DESIGN AND PERFORMANCE ANALYSIS OF THERMAL TO ELECTRICAL ENERGY CONVERSION AND MONITORING SYSTEM FOR HYBRID ELECTRIC VEHICLE APPLICATIONS

Thesis Submitted for the Award of Degree of

DOCTOR OF PHILOSOPHY

in

ELECTRICAL ENGINEERING

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Transforming Education Transforming India

LOVELY PROFESSIONAL UNIVERSITY, PUNJAB

2025

DECLARATION

I hereby declare that the thesis entitled "**Design and performance analysis of thermal to electrical energy conversion and monitoring system for hybrid electric vehicle applications**" in fulfilment of degree of **Doctor of Philosophy (Ph. D.)** is outcome of research work carried out by me under supervision of **Dr. G RaamDheep,** working as **Assistant Professor**, in the **School of Electronic and Electrical Engineering** of Lovely Professional University, Punjab, India. In keeping with general practice of reporting scientific observations, due acknowledgements have been made whenever work described here has been based on findings of other investigator. This work has not been submitted in part or full to any other University or Institute for the award of any degree.

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CERTIFICATE

This is to certify that the work reported in the Ph. D. thesis entitled "**Design and performance analysis of thermal to electrical energy conversion and monitoring system for hybrid electric vehicle application"** submitted in fulfillment of the requirement for the award of degree of **Doctor of Philosophy (Ph.D.)** in the School of **Electronics and Electrical Engineering**, is a research work carried out by Nukala Jaswanth, 41900487, is bonafide record of his original work carried out under my supervision and that no part of thesis has been submitted for any other degree, diploma or equivalent course.

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ABSTRACT

Renewable energy sources have become a critical area of research due to rising energy prices and increasing electricity costs, exacerbated by pollution and climate change. To address these challenges, researchers are focusing on optimizing energy harvesting systems. Among these technologies, thermoelectric generators (TEGs) have shown significant promise in directly converting heat into electricity via the Seebeck effect. TEGs are environmentally friendly, as they are manufactured using materials like silicon, polymers, and ceramic substrates, eliminating the need for toxic substances or mechanical components.

This research focuses on power generation through waste heat recovery from exhaust gases in heavy electric vehicles. Studies on diesel-powered heavy vehicles have highlighted their substantial pollutant emissions and greenhouse gas contributions. To tackle this issue, a computational modeling approach was adopted, employing TEG modules. Preliminary analyses using MATLAB simulations were performed with input parameters such as temperature and power variation, while output parameters such as power, voltage, and current were evaluated.

Four Maximum Power Point Tracking (MPPT) techniques—Perturb and Observe (P&O), Incremental Conductance, Fuzzy Logic Controller, and Neural Network—were examined. Additionally, a model comprising four TEGs was developed in ANSYS, utilizing the Computational Fluid Dynamics (CFD) module to analyze performance at varying temperatures. Exhaust gas served as the working fluid, and stainless steel was selected as the module material. Sudden cooling simulations were implemented to enhance the Seebeck effect and assess voltage and power output through the integration of a thermoelectric module with the CFD setup.

The computational results revealed that systems using four TEG modules performed more efficiently than those with two modules. To validate these findings, an experimental setup was developed with an IoT module to measure experimental losses and compare them with computational predictions. The final results, validated against previous studies, demonstrated a 15% increase in power output compared to earlier setups.

In conclusion, the design and placement of TEG modules are critical for the effective utilization of waste heat in power generation, offering a sustainable solution for reducing emissions and enhancing energy efficiency.

ACKNOWLEDGEMENT

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Nukala Jaswanth

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LIST OF ABBREVIATIONS

Abbreviations		Description
TEG	-	Thermoelectric generator
TE	-	Thermal energy
TEM	-	Thermoelectric module
HEV	-	Hybrid Electric Vehicle
MCFC	-	Molten Carbonate fuel cells
PAFC	-	Phosphoric Acid fuel cells
PEM	-	Proton Exchange Membrane
SOFC	-	Solid Oxide fuel cells
ICE	-	Internal combustion engine
FC	-	Fuel cells
TES	-	Thermoelectric energy storage
HFCs	-	Hydrogen fuel cells
CFD	-	Computational fluid dynamics
IOT	-	Internet of Things

CHAPTER- 1
INTRODUCTION

Thermoelectric effects, including the Seebeck and Peltier effects, enable the direct conversion of heat into electricity and vice versa, without the need for any moving parts. These effects make thermoelectric devices versatile for applications such as refrigeration, waste heat recovery for electricity generation, and solar power utilization. Despite their low efficiency, thermoelectric devices hold significant promise in scenarios where reliability, predictability, and availability are prioritized over cost and efficiency. Examples include medical devices, laboratory equipment, and space probes. The integration of nanotechnology has further enhanced the performance of thermoelectric materials, positioning them as a frontrunner in renewable energy production and waste heat recovery.

The Seebeck effect generates an electric potential across a temperature gradient between two conductors. Thermoelectric generators (TEGs), leveraging this phenomenon, are solid-state devices that operate without noise and exhibit long operational lifespans. TEGs can harvest waste heat from various sources, including industrial processes, vehicles, power plants, and even human body heat, and convert it into usable energy. They can power applications such as sensors, wireless transmitters, and spacecraft, using heat sources like radioactive materials or solar energy.

Thermoelectric power generators directly convert thermal energy into electricity, making the technology both environmentally friendly and sustainable. TEGs offer benefits such as durability, scalability, and silent operation due to their lack of moving parts. Although their efficiency ranges from only 5-10%, they are valuable for recycling wasted energy in diverse settings, such as automotive engines, geothermal sites, power plants, and electronic devices. The economic feasibility of TEGs is further enhanced by their ability to utilize renewable energy sources, despite their relatively low productivity.

Thermoelectric modules (TEMs), which form the building blocks of TEGs, rely on thermoelements linked electrically in series to enhance voltage and thermally in parallel to improve thermal conductivity. This structural design improves the overall efficiency and functionality of TEG systems. Consequently, the recycling of waste heat has become a central focus of many recent studies, emphasizing the role of TEGs in sustainable energy systems.

Thermoelectric coolers (TECs) operate on similar principles but in reverse. TECs use electric current to transfer heat from a cooler surface to a heated surface through the Peltier effect. These solid-state devices, while similar in some components to TEGs, are typically designed differently to optimize cooling. Applications of thermoelectric cooling include air conditioning, refrigeration, temperature management, and ventilation. By utilizing the Peltier effect, TECs have become an essential technology for managing heat in a wide range of systems.

1.1 INTRODUCTION TO THERMOELECTRIC GENERATOR (TEG)

Thermoelectric effects, such as the Seebeck and Peltier effects, enable the direct conversion of heat into electricity and vice versa, without the need for moving parts. These effects make thermoelectric devices valuable for applications such as refrigeration, waste heat recovery for electricity generation, and solar power. While their efficiency is relatively low, thermoelectricity shows significant promise in areas where availability, reliability, and predictability are more critical than cost or efficiency. Such applications include medical devices, laboratory equipment, and space probes. Furthermore, advancements in nanotechnology have enhanced thermoelectric materials, increasing their potential to lead renewable energy production and waste heat recovery efforts.

Thermoelectric coolers (TECs) operate on principles similar to thermoelectric generators (TEGs), but their functionality is reversed. TECs use an applied voltage to generate electric current, which drives the Peltier effect. This effect facilitates heat transfer from a cooler surface to a heated surface. While TECs share some components with TEGs, their designs differ to optimize their cooling function. TECs, as semiconductor-based solid-state devices, offer a compact and reliable solution for temperature control.

Thermoelectric devices, whether used for cooling or power generation, provide versatile solutions for managing thermal energy. TECs are widely employed in air conditioning, refrigeration, temperature regulation, and ventilation systems. In contrast, TEGs focus on generating electricity by harvesting waste heat, thereby contributing to sustainable energy systems. Together, these technologies represent critical tools in addressing energy efficiency and renewable energy challenges.

1.2 THERMOELECTRIC GENERATOR TYPES

Considerations like as device size, heat source/sink, power output, and intended usage classify TEGs into one of three main groups.

- Generators that run on fossil fuels
- Generators powered by nuclear fuel
- Generators powered by solar energy

1.2.1 Fossil Fuel Generators

The fuels used for this kind of generator include kerosene, natural gas, butane, wood, propane, and jet fuel. The wattage can be anywhere from 10 to 100 watts, making it suitable for industrial use. These thermoelectric generators are used in far-flung places for things like cathodic safety to prevent electrolysis from corroding metal pipes and naval systems and navigational aids, data collection, and communication networks.

1.2.2 Nuclear Fuelled Generators

TEG generators might benefit from using the high-temperature heat produced by radioactive isotope decay. These thermoelectric generators powered by nuclear energy are utilised in remote locations since they are radioactive-radiation-sensitive and the heat source element may be recycled for several uses.

1.2.3 Solar Source Generators

Solar TEG have met with mixed results in undeveloped areas for powering small irrigation pumps. Solar thermoelectric generators can provide electricity to spacecraft in orbit.

1.3 HYBRID ELECTRIC VEHICLE (HEV):

The electric motor of a hybrid electric vehicle is linked to a battery pack, and the vehicle also has an internal combustion engine. The advantages of both technologies are combined in HEVs, which provide better gas mileage and fewer emissions without sacrificing the range or power of conventional vehicles. A hybrid electric vehicles (HEV) electric motor allows for a smaller, more fuel-efficient engine. A larger battery is used to power additional loads, and a start/stop engine function prevents wasted gasoline from being burned when the engine is idling. When these factors are combined, fuel economy is enhanced without any compromise in performance. A renewable car battery contains the electricity needed to jump-start the vehicle and any other electrical accessories. The alternator begins recharging and, in some cases, providing power to additional equipment as soon as the engine is started. A car battery can rapidly produce its maximum current. "SLI" stands for "starting, lighting, and ignition," which are the three primary uses of a car battery. The two main varieties of automotive batteries used today are lead-acid and lithium-ion. With a long service life, low environmental impact, high power density, and energy density, lithium-ion batteries provide numerous benefits over other popular battery types. When it comes to electric and hybrid vehicles, lithium-ion batteries are necessary. Lead-acid (Lead) batteries are bulkier and produce less power per unit weight than their lithium-ion (Li-ion) counterparts. Various ways can be used to recharge a vehicle's batteries: the alternator/generator, the use of regenerative braking, plug-in charging, fuel cells, solar power, and thermoelectric. When combined with multiple renewable energy sources, a hybrid electric vehicle achieves greater efficiency and lessens its environmental impact. It is not possible to recharge the battery of an average hybrid electric car by connecting it to external power sources. The electric motor in mild and micro-hybrid vehicles is a generator to recharge the battery from the energy lost during braking.

1.4 FUEL CELL:

Chemical energy is converted into electricity by fuel cells always have positively charged anode and negatively charged cathode electrodes. Electricity is produced by chemical reactions between two electrodes. An electrolyte, responsible for transporting electrons between the fuel cell's electrodes, and a catalyst, which expedites chemical processes between the electrodes, round out every fuel cell. In order to produce direct current (DC), multiple fuel cells are often stacked together.

1.4.1 Types of Fuel Cells

A fuel cell can generate power in the presence of a fuel source and an oxidising agent, the most common of which being oxygen. These cells may continuously generate electricity as long as fuel and oxygen are accessible.

1.4.1.1 Alkali fuel cells:

Hydrogen and oxygen under pressure allow it to operate. Typically, an electrolyte would be a solution of potassium hydroxide in water. At 300–400 degrees Fahrenheit, it operates with an efficiency of around 70%. Anywhere from 300 W to 5 kW could be the output power of a single cell. Powering the Apollo spacecraft and providing potable water were the alkali cells. But their platinum electrode catalysts are pricey, and they can only use fuel that is 100% hydrogen. Their potential for leakage is the same as that of any container containing fluid.

1.4.1.2 Molten Carbonate fuel cells (MCFC):

It is used as the electrolyte in high-temperature salt compounds (such as sodium or magnesium). It operates at a temperature of around 650 °C and has an efficiency of 60–80%. The construction of 2 MW units is complete, and 100 MW units are conceptualized. Because of the high temperature, the cell is protected against carbon monoxide "toxicity," and excess heat can be utilised to produce further energy. Unlike platinum, which is utilized in most other cells, nickel is used as an electrode catalyst in cheaper models. However, MCFCs are limited in both their materials and safe applications due to their high temperature, making them unsuitable for use in most domestic settings. The reactions consume the carbonate ions from the electrolyte; thus carbon dioxide is added as a replacement.

1.4.1.3 Phosphoric Acid fuel cells (PAFC):

It is Use an electrolyte composed of phosphoric acid. Operating temperature is around 300–400^{0}Cand efficiency is somewhere from 40–80%. There are currently phosphoric acid cells that can generate up to 200 kW, and 11 MW units have been tested. One reason PAFCs can run on more fuels is their high carbon monoxide tolerance. Sulfur must be removed from gasoline before it can be utilized. Electrode-catalysts made of platinum are required, and all moving parts must be resistant to the acid.

1.4.1.4 Proton Exchange Membrane (PEM):

In fuel cells, the electrolyte is a semipermeable polymer membrane. Approximately 40–50% efficiency at 80–150 ^{0}C when functioning. The typical range for cell outputs is between 50 kW and 250 kW. These cells are safe for use in homes and vehicles because to their low operating temperature and solid, flexible electrolyte that cannot fracture or leak. Using a platinum catalyst to purify their fuels on both sides of the membrane increases the production cost.

1.4.1.5 Solid Oxide fuel cells (SOFC):

The electrolyte used is an inorganic ceramic composition comprising metal oxides (such calcium or zirconium) and oxygen (O2). The typical operating temperature is over 1,000^{0}Cand the efficiency is around 60%. Power output from cells can reach 100 kW. Hydrogen may be extracted directly from the fuel at these temperatures without the use of a reformer, and the excess heat can be used to generate more energy. Large SOFC units and their high operating temperature restrict their application. Electrolytes that are solid can't leak, but they can break.

1.5 FUEL CELL IN ELECTRO VEHICLES:

The fuel cell hybrid offers significant efficiency gains over conventional automobiles and produces no harmful emissions. In order to maximize efficiency gains from hybridization, a sophisticated energy management system is required to coordinate the use of both the primary and secondary power sources. Hybrid power topologies storage systems often involve the combination of fuel cells with other energy storage devices such rechargeable batteries or ultracapacitors. Transient power need is met by coupling high-energy- and high-power-density batteries and ultracapacitors to a DC bus, which in turn reduces the size, cost, and burden on the fuel cell stack to meet the average energy requirement over the course of a driving cycle. Hybrid electric vehicles, since they use multiple energy sources, are more reliable as well as effective than conventional electric vehicles. However, practical systems for controlling energy management are required to govern electricity flow among the various energy sources. The internal combustion engine (ICE) based hybrid electric vehicles (HEV's) primary source of electricity is fossil fuels. Some excellent HEV examples include the Honda Insight and the Toyota Prius. Scientists investigate fuel cell technology because of its two salient characteristics. Thus, tank-to-wheel operation generates no waste and uses very inefficient energy. As a result of these two benefits, IC engines are becoming obsolete and being replaced by fuel cell technology-energy component control hybridization and two additional secondary energy sources. Fuel cells (FCs) will rely on batteries and ultracapacitors for a very long time.

The fuel cell vehicle is just entering the market; however, they need to be more competitive with old technology. They are only available in certain places due to pricing, reliability, range, and lack of supporting infrastructure. Due to their high price, early BEVs were aimed at the luxury market as a second car. Over the next decade, we anticipate significant technological advancements, reduced costs due to technological enrichment, and peak production volumes of 5 million units or more. This will make FCHEVs competitive with today's ICE hybrid powertrains. During the vehicle's acceleration phase, the FC power module acts as the primary generator in a hybrid system. The second generator captures kinetic energy during deceleration and provides additional power during high-velocity and peak-load operations. Thus, the concentration on the FC power module and associated costs will be reduced. The power train's transient performance and the efficiency of the energy storage system will both see gains. Ultracapacitors are distinguished by their high-power density but accurately low energy density. It can improve battery performance and extend its cycle life by many years. Because ultracapacitors have a higher capacitance than regular capacitors, they can provide the extra energy needed to boost acceleration.

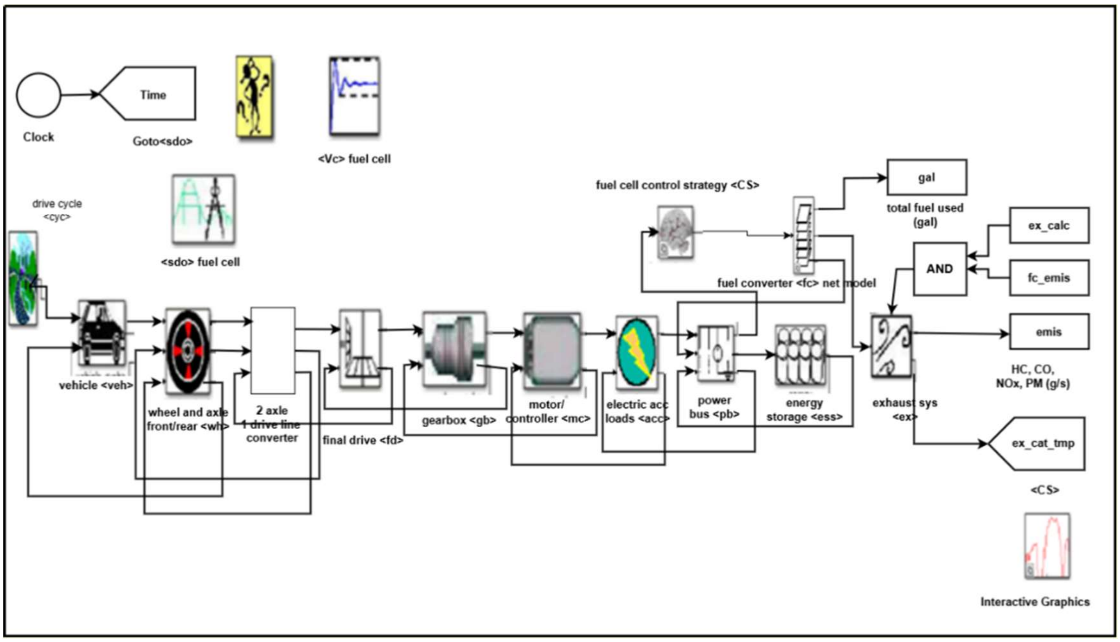


Figure:1.1 Block diagram of the fuel cell hybrid vehicle

Figure 1.1 There are models for the drive cycle, the vehicle's dynamics, the wheels and axles, the power transmission, the hybrid system, the power electronics, and the control strategy. Each model contributes to the overall model of the hybrid vehicle.

1.6 FEUL CELL VEHICLES:

Fueling an FCEV is as easy as filling up a regular automobile, so it's convenient and fast. As a result, a fuel cell car can be fully charged in just a few minutes, opposed to the hours required by existing BEVs. FCEVs have limits despite all of the above promises. One is that until recently, it was difficult to produce fuel cells small enough to power a car. As fuel cell car production increases, this problem should be eliminated. However, a much more severe problem is the lack of readily available hydrogen. This generates the energy that drives the FCEV. Hydrogen is quite plentiful, although the highly combustible gas state of this element is rarely encountered in nature. Most of the time, it forms compounds with other substances, such as hydrocarbons like oil and natural gas, or with oxygen to form water.

1.7 SEEBECK EFFECT

Thomas Johann Seebeck discovered that a voltage differential exists between metals at different temperatures. The P-type and N-type electrical wires depicted to the right are deserving of closer inspection. What occurs is that the hot electrons move to where the cold ones are (shown by the downward-pointing positive and negative arrows). When an electrical circuit is made between the two, a direct current is produced.

Seebeck Effect versus Peltier Effect

The Peltier Effect operates in the opposite direction. Electrical current is transmitted through the materials in place of a heat differential to create heating or cooling.

Seebeck Effect Inside a TEG Module

The Seebeck Effect generates low voltages that vary with the type of material and the temperature differential. A conventional transistor cannot boost current or voltage by coupling multiple P-type and N-type connects in series together, only by coupling them in parallel, neither option is available with a TEG module. To the right, you can see a schematic depicting a series connection between P-type and N-type materials indicated by yellow lines.

Thermoelectric Generator utilize the Seebeck Effect:

Thermocouples are the backbone of thermoelectric generators. A thermocouple consists of two different types of semiconductors, often P and N. The semiconductors form a series network that is linked together using a metal strip.

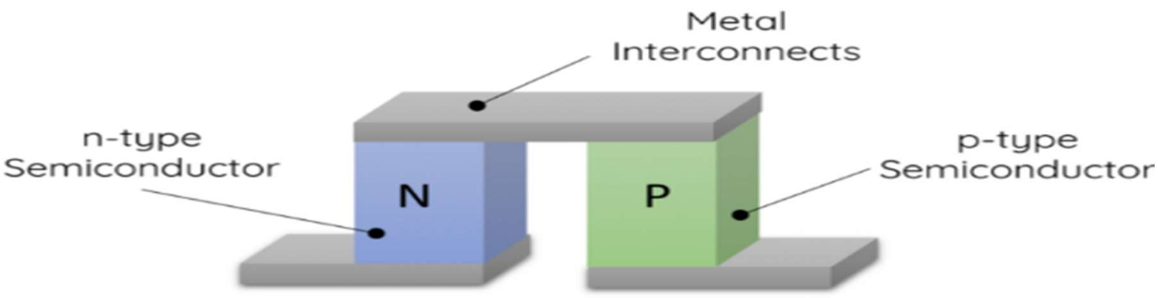


Figure:1.2 Thermometric Generator Couple

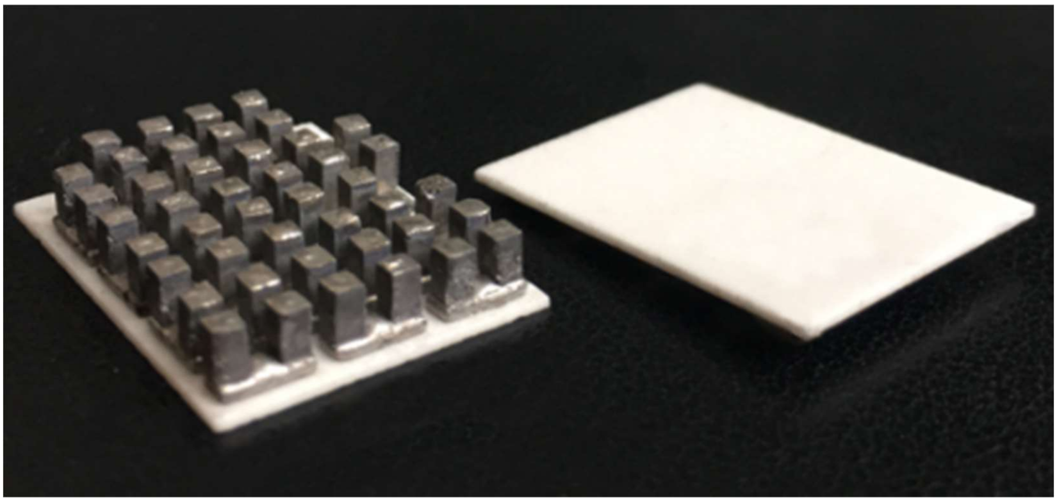


Figure:1.3 Generators (Pellets, Dice, Semiconductors, Thermocouples)

The Seebeck effect is a result of transforming thermal energy into an electric field. As charge carriers flow across semiconductors, the Seebeck effect is produced. Semiconductors that are p-type have holes as charge carriers, while those that are n-type contain electrons. As a matter of course, charge carriers in the material will avoid the higher area. The accumulation of charge carriers at one end is a result of this diffusion. The charge constructs up over time to produce a voltage whose value is directly related to the difference in temperature between the two sides of the transistor.

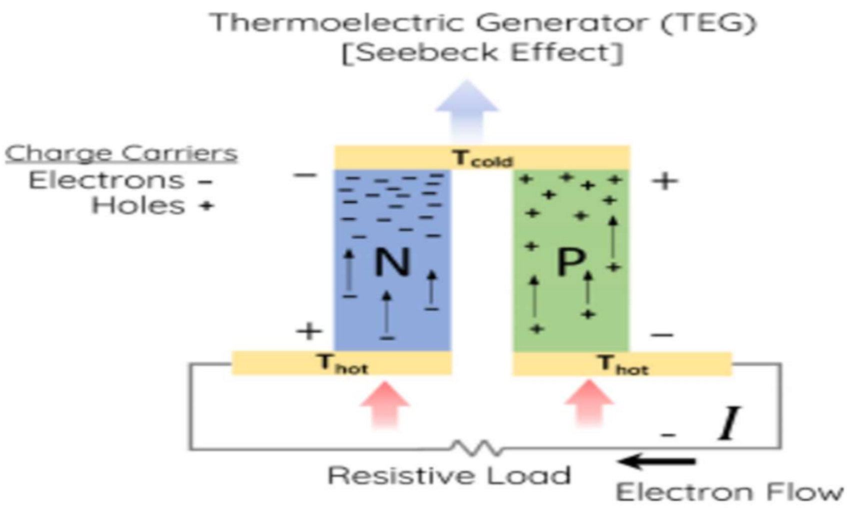


Figure:1.4 Thermoelectric Generator Charge Carriers

1.8 POWER GENERATION USING TEG

Recently, the majority of our electricity has been generated by fossil fuels. However, oil and gas are the least abundant fossil fuels, thus our supplies will continue to decrease. Due to a decrease in supply (of oil, gas, and coal), the price of power per unit has risen to unpredictably high levels in recent years. Thus, renewable energies are more alluring than fossil fuels as a means of producing power since they reduce costs without compromising reliability. In this cutting-edge endeavor, we're using a thermoelectric generator an instrument first developed and used by humans to produce electricity from waste heat. There is general agreement that renewable energy sources like solar, wind, hydro, periodic event, and so on may be used to provide power. There are a few drawbacks to consider. When it comes to things like home industrial and satellite electrical systems, star cells are the most commonly used type of cell. However, the production of electricity relies on a number of factors, including sunlight. It is impossible to generate electricity in the absence of sunshine. or a way to save energy for when it's needed. Hydroelectric power and wind power both have their limitations, which limits their usefulness and causes them to produce less power overall.. Heat is converted into voltage by the gadget. The energy produced by this thermoelectric generator is suitable for use in unmanned facilities, satellites, and broad-area surveys. Many satellites have taken up permanent residence in orbit around the Earth. thermoelectrical devices are used to generate electricity from the exhaust heat of an internal combustion engine, for instance. The Seebeck effect is used to directly fuel the

TEG's ability to transform thermal energy (heat) into electricity. There is a shift in the media's charge here. Thermoelectric power plants have many advantages. Reduced bulk and dimensions young, incompetent, and in the field of Technology. – Boost the strength all the way up (by 5% to 8%). -Different forms of renewable energy production. Reduces the per-unit cost of the devices while requiring less space and money than alternative sources of waste heat. TEG is used in a wide variety of products, including those that use a reaction engine, an IC engine, a chamber cowl, a plight tube, or a white-goods oven. Personal computer, laptop user moisture etc.

1.9 THERMAL STORAGE SYSTEM WITH TEG

Thermoelectric energy storage (TES) makes it possible to save energy by storing heat or cold for later use. TES works best in situations when there is a gap between energy production and consumption. The future's energy needs will be met by the charge, storage, and discharge phases of a TES system's storage cycle. The diagram depicts both active and passive forms of storage. Active storage systems are distinguished by their use of convective heat forcing into storage materials. As the medium being stored moves through the system, it makes use of various components, such as a heat exchanger, solar receiver, or steam generator.

Thermal energy storage, or TES, is the practice of storing heat or cold for later use. Originating hundreds of years ago, the TES has now spread over the globe. Power storage devices can significantly lessen the time or rate disparity between the two parties' energy requirements and supply. Power grids benefit from energy storage because supply is more reliable and consistent. Storage can improve power plant efficiency, for example, by smoothing out demand spikes and valleys. Higher output would decrease energy use and expenses. Renewable energy sources only provide power on demand. Solar energy's intermittent, unpredictable, and dispersed nature is a major drawback to its otherwise advantageous characteristics. This source of power has a low energy flux density compared to typical fossil fuel appliances like coal or oil-fired furnaces.

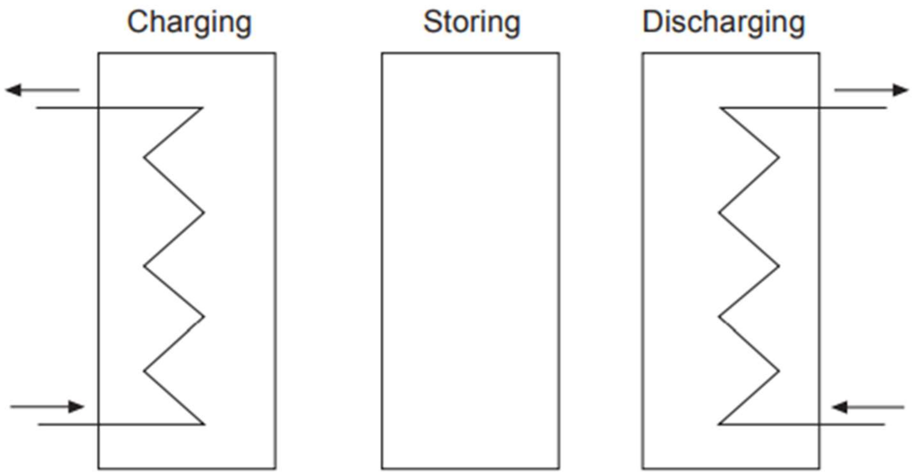


Figure 1.5 TES Complete storage cycle

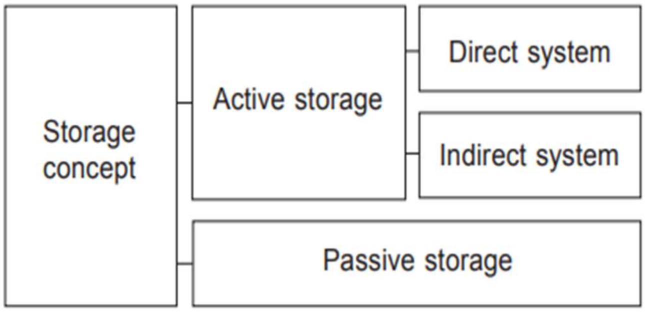


Figure:1.6 A classification of storage systems that corresponds to the storage concept

When heat is stored in something other than water HTFs are used to charge and discharge solid substances in passive storage systems, making them dual-medium systems. Storage capacity and heat transfer from the HTF to the storage material are the main criteria for designing a TES system. The storage material needs to be chemically and mechanically stable, as well as meeting the following criteria: compatibility with the container material, full reversibility of numerous cycles, low heat losses during storage, easy control, and low costs. The main design considerations include the application's overall strategy, maximum load, nominal temperature, enthalpy loss, and system integration.

Thus, a good system should be able to store a lot of energy while using a small amount of space. If their mass specific heat capacity is not too low, denser materials can store more energy in the same volume. In transportation as well as habitat applications, space is at a premium. Current storage methods take up a lot of space, which could be a major limiting factor in terms of storage capacity. The price determines the capacity of the energy storage system. One of the factors in determining the optimal size of storage is the cost of floor space or volumetric space. Modern society stands to benefit greatly from the advancements made in thermal energy storage technology. Aside from its scientific use, thermal storage was mostly used to keep homes toasty on chilly winter evenings. It was common practice to build a fire in the evening and utilize large stones, blocks of cast iron, and pottery to preserve the heat for the duration of the night. Thermal energy storage was first introduced as a byproduct of energy generation during the industrial revolution. Different methods of thermal energy storage have recently become feasible. Today, residential buildings are one of the most common uses for thermal storage. Power plants commonly utilize steam or hot water for short-term heat storage. Heat storage substances for electric utilities have recently been proposed to include other materials, such as oils with a very high boiling point. It has also been proposed to use other materials with a high heat of fusion at high temperatures. Thermal energy storage has many applications in the electric utility sector, one of which is the supply of hot water. When it comes to thermal energy storage, solar-heated structures are the most promising, and almost any material can be used.

1.10 THERMOELECTRIC GENERATOR APPLICATIONS:

This thermal image shows Seebeck's heat-powered Ecofan 812 Airmax, which is the principal use of TEG modules for converting thermal energy into electricity. Peltier, a scientist, is responsible for the second discovery since he proved the opposite of the first to be true. TEG modules, which can generate heat or cold, have become possible as a result. Both the first and second applications use identical modules, the only difference being how they are utilized and how their electrical circuits are built. TEG modules and their applications to maximize space and dependability, TEG modules are implemented. Because of their dependability and lack of maintenance services, they are often used to power space modules like the Mars Rover. These modules would otherwise be stranded without power. Here are some other applications for these electronic devices.

- TEG devices are typically used to improve vehicles' gas mileage. The vehicle's operation heat is harnessed by these generators.

- To keep the spaceship running, engineers rely on Seebeck Power Generation.
- Power for weather stations, relay networks, and other operations will come from thermoelectric generators.

1.11 ADVANTAGES:

Primary and secondary power sources for commercial, industrial, residential, and remote/inaccessible places include fuel cells. Forklifts, cars, buses, trains, boats, motorbikes, and even submarines can all be powered by fuel cells.

Renewable and Easily Accessible

Hydrogen is found in the greatest quantities of any element on our planet. This renewable energy source has the potential to fulfil our future demands for zero-carbon integrating heat and power, even though it is not easy to extract from water.

Zero-Emission Power

Hydrogen fuel cells (HFCs) don't give off any dangerous byproducts, therefore there are no cleanup or storage fees to worry about while using them. Pure hydrogen fuel produces only heat and water as byproducts, making our products a sustainable, emission-free power source. Many corporations have included hydrogen fuel cell systems into their carefully crafted sustainability strategies.

Minimal Sound Pollution

Hydrogen fuel cells are much more silent than other renewable power sources like wind power. It also implies that, similar to electric vehicles, hydrogen-fueled cars produce less noise than those powered by traditional internal combustion engines.

Improved Efficiency

The standard efficiency of fuel cells made from hydrogen is estimated by the U.S. Department of Energy to be 40 to 60%. This is consistent with the electrical efficiency of a typical car's engine, which is around 25%. Warehouse productivity can be elevated by 15% with the help of fuel cell pickups that make optimum use of hydrogen.

Lower Operational Costs

Comparatively, fuel cells have lower operating costs than both batteries and traditional power plants. Removing the need for peak-use battery maintenance (replacing, charging, and managing) reduces the need for workers, space, and electricity. Devices may be recharged in as little as three minutes, reducing vehicle and employee downtime dramatically, and they last longer than lead-acid batteries. Because of the ease of maintenance and decreased frequency of on-site inspections, the cost of operation is often 84% lower than that of combustion generators for stationary energy. Rather than scheduling maintenance visits every three months, mission-critical tasks can be kept at the forefront of site staff's attention thanks to high reliability.

Charging takes Little Time

Hydrogen fuel cell electric vehicles have a far faster charging rate than conventional electric vehicles that use rechargeable batteries. This charging pace is comparable to that of traditional internal combustion engines (ICE). In comparison to the several hours needed to fully charge an electric vehicle, refueling a hydrogen fuel cell could take as little as five minutes. Hydrogen-powered vehicles may seem as functional as regular vehicles because of the short time it takes to charge vehicles.

Suitable for Use in Remote Locations

Diesel-based energy and heaters can be replaced with hydrogen generation and storage in off-the-grid areas due to local constraints. Importing fuels would decrease if clean energy could be produced from locally available resources, which would increase living standards for those in remote regions.

Robust Reliability

Hydrogen fuel cell technology has been tested in a wide variety of circumstances, ranging from those with temperatures as low as -40 ^{0}C to those with hurricanes, deserts, and winter storms.

Ability to Adapt

Hydrogen fuel cells would be ready to supply power for a wide range of stationery and consumer devices once the necessary technology is developed. Not only may hydrogen fuel cells be used to power cars, but they can also be incorporated into more compact systems, such as residential or commercial space heating. Similar to how ICE power plants divide up the tasks between the generator and the generator's fuel tank, this design divides the energy storage system and the engine capacity. However, the design flexibility provided by rechargeable batteries grows as the square of the device's mass.

Decentralization of Power Supply

Hydrogen fuel cells have the potential to reduce a country's dependency on non-renewable resources, making electricity and energy more accessible to more people. Different countries that rely primarily on fossil energy supply are starting to take notice of this trend. The problem of rising fossil fuel prices should, however, go away when reserves decrease.

Scalable

The benefits of a modular product are substantial: better durability and less hassle when servicing. Scalability, as well as cost savings from buying and utilizing fuel cells, may be the most valuable advantages of fuel cells. Products in this category can be custom-designed to fulfill a wide range of applications, from stationary power to mobile fleets of forklifts and other industrial machinery. It makes perfect sense to purchase only what you required.

1.12 THERMO ELECTRIC GENERATOR ANALYSIS USING MATLAB

The Seebeck effect drives the thermoelectric, an energy-conversion device made of a solid state. Thermoelectric power generation doesn't produce any harmful byproducts. Thermoelectric generators can generate electricity whether they are kept on a flat plate or a curved surface. The thermoelectric module immediately transforms the temperature gradient between its upper and lower surfaces into electrical power. Thermoelectric modules can either be used as a generator or a cooler. The Peltier effect is the basis for thermoelectric coolers. No moving or mechanical parts were used in the creation of this system. Noiseless, dependable, and stable performance is possible with the help of thermoelectric modules. Thermoelectric coolers are also put to use in the realm of climate regulation. Thermoelectric generators are used to harness thermal energy for use in the energy sector. Thermo electric generators are crucial in wireless communication and self-powered, off-grid waste heat systems.

1.13 INTRODUCTION TO ANSYS:

Ansys Workbench's centralized simulation data facilitates Integrated into all Ansys physics-based software suites, it facilitates data communication and integration across engineering simulations for more precise and efficient model creation.

- Manage data across all Ansys products easily
- Provide a single interface for multiple analyses
- Automate data transfer to save time
- Develop models with a higher degree of fidelity

Millions of engineers throughout the world rely on this program because of how simple and adaptable it is for analyzing and simulating engineering ideas. Importing a 3D model of a complex assembly into ANSYS Mechanical Solution allows us to quickly find solutions to the assembly's complex geometries and run analyses on the system's stress, strength, vibration, and motion.

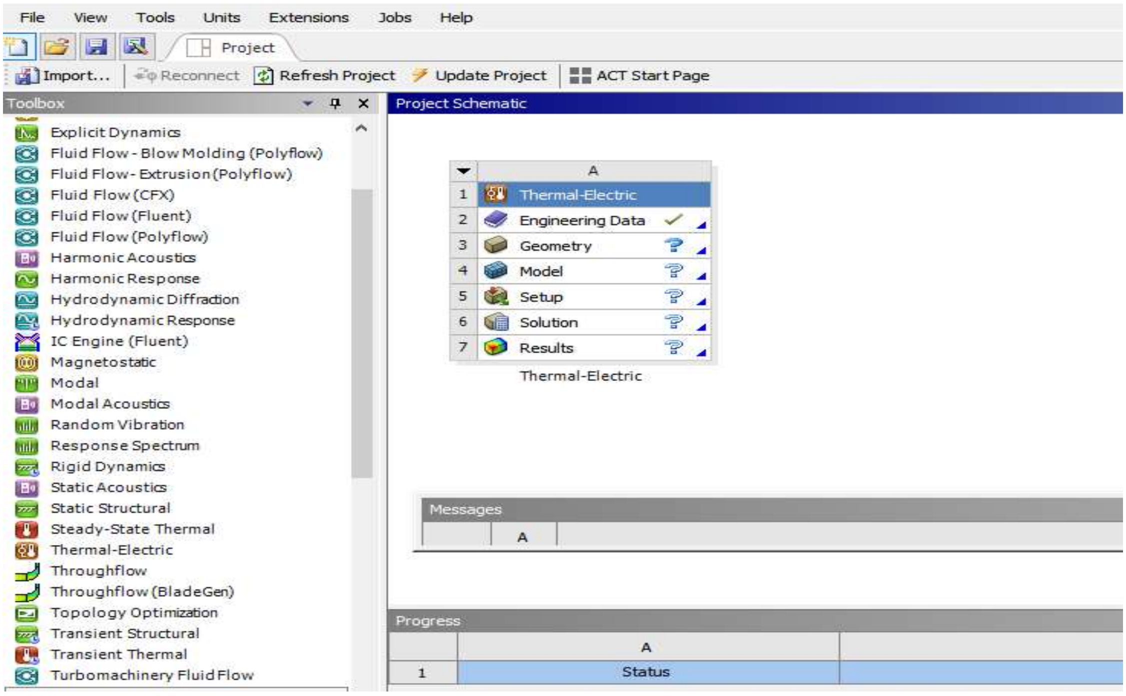


Figure:1.7 ANSYS Work bench layout

In ANSYS Structural Solution, stress, deformation, vibration, and dynamic effects can all be studied and simulated. Simulating critical structures is easy and highly accurate.

1.13.1 Thermoelectric analysis

ANSYS simulation software was used to assess the TEG's efficiency. An electromagnetic, thermal, and thermoelectric thermal analysis were all performed with the use of the software. Using ANSYS Workbench, we performed a steady-state evaluation of the TEG, which allowed us to model the geometry of the system and run a number of simulations within the TEG module, such as those for current density, temperature distribution, electric voltage, and heat flow. There are three main processes at play in this simulation, and they are as follows:

- Modelling of the 3D using the ANSYS Modeller to construct the model geometry
- Selecting of the Thermal-electric for TEG modelling
- Inputting of the TEG engineering data

ANSYS Meshing is used to produce the net finite element. TEG measurements were used to get engineering data for the contact and ceramic substrate parameters from the datasheet and experimental results. Constant thermal boundary conditions were maintained on the Th and Tc substrates during the development of the 3D model. The two-terminal thermoelectric generator is depicted graphically in Fig. The structure as a whole is made up of a p-type region that possesses thermal conductivity, isotropic resistance, and a Seebeck coefficient, and a copper alloy.

- In ANSYS Mechanical, the Steady-State Thermal-Electric Conduction study considers both heat and electricity. The capacity models of linked fields for Joule heating in resistive materials; the Seebeck, Peltier, and Thomson effects in thermal electricity
- ANSYS The AIM platform allows designers to quickly and easily tackle problems involving several physics. AIM's graphical user interface and workflow wizards make it easy to use.
- AIM includes DC electric conduction analysis, which helps with product design by calculating power loss, voltage drop, and current distribution.
- AIM offers a number of multi-physics simulation methods; one of them, "completely coupled thermoelectric-stress analysis," uses power loss to

calculate product designs' temperatures, and thus their thermal deformation and stress.

1.14 INTRODUCTION TO CFD:

Recent advancements in thermoelectric producing materials have resulted in cutting-edge systems that harness wasted heat to produce usable electricity. The environmental and economic benefits of these technologies have become increasingly apparent in the face of global warming concerns and rising fuel costs. Five thermoelectric generator (TEG) modules were placed between two aluminium blocks, and a CFD model of this configuration was produced in this study. However, TEGs have gained popularity in recent decades due to their efficiency as a heat recovery method. They are thermal energy converters that use the Seebeck effect in solid-state devices. Solar and geothermal heat recovery are just two of the many uses for stationary heat recovery systems. Automotive applications and space travel are only two examples of where mobile heat recovery systems have been put to use. TEGs are a great option for cutting-edge applications including providing energy for radioisotope-powered spacecraft, powering navigational aids and telecommunications systems, and being compact and efficient.

The error patterns produced by various numerical algorithms are distinct. Numerical diffusion, false diffusion, and even numerical flow are common euphemisms for 'error' in CFD. An in-depth understanding of the algorithms is required to make educated guesses about the most likely mistake patterns. The user must determine whether or not the simulation's outcomes are satisfactory. Comparing the final results of a CFD code to those obtained through experimental testing is the only reliable method of determining the quality of the code's underlying physical and chemical models. If you want to utilize CFD seriously, you need to accept the fact that it is not meant to replace experimentation but rather serves as a powerful supplementary tool for doing so. In order to validate a CFD code, a great deal of data must be generated, and precise information on the problem's boundary conditions must be gathered. For them to be meaningfully validated, analogous experimental evidence is required. In order to monitor flow rates, a software may employ particle image velocimetry, laser Harmonic anemometry, or hot-wire anemometry. If such sensitive laboratory equipment is unavailable or cannot endure the environment, static pressure and temperature measurements, as well as pitot-static tube traverses, might be helpful to validate certain properties of a flow field.

1.15 EXPERIMENTATION WITH IOT APPLICATIONS

Electricity is unavailable to approximately 300 million people worldwide. This disproportionately affects rural areas. Getting power through normal routes will take some time. Many forested and mountainous regions are too far from the grid to get regular electricity service, so residents there must find other ways to power their homes. Using a network of sensors and the internet, the IoT allows for real-time, global communication between humans and machines. Despite this, the problem of energy supply is a barrier to the wide-scale adoption of the Internet of Things. With their capacity to immediately transform temperature gradients into power, thermoelectric generators (TEGs) have garnered significant interest in the Internet of Things (IoT) sector due to their many advantages. In addition to resolving the issue of energy supply in IoT applications, the employment of TEGs for this purpose might pave the way for the actualization of self-powered IoT systems, which can be used in a wide range of contexts, from smart cities to healthcare infrastructure. When used to Internet of Things (IoT) applications, TEGs offer a long-term, renewable, and affordable energy source that can drastically cut down on operational expenses and boost energy efficiency. Therefore, the most recent findings in the field of TEGs need to be incorporated into IoT. TEGs are advantageous in that they do not need to be plugged into a wall outlet because they draw their power directly from a person's body heat. Because of this, they are ideally suited for uses in which the use of more conventional power sources would be inconvenient or impossible. Furthermore, TEGs are sustainable and renewable, so they may offer steady energy throughout the device's lifetime, extending its useful life and cutting down on maintenance costs. Scene sensors for IOT applications are then discussed, with applications ranging from energy management in buildings to airplanes.

1.16 Background of the study:

Energy resources have a significant impact on the expansion of human life. The most common application of energy sources is in the generation of electricity. This electrical energy is commonly used in sectors like health, transportation, communication, information technology, automotive, residential and industrial electrification, etc.

Primarily in developing countries, fulfilment of the increasing electricity demand, at different locations with limited resources, is a challenge. The energy sector comprises four main components viz. generation, transmission, distribution, and consumption. For the generation of electricity, energy sources are further categorized as, a) Renewable and non-renewable energy sources are the two main categories. The use of renewable energy sources is rapidly replacing that of fossil fuels. Biomass, solar, wind, hydro, and geothermal power are all part of this category. While all of the aforementioned options can generate energy, they do so with different advantages and disadvantages. Generation of electrical energy has relied heavily on fossil fuels for a long time. An urgent need exists to employ renewable or alternative energy sources as the traditional ones continue to dwindle owing to over consumption. These days, renewable energy sources are preferred over non-renewable ones because of the time and effort needed to replenish them, the damage they do to the environment, and the scarcity naturally developing.

1.17 PROBLEM STATEMENT:

The exhaust of a car engine is responsible for losing about 25%-30% of the energy it produces to the atmosphere. Consequently, harmful gases were released and global warming and environmental issues increased. Due to this, efforts have been put into improving industrial processes' efficiency. Utilising thermoelectric generators that draw heat from vehicle exhaust is an essential step. In order to improve a car's performance, a solid-state device is used to convert the heat energy that is emitted by the exhaust system into electricity. Using free heat, or energy from a heat source that doesn't cost anything, as an input makes TEGs a possible alternative green technology despite their low efficiency. Both the site of the installation and the thermoelectric materials it employs have a significant role in determining its overall performance.

CHAPTER 2

LITERATURE REVIEW

The literature reviewed suggests that the unused PCM energy in TEG integrated PCM systems is discharged from the TEG's cold side. No research on recycling the wasted heat for other use, such as heating or cooling, has been published. TEG-enhanced PCM system performance studies reporting strong sun irradiation and substantial ambient temperature change are also few. There is a shortage of theoretical and experimental investigations of TEG-PCM systems that provide a complete picture. Therefore, it is crucial to solve these problems by adopting integrated systems to ensure a steady energy flow. The experimental setup of a hybrid system that includes a STEG-connected latent heat storage and cooling system is shown in this research. The TEG's efficiency throughout the day and night is the reason behind this arrangement. The proposed technique raises the temperature differential between the hot and cold sides of the TEG by passively decreasing the cooling of the cold side during the day.

A. Costaa et al (2014). The present endeavour consists of creating a self-sufficient, low-cost, dependable energy scavenger sensor with potential uses in the automotive industry. Thermometric generators are well suited for applications that don't require constant power but can run on their own because of their poor efficiency and great reliability. Even when tested with the engine running, the prototype's signal transmission rate remained constant. Installing the sensor directly at the measuring site improved the system's reliability and made it easier to avoid wiring connections to hot and vibrating elements.

Albert Patrick (2017) TEG technology has been at the forefront of recent advancements in the field of energy conversion by reusing waste heat. It is being integrated into the renewable energy market in a number of different ways. TEG has previously been shown to be a viable waste heat gathering method. The increasing need for fossil fuels around the world has prompted researchers to focus on developing viable alternatives. Scientists took a gamble on a heat-to-electricity conversion method. A considerable amount of the credit for this goes to the Seebeck effect. Utilizing TEGs allows for the conversion of heat into their strength. TEGs are electronic devices based on semiconductors. The study's authors developed a generator that stores energy for later use with renewable sources. The power has multiple applications, one of which is the recharging of mobile devices.

Amirul Abdul Rashid et al (2021) Researchers investigated the efficiency and effectiveness of a TEG module comprised of several cells. There was a heating element, the actual testing area, and a cooling area on the bench. To simulate the byproduct heat from a real PEMFC stack, a heating element produced hot streams at 53 and 58 degrees Celsius. In this component, four TEG cells were used, with the cells being connected through heat pipes and a heat sink. The cooling performance of TEGs was determined by balancing the effects of natural convection.This first, reasonably straightforward design of a TEG module shows great promise in mitigating the detrimental effects of a PEMFC's extremely cold waste heat. The outputs of PEMFC systems can be improved and their long-term viability enhanced if future module designs identify a more optimal technique.

Avishkar Phulari (2018). The increasing pollution problem is an important problem nowadays. Vehicle exhaust is a contributing factor to pollution in today's globe. As the number of cars on the road grows, so does the amount of pollution it produces. Internal combustion engines (IC engines) contribute to environmental degradation due to the significant amount of lost energy that is utilised to fuel combustion. The result is an increase in average temperatures around the planet. Therefore, it is crucial to make use of the I.C. engine's exhaust heat. Various techniques exist for recycling the heat produced by internal combustion engines. As soon as their research is over, we will explain these various waste heat recovery technologies.

Beytullah Erdogan (2021). Many modern automobiles use internal combustion engines. The emissions from cities' millions of cars are particularly harmful because they are primarily powered by fossil fuels. The exhaust of an internal combustion engine not only releases harmful pollutants into the atmosphere, but it also wastes a significant amount of potential energy. Modern technology allows us to collect and repurpose some of the exhaust heat that would otherwise be squandered. The intriguing area of energy recovery known as thermoelectric generators for generating electricity from waste heat in vehicle exhaust has recently attracted a great deal of academic attention. By coming into contact with both surfaces, a thermometric generator can harness the energy differential between a heat source and a heat sink. In order to help lower the pollution rate per unit of energy produced, recovering waste heat is crucial. Using a hexagonal aluminium exhaust heat exchanger and 24 TEG (Thermometric Generator) modules sandwiched between copper cooling blocks and the exchanger, this study conducted experimental research into the thermoelectric generator's potential applicability.

Corina Covaci (2020). Primarily concerned on piezoelectric energy harvesting, their research intends to provide an exhaustive review of all existing technologies. The capacity of piezoelectric materials to generate an electric field is the bedrock of mechanical force energy harvesting. These actions are defined by the direct piezoelectric effect. Because of its malleability in form and substance, piezoelectric transducers are ideal for a broad range of applications. In order to make the most of piezoelectric devices, it is helpful to have a model to analyse their operation in the time and frequency domains. In addition to exploring several facets of piezoelectric modelling, the authors of this paper also provide a number of circuits that can be utilised to increase the amount of energy obtained.

