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Material Failure Analysis and Selection Criteria for PCM-Integrated Solar Flat Plate Collectors

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Abstract: ***Present research paper is depicting the challenges to make a leak-proof solar flat plate collector (FPC) containing Phase-change material (PCM).A lot of leakage problem in PCM panels was observed during the fabrication, testing and experimental work; therefore, efforts have been made to prevent leakage in PCM panels by using different types of sealants and different materials.***
The best leak proof results were obtained by iron tube in which rubber gasket is inserting at the opening and covered through the iron gasket using Teflon tape. Two solar water heaters have been designed and fabricated with compact type boxes of size of 24"×16"×4", one with conventional FPC and the other with PCM.A simple water heater heats water up to 70°C by 12 noon, while a PCM filled collector heats water up to 95°C by 12 noon and continues heating water even after sunset. It was observed that even at 10 pm it continues to heat water up to 40 °C. Therefore, it can be concluded that solar FPC showcases better efficiency and reliability with PCM as compared to conventional FPC. The integration of phase change materials (PCMs) into solar flat plate collectors offers significant advantages in thermal energy storage, improving efficiency and energy retention. However, operating conditions can cause the material to fail, affecting performance and longevity. This study explores various failure mechanisms, including thermal stress, mechanical degradation, and chemical instability. It also discusses non-destructive evaluation methods as well as advanced diagnostic techniques such as thermal, mechanical, and chemical analysis. Mitigation strategies, including material selection, design optimization, protective coatings, and improved PCM formulations, have been proposed to enhance system reliability.
Keywords: Solar Energy, Heat Transfer, PCM, Flat Plate Collector, Iron Tubes, Flexible tube

I. INTRODUCTION

The qualities of available water for rural residents are not up to mark. The public's health and cleanliness are thereby compromised. Water is mostly utilized for drinking, cooking, and cleaning in rural homes. Hot water is ideal for cleaning purposes like cooking, bathing, washing of clothes and utensils etc.
It is useful for maintaining the hygiene in routine life. The proposed solar flat plate collector containing Phase-change material water heater is useful for the rural residents. A household's average daily consumption of drinking water is determined by the fact that each member needs at least thirty litres [1]. In general, average household of five adults require between 120 to 150 litres of potable water daily. Generally as per rural households use hot water throughout the day, the usage is almost same both during sunrise and after sunset, but less all through the afternoon.
Sunlight energy systems are with time implementation phase change materials (PCMs) for thermal power stockpiling because of their high energy thickness and capacity to control temperature. One such application is the PCM-filled solar flat plate collector, where the PCM is integrated into the system to enhance efficiency and energy retention. However, these systems face challenges related to material failure under operational conditions, which can hamper their performance and lifetime [2].

A. Types of Failures in PCM Systems

Material failure in PCM-filled solar collectors results from a combination of thermal, mechanical, and chemical factors:

1) Mechanical degradation: Long-term operational stress can weaken structural components, especially at joints or connections. Distortion of PCM control due to volumetric changes during phase transition [3].
2) Chemical instability: Degradation of the PCM due to oxidation, contamination, or incompatibility with the container material, Corrosion of metal components when exposed to certain types of PCM, particularly salt hydrates.

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3) Copper Flat-Plate Collector : The most popular kind of solar water heat system is a copper flat plate collector unit. It is made up of an iron box, a copper flat plate collector, and a surface covering that insulates heat. The fundamental design and operation of the flat-plate collector is as follows: solar radiation enters via the collector's surface cover, and when it comes into contact with the copper plate's absorbing film, it transforms into thermal energy. In order to heat the working medium that passes through the polymer tube, the absorbed heat energy is then transferred to the tube by thermal conduction and thermal convection [4]. The sides and bottom of the copper plate are covered in insulating material. The stream pace of the functioning medium inside the collector polymer line and warm assortment implies the effectiveness is higher [5, 6 and 7].

B. Stage Change Material

Phase change materials (PCM) are substances that contain a high concentration of a mixture that, due to melting and solidifying at a certain temperature, is good for handling and transporting a lot of energy. Heat is held or conveyed when the material changes from strong to fluid as well as the other way around; accordingly, PCMs are named inert intensity stockpiling (LHS) units. Stage Change Materials (PCMs) or latent heat is "inactive" energy capacity materials. They utilize substance bonds to store and deliver heat. They use chemical bonds to store and release heat. Move happens when a material changes from a strong to a fluid or from a fluid to a strong. This is known as an adjustment of state or stage. [8]

It retains a lot of intensity during the time spent changing from strong to fluid stage and this outcome in cooling of the environmental factors. Yet, imagine a scenario in which you require this intensity at a temperature other than nothing. Latent heat can give out inert intensity at a great many temperatures from freezing to a few hundred degrees. This intensity heat-on-demand necessity is fulfilled by PCMs which work at determined temperatures. We have fostered an extensive variety of latent heat for various applications [9-11].

