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Design of a Sustainable, Energy-Conserving Portable Refrigeration System

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Abstract: In present research work, we have designed a portable refrigeration system that will be ideal for off grid applications in remote areas. The present refrigeration systems are struggling with challenges like more energy consumption, limited reliability and lack in environment sustainability, which have become a major concern in off grid applications. To tackle the same, the proposed design combines innovative, sustainable and energy efficient features like wool wood, duct fans, heat sinks and water circulation pipe grids. Wool wood, a natural material known for its excellent thermal properties. Along duct fans to create pressure difference, heat sinks for heat exchange and a water circulated pipe grid, for better heat transfer properties. These features collectively create a system which is environment friendly and gives better performance in comparison with conventional refrigeration systems. The application of this system include uses in remote and rural communities, emergency medical transport and fieldwork in isolated areas. The system's reliability, performance and the energy saving features have been calculated using computational simulations. The key limitations in a conventional refrigeration system are addressed in this paper, giving more temperature consistency, energy efficiency and with that addressing the growing demand in sustainable technology and off grid scenarios.
Keywords: Portable, sustainable Technology, Energy Saving, efficiency, off grid applications

I. INTRODUCTION

Portable refrigerators offer an effective solution for modern refrigeration system, providingmobility and efficiency in scenarios where traditional cooling systems might be inadequate. These cooling systems are designed to meet diverse needs, including road trips, outdoor adventures, expeditions in remote areas, emergency medical transport kit, and various field researches. Theymaintain proper temperature under different environmentalconditions andensure the safety of food and temperature-sensitive items in any location.

The portable refrigeration systems are versatile, capable of operating on various power sources such as batteries and vehicle DC power(Wu et al., n.d.-a). During outdoor activities, people can rely on these portable refrigeration devices to keep their food and beverages fresh for prolongedperiod of time(Bodys et al., 2018a). Healthcare professionals use them to ensure the safety transport of vaccines, blood samples, and temperaturesensitive medical supplies. Field researchers those who are working in remote conditions benefits themselves for preserving biological samples and other critical materials under extreme temperature conditions(Wu et al., n.d.-a).

As the demand for portable cooling system increases, it become more important to develop more efficient system that are more user compatible and durable taking portability and efficiency into consideration. This research focuses on designing a prototype of portable refrigeration that addresses these key limitations of existing models, such as high energy consumption, less portability and less cooling efficiency. The material that are used in this system are eco-friendly, including the use of heat sink and pipe grid cooling system that are the convectional way of cooling used in old days, the insulation of wool wood is used to trap the heat and dissipate it throughout the entire system(Liu et al., 2021).

The main goal of this research is to create a portable refrigerator that is both practical possible and sustainably beneficial. To achieve this, the design primarily focus on developing prototype for low energy consumption and higher efficiency cooling refrigeration system, that would be less bulkier and easy for portable use. Different temperature management systems are also incorporated to ensure precise control and reduce unnecessary energy use, further enhancing efficiency. The system is prototyped taking durability and adaptability into consideration making it useful for various range of application, from rugged outdoor environments to critical medical scenarios.(Alghanima et al., 2022a)

For future scope of work the portable refrigeration system can be upgraded to Looking to the future, continuous advancements in portable refrigeration system involve integration of light weight material, more storage space, integration with IoT device to remotely monitoring and operating portable refrigeration device. Additionally, the increasing adoption of renewable energy sources will make these units more sustainable and accessible to a wider audience. By addressing both environmental and practical challenges, thisaims to contribute to the development of portable refrigerators that are not only effective and reliable but also highly sustainable and it reduces the carbon footprint.

