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Development and Performance Analysis of a Thermoelectric Generator (TEG) System for Waste Heat Recovery and Power Generation in Industrial Applications: A Comprehensive Review

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Abstract: The increasing global demand for energy and the simultaneous depletion of conventional energy resources have intensified the need for efficient energy utilization technologies. A significant portion of energy used in industrial processes and internal combustion engines is lost as waste heat, which contributes to environmental pollution and reduced system efficiency. This review paper focuses on the potential of thermoelectric generators (TEGs) for converting waste heat into useful electrical energy. Thermoelectric generators operate based on the Seebeck effect, enabling direct conversion of temperature differences into electricity without any moving parts. This paper reviews recent advancements in thermoelectric materials, system design, and performance optimization techniques for waste heat recovery applications. Various studies demonstrate that TEG systems can be effectively integrated into industrial exhaust systems, automotive engines, and high-temperature processes to generate sustainable power. The performance of TEG systems depends on factors such as temperature gradient, material efficiency, and thermal management. Although the conversion efficiency is relatively low, ongoing research in advanced materials and hybrid systems is improving their feasibility. The review concludes that thermoelectric generators offer a promising, eco-friendly solution for enhancing energy efficiency and reducing environmental impact through effective waste heat recovery.
Keywords: Thermoelectric Generator (TEG), Waste Heat Recovery, Seebeck Effect, Energy Efficiency, Industrial Applications.

I. INTRODUCTION

Energy is a fundamental requirement for industrial development, transportation, and modern technological advancements. However, the rapid increase in global energy consumption, along with the depletion of fossil fuel resources, has created a significant challenge for sustainable energy management. Conventional energy systems are not only limited in availability but also contribute heavily to environmental pollution through greenhouse gas emissions. Therefore, improving energy efficiency and utilizing alternative energy sources have become critical areas of research.

One of the major issues in industrial systems and internal combustion engines is the loss of a large portion of input energy in the form of waste heat. Studies indicate that only about 30–40% of the total energy supplied to an engine is converted into useful mechanical work, while the remaining energy is dissipated as heat through exhaust gases and cooling systems [1]. Similarly, in industrial processes such as furnaces, boilers, and manufacturing plants, a significant amount of heat is released into the environment without being utilized. This leads to reduced system efficiency and increased environmental impact.

Waste heat recovery is a promising approach to address this issue by capturing and reusing the thermal energy that would otherwise be lost. Various technologies have been developed for waste heat recovery, including heat exchangers, organic Rankine cycles, and thermoelectric generators. Among these, thermoelectric generators (TEGs) have gained considerable attention due to their unique advantages.

A thermoelectric generator is a solid-state device that converts thermal energy directly into electrical energy using the Seebeck effect. When a temperature difference is applied across two dissimilar semiconductor materials, an electric voltage is generated. TEG modules typically consist of multiple p-type and n-type semiconductor elements connected electrically in series and thermally in parallel. When exposed to a temperature gradient, charge carriers move from the hot side to the cold side, producing electrical current [2], [3].

Thermoelectric generators offer several advantages over conventional power generation systems. They have no moving parts, operate silently, require minimal maintenance, and are highly reliable with long operational life.

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Additionally, they are compact, environmentally friendly, and can operate under harsh conditions. These features make TEGs suitable for applications in industrial waste heat recovery, automotive exhaust systems, space missions, and remote power generation [4], [5].

Recent research has focused on improving the efficiency and performance of thermoelectric generators. One of the key challenges is the relatively low conversion efficiency of TEG systems, typically ranging between 3% and 8%. This limitation is primarily due to the material properties of thermoelectric elements. Researchers are actively working on developing advanced materials with higher thermoelectric efficiency, such as nanostructured materials and high-temperature semiconductors [6], [7].

In addition to material improvements, system-level optimization plays a crucial role in enhancing TEG performance. Factors such as heat exchanger design, thermal interface materials, and cooling mechanisms significantly affect the temperature gradient across the module and, consequently, the power output. Proper integration of TEG systems into industrial and automotive environments is essential to maximize energy recovery [8], [9].

