A MAJOR PROJECT REPORT

ON

SIMULATION OF TEG MODULE USING MATLAB

Submitted in the partial fulfilment
for the award of a degree in

Bachelor of Technology

in

Electrical Engineering

Submitted By

Mohammad Azhar Naushad (22EE78LE)
Vishwas Kumar (22EE78LE)
Sonu Kumar (22EE78LE)
Amresh Gaurav (22EE83LE)

Under the supervision of

Prof. Kumar Saurabh, Assistant Professor
Department of Electrical Engineering

Academic Year 2022-25 LE

Department of Electrical Engineering,

Government Engineering College, Bhojpur

South East Ramna Road, Near Maharaja College, Ara,

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DEPARTMENT OF ELECTRICAL ENGINEERING
GOVERNMENT ENGINEERING COLLEGE, BHOJPUR
South East Ramna Road, Near Maharaja College, Ara

CERTIFICATE

This is to certify that the project work entitled "Simulation of TEG Module using MATLAB" submitted by Mohammad Azhar Naushad (22EE81LE), Vishwas kumar (22EE78LE), Sonu Kumar (22EE74LE) and Amresh Gaurav (22EE83LE) to the Department of Electrical Engineering, Government Engineering College,Bhojpur in partial fulfilment of the requirement for the award of the Degree of Bachelor of Technology in Electrical Engineering is an authentic work carried out by them under my supervision and guidance.

The matter embodied in the report has not been submitted to any other University/ Institute for the award of any degree or diploma.

Date: -

Prof…………………..

(Project Supervisor)

Examined and Approved

Signature of Project Coordinator/ Internal Examiner

Signature of External Examiner

Head of the Department

DEPARTMENT OF ELECTRICAL ENGINEERING
GOVERNMENT ENGINEERING COLLEGE, BHOJPUR
South East Ramna Road, Near Maharaja College, Ara

CANDIDATE'S DECLARATION

We hereby declare that the work presented in this report titled "Simulation of TEG Module using MATLAB" is an authentic record of our own work carried out at the Department of Electrical Engineering, Government Engineering College, Bhojpur as requirements for the award of the degree of Bachelor of Technology in Electrical Engineering, submitted in Government Engineering College, Bhojpur for the session 2021-25 under the supervision of Prof. Kumar Saurabh.

We also, hereby declare that we have not adopted any practice that can be quoted as plagiarism. In case of plagiarism, we take sole responsibility for the act.

Md. Azhar Naushad	*22103156918*
Vishwas kumar	*22103156910*
Sonu Kumar	*22103156914*
Amresh Gaurav	*22103156916*

Acknowledgement

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We wish to express our profound gratitude to my esteemed Project Guide, *Prof. Kumar Saurabh*, Assistant Professor, Department of Electrial Engineering, whose unwavering guidance has been more than a mentor; they have been a source of inspiration, pushing boundaries, challenging perspectives, and instilling in me a passion for excellence. His expertise, coupled with their patience and encouragement, has transformed hurdles into stepping stones, propelling me toward success.

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Place: Department of Electrial Engineering,
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ABSTRACT

This experiment is an extended form of our Previous experiment which is Hybrid Vehicle Thermo Electricity Generation.Where we analyse performance of TEG using Hardware apparatus as well as MATLAB Simulation.

Thermoelectric Generator (TEG) modules, which harness the Seebeck effect to convert temperature gradients into electrical energy, have diverse applications across various industries and scenarios. It has been widely used in many industries like Space Exploration, Military and Emergency Use, Environmental Monitoring etc. It is also used by BMW to utilize Heat from heat from vehicle exhaust systems or engines into electricity to power onboard electronics, reducing fuel consumption. This Report aims to give a brief review on key technology of Thermo electricity Generation and its application in Hybrid Vehicles. Improving the efficiency of an internal combustion engine (ICE) leads to the reduction of fuel consumption, which improves the performance of a hybrid vehicle. Waste heat recovery (WHR) systems offer options to improve the efficiency of an ICE. This is due to the ICE releasing approximately one third of the combustion energy as waste heat. Thermoelectric generator (TEG) can be used as a waste heat recovery system in a hybrid electric vehicle. It also contains Practical observations and Results considering speed of wheels at 2000RPM. We have taken all necessary data and analysis from several Pre-published Research Papers.

We have analysed the generation of electrical energy through Practical Observations as well as through MATLAB Simulations. We have used MATLAB R2024A to Simulate our TEG model, more economically and precisely. MATLAB is a software which used to perform several experiments efficiently and it can lead to enhance our knowlwdge thoroughly.

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Chapter 01

Introduction

By 2040 it is estimated that the world's energy consumption will increase by almost 50%. The development of electric vehicles such as hybrid electric vehicles (HEVs) and battery electric vehicles (BEVs)

A HEV contains both an internal combustion engine (ICE) and an electric propulsion system. All vehicles that use combustion engines experience energy loss in terms of heat loss. Current internal combustion engines are approximately 25% efficient under current driving cycle certification. The range of efficiency can vary between 35% and 45% for modern engines depending on the type of engine and driving cycle.

We use TEG modules for waste heat recovery (WHR). We want to increase overall efficiency of the Hybrid Electric Vehicles.

The TEG system converts the heat loss directly into electrical power. But the efficiency of TEG is lies between 6% to 18%.

We are trying to perform an experiment through which we find out the real time variation in the output and temperature changes.

There are several prior research works has been published for the waste heat recovery of Internal Combustion Engine of Hybrid cars. But these researches use exhaust gases and engine coolant.

They Create the required temperature difference for the TEG modules to generate electricity. The Exhaust gases heat up the up surface of TEG module and the coolness from the Coolant of the radiator pipe.

Chapter 02

Problem Statement

The efficiency of an internal combustion engine (ICE) leads to the reduction of fuel consumption, which improves the performance of a hybrid vehicle. Waste heat recovery (WHR) systems offer options to improve the efficiency of an ICE. This is due to the ICE releasing approximately one third of the combustion energy as waste heat into the atmosphere. A Typical HEV has the efficiency of 30–40% only.

Heat loss from the ICE and electric systems lowers the vehicle's overall energy utilization.

- **Primary Heat Loss**:

  Exhaust Gas: ~30–40% of fuel energy is lost as heat through the exhaust. **Cooling System**: ~20–30% of energy is dissipated via the radiator. **Friction and Mechanical Losses**: ~5–10% of energy is wasted in engine components (e.g., pistons, bearings).

- **Impact**: Limits overall efficiency (ICE efficiency: 20–35%) and increases fuel consumption.

In this Project we want to utilize the lost energy in the form of Heat to Electricity by using TEG modules.

CHAPTER 3

Literature Survey

1. Hybrid Vehicle: -

Hybrid vehicles represent a significant advancement in automotive technology, combining the benefits of internal combustion engines (ICEs) and electric propulsion systems to improve fuel efficiency, reduce emissions, and enhance overall performance. These vehicles utilize a dual powertrain system that integrates an ICE with one or more electric motors and a battery pack, enabling them to operate in various modes depending on driving conditions. Below, we provide a detailed explanation of hybrid vehicles, including their working principles, types, advantages, challenges, and ongoing research trends.

Types of Hybrid Vehicles: -

a) Series Hybrid Vehicles: -

A **series hybrid vehicle** is a type of hybrid electric vehicle (HEV) that uses an internal combustion engine (ICE) solely to generate electricity, which then powers an electric motor that drives the wheels. Unlike parallel or series-parallel hybrids, the ICE in a series hybrid does not directly provide mechanical power to the wheels. Instead, it acts as a generator, making series hybrids unique in their design and operation. Below, we explore the working principle, components, advantages, disadvantages, and applications of series hybrid vehicles in detail.

1. Working Principle of Series Hybrid Vehicles

In a series hybrid vehicle, the powertrain is designed such that the ICE and the wheels are not mechanically connected. Instead, the ICE drives a generator, which produces electricity to power the electric motor(s) that drive the wheels. The key components and their interactions are as follows:

Key Components:

1. **Internal Combustion Engine (ICE)**: Typically, a gasoline or diesel engine that operates at a constant, optimal speed to generate electricity.
2. **Generator**: Converts mechanical energy from the ICE into electrical energy.
3. **Electric Motor(s)**: Provides propulsion by converting electrical energy into mechanical energy to drive the wheels.
4. **Battery Pack**: Stores electrical energy for use by the electric motor(s) and is recharged by the generator or through regenerative braking.

5. **Power Control Unit (PCU)**: Manages the flow of electricity between the generator, battery, and electric motor(s). 6. **Transmission**: Transfers power from the electric motor(s) to the
wheels.

Modes of Operation:

1. **Electric-Only Mode**: The vehicle runs solely on electric power from the battery, with the ICE turned off. This mode is used for short distances or low-speed driving.
2. **Series Hybrid Mode**: The ICE generates electricity to power the electric motor(s) and recharge the battery. The ICE operates at its most efficient RPM range, regardless of vehicle speed.
3. **Regenerative Braking**: The electric motor(s) act as generators during braking or deceleration, converting kinetic energy into electrical energy to recharge the battery.

2. Advantages of Series Hybrid Vehicles

1. **Optimized ICE Operation**: The ICE operates at a constant, optimal speed to generate electricity, maximizing fuel efficiency and minimizing emissions.
2. **Simplified Mechanical Design**: Since the ICE is not mechanically connected to the wheels, the drivetrain is simpler compared to parallel or series-parallel hybrids.
3. **Flexible ICE Placement**: The ICE and generator can be placed anywhere in the vehicle, allowing for greater design flexibility.
4. **Smooth and Quiet Operation**: The electric motor(s) provide smooth and quiet propulsion, especially in electric-only mode.
5. **Reduced Emissions**: By operating the ICE at its most efficient point and enabling electriconly driving, series hybrids produce fewer emissions than conventional vehicles.
6. **Energy Recovery**: Regenerative braking captures energy that would otherwise be wasted as heat.

Disadvantages of Series Hybrid Vehicles

1. **Energy Conversion Losses**: Converting mechanical energy from the ICE into electrical energy and then back into mechanical energy for propulsion results in energy losses, reducing overall efficiency.
2. **Limited High-Speed Performance**: Series hybrids may struggle with high-speed performance or heavy loads due to the reliance on electric motor(s) for propulsion.
3. **Battery Dependency**: The vehicle's performance is heavily dependent on the battery's state of charge, which can limit range and power output.
4. **Higher Cost**: The need for a larger battery pack and more powerful electric motor(s) can increase the cost of series hybrids compared to conventional vehicles.

5. **Complex Power Management**: Efficiently managing the flow of electricity between the generator, battery, and electric motor(s) requires sophisticated control systems.