II. LITERATURE REVIEW

Features existing refrigeration system		References
Type of Portable refrigeration	Compressor- based system: Compact and energy efficient using less power. Thermoelectric cooler: Low power but less efficient in extreme conditions. Absorption refrigeration: Use of eco-friendly refrigerants such as R290 (propane).	(Bodys et al., 2018a)
Performance in hot climates	Cooling efficiency decreases by 20-40% in extreme climates (>40°C), especially for thermoelectric systems. Advanced insulation materials like VIPs or PCMs improve thermal efficiency by reducing heat loss. Compressor-based units perform better in extreme temperatures, reaching lower internal temperatures than TECs. Compressors are better suited for high-demand applications like medical transport.	Kalaiselvam, S., &Parameshwaran, R. (2014)
Cooling Technology	Compressor-Based Cooling: Achieves temperatures as low as -18°C or below, offering superior cooling performance. Thermoelectric Cooling: Less effective in hot climates but lighter and quieter, suitable for moderate environments. Cryogenic Cooling: High-end models use this technology for efficient cooling, though it's costly and bulkier.	(Polonara, n.d.)
Durability and Portability	Structural Weaknesses: Portable refrigerators face damage during transport; rugged materials like hard plastics and aluminum alloys enhance durability. Noise from Compressors: Innovations like soundproof housing and anti-vibration tech reduce compressor noise. Design Improvements: Shock absorbers, reinforced corners, and weatherproofing features boost durability.	(Ho &Ambrosini, 2014)
Material and Insulation	Insulation Technologies: Polyurethane foam is common, but VIPs improve insulation without adding bulk. Lightweight Materials: Advanced polymers and composites offer lightweight yet durable refrigeration units.	(Ashrae, 2019)

III. MATERIALS

A. *Conceptual design and initial seeding:*

The conceptual design of this portable refrigerator consists of various essential components such as wool wood, that is arranged in alternate layers to facilitate convective heat transfer. After the layer of wool wood, a system of pipe gride is arranged through which water is flown to remove excess heat and also it is used to partially cool the system. Then this layer is again covered by sandwiching wool wood, which then absorb coldness from the pipe and it helps in enhancing the heat exchange process. The components that are used inside this refrigeration system is 2 heat sinks, that is used for effective heat dissipation, a set of compressor duct fans at top and bottom are used to circulate cold air that is contained inside the insulating enclosure to maximise cooling efficiency.

After completing the conceptual selection of the model, an in-depth analysis is conducted for the selection of material on the basics of their properties. The electric component is selected on the basic of their specification such as drawn voltage, current consumption, power and compatibility with another used component. This allows thorough assessment allows for optimized functionality and energy efficiency in the final design, ensuring that all materials and electronics are suited for reliable, long-term operation in the intended application.

B. *Wool wood:*

Wool wood sheets are lightweight and it absorbs coldness from cooling pipes, enhancing the overall heat exchange process. It is often used as an insulation material in refrigeration systems to prevent heat exchange between the interior of the refrigeration unit and the external environmental(O. Caleb et al., 2020)

Fig1: wool wood

C. *Heat sink:*

A passive heat exchanger device that transfers heat generated by a source to a fluid medium, often air or a liquid coolant. 2 heat sinks with dimension 3.5 x 3.5 inches will be used in this refrigerator. Each heat sink will be attached to hot and cold side of the device and hence dissipating respective temperature outcomes. On each heat sink, a cooling fan is installed to help in dissipating the respective temperature(Alghanima et al., 2022b)

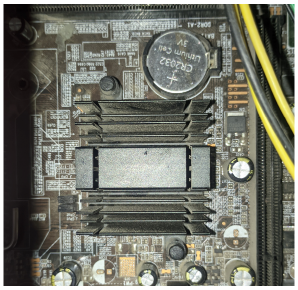


Fig2: Heat sink

D. *Duct Fans:*

Two cooling fans are used on each side of device, one for circulating the cool air and other to dissipate the hot air. Hence the hot side with help of fan will dissipate hot air outside the refrigeration box while the cold side with help of cooling fan will dissipate inside the box(Pengju Zhang et al., n.d.)