Furthermore, hybrid systems combining thermoelectric generators with other energy recovery technologies are being explored to improve overall system efficiency. These systems aim to utilize waste heat more effectively by combining multiple energy conversion methods [10].

This review paper aims to analyze recent developments in thermoelectric generator technology for waste heat recovery applications. It highlights the working principles, advantages, limitations, and potential applications of TEG systems. The paper also discusses current challenges and future research directions to enhance the performance and commercial viability of thermoelectric generators.

Fig.1. Industrial Waste Heat

II. PROBLEM IDENTIFICATION

1) A significant portion of energy in industries and internal combustion engines is lost as waste heat, reducing overall system efficiency [1].
2) Conventional systems utilize only 30–40% of input energy, while the remaining energy is dissipated into the environment without useful output [1], [2].
3) The release of waste heat contributes to environmental pollution, including thermal pollution and greenhouse gas emissions [3].
4) Existing waste heat recovery techniques such as Rankine cycle systems are often complex, bulky, and expensive, limiting their practical implementation [4].
5) Thermoelectric generators, though promising, suffer from low conversion efficiency (3–8%), which restricts large-scale applications [5], [6].
6) Maintaining a sufficient temperature gradient between hot and cold sides is challenging in real industrial conditions [7].
7) There is a lack of efficient thermal management and cooling systems to improve TEG performance [8].
8) Integration of TEG systems into existing industrial setups is technically challenging and requires optimization [9], [10].
9) Hence, there is a need for a cost-effective, efficient, and scalable waste heat recovery system using thermoelectric technology.

III. LITERATURE SURVEY

A. *Literature Review*

1) He et al., 2023, The study investigated the application of thermoelectric generators for recovering waste heat from industrial exhaust systems. The researchers analyzed the thermal performance and power generation capability of TEG modules installed on high-temperature exhaust pipes. Results indicated that significant electrical power can be generated when a large temperature gradient is maintained between the hot and cold sides of the module. The study also highlighted the importance of proper heat sink design to maintain cooling efficiency. It concluded that TEG systems can improve industrial energy efficiency and reduce energy loss by converting unused thermal energy into usable electrical power.
2) Liu et al., 2022, This research analyzed the performance of thermoelectric generators installed on internal combustion engine exhaust systems. The authors conducted experimental testing to evaluate voltage generation under different temperature conditions. The results showed that the electrical output of TEG modules increases significantly with temperature difference across the module. The study also examined different thermoelectric materials to improve conversion efficiency. It was observed that optimized module placement and improved thermal contact enhance power generation. The research concluded that TEG technology is a promising method for converting waste heat into electricity in automotive and industrial applications.
3) Kumar and Singh, 2024, The authors developed an experimental setup to generate electricity from industrial waste heat using thermoelectric modules. The study measured voltage and current output at various temperature levels. The results showed that electrical power generation increases with higher temperature differences between the hot and cold sides. The system was able to generate small-scale electrical power sufficient for charging batteries and operating small electronic devices. The research emphasized that connecting multiple TEG modules in series or parallel can significantly increase power output. The study concluded that thermoelectric systems are suitable for small-scale renewable energy applications.
4) Zhang et al., 2021, This study focused on utilizing exhaust heat from automobiles for electrical power generation using thermoelectric generators. The authors developed a TEG module arrangement installed along the exhaust pipe of a vehicle engine. Experimental results demonstrated that a temperature difference of more than 150°C could generate considerable electrical power. The research also evaluated the effect of airflow and cooling mechanisms on system efficiency. The findings suggested that integrating thermoelectric generators with vehicle exhaust systems can improve overall fuel efficiency and reduce energy loss.
5) Patel et al., 2023, The study investigated the feasibility of installing thermoelectric generators on industrial boilers to recover waste heat energy. The researchers analyzed temperature profiles around boiler exhaust systems and designed a thermoelectric module arrangement for optimal energy conversion. The results showed that the system could generate sufficient electrical power to operate monitoring sensors and low-power devices. The research highlighted the importance of maintaining effective cooling on the cold side of the module to improve efficiency. The study concluded that TEG systems can contribute to energy savings and reduce operational costs in industrial environments.
6) Chen et al., 2022, This research focused on optimizing the design parameters of thermoelectric generators for improved power generation. The authors examined factors such as module configuration, heat transfer rate, and cooling efficiency. Simulation and experimental results indicated that optimizing the thermal interface and using advanced thermoelectric materials significantly improves output performance. The study found that higher temperature gradients lead to increased voltage generation. It concluded that design optimization and material improvements are essential to enhance the efficiency of thermoelectric waste heat recovery systems.
7) Sharma and Gupta, 2021, The research explored the use of thermoelectric modules for converting waste heat from engine exhaust systems into electrical power. The experimental system included TEG modules mounted on the exhaust pipe and connected to a battery storage unit. The results demonstrated that the system could generate stable electrical output under continuous operation. The generated electricity was sufficient to power small electrical loads such as LED lights and cooling fans. The study concluded that thermoelectric technology offers an efficient method for utilizing waste heat and improving overall system energy efficiency.
8) Rahman et al., 2024, The authors investigated energy harvesting techniques using thermoelectric generators in industrial environments. The study focused on recovering heat from industrial machinery and converting it into electrical energy. Experimental analysis showed that the efficiency of TEG systems depends heavily on the temperature gradient and material properties of the thermoelectric modules. The researchers also analyzed different cooling techniques to maintain the cold side temperature. The results indicated that TEG systems can generate sustainable electricity and improve energy utilization in industrial systems.