4. Applications of Series Hybrid Vehicles

Series hybrids are particularly well-suited for specific applications where their unique characteristics provide significant advantages: **a. Urban Transit Buses**

- **Advantages**: Frequent stops and starts allow for extensive use of regenerative braking, while the ICE operates at a constant, efficient speed to generate electricity.
- **Examples**: Many city buses, such as those produced by New Flyer and Volvo, use series hybrid systems.

b. Delivery Vehicles

- **Advantages**: Stop-and-go driving in urban areas benefits from electric propulsion and regenerative braking, while the ICE ensures sufficient range for longer routes.

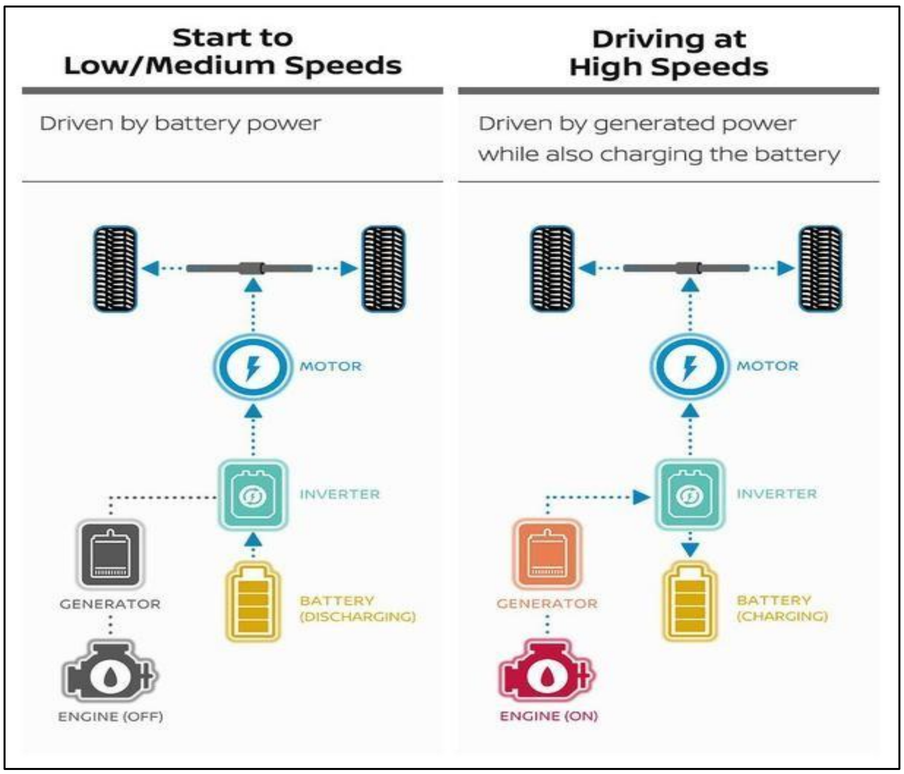


Fig 1.1 Series Hybrid Vehicle

b) Parallel Hybrid Vehicles: An In-Depth Exploration

A parallel hybrid vehicle is a hybrid electric vehicle (HEV) in which both the internal combustion engine (ICE) and the electric motor(s) are mechanically connected to the drivetrain, enabling either or both power sources to drive the wheels directly. This architecture allows for dynamic energy management, optimizing fuel efficiency and performance across diverse driving conditions. Below is a detailed breakdown of their design, operation, benefits, challenges, and applications.

1. Core Architecture and Operation

Key Components:

1. **Internal Combustion Engine (ICE):** Typically, gasoline or diesel-powered, used for highspeed cruising, long-range driving, or when battery power is depleted.
2. **Electric Motor(s):** Provides torque for acceleration, assists the ICE, and enables electric only driving at low speeds.
3. **Battery Pack**: Stores energy for the electric motor(s), recharged via regenerative braking or the ICE.
4. **Power Split Device (PSD)/Clutch:** Mechanically couples or decouples the ICE and electric motor(s) from the drivetrain.
5. **Transmission**: Transfers power to the wheels (e.g., automatic, CVT, or dual-clutch systems).
6. **Power Control Unit (PCU):** Manages energy flow between the ICE, motor(s), and battery.

Modes of Operation:

- **Electric-Only Mode**: The vehicle runs on the electric motor(s) alone, ideal for low-speed urban driving (e.g., Toyota Prius in EV mode).
- **ICE-Only Mode**: The ICE drives the wheels directly, typically at highway speeds or under heavy load.
- **Hybrid Mode:** Both the ICE and electric motor(s) work together to maximize efficiency and power (e.g., during acceleration).
- **Regenerative Braking:** Converts kinetic energy into electricity during deceleration, storing it in the battery.
- **Engine Charging**: The ICE generates electricity to recharge the battery when needed.

2. Advantages of Parallel Hybrids

1. **Fuel Efficiency:**
   - Achieves 20–35% better fuel economy than conventional ICE vehicles by optimizing power sources (e.g., Honda Insight: ~52 mpg).
   - Electric motor assists the ICE during acceleration, reducing fuel consumption.
2. **Reduced Emissions:**
   - Lower CO_2 and NO_x emissions, especially in stop-and-go traffic where electric mode dominates.
3. **Performance Enhancement:**
   - Electric motors provide instant torque, improving acceleration (e.g., BMW Active Hybrid models).
4. **Cost-Effectiveness:**
   - Simpler design than series hybrids, with smaller battery packs and no dedicated generator.
5. **Flexibility:**
   - Adapts seamlessly to urban and highway driving without range anxiety.

3. Challenges and Limitations

1. Complex Drivetrain:
   - Requires precise coordination between the ICE, motor(s), and transmission, increasing mechanical complexity.
2. **Limited Electric Range:**
   - smaller batteries restrict electric-only driving to short distances (typically 1–2 miles in non-plug-in hybrids).
3. **Weight Penalty:**
   - Added weight from the motor(s) and battery reduces efficiency gains (e.g., ~100– 200 kg extra).
4. **Higher Initial Cost:**
   - More expensive than conventional ICE vehicles due to hybrid components (offset by fuel savings over time).

5. **Battery Degradation:**

    o Frequent charge/discharge cycles in urban driving can shorten battery lifespan.

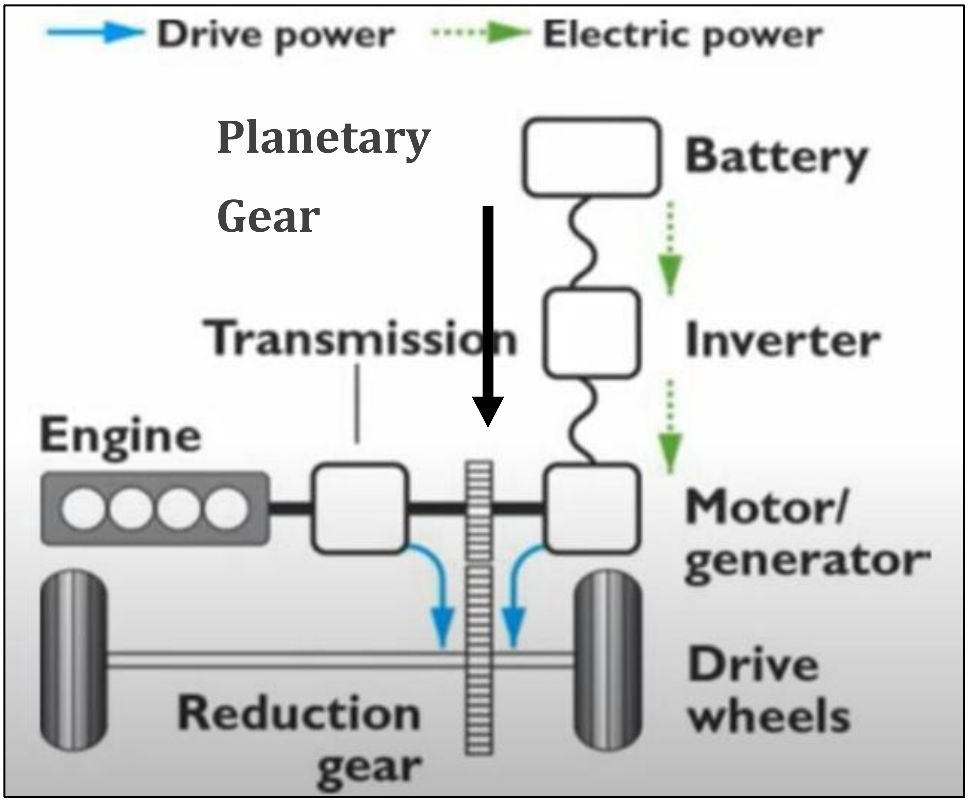


Fig. 1.2 Parallel Hybrid Vehicle

c) Series-Parallel Hybrid Vehicles: -

A series-parallel hybrid vehicle (often called a power-split hybrid) combines the features of both series and parallel hybrid architectures, allowing the internal combustion engine (ICE) and electric motor(s) to work independently or together to drive the wheels. This dual-mode operation maximizes efficiency, flexibility, and performance across diverse driving conditions. Below is a detailed breakdown of its design, operation, benefits, challenges, and applications.

1. Core Architecture and Components

Key Components:

1. **Internal Combustion Engine (ICE)**: Typically, gasoline or diesel-powered, used for highspeed cruising, long-range driving, or recharging the battery.

2. **Electric Motor(s):**

   o Primary Motor: Drives the wheels and regenerates energy during braking. o Generator Motor: Acts as a starter for the ICE and converts mechanical energy into electricity.

3. **Battery Pack:** Stores electrical energy (e.g., NiMH or Li-ion) for the electric motor(s).
4. **Power Split Device (PSD):** A planetary gearset (e.g., Toyota's Hybrid Synergy Drive) that mechanically and electronically distributes power between the ICE, motor(s), and wheels.
5. **Power Control Unit (PCU):** Manages energy flow between components.
6. **Transmission:** Often an electronically controlled continuously variable transmission (eCVT) for seamless power delivery.

2. Modes of Operation

The series-parallel hybrid dynamically switches between modes based on driving conditions: **a. Electric-Only Mode**

- Operation: The vehicle runs solely on the electric motor(s), powered by the battery.
- Use Case: Low-speed urban driving, short commutes (e.g., Toyota Prius at <25 mph).

b. Series Mode

- Operation: The ICE drives the generator to produce electricity, which powers the electric motor(s) or charges the battery.
- Use Case: Stop-and-go traffic, where ICE operation at optimal RPM improves efficiency.

c. Parallel Mode

- Operation: Both the ICE and electric motor(s) directly drive the wheels.
- Use Case: Highway cruising or heavy acceleration (e.g., merging onto a freeway).

d. Regenerative Braking

- Operation: The electric motor(s) act as generators, converting kinetic energy into electricity during deceleration.

e. Hybrid Mode

- Operation: The ICE drives the wheels while simultaneously charging the battery via the generator.