Fig3: Duct fan

E. *Peltier module:*

It is thermoelastic module that become cold while the other side heats up, making them ideal for precision cooling in electronics, portable refrigerators and temperature control systems(Al et al., n.d.)

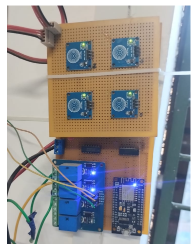


Fig4: Peltier module

F. *Relay module or MOSFETs:*

It is an electrically operated switch used to control high power devices by isolating the low power control circuit from high power load making is ideal for AC and DC. These are used to enhance the efficiency cooling systems by directing and circulating air flow(Wu et al., n.d.-b)

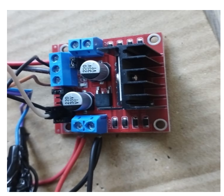


Fig5: MOSFET [13]

G. *Microcontroller:*

The Arduino UNO R3 can be used in portable refrigeration by controlling temperature, managing power and regulating the cooling system. By connecting a temperature sensor, the Arduino monitors the internal temperature and controls components like compressors or Peltier modules through relay MOSFETs. It can also adjust fan speeds using PWM for efficient cooling, while optimizing power consumption to ensure energy efficiency in battery power system(NazninNahar&RahmanMaruf, n.d.)

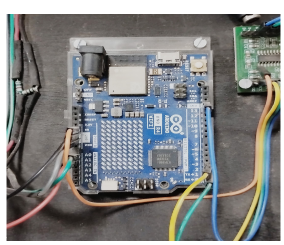


Fig6: ARD UNO R3

H. Flat pipe grid:

Through a network of pipes,a water pipe grid cooling system circulates water to absorb and transfer heat from different sources. The water flows through the grid, absorbs heat, and is then cooled in a heat exchanger or radiator before being recirculated in a continuous loop(Ai et al., 2024)

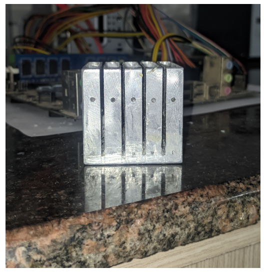


Fig7: Pipe grid

I. Water pump:

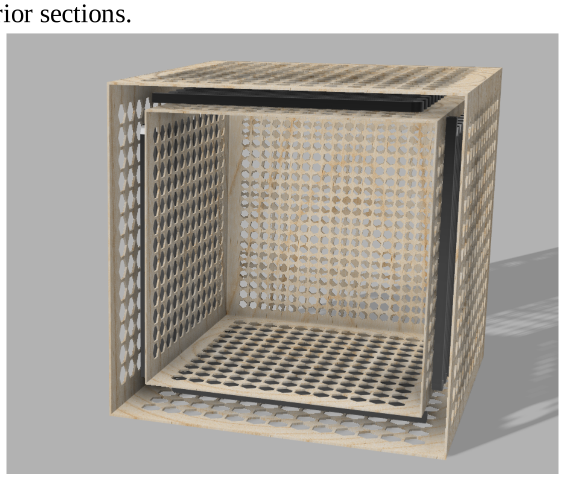
Its brushless motor ensures longer life with reduced maintenance, while its compact size and low power consumption make it suitable for battery-powered or solar systems. With a waterproof design and low noise levels, this pump is perfect for liquid circulation in projects that require reliability and energy efficiency, such as water cooling for electronics or small-scale water features to create a continuous circulation of water in flat pipes (Ong, 2016)that are used in the internal walls of the cooling chamber.