Daniel Champer (2017) This assessment of thermoelectric application discusses the significant added value but limited market presence of applications operating in harsh environments. Increasing temperature disparities are now possible with the help of modern thermoelectric modules due to their expanded operating ranges. According to the review's many research and real-world examples, TEG are a viable option for generating electricity in both developing and wealthy nations when grid connectivity is impossible. The efficiency of heat-generating equipment can be increased marginally or regularly due to this ability to create some power. The numerous possible uses of their research demonstrate that the inclusion of a TEG is pertinent in nearly every industrial and everyday context where heat is transported from a hot to a cool source.

Deepak Monga et al (2017) Energy recovery methods are becoming increasingly important due to the growing importance of environmental protection and the worldwide energy problem. A significant quantity of energy is lost as heat through exhaust gases from engines, making this a potential area for energy recovery. The engine's efficiency can be greatly improved by implementing the proper recovery procedures. Thermoelectric generators are offered as the best answer for this because they transform exhaust heat into power without the use of any moving components or gas emissions. Heat pipes are another interesting method for recovering wasted heat. Heat pipes combine the phase change of a fluid (usually water) with the superior thermal conductivity of the pipe itself to transmit heat quickly and effectively. Research findings show that these technologies have great potential for preserving non-renewable energy sources and lowering environmental deterioration.

Ditthaphat Tanpradit (2020). The main objective of this research is to develop a more efficient "CHEU"—a device that uses a thermoelectric generator (TEG) to transform waste heat energy into usable electricity. A device that turns the LPG cooker's waste heat into useable heat is installed on the appliance. To do this, certain devices employ series connections of four modules; one such device is the thermoelectric generator, which converts heat into electricity. Cooling systems that employ water also have the added advantage of lowering the surrounding temperature.

Govind Mishra (2017). An automotive thermoelectric generator (ATEG) converts the leftover heat from an internal combustion engine into electricity using the Seebeck Effect. The four main components of a typical ATEG are the compression assembly system, the thermoelectric materials, the heat exchangers (both hot and cold), and the heat exchangers The exhaust or coolant heat from an engine can be utilised to fuel an ATEG, which in turn produces electricity. ATEGs recover this lost power, which is then used to lessen the strain on the engine's electric generator. However, the expense of the unit itself and the extra gas required to move it around are also factors to consider.

Hrishikesh Kiran Sawant et al (2017) Research on cutting-edge technology, such as extremely efficient internal combustion engines, has received a significant boost in recent years thanks to heightened public and scientific interest in environmental and energy concerns. Exhaust gas from modern automobile engines contains a sizable amount of thermal energy. The most up-to-date and inventive methods for reusing exhaust gas heat include thermoelectric generators, the Organic Rankin cycle, the six-stroke cycle of internal combustion engines, and advanced turbocharger technology. If you have a thermoelectric power generator, you can convert this heat into usable electricity. There are now far fewer moving and rotating components. It is feasible to directly convert waste heat into electrical energy via thermodynamic power generation. By eliminating the source of the pollution, public faith in this environmentally friendly technology has increased.

Imansyah Ibnu Hakim (2018) Modules called thermoelectric generators (TEGs) combine the See beck effect and the Pettier effect to directly convert heat into electrical power, allowing them to increase energy efficiency by harnessing the heat produced by an inefficient instrument. Reduced fossil fuel consumption is a positive step towards a healthier planet. The objective of this research is to find out how the temperature difference between the hot and cold sides of the TEGs affects their output voltage. To make it work like hot water, we may use the heater to heat up one side of the module and the heat pipes on the other side to dissipate the heat. The 2.1-volt output from the system is sufficient for usage as a mobile phone charger, and it is generated by four TEG modules connected in a thermal series-series circuit and two heat pipes.

Jinlong Chen et al (2017). In recent years, low-temperature thermal resources especially those used to produce electricity have received a lot of attention. Most commercially available thermal (including geothermal) power-generation methods perform an indirect conversion of thermal energy to electric energy by doing mechanical labour first. However, the See beck effect can be used in conjunction with a TEG to directly convert thermal energy into electricity. Because there are no moving parts, TEG technology provides many benefits, including portability, silence, and dependability. The inefficiency with which TEGs convert thermal energy into electricity is one of its main drawbacks. This is why we upgraded our prior 1 KW TEG system with a new design and modifications. The system's output power was increased by around 34.6%, and the TEG system's instantaneous efficiency may reach around 6.5%. The output power has been measured in the lab in a variety of settings, including with different mechanical structures, hot and cold side temperatures, and connecting types for TEG modules. The TEG equipment was put through its paces, and the results are in. Oil fields that co-produce fossil and geothermal energies are only one example of where this type of TEG power system could be put to use.

Kanika Aggarwal, et al (2017) Electricity is crucial to human existence and the functioning of many modern enterprises, yet it is in short supply. Through this research, we provide a remedy. Their research focuses mostly on finding ways to reduce energy consumption by reusing exhaust heat from internal combustion engines This energy can be used to recharge the battery, which in turn extends the battery's life and decreases the vehicle's need for fuel. The They used ANSYS to look at the efficiency of TEG as well as the heat transmission within TEG as part of their research.

Kotaro Kawajiri (2021). They used a life cycle assessment (LCA) methodology to look at how using thermoelectric generators (TEGs) could lessen the impact on the environment. The environmental effects of TEGs during their whole useful life may now be evaluated thanks to a novel up-scaling technique. At various phases of manufacturing, we looked at conversion efficiencies of 7.2%.. A more efficient conversion of TEG and less stainless steel used in its production are two of the most important steps toward reducing the environmental impact of TEG production and use. It is important to examine the conversion efficiency and lifetime driving distance in order to accurately evaluate the benefit of TEG deployment.

Koushik Ahmed et al (2019) In recent decades, global warming and energy scarcity have become major issues of concern. As a result of the power outage, scientists have been looking at cleaner, cheaper, and more sustainable methods of producing electricity. The use of TEGs, a novel environmentally friendly technology, has been on the rise recently. Their research included breaking down the fundamentals of thermoelectric power production and developing a TEG module in ANSYS 19.0. Sizes of P-type and N-type materials are also quantified. Based on these modelling results, we can approximate the size and quantity of TEG modules needed to generate 1V. Furthermore, the rationales for utilising silicon are reviewed. Also covered are a number of possible applications and enhancements.

Kuo Huang et al (2018) The TEG has received growing interest from automakers and researchers alike over the past decade as a potentially effective means of waste heat recovery. Section one of this research gives a broad overview of recent developments in TEG heat exchangers and thermoelectric materials. Following this, we demonstrate how to correct the heat exchanger's defects by creating a TEG system with concentric cylindrical tubes. We present a concentric cylinder-based TEG system that, instead of using a standard square thermoelectric module, uses an annular module in conjunction with a heat pipe to increase radial heat transmission. Power output was highest for the water-inside circular cylindrical TEG system in our calculations, followed by the gas-inside arrangement.

LUAN Weiling (2004) Thermoelectric power generation (TEPG), which involves the direct conversion of heat to electricity, is one method of producing energy that is predicted to grow in popularity over the next few decades. TEPG stands out from competing technologies because it is portable, lightweight, silent in operation, free of carbon dioxide emissions and radioactive compounds, and has a long track record of reliability. However, some of the drawbacks include a low current conversion efficiency and a high price tag. Space travel, military operations, telecommunications, navigation, and the remote monitoring of unmanned vehicles are all examples of legitimately high-tech uses for TEPG. Additionally, TEPG does not add to environmental concerns like climate change-related pollution or the depletion of natural resources. In this work, we aim to survey existing TEPG research and practise in order to evaluate its current and future utility. Methods for fabricating high performance thermoelectric material are highlighted; this will help advance the efficiency of TEPG devices.

M. K. Shilpa et al (2022) Ammonia and Freon, byproducts of conventional refrigeration systems, are released into the atmosphere and contribute to warming the planet. Thermoelectric modules may hold the solution because they don't use coolants or refrigerants. However, if you compare these modules to standard refrigerators, you will find that their cooling performances are on the low end. Their research has covered a wide range of topics, including mechanical properties of thermoelectric materials, different types of thermoelectric devices, mathematical modelling of thermoelectric materials, and the numerous possible uses of these materials.

Mohamed Amine Zoui et al (2020). No moving parts are required in the thermoelectric conversion process, making it a prime candidate for use in remote locations. Thermoelectric devices are used in renewable energy, heat recovery, and refrigeration because of their niche market appeal despite their inefficiency. Space probes, laboratory apparatus, and medical devices are just a few examples of the kinds of places where thermoelectricity might be useful in situations where reliability, predictability, and availability are more important than efficiency and cost. The application of nanotechnology enhances thermoelectricity's potential to become a frontrunner in renewable energy generation and waste heat recovery. The latest thermoelectric generators, their uses, and their advancements are discussed here. Thermoelectric effect basics, including the principles and parameters that determine how effective both old and new thermoelectric materials are, are covered.

Mohd Zul Waqar et al (2018). The objective of their research is to create a thermoelectric generator (TEG) that can be powered by the waste heat produced by an air conditioner's compressor. There is currently a plethora of options for drawing power from renewable resources. While the potential for harnessing energy from waste heat sources is promising, further research is needed. Their research centred on reusing heat energy produced by household appliances, particularly air conditioners, through thermoelectricity. Compressor of the air conditioning system was used to collect experimental data, which comprises hot and cold side temperature. The resulting input data and output voltage were analysed with Mat lab SIMULINK, and the model was utilised to derive calculations for current and power consumption. Thermoelectric energy harvesting could be used to turn on a light bulb in a room utilising the waste heat from an air conditioning system.

Mohd.Quasim Khan (2018) Automobiles typically use internal combustion engines, which are only 25-30% efficient and release the rest of the heat energy produced during combustion as exhaust. As a result, pollution levels rose, causing more harm to the ecosystem and contributing to increasing temperatures around the globe. Consequently, increasing the effectiveness of every manufacturing procedure has become an urgent goal. Thermoelectric generators are prioritised over other methods for harnessing the energy contained in vehicle exhaust. It is a solid-state gadget that increases a vehicle's performance by harnessing the thermal energy contained in exhaust gas. Though a TEG's 4-5% efficiency is modest, the fact that it can be operated with no-cost input heat energy makes it a promising alternative green technology with a bright future. The location of the installation and the thermoelectric materials used greatly affect the efficiency optimisation.

Ms. Kiran A et al (2018). As our fuel resources dwindle, the need for energy continues to rise, yet there are fewer and fewer places to get it. The heat that is being squandered is valuable energy that has to be harnessed. It is possible to turn otherwise wasted heat into usable energy with the help of waste heat recycling, which is used by some systems. Conventional thermal power plants typically use recovered waste heat to create heat, which is subsequently transformed into electricity. The Seebeck Effect-driven thermoelectric generator module allows for the efficient generation of electricity from waste heat. Here, power can be generated simply by taking advantage of temperature differences. Today's automobiles convert over 70% of the energy they consume to move into heat, which is lost through the exhaust emissions. The research team's goal is to demonstrate that electricity may be generated from the waste heat of an automotive engine. In addition, the electrical energy produced might power the electric vehicle's LED headlights or be used to top out the battery.

Ms. Payal N (2019) Internal combustion engines are the norm for commercially available automobiles. Internal combustion engines (ICEs) discharge waste heat and exhaust gases into the atmosphere, wasting the majority of the fuel's primary energy source. Their findings summarise the waste heat recovery system and show how the ICE system can be significantly improved in terms of performance. Utilising TEGs, state-of-the-art research is performed. The exhaust energy recovery system can be constructed with the help of this technology, which allows for the direct heat-to-electric energy conversion with no moving elements in the vehicle.

Thermoelectric generators can be designed based on a temperature range, making use of thermometry as one of the strategies that aid in recovering waste heat. The new effort builds on their previous theoretical research to enhance the effectiveness of the system as it currently stands through the implementation of novel structural changes.

Muhammad Usman Ghani, et al (2016). Thermometric instruments are widely used today because of the synergistic effect of electrical and thermal energy. Heat recovery devices can be installed in exhaust systems because of their ability to transform thermal energy into electrical power. When inserted in the engine's hot exhaust, thermoelectric modules can generate electricity. There is only one step involved in the process, and it is controlled by the See beck effect. Electric appliances in moving vehicles can be powered by this energy source. TEG's ability to harness energy from the engine's byproducts has piqued an enormous amount of interest in the automotive sector.

Narayan Gurjar (2021) The rising need for transportation around the world has led to a rise in the popularity of internal combustion engines. Heat energy management and energy problems are at the forefront of the present scenario. There needs to be a mechanism to collect and repurpose the heat that goes into an internal combustion engine since the majority of it goes out the exhaust rather than being turned into useful energy. A thermometric module is a solid-state device that uses a temperature gradient to convert thermal energy into electrical energy. The outer surface of an engine's exhaust pipe can get very hot—up to 2,000 to 4,000 degrees Celsius (about 4,000 to 900 degrees Fahrenheit)—when the exhaust gases are passing through it, therefore this temperature differential can be determined from there. Considering the magnitude of the energy leakage problem, developing a solution to capture this escaping heat is an essential matter. An attempt is made to implement a waste heat recovery system in the study, with the help of a TEG made for a car's motor. Recycling exhaust heat is a common practise in the automotive industry, and there are many different approaches to this problem.

Naveen Kumar et al (2019). In recent years, the automotive industry has focused a great deal of R&D energy on developing methods of increasing vehicles' fuel efficiency. As a result, there has been a surge of focus on improving the efficiency of internal combustion engines. In the past, only about 25 percent to 30 percent of the energy produced by a vehicle was really utilised within it. Both the engine and the generator are powered by the usable energy. This means that the engine was extremely inefficient. However, efficiency can be increased by harnessing the heat energy normally lost out of a car's exhaust. Thermoelectric generators were found to be particularly effective in this regard. Thermoelectric generator power generation is the subject of our research and analysis here. Using the beck effect concept, the thermometric generator generates electricity by transferring heat from the exhaust gas flowing over its surface to a heat exchanger located in the gas's path. A single Bi2Te3 thermoelectric module produced 200mV of output Voltage at a temperature difference of 40o C, which can be used to charge batteries, headlights, G.P.S. systems, etc., and thus reduce the amount of frictional power used by the alternator to save fuel and increase engine efficiency in the automotive industry.

Nesrine Jaziri et al (2020) Today, we face challenges including rising energy prices, polluted environments, and the effects of global warming. Scientists are working to mitigate these problems by developing more efficient energy generators that harness the sun's rays. TEGs efficiently convert heated energy into electrical energy by means of the See-beck effect. They can be constructed on many different materials, including silicon, polymers, and ceramics, and operate silently without the use of any mechanical structures or moving parts.

Nicanor B. Fabracuer, Jr et al (2020) Solar, hydroelectric, and wind power are all examples of renewable energy sources that may generate electricity indefinitely. One new kind of renewable energy uses the heat that some machines generate. The reason behind this is that electrical producing units that rely on combustion engines to generate heat generate a substantial amount of waste heat energy while burning. This inquiry thus mainly focused on the thermoelectric generator in its role as a collector of waste thermal energy. It is impossible to generate thermodynamic power without the Seebeck effect. Creating a circuit for a 20-watt thermoelectric generator—sufficient to power an AC load—was the principal objective of this research. Certain measurements had to be obtained while the prototype was in use in order to validate the gadget that had been manufactured. As more research and development go into making this technology commercially viable, it is becoming a viable alternative energy source.

Nyoman Sugiartha (2018). The feasibility of using an exhaust heat recovery system in automobiles was studied by constructing a thermoelectric generating (TEG) unit. The TEG system also included data collection tools, an external resistive load, and an AC and DC power source. Commercial TEC1 12706 thermoelectric modules were used for this application. The TEG module relied on the heater, which imitated an exhaust heat source to power the TEG module's hot side. The cooling fan was employed to imitate airflow and guarantee that heat was being steadily dissipated from the heat sink. The experiment was conducted to determine an exact value for the TEG's performance. There were further measurements taken during testing of the TEG module's open circuit voltage, voltage at the output, and output current. Even though it has low output power and conversion effectiveness, the TEG unit can turn the waste heat energy from a model car's exhaust into useable electricity. Experiment findings indicate that the temperature differential between the hot and cold sides of a TEG module significantly impacts its efficiency.

P. Mohamed Shameer (2013) However, certain inevitable processes limit the engine's capability for optimal balanced efficiency. Rapid gas expansion within a cylinder result in significant temperature gradients, turbulence in the fluid, and rapid heat transfer between the fluid and the piston top and cylinder walls. The expanding exhaust gases formed by these rapid successions of events must be released from the cylinder while the gases are still expanding above atmospheric pressure. Thus, the exhaust valve and manifold can be utilised to channel the combustion process's byproducts, namely, high-temperature gases. A neighbouring power plant might be able to run on recovered waste heat energy from the outgoing flow of spent gases. There had been numerous unsuccessful attempts to convert the waste heat into energy. The thermoelectric waste heat energy recovery system described and implemented in this study could be useful for all vehicles that use internal combustion engines, including petrol and hybrid automobiles. The prospects for the suggested system's application in the car sector may be seen in the test results, which show its effectiveness in many scenarios.

P. Ragupathi, et al (2020). The current study focuses on developing methods to harness the thermal energy lost in an internal combustion (IC) engine's burned exhaust gas (BEG) and convert it into usable electricity. It was planned, built, and tested experimentally to see how well the HTSPD type HE could generate power in tandem with TEG. The TEG modules in HTSPD type HE were heated by water, which also served as the working fluid. For the experimental evaluation, a 6-kW diesel engine was used, and its load was changed from 25% to 100% in 25% increments. The use of TEG modules significantly reduces thermal pollution produced by high-temperature exhaust emissions, and their ability to generate electricity adds to higher overall efficiency.

Prashant Chandra Pujari (2019) The ICE underperforms when compared to other methods of converting chemical energy into mechanical energy. Roughly one-third of the energy produced during combustion is wasted as heat in the exhaust. Thermoelectric generators increase the engine's efficiency indirectly by generating power from the exhaust heat. Biodegradable thermoelectric generators use the Seebeck phenomenon to transform the thermal gradient between the generator's hot and cold sides into electrical current. As a means to control the TEGs' temperature and lower the system's thermal resistance, heat pipes are employed. Heat pipes have temperature and rate constraints, while TEGs are relatively inefficient and have limited temperature limits. Conversely, TEG and heat pipes are both inexpensive and long-lasting. This research shows how TEGs may be tested experimentally to offer reliable performance data throughout a wide temperature range, and how to set up heat dissipation for TEGs so that their exhaust efficiency can be analysed. The present research goes beyond just setting up TEGs to examine their potential applications.

Prathamesh Ramade et al (2014) A typical internal combustion engine operates at roughly 30% efficiency. Exhaust gases account for around 30% of the fuel energy lost, while cooling water accounts for another 30%, and miscellaneous losses account for the remaining 10%. Thirty percent of potential energy is lost in exhaust gases, and many are working to recover it. Recovering this otherwise lost heat energy can improve an engine's overall efficiency. In thermometric modules, a solid-state technology, thermal energy is transformed into electrical energy by means of the Seebeck effect. The results of their study prove that thermoelectric power generation is doable. The performance of thermoelectric generators at different engine speeds was the subject of extensive experimentation. The cold side heat exchanger and sink of a three-cylinder, four-stroke Marti 800cc SI engine were evaluated for efficiency. Two bismuth telluride (Bi_2Te_3)

thermometric modules were strategically placed to measure the exhaust gas side and engine coolant side temperature difference. Thermoelectric modules were put through their paces with the help of a rectangular heat exchanger. Based on these findings, thermoelectric generators may soon allow car manufacturers to either significantly downsize the alternator or do away with it altogether, freeing up space in the engine compartment.

Pratiksha Pohekar et al (2018). In their study to increasing energy needs, it must slow the depletion of non-renewable energy sources while increasing its usage of renewable energy. One strategy involves reusing the heat that would otherwise be wasted. Thermal energy, collected as waste heat, is converted into electrical energy in the majority of current systems. Thermometrics, the study of systems that transform heat into electricity, is its own scientific discipline. Thanks to thermoelectric automotive thermoelectric generators, lost heat from vehicles can be recovered and used for other purposes. Energy recovery from today's waste has tremendous potential for boosting the performance of ICE systems. Latest research results on thermoelectric generator (TEG) based exhaust waste heat recovery systems are summarised in their study. Exhaust energy recovery systems can be built with little mechanical moving parts thanks to these technologies, which directly convert waste heat into useable electricity. This article will serve as a primer on the fundamental parameters, components, and factors that affect the efficiency of exhaust energy recovery systems in vehicle engines.

R. Radermacher (2007). Thermoelectricity is the process of transforming heat into electrical current and vice versa. In 1823, a German scientist named Thomas See beck discovered the basic idea of thermoelectricity by observing that a continuous electric current runs across a closed circuit made by two different conductors with their joints maintained at high and low temperatures. The Peltier effect, named after the French watchmaker who discovered it, Jean Charles Athanase Peltier, occurs when two dissimilar conductor metals in a circuit are used as an interface, causing heat to be absorbed at one joint and released at the other

R.A. Taylor (2008) Conventional sources of energy are running low, while the world's want for power grows steadily. Carbon emissions, the primary driver of climate change, are another problem with traditional energy sources. Since it uses renewable energy sources and produces no carbon dioxide, the thermoelectric (TE) system is an excellent choice. As the world's population grows, so does the demand for power, heating and cooling, refrigeration, air conditioning, etc., all of which contribute to rising greenhouse gas emissions. The emission of greenhouse gases can only be controlled, and an essential part in sustainable development played, by green technologies like wind power renewable energy sources. Carbon emissions are a global concern; thus several nations are working to establish new regulations for industries. Thermoelectric equipment has recently emerged as a viable choice for environmentally beneficial applications. The eco-friendliness and unique benefits of thermoelectric energy have led to its widespread use in a variety of contexts, including cooling and heating, refrigeration, electricity generation, ventilation, air conditioning, and more. A potential application of thermometric energy is the transformation of heat into electricity.

Raghav Kumar Raghu et al (2019) Waste heat recovery, also known as waste heat recoupling, is the process of reusing the heat that is produced as a byproduct of the functioning of a machine or other piece of equipment. A copper pipe is coiled around the drain pipe of a washbasin or shower to collect the heat that would otherwise be lost. Intricate heat recovery systems in data centres may repurpose waste heat from liquid cooling systems to heat areas that need it. In order to generate electricity without contributing to environmental problems like radioactivity, global warming, etc., new technologies have emerged, the most promising of which is the use of a thermoelectric generator. Waste heat accounts for an estimated 20% to 50% of industrial energy consumption. Exhaust gases, cooling water, equipment surfaces, and completed goods all contribute to this type of heat. Waste heat recovery offers an attractive option for a cheaper and emission-free energy supply as the industrial sector is trying to get more efficient with its energy usage. You can choose from a variety of standalone and combined waste heat recovery solutions today.

Raşit Ahıska (2014). TEGs have been described as a key component in the process of transforming geothermal energy into electricity. The TEG structures employed in the generation of electrical energy have also been described. Both air cooling and power generating can benefit from thermoelectric (TE) technology. In addition to being silent and long-lasting because there are no moving components, TE technology is environmentally benign because it produces no greenhouse gases. However, commercially-available TEMs have a conversion efficiency of less than 10%.

Roozbeh Sheikh et al (2019) The vehicle's exhaust system quickly dissipates a significant amount of heat, which is then released into the atmosphere. Through thermoelectric generation (TEG), this thermal potential can be transformed into electrical energy. This project aims to extract electrical energy from vehicle exhaust by modelling and analysing nine various types of heat exchangers in three dimensions using CFD analysis. The layouts of these heat exchangers vary from basic to advanced. Group A's simulations pay special attention to how the bates' angle and thickness influence the heat transfer in the heat exchanger's intake. Group B modifies the bears' spacing and height, while Group C focuses on representing bates of a bigger size in a variety of layouts. Results demonstrate that, while pressure drops are within acceptable ranges for all models, group A's gas fowl velocity is nearly identical to that of the other models evaluated, while the group's power output is at least 7.25 percent greater. The optimal design for maximum output is also suggested and explored. The implementation of a defector is proven to cause a temperature gradient in only one direction.

S. O. Giwa et al (2019) Researchers have been looking into energy harvesting as a way to save and reuse energy that would otherwise go to waste due to inefficient use of power. In their research, they show how to convert the excess heat from common domestic appliances like kerosene stoves and generator exhaust pipes into usable electricity. For the purpose of waste heat harvesting, aluminium heat sinks and TEG modules were built and installed in close proximity to the heat sources. Power and energy harvesting were assessed by monitoring the TEG modules' hot and cold sides, as well as their associated output currents and voltages.

Shubham Suryawanshi et al (2017) The thermal efficiency of internal combustion engines is approximately 30% after accounting for the 30% loss in fuel energy due to exhaust gases, 30% loss in cooling water, and 10% loss due to other inexplicable causes. The energy contained in these gasses' accounts for around 30% of the whole, and we are working to put it to good use. By putting this excess energy back into the engine, we can make it run more efficiently. A solid-state device known as a thermometric module can exploit the Seebeck effect to generate electricity from a temperature gradient. A thermal energy generator (TEG) is incorporated into the process design to harness the potential energy contained in the temperature differential between the coolant and the hot exhaust stream. Heating and cooling are accomplished by means of heat exchangers that are attached to the modules on opposite sides.

Shyam Patidar (2018) The concept of TE energy is novel due to the fact that it allows for the reversible conversion of energy, such as from thermal to electrical and vice versa. The fundamental mechanisms for all uses of TE energy are the Seebeck and Peltier effects. Because of its ability to convert heat into electricity both ways, thermoelectricity has numerous practical uses. As a result of scientific progress and public anxiety over climate change, TE devices are becoming more commonplace due to their environmental friendliness and other advantages. Thermoelectric energy's versatility stems from its capacity to be used in a wide range of applications; this includes, but is not limited to, the production of electricity, the cooling of food, the heating of buildings, the operation of air conditioners, the operation of medical devices, and so on.

Siddique, (2017) A In their study, to comprehensive review of recent advances in TEG technology. That this evaluation classifies TEGs according to technology and type (vertical, mixed, and planar) is what makes it stand out. Modern thermoelectric materials and methods for efficiently achieving high power factors in different topologies utilising these materials will also be explored.

Sonal Renge, (2017). New inventions and scientific discoveries greet us each morning as the sun rises. Numerous innovations have been produced to simplify regular tasks thanks to the breadth of this spectrum, which encourages humans to find alternatives to outdated technologies. Using alternative energy sources to replace traditional grid electricity is a hot topic right now. Similar to how heat may be used to generate electricity. For such purposes, the Seebeck effect principle can be utilised. The German physicist Thomas See beck originally described it in 1820. The Seebeck effect is what happens when the two ends of a metal are at different temperatures and the metals are in touch with each other at a common point. This is also the case with the Pettier module. As part of our research on the best ways to make use of a pettier module, we have been experimenting with TEC-12706. Based on the findings of their analysis, it is clear that voltage and total power output vary depending on the heat source being utilised.

Sri Jagath H.R et al (2020) The interest in investigating alternate power generation technologies has grown in tandem with the public's growing awareness of environmental problems such as emissions and resource depletion. There has been a rise in interest in thermometric power producers as a practical environmentally friendly option. Indirectly transforming waste heat into usable electricity by thermometric power generation eliminates the need to account for the cost of the thermal energy intake. The overall efficiency of energy conversion systems could be improved by switching to more environmentally friendly technologies like those that use waste thermal energy to produce electricity. In their research, they explore and review the foundational principles of thermoelectric power generation and how it might be used to the treatment of waste heat.

Teuku Azuar Rizal et al (2020). The heat produced during combustion accounts for around 65% of the energy lost in combustion-powered vehicles. The exhaust system of a vehicle is a pathway for the heat energy released by the engine's combustion chamber. By hooking up to a car's exhaust system, a thermoelectric generator (TEG) may transform the heat from the exhaust into usable electricity. One way to cut down on gas mileage is to put TEG in motorcycle exhaust. This study builds and tests prototypes of cell phone chargers powered by thermal energy harvesting (TEG) applied to motorbike exhausts. The design was created in Autodesk Fusion 360 Student Edition, and further prototype was accomplished by hand-assembling all the parts. Instruments used for measurement during prototype testing included a DC voltage sensor and a k-type thermocouple connected to a data logger and laptop. Our laboratory engine ran at 4000 rpm. When the motorcycle was at a stop or idling, the heat pipe test achieved a cold side temperature of 115 degrees Fahrenheit at a voltage of 4.47 volts, which was significantly higher than the heat sink test.

Umar Abubakar Saleha et al (2021). Renewable energy research and development, particularly solar, is crucial for satisfying expected energy needs in the future. Energy production and security can both benefit from solar cells that can harness more of the sun's spectral range. Unfortunately, PV technology can only convert a small percentage of the spectrum into power. Solar PV cells lose efficiency and wear out faster because of the excess heat produced by the sun. Surprisingly, when combined with a PV, thermoelectric generators (TEGs) can operate as heat engines, transforming waste heat into electricity via thermoelectric effects. These generators reduce the amount of heat that solar cells create while simultaneously increasing the efficiency of the device. Many studies have looked into the hybrid PV-TEG system's efficiency, and more are in the works. In this study, we look at thermoelectric and photovoltaic theories. Along with other methods for integrating hybrid systems, this article emphasises the importance of experimental and numerical research in improving the efficiency of PV-TEG hybrid systems. This research not only evaluates the impact of key parameters on PV-TEG performance, but also suggests avenues for future investigation that could add to what is already known about hybrid energy systems based on PV and TEG.

Vivek Jangra (2022) Thermometric (TE) materials based on conjugated/conductive polymers have the potential to revolutionize cooling and energy harvesting systems by directly converting heat into electricity.

Weera Punin (2018). To evaluate the potential for generating electricity from sugarcane industry waste heat, Thermoelectric power generation technology was created. Conclusions drawn from this study suggest that low-grade heat sources could be converted into energy using the thermoelectric cooling of the TEC1-12708T200. Researchers used an aluminium water block attached to the outside of the sugar boiler and ten thermoelectric modules to simulate the performance of a standard system. Electricity equal to 12.5 percent of the thermal energy generated by the thermoelectric generator. Therefore, this study's findings offer hope that sugarcane industries may find the thermoelectric power production system they created here to be a practical solution for waste heat recovery.

Wei He et al (2016) TEGs are a viable choice for transforming low-level thermal energy into electricity, making them a prime candidate for use in waste heat recovery systems. They offer a detailed mathematical model that takes into consideration both internal and external irreversibility, as well as temperature variations along the flow direction, by use of series-coupled multi-element thermoelectric components. To perform the numerical calculations, a computer programme known as FORTRAN was utilized. Thermoelectric performance is studied by constructing temperature gradients using various cooling methods. The results demonstrated the need, independent of fluid intake temperature, of selecting a module area appropriate to the mass flow rate of the fluids during TEG system design. Because of how similar the water-cooling and air-cooling processes are, distinguishing between the colour and counterblow approaches wasn't necessary.

Yan Chen et al (2018) Innovative, eco-friendly, and energy-efficient power production technology has emerged in the form of semiconductor thermoelectric materials, which directly transform thermal energy into electrical energy. This article provides a brief overview of thermoelectric materials and semiconductor thermoelectric power generation, as well as an analysis of current advances in both areas, with a focus on semiconductor materials and thermoelectric generators based on Bi2Te3.

B. Tang, et al (2015). Several car manufacturers have already used TEGs to collect exhaust waste heat, including BMW in Germany and General Motors in the US, as per our research. Despite the challenges of economically producing and using based thermoelectric materials in the complex automotive environment, most automakers opt to employ them. The electrical performances of TEM and TEG systems are investigated in this study under various operating temperature limitations and varying module-to-module temperature distributions.

2.1 PERFORMANCE EVALUATION OF TEG MAXIMUM POWER POINT TRACKING FOR EV

Chien-Chang WANG (2013). The efficiency of a working thermoelectric generator (TEG) system is impacted by a wide variety of non-reversible phenomena. In this energy-based study, we assess how different types of irreversibility affect TEG functionality. Two performance indices are employed, the energy efficiency and the energy efficiency, both of which are derived from the energy analysis. To simulate the TEG setup, a finite element method is used. Consideration is given to heat dissipation from the TEG and the characteristics of the materials as they change with temperature. According to the findings, the TEG energy efficiency can be enhanced by either lowering the hot-reservoir temperature or raising the cold-reservoir temperature when the application of the tiny electrical current is taken into consideration. Although heat loss reduces maximum energy and energy efficiency by a little amount, it can increase energy and energy efficiency in the case of a high electrical current. However, when the See beck coefficient or thermal conductivity varies with temperature, both the maximum and average energy efficiencies rise as the hot-reservoir temperature rises.

Hayati Mamur (2015). TEGs can improve energy efficiency by producing electricity from geothermal or waste heat. Additional electronic hardware is needed for maximum capacity functioning since the resistances of the devices linked across TEGs are not equal to the resistances of the TEGs themselves.

Makbul A.M. Ramli (2017) In their study, DG in Saudi Arabia is studied from multiple angles at once to make the most efficient use of the country's abundant solar and wind power. Wind and solar energy resources in Saudi Arabia are first examined in terms of their potential for use in DG applications. Research, planning, and utilisation of wind and solar energy resources for DG applications are then discussed. The value of DG to the Saudi Arabian energy sector has been evaluated, and the obstacles to widespread adoption of DG technology there have been identified, along with potential solutions to those problems. Findings show that the country has set a goal of 50 GW of wind and solar capacity by 2040, given the vast potential of wind and solar resources for DG applications.

Muhammad Fairuz Remeli et al (2015). This study investigates the feasibility of utilising heat pipes and thermoelectric generators (HP-TEG) to recover both heat and electricity from waste sources. TEGs based on Bismuth Telluride (Bi2Te3) are used in the HP-TEG system. These TEGs are sandwiched between two finned heat pipes to generate energy via a temperature differential across the TEG. Theoretical modelling allows for the prediction of HP-TEG system performance over a wide variety of factors, including its ability to recover waste heat and convert it into power. The simulations show that the HP-TEG system, when equipped with 8 TEGs, can recover 1.345 kW of waste heat and generate 10.39 W of power. A discussion of the planning and execution of an HP-TEG system experimental test bench is presented.

R.J.M. Vullers et al (2009) Energy harvesting from sources such as heat, motion, vibration, and even electromagnetic radiation has been studied for over a decade, and the results have been increased power output and smaller physical implementations. The efficiency with which these energy harvesters' electricity can be converted via rectifier and DC-DC converter circuits is improving. Power management circuits and the latest findings in energy harvesting are summed up in their research.

Weishu Liu, et al (2015). Thermoelectric power generation (TEG) is one of the most environmentally friendly ways to convert energy. It has several potential uses, from recovering otherwise wasted heat to transforming solar power into usable electricity. In the last few years, numerous thermoelectric (TE) material systems have made tremendous strides forward. Phonon transport can be fine-tuned by introducing nanostructures, and electron transport can be fine-tuned by manipulating the band structure.

X. Liu, Y.D. Deng (2015) Thermoelectric power plants are a viable alternative energy technology. TEG system is built in this case study to convert the heat from an automobile's exhaust pipe into electricity. In order to determine whether or not TEG systems can be safely implemented in automobiles, a test bench has been built to analyse their operational properties. Using the test bench as a starting point, we developed a new system we call the "four-TEGs" system and integrated it into a prototype vehicle we call the "Warrior." We put the vehicle through its paces on the road and on a revolving drum test table to learn more about the system's performance in real life.

X.F. Zheng et al (2014) Since environmental challenges including global warming and the limits on available energy sources have steadily garnered worldwide attention in recent years, TE devices have emerged as possible alternative environmentally friendly applications for heat pumps and power generators. In an effort to create systems that are less cumbersome to the planet and its inhabitants, thermoelectric technology has been employed in various fields. From its first use in a kerosene lamp, thermometry has spread to the aerospace industry, the transportation sector, the industrial sector, the medical sector, the electronic sector, and temperature-detecting and -measuring facilities. Despite the low efficiency of current thermoelectric converters, it has been determined that there is a market for TE's ability to convert thermal energy into electricity without any additional heat loss or gain. This is especially true in situations where the cost of thermal energy input is not a factor, such as waste heat utilisation.

2.2 HIGH EFFICIENCY THERMOELECTRICAL BATTERY-CHARGER BASED ON SEPIC CONVERTER

A. Montecucco (2015). Electricity consumption and temperature differential between thermoelectric generators (TEGs) are directly related to the amount of power that TEGs can produce. Efficient power electronic converters that are guided by an MPPT algorithm are crucial for monitoring the optimal electrical operating point. An MPPT method dependent on open-circuit voltage is anticipated to produce optimal results with TEGs due to their linear electrical the natural world. The prototype MPPT converter is run by a low-cost microprocessor and stores power in a lead-acid battery. Commercial TEG devices were used in experiments to verify that the converter accurately tracked the maximum power point across the temperature range.

B. Bijukumar et al (2018). In their study introduces a novel Maximum Power Point Tracking (MPPT) method for maximising energy harvest from TEGs. A TEG source has linear I-V characteristics; hence the suggested method makes use of the linear extrapolation principle. In order to determine the new MPP, the I-V coordinates of two randomly selected operational points are employed. It turns shown that under any dynamic conditions, the MPP may be reached with only three sample intervals using the proposed strategy. Compared to other MPPT methods, the one based on linear extrapolation has a number of benefits, including an easy analysis, a short convergence time, a low learning curve, and a high tracking efficiency because it doesn't experience steady-state oscillations. Additionally, the open-circuit voltage of TEG can be measured without interrupting the circuit. No other hardware like switches or connectors is needed, either. Compared to the perturb and observe algorithm, the proposed technique performs better in simulations and experiments.

Bo Yang et al (2019) .In their study a new adaptive compass search (ACS) is proposed for MPPT of a centralised thermoelectric generating (TEG) system operating in a non-uniform temperature distribution (NTD). In comparison to string-type and modularized configurations, the centralised TEG system only requires a single converter, thereby reducing the cost of both installation and upkeep. An adaptive sequence of exploration directions based on previous search results is used to conduct a more efficient and effective search for the global MPP than the initial compass search (CS) associated with fixed sequence exploration.

Chuang Yu (2009). Their study lays out a thermoelectric strategy for reusing heat from vehicle exhaust that might be used to hybrid electric vehicles and gas-powered vehicles that use internal combustion engines. The secret is in harnessing the thermal energy of the vehicle's exhaust and transforming it into electricity. A DC-DC converter then controls the process, allowing the battery to be charged through the most efficient power point tracking system. That means the battery can store more electrical energy. The research and practical findings show that the proposed system performs effectively in a variety of settings and holds great promise for the automobile sector.

I. Kashif, et al (2019) Increasing building occupancy and the adoption of more power-hungry HVAC systems have made energy consumption an urgent problem. One of the potential ways to deal with this issue is to use an alternative energy source. This study provides an overview of the technologies used in green building construction, specifically photovoltaic (PV) and thermoelectric (TE). It discusses and analyses these technologies. Next, the solar panel and its performance metrics are detailed. They then looked at the potential energy savings from PV panels mounted on building walls. Research has demonstrated that a building's HVAC requirements can be cut in half by installing PV panels on an outside wall. Additionally, the article covers literature on the usage of thermoelectric modules and photovoltaics in building applications and talks about how they can replace air conditioning technology.

I. Laird (2013) The internal voltage and current stresses of the converter can be studied by designing a TEG that achieves a high step-up gain with a low duty cycle. The P-I criterion that results from a linear V-I criterion is less stringent than other possible arguments. To minimise operating-point movements, it is recommended to use a low steady-state error approach for maximum power point tracking (MPPT). With fewer components, the suggested converter achieves a larger gain than conventional high step-up dc/dc converters.

N. Phillip, et al (2013) In their study extreme seeking control (ESC) algorithm and the perturb and observe (P&O) method are two MPPT algorithms that are studied here. When it comes to DC-DC converter topologies, an MPPT algorithm and a synchronous buck-boost converter are the ones that finish off the PCU design.

Qimin Cao (2018) In this research Specifically, they advocate for a new high-performance thermoelectric generator (HP-TEG) for reusing exhaust heat. The optimal Dhp and hp values for the thermoelectric device were determined by constructing a prototype and conducting experimental tests. An HP-TEG device was created once the optimum depth and angle for the heat pipes were identified. More investigation into the operational parameters of TEG has been done in an effort to boost its efficiency. Based on testing data, we know that HP-TEG performs best when its exhaust temperature is high, the water is cold, and there is a lot of it. After testing 36 TEMs, we found that their highest open circuit voltage was 81.09 V.

Shi-jun Wu et al (2018). Thermoelectric generators (TEGs) find extensive use as a direct thermal-to-electricity converter. We propose a strategy for managing TEGs' energy use and storage in order to maximise the devices' potential for usefulness. Because the temperature difference between the hot and cold sides of TEGs can fluctuate, we take that into account, along with the fact that loads can shift in unpredictable ways, necessitating the use of a storage unit made up of a battery and a super capacitor to stabilise the system's output. The battery provides a backup power source, storing energy for use during periods of high load power demand, while the super capacitor smoothes out energy swings and dampens bus voltage transients.

Ssennoga Twaha et al (2017). The use of TEGs allows for the conversion of thermal energy into an electrical current. In order to run the load, a power conditioning system is required because TEG's power supply is unstable. Maximum power must be drawn from TEG devices at all times, hence monitoring the MPP is essential.

Y.-L. Zhao, et al (2017) Flue gas from natural gas boilers contains a high concentration of water vapour, which means that the quantity of energy lost depends on both the sensible heat of burning and the latent heat of condensation. We developed a generation model to study the thermoelectric generating properties of the discarded flue gas heat. The calculated findings demonstrate that the characteristics curves can be split into two zones, one for producing sensible heat and another for producing mixed power, with each region's power generating performance exhibiting its own unique traits. The study's authors suggest humidifying the flue gas to boost the generator's performance. This would increase the maximum output power and decrease the area of the thermoelectric module needed to produce that power, thanks to the larger heat transfer coefficient of humid flue gas compared to dry flue gas.

2.3 ARTIFICIAL INTELLIGENCE-BASED ENERGY HARVESTING SYSTEM FOR TEG GENERATOR

A. Belkaid, I (2017) The decreasing cost and expanding range of possible uses for thermo electrical (TE) modules have contributed to their recent surge in popularity. Modelling, simulating, and controlling the power output of a thermoelectric generator (TEG) were presented in their research. An MPPT controller based on sliding mode control (SMC) was developed on a boost DC/DC converter with the intention of maximising the power from the TEG under all input situations. Using a HZ-20 module that was fed a resistor through a chopper, the MPPT method's modelling and actual performance were investigated. The suggested tracker outperforms the state-of-the-art Perturb and Observe (P&O) technological approach in both the static and dynamic regimes. The results show that the proposed strategy, on average, is 98.58% more effective than P&O, which is only 96.02% effective.

Andreas Patyk (2013) Thermoelectric (TE) technology is seen as having a bright future in the field of reusing waste heat from internal combustion engine exhaust gas in power and combined heat and power facilities. A number of recent research have shed light on the topic of the energy efficiency of present and potential TEGs. Accurately modelling power units and their operation, or quantifying power production by TEGs, has been the primary emphasis of these investigations. Costs and carbon dioxide emissions from fuel burning were also evaluated in one study, but only in the absence of equipment and fuel. Prior to this study, there was no life cycle analysis that took into account TEG and power unit production, environmental implications beyond climate change, and alternative methods for utilising waste heat. To address this knowledge gap, the current study compares TEGs to a competing technology, the steam expander, using a life cycle approach and factoring in a wide range of environmental consequences and costs.

B. Bijukumar (2020) .In their study presents TEG current controlled grid connected inverter digital implementation. The electrical parameters of a TEG source are discussed in detail, as are several of the most important considerations a designer must make when selecting the rating of power converters for grid-connected operation. Line current control is an integral aspect of the closed-loop regulation of power injection for a VSI fed by a TEG linked to the grid. To find the settings for the digital current controller, a simpler way is suggested for simulating the inverter, current sensor, and line inductor. The current control mechanism in VSI with TEG power is implemented using Altera Cyclone II Field Programmable Gate Array (FPGA) cards. Results from experiments, simulations, and the time domain have all corroborated the suggested design approach.

Biswas K, et al (2012) Optimal thermoelectric materials have bidirectional heat-to-electricity conversion capabilities. Nevertheless, the present low figure of merit (ZT) of thermoelectric materials limits their practical application; ZT establishes the Carnot efficiency in compliance with the second law of thermodynamics. Recent work employing nanostructures has been effective in reducing thermal conductivity; however, the ZT values achieved using this method (1.5-1.8 at 750-900 kelvin) do not meet the widely desired 2 threshold. Nanostructures in bulk thermoelectric materials effectively scatter the majority of the phonon spectrum, with the exception of phonons with long mean free paths, which are mostly unaffected.

Champier, D (2013). This research details the development of a prototype thermoelectric generator (TEG) for use in off-grid settings, such as rural communities. The idea of using biomass stoves as a source of waste heat to generate power is gaining popularity for both environmental and financial reasons. TEGs are appealing for small-scale power generation in remote places because they don't need frequent maintenance. Our lab's prototype was made with the express purpose of being installed in stoves that double as home water heaters. The goal of this setup is to give homeowners access to a few watts of power for basic needs like charging electronic devices and lighting the home. Using commercially available bismuth telluride thermoelectric modules, a fully functional prototype TEG with integrated electric DC/DC converter has been constructed.

Cramer, C.L (2018) . Thermoelectric generators (TEGs) that perform direct energy conversion are becoming an increasingly popular topic of study due to their potential to significantly improve energy efficiency. Thermoelectric modules in bulk find widespread application in industry as Pettier coolers. The only commercially available modules for use in power generation are made of bismuth telluride. Laboratory scale (5-20 g) improvements to the figure of merit (zT) have been the focus of extensive research into viable materials and methodologies. Segmentation, geometric pinning, and property gradients are just few of the methods looked into to increase the output and useable temperature range of typical industrial TEGs manufactured from bulk polycrystalline materials. However, advancement at the level of individual devices (500-1000 g and above) is extremely constrained. Cracks happen in TEGs because of thermal pressures caused by transitory heat sources, which contributes to thermal degradation and ultimately a shorter lifespan.

D. E. Schwartz (2012). In terms of compact solid-state heat engines, the TEG is generally thought of as the best. A regulated power converter, when installed between the source and the load, can enhance the output power of the TEG, leading to more efficient utilisation of the heat resource. Here we offer a very efficient design for a maximum power point tracking system that is compatible with pulse width modulation (PWM) converters. The input voltage-sampling-based control system can be constructed from readily accessible discrete components, without the need for a microprocessor or an analog-to-digital converter. The concept is confirmed by the measurement findings presented, which were obtained using a demonstration SEPIC converter.

D.M. Rowe (1999). When it comes to heat engines, a thermoelectric generator is one of a kind because the charge carriers themselves act as the working fluid. It's incredibly dependable, runs silently, and there are no moving components. Its low efficiency (about 5%) has, however, limited its employment to niche fields such as the medical, military, and space sectors, where budgetary constraints are less of a concern. In the last decade, thermoelectric has come into its own as a 'green' and adaptable electricity source capable of meeting a variety of power needs. Recent research has shown that when the source of heat is free or inexpensive, such as using waste heat, optimising the conversion system's efficiency is less important.

Daniela Charris, et al (2020) .In their study thermoelectric harvesting-driven Internet of Things sensor that operates without external power. Keeping the sides of the thermoelectric generator at different temperatures by at least 26.31 K is essential to the process of thermal harvesting. Metal is used for the "hot" side, while a phase-change material serves as an efficient passive dissipative material for the "cold" side. By maintaining the ideal temperature gradient, power conversion efficiencies of around 26.43 percent can be claimed, without the losses often seen due to heating and soiling. In this study, we characterise a commercially available thermoelectric generator and show that it may be used to predictably generate at least 407.3 mW,

H. Nagayoshi (2006). A novel approach to controlling TEG systems that limits power points to a maximum could be useful. It is possible to maintain a constant virtual load conductance and an internal TE array conductance by means of feedback control with a DC-DC converter. We have built a functional prototype of an MPPT circuit using a buck-boost DC-DC converter. The circuit's wide matching ability and high-quality tracking performance as MPPT were on display as the load and heat source temperature increased.

J. Leema Rose (2016). The research team modelled and presented a DC-DC converter called a single-ended primary inductance converter Because of issues including inverted output, pulsating input current, and high voltage stress, conventional buck boost converters are unstable across a large operating range; that's why SEPIC converters are vital. The method is being tested with MATLAB simulation to prove its validity and demonstrate the design's efficiency.

Joseph Davidson (2014). In their study evaluates the state of energy harvesting technology in light of its potential use in structural health monitoring. Many industries would benefit greatly from the availability of technology to track the condition of their equipment and buildings. The requirement for comprehensive autonomous building monitoring, for instance, has grown substantially over the past few years. The standard components of autonomous SHM systems include integrated sensors, data collecting, wireless networking, and energy harvesting. Current SHM systems rely heavily on wireless communications and low-power sensors, thus researchers have been looking at energy harvesting devices to power SHM systems autonomously in remote regions. Vibration, temperature differences, sunlight, wind, pressure, and other forms of environmental energy are all examples. It may be possible to derive the necessary power from the structure itself if the loading is sufficiently dense.

K N Khamil et al (2020). The current technologies used to generate electricity are inefficient and not fully optimised. The world is undergoing the Industrial Revolution 4.0 (IR4.0), which has sparked interest in energy harvesting studies due to the surplus energy being produced by machines, systems, and infrastructure. Voltage, current, efficiency and performance coefficient, thermal resistivity, total resistance within, and See beck coefficients of the module are just some of the major metrics explored in this article. The module's manufacturer will often supply these figures in a datasheet. Simulations were run using MATLAB/Simulink starting with the underlying equations. Several programmes in Mat lab's command window can be used to make graphical representations of the results.

K. V. Selvan (2018) In their study of metals employed as potential thermoelectric materials or thermal elements on a flexible copper (Cu) clad polyimide substrate for thermoelectric generators. The constructed thick film generators are both flat and elongated, with a lateral heat flow and thermopile design. To that end, we fabricate two working models of a thermoelectric generator, one using copper (Cu) and nickel (Ni) as the positive and negative thermal elements, and the other using copper (Cu) and cobalt (Co). The length and width of the thermo leg as well as the size of the generator are two examples of geometrical features that are examined in their study for their potential to facilitate increased thermoelectric power output. For both prototypes, the length, width, and thickness of 5 mm, 1000 m, and 31 m, respectively, were found to yield the best performance, while the length and width of 1.1 cm and 4.3 cm, respectively, were found to yield the best dimensions for the generators.

Lihua Chen et al (2008) In their study, the thermoelectric module's principle and basic structure are described. One TE module's static and dynamic behaviours are described. It is possible to include the resulting electric model of TE modules into simulation software for use in circuit analysis and design. In this piece, we analyse and highlight the problems that arise when putting TEG models into action. Thermoelectric power generation problems can be solved with the use of power electronics technology, which enables functions like load interface, MPPT power conditioning, and failed module bypassing. An inexpensive microcontroller and a DC-DC converter allow us to build a device that can monitor the peak power. In spite of changes in heat flow and load impedance, the experimental findings demonstrate that the power electronic circuit can effectively supply electric loads with the maximum amount of power captured from the thermoelectric modules.

M Hayati, (2020) In this research, TEGs were modelled with a boost converter that included a maximum power point tracker. Modelling, simulation, and validation of TEGs were carried out in MATLAB/Simulink with a range of parameters, such as See beck coefficient, hot/cold side temperatures, and module count. In addition to the TEG investigation, a boost converter code based on a perturb and observation (P&O) MPPT algorithm was also simulated. With the output equations in hand, TEG modelling was carried out by means of manufacturer data sheets. We measured a maximum power production of 98.64% thanks to the TEG model and the boost converter with P&O MPPT. The power we received from the TEG was only slightly affected by fluctuations in load. In order to demonstrate the worth of the technology, we compared the system's power outputs with and without MPPT. The results of these calculations were confirmed with a real laboratory instrument. An MPPT-equipped boost converter and TEG system is the final product of the proposed modelling.

Meta RJ et al (2012) Efforts have recently focused on developing nanostructuring and alloying procedures to get bulk p-type alloys with ZT>1, which is a challenge in thin films. Our results demonstrate the feasibility of combining Nano structure with sub-atomic-percent doping to generate a new family of p- and n-type bulk Nano materials with room-temperature ZT values up to 1.1. Our Nano material was constructed by first sculpting nano-sized plates of pnictogen chalcogenide using a scalable microwave-stimulated wet-chemical technique, and then building them up from the bottom. When compared to non-nanostructured bulk materials and cutting-edge alloys, ZT is 25–250% higher in bulk nanomaterials made from single-component assemblies or Nano plate combinations of multiple components.