II. MATERIALS AND MEASUREMENT

In this section, various materials have been used for construction, and failure analysis is presented.

A. Copper Flat-Plate Collector

Two Copper flat-plate collectors were made one with a simple copper foil and flexible tube and the other with an iron tube filled with PCM as shown in Fig. 1.

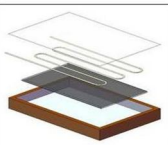
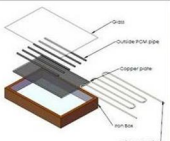
S. No.	Layers	Slide work image	Actual image
1.	1. Toughen Glass 2. Copper foil 3. Fluid Tube 4. Insulation 5. Iron box collector.		
2.	1. Toughen Glass 2. Copper foil 3. Fluid Tube 4. Iron tube 5. Insulation 6. Iron box collectors		

Fig. 1: Schematic Drawing and Actual Image of SFPC Assembly

There are two methods of Fabrication of SFPC, one is panel Fabrication and the other is iron box Fabrication as given below.

1) Fabrication of Iron Box

First of all took my own design and got an iron box made with the help of a manufacturer. Whose size is 24"×16"×4" inches. A variety of materials are used in the fabrication of iron boxes such as adhesives, thermo cool sheets and aluminium foil, brown paint and primer etc. A layer of primer is applied to the iron box. After applying the first coat of primer, leave it to dry for some time. This process is similar to browning twice. Take an iron box, apply adhesive inside all the walls and bottom of the box, then cut the thermo cool sheet to the size of the walls and bottom of the box, then fix all the pieces inside the box one by one .Again apply thermo cool sheet and adhesive material on the bottom of the box, then apply aluminium foil on the walls and bottom of the box and then leave it for some time. The insulating iron box is ready.

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Fig. 2: Iron Box Fabrications with Different Steps

2) Fabrication of Simple Copper Foil Sheet-and-Tubes Panel

As shown in Figure 3, it is a complete assembly copper-foil-and-tube, the size of the copper foil sheet is 53cmx34cm double folded and which type and the size of the fluid tube is 3.5m. Take a sheet of copper foil and make marks with a marker at a distance of 6-6 cm. Then fix the fluid tubes with the help of soldering with small pieces of copper foil between the sheets of copper foil. The sandwich type panel is ready by stapling it with a stapler. A black coat with matte finish black paint is applied and left for some time, after which a second coat is applied and then left for some time. The copper foil-and-tube panel is ready for use.



Fig. 3: Simple Copper Foil Sheet-and-Tubes Panel

3) Fabrication of Copper Foil Sheet Panel with PCM

This is a complete assembly of iron pipe cut into a size of 12 mm x 450 mm, 6 pieces of iron pipe and a 3.5 m length of fluid tube, rubber sockets (size 12 mm), silicon silent adhesive, etc. Take 6 pieces of iron pipes, insert the fluid tube with rubber sockets, and fill out the silicon silent of each socket. Once on a side, have closed and filled out the PCM on the other side, then close. Tightly closed rubber sockets into the both sides of the iron pipes and leaves once in a day for the setting (dry). Take a copper foil sheet; fit the iron pipe 6–6 cm distance fix with the help of soldering into small pieces of copper foil between the copper foil sheets, and fold the copper foil sheets sandwich type as shown in Figure 4. Copper foil sheets with PCM-filled iron tube panels are ready. Put the copper panel in an insulated box and covered the class sealing with silicon sealant. A Copper flat-plate collector is ready for the experiment.

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Fig. 4: Copper Foil Sheets with Iron Pipe Filling PCM and Class Covered

III.EQUATIONS, FAILURE ANALYSIS AND EXPERIMENT SETUP

A. Equations

The proficiency of sun-based flat plate water heater system is resolved altogether by the viability of the collector, acquired from looking at collector assistant energy through heated water and sun-arranged energy. The genuine helper energy, considering Qu, inlet and outlet water temperature, estimates, is determined as follows:

$$Qu = m\ C_p\ \Delta T \qquad (1)$$

Where ΔT is difference between inlet and outlet water m is the mass flow rate (kg/s) and C_p is explicit intensity (kJ/kg °C).