3. Advantages of Series-Parallel Hybrids

1. **Optimized Efficiency:**
   - The ICE operates at its most efficient RPM range, whether driving the wheels or generating electricity.
   - Fuel economy improvements of 30–50% over conventional ICE vehicles (e.g., Toyota Prius: 54–56 mpg).
2. **Flexibility:**
   - Seamlessly adapts to urban, highway, and mixed driving conditions.
3. **Reduced Emissions:**
   - Lower CO_2 and NO_x emissions due to minimized ICE use in urban areas.
4. **Smooth Performance:**
   - The e-CVT eliminates gear shifts, providing linear acceleration.
5. **Extended Electric Range (in PHEVs):**
   - Plug-in variants (e.g., Toyota Prius Prime) offer 25–40 miles of electric-only range.

4. Challenges and Limitations

1. **Complexity:**
   - The planetary gearset and dual motor/generator system increase mechanical and control complexity.
2. **Cost:**
   - Higher upfront cost due to advanced components (e.g., battery, e-CVT).

3. **Weight:**
    - Additional components add 150–300 kg compared to ICE vehicles.
4. **Battery Degradation:**
    - Frequent cycling in urban driving can reduce battery lifespan.

5. Applications and Examples

a. Passenger Cars

- Toyota Prius: The most iconic series-parallel hybrid, with over 15 million units sold globally.
- Ford Escape Hybrid: Uses a similar power-split architecture for SUVs.
- Lexus RX 450h: Luxury SUV with a refined hybrid system.

b. Commercial Vehicles

- Toyota Camry Hybrid: Used in taxi fleets for urban efficiency.
- Hyundai Tucson Hybrid: Combines SUV utility with hybrid efficiency.

c. Public Transport

- Toyota Coaster Hybrid: Minibus for city tours and shuttle services.

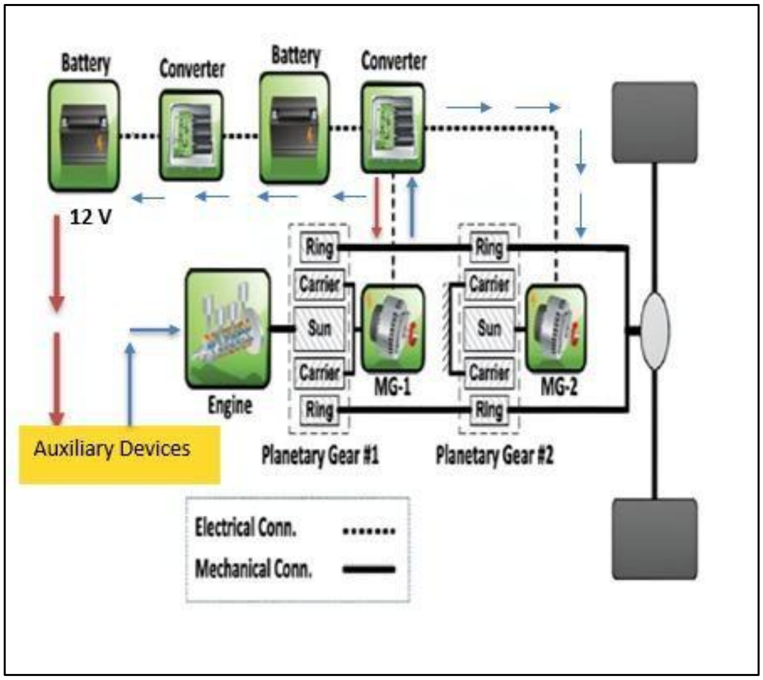


Fig. 1.3 Series-Parallel Hybrid Vehicles

Cooling System of Hybrid Vehicle

Cooling System of Hybrid Vehicles Through Coolant

Hybrid vehicles integrate an internal combustion engine (ICE) with electric motors and high voltage battery systems, necessitating a sophisticated cooling system to manage heat from multiple components. The coolant-based thermal management system is critical for optimizing performance, efficiency, and safety. Below is a structured explanation of how this system operates:

1. Components Generating Heat

- Internal Combustion Engine (ICE): Operates at high temperatures (~90–100°C).
- Electric Motors/Generators: Generate heat during power delivery and regeneration.
- Battery Pack (Li-ion): Requires cooling during charging/discharging (optimal range: 20– 40°C).
- Power Electronics (Inverter, Converter): Produce heat during energy conversion.

2. Cooling System Architecture

Dual or Multi-Loop Systems:

ICE Loop: Similar to traditional vehicles, using a water-ethylene glycol coolant mixture circulated via a mechanical pump.

Battery/Electronics Loop: A separate liquid-cooling circuit with electric pumps and dedicated radiators to maintain lower temperatures.

Integrated Systems: Advanced hybrids may use a shared coolant loop with heat exchangers and valves to prioritize cooling based on component needs.

3. Key Mechanisms

Coolant Types: Ethylene/propylene glycol-based fluids with anti-corrosion and anti-conductive additives to safeguard high-voltage components.

Thermal Regulation:

Sensors and Control Units: Monitor temperatures in real-time (e.g., battery cells, motor windings) and adjust coolant flow via electric pumps and valves.

Heat Exchangers: Transfer excess heat between loops (e.g., using ICE waste heat to warm the battery in cold climates).

Radiators and Fans: Dissipate heat to the environment, often with variable-speed fans for efficiency.

4. Specialized Features

Battery Cooling:

- Liquid-cooled plates or cold plates integrated into the battery module.
- Coolant channels direct flow around cells to maintain uniform temperatures.

Preconditioning:

In cold weather, waste heat from the ICE or electric heaters warms the battery to optimal operating temperatures.

Energy Efficiency:

- Electric pumps and fans reduce parasitic losses compared to engine-driven components.
- Smart algorithms balance cooling demands with energy consumption to preserve battery range.
-

5. Safety and Redundancy

- **Fail-Safes:** Redundant pumps, temperature sensors, and software limits to prevent overheating
- **Thermal Runaway Mitigation:** Rapid cooling protocols and isolation of faulty battery cells to prevent cascading failures.

6. Challenges and Innovations

Complexity: Managing multiple temperature zones requires precise control systems.

Material Advancements: Dielectric coolants for direct immersion cooling of batteries.

Integration with HVAC: Cabin heating/cooling systems may share thermal resources with the battery loop for efficiency.

7. Example Applications

Toyota Prius: Uses a dual-loop system with a dedicated battery coolant circuit.

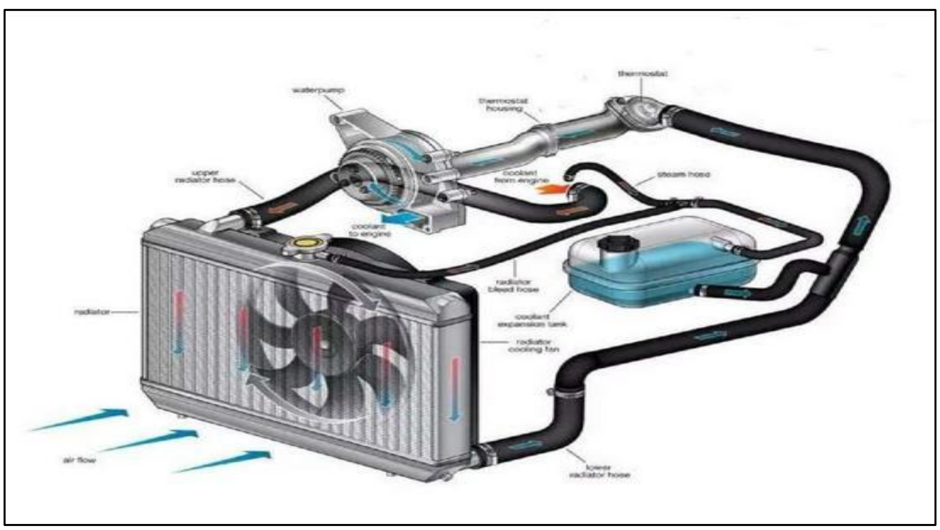
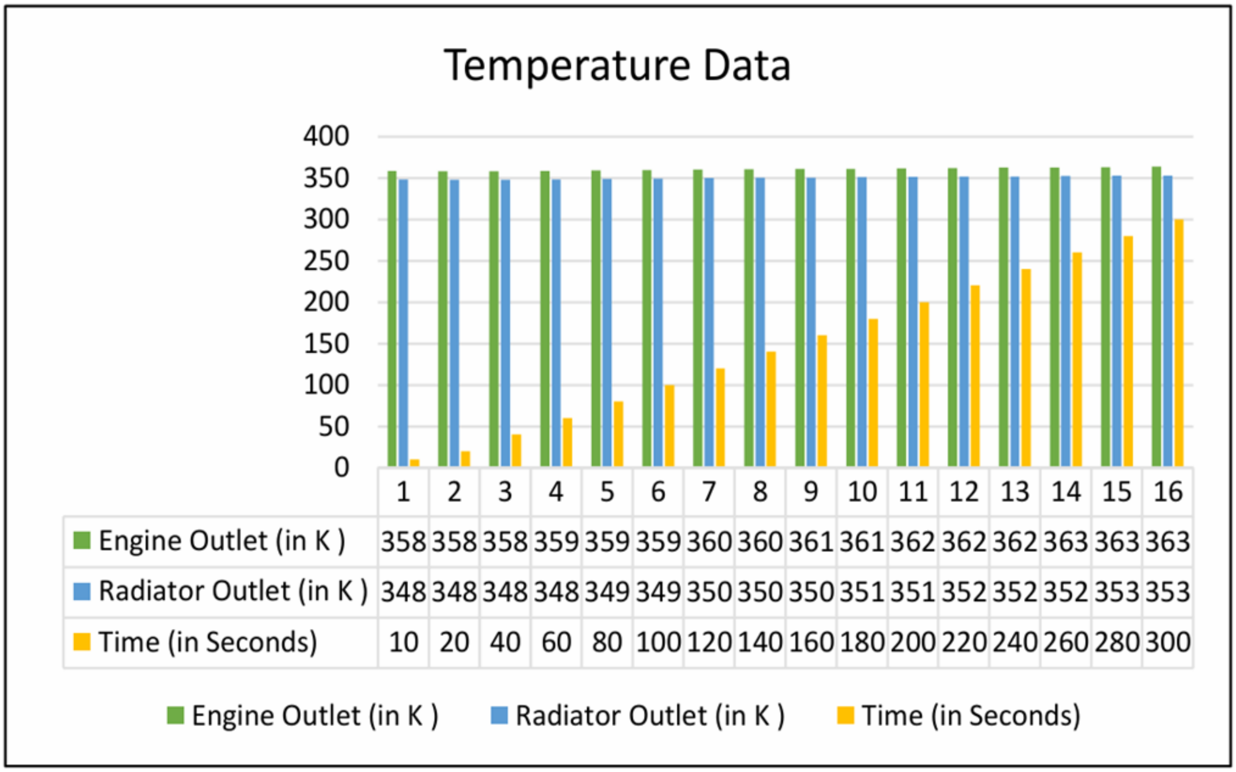


Fig. 1.4 Cooling System of ICE Engine

Temperature Data of Heat Generation and Heat Reimbursement of ICE System at speed of 2000RPM



<u>**Graph 1.1 Temperature Data**</u>

Thermo-Electric Generator (TEG)

What is TEG?