Meysam Karami Rad et al (2019). Analysing the Seebeck coefficient, thermal resistance, and electrical resistivity, this work seeks to bridge gaps in our understanding of the total effect of material attributes on TEG performance. A theoretical framework was devised and validated using experimental data in order to compare and contrast multiple thermoelectric (TE) substances with a unit factor of merit (ZT = 1) and different features. Based on the findings, increasing the power factor by 15% can enhance the production of electricity by up to 45% for a specific amount of ZT. A 13.3-fold increase in heat conductivity from its initial value would have no effect. Also, the results show that power output is more affected by lower temperatures of the heat sink and source and a smaller fill factor (FF) than by a bigger power factor.

Mohamed Amine Zoui (2020) In their study to Direct conversion of heat energy to electricity is possible thanks to the thermoelectric effect (See Beck effect). Space probes, laboratory equipment, and medical applications are only a few examples of which thermoelectricity's availability, reliability, and predictability would be prioritised over its cost and efficiency. The use of nanotechnology raises challenges for the promotion of thermoelectricity as the industry standard for future waste heat recovery and renewable energy. In this post, we will go through the most recent advancements in thermoelectric generators, including their uses and scientific advances.

Mohammed A et al (2021). TEGs, or thermometric generators, are machines that can transform thermal energy into electrical current. An MPPT technique suitable for a TEG module was the main focus of their investigation. The integrated circuit is comprised of 204 TEGs. Using a DC/DC boost converter, it is linked to the load. An Interval Type 2 Fuzzy Logic Controller was used as the MPPT approach in this investigation. This is done by contrasting the IT2FLC's steady-state power and voltage response with that of a conventional Perturb and Observe (P&O) MPPT algorithm operating across a wide temperature (T) range.

N. Kanagaraj et al (2020) In their study aims MPPT is a revolutionary strategy for improving the performance of TEG models. Here, we propose a strategy for employing a VFOFLC that rapidly relocates the TEG's operating point to its optimum location. To improve tracking and output consistency around the MPP, the MPPT algorithm introduces a fraction order term that can either enlarge or reduce the FLC's input domain. TEG model simulations validated the success of the suggested MPPT approach.

R Hegazy, (2020). It It is essential to keep an eye on the cell's temperature and the water content of its membrane when utilising a fuel cell to produce electricity. Every graph showing the relationship between the input current to a fuel cell (FC) and its output will always have a single maximum power point (MPP). Where the MPP could be located is dependent on the current status of things. The fuel cell cannot function at its maximum power point (MPP) without an MPPT. In this study, we suggest a method called VSS-INR for monitoring the MPP of PEMFCs. In most cases, PEMFC integration into MPPT systems requires temperature, humidity, and voltage sensors. In contrast, the suggested VSS-INR simply requires current and voltage sensors. The strength of the error signal is related to the VSS-INR step size. Consequently, as the error decreases to negligible levels, the step size will shrink until it reaches a minimum just at the maximum power point.

R. -Y. Kim et al (2009). An incremental impedance-based MPPT technique is provided together with its analysis and design. We analytically derive a small-signal model and examine the frequency-domain effects of the model's two most important design parameters the scaling factor and the sampling interval. There is also a comprehensive discussion of four elements that influence the MPPT response. The results of this study are used to establish a methodology for designing systems with the desired transient response while maintaining their stability. Hardware investigations on a thermoelectric generator battery energy storage system confirm the design process and show that the dynamic response and the target bandwidth are in agreement.

W. Xie et al (2017) Their study used the TEG modules' output properties to guide the creation of a controller using an adjusted perturbs and observe (P&O) approach. Supercapacitors store electric current, which is derived from thermoelectric energy. Experimental results showed that at a temperature differential of T=75°C, the MPPT controller could increase charging power by 89.65%, the thermoelectric generator's output voltage could reach over 5 V, and the generator's output power could reach over 2W.

Wissam Bou Nader (2019) These machines are most suited for use in range extenders and other electrified powertrains that use electric propulsion, as this is the only scenario in which the energy converter can maintain its highest efficiency by consistently delivering a set amount of power. The efficiency of the energy converter plays a crucial role in determining how much gasoline these powertrains use. Their research is the first to look at the fuel savings potential of a long-range hybrid electric car by using a thermoelectric generator system as an energy converter instead of a standard internal combustion engine. To isolate the various thermodynamic states, an explicit exergue-technological analysis is performed. One model of a vehicle with a greater range than usual is investigated, and several configurations are incorporated as an auxiliary power unit.

SUMMARY OF THE LITERATURE REVIEW

Summary The literature review presented in this chapter confirms that TEG's have enormous potential to be widely used. These power plants have the potential to make our lives more manageable and environmentally friendly. The use of low-temperature TEGs to provide energy for mobile phones, wearable sensors, and medical devices is now under investigation. Industrial waste heat recovery has the potential to bring about major economic benefits and mitigate the risk of another energy crisis. But we still need more study before we can create truly effective tools. Snyder's research on segmented leg generators is one of the most important discoveries of the past few decades. In most cases, the improved efficiency of segmented TEGs can be attributed to the fact that the materials used operate in their optimum temperature range. Snyder's compatibility factor enables researchers to choose optimal material configurations for segmented TEGs

2.4. Latest Literature

Table 2.1 Latest Literature

Author and Year	Title	Methodology	Remarks
Jie Miao, Houpeng Chen, Yu Lei, Yi Lv, Weili Liu and Zhitang Song, 2021	MPPT Circuit Using Time Exponential Rate Perturbation and Observation for Enhanced Tracking Efficiency for a Wide Resistance Range of Thermoelectric Generator	Time Exponential Rate Perturbation and Observation (P&O) technique	Its limitation to Single-Input Single-Output (SISO) systems highlights the need for further development to adapt it for modern MIMO energy harvesting scenarios. Addressing these challenges could significantly expand its utility in advanced applications.
A.M Abdulla, Hegazy Rezk, Abdelrahman Elbloye, Mohamed K. Hassana and A.F. Mohamed 2021	Grey Wolf Optimizer-Based Fractional MPPT for Thermoelectric Generator	Optimized Fractional MPPT (OFMPPT) technique for thermoelectric generators (TEGs), using Grey Wolf Optimizer (GWO) and Genetic Algorithm (GA)	The GWO outperformed PSO and GA, achieving the highest efficiency (88.80%) and lowest standard deviation. The OFMPPT demonstrated superior dynamic response and steady-state stability, overcoming limitations of traditional methods like INRT and P&O. However, the study's limitations include the reliance on

			simulation data, which may not fully capture real-world complexities, and the higher computational effort required for GWO optimization.
Adel El-shahat,Md Sadequr Rahman Bhuiyan, 2021	Thermoelectric Generator performances and efficiency analysis integrated with MPPT techniques	Integrated with three Maximum Power Point Tracking (MPPT) techniques: 1. Perturb and Observe (P&O) 2. Incremental Conductance (IncCond) 3. Particle Swarm Optimization (PSO)	Integrating MPPT techniques (P&O, IncCond, and PSO) with thermoelectric generators significantly improves efficiency, with PSO achieving the highest at 16.58%. However, TEG's low baseline efficiency, dependence on dynamic temperature gradients, and implementation challenges—such as P&O's oscillations, IncCond's computational demands, and PSO's complexity—limit its scalability for broader applications.
Hayati Mamur, Mohammad Ruhul Amin Bhuiyan, 2022	Future perspective and current situation of maximum power point tracking methods in thermoelectric generators	Future perspective and current situation of maximum power point tracking	MPPT techniques optimize TEG efficiency, with methods like P&O and AI-based approaches offering trade-offs in accuracy and complexity. Simpler methods may oscillate around the MPP, while advanced ones demand higher resources. Environmental factors, such as temperature fluctuations, further challenge real-time tracking, requiring method selection based on system

			constraints.
Fusheng Li, Dan Lin, Tao Yu, Jiawen Li, Keying Wang, Xiaoshum Zhang, Bo Yang, Yufeng Wu, 2020	Adaptive rapid neural optimization: A data-driven approach to MPPT for centralized TEG systems	Adaptive Rapid Neural Optimization (ARNO) approach for Maximum Power Point Tracking (MPPT) in centralized Thermoelectric Generator (TEG) systems under non-uniform temperature distribution (NTD)	The ARNO-based MPPT method effectively tracks the optimal maximum power point in TEG systems under NTD, surpassing traditional and meta-heuristic methods in speed, energy output, and power stability. The combination of GRNN and greedy search minimizes power fluctuations and enhances optimization precision. However, ARNO may converge to lower-quality local maxima under certain stochastic temperature changes, and practical implementation requires careful balancing of system costs, converter quantity, and efficiency. Future research should address these practical limitations to optimize economic and operational trade-offs.
Majad Mansoor, Adeel Feroz Mirza, Shihui Duan, Jin Zhu, Baoqun Yin, 2021	Maximum energy harvesting of centralized thermoelectric power generation systems with non-uniform temperature distribution based on novel equilibrium optimizer	Equilibrium Optimization (EQO) technique for Maximum Power Point Tracking (MPPT) in Thermoelectric Generator (TEG) systems under conditions of non-uniform temperature	The EQO-based MPPT technique demonstrates superior performance compared to conventional methods like P&O, PSO, CSA, and GWO, achieving up to 99.68% power tracking efficiency and up to 6% higher energy harvesting. Its robust performance, faster tracking, and stable transients make it suitable for real-world applications in

		distribution (NUTD)	various thermal environments. However, the limitations include sensitivity to the initial conditions of search agents and the computational complexity of maintaining equilibrium dynamics, which could be challenging in extremely dynamic thermal conditions or for low-cost hardware with limited processing power.
Jie Miao, Houpeng Chen, Yu Lei, Yi Lv, Weili Liu and Zhitang Song, 2021	MPPT Circuit Using Time Exponential Rate Perturbation and Observation for Enhanced Tracking Efficiency for a Wide Resistance Range of Thermoelectric Generator	Time exponential rate Perturbation and Observation (P&O)	The proposed time exponential rate P&O technique significantly enhances tracking efficiency for TEGs by dynamically adjusting the on-time of the NMOS transistor, achieving consistent performance over a broad resistance range. The implementation demonstrates improved adaptability and simplifies circuit design, maintaining high tracking efficiency (98.9%–99.5%) under varying conditions. However, the system is limited to single-input single-output (SISO) configurations and lacks compatibility with emerging multi-input multi-output (MIMO) energy harvesting systems. Future research should explore extending the method to MIMO systems,

			addressing challenges in low storage capacitor voltage and reduced conversion rates to meet broader application demands.
Mirza Imran Tariq, Majad Mansoor, Adeel Feroz Mirza, Nouman Mujeeb Khan, Muhammad Hamza Zafar, Abbas Z Kouzani and M A Parvez Mahmud 2021	Optimal Control of Centralized Thermoelectric Generation System under Nonuniform Temperature Distribution Using Barnacles Mating Optimization Algorithm	Barnacle Mating Optimization (BMO) algorithm as the MPPT technique for Thermoelectric Generators (TEG) under nonuniform temperature distribution. This technique outperforms other methods like Particle Swarm Optimization (PSO), Grey Wolf Optimization (GWO), and Cuckoo Search (CS) in tracking efficiency, power yield, and settling time.	The BMO-based MPPT control for centralized TEG systems achieves a tracking efficiency of 99.93%, with faster settling times and negligible oscillations, outperforming PSO, GWO, and CS in both dynamic and steady-state conditions. The method ensures robust operation under varying load and temperature conditions, demonstrating superior energy harvesting by 5.6% compared to alternatives. Additionally, its low implementation complexity makes it viable for low-cost hardware. However, the approach may still require further real-world testing to validate long-term reliability under industrial conditions, and its dependence on heuristic tuning may limit adaptability in highly dynamic environments.
Jun Wang, Xiangxiang Song, Qiqiang Ni, Xingjun Li, Qingtian	Experimental investigation on the influence of phase change material on the output performance of thermoelectric generator	Phase change material (PCM) for thermal management in thermoelectric generator (TEG)	The study concludes that integrating PCM into TEG systems significantly reduces temperature fluctuations on the TEG's hot and cold sides,

Meng, 2021		systems under pulse transient thermal boundary conditions	providing stable power output under intermittent thermal conditions, which is crucial for protecting the TEG and extending its operational life. While the PCM-TEG system delivers more stable and extended power generation, its peak power output and overall energy recovery are lower than traditional TEG systems, primarily due to the poor thermal conductivity of PCM. Enhancements like adding nanoparticles or metal foams could address this limitation, making the system more efficient for waste heat recovery and other applications requiring stable power generation.
Ruining Shao, Bo Yang, Nuo Chen and Yiming Han, 2022	Maximum Power Point Tracking of Thermoelectric Generation Systems Under Nonuniform Temperature Distribution: A State-of-the-Art Evaluation	Different MPPT technique is used	TEG systems benefit significantly from MPPT algorithms, particularly advanced metaheuristic methods, which provide better performance under dynamic and NUTD conditions. However, challenges persist, including the need for large-scale practical validations, standardization of system design parameters, and development of stable, scalable algorithms. Addressing these issues could enhance the efficiency and

			feasibility of MPPT in both standalone and hybrid systems.
Khalid Yahya, Osama Alomari, 2020	A new maximum power point tracking algorithm based on power differentials method for thermoelectric generators	Power Differentials Maximum Power Point Tracking (PD-MPPT) technique	The proposed PD-MPPT algorithm demonstrates effectiveness in accurately tracking the maximum power point under steady-state conditions with over 97.7% efficiency, leveraging a boost converter and Kalman filter to improve performance. It eliminates the need for additional circuitry like snubber circuits and is cost-effective. However, the algorithm exhibits slower convergence due to the iterative comparison process and may require further optimization to enhance convergence speed and reduce system complexity. Addressing these limitations is crucial for improving system viability and efficiency under varying thermal conditions.
Dan Zhang, Lan Song, Long Wang, Xiang Li, Xucheng Chang, and Peng Wu, 2022	A Systematic Review and Analysis of MPPT Techniques for TEG Systems Under Nonuniform Temperature Distribution	Various Maximum Power Point Tracking (MPPT) techniques for Thermoelectric Generator (TEG) systems, particularly under nonuniform	The study highlights that while traditional MPPT methods like P&O and INC are simple and widely used, they often suffer from limitations such as getting trapped in local maxima and oscillating around the true maximum power point,

		temperature distribution (NTD) conditions. The techniques include classical methods like Perturb and Observe (P&O), Incremental Conductance (INC), Open-Circuit Voltage (OCV), and Short-Circuit Current (SCC), as well as advanced intelligent methods using artificial intelligence (AI) such as neural networks, particle swarm optimization (PSO), and equilibrium optimization algorithms.	particularly under NTD conditions. On the other hand, intelligent MPPT techniques, leveraging AI and optimization algorithms, demonstrate higher efficiency, adaptability, and robustness but are constrained by high implementation costs and potential complexity. Future research should focus on improving the practicality of intelligent MPPT methods by addressing cost and reliability challenges, thereby enhancing the scalability of TEG systems for real-world applications.

2.5 Research Gaps

1. While converting heat energy to electrical energy there will be loss in the system due to this the conversion efficiency gets reduced.
2. To measure the open circuit voltage the TEG, need to disconnect this will affect the continuity of the supply.
3. TEG build with semiconductor device so there will the instability issue and hormonal are generated in the system

4. This system also finds issues like slow steady state response, overall cost of generation and low accuracy.

2.6 Research Objectives

1. Design of fast acting MPPT for Thermo-Electric Generator based power generation applications.
2. Optimization and analysis of power generation and efficiency.
3. Numerical analysis on heat characteristics of fabricated system.
4. To interface the fabricated system with Internet of things (IOT) for monitoring the utilization of energy.

2.7 Novelty and extension of existing work

The research focuses on integrating thermoelectric generator (TEG) technology with the Internet of Things (IoT) to create innovative power generation systems. This approach aims to enhance energy efficiency and enable real-time monitoring and control of power systems. This novel approach aims to harness waste heat energy and convert it into electricity, enabling smart energy management and monitoring through IoT connectivity. This innovative approach not only enhances energy efficiency but also enables remote monitoring and control through IoT integration. By harnessing waste heat and converting it into electricity, these systems can efficiently power IoT devices, opening up new possibilities for sustainable energy solutions in various applications.

Chapter 3

SEPIC converter based highly efficient thermoelectric battery-charger for E-vehicle applications

Two variable controllers adopted to compare the output power with see-beck effect one is Fuzzy, and another is ANN. Always using a switching converter when hooking up a TEG. Direct connections between the battery and TEG module still require a non-return diode. Switching converters are typically used to modify the power supply's output voltage for specific applications.

3.1 SYSTEM CONFIGURATION

The SEPIC converter provides a stable output voltage independent of the dc voltage setting. SEPICs are essentially buck-boost converters with a series capacitor instead of an inductor, making them far more efficient. Fig 3.1 illustrates the entire TEG system, which includes SEPIC converters, P&O MPPT, and load control.

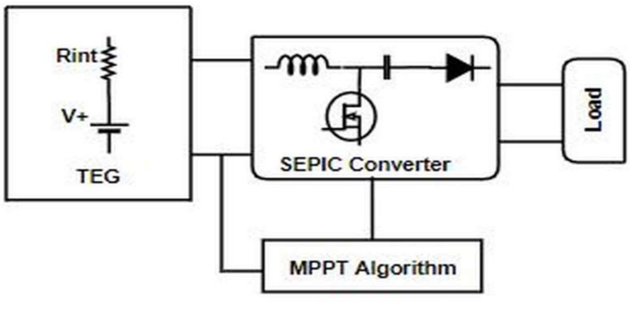


Figure: 3.1 Visual representation of the TEG System

3.2 TEG CHARACTERISTICS

Several thermocouple components are connected in series to form the TEG (Thermometric Generator). A thermocouple element is illustrated in Figure 3.2 as an example of its basic structural design. TEGs are made up of two heavily doped semiconductors and a conductor. An electric loop is created in semiconductors when the edges are linked together. Figure 3.2 shows temperatures at two such junctions, T_H and T_C. When a transistor is turned on, holes and electrons travel back and forth between its hot and cold inputs.

$$V_{TEG,OC} = V_{TEG|TEG=0} = \alpha_{pm} (T_H - T_C) = \alpha_{pm}\Delta T \qquad (1)$$

In this formula, heat and cold have equivalent roles. The power equation is rewritten to reflect this relationship, which is represented by the Seebeck coefficient pn (V/0C).

$$P_{TEG} = \frac{\left(V_{TEG,OC}\frac{R_L}{R_{TEG}+R_L}\right)^2}{R_L} = \frac{\alpha_{pm}^2 \Delta T^2 R_L}{(R_{TEG}+R_L)^2} \qquad (2)$$

The internal electric resistance of a thermometric element is called R_{TEG} (Ω). Thermal conductivity obtained by embedding ceramic plates with high thermal conductivity is close to ΔT. We may then optimize the thermometric energy conversion device's power output in this approach.

When the design temperature (D_{TEG}) is equal to the reference temperature (R_{TEG}), the power transfer efficiency is maximized. The equation can be used to predict the amount of power that will be transferred to a load (3).

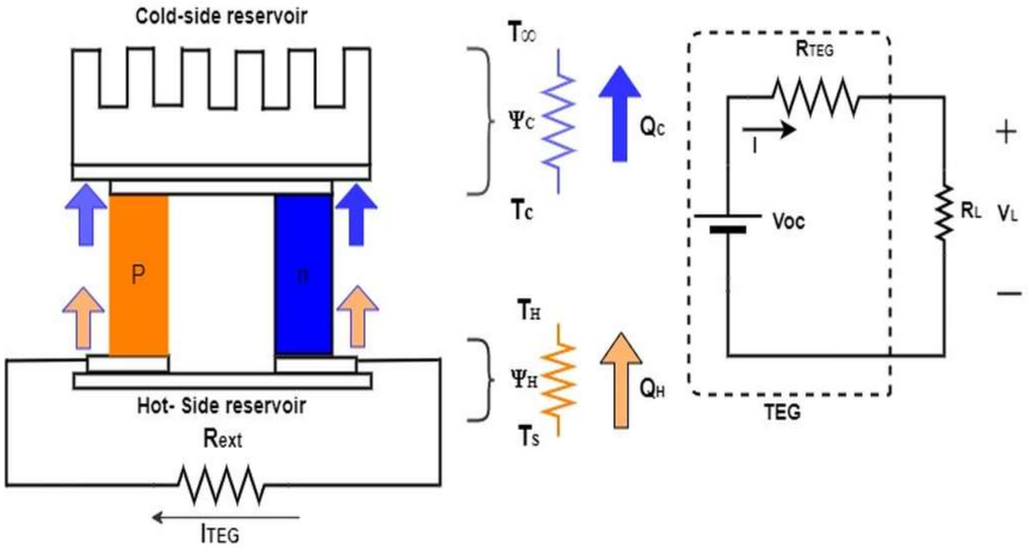
$$P_{TEG} = \frac{\alpha_{pm}^2 \Delta T^2}{4R_{TEG}} \qquad (3)$$

A novel MPPT approach to modelling TEGs is being developed and deployed, and their operational and modelling properties are shown in Figure.

3.3 SWITCHING CONVERTER ANALYSIS

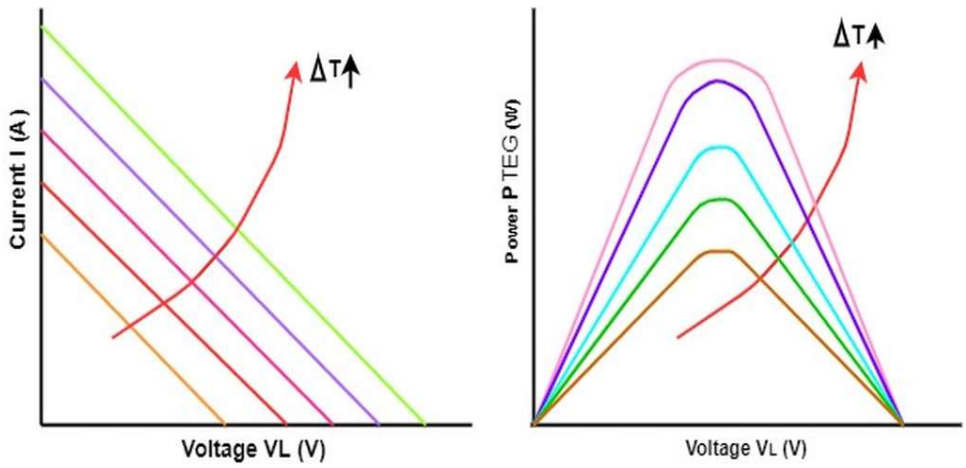
Conversion converters are always needed when connecting a TEG. Even more so, a no-return diode must be used to link the battery straight to the PV panel. In all likelihood, the intended use necessitates a voltage modification. The TEG systems that are most frequently utilised are DC-DC coppers. In Figure 3.4, we can see a schematic of the SEPIC converter. Through the SEPIC converter, it comes into contact with the load. The SEPIC topology has restrictions on both the current ripples and the MPPT efficiency. The TEG's temperature is irrelevant to the accuracy with which the voltage can be transformed.

SEPIC switching power supplies can work with an expanded range of inductors due to the inclusion of two inductors. Compared to ripple current, it has the advantage of having a lower ripple current. A boost converter appears to be a SEPIC converter as long as it passes positive current through the inductor L_1. Input-output isolation has been eliminated using the capacitor C_P, which gives this converter an edge. Short-circuit or overload protection is provided by the condenser C_p.



(a) (b)

Figure:3.2 A TEG element: (a) structure and (b) equivalent circuit



(a) (b)

Figure:3.3 TEG characteristics at different temperatures (a) I-V curves (b) P-V curves

The Seebeck effect causes p and n semiconductors to generate heat as a result of the resulting electric field. As shown in Figure 3.3 (a), the V_{TEG}, DC (V) voltage produced at the cold junction is proportional to the difference between the heat and cold junctions [T]. Semiconductors can have either a positive (p) or negative (n) Seebeck coefficient. Parameter pn is positive, to put it another way. If you take two, the end outcome is the same in both: To calculate the full effect of the hot junction and hot source, current (I) add up the energy flowing from both locations. This is illustrated in Fig. 3.2(a), as well as Fig. 3.2(b), which illustrates thermal transfer from a thermal source to a warm junction. 3.2(a), from the ceramic plates at the top to the ceramic plates at the bottom. The thermometric generator (TEG) shown in Figure 3.2(b) can produce electricity when hooked up to an electrical load. The output power of a TEG generator can be determined by connecting a load, R_L, to the terminals shown in Figure 3.2(a).

The input-output voltage connection is equation is written as (4):

$$V_{out} = V_{TEG} \frac{D}{1-D} \tag{4}$$

It is possible to rewrite the equation using the power equation if one assumes flawless power conversion without considering losses. (5):

$$P_{TEG} = P_{out} \tag{5}$$

The final voltage and the currents for the power generation is defined by the equation (6):

$$V_{TEG} I_{TEG} = V_{out} I_{out} \tag{6}$$

Substituting (4) into (6), we obtain-current output as (7):

$$I_{out} = I_{TEG} \frac{1-D}{D} \tag{7}$$

It was only the continuous-mode (CCM) converter studied that provides the actual voltage in the conductor to never be zero. In nearly half of all operations, TEG equals output voltage. Duties are assigned to each position on a constant basis, and it is defined by the equation (8):

$$D = \frac{V_{out} + V_D}{V_{TEG} + V_{out} + V_D} \tag{8}$$

Depending on the voltage of the TEG, the duty cycle can be changed. In order to determine the inductance value, we take into account the maximum possible value of ripple current. There is an allowable ripple (40% of the TEG current) of half the current (in amperes). This ripple has the following formula (9):

$$\Delta I_1 = I_{TEG} * 40\% = V_{out} * \frac{V_{out}}{V_{TEG(min)}} * 40\% \tag{9}$$

The Values of the L_1 and L_2 must choose as given by the formula (10):

$$L_1 = L_2 = \frac{V_{TEG(min)}}{\Delta I_1 * f_{sw}} * D_{max} \quad (10)$$

By plugging the target ripple voltage into equation (11) we can determine the condenser Cp:

$$\Delta V_C \frac{I_{out} + D_{max}}{C_p * f_{sw}} \quad (11)$$

Filtering capacitors C_{in} and C_{out} are define by the equation (12):

$$C_{in} = C_{out} \geq \frac{I_{out} * D_{max}}{V_{ripple} * F_{sw}} \quad (12)$$

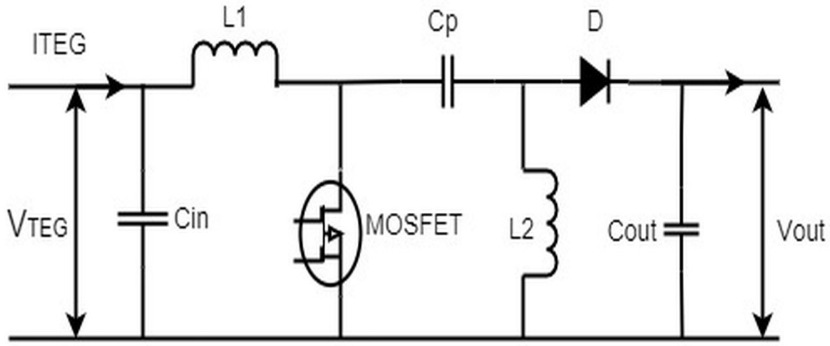


Figure:3.4 SEPIC converter schematic

Table 3.1: Parameters of the TEG

Parameters	Variable	Value
Current at max power	I_{mpp}	4.34 [A]
Parallel resistance	R_p	866.923[Ω]
Maximum Power	P_{mpp}	75 [W]
Short circuit current	I_{sc}	4.6[A]
Maximum Voltage	V_{mpp}	17.3 [V]
Open circuit voltage	V_{oc}	21.6 [V]
Number of series cells	N_s	36

The values of TEG for the present simulation given in the table 3.1 to ensure the maximum power output generated by whole system.

3.4 DESCRIPTION OF MPPT METHODS

The MPPT control maximizes TEG's energy production. This control greatly impacts the TEG system's effectiveness. In order for MPPT efficiency control to be effective, it must be dynamic, efficient, and low-cost, the variable values of MPPT board given in the table 3.2.

Table: 3.2. MPPT board variable values

Parameters	Variable	Value
Inductor	$L_1 = L_2$	274 µH
Capacitor	$C_{in} = C_{out}$	2200 µF
Coupling Capacitor	C_p	1000 µF
Switching frequency	f_{sw}	10 K HZ

Perturb and Observer

To determine input power control, MPPT requires two parameters (P_{in}): input current control pitch (I_{in}) and input voltage control pitch (V_{in}).

$$P_{in}(n) = V_{in}(n) * I_{in}(n) \quad (13)$$

These two parameters yield power (P_{in}) and voltage (V_{in}) that are different from the prior read data parameters (n-1) in comparison to these new parameters (n-1). The calculation for potential change and volume change is denoted as ΔP and ÏV, respectively.

$$\Delta V = V_{in}(n) - V_{in}(n-1) \quad (14)$$

$$\Delta P = P_{in}(n) - P_{in}(n-1) \quad (15)$$

The slope is the end result of division ΔP and ΔV.

$$\text{Slope} = \frac{\Delta P}{\Delta V} \quad (16)$$

Figure 3.5 shows three points at three different locations. The equation dP/dV = 0 applies to a positive dP/dV on the right side of the peak, but the equation dP/dV < 0 applies to a negative dP/dV on the same side. When the left-hand derivative of P/dV is smaller than zero, the TEG operating voltage is presumed to be advanced. When dP/dV is changed, TEG is removed from MPP. P&O can re-direct disturbances.

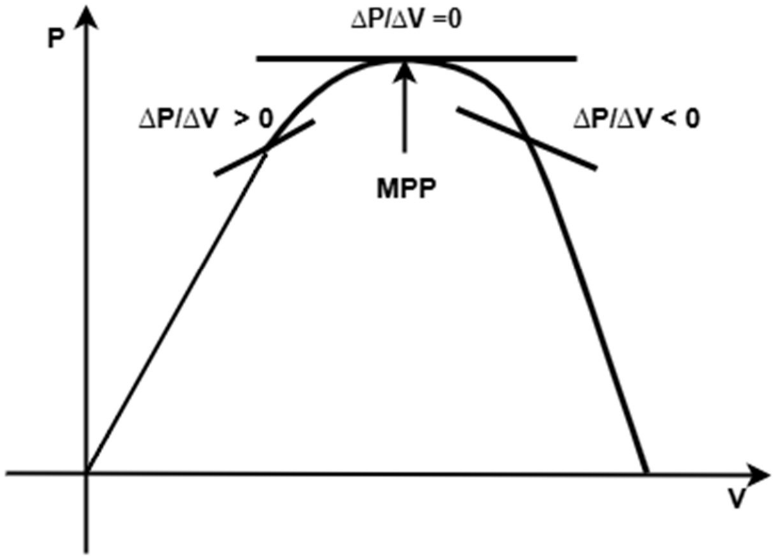


Figure: 3.5 P- V Characteristic of TEG module

The P&O flow diagram can be seen in Figure 3.6. Primarily, measuring or sensing PV voltage (VK) and current o+utput (IK). To find the power, multiply the voltage by the resultant current (PK). Plus, its power (Pk-1) is greater than the current's (PK).

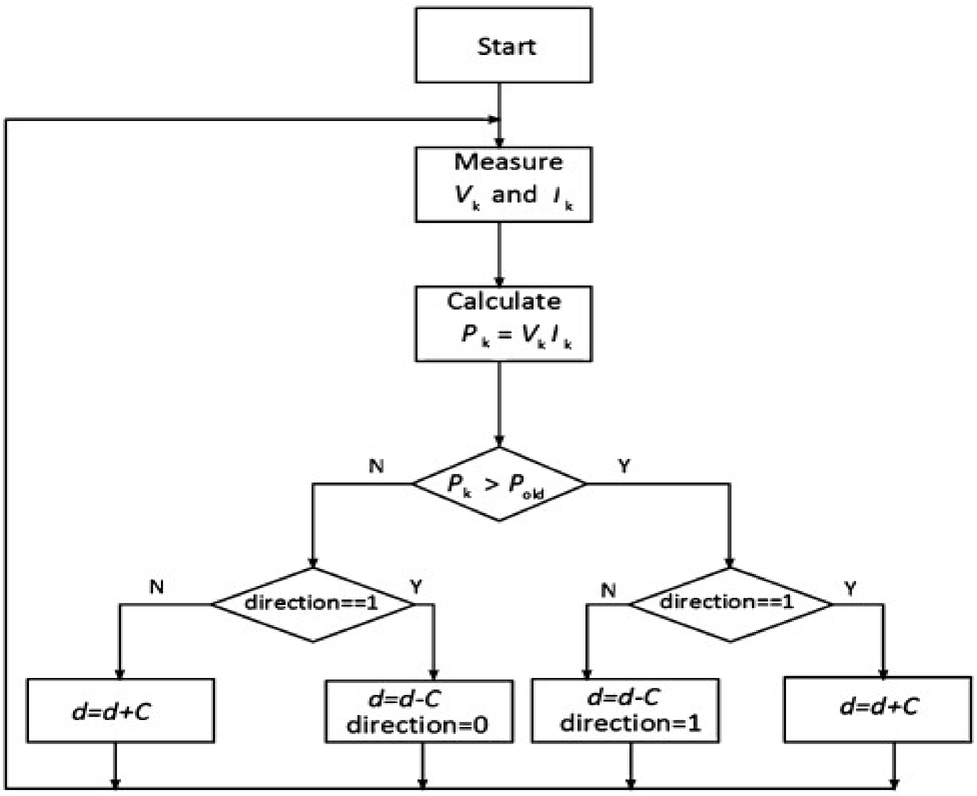


Figure 3.6: Flowchart of MPPT technique

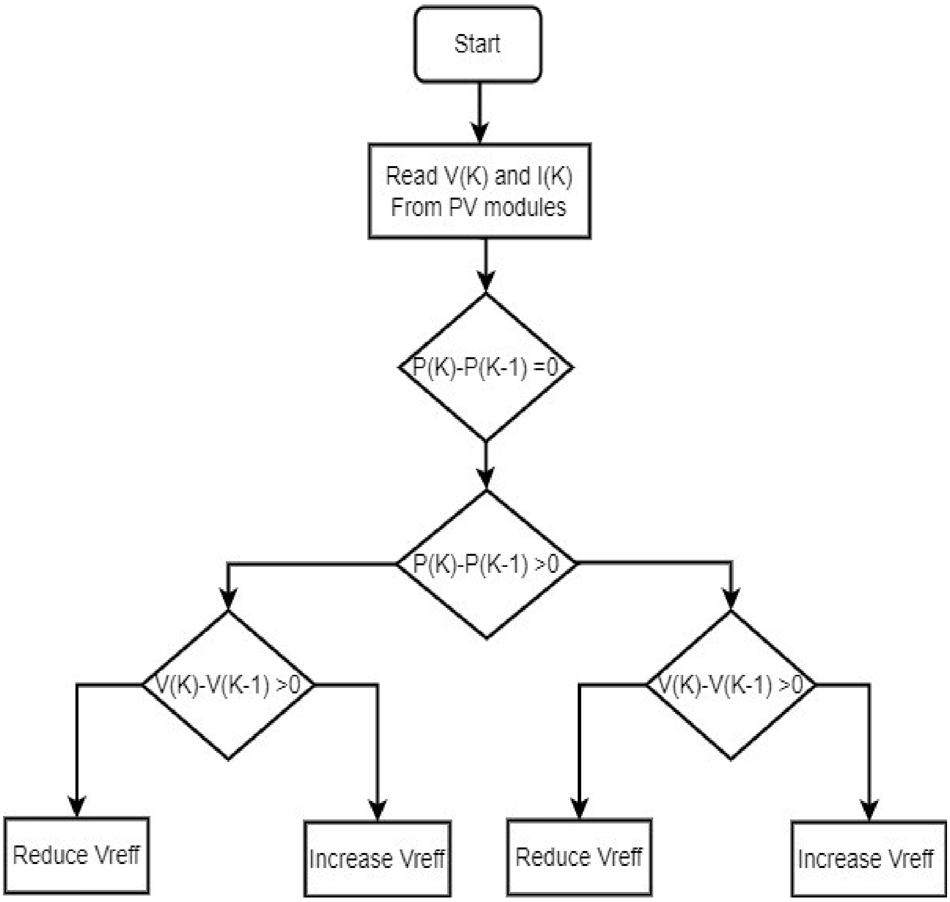


Figure 3.7: Flowchart of MPPT technique

From the MPPT flow chart the current voltage (V_K) should be compared to the last voltage (V_{K-1}). The converter tariff cycle will increase if yes, nation V_{ref}. To avoid the issue, lower the V_{ref} or reduce the tariff cycle. A difference should not exist between the current tension (V_K) and the previous tension (P_{K-1}). Then, check it against the prior tension (P_{K-1}); increasing the converter's timing cycle is possible with V_{ref} naiakn in place. Reducing the duty cycle will likewise cause the V_{ref} to decrease. It would be wise to check if the present voltage (V_K) and the voltage before it (V_{K-1}) is identical. As the duty cycle is raised, the V_{ref} will also rise, and as the duty cycle is lowered, the V_{ref} will fall.

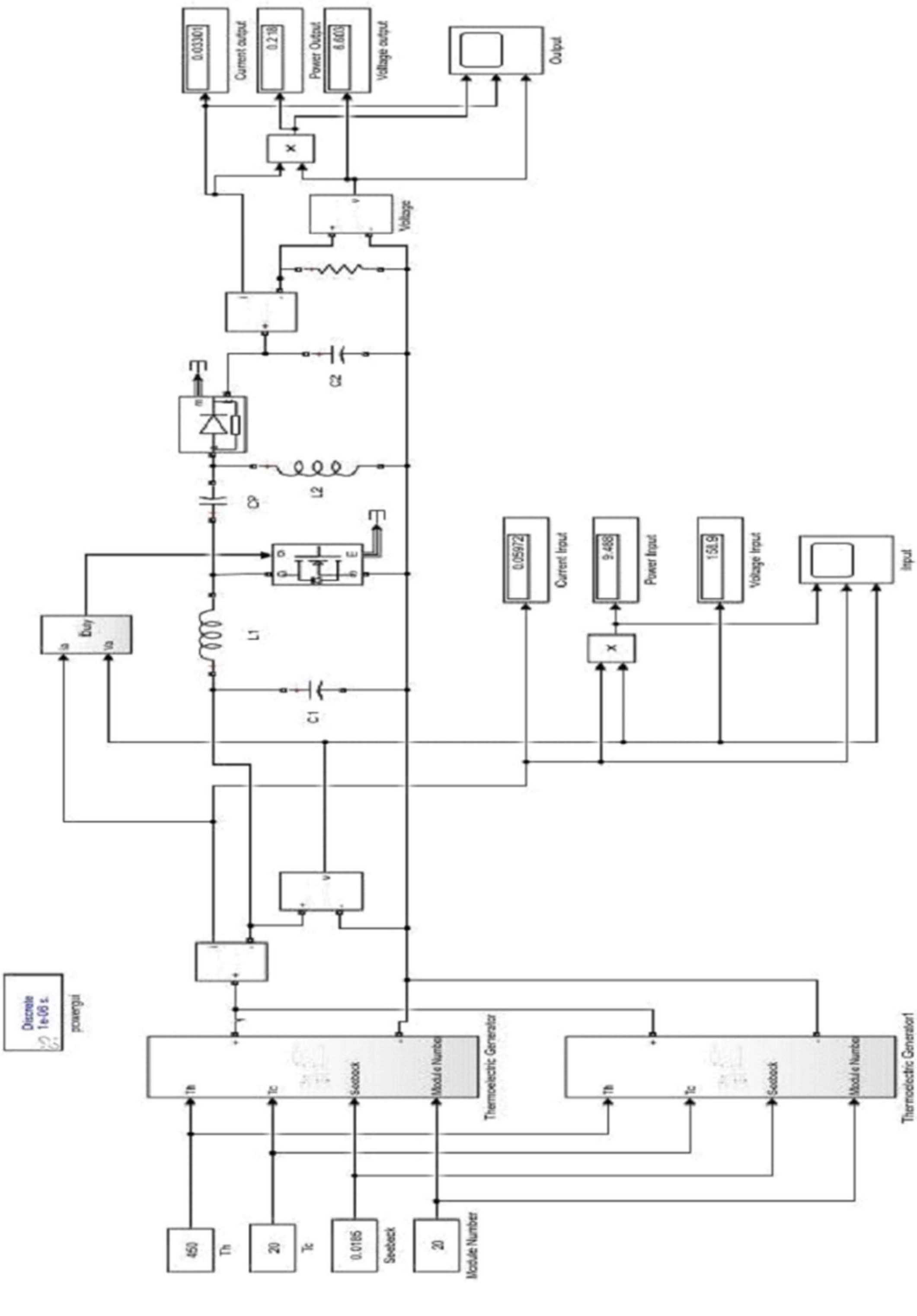


Figure:3.8 MPPT circuit for TEG in MATLAB/Simulink

3.5 COMPONENTS AND MODELLING OF THE TEG SYSTEM

Referring to Fig. 3.9, the proposed TEG system includes a TEG module coupled to a SEPIC converter managed by fuzzy logic-based MPPT to supply the load. For the TEG module's voltage and current output, several thermoelectric generators are coupled in series and parallel. The SEPIC converter allows the TEG system to track maximum power with the help of fuzzy logic-based MPPT

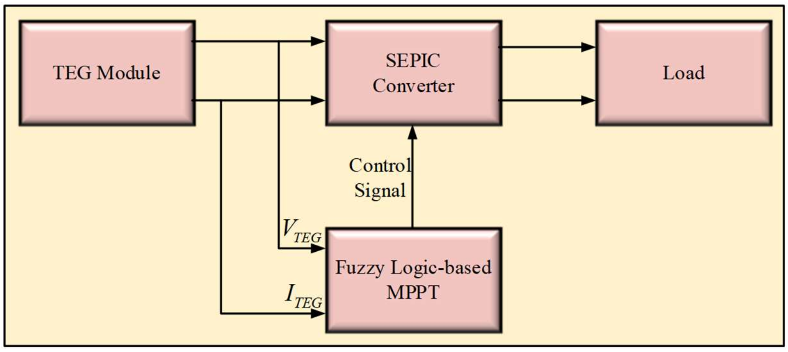


Figure:3.9 Block diagram of TEG system

3.5.1 Modelling of TEG

The TEG module produces electricity proportionate to the difference in voltage between the thermoelectric generator's legs. Figure shows a thermoelectric generator's thermal circuit diagram. TEG heat flow equations are as follows:

$$Q_H = Q_{peltier} + Q_{cond} - Q_{JH} = \frac{T_S - T_H}{\psi_H} \quad (17)$$

$$Q_C = Q_{peltier} + Q_{cond} - Q_{JH} = \frac{T_C - T_\infty}{\psi_C} \quad (18)$$

Heat transmission from the hot side (Q_H) to the cold side (Q_C) of the thermoelectric element; heat conduction (Q_{Cond}), Peltier heating/cooling (Q_{Peltie}r), and Joule heating (Q_{JH}) within the thermoelectric material. The hot and cold sides each have their own thermal resistance, denoted by H and C. The symbols T_H, T_S, T_C, and T represent the hot surface temperature, the heat source temperature, the cold surface temperature, and the ambient air temperature Ψ_H and Ψ_C, respectively. There are also further generalizations of the energy conservation equations.

$$Q_H = K(T_H - T_C) + \infty I_{TEG} T_H - \frac{1}{2} I_{TEG}^2 R_{int} \quad (19)$$

$$Q_C = K(T_H - T_C) + \infty I_{TEG} T_C - \frac{1}{2} I_{TEG}^2 R_{int} \quad (20)$$

The Seebeck coefficient (α) of TEG material is equal to the thermal conductance of TEG material, which is indicated by K. where R_{int} is the internal resistance of the TEG material and I_{TEG} is the TEG output current. In the operating range of TEG, the Seebeck coefficient and internal resistance are constants [16]. Therefore, the TEG module's output power is provided by

$$P = Q_H - Q_C \quad (21)$$

By observing (3) and (4), The TEG output current is a function of $Q_{Pelterier}$ and Q_{JH}. The TEG output power changes with the output current, even while the temperature differential between T_C and T_H stays the same. The output current of a particular source also affects T_C and T_H. The surrounding temps are small. The conventional maximum power output condition ($R_{int} = R_{ext}$) gives maximum current output. Many researchers have addressed this type of approach, which suffers from inaccuracy in real-world applications [17-20].

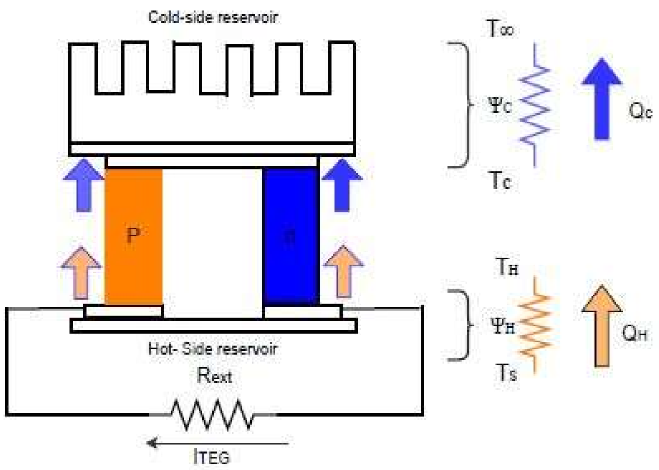


Figure:3.10 A typical thermoelectric module schematic and thermal circuit model

As per A Edvin Risseh, Olof Erlandsson , the exhaust temperature of heavy vehicles is from 100 to 500 ˚C

3.5.2 SEPIC Converter Analysis

A switching converter is always required for harvesting energy from TEG. In this regard, a SEPIC converter is used to fulfil the maximum energy harvesting from TEG. The SEPIC converter is more advantageous than the DC-DC converter due to its low current ripple and high MPPT efficiency. This converter acts as an intermediate stage to serve the load from TEG. Fig.3.11 shows a schematic representation of the SEPIC converter.

The SEPIC converter contains two inductors (L_1 and L_2), allowing greater flexibility in selecting inductor values for ripple-free current. Further, it has input (C_{in}) and (C_{out}) output capacitors to control voltage fluctuations and provides isolation. The condenser (C_p) provides the main isolation between the load and the converter. The advantage of this isolation protects the converter and TEG from load side faults. The converter is able to vary the output voltage 0 to the desired value based on the capacitor and inductor values.

Thus, equation (25) expresses the relationship between input and output voltage as a function of duty cycle:

$$V_{out} = V_{in} \frac{D}{1-D} \tag{22}$$

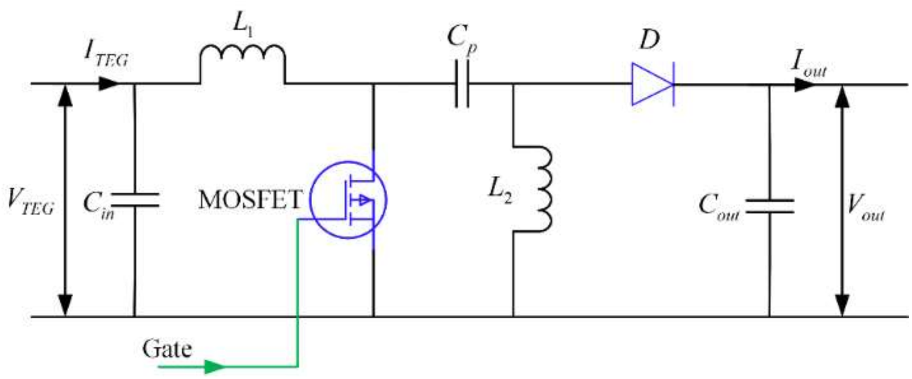


Figure 3.11. Schematic of the SEPIC Converter

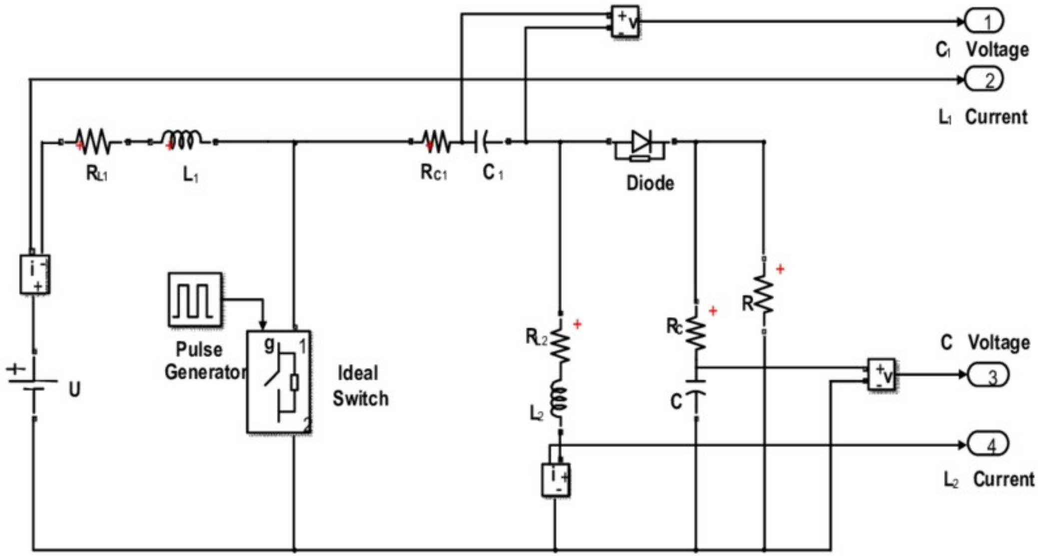


Figure 3.12. MATLAB circuit of the SEPIC Converter

Fig.3.12 shows a the MATLAB circuit of the SEPIC converter. It consists of resistors, inductors, capacitors and switches.

In a lossless converter, the input power is directly proportional to the output power. And hence, the power equation looks like this in equation (23):

$$P_{in} = P_{out} \tag{23}$$

Multiplying the input voltage and current, i.e., the TEG's voltage and current, gives the input power. Multiplying SEPIC converter voltage with output current produces output power. Hence, the power balance equation is shown in (24) as follows:

$$V_{TEG} I_{TEG} = V_{out} I_{out} \tag{24}$$

Substituting (22) in (24) gives the current in the function of the duty cycle as represented as (26).

$$I_{out} = I_{TEG} \frac{1-D}{D} \tag{25}$$

In order for the converter to meet the load requirements, continuous conduction mode (CCM) must be operational. For this reason, a duty cycle of half should not cause the inductor to be zero. The output voltage and TEG voltage are same in this case. The duty cycle can be expressed with the below equation along with the duty cycle voltage derived by equation (26)

$$D = \frac{V_{out}+V_D}{V_{out}+V_{TEG}+V_D} \quad (26)$$

The duty cycle is proportional to the applied TEG voltage. As a result, it can have a maximum value.

The accepted current ripple is the primary determinant of the inductance value. The recommended maximum ripple current is 40% of the total electrical current (TEG). A current ripple is defined by equation (27):

$$\nabla I_l = I_{TEG} * 40\% = V_{out} \frac{V_{out}}{V_{TEG(min)}} * 40\% \quad (27)$$

Based on the ripple, the values of inductors must be chosen, as represented by the equation (28) below.

$$L_1 = L_2 = \frac{V_{TEG(min)}}{\Delta I_l * f_{sw}} D_{max} \quad (28)$$

Based on the voltage ripple, the capacitor value C_p can be chosen by the following equation (29):

$$\Delta V_c = \frac{I_{out}+D_{max}}{C_p * f_{sw}} \quad (29)$$

Further, the input and output capacitor values are chosen by using the equation (30) given below:

$$C_{in} = C_{out} \geq \frac{I_{out} * D_{max}}{V_{ripple} * f_{sw}} \quad (30)$$

Table 3.3 displays the TEG specifications, while Table 3.6 displays the SEPIC converter values.