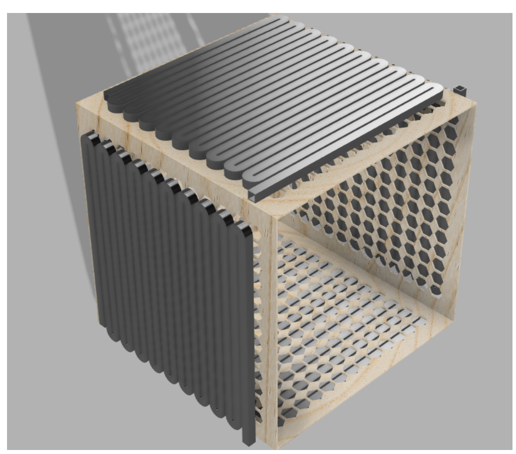
Fig8: Water pump

IV. METHODOLOGY

Once the component selection is complete, the prototyping and design phase begins, using software like Fusion 360 to construct the desired model of the refrigeration system.

The design defines the inner wall structure, where the outer and inner walls are made of wool wood. Sandwiched between the components,a flat pipe grid is serving as a heat exchanger, which significantly reduces the temperature from the exterior to the interior sections.





Essential parameters, components, and design choices were assessedto maintain the refrigerator's temperature between 0°C and 5°C, focusing on insulation, efficient cooling mechanisms, and power use. Thermodynamic calculations evaluated energy needs, with cooling load determining compressor requirements and the Coefficient of Performance (COP) assessing efficiency. Heat transfer analysis confirmed insulation effectiveness, minimizing external heat impact. Together, these calculations established a strong foundation for reliable, energy-efficient performance suited for sustainable, off-grid applications.

A. CRITERIA

The targeted internal volume of the system is considered to be 30 liters. This system can be used for medical and pharmaceutical uses, vaccines and medicines that are temperature sensitive. It can also be used to preserve biological samples, blood or organs. It can also be used in emergency situation such as disaster relief and emergency services or it can be used in military operations.This refrigeration system is can be used by outdoor activists and adventurers in camping, hiking to store drinks and food. It also can be used for fishing to preserve fish or baits in outdoor conditions. This system can used for travelling and transportation such as road trips, caravans, boating and sailing to keep perishables fresh during marine trips. And other places where this can be used are catering and food delivery, photography and videography, personal and office use, scientific research, agriculture and many more. This portable refrigerator is DC operated and can be used

B. COOLING LOAD CALCULATION

The cooling load represents the amount of heat that must be removed from the refrigerated space to maintain a temperature between 0°C and 5°C. Let us presume 30 minute as the cooling time from 30 to 5 degree Celsius as, for a normal refrigerator it takes 30 minute to get to optimal temperature. All taken values are ideal, taken according to universal constant.("Design and Simulations of Refrigerated Sea Water Chillers with CO2 Ejector Pumps for Marine Applications in Hot Climates," 2018b)

- Outside Temperature (ΔT): 30°C = 303 K
- Inside Temperature (T): 5°C = 278 K
- Refrigerator Volume (V): 30 L = 0.03 m^3
- Specific Heat Capacity of Air (c_p): 1005 J/kg·K
- Density of Air (ρ): 1.225 kg/m^3

The calculation uses the heat transfer equation

The energy (Q) required to cool the air is given by:("Design and Simulations of Refrigerated Sea Water Chillers with CO2 Ejector Pumps for Marine Applications in Hot Climates," 2018b)).

$Q = m \cdot c_p \cdot \Delta T$

Where:

$m = \rho \cdot V = 1.225 \times 0.03 = 0.03675$ kg

$\Delta T = T_{outside} - T_{inside} = 303 - 278 = 25$ K

Substitute the values:

$Q = 0.03675 \times 1005 \times 25 = 922.69$ J

To achieve cooling in 30min the cooling system needs to remove Q = 922.69J

$P_{required} = Q/t = 922.69 / 1800 = 0.512$W

Compressor Work and Coefficient of Performance (COP)(Faramarzi; John Wiley & Sons et al., 2018).