While hypothetical helpful energy, Qu is entirely set in stone as following

$$Qu = A_c.\ F_R\ [S - U_L\ (T_i - T_a)] \qquad (2)$$

Where Fr is heat release factor, S is sun fuelled radiation polished off by the safeguard plate (W/m²), U_L is outright force mishaps (complete intensity misfortunes) (W/m² K), T_i is inlet water temperature and T_a is ambient temperature

Collector efficiency η is:

$$\eta = Qu\ /I_T\ A_c \qquad (3)$$

Where A_c is surface area of the collector (m^2) and I_T is the solar intensity (W/m^2)
All inlet temperatures and outlet temperatures and proficiency of collectors are acquired from the above formulas.

B. Mechanical testing

Tensile, compression and fatigue tests evaluate the durability of the materials used in the collector and PCM containment.

C. Experimental Setup

Both collectors were prepared for outdoor testing. Testing was started on the roof of UIT-RGPV college building, Bhopal. Flat plate collectors were installed on stands and connected to the solar water storage container, an over head water container was connected for water supply. As shown in Figure 5, data is collected in the data logger with the help of J-type thermocouple. The water flow rate is 1 liter/Minute and readings of both the SFPCs were taken for four days.

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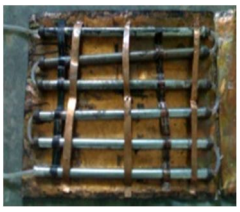
Fig. 5: Experimental set up of flat plate collector

D. Failure Analysis

To address these challenges, various methods are used in the failure analysis of PCM-filled solar flat plate collectors. During the experiment, there was a lot of leakage problem in the PCM panel, so the panel was opened several times. Attempts have been made to prevent leakage in PCM panels by using a variety of sealants and various materials, some of which are detailed in the table [I].

TABLE II: Failure Analysis

S. No.	**Adhesive**	**Material**	**Remark**	**Image**
1	ACC sealant, Neo seal 305, M-seal	PVC black pipe, PVC nozzle, copper wire, fluid tube	Sealing fails at both ends of PVC black pipe.	
2	Jack-bond adhesive, fevicoal glue	PVC black pipe, PVC two in one nozzle, iron claims, nozzle, rubber tube, insulation tap, fluid tube	The sealing has failed because PCM has leaked at both ends of the PVC pipe. The two in one PVC nozzle is broken. The rubber tube has burst.	

3	SR adhesive, fevikwik,	PVC pipe, plastic nozzle, PVC socket, Teflon tape, fluid tube	PCM fluid is leaking from the tube. Socket not sticking properly with SR adhesive hence sealing failed.	
4	SR glue, fevikwik,	PVC pipe, plastic nozzle, PVC socket, gasket Teflon tape, fluid tube	PCM is not leaking but PVC pipe is torn at many places so the material of PVC pipe has been changed.	
5	SR adhesive, fevicoal fevikwik	Iron pipe, gasket, fluid tube, Teflon tape	PCM Leaking Since the gasket contracts when heated due to temperature, PCM fluid starts leaking into the tube.	
6	Pouch(basically food packing polythene)	Pouch (basically food packing polythene), sealing machine, staplers , fluid tube, insulating tapes	The PCM leaked because the PCM had leaked out from both ends of the pouch (packing) due to increased temperature. Again the material was changed to iron pipe	
7	SR adhesive, fevikwik, silicon sealant,	Iron pipe, iron socket, fluid tube, Teflon tape, PVC baser, rubber baser	The PCM did not leak because the iron pipe was filled with silicone sealant and the iron nozzle was tightened with Teflon tape.	

While conducting the experiments, a lot of materials were used to protect the PCM from leakage. And whatever material failed during testing, that material was replaced with some other new material and tested, as given in the above table [III].
While testing was being done by changing the materials, a test was also conducted with iron tube to fill with PCM and it was found that its combination could prevent PCM leakage. The panel was then designed and experimented with and a leak proof PCM field solar water heater could be created.

IV. RESULT

This test can also be called conventional type without PCM i.e. it has been tested by installing it with only, flexible tube and copper foil. During the experiment it was found that the temperature here went up to 70degrees Celsius during the noon but in the evening the temperature reached 55 degrees Celsius. It can be said that it is a good alternative without copper tube that can be made from low-cost materials. As given in the chart below [fig. 6].