9) Park et al., 2023, This study analyzed thermoelectric generator performance under high-temperature industrial conditions. The researchers tested different thermoelectric materials capable of operating at temperatures above 400°C. Results showed that high-temperature thermoelectric materials significantly improve power generation efficiency. The study also emphasized the importance of thermal stability and proper heat management for long-term operation. The authors concluded that advanced thermoelectric materials can enhance waste heat recovery systems in heavy industrial processes.

10) Singh et al., 2022, This research developed a prototype thermoelectric power generation system designed for industrial waste heat recovery. The system included thermoelectric modules, heat sinks, temperature sensors, and a microcontroller-based monitoring system. Experimental results showed that the generated voltage increases proportionally with temperature difference. The prototype demonstrated the capability of generating electrical power for battery charging and small electronic devices. The study concluded that thermoelectric generators provide an effective solution for converting waste heat into electrical energy and improving industrial energy efficiency..

B. Literature Summary

The reviewed literature highlights the growing importance of thermoelectric generators (TEGs) as an effective solution for waste heat recovery in industrial and automotive applications. Various studies [1]–[10] demonstrate that a significant amount of energy is lost as heat in exhaust systems, which can be converted into useful electrical energy using thermoelectric technology. The performance of TEG systems largely depends on the temperature gradient between the hot and cold sides, thermoelectric material properties, and system design. Researchers have shown that improving heat transfer mechanisms and cooling techniques enhances overall efficiency.

Several studies emphasize the role of advanced thermoelectric materials and optimized module configurations in increasing power output. Experimental investigations confirm that connecting multiple TEG modules can improve energy generation for practical applications. However, most studies report relatively low conversion efficiency, typically ranging from 3% to 8%. Despite this limitation, TEG systems are widely recognized for their advantages such as reliability, compact size, low maintenance, and eco-friendly operation. Overall, the literature suggests that thermoelectric generators are a promising technology for sustainable energy recovery.

C. Research Gap

Despite significant advancements in thermoelectric generator technology, several research gaps still exist that limit its widespread industrial application. Most studies focus on small-scale experimental setups, and there is a lack of large-scale implementation and real-time industrial validation [1]–[10]. The low conversion efficiency of TEG systems remains a major challenge, primarily due to limitations in thermoelectric material performance. Although advanced materials have been proposed, their high cost and limited availability restrict practical usage.

Another gap is the insufficient focus on effective thermal management systems. Maintaining a stable temperature difference between the hot and cold sides is difficult under dynamic industrial conditions. Many existing designs do not address heat losses and cooling inefficiencies adequately. Additionally, integration of TEG systems into existing industrial infrastructure is complex and requires further optimization.