Table 3.3: TEG Specifications

Parameter	Variable	Value
Maximum Voltage	V_{mpp}	17.3V
Maximum Power	P_{mpp}	75W
Open circuit voltage	V_{oc}	21.6V
Current at maximum power	I_{mpp}	4.34A
Parallel resistance	R_p	866.923 Ω
Short circuit current	I_{SC}	4.6A
Number of series cells	N_s	36

Table 3.4: Current values at different temperatures

Temperature	TEG1	TEG2	TEG3	TEG4	Total current
200	0.1	0.09	0.08	0.07	0.34
250	0.11	0.09	0.09	0.08	0.37
300	0.11	0.1	0.1	0.09	0.40
350	0.12	0.1	0.1	0.08	0.42

From the table 3.4 it is observed that current increase with increasing temperature by Seebeck effect. Power generated by the TEG 1to TEG4 decreased because of flow temperature reduces. Voltage also increased with the temperature as shown in table 3.5.

Table 3.5: Voltage values at different temperatures

Temperature	TEG1	TEG2	TEG3	TEG4	Total Voltage
200	3.15	2.8	2.5	2.35	10.8
250	3.2	2.9	2.6	2.6	11.3
300	3.3	3.1	2.9	2.8	12.1
350	3.6	3.4	3.3	3.0	13.3

Table 3.6: SEPIC Converter Values

Parameter	Variable	Value
Capacitor	$C_{in} = C_{out}$	2200 μF
Inductor	$L_1 = L_2$	274 μH
Coupling capacitor	C_p	1000 μF
Switching frequency	f_{sw}	10 HZ

3.5.3 Advantages of the SEPIC converter

The SEPIC Converter is the most versatile and effective for TEG systems, handling fluctuating voltages and maintaining stable performance of TEG. Table 3.7 highlighting the advantages of the SEPIC converter over Boost, Buck, and Cuk converters for Thermoelectric Generator (TEG) applications:

Table 3.7: Comparison of SEPIC, Boost, Buck, and Cuk Converters for Thermoelectric Generator Applications

Feature	SEPIC Converter	Boost Converter	Buck Converter	Cuk Converter
Step-Up and Step-Down	Handles both efficiently, ideal for variable TEG output	Only steps up voltage, unsuitable for low input	Only steps down voltage, unsuitable for higher inputs	Handles both but with inverted output voltage
Output Polarity	Non- inverted output	Non- inverted output	Non- inverted output	Inverted output, requires additional components
Input Current	Continuous input current, reducing stress on TEG	Continuous input current but no step down capability	Continuous input current but no step down capability	Pulsating input current, less efficient for TEGs
Efficiency	High efficiency for variable input voltages	Efficient for stepping up only	Efficient for stepping down only	Efficiency depends on additional components
EMI (Electromagnetic Interference)	Low EMI due to smooth input current	Moderate EMI, depending on design	Moderate EMI, depending on design	Higher EMI due to pulsating current
Complexity	Moderate, requires one active switch and two	Simple, single inductor design.	Simple, single inductor design.	Complex, requires two inductors and coupling

	inductors.			capacitor.
Applications	Versatile for variable TEG outputs (e.g., IoT, sensors).	Best for high-voltage TEG outputs.	Best for low-voltage TEG outputs.	Suitable but adds design complexity.
Scalability	Easily scalable to different power levels.	Limited to applications requiring step-up.	Limited to applications requiring step-down.	Scalable but with complexity trade-offs.

3.6 DESCRIPTION OF THE MPPT TECHNIQUE

In order to make use of the full TEG potential and transfer it to the load, this MPPT control is in place. This control is considered one of the most critical elements in TEG efficiency improvement. The efficiency control requirement for MPPT is quick dynamics, good performance, high efficiency, and low design cost. TEG systems have been assessed with some MPPT techniques to improve their efficiency. The behaviour of a fuzzy logic controller under varying loads and temperatures is examined in the following sections. It has been found that using this new MPPT approach improves the efficiency of the TEG during conversion. The selected rules of fuzzy for present simulation given in the table 3.8.

Table:3.8 Fuzzy Rule base

Input		$e(P_g)$						
		NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
$e(T_{LPT})$	**NB**	ZE	ZE	ZE	NB	NB	NB	NM
	NM	ZE	ZE	ZE	NS	NM	NM	NM
	NS	NS	ZE	ZE	ZE	NS	NS	NS
	ZE	NM	NS	ZE	ZE	ZE	PS	PM
	PS	PS	PM	PM	PS	ZE	ZE	ZE
	PM	PM	PM	PM	ZE	ZE	ZE	ZE
	PB	PB	PB	PB	ZE	ZE	ZE	ZE

Figure 3.13 depicts the TEG module's P-V characteristic. There are three kinds of points in three different places. If dP/dV is more than 0, the curve will be dP/dV = 0, and if it is less than 0, the curve will be dP/dV< 0. The power changes on the left side of the MPP when the voltage dP/dV > 0, but it changes on the right side when the voltage

dP/dV < 0. It's common knowledge that MPP control, by means of perturbation, advances the TEG operating voltage. TEG is now directed away from MPP if dP/dV is true.

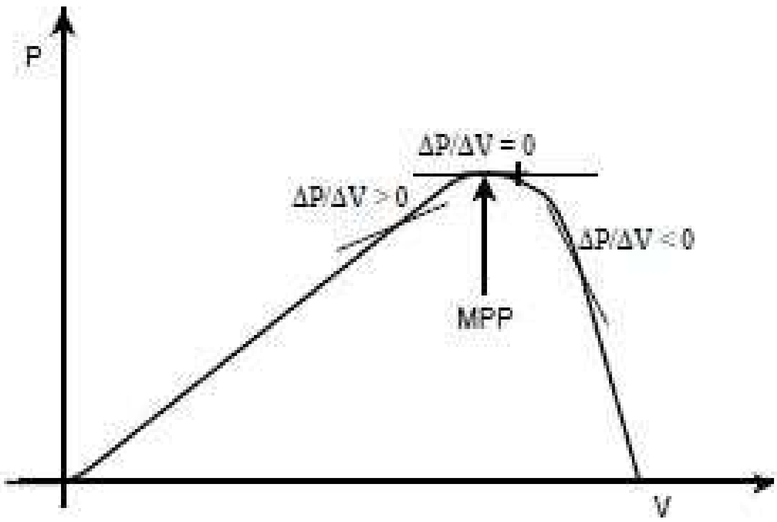


Figure:3.13 P- V Characteristic of TEG module

3.6.1 Fuzzy Logic MPPT Controller

Fuzzy logic controllers are employed in this paper to assist with tracking the MPP in the TEG system. Because they do not require exact model information, they are robust and relatively simple to construct. However, they require the designer to have a complete understanding of the operation of the TEG system.

3.6.2 Fuzzification

There are two input and one output in the proposed system: one input is the power Error e (P_g), and the other is a temperature change T_{LCA}. Where δD is the controller output and is referred to as the perturbation step size. The shape of the membership function is determined by the partitioning of fuzzy subsets, as shown in Fig 3.15.

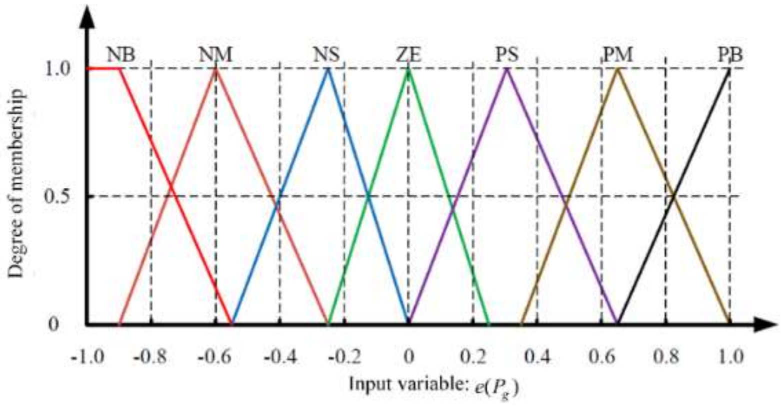


Figure:3.14 (a) Membership function plots for Error

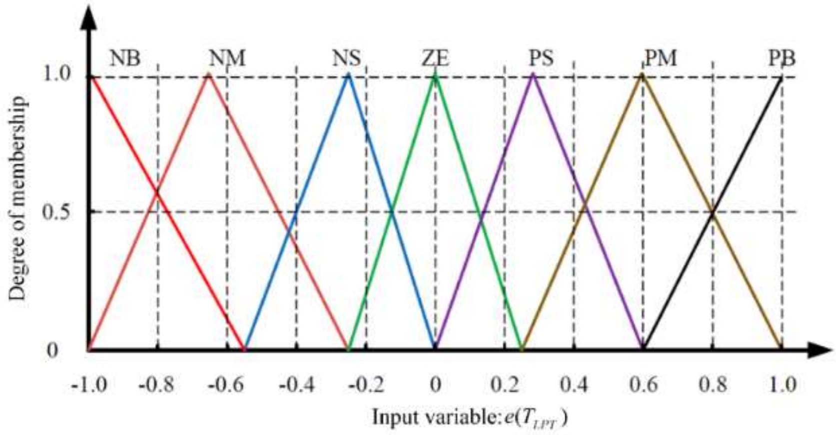


Figure:3.15 (b) Membership function plots for change in temperature

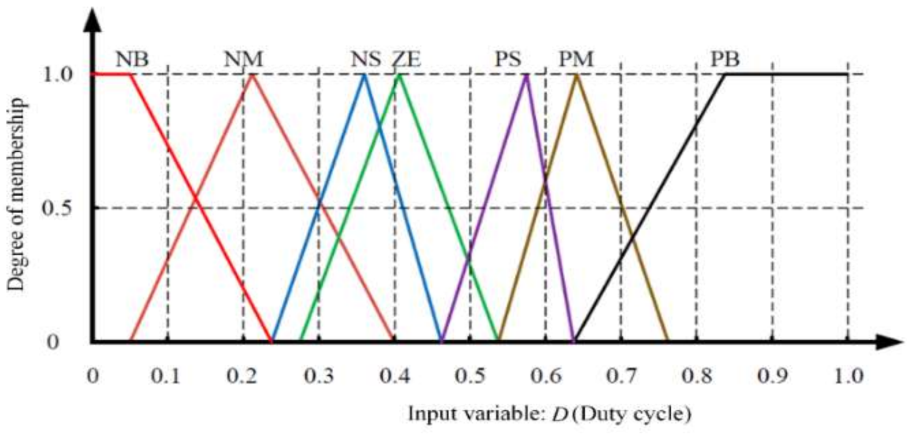


Figure 3.16: (c) Membership function plots for changes in duty cycle

3.6.3 Inference Method

Its primary building blocks are fuzzy rule bases and fuzzy implication blocks. Now that the inputs to the rule-base have been fuzziness, rules are applied once they've been provided to the inference engine. When it comes to output settings, there is a technique called fuzzy implication.

3.6.4 Defuzzification

The duty ratio is the system's output (cycle). In a SEPIC converter, the MOSFET switch is regulated by the duty ratio, which is produced through fuzzy logic control via PWM.

3.7 ARTIFICIAL NEURAL NETWORK

Parallel essential elements make artificial neural networks (ANN) tick. These parts are based on actual organisms' neural systems. As in the natural world, the strength of the bonds between nodes in a network determines overall performance. Modifying the weights (connections) between nodes in an ANN allows it to be trained to perform various functions.

It is commonly used to "train" neural networks so that they always produce the expected results when given an input. This is illustrated in a specific scenario in Figure 3.17. The network is then tweaked depending on the comparison between its output and the target. The process repeats until the network's output is identical to its purpose. Input/output pairs should be plentiful for training a neural network.

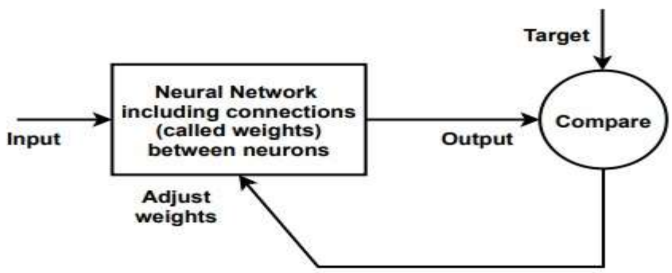


Figure 3.17: Operating of ANN

In this investigation, a neural network is used to locate the optimal operating point. Figure 3.18 shows a three-layer neural network being used to get to MPP.

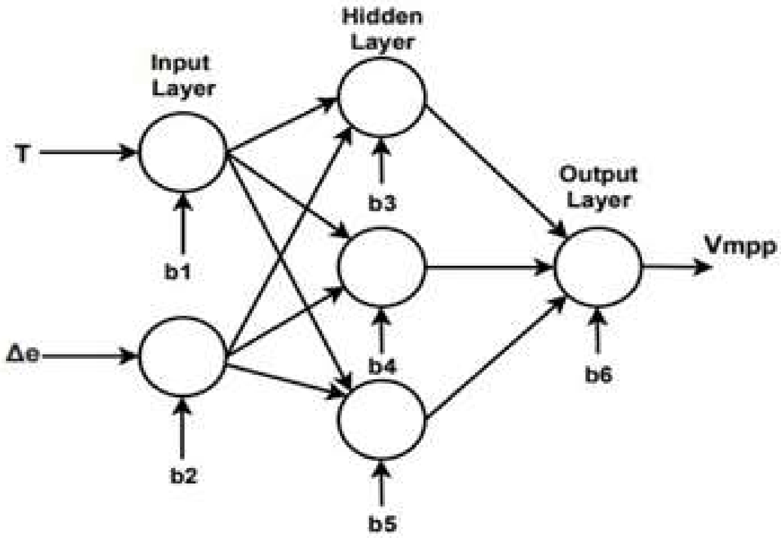


Figure3.18: Neural network structure

The ANN takes two parameters, temperature (T) and error (e), and produces a voltage (Vmpp) instead. When training a neural network, it's important to collect data on both the input and the output. This allows for the computation of neuron weights throughout all layers. The TEG model is controlled using MATLAB code in order to gather data. ANN can be trained in multiple ways. For the purpose of this research, we train the ANN using the backpropagation technique.

The output will be Vmpp when the ANN is fed T and e as inputs and its weights are defined. The V-I characteristic of the simulated TEG can now be used to determine Impp, the maximum power point current. Therefore, Impp is multiplied by Vmpp to get Pmax.

3.8 RESULTS AND DISCUSSION ANN

In order to create the simulation, four TEG are connected in a serial and parallel fashion. Here we have a resistive load, a voltage sensor, a current sensor, and a SEPIC converter. To ensure the converter runs as efficiently as possible, the MPPT controller receives data on power, current, and voltage, and then produces a signal with instructions for the optimal output.

It is possible to adjust the cold side of the TEG to 50^0 C for testing, while the hot side can reach temperatures between 200^0 and 450^0 C. The variable output voltage, power, and current as a function of temperature and load resistance are illustrated in Figures 3.19–3.22. On plot 3.19, we can see the relationship between output voltage and load resistance at different system hot sides. With an 100 ohm impedance, the hot side reaches a temperature of 450^0 degrees Celsius, as shown in Figure 3.19. The output voltage is 38.06 volts. The changing values of output power and load resistance as a function of hot side temperature are illustrated in Figure 3.20. Raising and then lowering the load resistance showed the increase in output power. At an output resistance of 70 ohm, the most power is produced, while at an output resistance of 10 ohm, the smallest power is attained, as shown in Figure 3.20.

At 450 degrees Celsius and 35 volts, the data show maximum output power. Power output increases as temperature rises. The increase in hot-side temperatures is likely due to temperature differences.

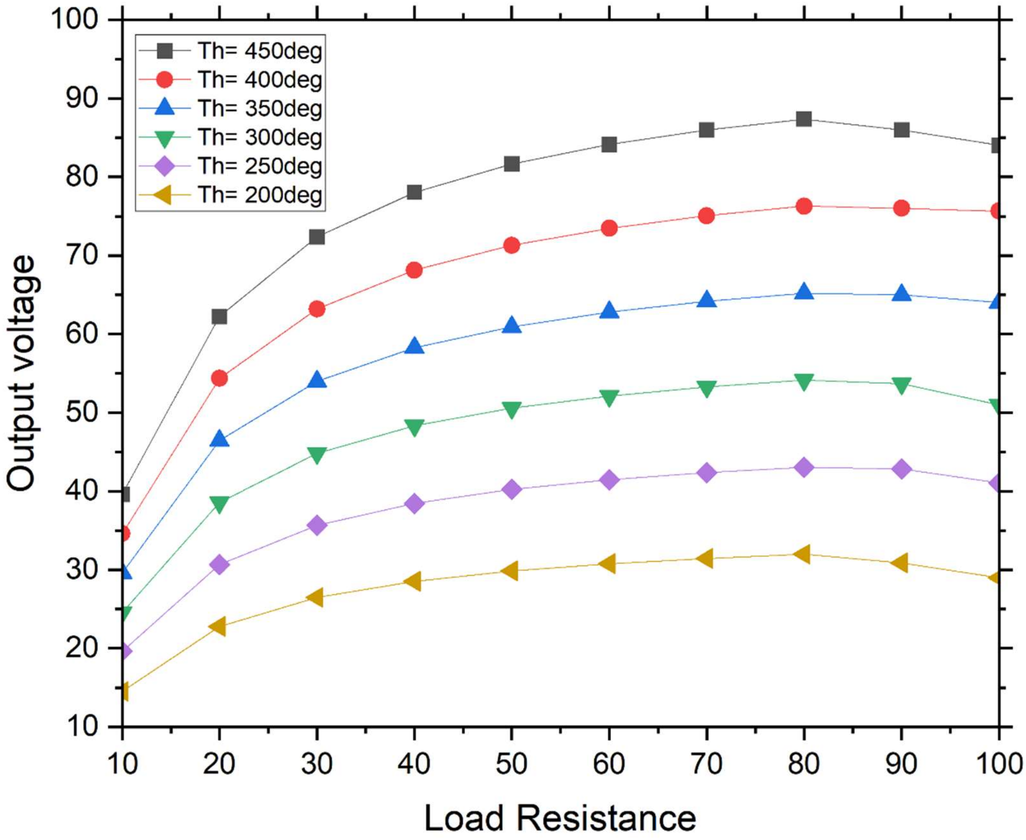


Figure 3.19: Hot side voltage output vs load resistance at varying temperatures

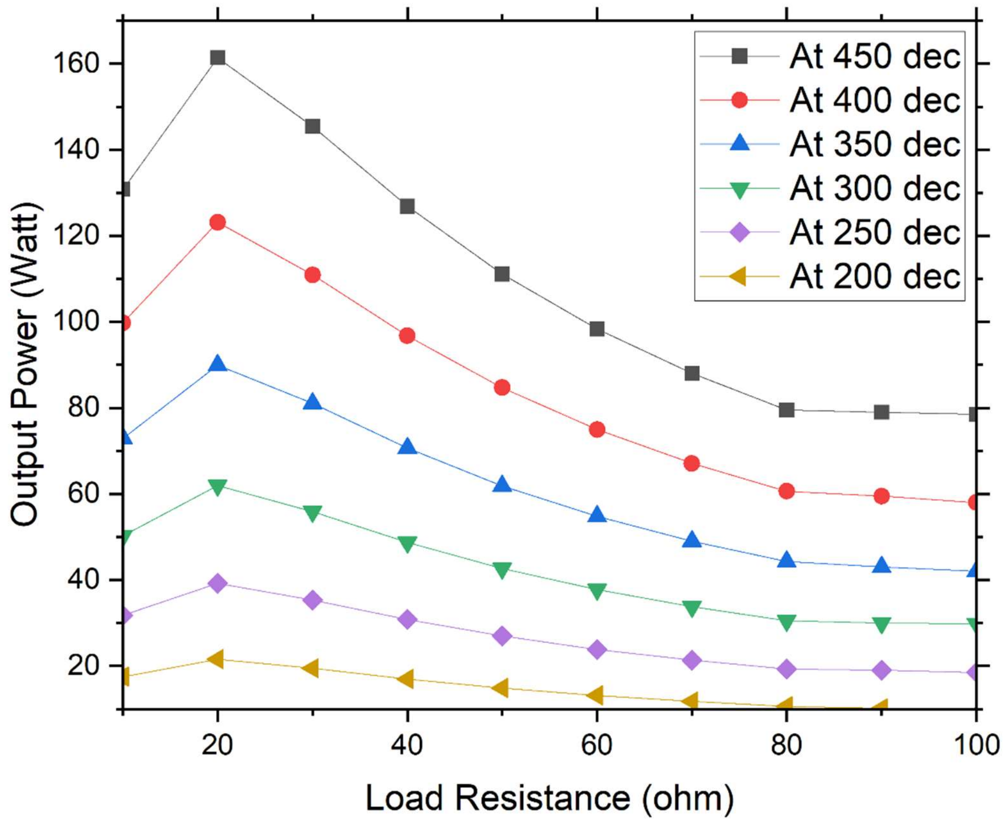


Figure 3.20: The relationship between power output and load resistance at various hot sides

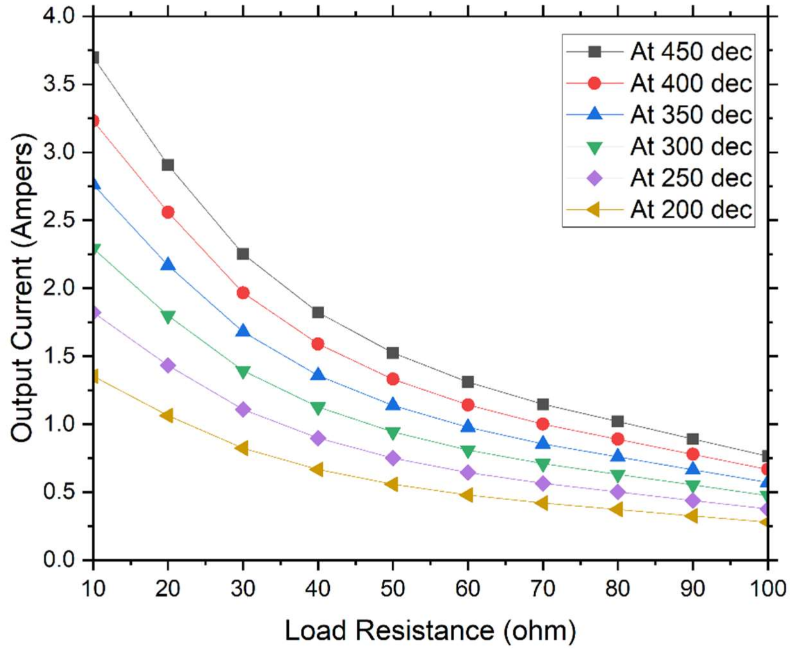


Figure 3.21: The output current-load resistance relationship as hot side temperature varies

Figure 3.21 illustrates the current produced by the TEG as a function of load resistance at a constant temperature. It is fascinating to observe the gradual drop in output current as load resistance increases. This results in a higher current output on the hot side (T_h) at 450 degrees Celsius.

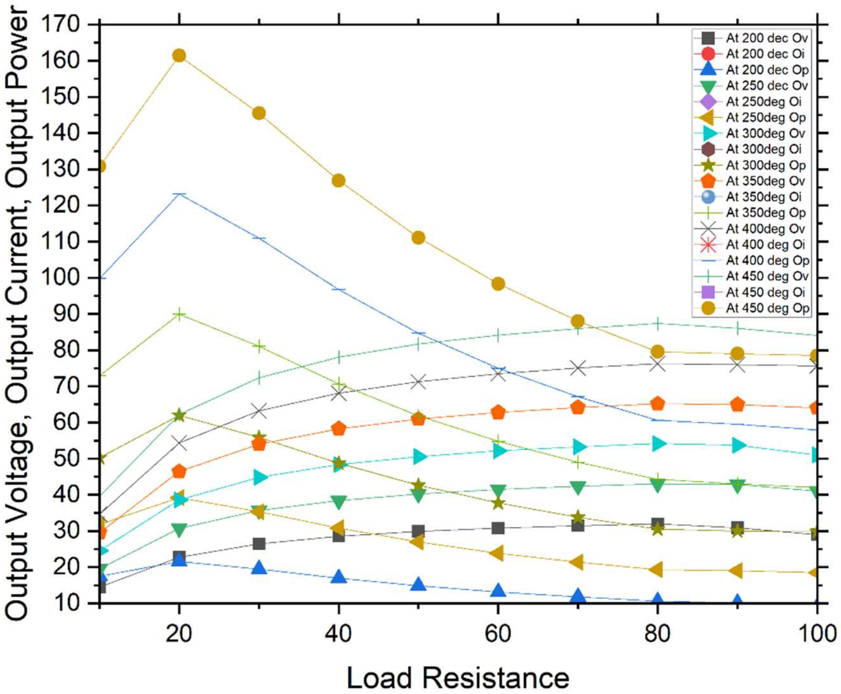


Figure 3.22: Changes in power, current, and voltage at the output in relation to load resistance

Based on the load resistance, figure 3.22 illustrates how output voltage, current, and power were measured. The maximum values were obtained for all parameters at 450^0c. A maximum output voltage of 37.5 V is achieved at 80°C. The maximum current and power output are 7.5W and 0.3A, respectively, at 450^0C. Evidence from TEG measurements taken at a range of temperatures suggests that both convergence velocity and conversion efficiency are enhanced. Conventional methods were found to be less efficient than the proposed system.

3.9 DESCRIPTION OF THE MPPT TECHNIQUE

MATLAB/ SIMULINK are used to accomplish the modelling, and the modeled circuit's then analyzed. To evaluate the performance of the conversion system between 200^0 and 450^0 Celsius, we set the cold side temperature to 50 degrees Celsius and the hot side temperature to 200^0, 250^0, 300^0, 350^0, 400^0, and 450^0 Celsius. To simulate this arrangement, we've made the model to modulate the number of TEG modules in series/parallel. When TEG converts heat into electrical energy, they are powered by a Fuzzy logic converter into the SEPIC converter and can extract maximum power.

At various system hot sides, Figure 3.24 shows the output voltage vs the load resistance. The output voltage increased consistently as seen in Figure 3.24 for different temperatures when the load resistance was adjusted. Figure shows that at 450 degrees Celsius on the hot side, the output voltage is 72 volts with an impedance of 80 ohms, which is considerable.

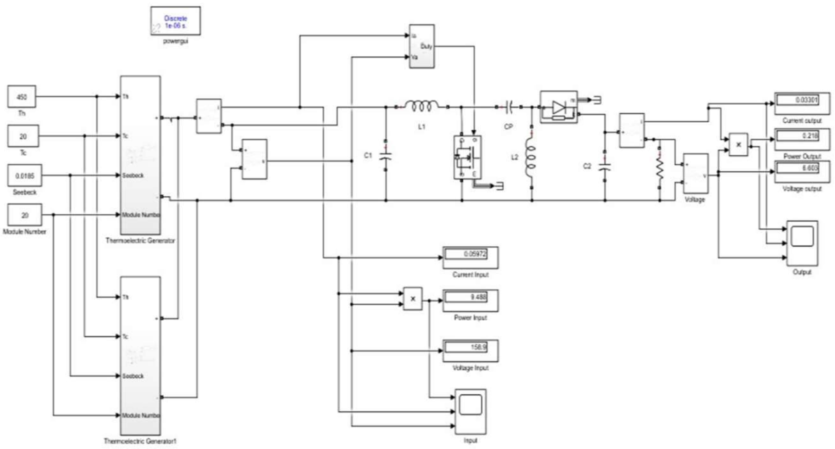


Figure: 3.23 Fuzzy MPPT for TEG in MATLAB/Simulink

- It shows that the output power is proportional to the load resistance up to a certain point, and then drops off.
- The greatest output power is achieved at an output resistance of 20 ohms, and the minimum is achieved at an output resistance of 10 ohms. Based on the data, the maximum output power is 132 watts at 20 ohms.
- In all circumstances, higher temperatures result in greater output power. An increase in hot side temperature as a result of larger temperature differences is thought to be the driving force.

The dependence of the output current on the load resistance with respect to the hot side temperature is seen in Figure 3.26. Additionally, the output current drops with increasing converter load, which is a reflection of the rising converter temperature.

So, the hot side temperature (Th) is defined as 450 oC, and at this temperature, the output current is higher.

Figure 3.27 The output voltage, current, power, verses load resistance at various hot sides temperature. Converter load also raises input and voltage, making it clearer that from zero resistance to 20 Ω, the voltage rise by however much voltage is observed.

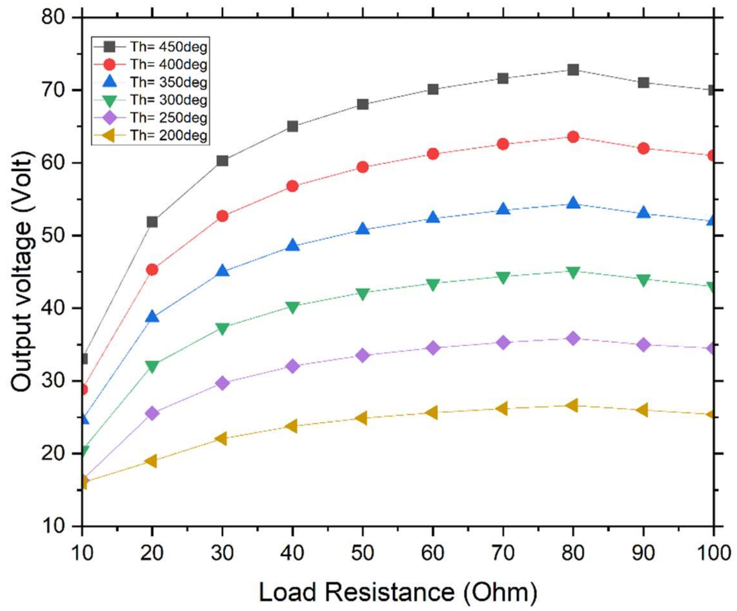


Figure: 3.24 A comparison of output voltage and load resistance at various hot side temperatures

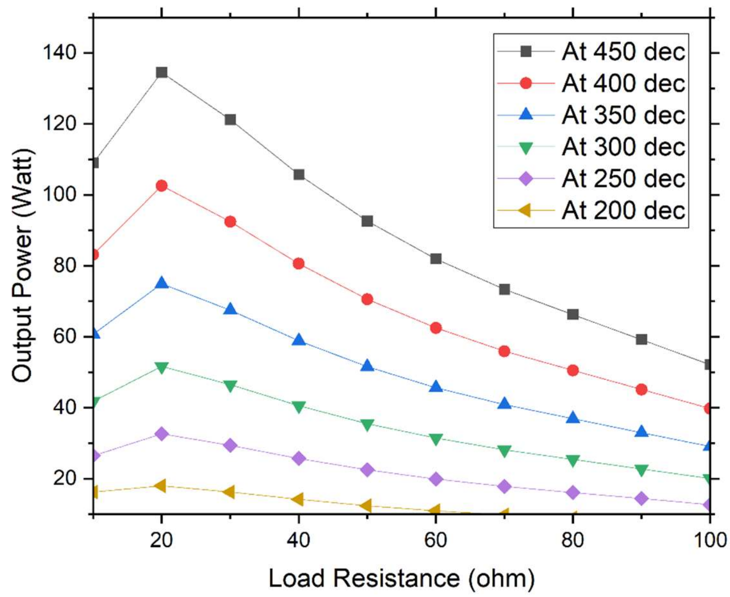


Figure: 3.25 At different Hot side temperature output power versus load resistance

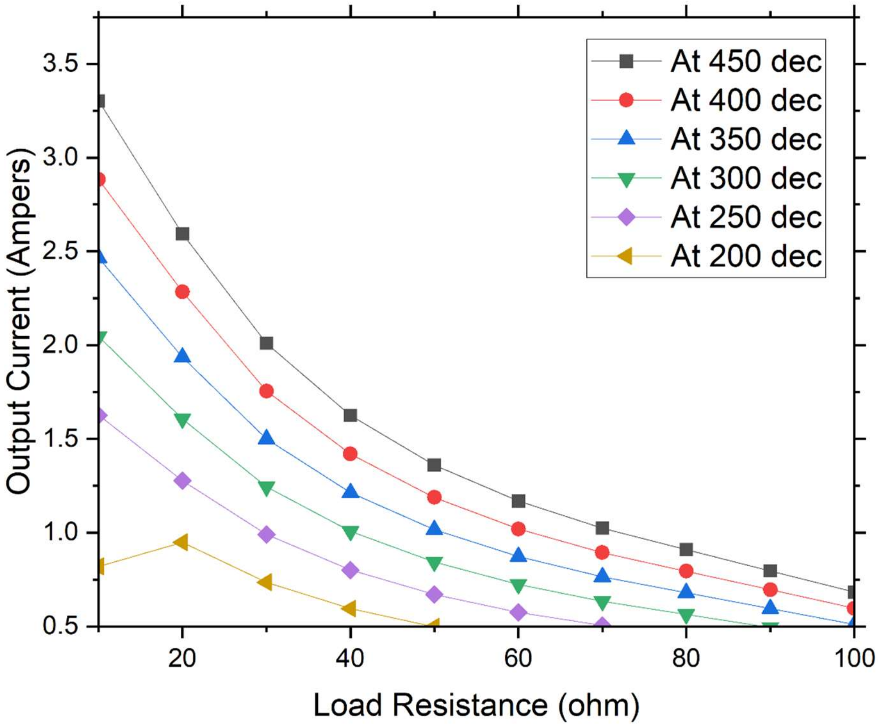


Figure: 3.26 Temperature-dependent output current vs load resistance

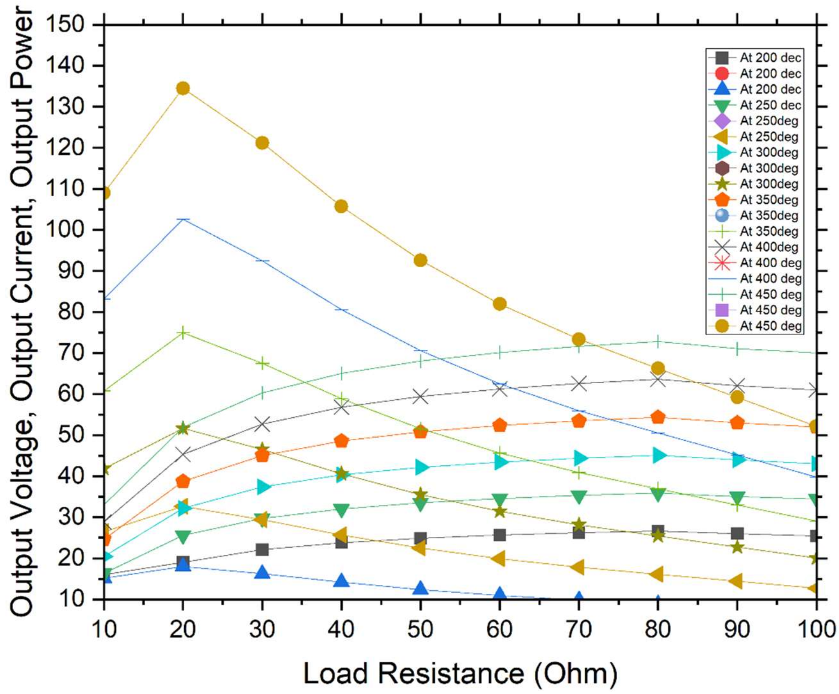


Figure: 3.27 The effect of temperature on voltage, current, and power

3.10 DISCUSSIONS

This study uses MATLAB/SIMULINK to apply a new MPPT algorithm that takes into consideration the fact that the input and load temperatures can vary. According to the study's findings, the modified P&O MPPT approach was used to successfully regulate the SEPIC converter's duty cycle. The TEG extraction method is flexible enough to handle a wide range of temperatures and weights. Our energy conversion efficiency went up while our tracking time went down thanks to our adoption of the modernised P&O-based MPPT method. For the first time, P&O's MPP will have this SEPIC converter, which is tailored for use with TEG and E-Vehicles.

3.11 ANN RESULTS

Data containing PowerPoint's maximum temperatures, mistakes, and voltages are used to train the neural network model initially. In order to train ANNs, error backpropagation is employed. Neuronal weights obtained from the control unit are used in the MATLAB/SIMULINK simulation of the neural network model. $V_{ref,mpp}$ is automatically connected to ANN outputs regardless of the inputs T and Δe.

Figure 3.28 shows the automatic neural network maximum power point tracking (ANN MPPT) for TEG circuits implemented in MATLAB/Simulink for the TEG module, SEPIC converter, and load. A distinct temperature and inaccuracy are modelled in each of the three states. With the help of the error bars and three separate temperatures, Figure 3.28 displays the simulation circuit. Figures 3.29-3.32 depict neural network topologies, and they illustrate the maximum power point reference voltage ($V_{ref,mpp}$) for various combinations of T and e. Accessing the reference current ($I_{ref,mpp}$) in PowerPoint is possible with the help of the $V_{ref,mpp}$ standard. $V_{ref, MPP}$ and $I_{ref, MPP}$ are controlled by the chopper control unit, which regulates the current and voltage at TEG's output. To get the most out of a SEPIC converter, use a Neural network converter once the heat has been transformed into electricity. the effect of the load resistor on voltage output as a result of changing the hot side temperature in Figure 3.29 When the load resistance increases, the side temperature rises as well, leading to a voltage rise. We can see the correlation between high heat and load resistance in Figure 3.30. You can lower the output power by changing the load resistance. Increasing the temperature to 300^0C and connecting it to a load of 20 ohms resulted in the highest power output. At high temperatures, the equation for the connection between output current and load resistance is shown in Figure 3.31. A higher load resistance results in a lower available current. Power production, current, and voltage are all impacted by the load resistance at various hot side temperatures (Figure 3.32). Determine the maximum power reference by comparing the TEG's power output to it. Based on the data, the controller demonstrates remarkable dynamic performance in monitoring MPP, voltage, and current.

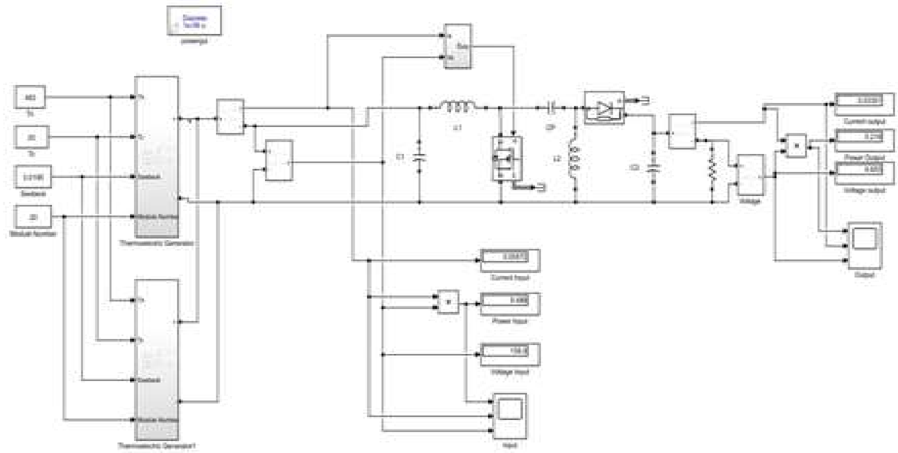


Figure.3.28 Circuit for neural network MPPT in MATLAB/Simulink

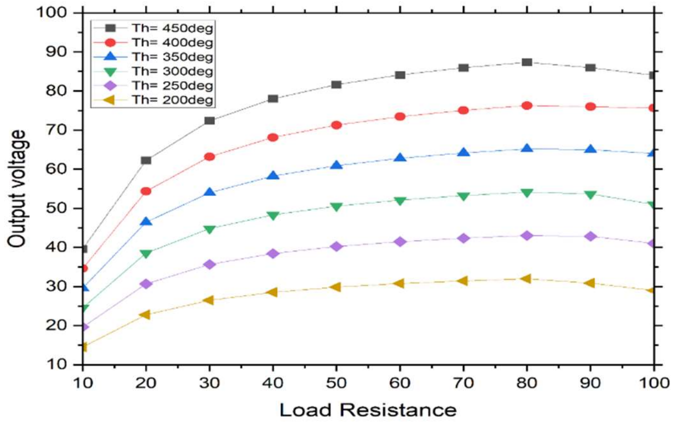


Figure. 3.29. Hot side temperature and output voltage vs load resistance

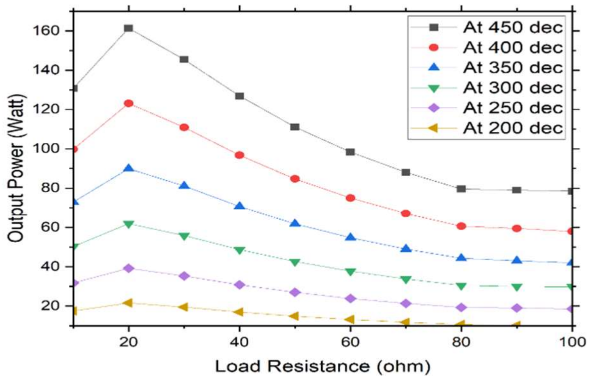


Figure. 3.30. Transient power output vs load resistance as temperature rises on the hot side

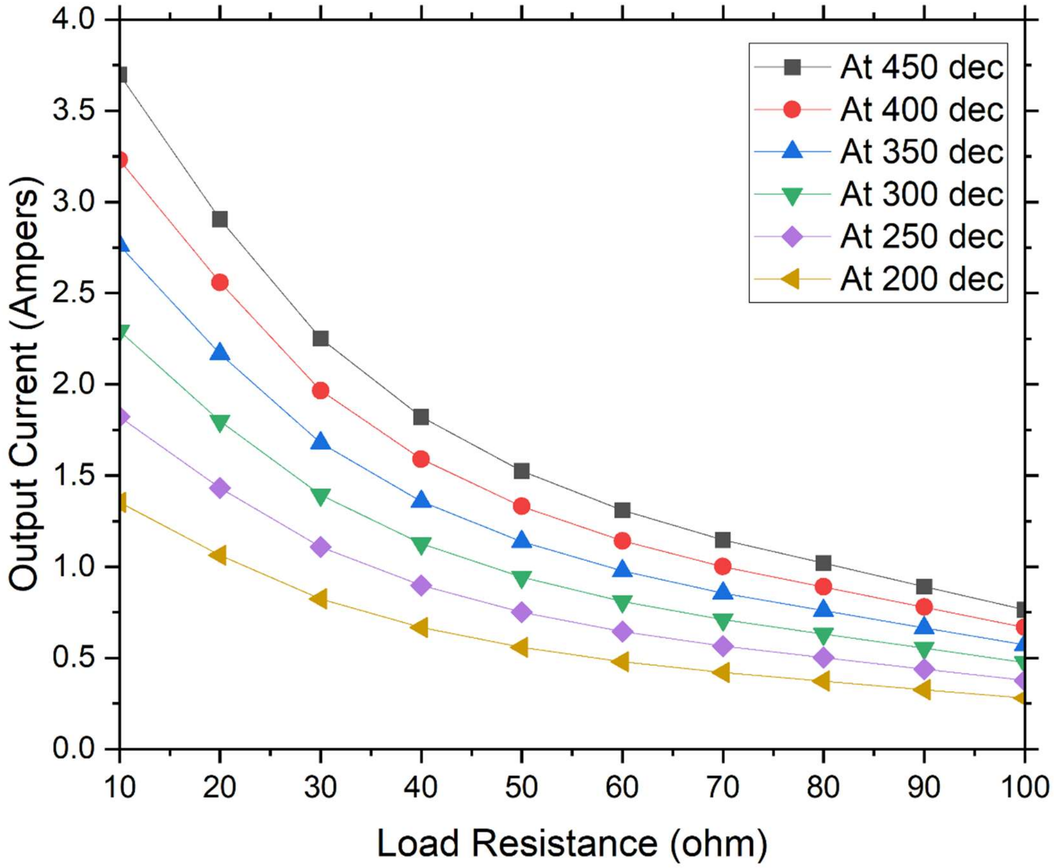


Figure. 3.31. Temperature-dependent output current vs load resistance

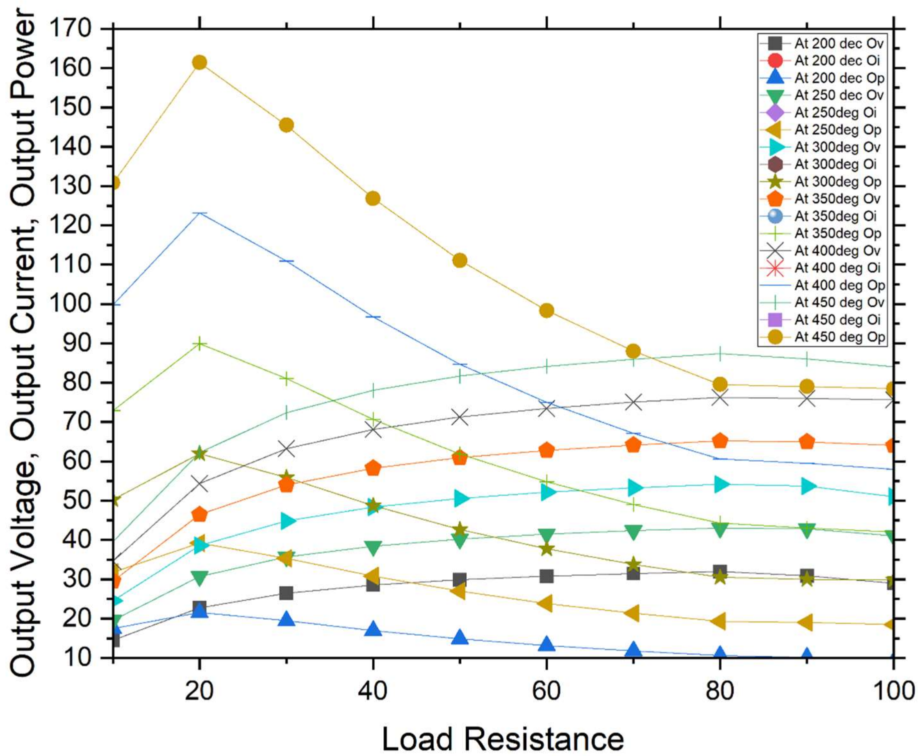
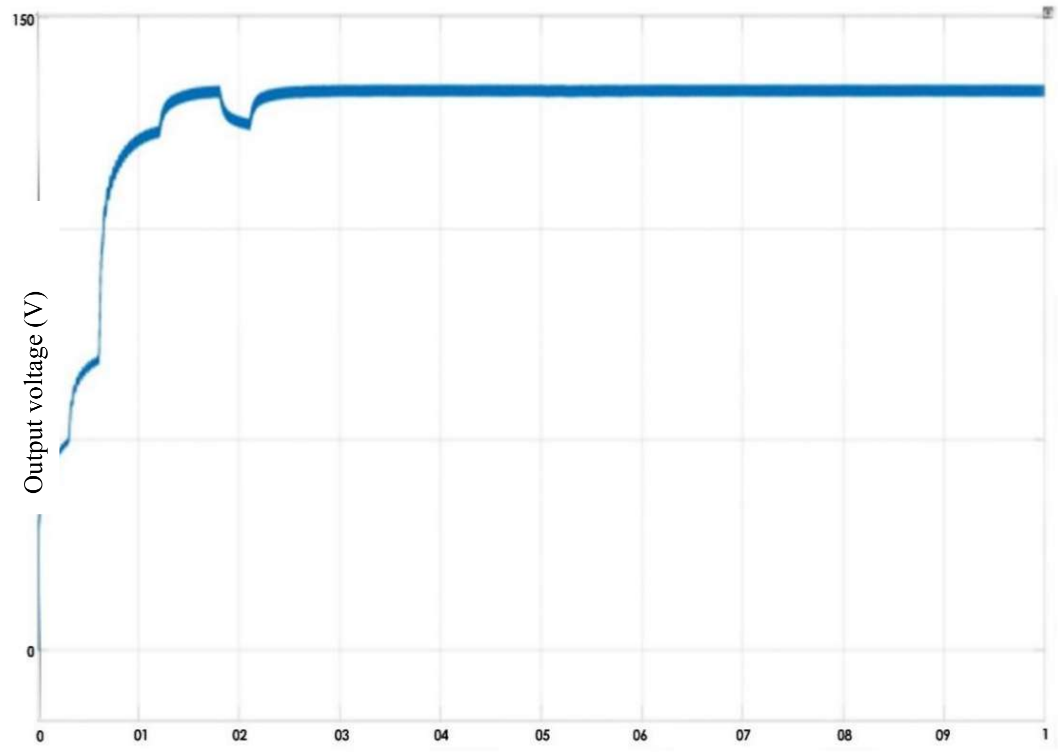
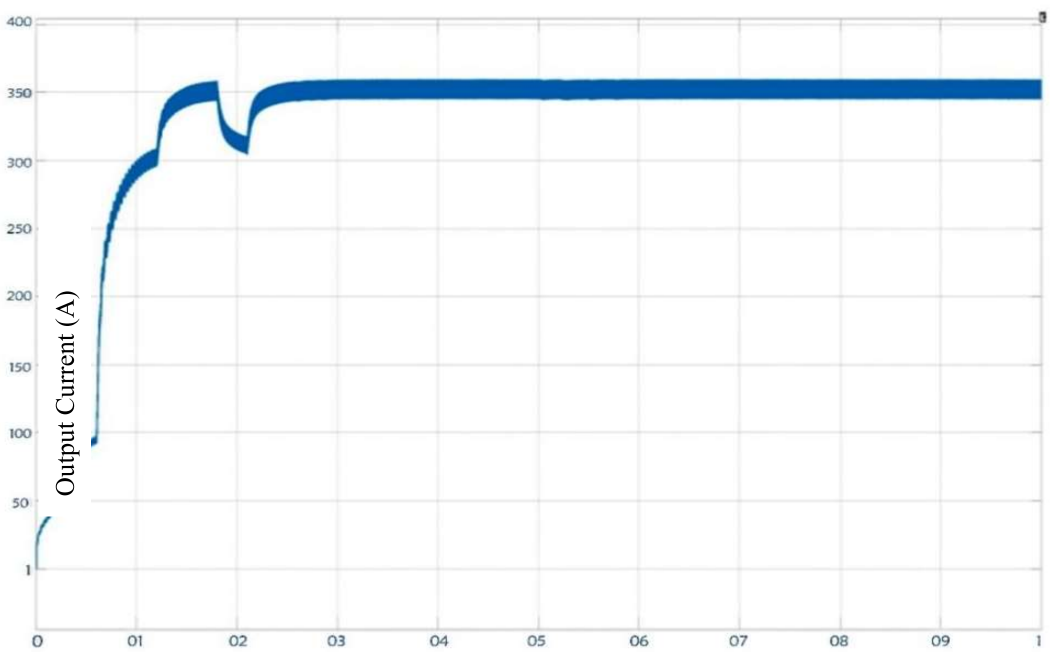


Figure. 3.32. Various hot side temperatures are shown against load resistance, along with voltage, current, and power generation.