Thermoelectric generators (TEGs) represent a transformative technology in the field of energy harvesting, offering a direct method to convert thermal energy into electrical energy through the Seebeck effect. As global energy demands rise and environmental concerns over fossil fuel consumption intensify, TEGs have emerged as a promising solution for sustainable power generation, particularly in recovering waste heat—a vast and underutilized energy resource. This technology bridges the gap between thermodynamics and materials science, providing silent, maintenance free, and scalable energy conversion systems with applications spanning industries, transportation, aerospace, and remote sensing.

Principles of Operation

TEGs operate on the principle of the Seebeck effect, discovered by Thomas Johann Seebeck in 1821, wherein a temperature gradient across two dissimilar conductive or semiconductive materials generates an electromotive force (EMF). Modern TEGs leverage advanced thermoelectric (TE) materials arranged in modular configurations of p-type and n-type semiconductor legs. When one side of these legs is heated (e.g., by waste heat) and the other is cooled, charge carriers diffuse from the hot to the cold junction, producing a continuous direct current (DC). Unlike conventional heat engines, TEGs require no moving parts, eliminating mechanical wear and enabling operation in harsh environments.

Principle behind TEG

1. Core Phenomenon: The Seebeck Effect

- **Definition**: When a temperature gradient is applied across two dissimilar conductive or semiconductive materials, a voltage difference (thermoelectric voltage) is generated. This is the Seebeck effect.
- **Charge Carrier Movement:**
  - in n-type semiconductors (electron-rich), heat causes electrons to diffuse from the hot side to the cold side.
  - in p-type semiconductors (hole-rich), holes (positive charge carriers) migrate toward the cold side.
- **Result:** A potential difference develops between the hot and cold junctions, driving an electric current when connected to a load.

2. Module Structure

- **Thermocouples**: A TEG comprises multiple p-n semiconductor pairs (thermocouples) connected electrically in series and thermally in parallel.
- **Interconnects:** Metal strips (e.g., copper) link the semiconductors, forming a circuit. The hot and cold sides are typically ceramic plates for electrical insulation and thermal conduction.

3. Energy Conversion Process

- Temperature Gradient: Heat applied to one side (e.g., via waste heat) creates a temperature difference (ΔT) across the module.
- Charge Separation:
- Electrons in n-type and holes in p-type move toward the cold side, creating a voltage.
- The p-n pairs are arranged so their voltages add cumulatively, enhancing total output.
- Power Generation: The voltage drives a direct current (DC) through an external load

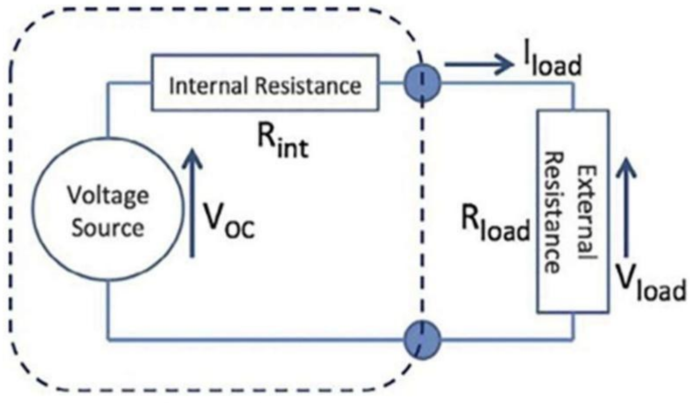


Fig. 1.6 TEG Circuit Diagram

4. Thermal Management

- Heat Sinks: Critical on the cold side to dissipate heat and sustain ΔT.
- Heat Sources: Common sources include exhaust systems, industrial processes, or even body heat.

5. Performance Factors

- Temperature Difference (ΔT): Output power scales with ΔT2ΔT2. Larger ΔT significantly boosts efficiency.
- Load Matching: Optimal power transfer occurs when the load resistance matches the TEG's internal resistance.
- Efficiency: Typically, 5–10% for commercial modules, limited by material properties and heat losses.

Working Capabilities of TEG

1. Fundamental Physics: The Seebeck Effect

The Seebeck effect, discovered by Thomas Johann Seebeck in 1821, is the cornerstone of TEG operation. It describes the generation of an electric voltage (ΔV) across a material when a temperature gradient (ΔT) is applied. This phenomenon arises due to:

Charge Carrier Diffusion:

In a temperature gradient, charge carriers (electrons in n-type, holes in p-type semiconductors) diffuse from the hot side (high thermal energy) to the cold side (low thermal energy).

Electric Field Formation: The accumulation of carriers at the cold side creates an internal electric field opposing further diffusion. At equilibrium, the Seebeck voltage ($\Delta V = S \cdot \Delta T$) is established, where S is the Seebeck coefficient (material-specific, in $\mu V/K$).

For a TEG module, the voltage output scales with the number of thermocouples (p-n pairs) in series.

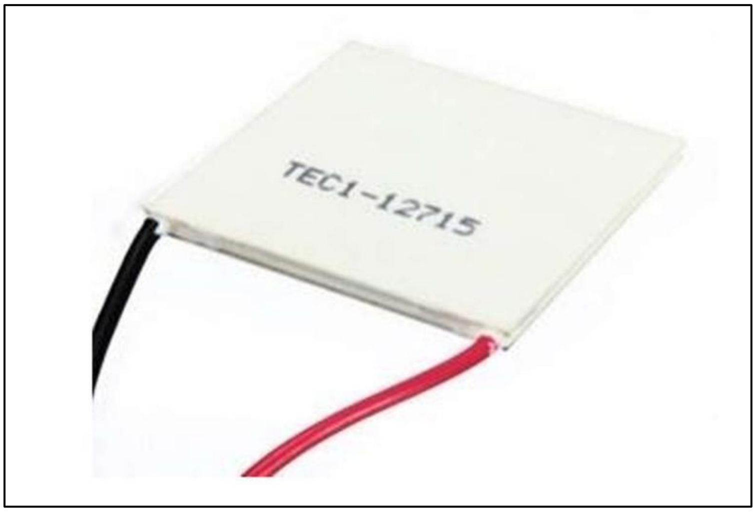


Fig. 1.7 TEC Module

2. TEG Module Architecture **A TEG module consists of:**

- p-n Thermocouples: Alternating p-type (hole-dominated) and n-type (electron dominated) semiconductor legs connected electrically in series and thermally in parallel.
- Interconnects: Metallic conductors (e.g., copper) that bridge the semiconductor legs, forming a closed circuit.
- Ceramic Substrates: Electrically insulating, thermally conductive plates that sandwich the thermocouples, ensuring mechanical stability and heat transfer.

Key Geometrical Parameters:

- Leg length (L) and cross-sectional area (A)

- Number of thermocouples (N)

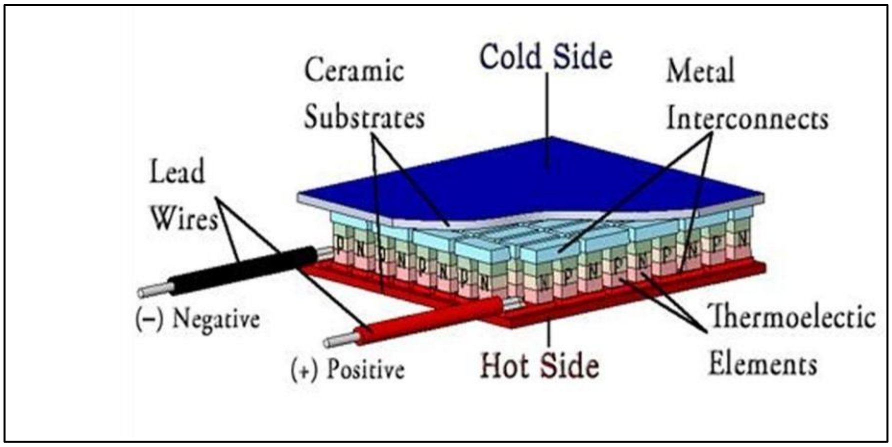


Fig. 1.8 Section of TEG

3. Energy Conversion Process

Thermal Input

Heat flows from a high-temperature source through the TEG module to a low temperature sink establishing ΔT.

Electrical Output

The generated voltage drives a current (I) through an external load delivering power

4. Material Science Considerations: -

State-of-the-Art Materials

1. Bismuth: Dominates near-room-temperature applications (ZT ≈ 1).
2. Skutterudites: Filled with rare-earth atoms (e.g., $CoSb_3$) to reduce; ZT ≈ 1.2 at 800 K.
3. Half-Heusler Alloys: High-temperature stability (ZT ≈ 1.5 at 1000 K).
4. Nanostructured Materials: Quantum confinement and phonon scattering enhance ZT (e.g., PbTe nanocomposites).

Material Optimization Strategies

- Doping: Adjust carrier concentration to balance
- Nano structuring: Introduce grain boundaries or nanoparticles to scatter phonons
- - Band Engineering: Tune electronic band structures (e.g., convergence of multiple bands) to boost

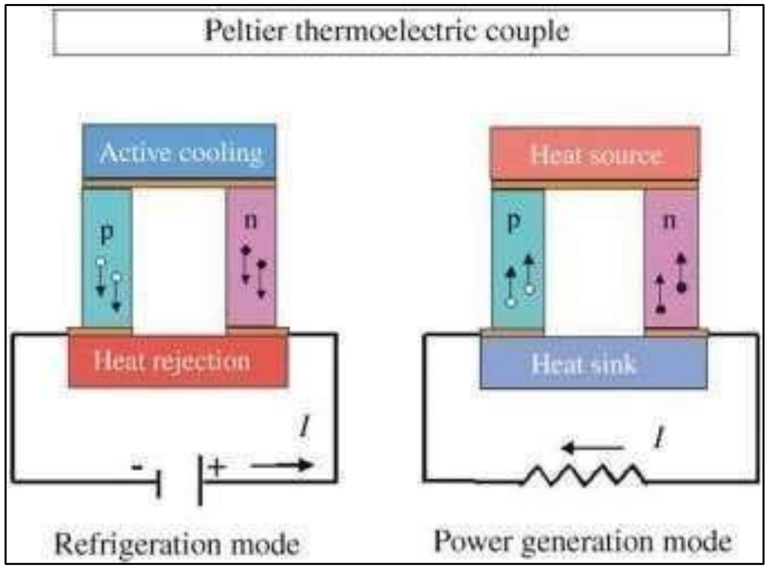


Fig. 1.9 2 Modes in TEG/TEC Module

6. Thermal and Electrical Transport Phenomena

- **Thermal Challenges**

Parasitic Heat Losses: Heat bypassing the thermocouples via radiation/convection reduces ΔT.