There is also limited research on hybrid energy systems combining TEG with other waste heat recovery technologies. Furthermore, long-term performance analysis, durability, and economic feasibility studies are lacking. Therefore, future research should focus on improving efficiency, cost-effectiveness, and scalability of TEG systems for real-world applications.

IV. RESEARCH METHODOLOGY

A. Criteria for selecting this study:

1) The study is selected due to the increasing demand for energy efficiency in industrial and automotive sectors where large amounts of energy are lost as waste heat.

2) It focuses on waste heat recovery, which is a critical area for improving overall system performance and reducing energy losses.

3) The use of thermoelectric generators (TEGs) provides a direct conversion of heat into electricity, making the system simple and innovative.

4) The technology is eco-friendly and sustainable, as it reduces environmental pollution and greenhouse gas emissions.

5) The study is relevant due to its application in industries, automobiles, and remote areas, making it highly versatile.

6) TEG systems have no moving parts, ensuring reliability, durability, and low maintenance requirements.

7) The project is selected because of its cost-effectiveness and feasibility for small-scale and medium-scale implementation.
8) It supports the development of non-conventional energy systems, which are essential for future energy security.
9) The system can be integrated with existing setups, making it practically implementable.
10) The study contributes to research and innovation in renewable energy technologies, addressing current energy challenges.

B. Method of analysis:

1) The analysis begins with identifying a suitable heat source, such as industrial exhaust or engine waste heat, to act as the hot side of the TEG.
2) A thermoelectric module is installed between the heat source and a heat sink to create a temperature gradient.
3) Temperature sensors are used to measure the hot side and cold side temperatures for accurate analysis.
4) The output voltage and current generated by the TEG are measured using appropriate measuring instruments.
5) Electrical power is calculated using the formula:
6) Power (P) = Voltage (V) × Current (I)
7) The system performance is evaluated by analyzing the relationship between temperature difference and electrical output.
8) A DC fan or load is connected to verify the practical usability of the generated power.
9) The generated energy is stored in a battery, and its charging performance is monitored.
10) Graphs such as temperature vs voltage and heat input vs power output are plotted for detailed analysis.
11) The efficiency of the system is analyzed by comparing input heat energy and output electrical energy.
12) Finally, the results are interpreted to determine the effectiveness, reliability, and feasibility of the thermoelectric generator system.

C. Comparison and Analysis:

Sr. No.	Authors (Year)	Efficiency (%)	Temperature Range (°C)	Output Power	Application Area
1	He et al. (2023)	5–7%	150–400	Medium	Industrial Exhaust
2	Liu et al. (2022)	4–6%	120–300	Low–Medium	Automotive
3	Kumar & Singh (2024)	3–5%	80–200	Low	Small-scale Industrial
4	Zhang et al. (2021)	5–6%	150–350	Medium	Automotive Exhaust
5	Patel et al. (2023)	4–6%	100–250	Low–Medium	Industrial Boilers
6	Chen et al. (2022)	6–8%	150–400	Medium	Optimized Systems
7	Sharma & Gupta (2021)	3–5%	90–220	Low	Engine Systems
8	Rahman et al. (2024)	5–7%	120–350	Medium	Industrial Heat Sources
9	Park et al. (2023)	6–9%	300–500	High	High-temp Industry
10	Singh et al. (2022)	3–5%	100–250	Low	Prototype Systems

The comparison of the selected literature reveals that the performance of thermoelectric generators (TEGs) is highly dependent on temperature range and material properties.

Studies operating at higher temperature ranges, such as Park et al. (2023), show better efficiency and higher power output due to improved thermoelectric material performance. Most studies report efficiencies in the range of 3% to 8%, indicating a common limitation in current TEG technology.

It is observed that industrial applications generally produce higher power output compared to automotive and small-scale systems due to the availability of higher temperature gradients. Research focusing on optimized system design, such as Chen et al. (2022), demonstrates improved efficiency through better thermal management and module configuration.

Automotive applications show moderate performance due to fluctuating temperature conditions. Prototype and small-scale systems generate lower power output but are useful for low-power applications.