Time (s)
Figure. 3.33. The output voltage when T= 300^{0}C R_L = 50 Ω



Time (s)
Figure. 3.34. The output current when T= 300^{0}C R_L = 50 Ω

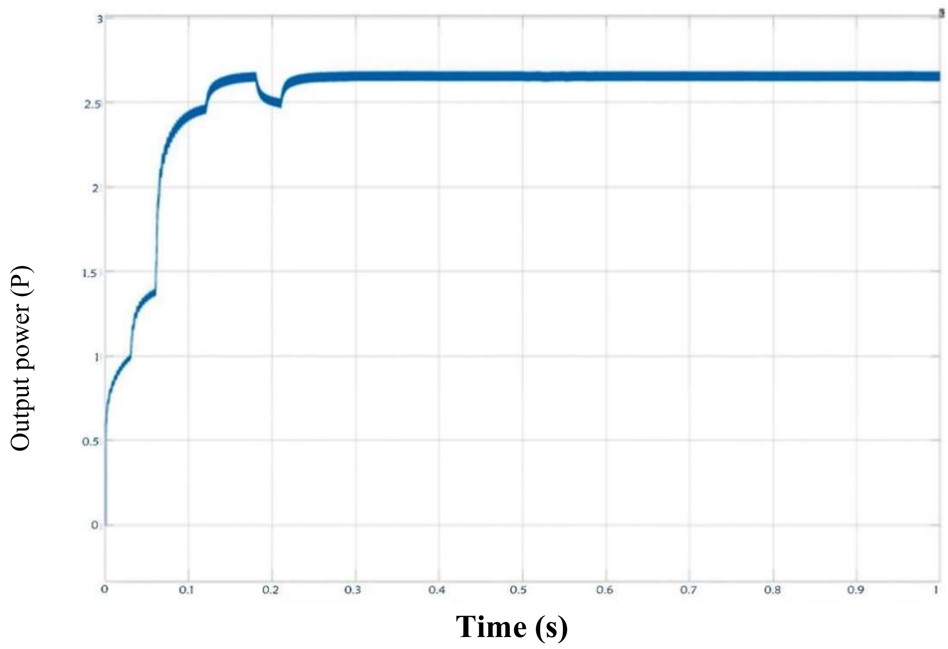


Figure. 3.35. The output power when T= 300^{0}C R_L = 50 Ω

A resistance of 50 Ohm is shown in Figure 3.33 for 300^0 C. 133V is the maximum output voltage of the SEPIC converter. Temperatures are initially within acceptable limits. A second factor to consider is that the load resistance consumes a great deal of power. There is a change in output voltage every second. According to Figure 3.34, there is a load resistance of 50 ohm send output when TEMs are operating at 300^0 C. As the output current increases, the MPP can be found. At startup, a SEPIC converter uses an initial I_0 of 0.5A to monitor MPP. The output current is 2.75A, as shown in Figure 3.35. Here, the algorithm recommends using the transition mode. When an ANN is in this mode, the current command takes on the value of the ANN. It is also possible to keep the MPP by adjusting the output voltage, which is monitored. A default value is set for the current command and transition mode is disengaged when the algorithm determines that the output current is approaching the maximum current. This ensures the power supply operates safely and efficiently. In Figure 3.35 the output power of SEPIC converters is simulated. The retaining power in this case is 50 (Rext). A total of 325 W to 360 W was delivered to the load on average. MPPT operating cycle for 0.22 s was found by the converter control to be 0.75.

Table 3.9: Comparation between Fuzzy MPPT & ANN MPPT at different hot side temperature with load resistance of 60 ohm

Temperature in degrees	**Output Voltage in Volts**		**Output Current in Ampers**		**Output Power in watts**	
	Fuzzy MPPT	ANN MPPT	Fuzzy MPPT	ANN MPPT	Fuzzy MPPT	ANN MPPT
200	25	50	0.3	1	7	50
250	30	70	0.5	1.25	20	115
300	40	80	0.7	1.5	30	150
350	50	100	1.0	2.0	40	225
400	60	120	1.15	2.5	60	275
450	70	140	1.25	2.75	80	350

Table 3.10: Comparison of Conventional MPPT Methods, Fuzzy Logic, and Artificial Neural Networks (ANN) for TEG Optimization

Feature	**Conventional Methods**	**Fuzzy Logic**	**Artificial Neural Networks (ANN)**
Adaptability to Nonlinearities	Limited adaptability to nonlinear TEG behavior.	Excellent at handling nonlinear relationships through fuzzy rules.	Highly adaptable, learns complex nonlinear patterns through training.
Response Time	Slower response due to predefined static algorithms.	Faster response as it adjusts dynamically to changing inputs.	Very fast once trained, processes data in real time.
Precision	Fixed precision based on predefined equations.	High precision due to fuzzy logic handling uncertainties.	Extremely precise with sufficient training data.

Scalability	Difficult to scale for complex or large systems.	Scales well by adding more rules.	Easily scales with more neurons and layers in the network.
Training Requirements	No training required, uses fixed equations.	Requires rule creation but no explicit training.	Requires extensive training with large datasets.
Robustness to Disturbances	Poor, cannot dynamically adapt to sudden changes.	Robust, quickly adjusts to external disturbances.	Very robust after training, resilient to variations.
Design Complexity	Simple design but lacks flexibility.	Moderate complexity due to rule-based structure.	Higher complexity due to training and tuning processes.
Energy Efficiency	Moderate, as it doesn't optimize real-time performance.	Optimized for energy savings through adaptive control.	Maximizes energy efficiency by finding the best operational point.
Usability in Dynamic Conditions	Struggles in dynamic environments.	Well-suited for dynamic and uncertain conditions.	Performs exceptionally well in dynamic and complex environments.

Table 3.9: Comparation between Fuzzy MPPT & ANN MPPT at different hot side temperature with load resistance of 60 ohm. Table 3.10 shows the Comparison of Conventional MPPT Methods, Fuzzy Logic, and Artificial Neural Networks (ANN) for TEG Optimization. Conventional methods lack adaptability and struggle with nonlinearities in TEG systems, making them less effective in dynamic environments. Fuzzy Logic offers better adaptability and precision by handling uncertainties with rule-based control, making it suitable for moderately complex scenarios. ANN excels in managing complex nonlinear systems and dynamic conditions due to its ability to learn and adapt, but it requires significant training and

computational resources. While conventional methods are simple, they fall short in energy efficiency and robustness. Fuzzy Logic and ANN provide superior performance, with ANN being the best choice for highly dynamic and complex systems.

3.12 CONCLUSIONS

An autonomous fuzzy logic system It is suggested in this chapter that TEG energy harvesting devices use the MPPT method. The MPP reference voltage is based on the feed-forward TEG OCV model, and the system uses it. There is no need to measure current or disturb power when using the proposed MPPT technique; it is autonomous. Further, it doesn't require source disconnection to accurately track any TEG system's MPP, which maximizes energy harvesting irrespective of temperature or load conditions. The results, which indicate a considerable decrease in output voltage variations, demonstrate the efficacy of the proposed combination. In this study, we show that the highest power point in a TEG-based generation circuit can be tracked using an ANN methodology. The SEPIC converter is able to regulate the load conditions for TEG-generated electricity while still maintaining an adequate yield. In spite of fluctuations in ambient temperature, neural networks can reliably pinpoint the precise moment when power is at its peak. Since neural networks provide superior dynamic performance over other methods for tracking maximum power points in TEG, they are used for tracking these points. A maximum PowerPoint is also monitored by the SEPIC converter. Power conditioning system control methods have been demonstrated to be effective, and mode transitions and MPP tracking have been shown to be satisfactory.

CHAPTER -4

TEG THERMO -ELECTRIC ANALYSIS WITH CFD

4.1 INTRODUCTION

Renewable energy sources continue to expand, resulting in new research criteria. Pollution and climate change have raised energy costs, and so are electricity rates. TEGs convert thermal energy into electrical current via the Seebeck effect. Silicon, polymers, and ceramic substrates allow for their creation without the use of any harmful materials, moving parts, or mechanical support. TEGs are not only position-independent and have extended operational lifetimes, but they are also easy to integrate into flexible and heavy devices. A TEG hybrid module connected to a single-phase inverter is shown in a three-dimensional transient model. The performance of the TEG system was evaluated using the following variables: ambient temperature, intensity of solar radiation, and velocity of emission gas. Utilising Ansys 2020R1, a numerical model was created that incorporates Thomson's, Seebeck's, and Joule's heat. Also examined was the overall electrical system's efficiency. By utilising a heat transfer surface and fan-assisted air movement, the passive heat sink significantly reduced electrical power consumption. Applying a TEG system to mimic a single-phase inverter allows one to acquire real-time data about power characteristics. Better co-design of a workable TEG-inverter hybrid system may be possible as a result of these conclusions.

4.2 METHODOLOGY AND MATERIALS

One-dimensional analytical models could be used as a quick method of analysing the overall performance shift of energy systems brought on by TEG. The most important analysis tools would be a sophisticated CFD model, TEG model, and multidimensional integration. For this purpose, a multidimensional TEG model has been implemented in FLUENT, allowing for the numerical solution of nonlinear thermoelectric equations. This allows the TEG model to communicate with the several fluid flow and combustion sub models in FLUENT as if they were an integral part of a single system.

Transient thermal and CFD analysis utilising ANSYS computational tool was used to examine the generative thermal effects of a chamber made of stainless steel with a connected outlet and copper TEGs.

An approximation of Re 10, 100, and 1000 W/mm2 K1 is provided for natural air convection, forced air convection, and n in the convection heat transfer coefficients. Flue gas inlet temperatures of 373.15, 573.15, and 773.15 K were considered. Mathematical solutions for fluid flow and heat transfer are presented, along with a brief summary of the governing equations. The answer relies on the conservation of momentum, mass, and energy. Given below are the CFD computational equations:

Mass conservation is expressed by formula1 in the equation

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \qquad (1)$$

In formula2, momentum changes at a rate of change

$$\frac{\partial}{\partial x_i}(\rho u_i u_j) = \frac{\partial}{\partial x_i}\left(\mu \frac{\partial u_j}{\partial x_i}\right) - \frac{\partial p}{\partial x_j} \qquad (2)$$

The law of energy equation in formula3

$$\frac{\partial}{\partial x_i}(\rho u_i T) = \frac{\partial}{\partial x_i}\left(\frac{K}{C_p}\frac{\partial u_j}{\partial x_i}\right) \qquad (3)$$

Boundary conditions at the inlet include temperature and velocity, while at the outflow, mass and energy conservation are paramount. At all times, the pressure at the outlet is 1 atm. The no-slip limit is applied to the channel walls. If the channel walls are adiabatic, then when they come into touch with the TEM, they must be able to transfer heat evenly between the two surfaces. The equation for the Seebeck effect is given by Formula 4.

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} - \left[\frac{\frac{s^2 \Delta T^2}{4R^2}}{\forall K}\right] = 0 \qquad (4)$$

Formula 5 is an adaptation of the original modulus-volume-heat equation.

$$\frac{d^2 T}{dx^2} + \frac{g}{K} = 0 \qquad (5)$$

Formula 6 represents the temperature distribution from the module to the TEG.

$$T(x) = -\frac{g}{2K}x^2 + c_1 x + c_2 \qquad (6)$$

Formula 7 is the efficiency equation including heat transport.

$$\eta(\%) = \frac{P}{Q_H} \times 100 = \frac{\dot{q}_H - \dot{q}_L}{\dot{q}_H} \times 100 \qquad (7)$$

the output power, the heat flux, and the heat flow rate at the hot side surface are all represented by QH and q̇, respectively.

The impact of the Reynolds number, as illustrated in equation 8,

$$\mathrm{Re} = \frac{\rho \mathrm{VD}}{\mu} \qquad (8)$$

at what location does the flue gas density lie? Here, V stands for its velocity, D for its hydraulic diameter, and for the dynamic viscosity. Various convection heat transfer coefficients are provided, with approximate values of 10,000, 30,000, 80,000, and 80,000 Wm^2 K1 for natural air convection, forced air conduction, oil forced convection, and water forced convection, respectively.

Material selection for the chamber's flow duct and TEG was based on thermal conductivity and heat transfer qualities of materials free of rust in order to prevent the accumulation of excess heat at the TEG. Properties of TEG materials and duct materials along with dimensions has been given in the table 4.1.

Table 4.1: Flow duct and TEG materials

S. No	Material	Length	Width	Height	Thermal conductivity at elevated temperatures
Fluid chamber	SS316	180mm	50mm	30mm	16.3 W/m-K
TEG	Copper	40mm	40mm	3.7mm	385 W/m-K

4.3 STRUCTURAL STEEL:

Steel used in building is known as structural steel. To be used as a structural component in buildings, roads, bridges, etc., it is made to have a high strength-to-weight ratio (also known as specific strength) and low cost. Thermal properties of structural steel, bismuth and aluminium allay taken from ANSYS library as shown in tables 4.2,4.3 and 4.4.

Table 4.2: Properties assignment of structural steel

Structural Steel

Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1

Density	7.85e-06 kg/mm³
Structural	
Thermal	
Isotropic Thermal Conductivity	0.0605 W/mm·°C
Specific Heat Constant Pressure	4.34e+05 mJ/kg·°C
Electric	
Isotropic Resistivity	0.00017 ohm·mm
Magnetic	
Isotropic Relative Permeability	10000

PCB Laminate: Printed circuit boards (PCBs) can be made with a material called laminate. Additionally, it is constructed from alternating layers of materials that are usually fused together using heat and pressure.

Table 4.3: Properties assignment of structural steel

PCB laminate, Bismaleimide-Triazine

Bismaleimide-Triazine, PCB laminate

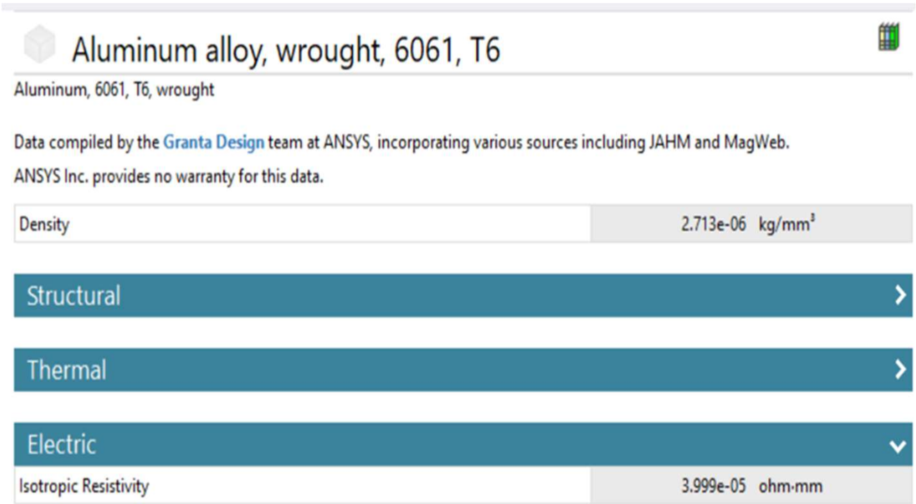
Data compiled by the Granta Design team at ANSYS, incorporating various sources including JAHM and MagWeb.
ANSYS Inc. provides no warranty for this data.

Density	1.85e-06 kg/mm³
Structural	
Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	24050 MPa
Poisson's Ratio	0.182
Bulk Modulus	12605 MPa
Shear Modulus	10173 MPa
Isotropic Secant Coefficient of Thermal Expansion	1.53e-05 1/°C
Tensile Ultimate Strength	321 MPa
Tensile Yield Strength	321 MPa
Thermal	
Isotropic Thermal Conductivity	0.0005 W/mm·°C

4.4 ALUMINUM ALLOY:

An alloy in which aluminium (Al) is the most abundant constituent is known as an aluminium alloy (or aluminium alloy; see spelling variations). Nickel, zinc, copper, manganese, silicon, tin, and magnesium are common elements in alloys. Casting alloys and wrought alloys are the two main types of alloys, with heat-treatable and non-heat-treatable subtypes within each of includes rolled plate, foils, and extrusions.

Table 4.4: Properties assignment of Aluminum at TEG



Aluminum alloy, wrought, 6061, T6

Aluminum, 6061, T6, wrought

Data compiled by the Granta Design team at ANSYS, incorporating various sources including JAHM and MagWeb.
ANSYS Inc. provides no warranty for this data.

Density	2.713e-06 kg/mm³

Structural

Thermal

Electric

Isotropic Resistivity	3.999e-05 ohm-mm

4.5 MODELLING OF TEG IN NX 12.0

In order to import a shell-type module into ANSYS CFD for further analysis, a box-type TEG placement model was developed in Siemens-PLM version 12.0 for the dimensions 3d output. The figure shows where the TEG was linked to the heated material. To correct the body for the temperature environment, the export file option was used to convert the files to IGES. The dimensions of TEG duct shown in figure 4.1.

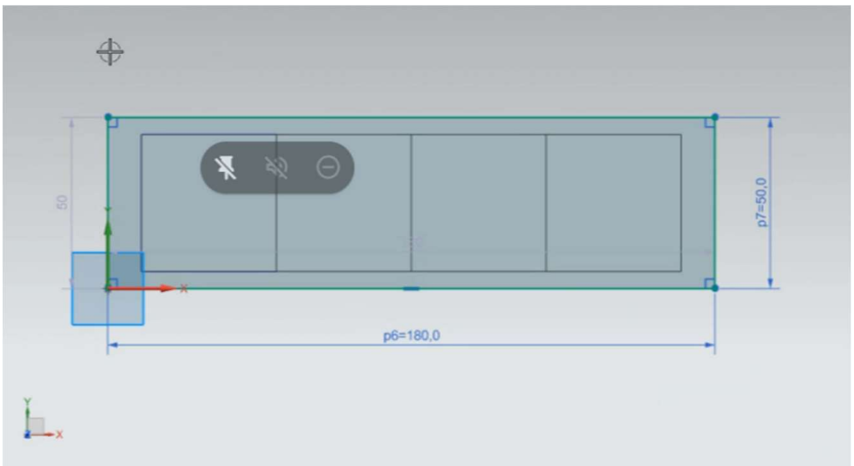


Figure 4.1: Base chamber with wall thickness 1.5mm

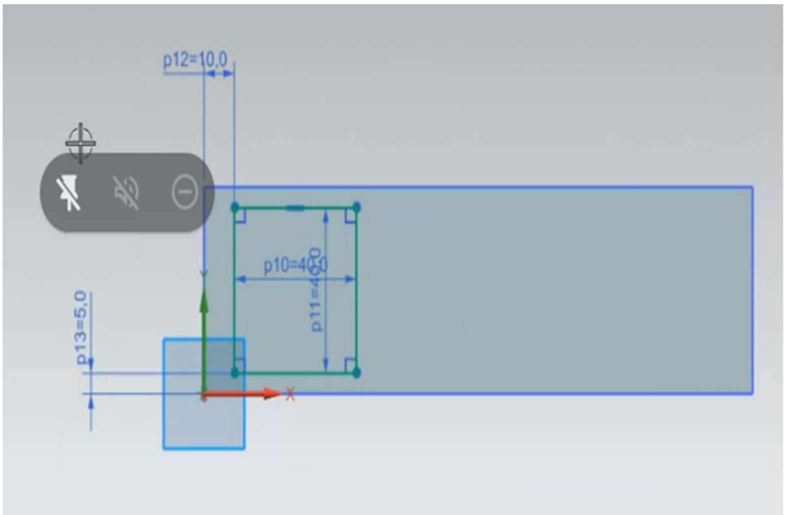


Figure 4.2: TEG Design dimensions

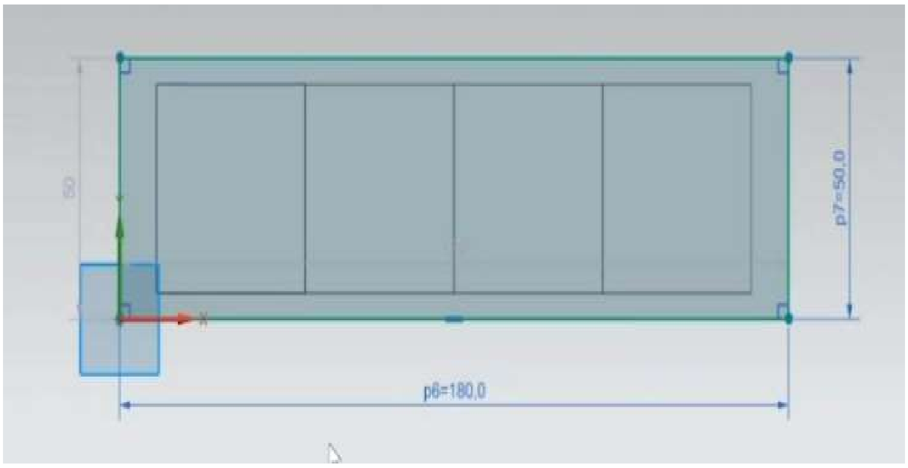


Figure 4.3: TEG placing on chamber

The dimensions of TEG and the outer dimensions of the duct with 3D model has been shown in Figures 4.2,4.3, 4.4 respectively.

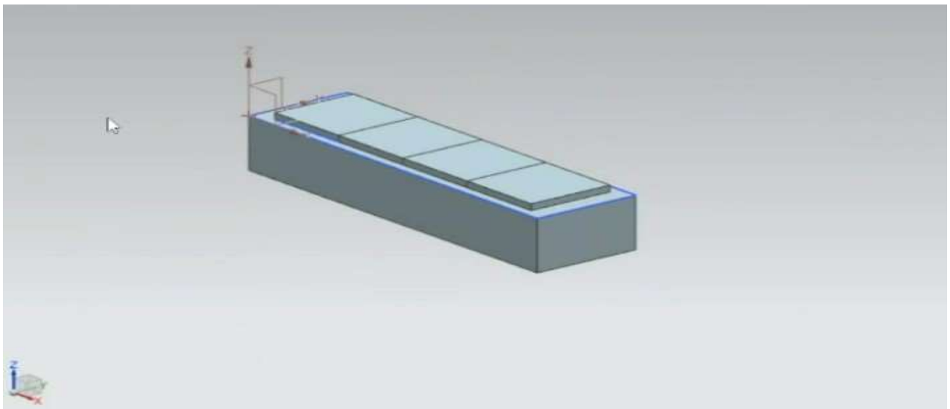


Figure 4.4: Exclude chamber & TEG

The TEG model was developed with the car's integrated fuel-burning emission system in mind. To reduce environmental impact from thermal losses caused by emission gases, four TEGs of identical diameters are joined side by side. Attaching TEGs to side pipes to simulate the See-beck effect in emission modelling has become standard practise for shell tubes.

4.6 TRANSIENT THERMAL ANALYSIS GEOMETRY IN ANSYS

Transient thermal analyses of gaseous flows leading to sudden cooling to ambient temperatures are extremely helpful for heat transfer studies, such as thermo-electric combinations. Using thermal contours, we can identify exactly where the majority of the heat is being deposited, and we examine the impact of air temperature on emission temperature convection studies in the current circumstance. The placement of TEG in a ANSYS geometry shown in figure 4.5with colour differention in mode simulation has been shown in figure 4.6.

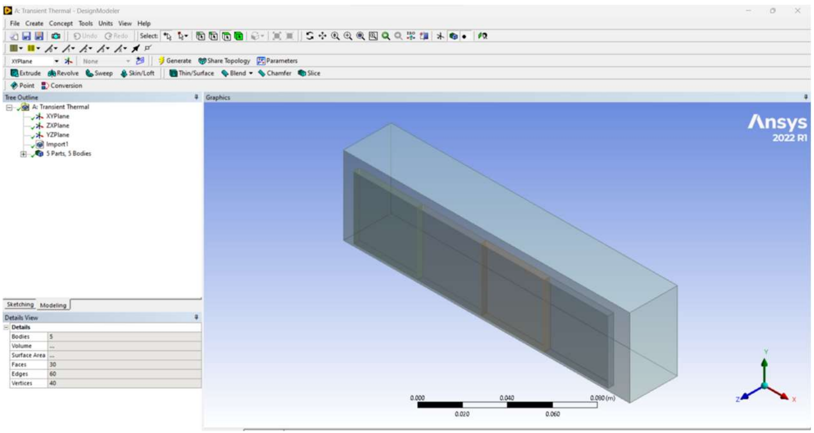


Figure 4.5: Geometry of TEG

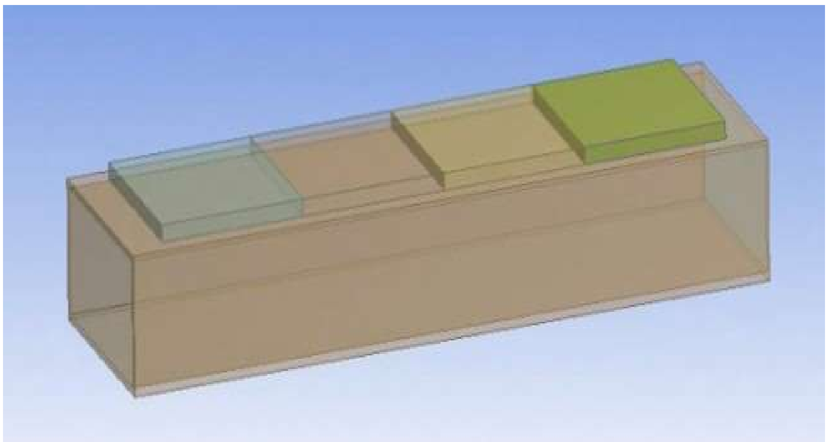


Figure 4.6: TEG Shell module

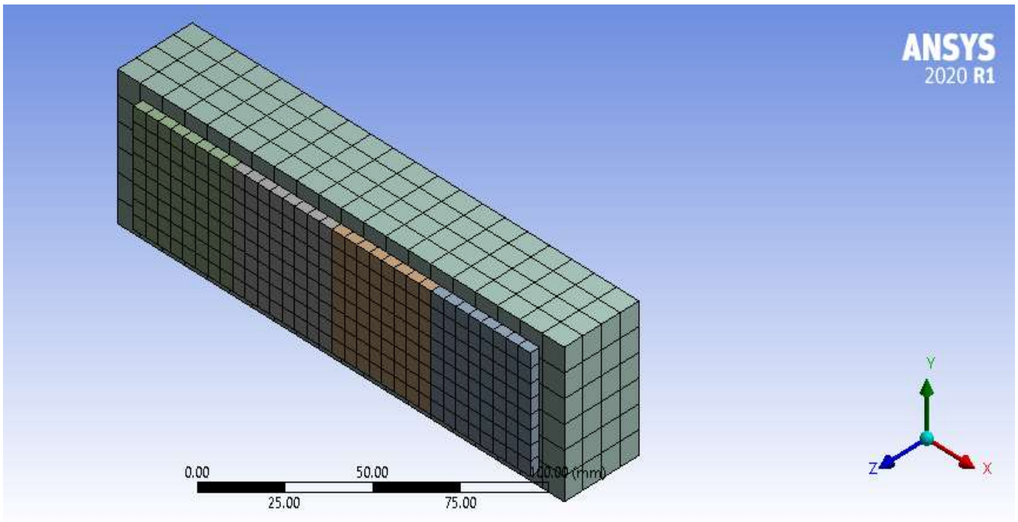


Figure 4.7: Meshing model

Table 4.5: Meshing statistics for TEG module

Details of "Mesh"	
Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	Mechanical
Element Order	Program Controlled
Element Size	Default
Sizing	
Quality	
Inflation	
Advanced	
Statistics	
Nodes	4777
Elements	736

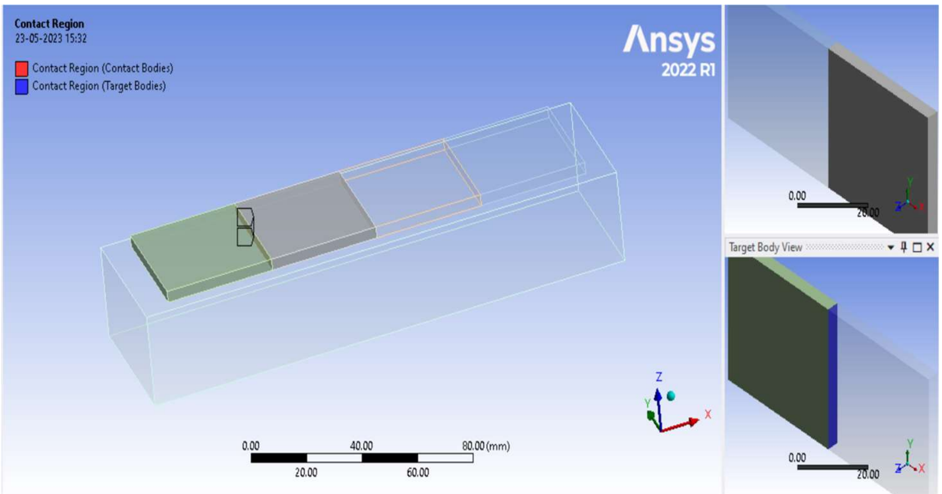


Figure 4.8: Connectivity contact regions

Figure 4.7 shows meshing in Ansys and Figure 4.8 shows interconnectivity between T EG and duct. The mesh values of the model given in the table 4.5.

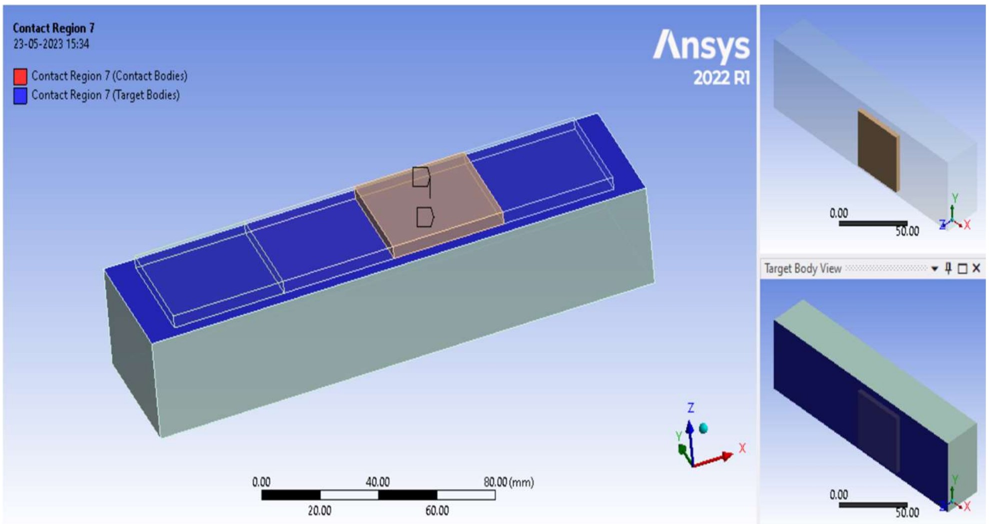


Figure 4.9: TEG Shell module attachments

Transient thermal conductivity analysis makes use of a finite element mesh that incorporates a tetra element to cover the whole object, with the fluid velocity and temperature faces selected from the tetra equilateral triangle (TEG). When calculating the contact region between the ambient temperature and the convection, both base and TEG connectivity were taken into account. You can see the interconnection between TEG and TEG in figure 4.9. You can see the thermal-electrical interface in the Ansys layout in figure 4.10.

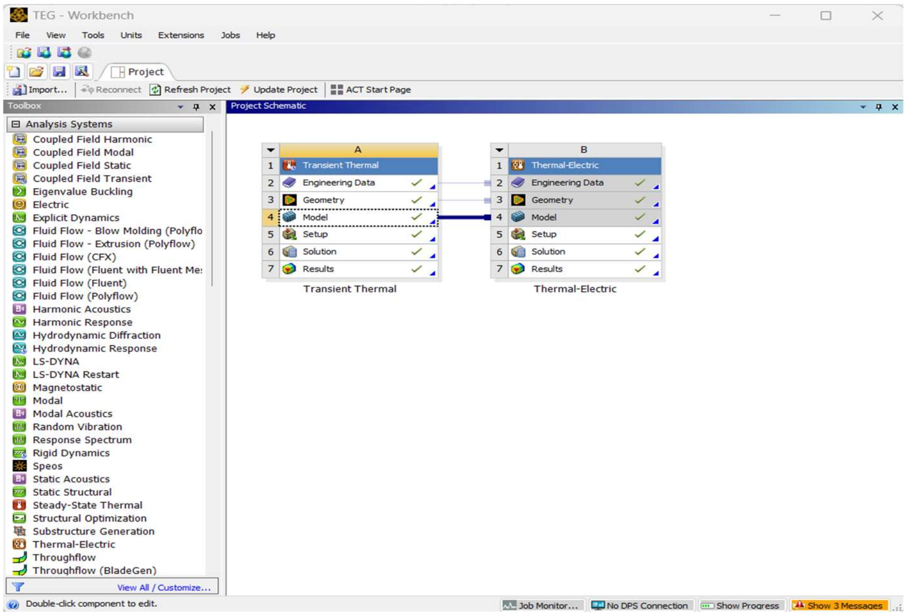


Figure 4.10: Method of Power Generation analysis in Ansys

Ansys simulation of power generation under thermal electrical circumstances, as depicted in Figure 4.11.

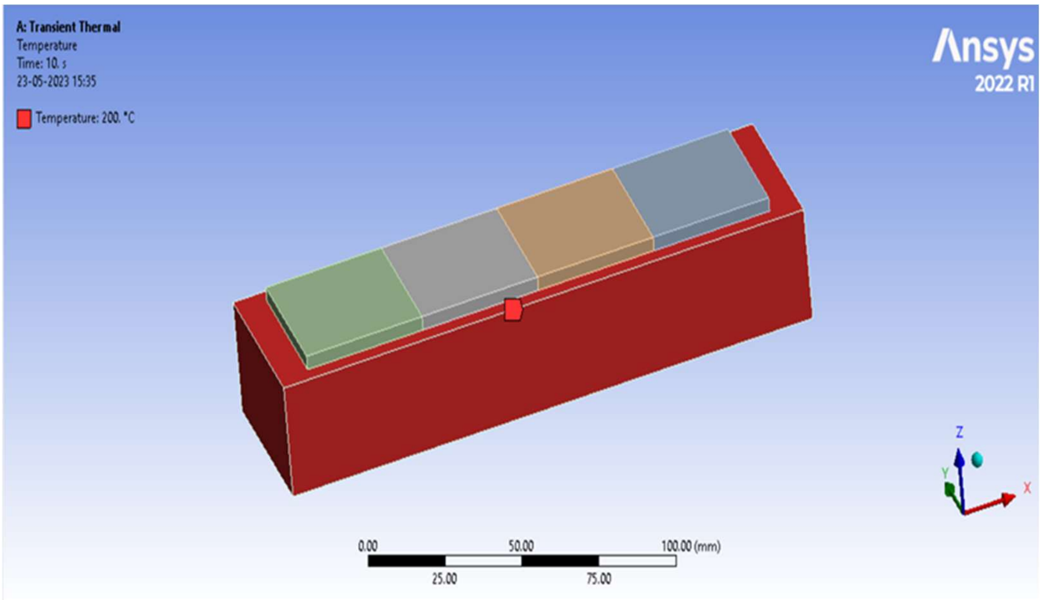


Figure 4.11: Initial temperature 200^{0}C

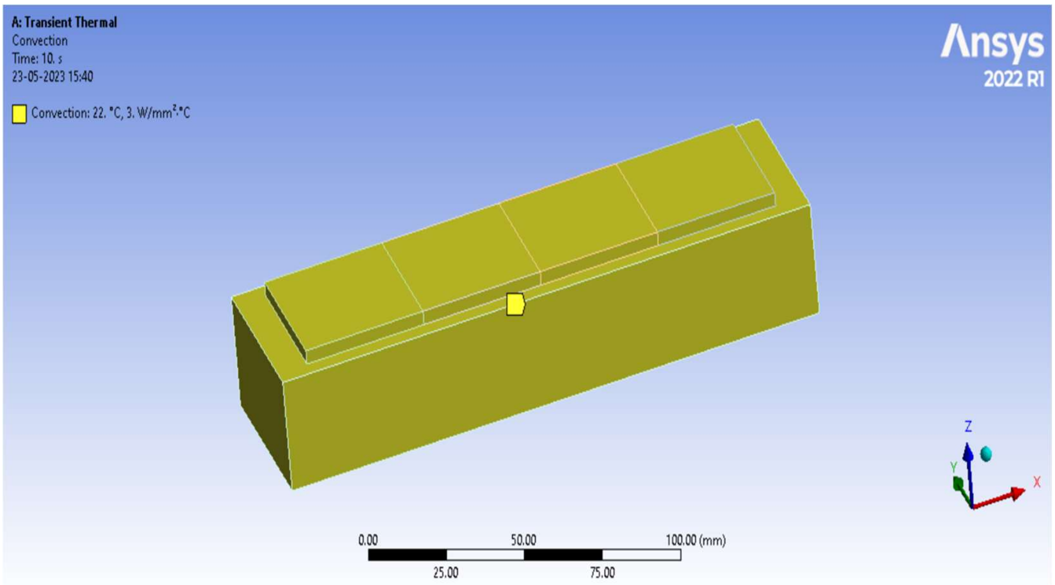


Figure 4.12: Temperature Assignment for convection

The convection of temperature including TEG with whole body has been shown in figure 4.12. For the selected temperature results has been shown in figures 4.13 & 4.14 .

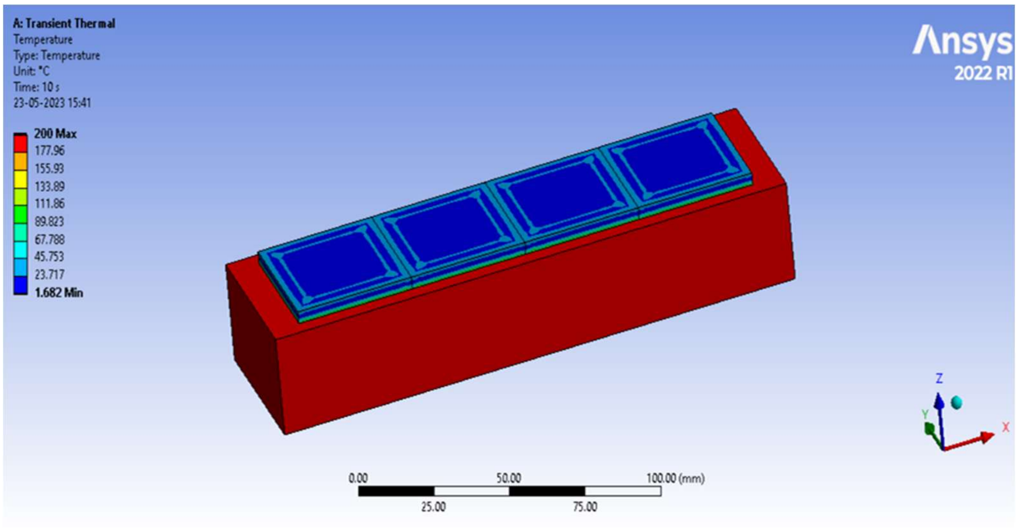


Figure 4.13: Temperature

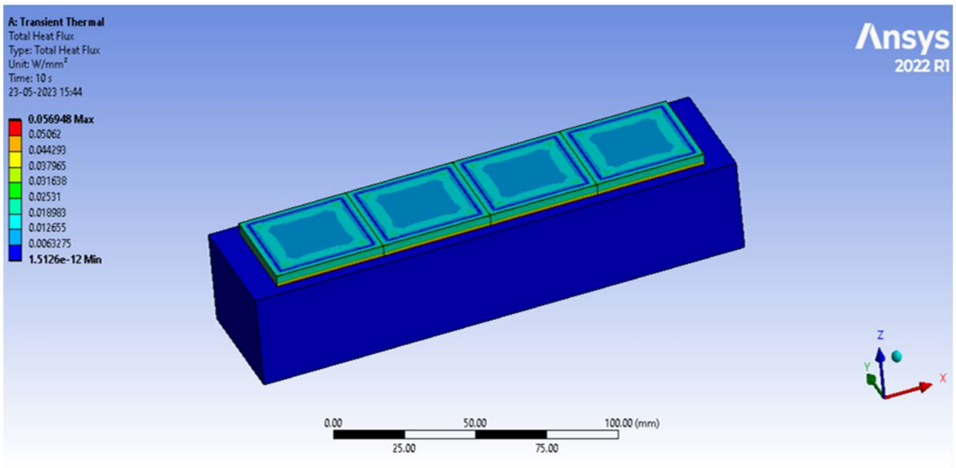


Figure 4.14: Total heat flux

4.7 TRANSIENT THERMAL ANALYSIS OF TEG AT 250^{0}C:

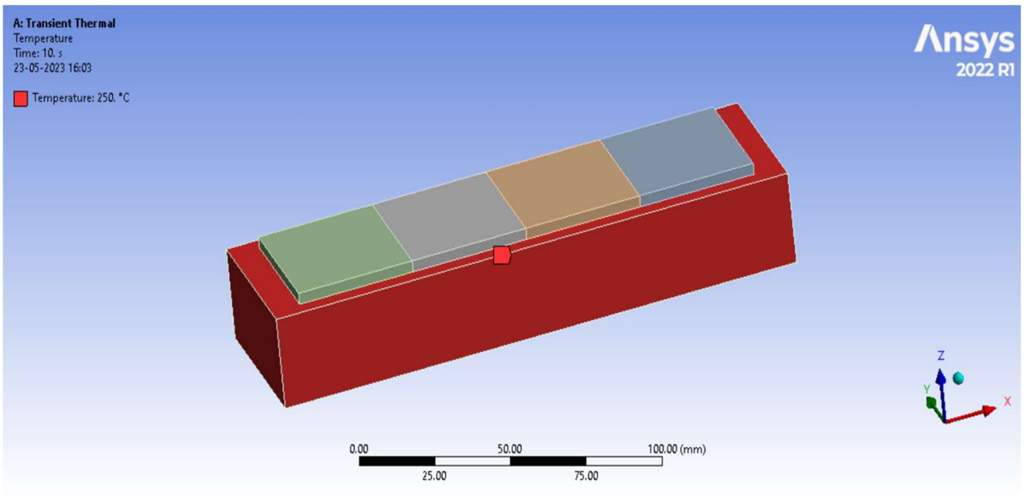


Figure 4.15: Initial temperature 250^{0}C

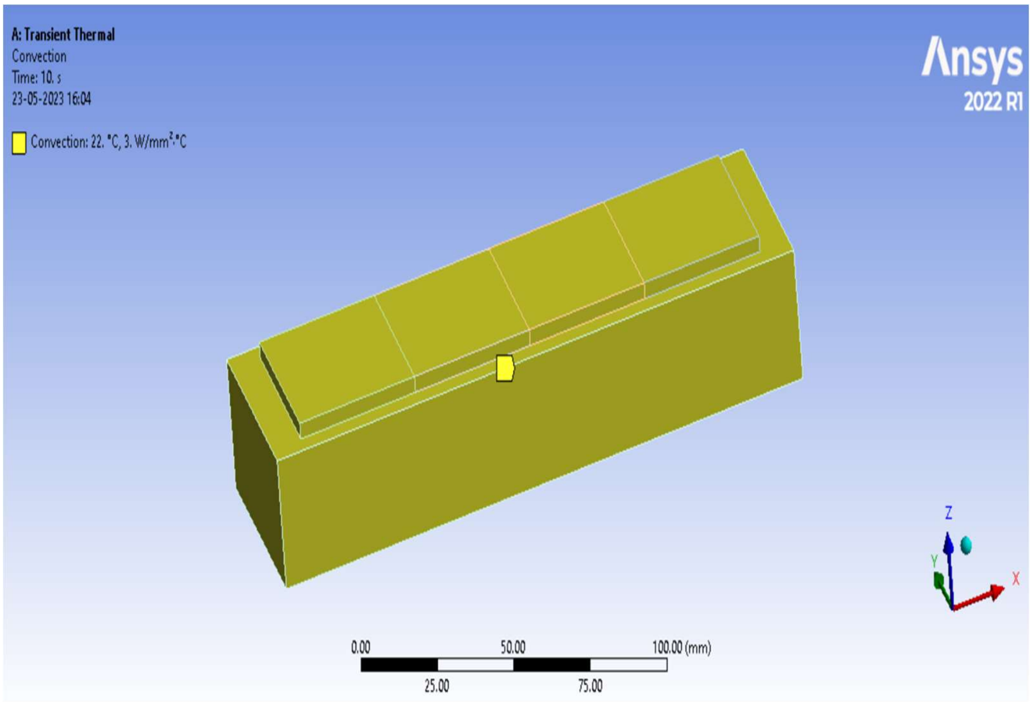


Figure 4.16: Temperature Assignment for convection

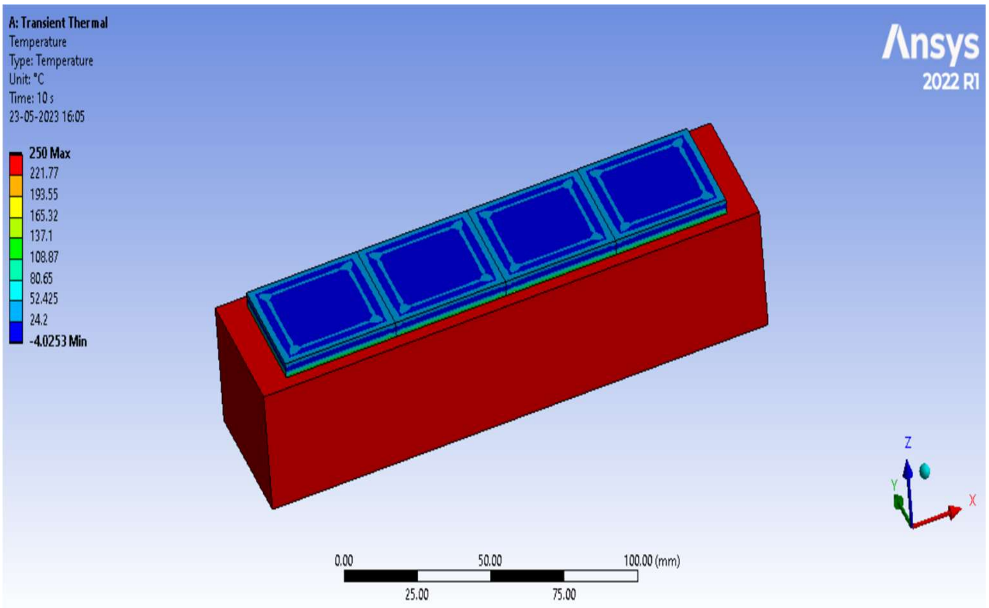


Figure 4.17: Temperature

The convection of temperature at 250^{0}C including TEG with whole body has been shown in figure 4.15. For the selected temperature results has been shown in figures 4.16, 4.17 & 4.18.

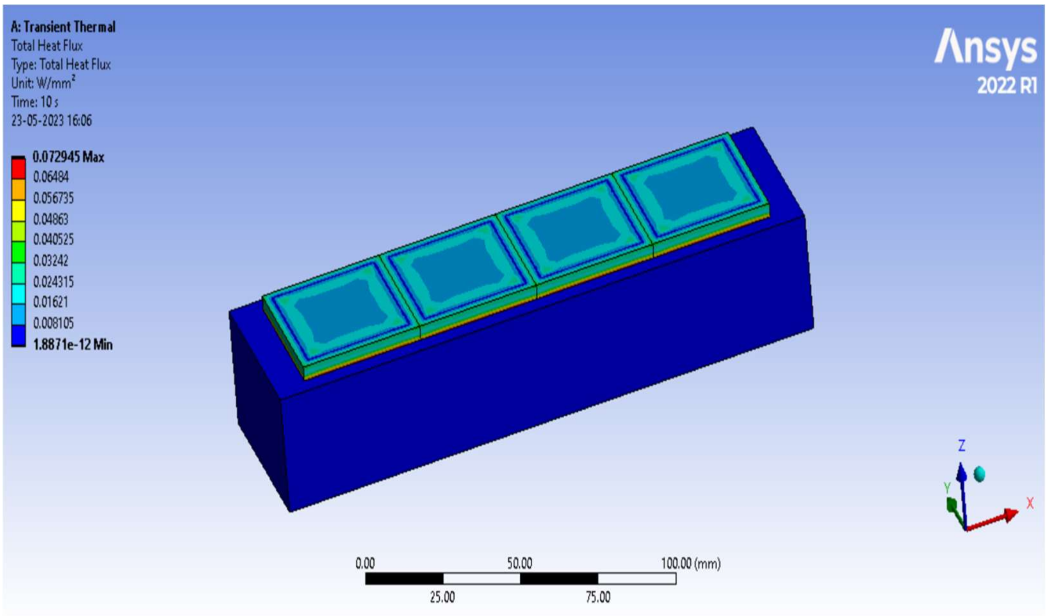


Figure 4.18: Heat flux

4.8 TRANSIENT THERMAL ANALYSIS OF TEG AT 300^{0}C:

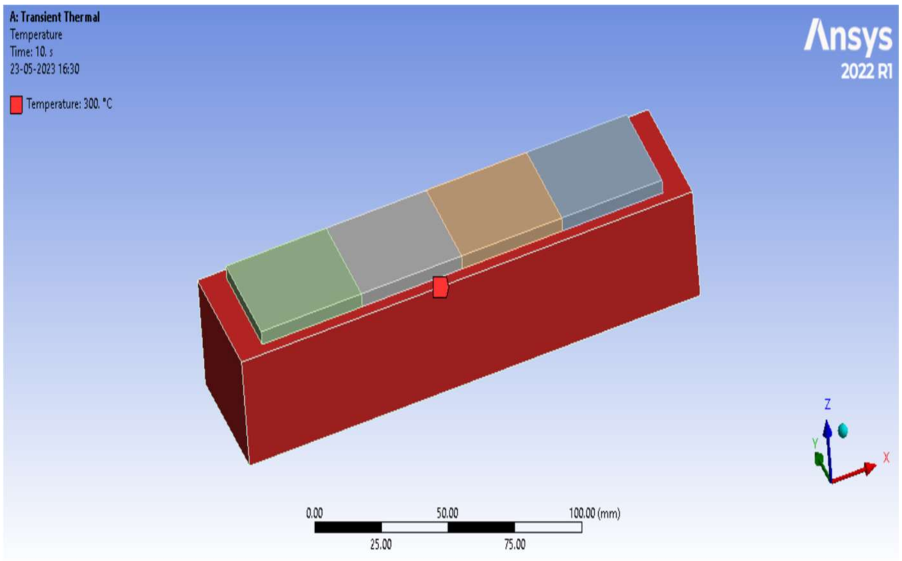


Figure 4.19: Initial temperature 300^{0}C

The convection of temperature at 300^{0}C including TEG with whole body has been shown in figure 4.19. For the selected temperature results has been shown in figures 4.20, 4.21 & 4.22.