Interfacial Resistance: Poor thermal contact at junctions increases.

Thermal Expansion Mismatch: Mechanical stress from cyclic heating/cooling degrades module longevity.

- **Electrical Losses**

Joule Heating: (I^2R) losses due to finite electrical resistance.

Contact Resistance: Imperfect interconnects reduce output power.

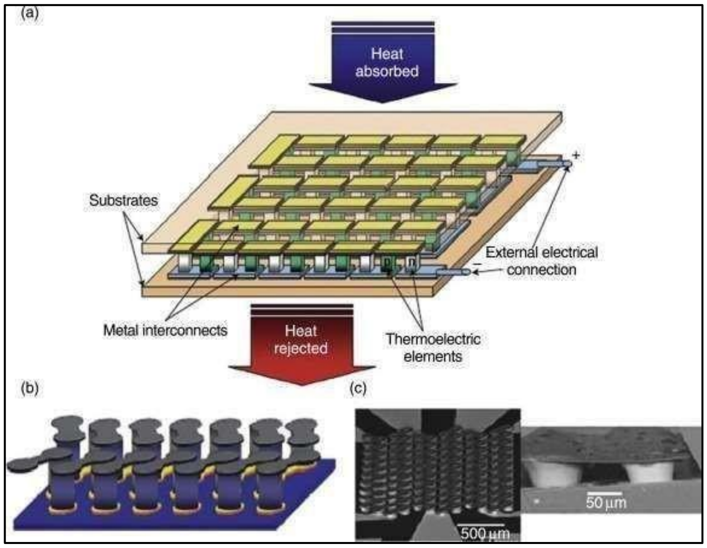


Fig. 2.1 Internal Sections of TEG

Performance Optimization

Module Design

Leg Geometry: Shorter legs reduce (R), but compromise ΔT. Optimal (L/A) ratios balance resistive and conductive losses.

Load Matching: Maximum power transfer occurs when R load = R internal.

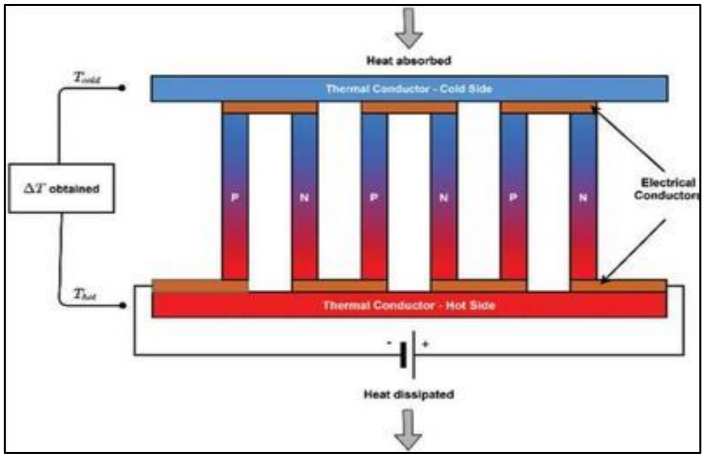


Fig 2.2 Peltier mode in TEEG

- **Thermal Management**

Heat Exchangers: Enhance heat flux at the hot side (e.g., finned structures).

Active Cooling: Use Peltier coolers or liquid cooling to sustain ΔT.

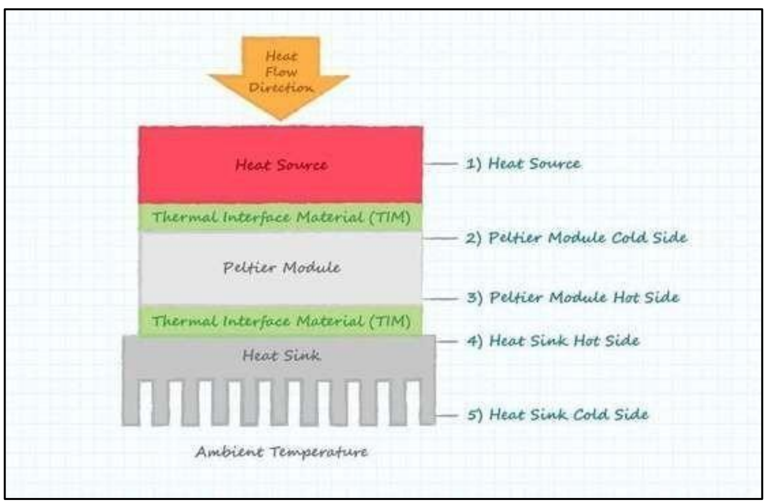


Fig. 2.3 Sections of TEG Modules System

MATLAB Software: -

MATLAB is a powerful computing environment and programming language developed by MathWorks. It's widely used by engineers, scientists, and researchers for numerical computing, data analysis, algorithm development, and visualization. One of its strengths is its ability to handle matrix operations efficiently, which makes it popular in fields like signal processing, machine learning, control systems, and computational mathematics.

In addition to its core programming capabilities, MATLAB offers specialized toolboxes for areas like image processing, robotics, and finance, allowing users to tackle complex problems with built-in functions and algorithms.

MATLAB, short for MATrix LABoratory, is a proprietary multi-paradigm programming language and numeric computing environment developed by MathWorks. It is widely used for engineering, scientific computing, and data analysis. MATLAB allows users to perform matrix manipulations, function plotting, algorithm implementation, and user interface creation.

Key Features of MATLAB:

- Programming Language: MATLAB includes a high-level language designed for numerical computation.
- Toolboxes: Specialized libraries for areas like signal processing, image processing, control systems, and machine learning.
- Simulink: A graphical environment for multi-domain simulation and model-based design.
- Cross-Platform Compatibility: Available on Windows, macOS, and Linux.
- Extensive Community: Used by engineers, scientists, students, and researchers worldwide.

MATLAB is particularly useful in industries such as automotive, aerospace, energy, medical devices, and finance. It simplifies complex mathematical computations and provides built-in functions for linear algebra, statistics, and optimization.

CHAPTER 04

Practical Experiment

Aim: -

To Study the Relationship Between amount of change in temperature applied across the Peltier surfaces and the EMF generated at the output terminals.

Apparatus required: -

1. Two Peltier Modules (12706)
2. Rectangular Aluminium Framework
3. Hack-Saw with blade
4. Round File
5. Cutter
6. T7000 Glue
7. Thermal Paste
8. Rheostat (0 to 260 ohm)
9. Three Multimeters (Voltmeter, Ammeter, Ohmmeter)
10. Two scientific Thermometers
11. Two Plastic Containers
12. Two Heat sinks
13. Hot Glue gun
14. Hot Water and Cold Water
15. Connecting Probes

Procedure: -

1. Take the rectangular aluminium framework and cut it into two flat rectangular pieces of Dimensions 10*4*0.2.
2. Now the Heat and Cold Spreader is ready.

Fig.4.1 Spreader

3. Now Take a Plastic Container and make a rectangular cut on the cap of the container.
4. Put the rectangular heat sink in the cut.
5. Use Hot glue gun to seal the sink in the cap of the container.

Fig 4.2 Heatsink

7. Take another Container and make a hole by using

cutter.

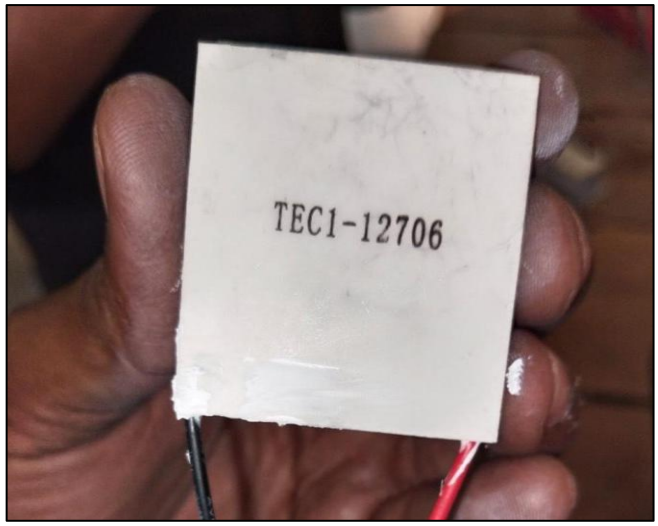
8. Now put the circular heat sink in the hole.
9. Use Hot glue gun to make it water proof and use T7000 glue to seal it.

Fig 4.3 Container Assembly

11. Now place the Sprader on the top of both heat sinks

Fig. 4.4 Spreader on container

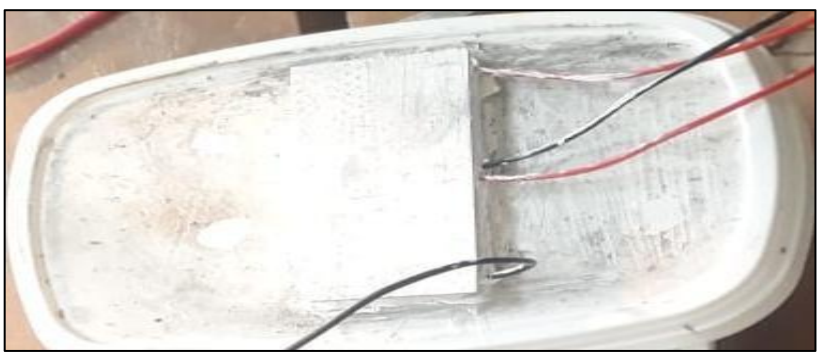
12. Now apply Thermal Compound on Both of the Spreaders.



<u>Fig 4.5 Thermal Compound</u>

<u>Fig 4.6 Peltier module</u>

13. Now place the Peltier module on the Spreader of the base Container after applying Thermal compound on the both surfaces of the Peltier modules.