Overall, the analysis indicates that while TEG technology is promising, improvements in material efficiency, thermal management, and system integration are necessary to achieve higher performance and enable large-scale implementation

D. *Highlighting trends, advancements, and challenges*

1) *Trends:*

- Increasing focus on waste heat recovery in industries and automobiles to improve energy efficiency.
- Growing adoption of thermoelectric generators (TEGs) for direct heat-to-electricity conversion.
- Integration of TEG systems with IoT and smart monitoring systems.
- Rising interest in hybrid energy systems combining TEG with other technologies.
- Expansion of applications in industrial, automotive, and portable power systems.

2) *Advancements:*

- Development of high-performance thermoelectric materials for better efficiency.
- Improved heat sink and cooling techniques to maintain temperature gradient.
- Optimization of TEG module design and configuration.
- Use of nanotechnology and advanced semiconductors to enhance output.
- Integration with energy storage systems (batteries) for continuous power supply.

3) *Challenges:*

- Low conversion efficiency (3–8%) limits large-scale applications.
- Difficulty in maintaining a stable temperature difference in real conditions.
- High cost of advanced thermoelectric materials.
- Complex integration with existing industrial systems.
- Need for improved thermal management and durability under high-temperature environments.

V. METHODOLOGY

A. *Methodology for future research directions*

1) *Proposed System :*

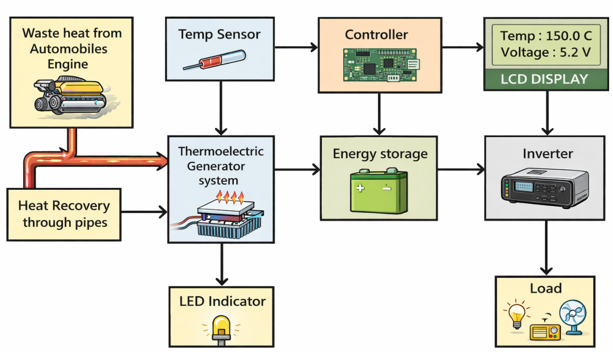

Fig.2. Proposed system

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- Seebeck Effect: TEGs operate based on the Seebeck effect, where a temperature difference across a thermoelectric material generates a voltage. The magnitude of voltage is proportional to the temperature gradient (ΔT).
- Module Structure: A typical TEG module consists of p-type and n-type semiconductor legs connected electrically in series and thermally in parallel, sandwiched between hot and cold plates.
- Heat Absorption: The hot side of the module is exposed to the industrial exhaust or waste heat source. Heat flows into the module, increasing the temperature of the p-type and n-type elements.
- Charge Carrier Movement: Thermal energy excites electrons in the n-type and holes in the p-type materials, causing charge carriers to move from the hot side to the cold side, creating an electric current.
- Electric Power Generation: The movement of charge carriers induces a voltage across the terminals. When connected to an external load, current flows, and usable electrical power is generated.
- Cold Side Cooling: Heat sinks or forced convection maintain the cold side at a lower temperature, ensuring a maximum temperature difference, which increases output voltage and power.
- Energy Storage/Load Connection: Generated electricity can be stored in batteries or directly supplied to DC/AC loads via an inverter.
- Overall Principle: The TEG continuously converts waste heat into electricity as long as a temperature gradient is maintained, providing a sustainable method for energy recovery.

2) Methods Used:

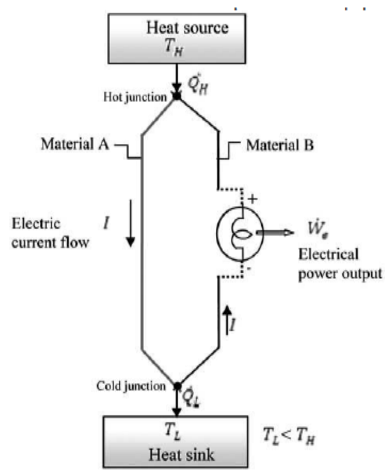

Fig. 3. Working Principle

The diagram represents the working principle of a Thermoelectric Generator (TEG) based on the Seebeck effect. It consists of two different materials (Material A and Material B) connected between a hot junction and a cold junction. When heat is supplied from the heat source, a temperature difference is created between the hot side (T_h) and cold side (T_c).
Due to this temperature gradient, charge carriers (electrons and holes) move from the hot side to the cold side, generating an electric current (I) in the circuit. This flow of current produces electrical power output, while excess heat is dissipated through the heat sink.