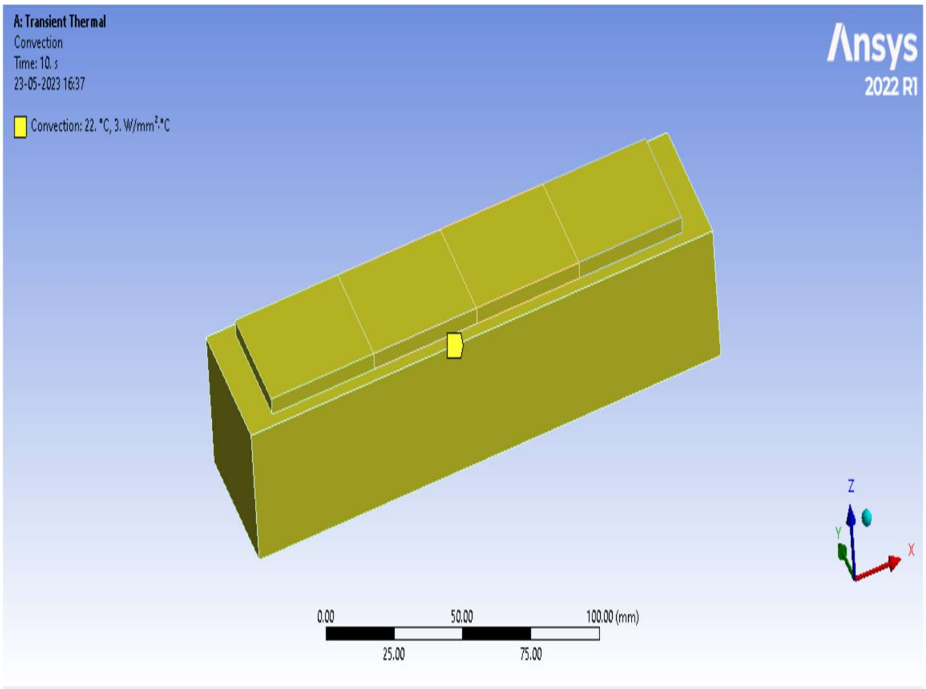


Figure 4.20: Temperature Assignment for convection

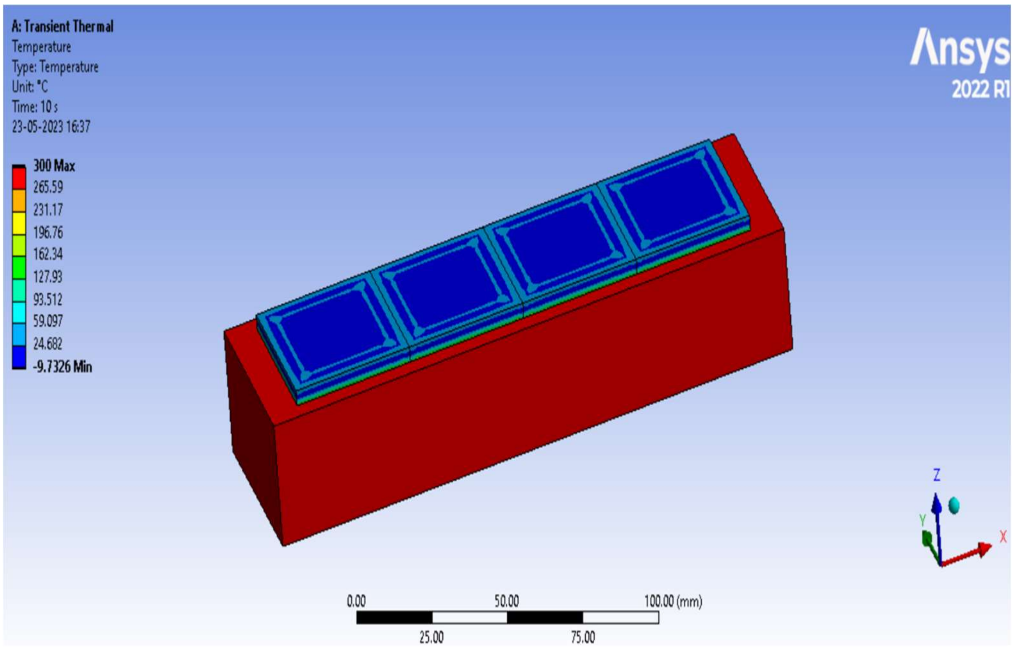


Figure 4.21: Temperature

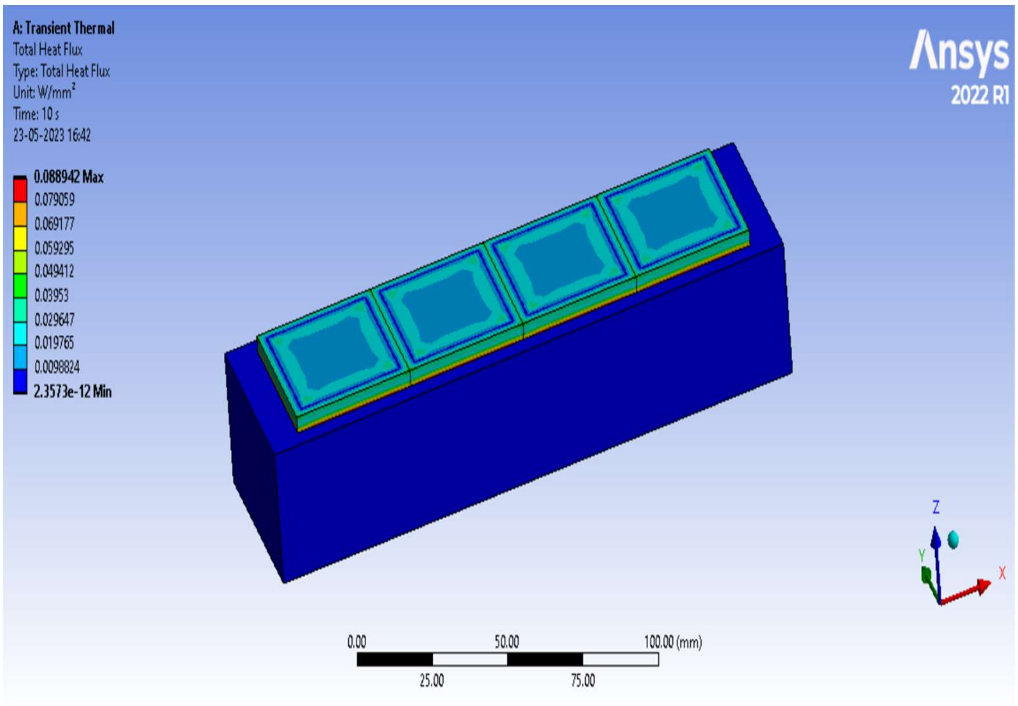


Figure 4.22: Heat flux

4.9 TRANSIENT THERMAL ANALYSIS OF TEG AT 350^{0}C:

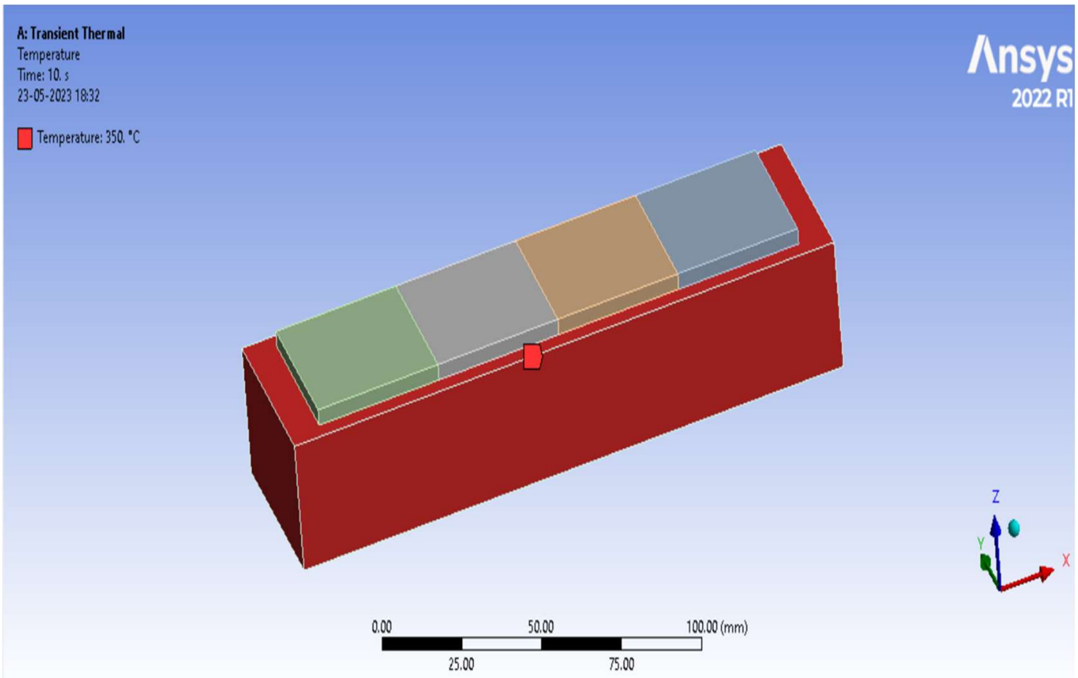


Figure 4.23: Initial temperature 350^{0}C

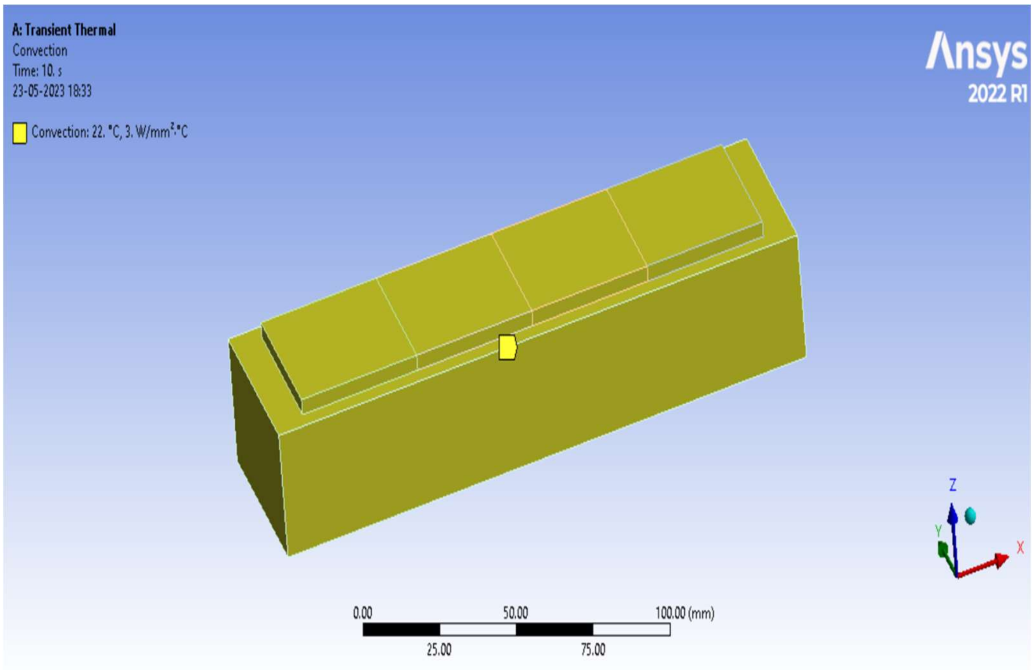


Figure 4.24: Temperature Assignment for convection

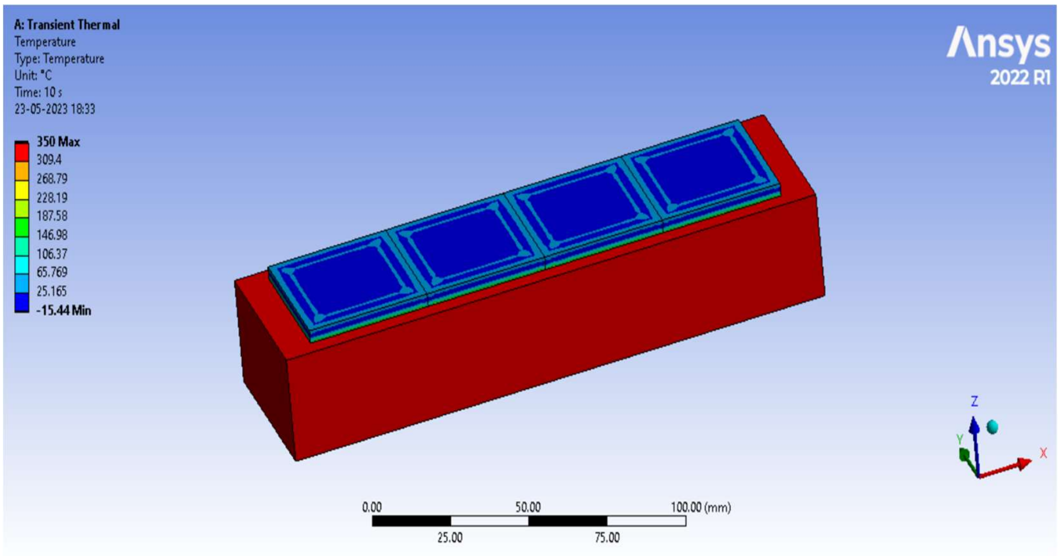


Figure 4.25: Temperature

The convection of temperature at 350^0C including TEG with whole body has been shown in figure 4.23. For the selected temperature results has been shown in figures 4.24, 4.25 & 4.26.

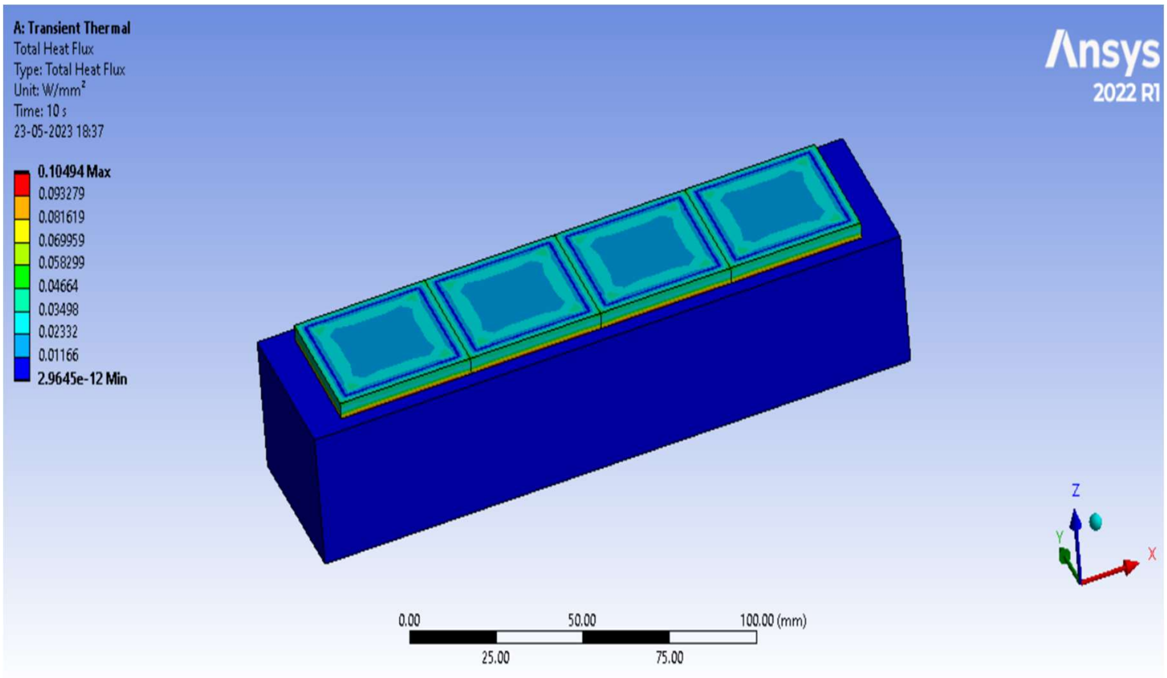


Figure 4.26: Heat flux

4.10 THERMOELECTRIC GENERATOR ANALYSIS

TEGs are constructed from different types of thermocouples using the Seebeck effect and wired in series for electricity but in thermal parallel for the best possible performance. Energy economy, no maintenance costs, and a long service life at temperatures as high as 200^{0}C, 250^{0}C, 300^{0}C, and 350^{0}C all contribute to TEGs' widespread adoption in a variety of applications.

In order to successfully harvest thermal energy, the thermoelectric generator (TEG) must function properly. In accordance with the See beck effect, a TEG can transform thermal energy into electrical power. This temperature differential is caused by the flow of charge carriers (electrons and holes) across the device's surface.

4.11 ANALYSIS OF THERMOELECTRIC GENERATOR PERFORMANCE AT 200^{0}C

Temperature assignment at 200^{0}C for power flow analysis shown in the figure 4.27 and convection shown in figure 4.28. The electrical voltage at TEG output with current density shown in the figures 4.29& 4.30 respectively. The total flux generated with temperature deposition also shown in figure 4.31.

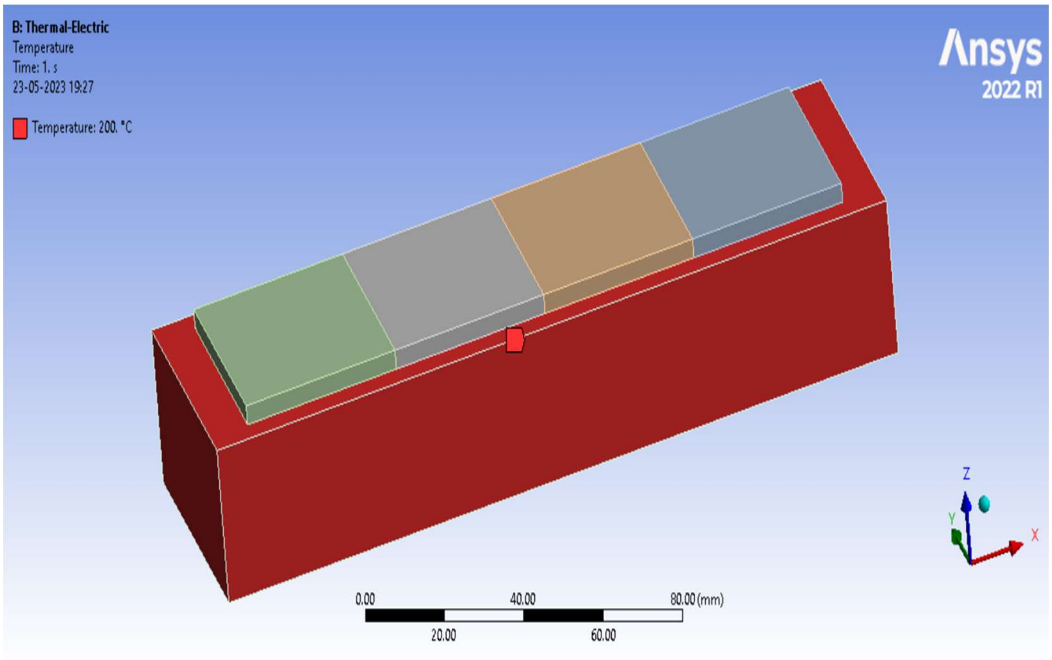


Figure 4.27: Temperature 200^{0}C

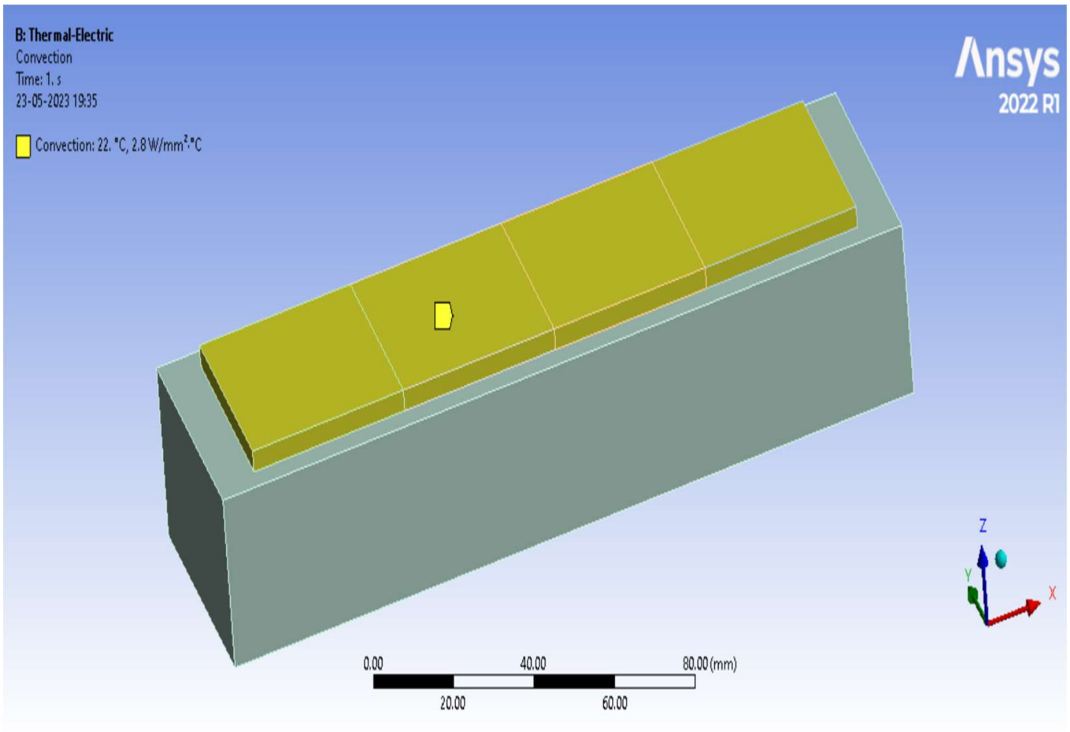


Figure 4.28: Temperature Assignment for convection

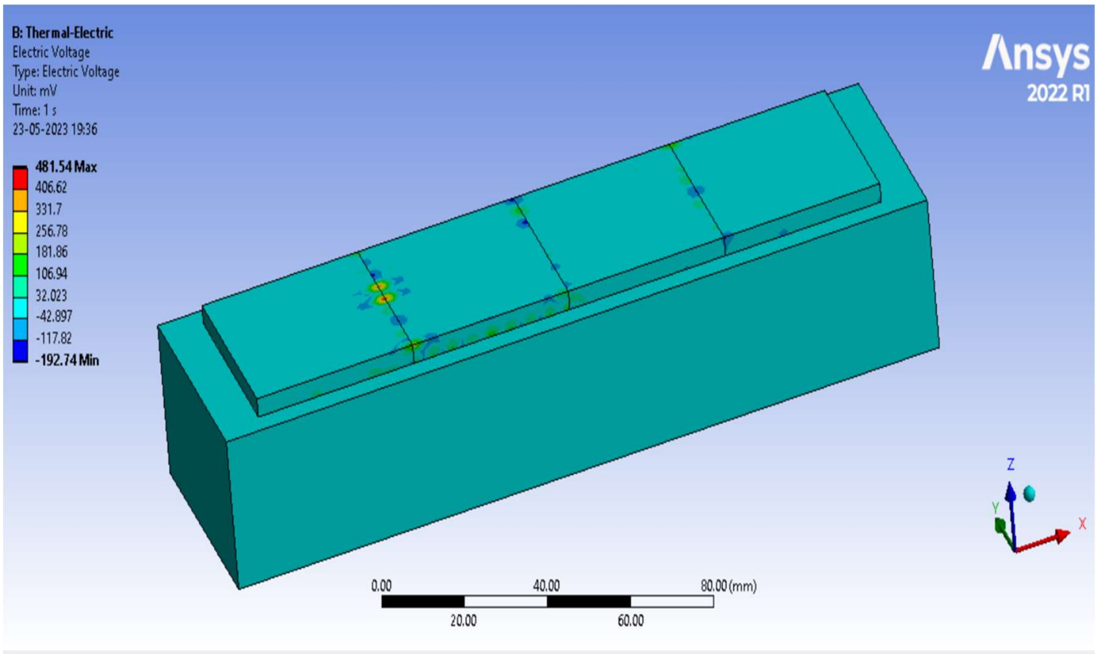


Figure 4.29: Electric voltage

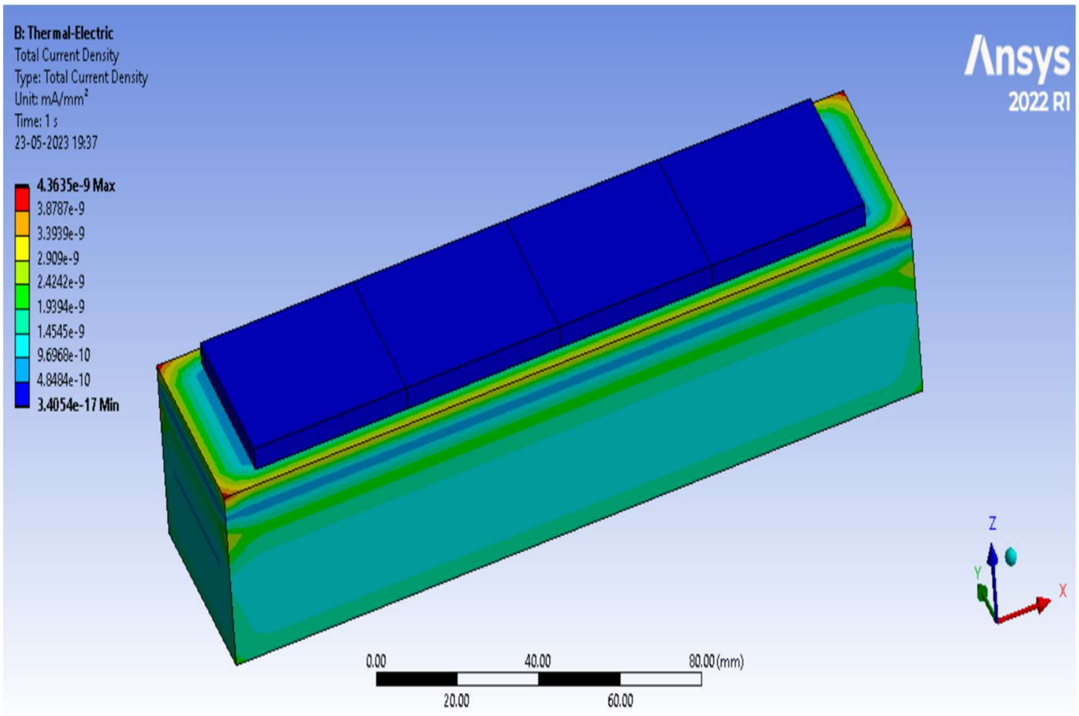


Figure 4.30: Current density

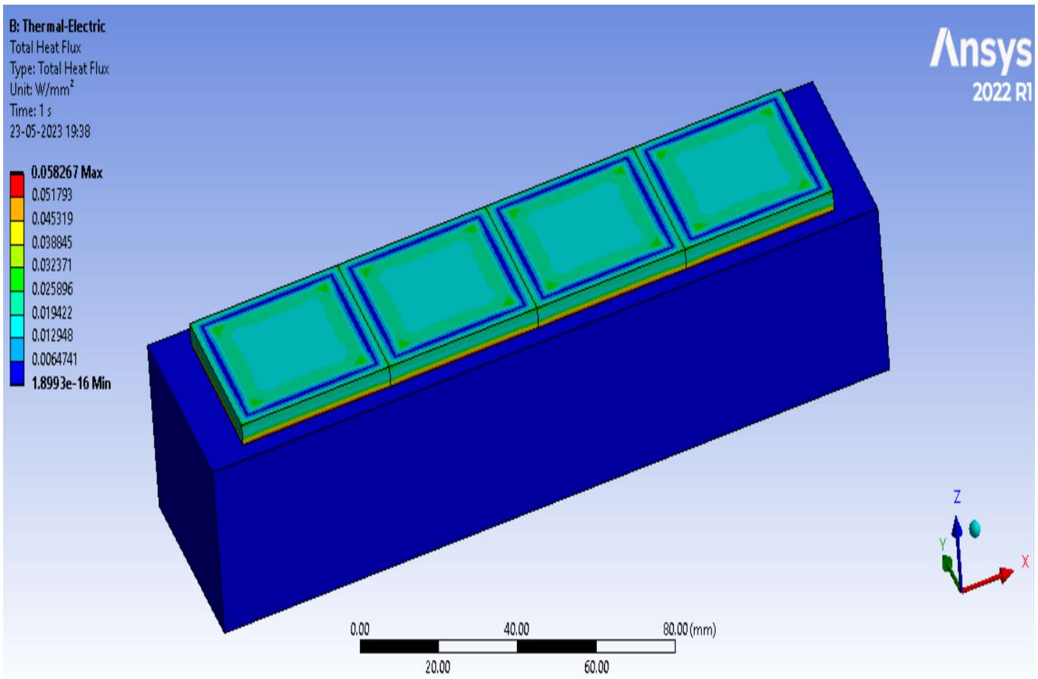


Figure 4.31: Total heat flux

4.12 ANALYSIS OF THERMOELECTRIC GENERATOR PERFORMANCE AT 250^{0}C

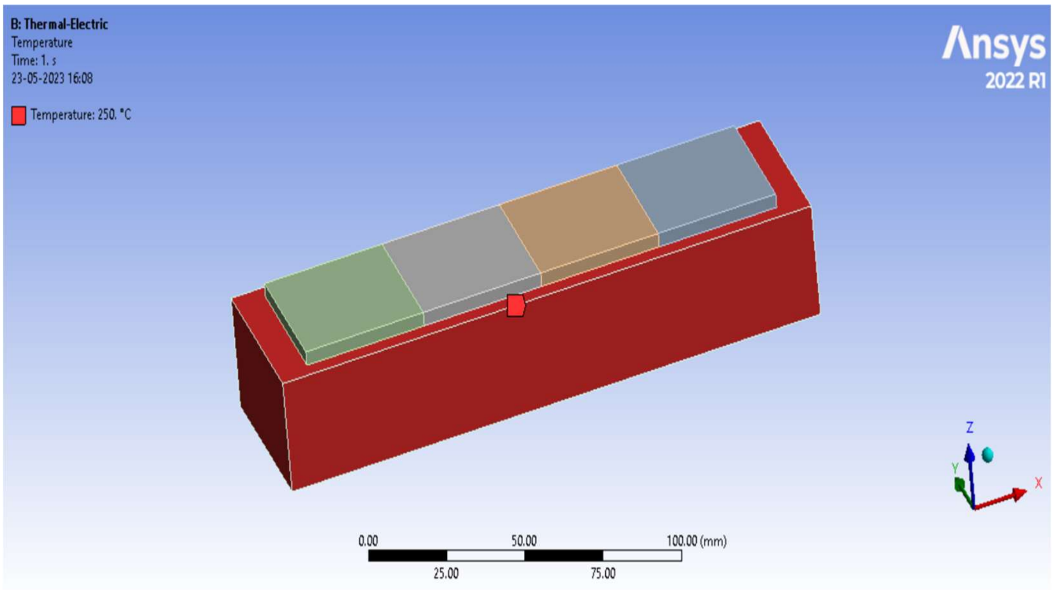


Figure 4.32: Temperature 250^{0}C

Temperature assignment at 250^{0}C for power flow analysis shown in the figure 4.32 and convection shown in figure 4.34. The electrical voltage at TEG output with current density shown in the figures 4.35& 4.36 respectively. The total flux generated with temperature deposition also shown in figure 4.37.

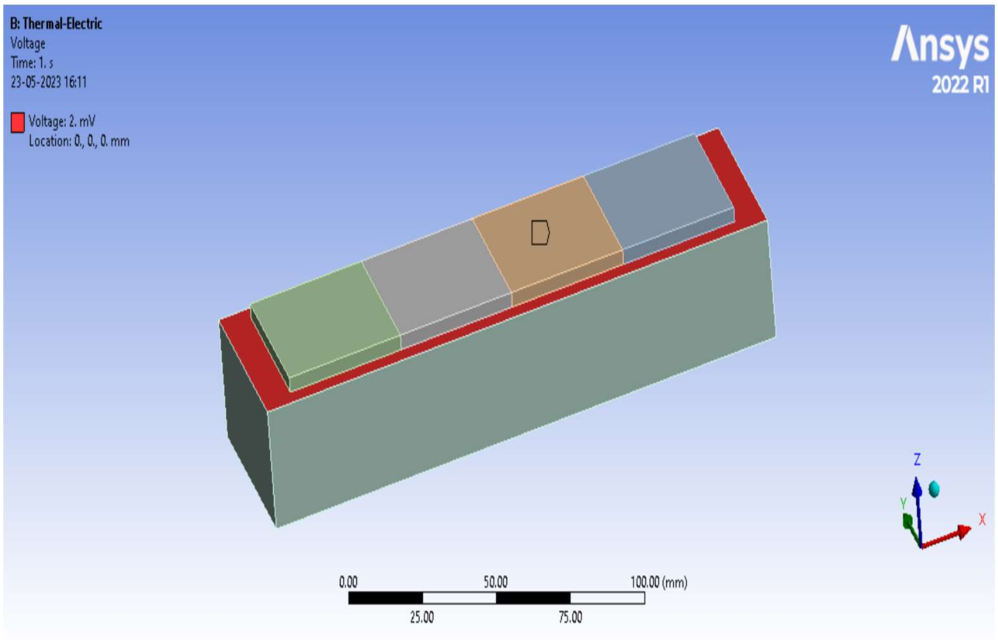


Figure 4.33: voltage 2mV

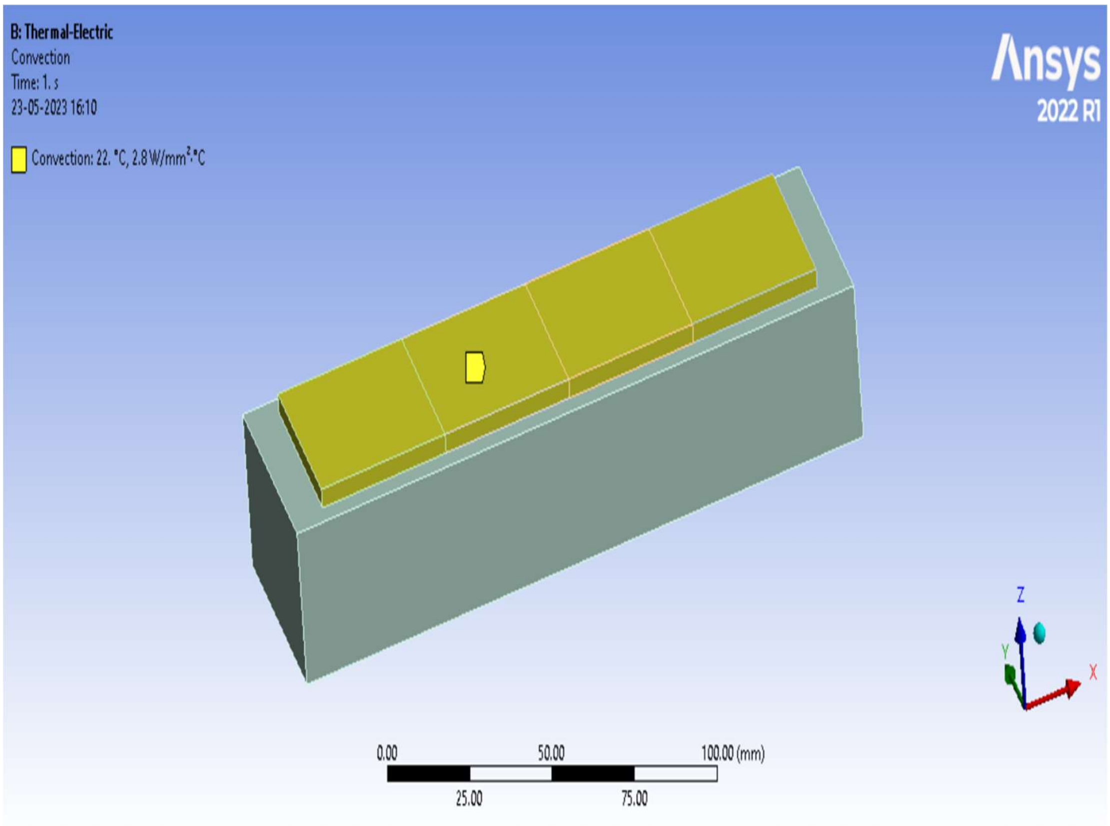


Figure 4.34: Temperature Assignment for convection

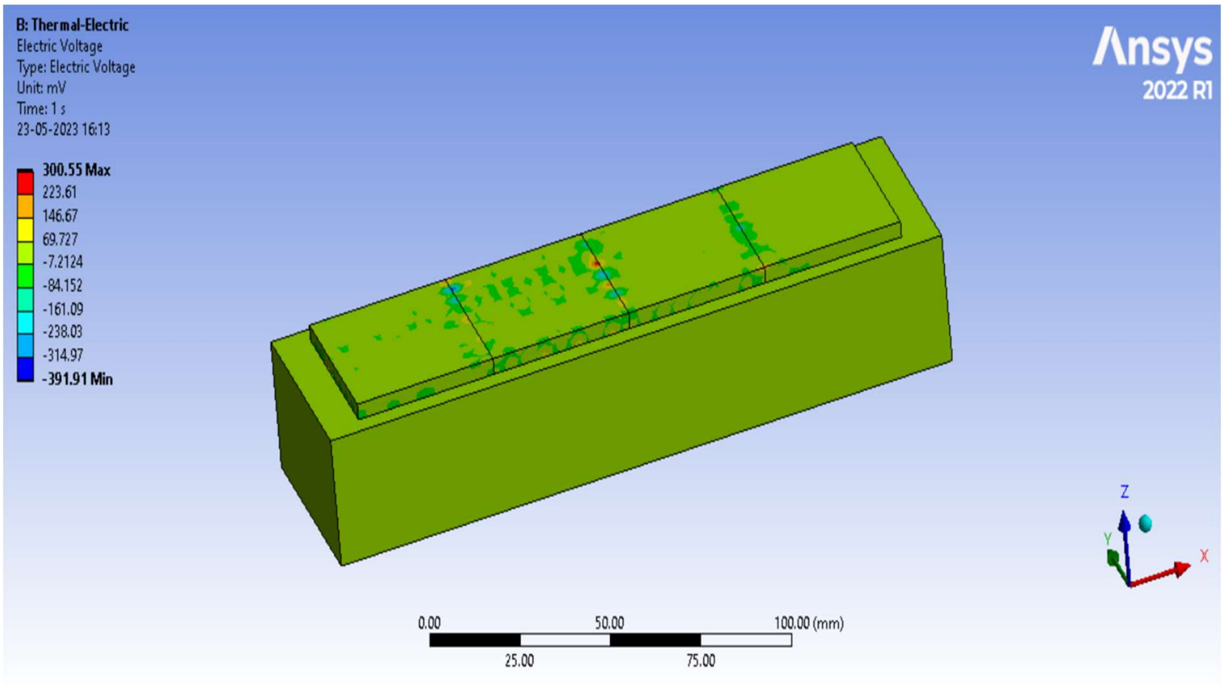


Figure 4.35: Electric voltage

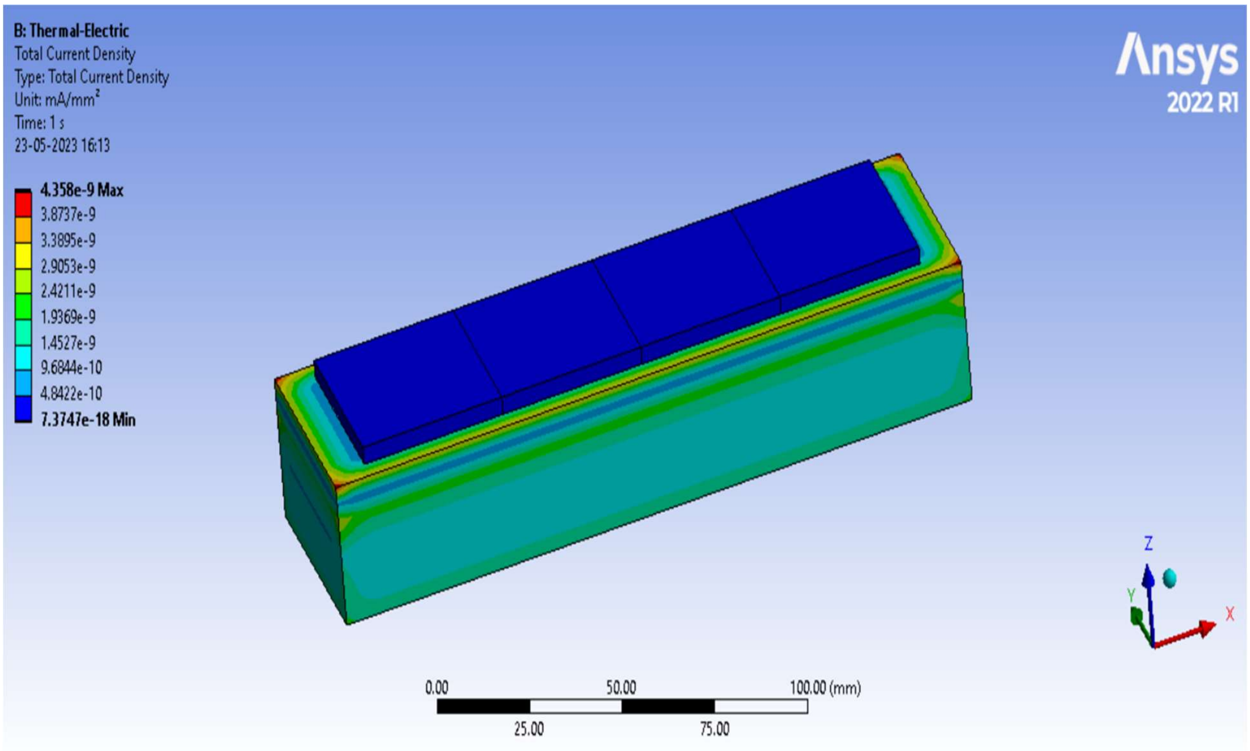


Figure 4.36: Current density

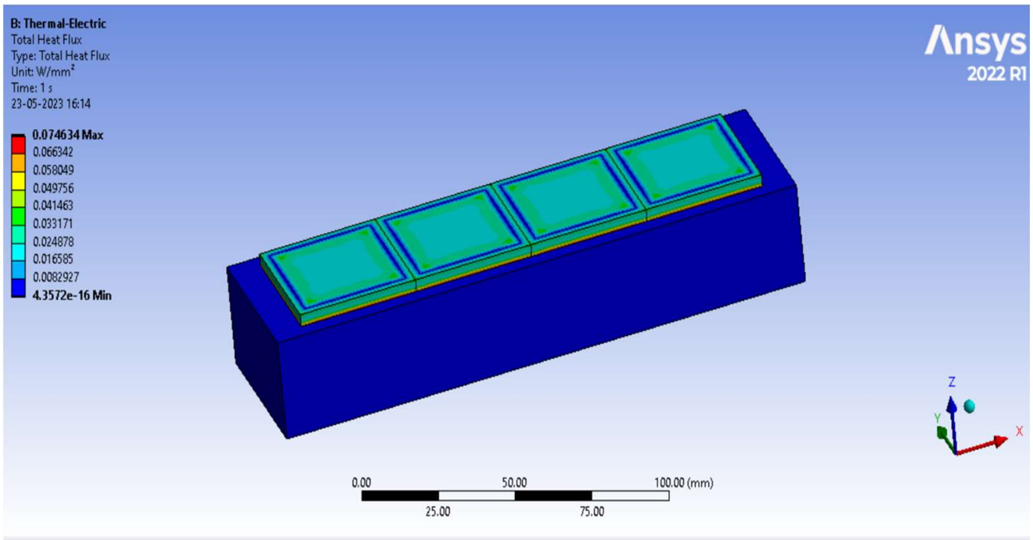


Figure 4.37: Heat Flux

4.13 ANALYSIS OF THERMOELECTRIC GENERATOR PERFORMANCE AT 300^{0}C

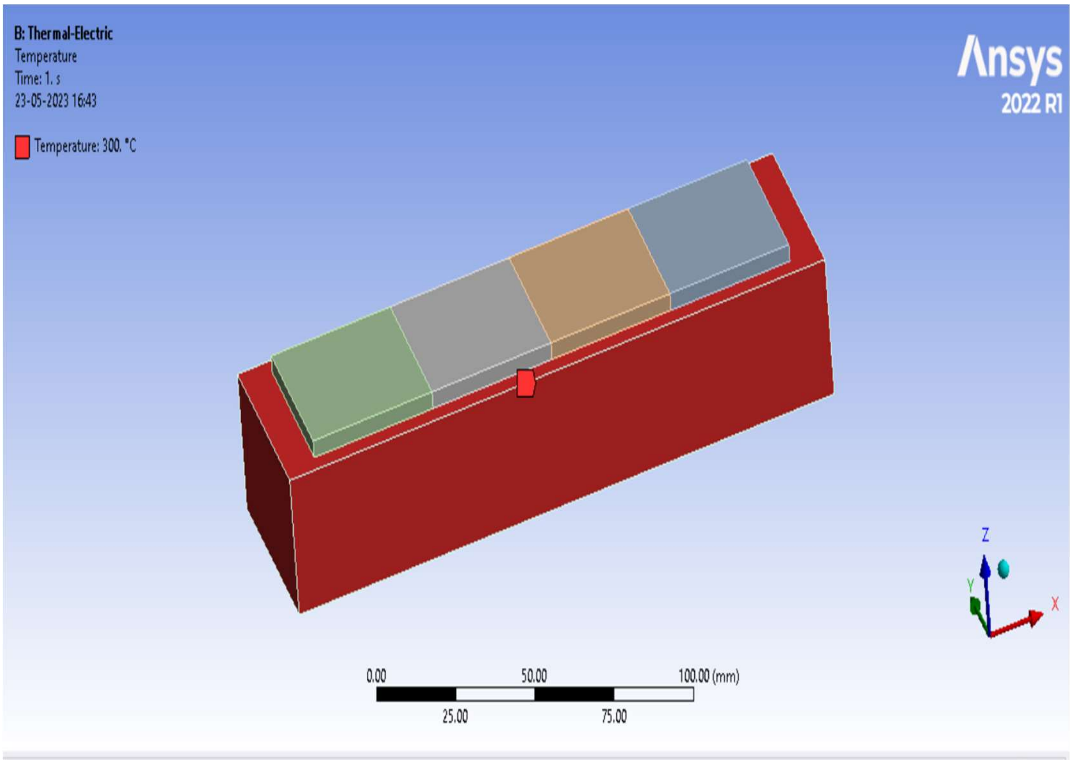


Figure 4.38: Temperature 300^{0}C

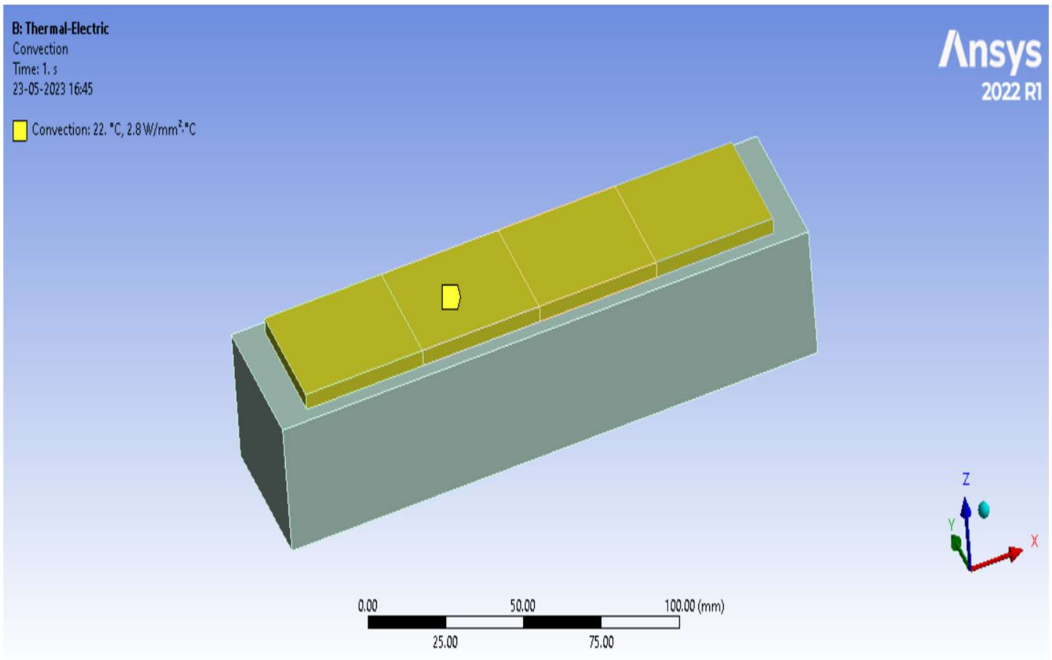


Figure 4.39: Temperature Assignment for convection

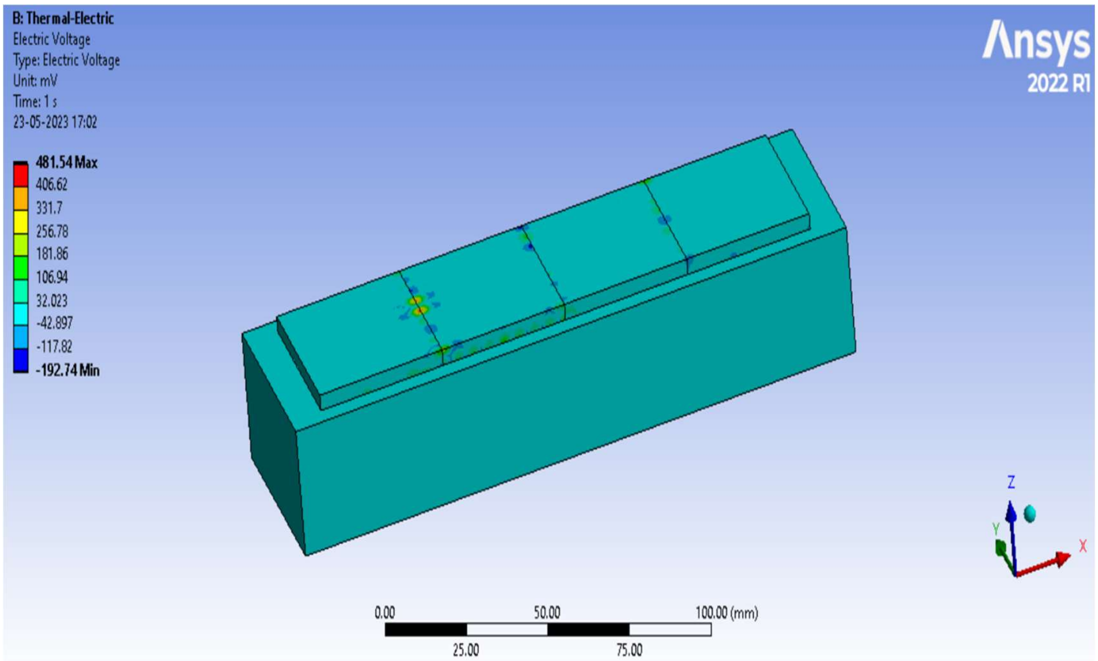


Figure 4.40: Electric voltage

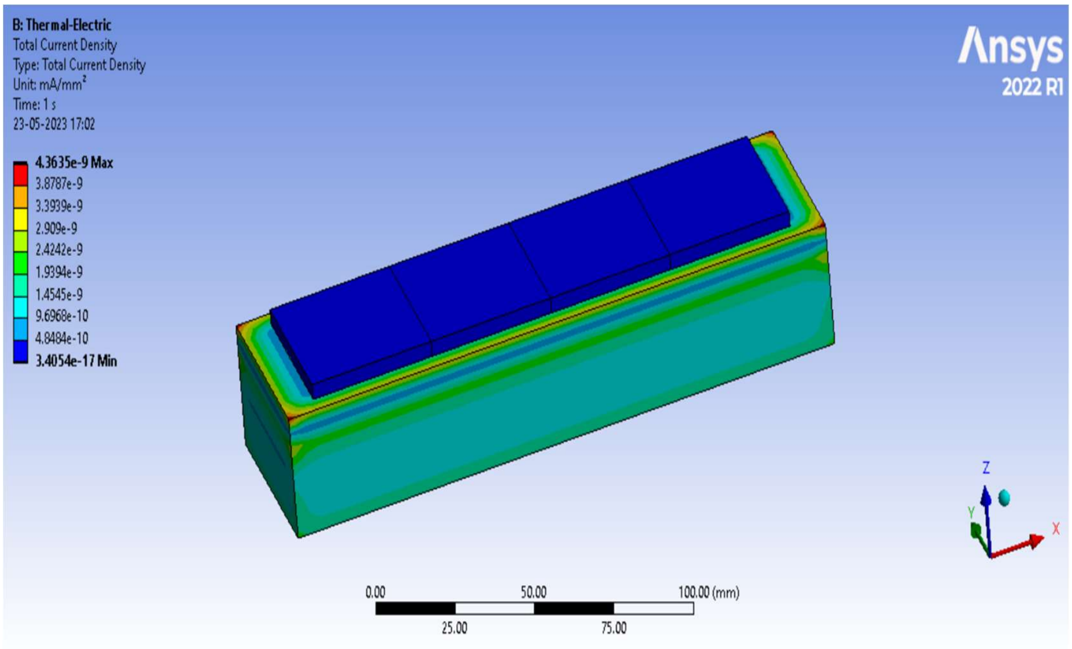


Figure 4.41: Current density

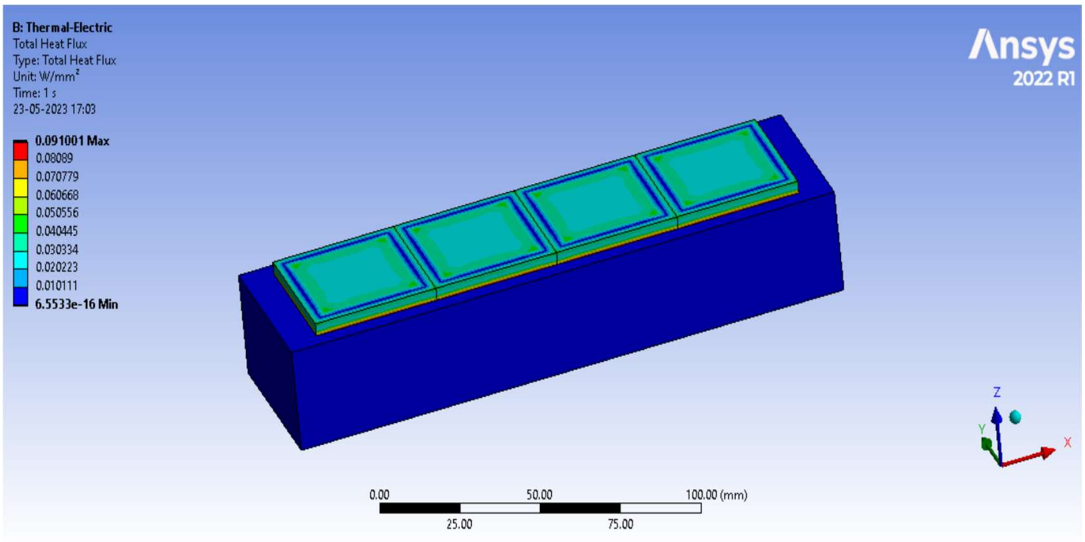


Figure 4.42: Heat Flux

Temperature assignment at 300^{0}C for power flow analysis shown in the figure 4.38 and convection shown in figure 4.39. The electrical voltage at TEG output with current density shown in the figures 4.40& 4.41 respectively. The total flux generated with temperature deposition also shown in figure 4.42.