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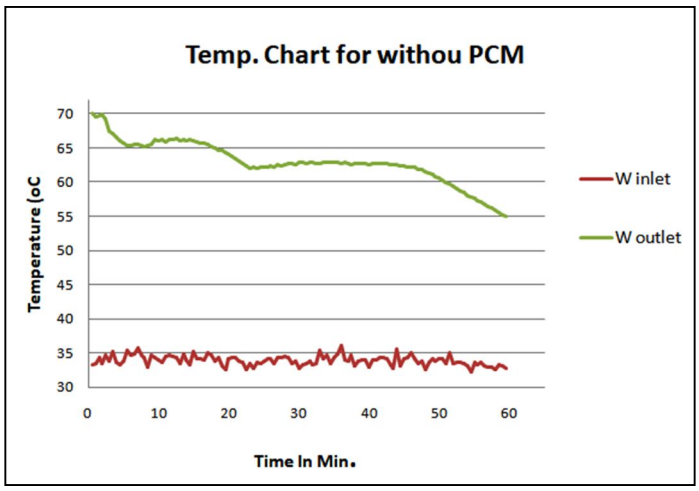


Fig. 6: Temperature V/S Time Chart without PCM

Within a few hours of testing, PCM was leaking repeatedly from the panel, hence the graph moving up and down. Later the graph started increasing and in 2-3 hours the PCM completely changed from strong to fluid and hence the temperature increased to 85-95ºC. As shown in the below the temperature chart with PCM 56º [fig. 7].

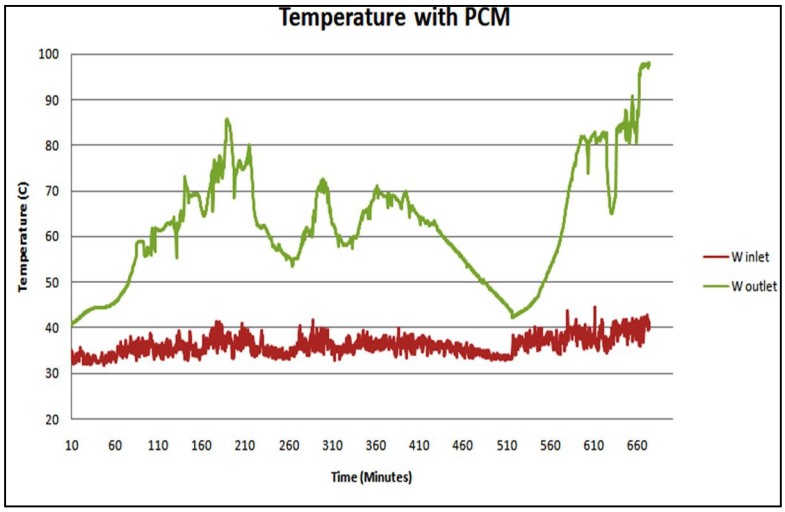


Figure 7: Temperature V/S Time Chart with PCM

As per the temperature chart above, several outdoor tests were conducted with and without PCM, but several problems were encountered while testing it, including the PCM filled tubes often leaking. Due to which the PCM panel had to be opened repeatedly and many new materials had to be used to prevent it from leaking. The setup is scheduled for four days as per all the standards of ASHRAE methodology for construction of this system.

V. DISCUSSION

The experiments with both models were performed for 4 days. In both cases, the water in the PCM was heated to a maximum temperature of 95 °C. The maximum temperature observed in a normal water heater was 70°C. Due to PCM leaking, a continuous decline in temperature was observed. There was a lot of leakage problem in PCM panels during the experiment; hence efforts have been made to prevent leakage in PCM panels by using different types of sealants and different materials. By combining it with an iron tube, its test was successful and it could be used. The data was recorded by MS-9700 loggers (Temperature Scanner) with the help of J-type thermocouples and according to a survey, all PCM-filled solar flat plate collectors manufactured so far have PCM filled in boxes and not in tubes, due to which there is very little contact between water and PCM. In this work, the iron pipe was filled with PCM and there is a flexible tubes protruding from the middle of the PCM.

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VI. CONCLUSION

Material failure analysis is critical to improving the performance and durability of PCM-filled solar flat plate collectors. By understanding the failure mechanisms and employing proper failure techniques, manufacturers can design systems that can withstand operational stresses.