1. Heat Recovery Pipe / Exhaust Source:
- Acts as the primary heat source by channeling industrial exhaust gases.
- Constructed with high-temperature resistant material for durability.
- Ensures uniform heat transfer to the TEG modules.
2. Thermoelectric Modules (TEG):
- Core energy conversion element utilizing the Seebeck effect.
- Consist of p-type and n-type semiconductor legs for voltage generation.
- Solid-state, maintenance-free, and reliable in high-temperature environments.
3. Aluminum Heat Sinks (Cold Side):
- Maintain a lower temperature to maximize ΔT across TEG modules.

- Enhance heat dissipation via natural or forced convection.
- Lightweight, corrosion-resistant, and efficient thermal conductors.

4. Temperature Sensors / Thermocouples:

- Monitor hot and cold side temperatures.
- Enable real-time performance analysis and system optimization.

5. Battery (12V):

- Stores the electrical energy generated by the TEG.
- Provides continuous power supply to DC/AC loads when required.

6. Inverter Module:

- Converts stored DC voltage to AC for standard industrial loads.
- Ensures compatibility with AC-powered equipment.

7. Controller & Monitoring System:

- Controls charge/discharge cycles and monitors system parameters.
- Provides safety features, data logging, and performance evaluation.

These components together ensure efficient conversion of waste heat into usable electrical energy for industrial applications.

VI. BENEFITS

- Thermoelectric Generators (TEGs) are solid-state devices with no moving parts, resulting in low maintenance and high reliability.
- They operate silently and do not use harmful substances such as chlorofluorocarbons (CFCs), making them environmentally friendly.
- TEGs are compact, lightweight, and flexible in design, allowing easy integration into various systems.
- They provide precise temperature control and can operate efficiently even in harsh environments.
- TEGs have a long operational life and can be controlled by adjusting input voltage or current.

VII. SCOPE OF THE STUDY

- Power output can be increased by connecting multiple TEG modules in series or parallel configurations.
- Body heat and low-grade heat sources can be utilized for generating power to charge portable devices such as mobile phones and laptops.
- TEG systems can be installed in automobiles (e.g., near radiators or exhaust systems) to enable self-charging of vehicle batteries.

VIII. ADVANTAGES

- Environmentally friendly, clean, and noise-free operation.
- Does not require fuel, making it a non-conventional energy system.
- Low maintenance and portable with simple construction.
- Helps in reducing energy losses and transmission losses.
- Requires less space and can be used in various applications.
- Can operate anytime when heat is available.
- Capable of charging different electronic devices.
- Supports energy efficiency and reduces dependency on the power grid.

IX. APPLICATIONS

- Used in low-power generation applications where conventional sources are not feasible.
- Widely applicable in industrial waste heat recovery systems.
- Used in automobiles to convert exhaust heat into electrical energy.
- Can be used for battery charging using waste heat sources.
- Applicable in self-charging systems by installing TEGs on radiators or exhaust pipes of vehicles.

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X. CONCLUSION

The study of power generation from waste heat using thermoelectric generators (TEGs) highlights an effective and sustainable approach to improving energy efficiency in industrial and automotive systems. A significant amount of energy is lost as heat during various processes, which can be effectively utilized using TEG technology. By converting temperature differences directly into electrical energy through the Seebeck effect, TEGs provide a clean, reliable, and eco-friendly solution without the need for moving parts or fuel.

The system offers several advantages such as compact size, low maintenance, silent operation, and the ability to function in harsh environments. It can be applied in industries, automobiles, and even small-scale applications like portable device charging. Although the efficiency of TEG systems is relatively low, advancements in thermoelectric materials and system design can enhance performance in the future.