4.14 ANALYSIS OF THERMOELECTRIC GENERATOR PERFORMANCE AT 350^{0}C

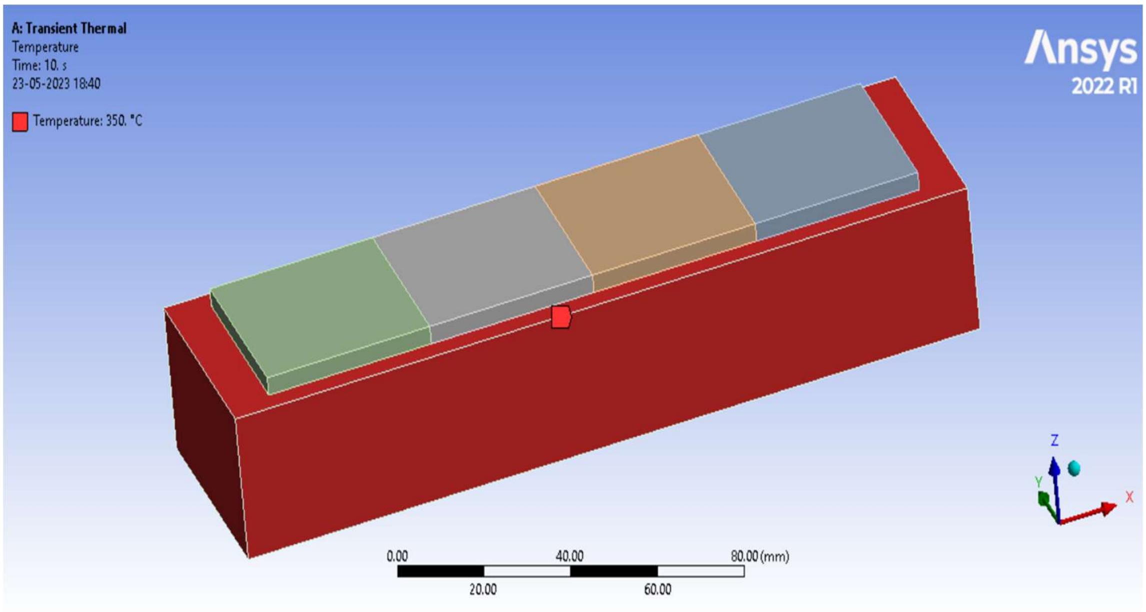


Figure 4.43: Temperature 350^{0}C

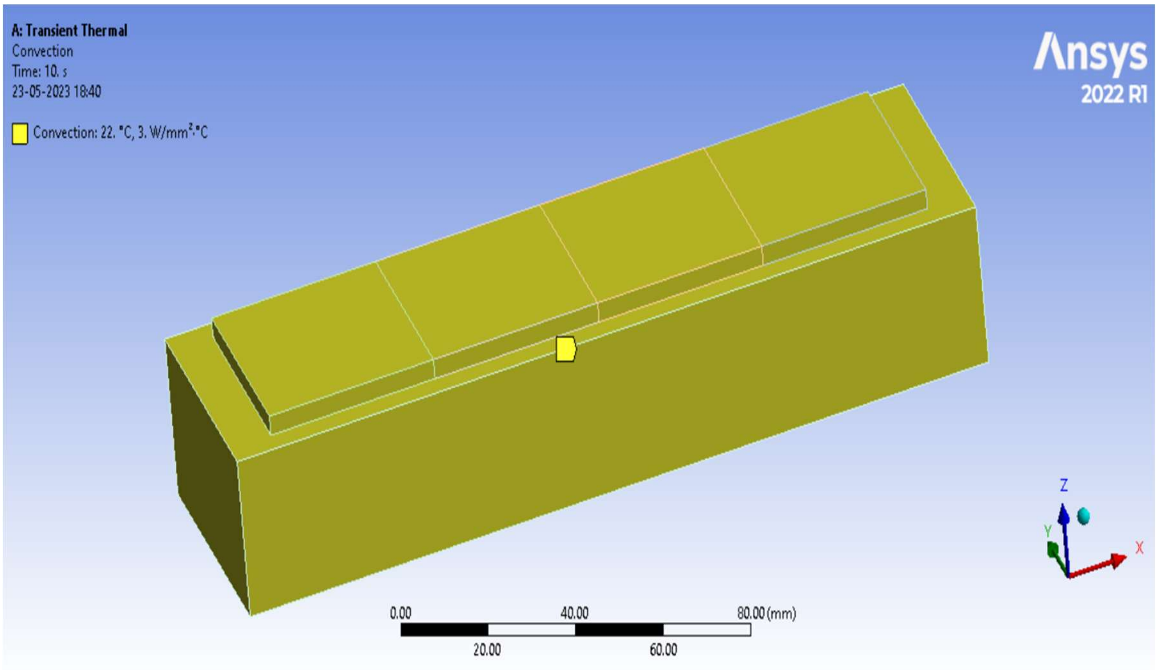


Figure 4.44: Temperature Assignment for convection

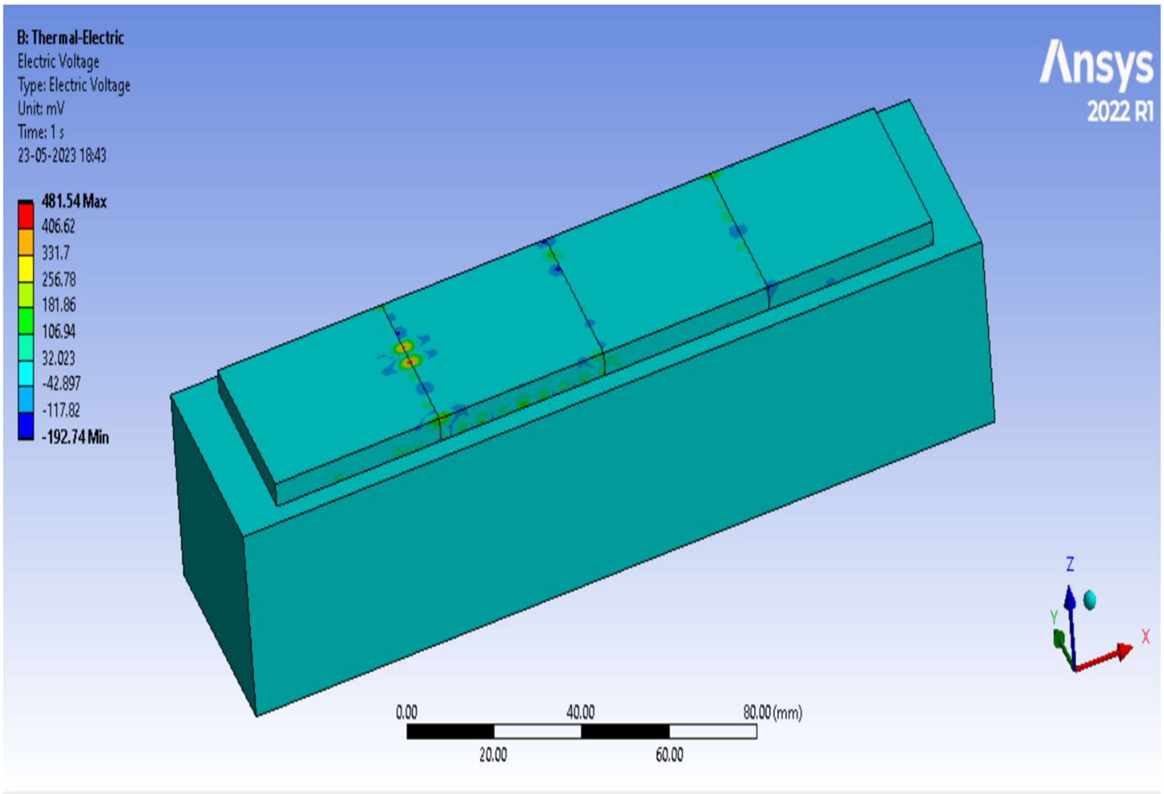


Figure 4.45: Electric voltage

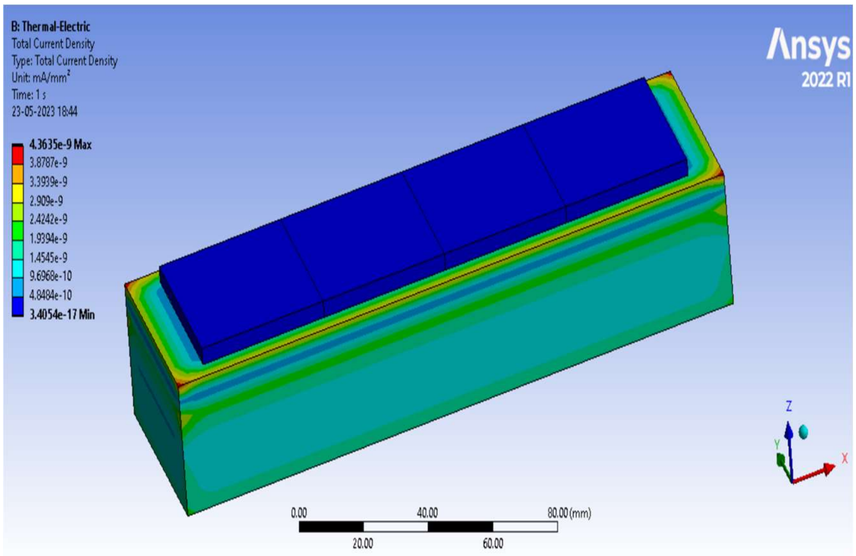


Figure 4.46: Current density

Temperature assignment at 350 0C for power flow analysis shown in the figure 4.43 and convection shown in figure 4.44. The electrical voltage at TEG output with current density shown in the figures 4.45 & 4.46 respectively. The total flux generated with temperature deposition also shown in figure 4.47.

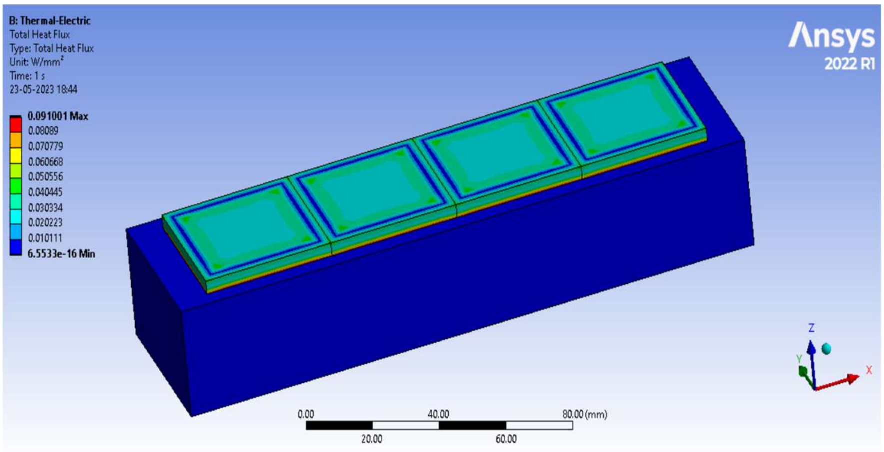


Figure 4.47: Heat Flux

Table 4.6: Transient Thermal Analysis TEG using SS316

Properties	200^0C	250^0C	300^0C	350^0C
Temperature (0^0C)	200	250	300	350
Heat Flux (W/mm²)	5.694	7.294	8.894	10.494

Temperature and the heat flux generated at different temperatures has been given in table 4.6, and the graphical compressions shown in figure 4.48.

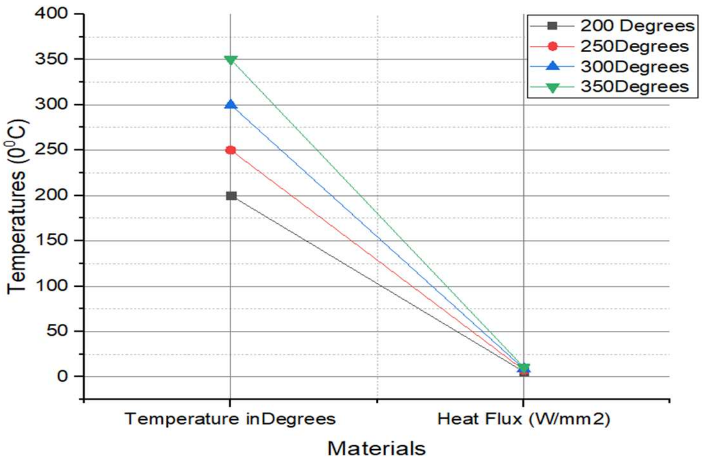


Figure 4.48: Validation of Transient Thermal Analysis TEG using SS316

Table 4.7: Transient Thermal Analysis TGA using SS316

Properties	200^0C	250^0C	300^0C	350^0C
Electric voltage (Mv)	481.54	300.55	481.54	481.53

Current density (mA/mm²)	4.363	4.358	4.363	4.632
Total heat flux (w/mm²)	5.826	7.463	9.100	9.100

At different temperatures, electric voltage, current density and the total heat flux generated has been given in table 4.7. and the graphical compressions shown in figure 4.49.

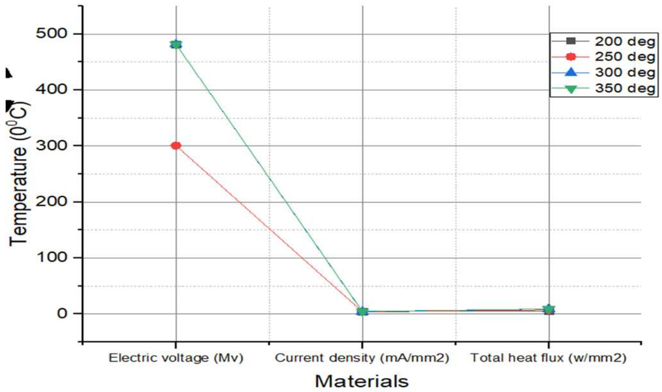


Figure 4.49: Validation of Thermoelectric generator Analysis using SS316

4.15 CFD ANALYSIS:

A study of the heat transfer setting has been carried out, with special attention paid to the generation of thermal flux and the mesh characteristics of the model. The diagram shows how heat is transferred from TEGs to the attached substance as part of a transient thermal examination. See-beck effect convection of heat and heat transfer between surfaces with certain thermal loads is shown graphically.

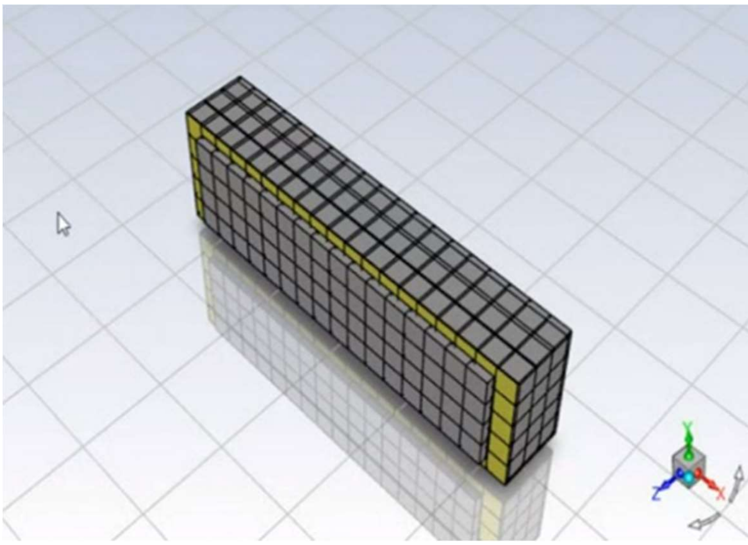


Figure 4.50: Fluid flow environment in CFD

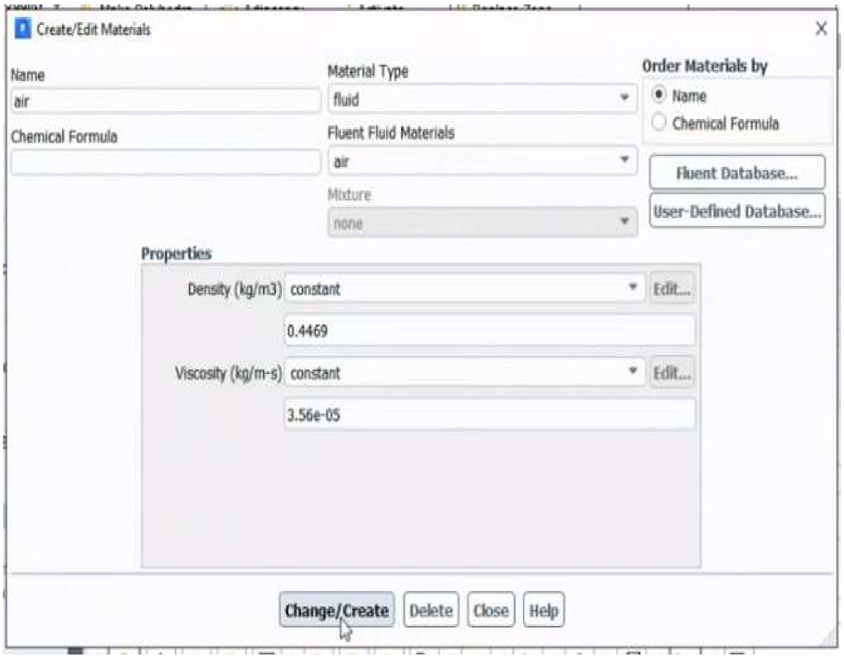


Figure 4.51: Properties of fluid

Import of TEG system to CFD environment shown in the figure 4.50. The properties o f hot air, fluid and material selected from Ansys Liberty has been given in the figure 4. 51, 4.52, 4.53 respectively.

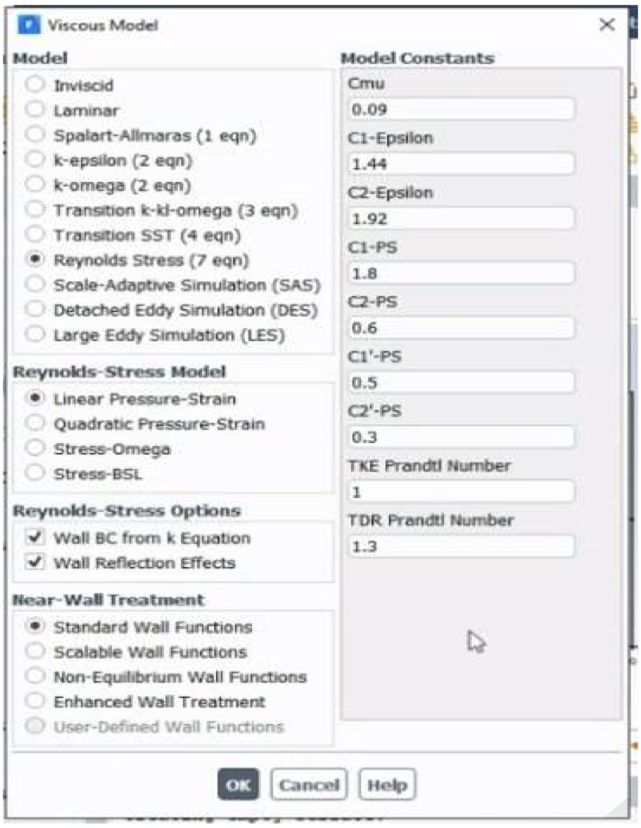


Figure 4.52: Properties of fluid

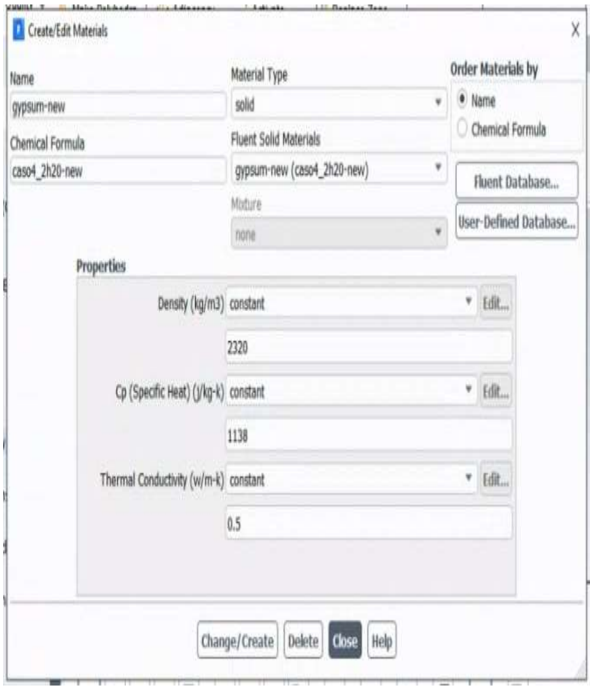


Figure 4.53: Properties of Material

For the purpose of studying the power density of an automobile accessory's thermally enhanced petrol (TEG) output with temperature gradients, hot fluid air as pores was taken as the heat generation medium. For fluid flow analysis, the figures show that the Seebeckeck coefficient of copper was set at 6.5 V/K and the thermal conductivity of SS316 was set at 16.3 W/mK.

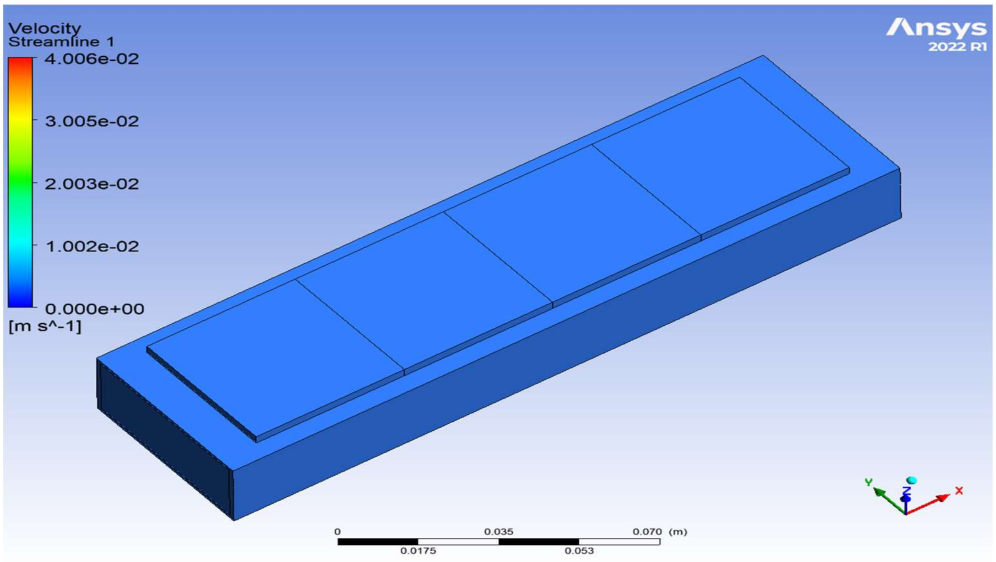


Figure 4.54: Velocity streamline

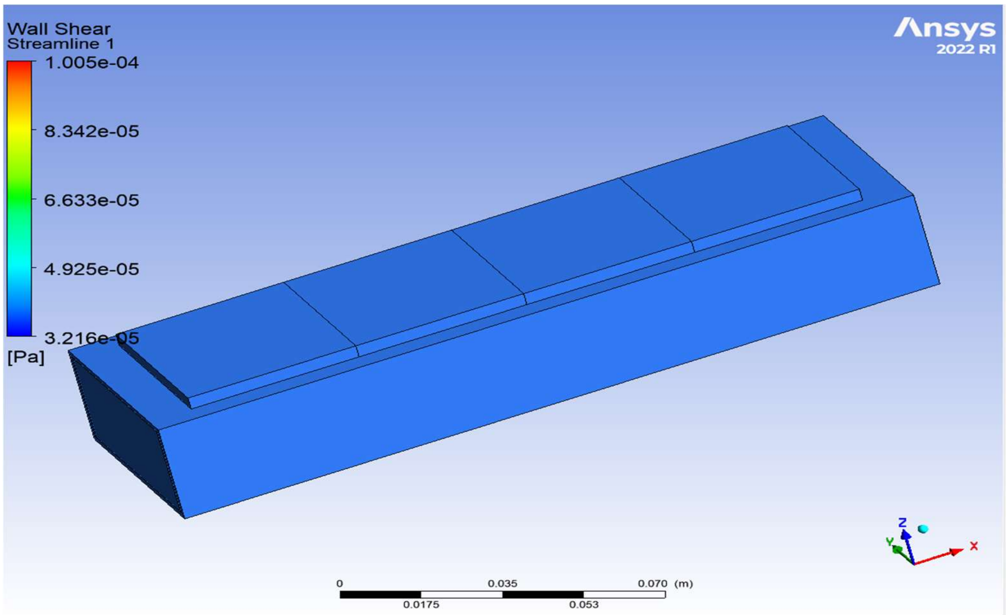


Figure 4.55: Shear temperature streamline

The flow conditions of the air inside the duct has been varied with the results as shown in figure 4.54 & 4.55.

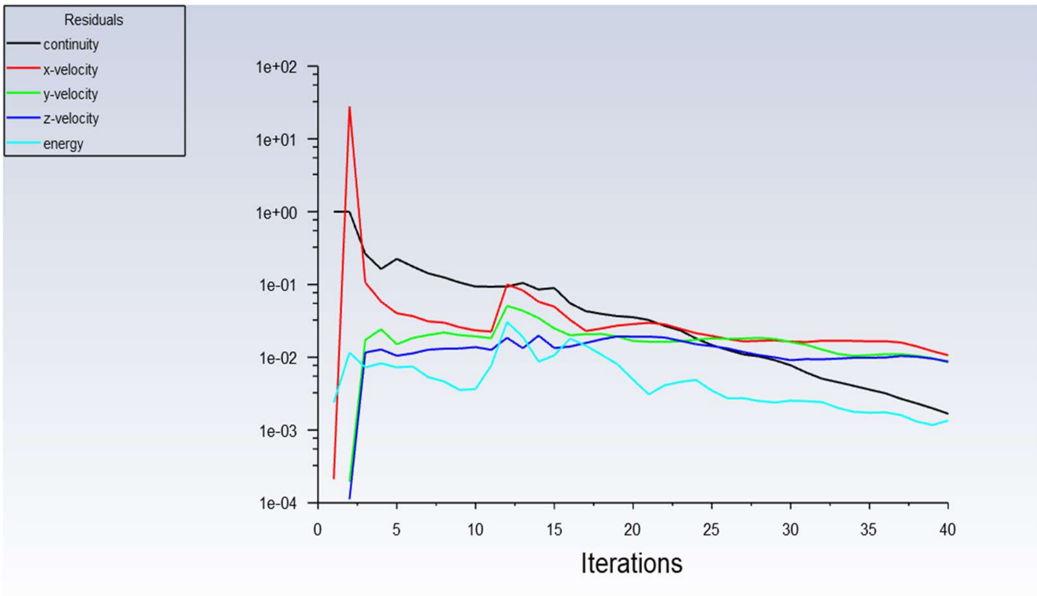


Figure 4.56: Heat deposition flow

Heat flow from a four-TEG system is cooled by electricity, and the total current density and temperature contour are analysed, and efficiency is determined by the user's input of the Reynolds number. Some example contours are shown in the figures we've supplied. Both the TEG's contact points with the model substance and the points where the two are connected were used to determine the peak temperature and rate of heat release. The flow ration of hot air in multiple directions has been in figure 4.56. The effects of varying temperatures on power and efficiency with respect to Reynolds number given in the table 4.8.

Table 4.8: The effects of varying temperatures on power and efficiency

	Temperature (°C)	Power (W)	Efficiency (%)
Reynolds value-1	200	0.25	0.45
	250	0.41	0.62
	300	0.64	0.78
	350	0.82	0.8
Reynolds value-10	200	0.38	0.56
	250	0.56	0.68
	300	0.74	0.82
	350	0.93	1
Reynolds value-100	200	0.68	0.61
	250	0.93	0.72
	300	1.24	0.88
	350	1.51	1.
Reynolds value-1000	200	2.24	0.63
	250	3.38	0.78
	300	4.26	0.92
	350	4.88	1.

Table 4.9: The total current that is produced at various temperatures

Temperature (°C)	TEG1 (A)	TEG2 (A)	TEG3 (A)	TEG4 (A)	Total Current (A)
200	0.1	0.09	0.08	0.07	0.34
250	0.11	0.09	0.09	0.08	0.37
300	0.11	0.1	0.1	0.09	0.40
350	0.12	0.1	0.1	0.08	0.42

Table 4.10: Total Voltage generated at different temperature

Temperature (^oC)	TEG1 (V)	TEG2 (V)	TEG3 (V)	TEG4 (V)	Total Voltage (V)
200	3.15	2.8	2.5	2.35	10.8
250	3.2	2.9	2.6	2.6	11.3
300	3.3	3.1	2.9	2.8	12.1
350	3.6	3.4	3.3	3.0	13.3

Table 4.9, 4.10 exhibit the acquired data, which include the current density and voltage, respectively. Figures 4.57 & 4.58 depict a comparison of the 4-TEG system's power and efficiency as a function of temperature for a range of Reynolds numbers.

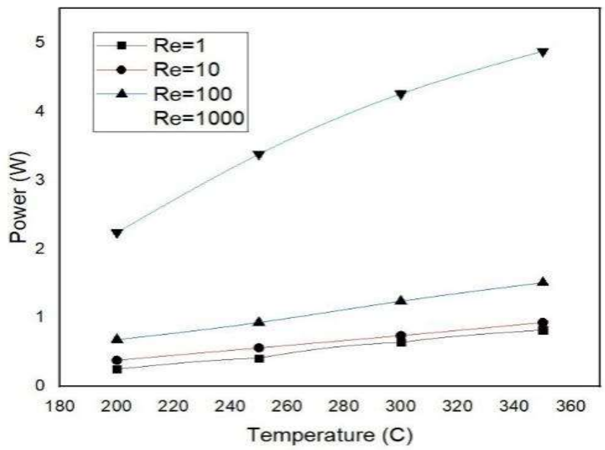


Figure 4.57: Power Vs Temperature

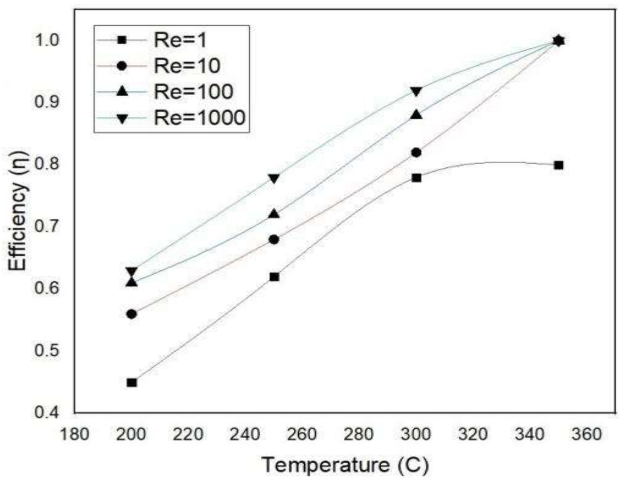
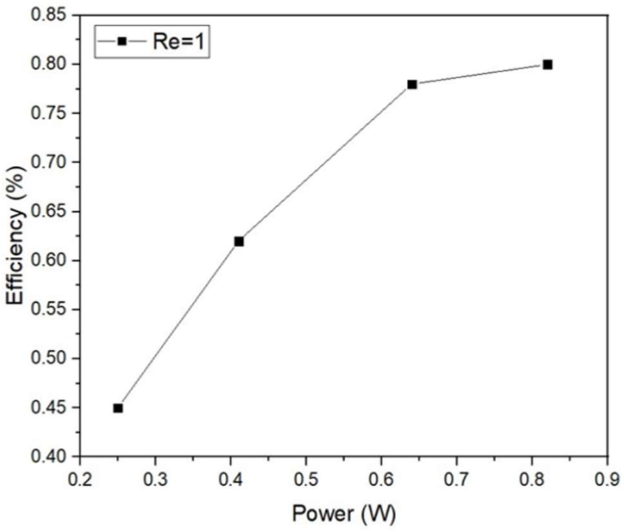
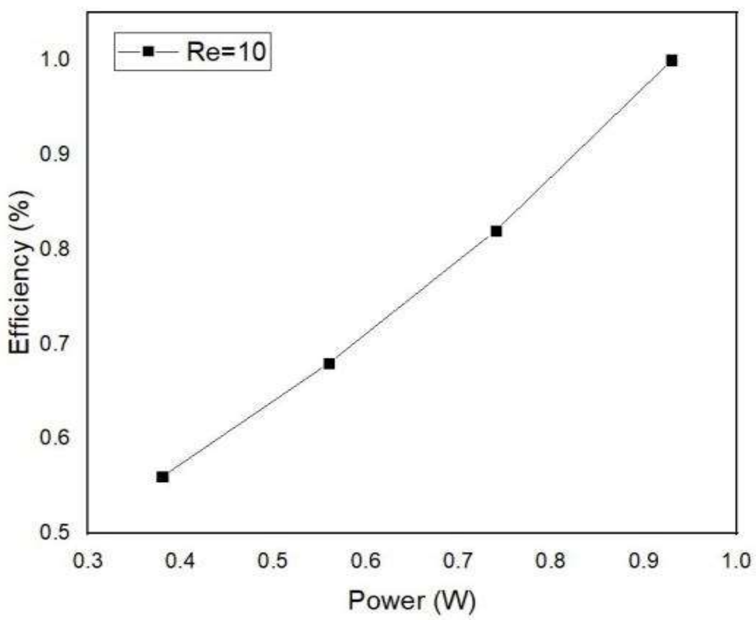


Figure 4.58: Temperature Vs Efficiency



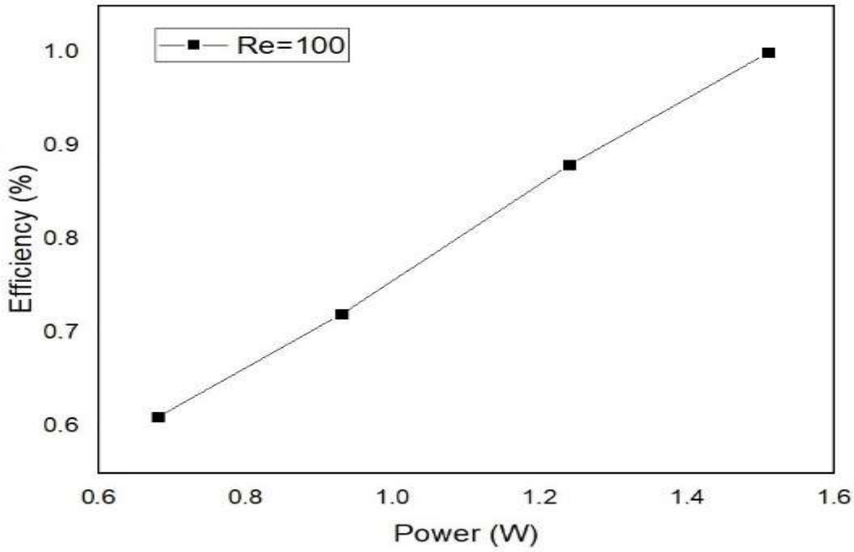
(A)



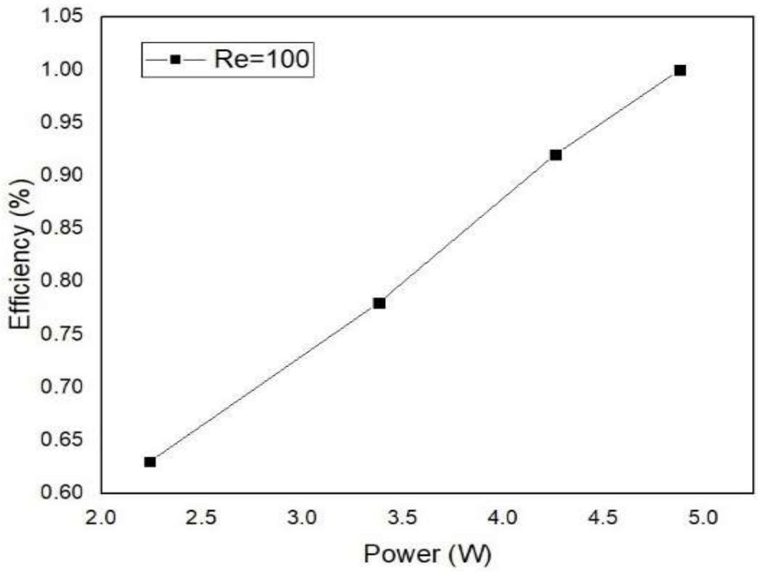
(B)

Figure 4.59: (A) Power Vs Efficiency at Re=1 (B) Power Vs Efficiency at Re =10

At low Re (1) and high Re (1000) number of fluid the efficiency of the system not incr eased in a continuous mode as shown in figure 4.59 (A) & 4.60 (B) while it comes to i ncrement of Re the efficiency increased gradually up to Re=100 as shown in figures 4. 59 (B) and 4.60 (A).



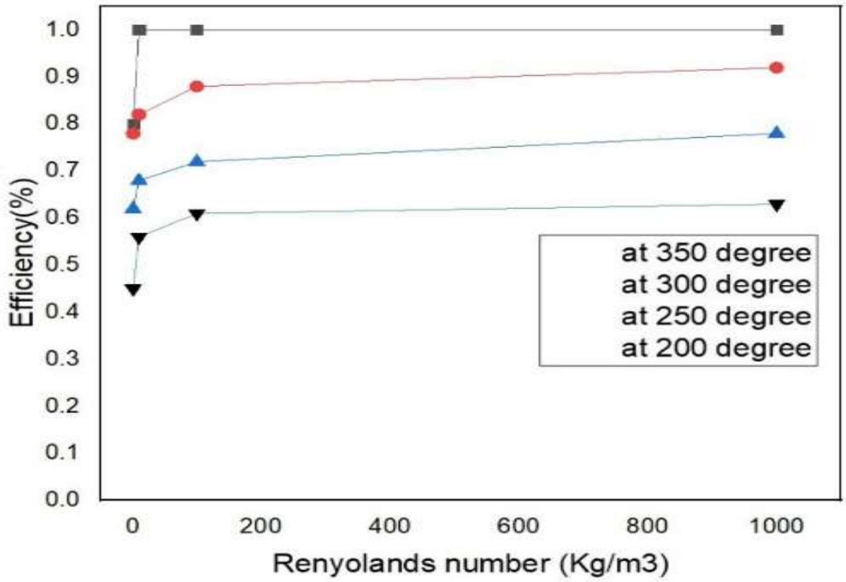
(A)



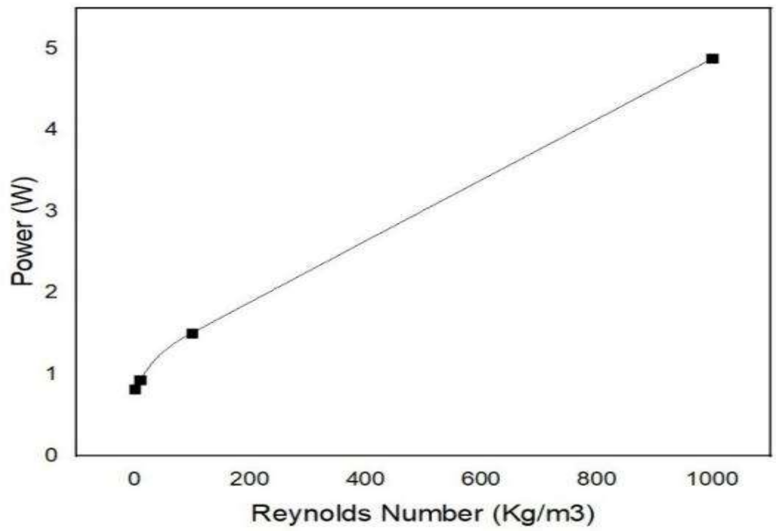
(B)

Figure 4.60: (A) Power Vs Efficiency at Re 100, (B) Power Vs Efficiency at Re =1 000

The power output increases linearly with efficiency up to a Reynolds number of 100 (as shown in Figure A), but then becomes irregular (as shown in Figure B). Nothing happens even when heated to 350^0 degrees Celsius. Power generation increased with the number of mould reuses, as seen in the table. Figure 4.61: (A) shown Efficiency Verses Reynolds Numbers at different temperatures and Power verses Reynolds Numbers has been shown in figure 4.61 (A).



(A)



(B)

Figure 4.61: (A) Efficiency Vs Reynolds Numbers at different temperatures (B) Power Vs Reynolds Numbers

Discussion:

Power increases with both fluid velocity and air temperature, as shown in fig 4.61 (B), while efficiency increases with Reynolds number and temperature, as shown in fig 4.61 (A). Both an increase in temperature and a rise in fluid velocity boosted the efficiency of the Seebeck effect.

4.16 Conclusion:

The effect of convection is taken into account to verify thermos- electric by natural cooling considered in the present work. With the increase in velocity flow of hot gases, the Reynolds number is considered for the present research. The increment in temperature with Reynolds number increases the efficiency of the seebeck effect as on mean of that power also increased, preliminary validation made with a comparison of chen et.al work with two TEG's increase of TEG to four given better results.

CHAPTER 5

IOT based module testing for TEG

5.1 Introduction

Integrating thermoelectric generator (TEG) modules with IoT systems requires careful consideration of several aspects. First, power management is critical, as TEGs often produce limited energy; therefore, IoT devices must be low-power and incorporate energy storage solutions like supercapacitors or batteries, along with voltage regulators to stabilize output. Sensors play a vital role in monitoring system performance, including temperature sensors to measure heat differentials, voltage and current sensors for power tracking, and environmental sensors for conditions like humidity and pressure.

Wireless communication capabilities are essential, utilizing protocols like LoRa, Zigbee, or BLE for efficient data transmission to a gateway or cloud system. IoT systems also need efficient data processing using low-power microcontrollers like ESP32 or STM32, with edge computing to minimize the data sent over networks. Cloud integration enables real-time monitoring, data logging, and analytics for predictive maintenance and long-term performance optimization.

The IoT modules should be designed to withstand mechanical and thermal stresses while incorporating heat sinks for effective thermal management. They must also be modular and scalable to accommodate multiple TEG modules in series or parallel, depending on application needs. In specific applications like industrial waste heat recovery, remote sensors, or wearable devices, the design should prioritize factors such as durability, compactness, and seamless connectivity.

Recent years have seen the development of waste heat recovery technologies, such as TEGs, which are now being used in the automotive industry in a variety of ways. TEG can be used as a waste heat harvesting method, according to previous research. The waste heat from internal combustion engines makes it possible for useful electricity to be generated even when efficiencies for TEGs are as low as 3-5%.

An innovative DC-DC conversion network based on thermoelectric generators is proposed in this thesis. According to this plan, the network will be built out in phases. The use of TEG in automobiles is a response to the shortcomings of conventional single-stage systems. The DC-DC converter is optimised as part of the development's effort to establish a systematic, bottom-up approach to the architecture of the network.

A solution to dynamic impedance matching is offered for the DC-DC converters used in the TEG system. In the first part, possible theoretical approaches to balance the large internal resistance of the TEG with the small input resistance of the converter are discussed, as well as their limitations. We then develop a model for maximum power point tracking (MPPT) regulation that addresses the temperature-sensitive nature of converters. Simulink/Simscape was used to model the MPPT regulatory processes and then integrate those models into the TEG-converter simulations. The developed model allows for MPPT matching efficiencies of greater than 99% in the 200°C to 300°C hot side temperature range. The proposed network is designed according to a design flow. Analysis is conducted regarding design flow. In order to generate electricity from waste heat harvesting on a vehicle, a wide variety of state-of-the-art thermoelectric materials are analyzed. It is suggested that optimal materials and configurations of TE couples be used. Further, at each conversion level within the network, prevailing DC-DC conversion techniques were compared. According to the system specifications, higher level design considerations are also discussed. Lastly, the proposed network is compared to traditional single-stage systems based on a case study. In the context of the studied case, the proposed network improves system conversion efficiency by 400%.

The experiments on the IoT interface for a Thermoelectric Generator (TEG) were conducted in the laboratory at Lovely Professional University (LPU). The primary goal of the experiments was to integrate TEG technology with IoT systems to enable real-time monitoring and optimization of power generation from the TEG.

In the setup, four TEG modules were used, coupled with a heat source to create a temperature gradient and a cooling mechanism such as heat sinks to maximize thermal efficiency. The output voltage from the TEG was initially low, so a DC-DC boost converter was employed to increase the voltage to usable levels. This energy was then stored in rechargeable batteries and used to power a simulated load to analyze the system's behavior under various conditions.

The experimental system was equipped with sensors, including voltage sensors for monitoring TEG output, temperature sensors to measure the gradient, and current sensors for tracking energy flow. These sensors were connected to a microcontroller, specifically an ESP32, chosen for its dual capabilities of data processing and wireless communication. The microcontroller was programmed to transmit data to a cloud-based IoT platform using Wi-Fi, enabling remote monitoring.

The IoT interface allowed real-time visualization of critical parameters such as voltage, current, and power efficiency through dashboards on platforms like ThingSpeak. Experiments were conducted to evaluate the thermal performance of the TEG, its energy conversion efficiency, and its stability under varying electrical loads. Additionally, long-term tests were performed to assess the reliability of the system, with IoT alerts configured to detect and respond to potential issues such as overheating or voltage drops.

These experiments demonstrated the successful integration of TEG with IoT, showcasing its potential for energy harvesting and remote monitoring applications. By leveraging the advanced facilities at the LPU lab, this research highlighted innovative ways to optimize renewable energy systems using IoT technology.

5.2 EXPERIMENTATION PROCEDURE OF TEG WITH MPPT

For a given load and system, MPPT can be used to determine the most efficient power generation point. TEGs and photovoltaics (PVs) are examples of variable output systems that require MPPT algorithms because of load mismatches that reduce output power. TEGs, for example, experience this power reduction due to their variable temperature when operating normally. Using maximum power point tracking (MPPT) in DC-DC converters allows TEG and PV systems to transmit maximum power efficiently at a fixed voltage. Usually, maximum power point tracking (MPPT) algorithms used in TEGs come from photovoltaic (PV) systems, since MPPT works great in TEGs. Some examples of these control strategies include the following: perturb and observe, incremental conductance, fractional open circuit voltage/short circuit current (Voc/Isc), and constant voltage/constant current. Since TEGs have a parabolic power curve and a linear voltage-current (V-I) characteristic, the fractional Voc technique uses half of that characteristic to compute the converter's duty cycle, which reduces computational demands. The fractional Voc technique can function without current sensing because it is unnecessary. In order to determine the current Voc value, the TEG needs to be separated from the load on an intermittent basis, which might lead to unwanted transients and decreased efficiency. In order to find out if perturbation gain has gone up or down, a hill climbing approach compares the present V-I values to the history. IC determines the power curve's gradient by taking the derivative of V-I values, whereas P&O compares V or I rather than IC. Given the ease of implementation of both methods in PV systems, IC can determine if the maximum power point (MPP) has been reached, but it is computationally costly, therefore it converges to the MPP slower. P&O is unable to attain genuine MPP because a continual disturbance causes the operating point to fluctuate around the MPP. The issue with IC and P&O approaches is that they can't accurately track transients since the perturbation gain has to be minimal to decrease the range of the limit cycle, which isn't practical for reliable MPP tracking. Optimal performance during transients and steady states, as well as the ability to operate without disconnecting the TEG and load, are necessary for an algorithm to overcome the shortcomings of the approaches described previously. The capacitor board and circuit diagram has shown in figure 5.1 including sensors location.

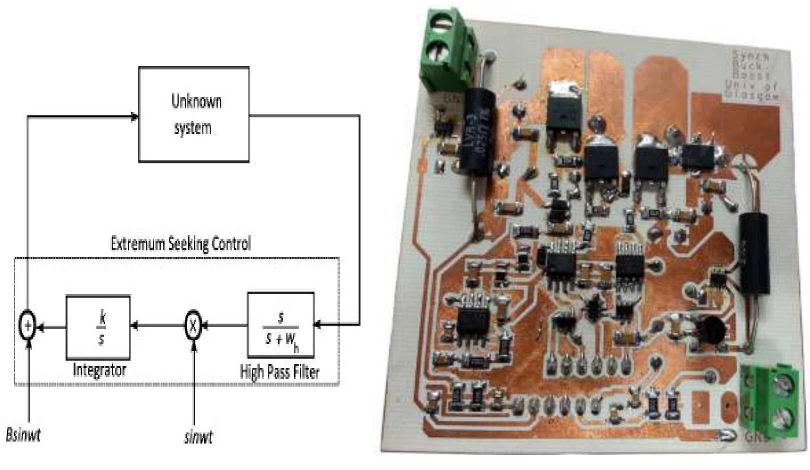


Figure 5.1. Schematic diagram of the extreme seeking controller and sensor with capacitor board.

There are several MPPT algorithms that have shown superior performance, including extreme seeking control (ESC) for solar panels. ESC is perceived to have an advantage because it converges more rapidly while maintaining similar steady-state performance to P&O. ESC for TEGs is indeed comparable to PV systems in terms of performance when compared with P&O, as Phillip et al. previously demonstrated via simulation. This study validates its results with experiments based on simulations. According to Figure 5.1 ESCs operate in closed loops. An initial duty cycle perturbation signal is sent to the unknown system. In order to calculate a new duty cycle, the output is high pass filtered to remove the DC offset and compared with the original perturbation signal. Figure. 5.1 illustrates the process of iteratively finding the optimal power point, which is then followed by a limit cycle as with P&O. A power of Pmax is defined as a maximum power, while its duty cycle is referred to as a duty cycle at maximum power. It has been shown that this method works well, but the main drawback is that there are many parameters that need to be adjusted for optimal performance. In the ESC, the following parameters are known: perturbation gain B, integrator gain K, perturbation frequency w, and high-pass filter frequency. The overall performance of ESC is dependent on these parameters. The experimental flowchart with test diagram shown in figure 5.2 with connecting devices and boards with storage battery.

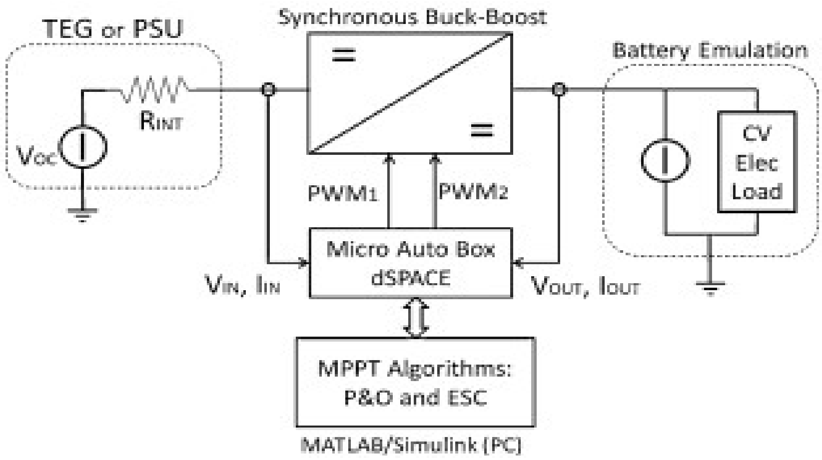


Figure 5.2: The experimental test apparatus and its associated components are depicted in a schematic diagram.

As stated in the introduction, a DC-DC converter governed by an MPPT algorithm is employed to link the TEG to a battery load, with the goal of optimizing the electrical power delivered from the TEG to the external circuit. In this part, we will go over the tools and equipment that were utilized to collect experimental data from physical TEGs. This mimics the way the TEGs act as well. The steady-state electrical characteristic of a transient electronic generator (TEG) can be represented by a voltage source in series with a resistor, allowing one to replicate steady-state behavior using a power supply unit (PSU) linked in series with an electronic load in constant-resistance mode. The experimental setup is depicted in figure 5.2. Synced buck-boost DC-DC converters are connected to the TEGs, and their outputs are connected parallel to a PSU with a CV load. DC–DC converters provide a constant output voltage, while batteries sink current, simulating the behavior of batteries. Micro Auto Box (dSPACE GmbH, Germany) is used to interface an electronic converter with a personal computer (PC) in real-time: the converter measures the output and input voltages, while the Micro Auto Box controls the DC–DC converter switching operation by sending pulse width modulation (PWM) signals, which are antiphase in nature.