The used method includes a low-cost assembly, which performs continued examination of the degradation of solar copper flat plate collector. It is observed that solar FPC is feasible for long-term use. There was a lot of leakage problem in PCM panels during the experiment; hence efforts have been made to prevent leakage in PCM panels by using different types of sealants and different materials. By combining it with an iron tube, its test was successful and it could be used. Two flat plate collectors were built for testing; these can be easily multiplied to make larger flat plate panels. While performing experiment, problems related to PCM filling in iron tubes was encountered. This made it difficult to quantify further investigation. The experiment covers several complementary assembly methods, such as creating a cheaper design by removing the copper tube. By using a good sealant with low cost, it will become much easier to manufacture SFPC using limited resources.

VII. ACKNOWLEDGMENT

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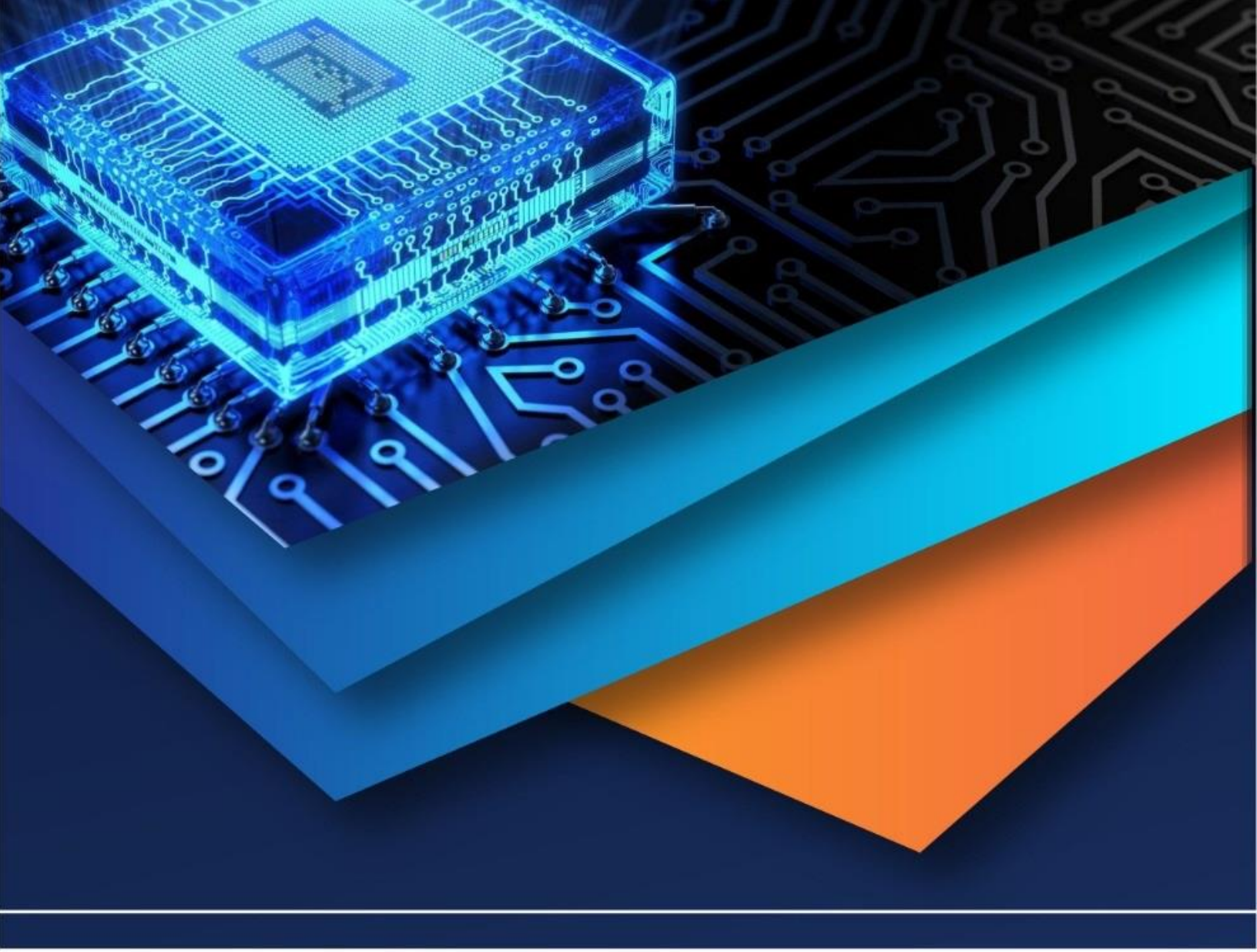
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