<u>Fig 4.7 Peltier assembly</u>

15. Now Place another Container on the top of the Peltier Module.

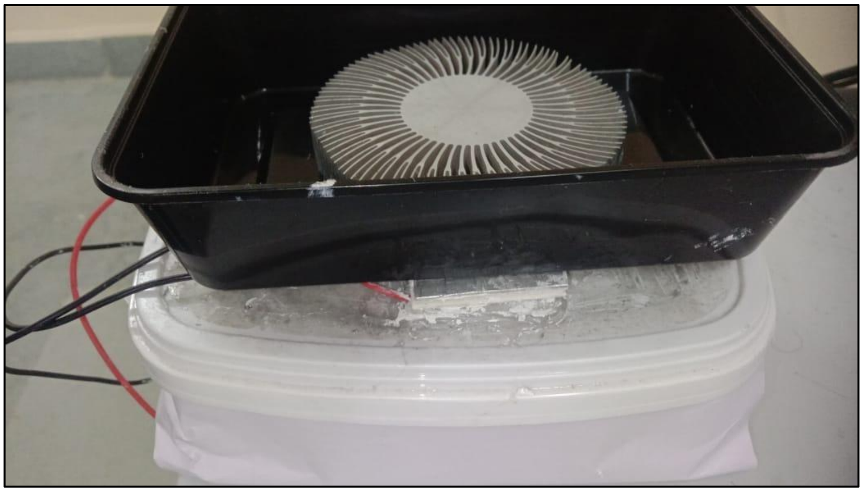


Fig 4.8 Complete assembly

16. Fill the Containers Hot water and Cold Water in the Separate Containers.
17. Connect the both Peltier modules in series.
18. Connect the ammeter in series with Rheostat.
19. Connect the Voltmeter in parallel with the Rheostat.
20. Now Connect the Ohmmeter across the Rheostat.
21. Make sure the connections are same as the Circuit Diagram.
22. Dip Both the Thermometers in both Containers.
23. Now Gradually Increase the value of Rheostat and Note down the Readings.
24. Note Down the Readings of Both Thermometers, Ammeter, Voltmeter and Ohmmeter.
25. Construct a Table and Plot the Graph of the Readings.

Circuit Diagram: -

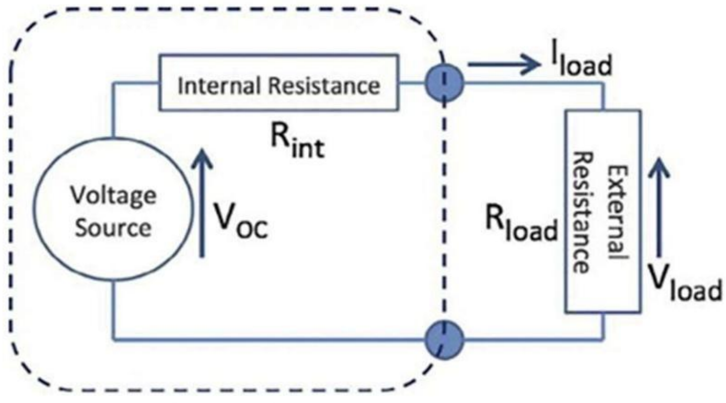


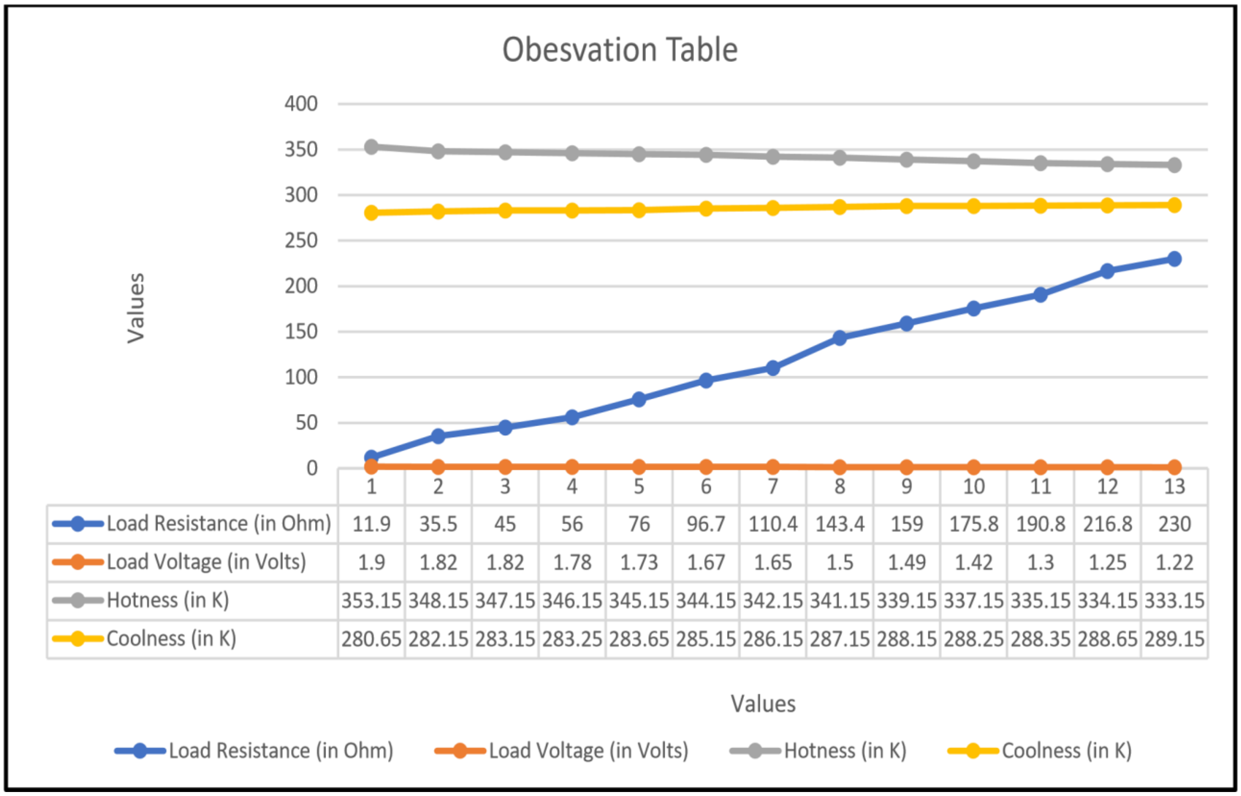
Fig 4.9 Peltier assembly

Observations Table: -

	1	2	3	4	5	6	7	8	9	10	11	12	13
Load Resistance (in Ohm)	11.9	35.5	45	56	76	96.7	110.4	143.4	159	175.8	190.8	216.8	230
Load Voltage (in Volts)	1.9	1.82	1.82	1.78	1.73	1.67	1.65	1.5	1.49	1.42	1.3	1.25	1.22
Hotness (in K)	353.15	348.15	347.15	346.15	345.15	344.15	342.15	341.15	339.15	337.15	335.15	334.15	333.15
Coolness (in K)	280.65	282.15	283.15	283.25	283.65	285.15	286.15	287.15	288.15	288.25	288.35	288.65	289.15

4.9.1 Observations table

Results: -



	1	2	3	4	5	6	7	8	9	10	11	12	13
Load Resistance (in Ohm)	11.9	35.5	45	56	76	96.7	110.4	143.4	159	175.8	190.8	216.8	230
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Hotness (in K)	353.15	348.15	347.15	346.15	345.15	344.15	342.15	341.15	339.15	337.15	335.15	334.15	333.15
Coolness (in K)	280.65	282.15	283.15	283.25	283.65	285.15	286.15	287.15	288.15	288.25	288.35	288.65	289.15

Graph 1.2 Results

CHAPTER 05

Simulation Work Using MATLAB

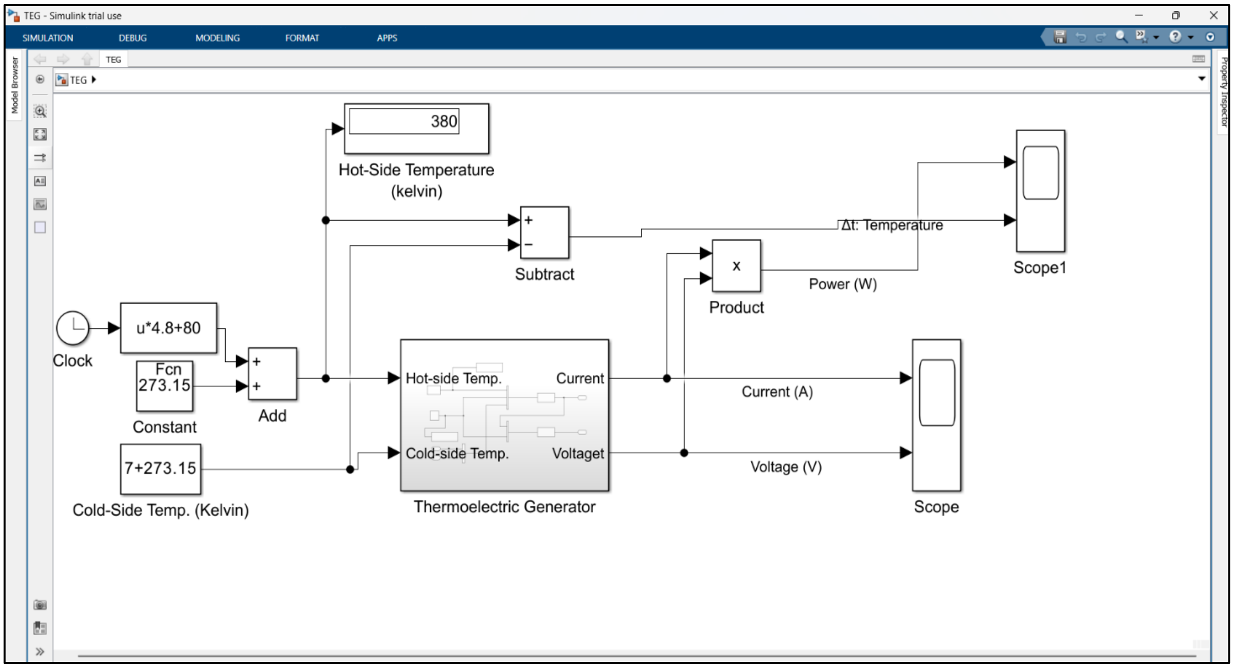


Fig 5.1 Simulation Model

Simulation is done by using MATLAB Software, where we use a reference TEG MATLAB Program to find output characteristics of our Practical testing model.