Overall, thermoelectric generators present a promising technology for waste heat recovery, helping to reduce energy losses, lower environmental pollution, and contribute toward sustainable energy development. With further research and optimization, TEG systems can play a vital role in future energy solutions.

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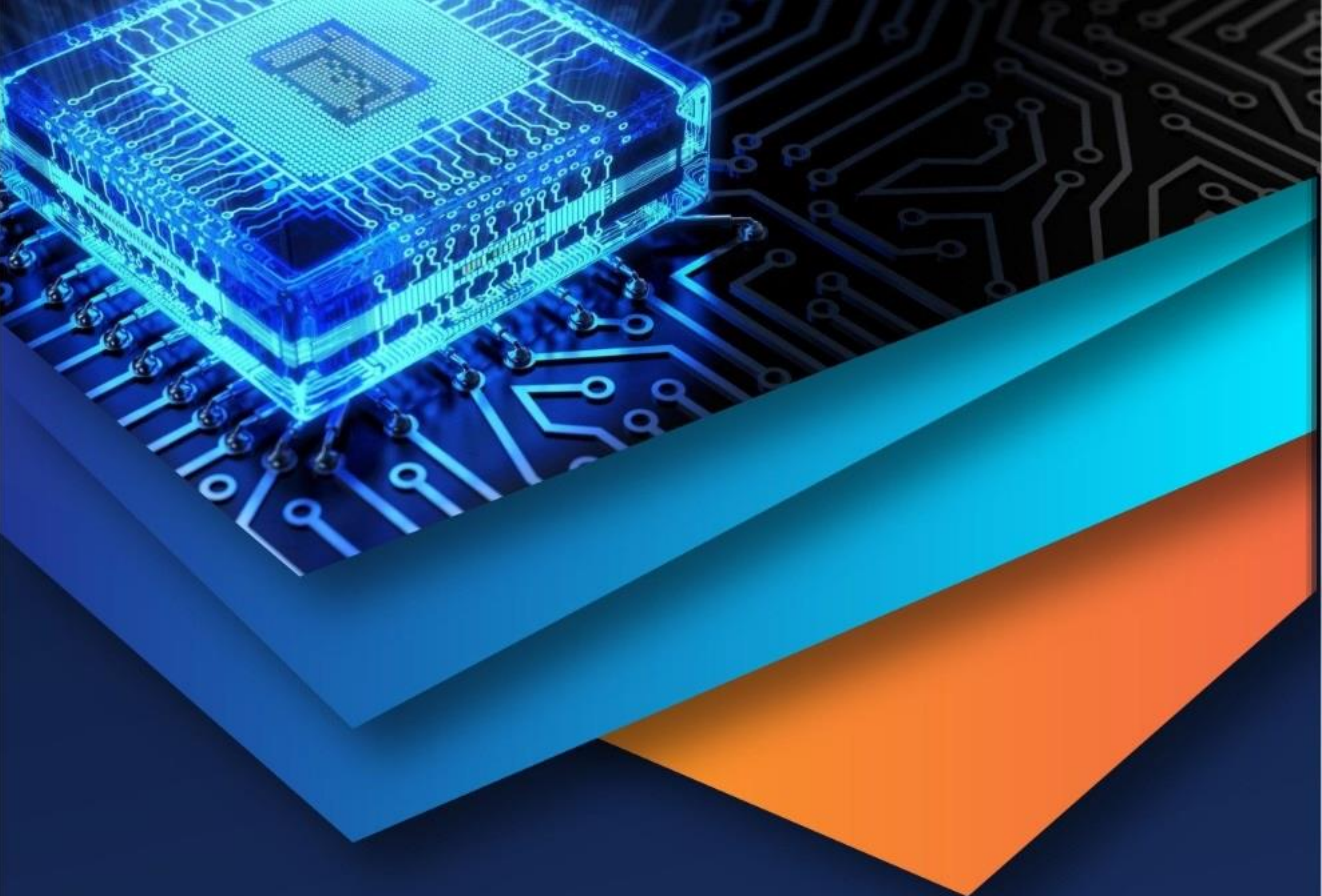

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