generators can last a very long time. The Voyager 1 spacecraft thermoelectric generator, as of this writing has been operational for 41 years. It has travelled over 13 billion miles without any maintenance or repairs.

2. **Quiet** - Thermoelectric generators can be designed to be completely silent.

3. **No Greenhouse Gases** - Thermoelectric generators do not require any greenhouse gases to operate. Some energy conversion technologies do.

4. **Wide Range of Fuel Sources** - Thermoelectric generators do not have restrictions on fuels that can be used to generate the needed heat. Many other energy conversion technologies do.

5. **Scalability** - Thermoelectric generators can be designed to output power levels smaller than microwatts and larger than kilowatts.

6. **Mountable in Any Orientation** - Thermoelectric generators operate in any orientation. Some energy conversion technologies are sensitive to their orientation relative to gravity.

7. **Operation Under high and Zero G-forces** - Thermoelectric generators can operate under zero-G or high-G conditions. Some other energy conversion technologies cannot.

8. **Direct Energy Conversion** - Thermoelectric generators convert heat directly into electricity. Many energy conversion technologies require intermediate steps when converting heat to electricity. For example, heat energy from fuel is converted into a turbine to mechanical energy, then mechanical energy is converted to electricity in a generator. Each energy conversion step adds losses in the form of waste heat. This makes thermoelectric generators less mechanically complex than some other energy conversion technologies.

9. **Compact Size** - Thermoelectric generators can be designed to be very compact. This leads to greater design flexibility.

Environmental Impact

Thermoelectric Generators are mainly used to recover waste heat. It can save costs by saving fuel and reduces the environmental burden. TEG does not use any chemical agents, so no harmful emissions to the environment. It reduces the temperature of the exhaust gas resulting in less heat emission to the environment. It can reduce global warming by the functions mentioned above.

Recommendations

TEG being a way to recover waste heat from the exhaust of IC engines, might have a significant impact on future energy recovery and saving technologies. Therefore, further experiments are recommended of the proposed model on other motorbike engines and further research is recommended on the materials and TEM configuration on the device.

6 Conclusions

The different cooling systems that are used have their benefits. The air-cooling system is cheaper and the design is simpler but it produces noise and pollutes the environment. The oil-cooling system needs passages to function properly and the liquid-cooling system has the least amount of detrimental effect but the cost is greater. The cooling system that needs to be applied should have the necessary considerations to fulfil the conditions. If the cost is not an issue, the liquid cooling system will give the best performance and it is also safer for the environment.

Thermoelectric generators are an intriguing way to generate renewable energy directly from waste heat. However, their efficiencies are limited due to their thermal and electrical properties being dependent on each other. Nevertheless, their solid-state scalable technology makes them appealing and even more efficient in selective applications. Implementing thermoelectric generators on vehicle exhaust manifolds would help reduce fuel consumption, which in turn would help preserve the world natural resources and reduce carbon emissions.

The special nature of using thermoelectric generators, to supply an electric current with a temperature difference of any small value and over a wide temperature range, has made them the core solution to certain energy problems regarding power generation and heat recovery in a static and non-polluting way, even under extreme environmental conditions. The low efficiency of this conversion technology has limited its development, except in certain sectors where the advantages of TEGs are more favourable over other technologies. The use of thermoelectricity in various laboratory and industrial sectors has resulted in there being different perspectives. It has achieved significant success in some applications and total failure in others. The current investigations into thermoelectric generators are focused on the development of new efficient thermoelectric materials to overcome the drawbacks of the interconnected electrical and thermal properties of these materials, and new designs of thermoelectric generators that allow better integration into energy conversion systems, from the point of view of efficiency and the environmental impact. Interest in this technology has been revived with the appearance of nanotechnology, which has made it possible to cross the historical barrier.ZT<1, resulting in an exponential increase in publications in this field.

The efficiency found in the implementation of the thermo-electric generator may seem only about 9%. But with the right implementation on millions of bikes, this TEG will be able to save a significant amount of energy. Today, energy-saving being the most prioritized goal for many industries and equipment, this device and technology may have a better implementation in various sectors and automobiles in the future. Already the research on implementing this technology on four-wheeled automobiles is being done and the results have been satisfactory.

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