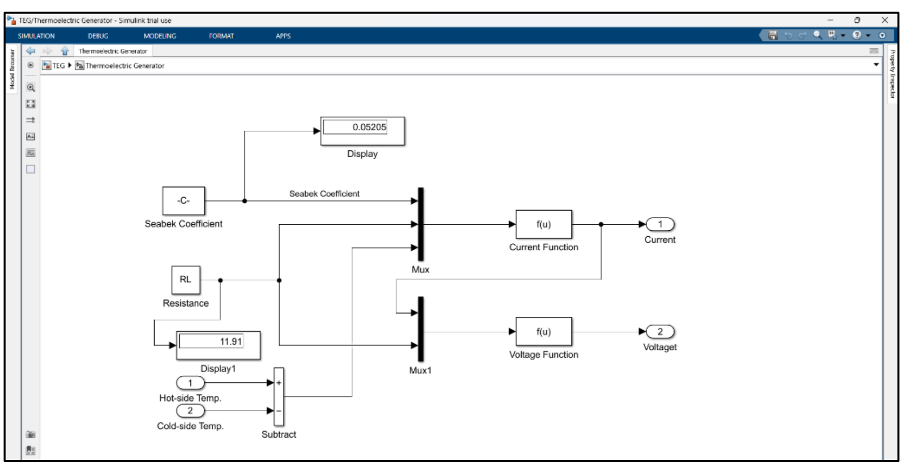
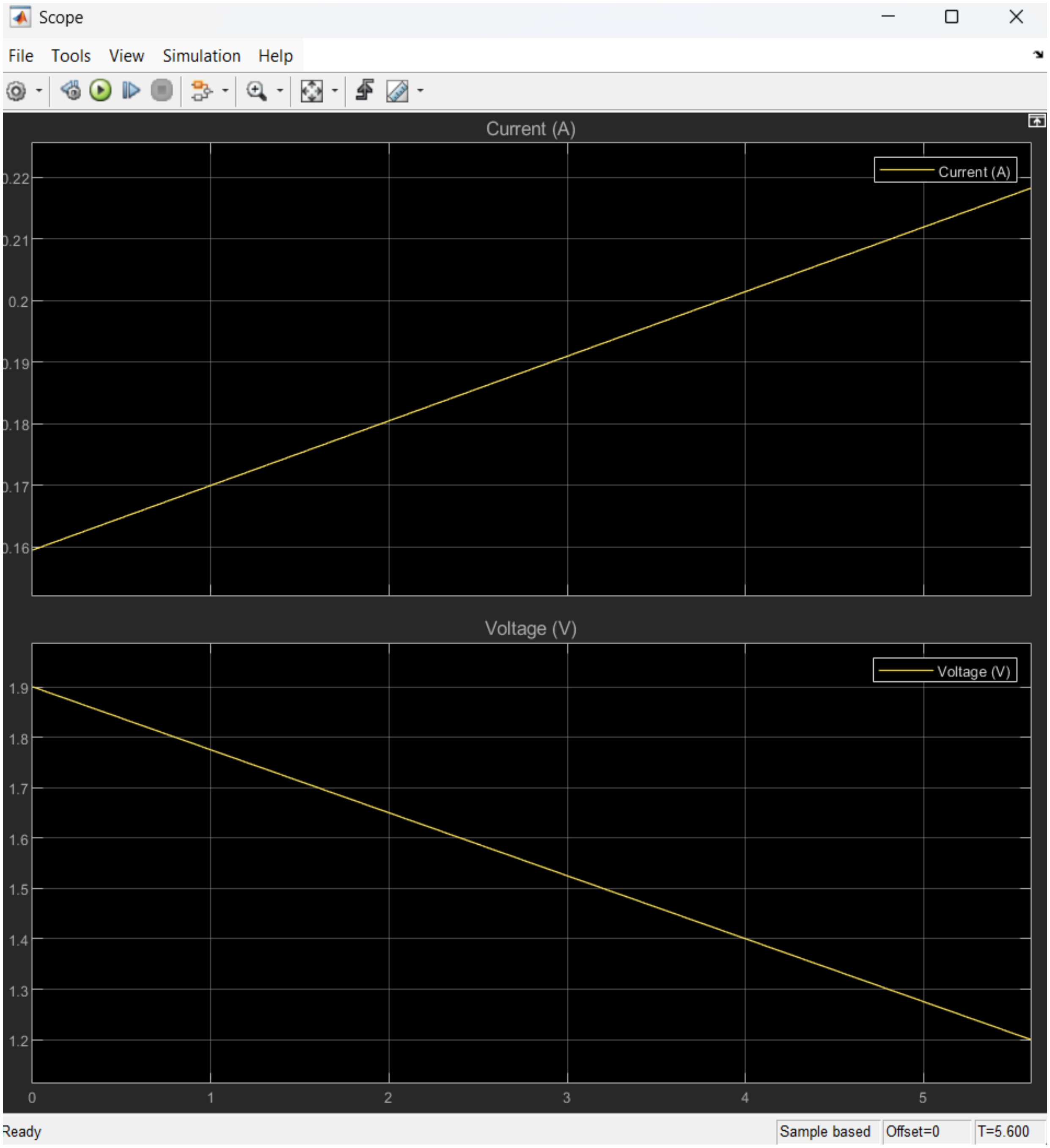


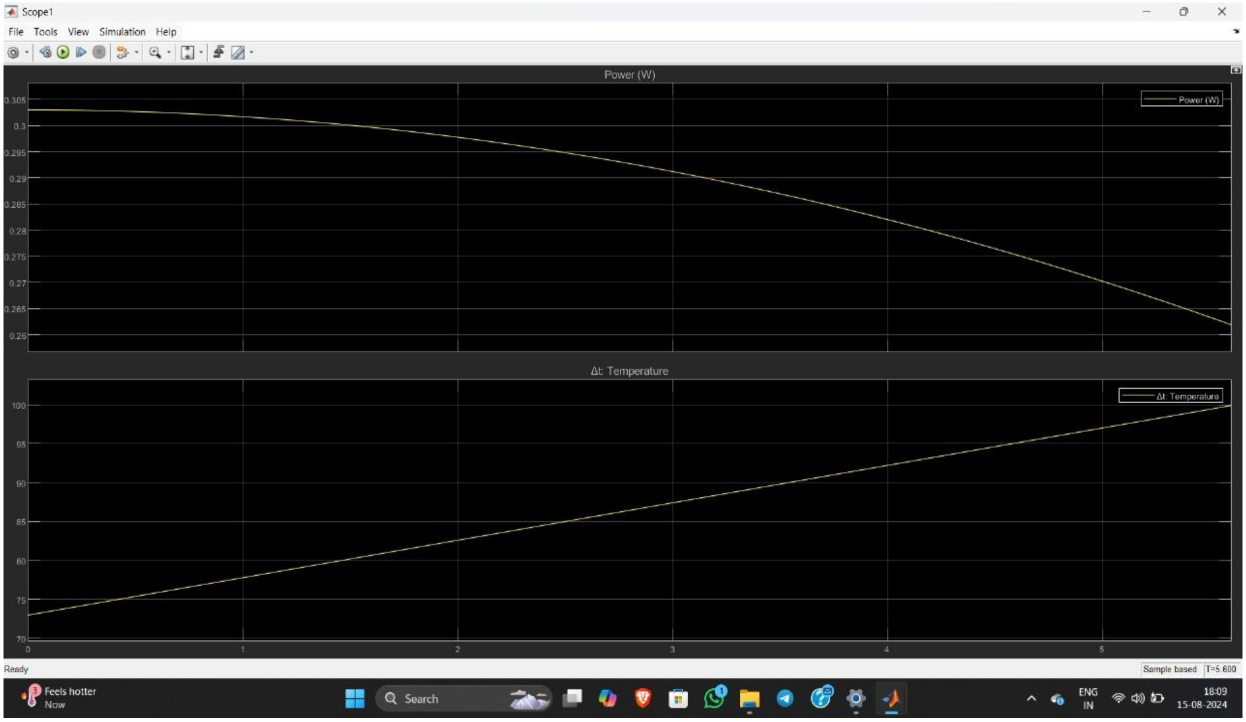
Fig 5.2 Simulation Block TEG

The above model is the Heart of the entire simulation which is able to generate electricity from Temperature differences.

Observation-Graphs: -



Graph 1.3 Wave of Current and Voltage



Graph 1.4 Power and Temperature

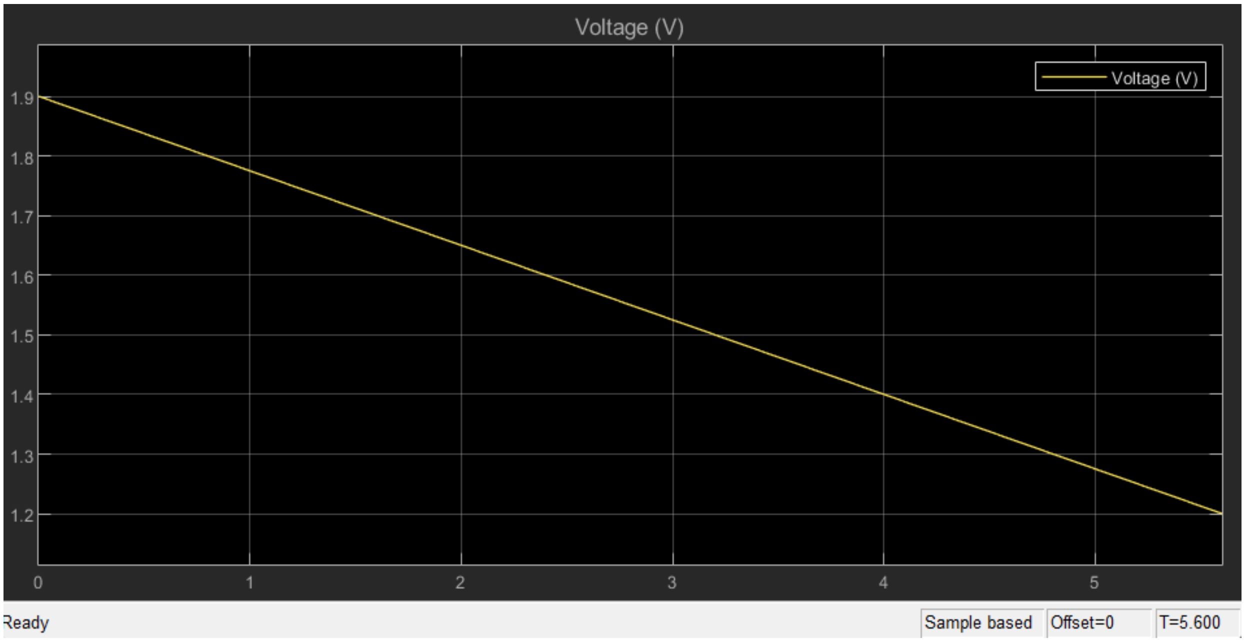
MATLAB CODE: -

```
%% Thermoelectric Generator Model and Study
%Author: Charles Kennedy; Date: 11/7/2019

%Updated By Mohammad Azhar Naushad
%Not all the equations are used in the symulink model some are just for reference



%% From Practical datasheet
%Estimated Thermal and Electrical Characteristics
%------------------------%Parameter Conditions:      min      typ      max
% Power Th=80°C, Tc=7°C @matched load          |     0.3      0.281    0.263 W
% Matched load Voltage Th=80°C, Tc=7°C         |     1.9      1.56     1.22 V
% Load Resistance Th=80°C, Tc=7°C              |     11.9     120.95   230 ohm
% Current Th=80°C, Tc=7°C @matched load        |     0.158    0.188    0.218 A
% Seebek Co-efficient (alpha)                  |     0.052 (Indium selenide)
% Temperature Difference (delta)               |     73.15             44


%% Temperature Conversions

%Kelvin (K) = Celsius (C) + 273.15
%
%Fahrenheit (F) = Celsius (C)*(1.8) + 32
%F = C*1.8 + 32

%% SIMULINK MODEL
%Th %Hot side temperature (Celsius)
Th = 80;
% Hot Side temperature (Kelvin)
Th = Th + 273.15;

%Tc %Cold Side Temperature (Celsius)
Tc = 7;
%Cold Side Temperature (Kelvin)
Tc = Tc + 273.15;

%delta_T %Temperature difference between the hot side and cold side
delta_T = Th - Tc;

%Vm %matched voltage
Vm = 1.9;

%Wm %Min Power
Wm = 0.303;

%R %internal Resistance
%RL %Load Resistance (matched to internal resistance where R=RL)
```