- $T_{cold} = 278$K
- $T_{hot} = 303$ K

$COP = T_{cold} / (T_{hot} – T_{cold}) = 11.12$

V. RESULTS

The conceptual model of the portable refrigerator was designed with key theoretical advancements in energy efficiency, durability, and cooling performance. This analysis is based on the predicted performances derived from the given design elements and principles.

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A. Temperature Consistency

The conceptual model is designed to ensure stable temperatures in the desired range by including a compressor system and a water-cooled flat pipe grid system. These components are designed to efficiently facilitate the heat transfer process, delivering consistent uniform cooling without fluctuations, making the system suitable for storage of perishable and temperature-sensitive products.

B. Energy Efficiency

This design integratesvarious energy-saving features, including theinnovative heat exchanger system and an optimized compressor mechanism. These parts are theorized to reduce energy consumption significantly while allowing the refrigerator to function efficiently on battery power making it suitable for various off-grid applications or scenarios where power sources are limited.

C. Advantages overConventional Designs

This conceptual model offers several advantages over the traditional portable refrigerators:

1) Improved Cooling in High Temperatures: The water-cooled flat pipe grid is expected to enhance cooling performance, ensuring stable operation even in hot environments.
2) Lower Energy Drain: Unlike conventional systems that rely heavily on continuous power, this design is theorized to minimize battery drainage, increasing operational time.
3) Compact and Lightweight Design: The model aims to reduce bulkiness while maximizing storage capacity, ensuring portability without compromising usability.

Result table	
Energy required	922.69J
Time to cool from 30 to 5 degree C	30 min
Power required	0.512 W
COP	11.12

The Coefficient of Performance (COP) for this system is 11.12.

This is the theoretical COP, assuming idealized operations. In practical approach, the COP differ and will be lower due to inefficiencies andheat transfer losses.

To conclude, the conceptual model of this portable refrigeratorhas addressed major limitations inexisting portable refrigeratorsby combining energy efficiency, enhanced cooling, and reducing time to cool from atmospheric temperature to 5 degrees Celsius. These provide a strong foundation for developingan energy-conserving and sustainable portable refrigeration system.

Cost estimation

S.No	Component	Items	Price (INR)
1	Material	Wool wood	1500
2		Duct fan	2000
3		Heat sink	400
4		Outer plastic layer	1000
5		Pipe grid	1500
6		Pump	600
7	Electronics	MOSFETs	500
8		Arduino UNO R3	500
9		Piltier Module	1000
10		Misc	2000
11		Other components and making charges.	2000
	Total		13000

VI. CONCLUSION

The conceptual model for a sustainable, energy-conserving portable refrigeration system offers innovative solutions to overcome the limitations of traditional portable refrigerators. By focusing on energy efficiency, durability, and effective cooling, the design demonstrates significant potential in addressing the needs of users in diverse environments.

Key Innovations and Their Impact

1) Energy efficiency

The use of heat sinks and water-cooled flat pipe grid and wool wood reduce the energy consumption significantly. As this refrigerator is battery operated it does doesn't require any power-hungry electric system. And the current consumption is very less compared to any other portable refrigerator as there is no use of compressor.

2) Enhanced Cooling Performance

The water-cooled flat pipe grid helps in maintaining temperature consistency, even in extreme environmental conditions. This feature ensures reliable cooling performance for applications such as medical transport, outdoor expeditions, and food storage. Unlike traditional models this refrigerator is more reliable in high temperature conditions and can also deliver efficient cooling.

3) Improved Portability and Durability

The traditional refrigerator are bulkier due to large compressor present in it, but this conceptual design minimize the bulkiness by using light weight material like wool wood and heat sinks.

4) Comparison with Existing Designs

When compared to traditional portable refrigerators, the conceptual model theoretically outperforms in several areas:

- Lower Battery Consumption: The design minimizes power drainage, which is a significant improvement for battery-dependent users.
- Eco-Friendliness: there is no use of refrigerant and compressor which lessen the emission of harmful gases.