5.3 PROPOSED EXPERIMENTATION WITH IOT

A Four TEG based module has been added to the IOT controller to check the voltage gain after experimentation through Seebeck effect. We proposed a power generative system using thermo electric generator obtained from the vehicle emissions heat recovery conversion. The module designed with 4-TEG placements on the top of the module with regular Seebeck effect conditions, the heat conduction with sudden cooling investigated with heat sensors attached to IOT. The total module fixed to a test equipment with assumption of flue gas temperature. To model data transmission, control, and collection in an EWSN, this simulation uses a mathematical description of the network's components, including DC/DC boost converter-powered sensors, a load, and a control algorithm. The parameters and attributes of the collected energy are explained in detail, and their potential applications are examined, in the findings section.

Peltier modules are useful since they do not require solar rays, can provide noiseless energy as needed with very little or no effect on the environment, and can operate with no need of solar rays. Seebeck effect occurs when a difference in conductivity or a difference in semiconductors between two dissimilar compounds produces a voltage difference between them. It is possible to run Peltier modules on latent heat generated by candles or campfires, and to dissipate heat on the other side by using a heat sink or chilled water/ice. Voltage is generated by creating a temperature difference by heating one side and cooling the other side. Depending on the user's needs and the number of

Peltier modules connected, generated voltages can be high or low, but they can be controlled and stabilized using DC choppers.

5.4 WORKING PRINCIPLE OF THE MODULE

A Peltier module is an apparatus that incorporates a heat sink and fan, or a metal tray with a cooling source, into a wooden enclosure. Thermal grease is used to secure Peltier modules, and a metal plate is placed over the hot side to disperse the heat and contain any noxious emissions. A cooling source is first delivered to the Peltier module, and then a heating source is given. Peltier modules generate voltages as a byproduct of their ability to convert thermal energy into electricity. There is complete silence throughout the process. When there is a temperature difference between two modules, a voltage is produced in proportion to the number of modules. A Peltier module can convert thermal energy into electrical current when subjected to a temperature gradient. It is possible to generate more energy from heat by passing it through a Peltier module, as the temperature differential, and thus the power output, increases. Peltier modules are made from the semiconducting materials bismuth telluride and lead telluride, in which some electrons are bonded to nuclei and others are free. The temperature difference is generated by heating and cooling the opposing surfaces of a Peltier module; this is possible because the modules contain semiconductors, which allow charges to flow from high energy to low energy. Potential difference between the charges, also known as voltage, is a measure of electricity that can be created during this process by creating a negative charge on one side and a positive charge on the other. A buck-boost converter is wired in so that a constant dc voltage can be produced. In buck-boost converters, the input voltage from the Peltier modules is higher than the output voltage. The voltage source, the boost inductor, the switched controller, the diode, the filter capacitor, and the load resistance are the six components of the circuit. In the first phase, the switch is open and the inductor receives no current. When the switch is closed for the first time, current cannot enter the RHS of the circuit and instead flows through the inductor, a passive part in the circuit. Inductors have a low current rating because they lower the source voltage to maintain that rating. As the current slowly increases, the inductor stores energy as a magnetic field by reducing the voltage drop across it. Diodes can have their energy released via RC circuits. TEG sensor connected to board and digital display of voltage and current shown in the figure 5.3 & the results shown in figure 5.4.

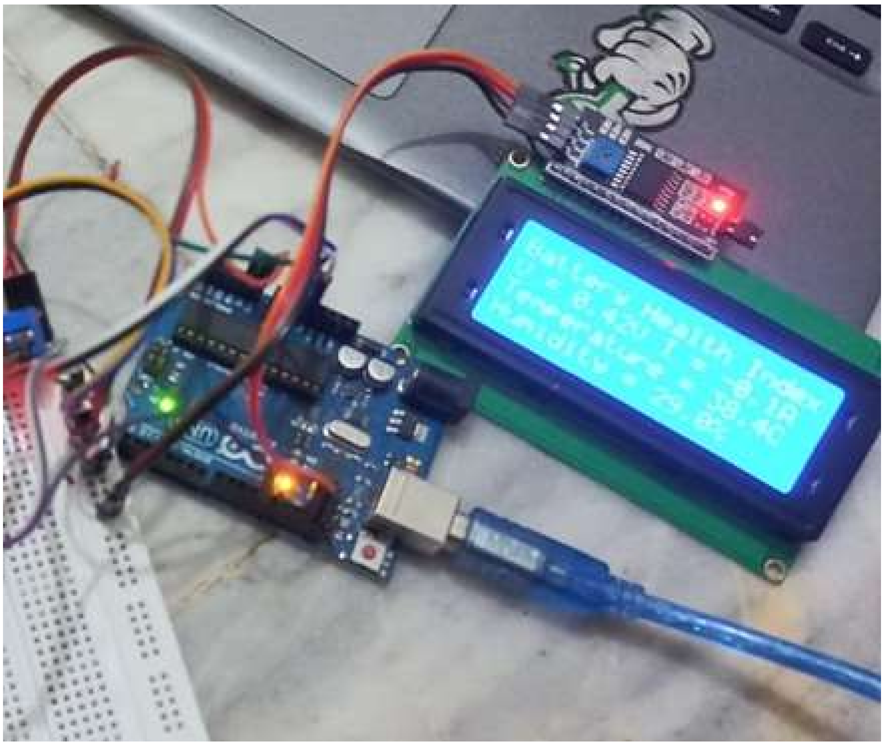


Figure:5.3 TEG sensor for voltage and power output

Assembly of TEG based IOT control has been developed for present testing with different temperatures. Even though the system releases hot gases the range input taken up to 60^0 C for system viability. Primary test has been checked with low temperatures for each TEG the minimum voltage observed as 0.22V.

Figure:5.4 Experiment results with TEG output

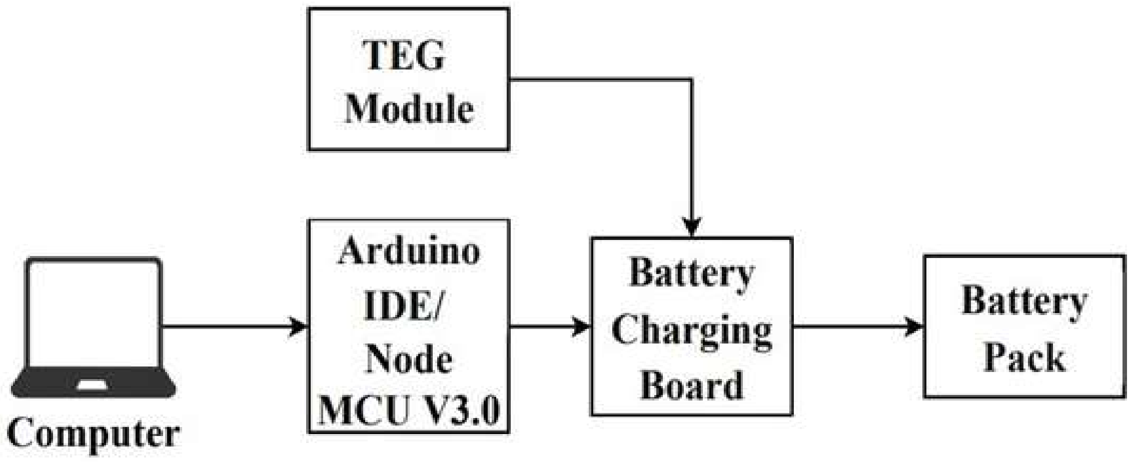


Figure:5.5 Working cycle schematic diagram

The basic flow diagram of TEG updated voltage and power at battery connected to digital system has shown in figure 5.5. IOT module with WI-FI connectivity to get SMS for the selected mobile to check the status of TEG upgraded in present work and the schematic has been shown in figure. 5.6.

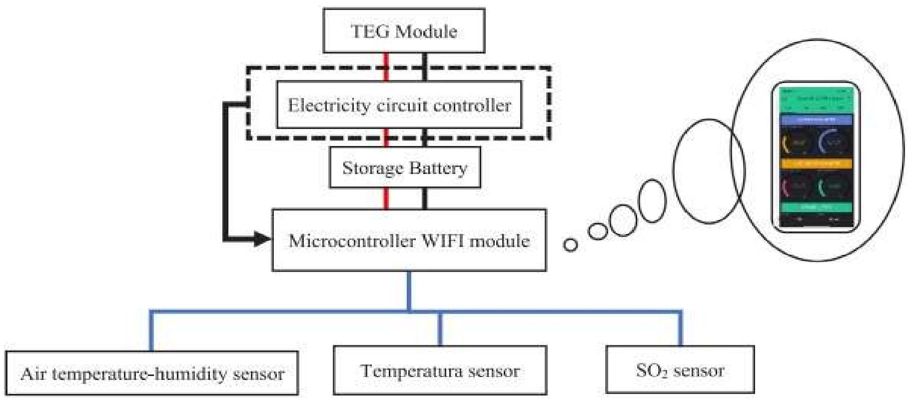


Figure:5.6 IOT attached schematic layout with Wi-Fi for SMS sensor

Hot water test conditions of 80, 75, 70, 65, 60, 55, and 50 degrees Celsius were established by shifting the testing position. The volume flow rates of cooling water were also predetermined to be between 150 and 250 mL/s, with 250 mL/s being the highest allowed. The IoT module was set to activate once each hour, taking exactly one minute to do so. As the IoT module rests, the battery is charged by the TEG modules. As a result of connecting four TEG modules in series, the maximum voltage for energy storage was achieved.

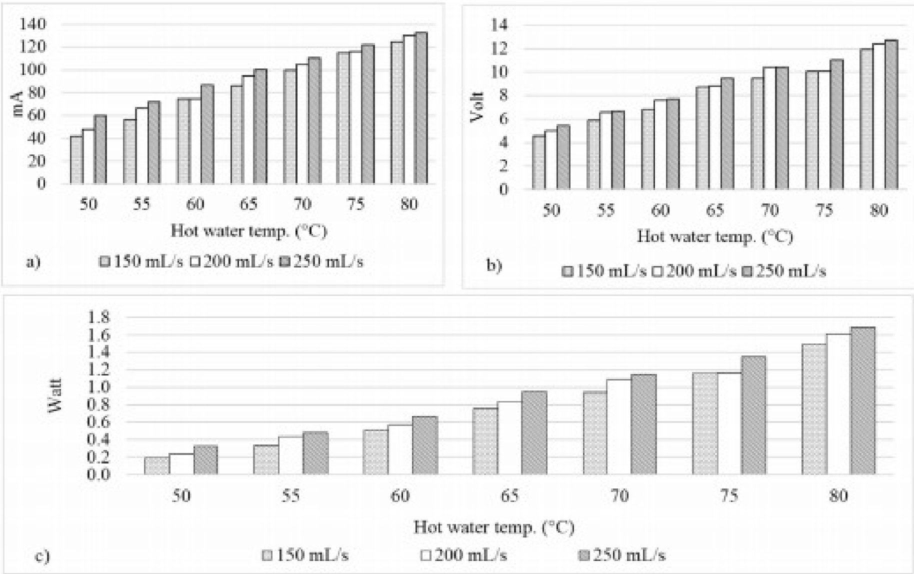


Figure:5.7 Current, voltage and power with respect to temperature for different capacity of hot water.

The primary work tested with Hot fluid as water the current and voltage with respect to temperature has been shown in the figure 5.7.

5.5 PRINCIPLE SCHEMES FOR PRESENT WORK

The TEG placement with hot surface connectivity including duct resource considering in the present work, the TEG layout shown in the figure 5.8.

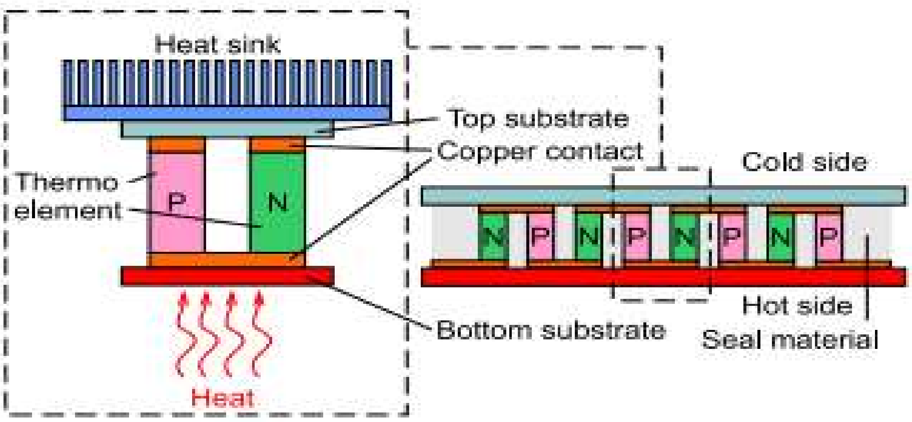


Figure:5.8 TEG layout for present experiment

In the n-junction, all positively charged carriers move to the n-junction; in the p-junction, all negatively charged carriers move to the p-junction. PbTe is the most common element used in thermoelectric generators. An electrically and thermally conductive material was selected for the flow of electrons. Indium arsenide (InAs), bismuth sulphide (Bi2S3), tin telluride (SnTe), bismuth telluride (Bi2Te3), and germanium telluride (GeTe) are often used to make these types of materials.

improve converters, also known as step-up converters, are among the most basic switch-mode converters because they simply enhance the input voltage. As the current is reduced from high to low, the DC voltage is increased from low to high. A boost converter consists of an inductor, a semiconductor switch, a diode, a capacitor, and an electrical load. To raise a converter's output voltage or current, an inductor's magnetic field must either oppose or allow the flow of current. When the switch is closed, energy is transferred into a magnetic field, which is stored by the inductor. Switching off reduces output current because of higher load impedance. Due to the reversal of polarity and the resulting reduction in the magnetic field, the voltage required to charge the capacitor rises. When the switch is rapidly flipped between charging phases, the inductor's output voltage exceeds the input voltage.

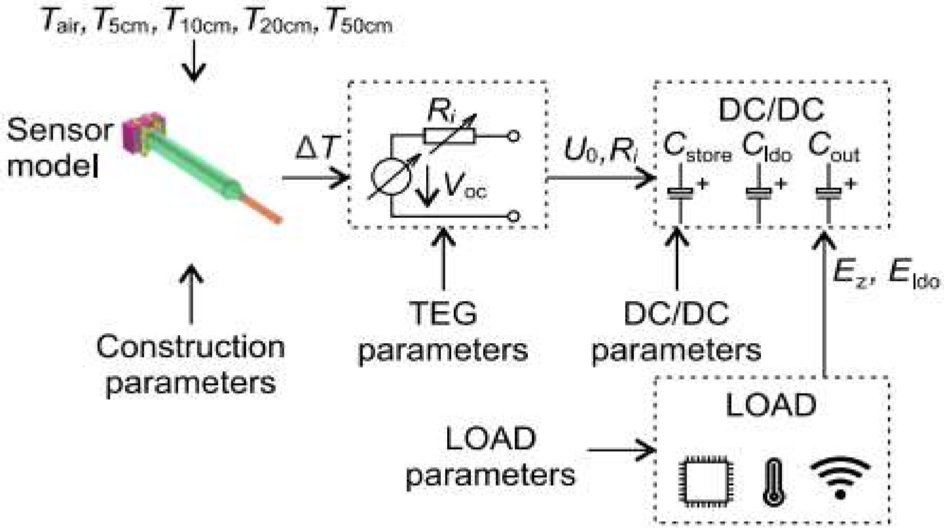


Figure:5.9 Model for TEG testing with IOT

The Serial Peripheral Interface (SPI) is a widely implemented bus for interfacing micro-controllers with peripheral devices. Protocol for the I2C Language: I2C uses pins A4 and A5 for communication; A4 is the serial data line (SDA) and is in charge of data transfer, and A5 is the serial clock line (SCL) and is in charge of data synchronisation over the I2C bus; the master device supplies this signal.

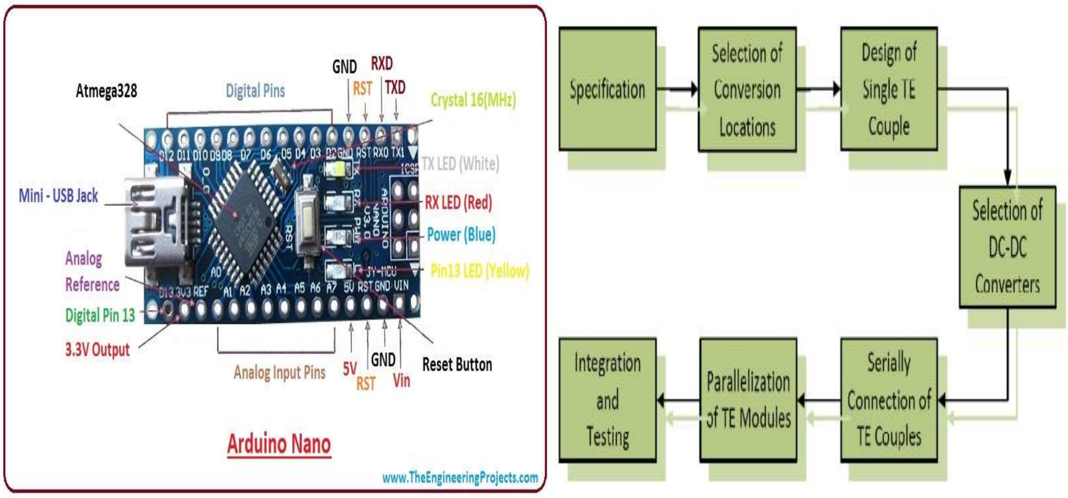


Figure:5.10 Integrated Arduino for present assembly

The layout of present system with IOT connected to heating module as well as tester setup schematic has been shown in figure 5.9. The integration of layout with Arduino in the present assembly shown in figure 5.10 and circuit diagram of IOT module shown in the figure 5.11.

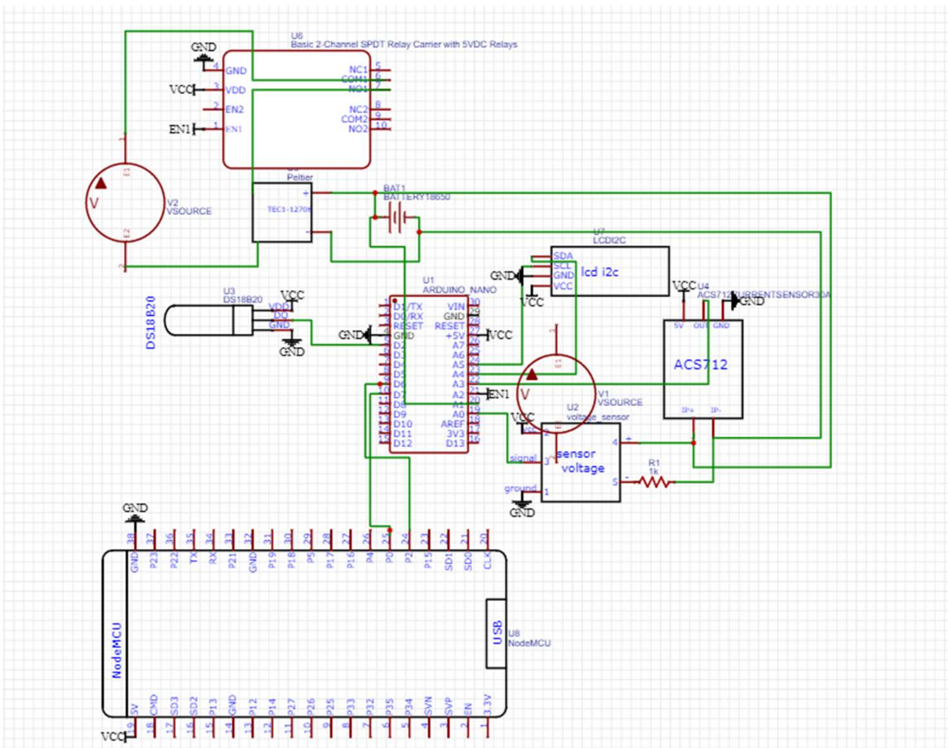


Figure :5.11 Circuit diagram for present IOT module.

5.6 Thermoelectric Materials with Nanotechnology

Micro-controllers and their peripherals typically talk to one another using the Serial Peripheral Interface (SPI) bus. Communication via the I2C Language Protocol: I2C communication makes use of pins A4 and A5; A4 is the serial data line (SDA) and transfers data, and A5 is the serial clock line (SCL) and synchronises devices on the I2C bus. The master device supplies this signal. Nanotechnology has allowed for the manipulation of TE material structure at the nano level, opening up opportunities to increase the efficiency of TE materials by modifying their thermal conductivity, electrical conductivity, and so on. Superlattice, nanowire, and quantum well are the three most important nanotechnologies.

Figures 5.22 show a superlattice made up of alternating nanosized layers with a thickness of less than 5 nm. These layers prevent the flow of heat-generating atomic vibrations but allow electrons to move freely as electrical current. The thermal conductivity can be lowered by introducing interfacial phonon scattering sites. More than twice as efficient as prior bulk thermoelectric materials, the superlattice architectures are promising. Because the nanowire structure prevents phonons from propagating freely, it enhances TE material properties. In the instance of Si nanowires, a notable advancement has been recorded. Thermoelectric performance suffers greatly in bulk Si. However, the Seebeck coefficient and electrical resistivity were largely unaffected by the use of Si nanowire arrays to lower thermal conductivity. Researchers synthesised rough Si nanowire arrays on a wafer scale with a diameter of 200-300 nm using electrochemical methods. In respect to electrical resistivity and the Seebeck coefficient, the material is identical to doped bulk Si. However, the thermal conductivity of Si nanowires with a diameter of around 50 nm was found to be reduced by a factor of 100 at room temperature, leading to a value of $ZT = 0.6$. It is also possible to construct a wide variety of converter circuits by manipulating fundamental converters in different ways (for instance, by connecting converters in a cascade), the boost converter diagram with input blocks shown in the figure 5.12.

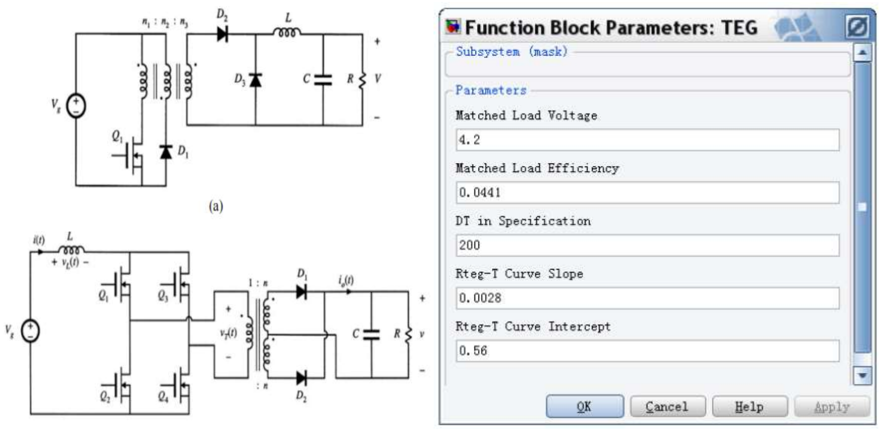


Figure:5.12 DC-DC boost converter and functional block

5.7 IMPEDANCE MATCHING

TEGs typically provide voltages that are too low to be used as a direct power supply for many electronic devices. Therefore, DC-DC converters are both useful and required for achieving the required voltage rise. Additionally, the DC-DC converter can regulate the variable TEG voltage under different environmental circumstances and the simplified TEG system diagram has shown in figure 5.13.

Figure:5.13 Simplified TEG system diagram

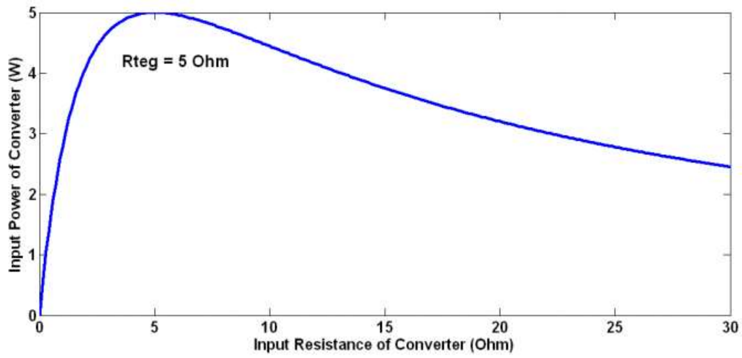


Figure: 5.14 Input power of converter as a function of *R*in

The converter resistance of selected module for the input power represented in the figure 5.14.

5.8 RESULTS AND DISCUSSIONS

The test apparatus was a TEG-based assembly composed of stainless steel (SS316). The major suggestion assumed a flu gas temperature range of roughly 90 to 120^{0}C. Figure 5.15 shows the heat losses during an experiment; the Seebeck effect varies by about 30%.

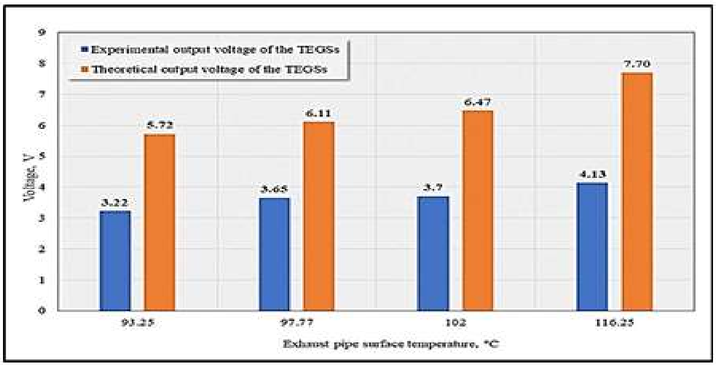


Figure: 5.15 The theoretical and experimental output voltage of TEGs

The test setup further checked with regular atmospheric temperatures with the TEG to check performance. The IOT connected flow charts are given with P& O algorithm with optimal voltage and power tracking after Seebeck effect has beed shown in figures 5.16 &5.17.

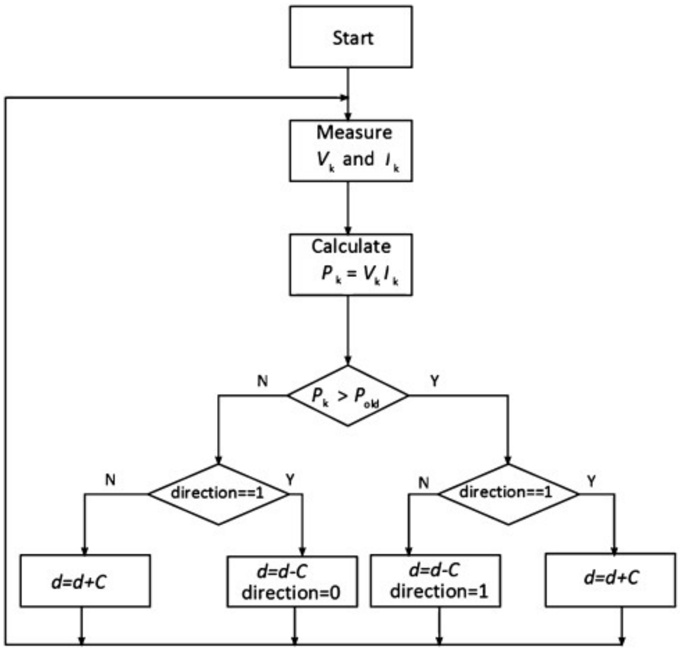


Figure 5.16: Control flow chart for the calculation using IOT results with P&O algorithm

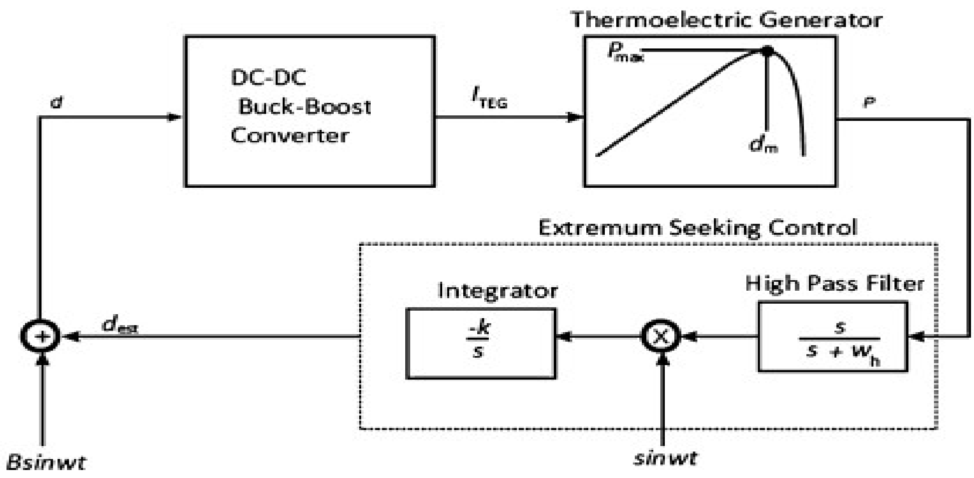


Figure 5.17: ESC block diagram for control

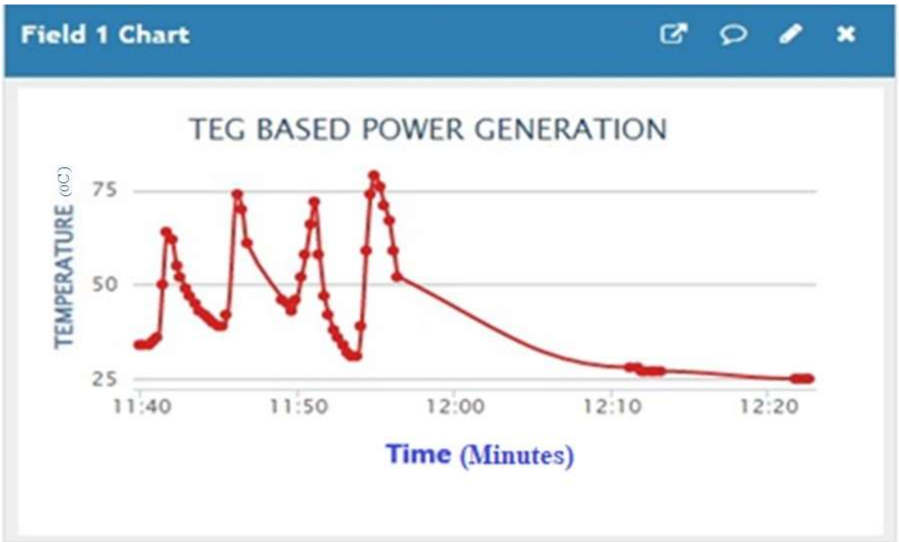


Figure 5.18: Temperature flow in the duct attached to TEG

Figure 5.19: Voltage variation attached to TEG with time

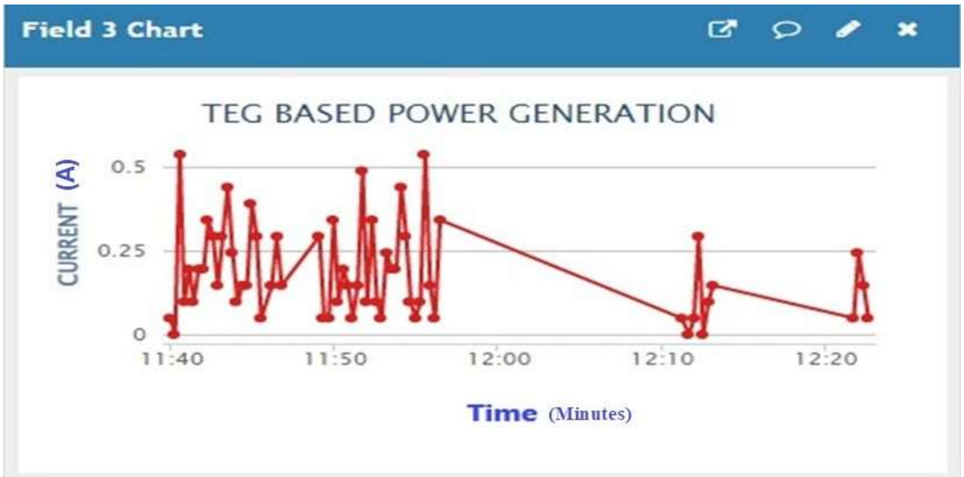


Figure 5.20: Current variation attached to TEG with time

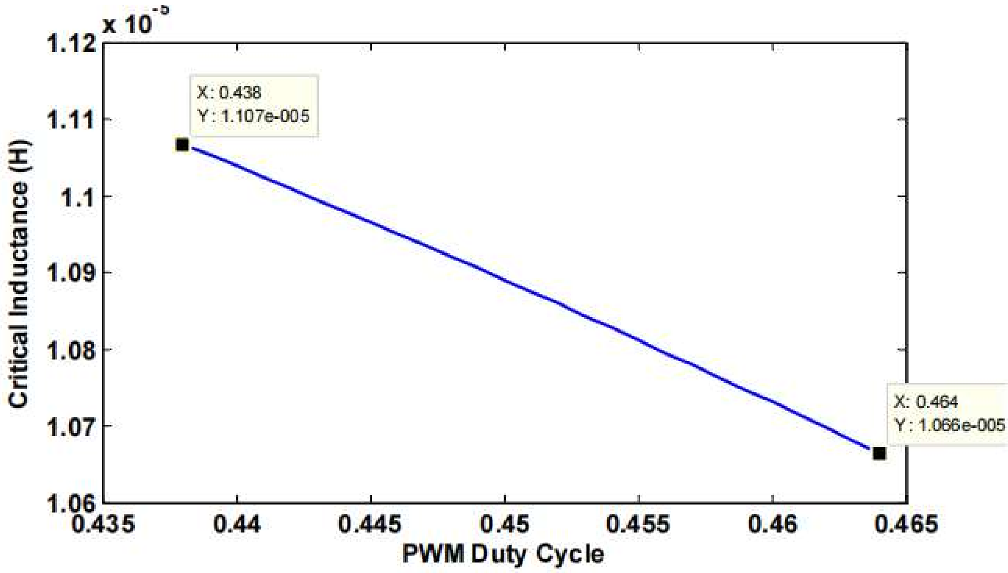


Figure 5.21: PMW duty cycle

Experimental results with IOT testing module the voltage (V), current (A) and temperature (^{0}C) in the selected time with duty cycle has been show in the figure 5.18,5.19,5.20 and 5.21 respectively.

Table:5.1 Power generation for single TEG

Time	Temperature (^{0}C)	Voltage (v)	Current (A)
11.40	30	0.6	0.15
11.50	40	0.75	0.36

12.00	54	0.9	0.52
12.10	28	0.35	0.14
12.20	24	0.2	0.12

Table:5.2 Power generation for four TEG

Temperature (^{0}C)	Voltage (v)	Current (A)
30	3	0.35
40	6	0.52
54	8	0.6
60	9	0.64
80	11	0.82

Table:5.3 Power generation for four TEG at higher temperatures

Temperature (^{0}C)	Voltage (v)	Current(A)
150	6	0.35
175	8	0.52
200	13	0.6
225	14.5	0.94
250	17	1.9

Discussions: Different temperatures were checked with the present assembly by assuming the vehicle in motion the output calculated using P&O algorithm and duty-cycle attachment. The results are tabulated in 5.1, 5.2, 5.3 and divided as nearby ambient, high and higher temperatures; it can be clearly shown that increase in temperature given good results. The table 5.1 shows a relationship between time, temperature, voltage, and current. The general trend is that as temperature increases, both voltage and current tend to increase, likely due to the device's negative TCR. The table 5.2 demonstrates a clear correlation between temperature, voltage, and current. The increasing voltage and current with temperature suggest a device with a negative TCR. The table 5.3 demonstrates a clear correlation between temperature, voltage, and current. The increasing voltage and current with temperature suggest a device with a positive TCR.

5.9 TEG placement in electric vehicle.

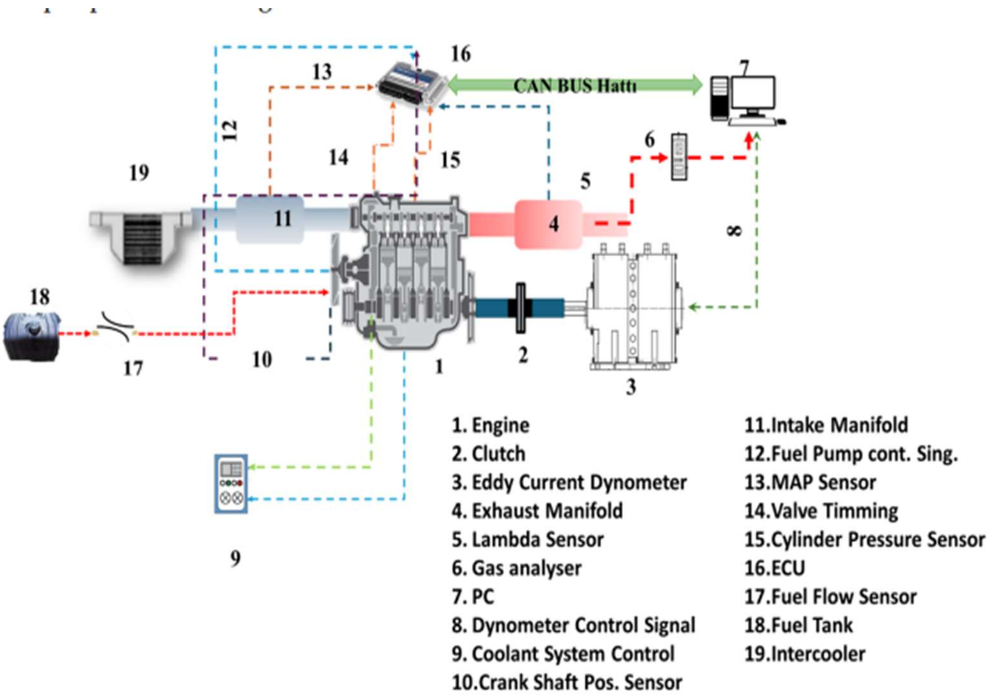


Figure 5.22. Schematic view of the experimental setup

The schematic view of experimental setup was show in figure 5.222. It consists of Engine, clutch, eddy current dynameter, exhaust manifold, lambda sensor, gas analyser, PC, dynameter control signal, coolant system control, crank shaft pos senor, intake manifold, fuel pump cont sign, MAP sensor, valve trimming, cylinder pressure sensor, ECU, fuel flow sensor, fuel tank, intercooler.

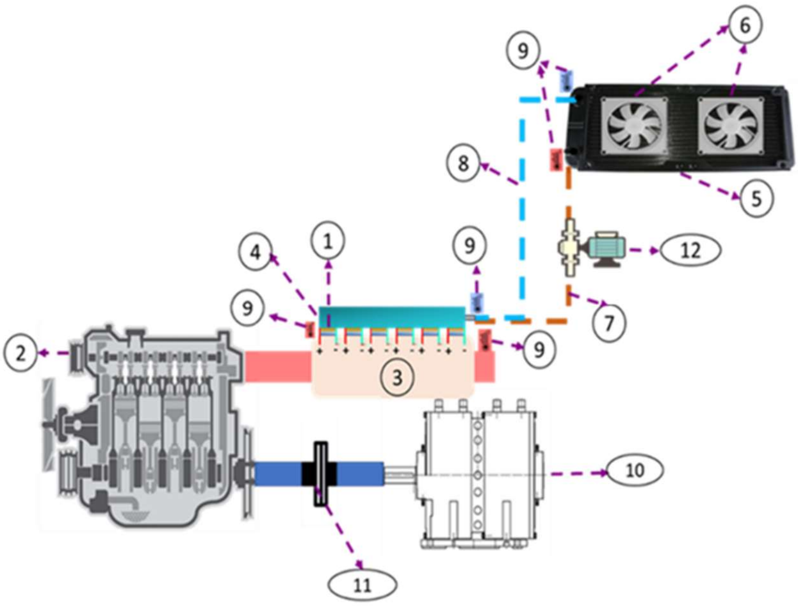


Figure 5.23: Schematic representation of the cooling circuit

Figure 5.23 shows the schematic representation of the cooling circuit which consists of Peltier modules, engine, exhaust manifold, cooler block, cooler radiator, fan motor, hot water line, coolant water line, thermometer, eddy current dyno, clutch, circulation pump.

Figure 5.24: TEG Placement in heavy vehicles.

In heavy vehicles TEG can be placed at exhaust system because at exhaust volume of 250 mm x 500 mm x 300 mm space is available. Figure 5.24 shows TEG placement in heavy vehicles.

Figure 5.25: Overall schematic setup for TEG Placement in heavy vehicle.

To keep the heat energy from the exhaust system, the TEG were placed downstream of the after-treatment system (ATS) as shown in Figure 5.25 where there is a free volume of 250 mm x 500 mm x 300 mm. Since all the exhaust gases pass through the ATS, the backpressure issue should also be considered and minimized.

5.10 Power Generation and Consumption in Thermoelectric Generators (TEGs)

Power generation with respect to temperature the results are shown in table 5.4, by observing these results increase of temperature.

Table 5.4: Power Generation as per our module

Temperature	Voltage (v)	Current(A)	Power (W)/ cycle per 10 second	Power Per hour (6*60) (in 1 minute 6 cycles) in Watt
150	6	0.35	2.1	756
175	8	0.52	4.16	1497.6
200	13	0.6	7.8	2808
225	14.5	0.94	13.63	4906.8
250	17	1.9	32.3	11592

Table 5.5: Power Consumption for Cooling of TEG Module

Equipment	Rating in Watt	Quantity	Power Consumption per hour in watt
Heater	2000	1	2000
Fans	40	2	80
Water Pump	100	1	100

Power for other modules	500	NA	500
		Power Consumed	2680 W
		10% Extra	268
		Total Power Consumed	**2960 W**

Table 5.6: Cost for TEG Module with Cooling System

Name of Equipment	Quantity	Rate	Price
TEG	4	1500	6000
Heater	1	4000	4000
Fans	2	300	300
Water Pump	1	500	500
Display	1	500	500
Sensors	4	500	2000
IOT Module	1	5000	5000
Pipes		2000	2000
Wires		1000	1000
PCB Board	1	3000	3000
Others		5000	5000
		Total Cost	**28300/-**

Comparison of voltage, current and power with the existing system for the duration of 1 minute

Power consumption with respect to temperature the results are shown in table 5.5, by observing these results increase of temperature. Table 5.6 show the Cost for TEG Module with Cooling System.

5.11 Conclusions:

Experimentation of testing has been conducted with the IOT attachment to check the power output instantly in their network region. Th outputs with practical outcome shows the practical voltage and power losses. The comparison of the simulation results find in chapter 3, the difference of experimentation about to be 5 to 8% less, can consider as heat loss. A comparison of simulation results obtained from MATLAB and CFD models with experimental data collected from an Internet of Things (IoT) setup. The system under investigation is a 4-TEG (Thermo electric Generator) system operating under different temperature conditions and a constant 14 kg engine load.

IOT is an experiment for the validation of two mathematical models of MATLAB and CFD. The specific conclusions are given below

1. At the temperature of 2000C the experiment result shows an output voltage of 10.26 which is the nearby voltage shown in CFD. The environment heat losses cannot be estimated in CFD the loss value in voltage is 0.44v can be considered. Likewise, the respective losses at 2500C is 0.57, 3000C is 0.6 and at 3500C it is0.66v.

2. The comparison made at the medium Reynolds number of air mixtures, the MATLAB shows the least values of Seebeck effect in voltage and current.

3. At the temperature of 200^{0}C the experiment result shows an output current of 0.32A which is the nearby voltage shown in CFD. The environment heat losses cannot be estimated in CFD the loss value in voltage is 0.34A can be considered. Likewise, the respective losses at 250^{0}C is 0.35, 3000C is 0.38 and at 350^{0}C it is 0.4A.

Chapter 6
CONCLUSIONS AND RECOMMENDATIONS

Comparative analysis of different approaches in the area of multiple TEG replacements on exhaust emission heat transfer module using Seebeck effect studied in the present research. A primary method of variation in various electrical parameters like voltage, current studied using MATLAB with two methods Fuzzy and ANN to check the output simulations under various temperature conditions of exhaust gas. The power conditions were noted to check with further mechanical modeling of four TEG tested with different temperatures and Reynolds number assuming the condition of exhaust emissions. The final approach done with addition of IOT module practically with practical prototype to validate the conditions of internal gas temperatures. All compared at this level to know the practical heat losses and power losses difference to simulation

The comparative analysis given below

Table 6.1: At 3 kg load for 4-TEG modeled

	MATLAB		CFD		Experiment (IOT)	
Temperature	Output Voltage	Output Current	Output Voltage	Output Current	Output Voltage	Output Current
200	9	0.18	10.8	0.34	10.26	0.32
250	10.6	0.42	11.3	0.37	10.73	0.35
300	11.8	0.6	12.1	0.40	11.50	0.39
350	13.0	0.63	13.3	0.42	12.64	0.4

Three methods have been compared from the experimental and simulated results for neural network optimization. Output current is better than the others. Thermos-electric with CFD analysis voltages are slightly higher than Mat-lab, where output power difference increases simultaneously. Based on the experiment, the values are almost equal to those predicted by the CFD of 4 TEGs. The break applicability of 3 kg was affected by a difference of 4 to 5 percent at lower load conditions. At high temperatures, the exhaust emission temperatures of electric vehicles are taken into account. As a result of the mixed emissions, exhaust temperatures could change, which may affect the calculations of power and efficiency. As shown in table 6.1 the difference between CFD, and the experimentation is approximately 1Volt. The study taken for instantaneous time, if time progress there may be a difference of 3 to 5%.

Table 6.2: comparative analysis with Reynolds number

	Temperature (^oC)	Power (W)	Efficiency (%)
Reynolds value-1	200	0.25	0.45
	250	0.41	0.62
	300	0.64	0.78
	350	0.82	0.8
Reynolds value-10	200	0.38	0.56
	250	0.56	0.68
	300	0.74	0.82
	350	0.93	1
Reynolds value-100	200	0.68	0.61
	250	0.93	0.72
	300	1.24	0.88
	350	1.51	1
Reynolds value-1000	200	2.24	0.63
	250	3.38	0.78
	300	4.26	0.92
	350	4.88	1

By observing the results obtained from different Reynolds number, efficiency increasing with the increase of Reynolds value as shown in table 6.2.

Table 6.3: Comparison of TEG results

Reference No	Temperature difference in	MPPT	Power in	No of

	Deg C	Technique	watts	TEGS
Reference No 102	230	P & O	253.2	20
Reference No 103	41.6	Fractional open-circuit voltage	0.02	2
Reference No 104	200	Power differentials	1.45	2
Reference No 105	200	High frequency injection	5.5	2
Reference No 106	26.85	Adaptive Duty cycle scaling algorithm	0.3	Not Specified
Reference No 107	200	Reduced voltage sensors count control	10.5	Not Specified
Reference No 108	200	Open-circuit voltage	10.2	Not specified
Our Work	250	Artificial Neural Networks	260	4

Table 6.3 shows comparison of TEG results. Hayat Mamur, Yusuf coban proposed P&O MPPT method for TEG where 20 TEGs is used and generates power of 253.3 W. Alexandros paraskevas, Eftichios Koutroulis proposed fractional open circuit voltage MPPT with two TEGs generated 0.02 W. As per Khalid Yahya, Osama Alomari proposed Power differentials MPPT with two TEGs generates power of 1.45 W. Romina Rodriguez, Matthias Preindl proposed high frequency injection MPPT with two TEGs generates 5.5 W. Trevor Hocksun Kwan, Xiaofeng Wu proposed adaptive duty cycle scaling MPPT algorithm generates 0.3 W. Zakariya M Dalala, Osama Saadeh proposed reduced voltage sensors count control MPPT generates 10.5W.

Andrea Montecucco, Andrew R Knox, proposed open circuit voltage MPPT at 200 deg C generates power of 10.2W. In our research we proposed artificial neural networks MPPT with four TEGs at 250 deg C generates power of 260 W. Compared to previous studies the present research gives 15% of additional power with the same setup followed in the previous one.

A TEG system for recovering waste heat from the exhaust of semi-truck engines was validated analytically and experimentally. The validation was conducted utilising a TEG system, which includes a temperature sensor, a thermometric module, and a heat exchanger. Validation results demonstrated that the TEG system could efficiently convert engine exhaust waste heat into electricity, with efficiency being defined as the quantity of energy transformed from waste heat to electricity. The efficiency of the TEG system is directly proportional to the temperature differential between the cooling medium and the exhaust gas. How well the cooling medium conducts heat also has a role. The efficiency increases as the temperature differential increases.. The optimal temperature difference for the TEG system was between 200-500°C, as this was the temperature range where the system generated the highest amount of electricity from the waste heat of the engine exhaust. At steady state, the system's energy balance and junction temperatures on both cold and hot sides were determined, as well as the junction temperature.

- Comparative results checked and the following conclusions were drawn from the entire work.
- This study's findings demonstrate the efficacy of the artificial neural network technology used to monitor the generation circuit's maximum power point through TEG.
- To maintain a sufficient output while modifying the electrical demand during TEG generation, the SEPIC converter can also be utilised.
- The optimal operating temperature for optimum power can be quickly and accurately identified using a neural network.
- Neural networks are used for TEG maximum power-point tracking due to their superior dynamic performance compared to other methods.

Maximum PowerPoint usage is also tracked by the SEPIC converter. Smooth mode transitions and respectable MPP tracking are just two experimental results demonstrating the efficacy of the proposed control approaches for the power conditioning system.

High fluid velocities and temperatures result in greater power output, and increasing efficiency correlates with increasing Reynolds numbers At high temperatures and fluid flow rates (high Re value), the efficiency of the Seebeck effect improved.

In this work, convection is used to confirm the thermoelectric effects of naturally cooling devices. The Reynolds number is taken into account in the present study due to its correlation with the rise in velocity flow of hot gases.

As temperature increases with Reynolds number, the Seebeck effect also becomes more efficient; preliminary validation was made by comparing Chen et.al's work with 2 TEG and our proposed duct with 4 TEG, which increased in efficiency.

The experiment was designed to help validate the accuracy of the analytical model by comparing the measured and predicted values of the TEG module.

The results of the experiment showed that the accuracy of the analytical model was quite good, indicating that it can be a reliable tool for estimating the thermal properties of materials. This agreement indicates that the analytical model can accurately calculate the thermal properties of the material. This is essential for many applications, such as thermal management systems.

The model is also useful in predicting materials' behaviour at temperatures not easily measurable. This is true in extreme environments or at high temperatures.

Additionally, the analytical model can be used to simulate thermal device performance, allowing engineers to optimize the design for maximum efficiency.

This improved the accuracy of the analytical results because it took into account all of the individual physical phenomena that are involved in thermal device performance, such as the contact resistances and Seebeck effects. This allowed engineers to more accurately simulate the performance of the device and optimize the design for maximum energy efficiency.

IoT-TEG 4.0 provides an intuitive interface that enables users to create events quickly and easily, without writing code.

This allows users to quickly create events that trigger actions, such as sending an alert or updating a log file, without having to write any code. It also makes it easier to manage events, as users can simply update the event definition instead of rewriting the entire event.

- In order to test IoT systems more accurately, we obtained test events 4.0.The test events obtained by 4.0. This is beneficial as it allows developers to test IoT systems using the same data that they would use in a real-world application, allowing them to gain a better understanding of how the system behaves in different contexts.
- It also allows for more accurate testing of system behaviors, since test events can be designed to provide a more real-world like experience. IoT-TEG 4.0 allows for more thorough testing of system behaviors, as it can simulate real-world conditions such as multiple device interactions, different user behaviors, and more complex scenarios.
- Additionally, it covers a wider range of use cases and different types of tests, allowing for a comprehensive evaluation of system behavior.
- The final testing module of 4-TEG connected to IOT given best results when compared with 2-TEG modules.
- The experimentation and simulation works are quite interesting and the obtained results deviation is much lower, the work can take a bench mark for future TEG based systems.

Future scope

1. Multiple TEG based attachment for waste heat recovery in automobile applications is main objective for present work. Multiple Array of TEG's can be tested for further extension.
2. Present work focused on limited range of temperatures and limited TEG; this can be increased in future work.
3. Materials of duct can be varied in future work.
4. The present research is limited for conversion of heat energy to electrical power by using multiple TEG. Cost analysis, economization of components needs to be researched further.

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