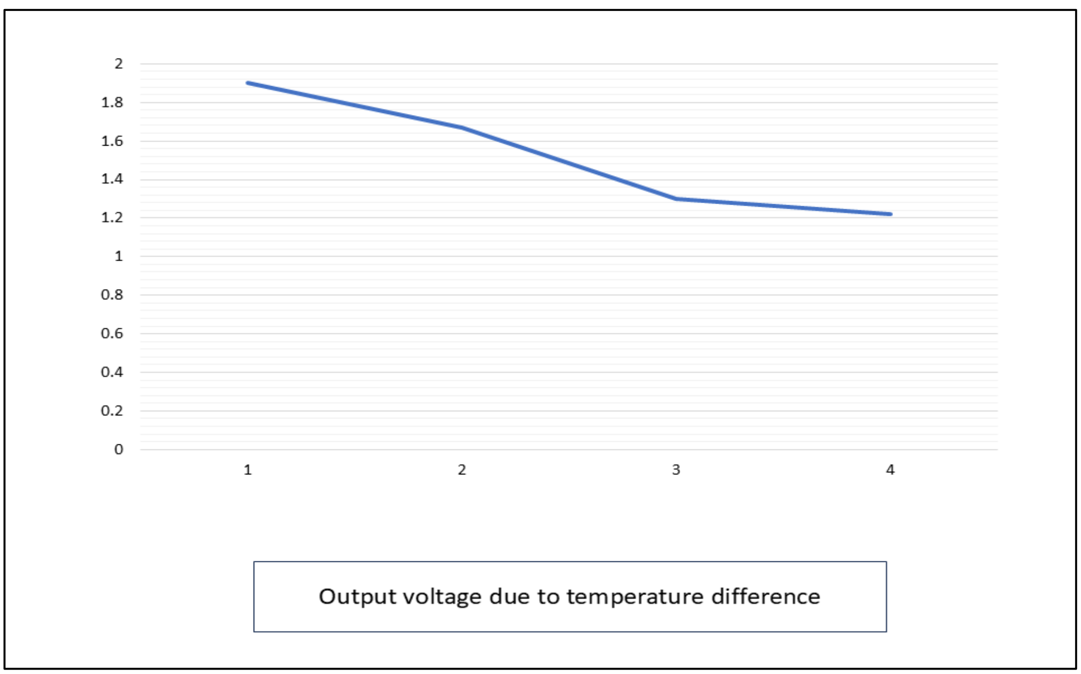
```
RL = (Vm^2)/Wm;
R = RL;

%Seebeck Coefficient
alpha = 2*Vm/delta_T;

%if RL = mR where m is the ratio between the internal and load
m = 1;

%I %Electric current
Ie = (alpha*delta_T)/((1+m)*R);
%  = (u(1)*u(3))/((1+m)*R)

%Im %Matched Load Current
Im = (alpha*delta_T)/(2*R);
%  = (u(1)*u(3))/(2*R)


%Isc %Short Circuit Current @Vl = 0     %Isc = 2*Im=(2*Wm)/Vm;
Isc = (Wm)/Vm;
Isc_1 = 2*Im;

%V %Output Voltage
V = -R*(Ie-Isc);
% = -u(2)*(u(1)-(2*Wm)/Vm)



%% Physical test model study

%Vo %Open Circuit Voltage
%Vl %Load Voltage
%Rl %load resistor
%look at datasheet for appropriate size in Ohms
%Vr %Voltage drop across resistor


%I_load %current from module
%I_load = Vr/Rl

%Ri %Internal Resistance
%Ri = (Vo * Vl)/I_load

%Pmax %Maximum Power Output
%Pmax = (Vo^2)/(4*Ri)
```

CHAPTER 06

Comparison Between Initial Results and Final Results



Graph 1.5 MATLAB Result



Graph 1.6 Practical Result

Final Conclusion

After this experiment we know that: -

After completing this project, we finally conclude that using TEG for low temperature is not economic. About 1.9 will generated from each TEG with temperature difference of 73.15-degree kelvin.

But when we compare it with Peltier module, peltier model is more efficient and reliable then TEG model for same temperature difference.

We can use it for waste heat recovery in Hybrid Vehicle but its efficiency is quite low.

So, we have to wait for better upcoming innovations, we wish it will use for waste heat recovery in ICE engines and Hybrid vehicles.

We have chosen it because Hybrid's Main Power Unit MPU is radiating more heat and making it more economical with respect to ICE engine-based cars alone.

The future of TEG modules is anchored in interdisciplinary innovation, spanning material science, nanotechnology, and energy systems. By addressing efficiency, cost, and scalability challenges, TEGs are poised to play a pivotal role in sustainable energy ecosystems, from personal electronics to industrial waste heat recovery. Ongoing research breakthroughs and industrial adoption will drive their transition from niche applications to mainstream energy solutions.

Efficiency of Peltier modules are very low.

We can use this method for Waste Heat Recovery (WHR) but it will be

Costly.

To enhance the efficiency of this setup we need good quality of TEG

modules.

We know that it can generate electricity statically.

Future Scope and Ongoing Researches on Thermoelectric Generator (TEG) Modules

Thermoelectric Generator (TEG) modules hold significant promise for sustainable energy conversion, leveraging the Seeback effect to transform waste heat into electricity. Below is an organized overview of the future scope and ongoing research directions in this field:

1. Material Innovations

- **High-ZT Materials**:
    - **Nanostructured Materials**: Engineering materials like quantum dots, nanowires, and superlattices to scatter phonons (reducing thermal conductivity) while preserving electron mobility.
    - **Skutterudites and Half-Heusler Alloys**: Investigating skutterudites (e.g., $CoSb_3$) with "rattling" atoms to lower thermal conductivity, and half-Heusler alloys (e.g., ZrNiSn) for high-temperature stability. o **Topological Insulators**: Exploring quantum materials with unique surface states for enhanced electronic transport.
- **Eco-Friendly Alternatives**: Reducing reliance on rare/toxic elements (e.g., tellurium) via organic thermoelectric or abundant materials like Mg_3Sb_2 and Cu_2Se.
- **Low-Dimensional Materials**: 2D materials (e.g., graphene, MoS_2) and hybrid perovskites for flexible, high-performance TEGs.

2. Advanced Manufacturing Techniques

- **Additive Manufacturing**: 3D printing to create complex geometries (e.g., porous structures) for optimized heat transfer and scalability.
- **Thin-Film Deposition**: Sputtering and molecular beam epitaxy (MBE) for lightweight, miniaturized TEGs in wearables and IoT devices.

3. Hybrid and Integrated Systems

- **Solar-TEG Hybrids**: Combining photovoltaic panels with TEGs to utilize waste heat, improving overall system efficiency (e.g., solar roof tiles with integrated TEGs).
- **Peltier-TEG Integration**: Leveraging bidirectional operation for both cooling and power generation in climate control systems.
- **Energy Harvesting Networks**: Deploying TEG arrays in industrial exhausts, vehicle engines, or geothermal sites for large-scale waste heat recovery.

4. Applications and Use Cases

- **Wearables and IoT**:
  - Flexible TEGs using polymer composites (e.g., PEDOT: PSS) to harvest body heat for medical sensors or smartwatches.
  - Low-grade heat recovery (<100°C) for self-powered environmental sensors.
- **Automotive**:
  - Embedding TEGs in exhaust systems (e.g., BMW's prototype recovering ~600 W) to improve fuel efficiency.
  - Thermal management integration with EV battery cooling systems.
- **Aerospace**:
  - Enhancing radioisotope thermoelectric generators (RTGs) for deep space missions with higher ZT materials.
- **Building Efficiency**:
  - TEG-integrated windows or HVAC systems to harness indoor-outdoor temperature gradients.

5. Sustainability and Scalability

- **Recycling and Lifecycle Analysis**: Developing closed-loop recycling processes for rare-earth thermoelectric materials.

- **Cost Reduction**: Scaling production of nanostructured bulk materials (e.g., PbTe nanocomposites) to lower $/W costs.
- **Policy-Driven Adoption**: Aligning with global carbon-neutrality goals to incentivize TEG deployment in industrial and residential sectors.

6. Computational and AI-Driven Research

- **Machine Learning**: Accelerating material discovery via high-throughput screening and predictive modelling of ZT values.
- **Multi-Scale Simulations**: Using density functional theory (DFT) and finite element analysis (FEA) to optimize thermal/electrical transport.

7. Challenges and Breakthrough Frontiers

- **Efficiency at Low ΔT**: Improving performance for small temperature gradients (<50°C) via graded materials or cascaded TEG designs.
- **Durability**: Addressing material degradation under thermal cycling through robust interfaces and coatings.
- **Thermal Interface Optimization**: Advanced TIMs (thermal interface materials) like graphene-enhanced pastes to minimize contact resistance.

8. Emerging Trends

- **Quantum Materials**: Exploring topological semimetals and Weyl fermions for anomalous thermoelectric effects.
- **Direct Ink Writing**: Customizable TEG fabrication for niche applications (e.g., curved surfaces in aerospace).
- **Global Collaborations**: Cross-industry partnerships (e.g., automotive OEMs + material startups) to commercialize next-gen TEGs.

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7. Nissan e-Power (Image)
8. Toyota Prius (Image)
9. Toyota Hamry (Image)

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