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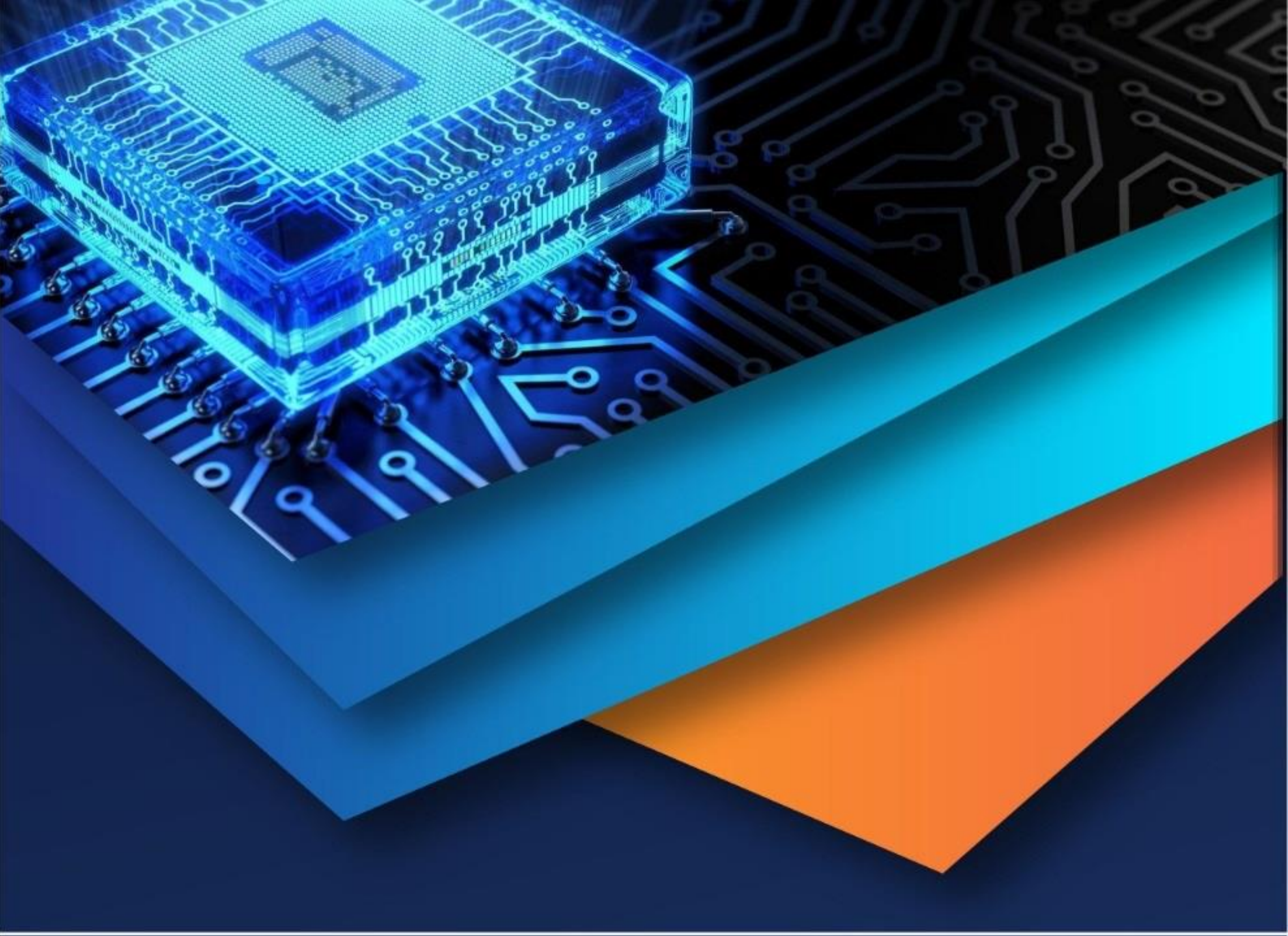

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