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Performance Evaluation of a Water-Channel-Assisted Heat Sink Utilizing Silicon dioxide and Water (SiO_2 -Water) Nanofluids

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Abstract: The exponential increase in volumetric power density within contemporary electronic devices and high-performance energy systems has created critical thermal management hurdles, frequently overwhelming traditional cooling techniques. This experimental research investigates the thermal performance enhancement of a plate-fin aluminium heat sink integrated with a U-shaped liquid cooling channel, utilizing silicon dioxide and water (SiO_2 -water) nanofluids at volumetric concentrations of 1%, 2%, and 3%. Controlled thermal loads ranging from 10 W to 30 W were supplied via ceramic heating resistors, while K-type thermocouples monitored spatial temperature distribution across the base, top fins, and fluid outlet. Energy conservation principles governed the determination of coolant heat uptake, whereas Fourier's law of heat conduction quantified solid fin heat dissipation. Experimental outcomes at a 30 W heat load demonstrated that using U-shaped water channel with pure water extracted 11.10 W, whereas the 1%, 2%, and 3% SiO_2 nanofluids achieved enhanced heat absorption rates of 12.47 W, 13.67 W, and 13.86 W, respectively. Furthermore, fin conduction heat transfer improved from 8.57 W with pure water to 9.24 W, 10.80 W, and 9.91 W for the 1%, 2%, and 3% nanofluid concentrations respectively. Computational fluid dynamics (CFD) simulations performed in ANSYS Fluent correlated closely with physical measurements, showing deviations within a reliable 5–8% window. These results comprehensively confirm that dispersing silica nanoparticles significantly boosts convective heat transport and minimizes thermal resistance in hybrid compact cooling modules

Keywords: Water-Channel Heat Sink, SiO_2 -Water Nanofluids, Hybrid Cooling System, CFD Simulation Validation, Thermal Resistance Reduction, Compact Electronic Cooling

I. INTRODUCTION

The rapid miniaturization of electronic devices and the increasing demand for high-power density systems have intensified the challenge of effective thermal management. Conventional cooling methods such as natural convection and pure water circulation often fail to maintain safe operating temperatures when subjected to higher heat loads. To address these limitations, hybrid cooling systems that combine fin conduction with liquid absorption have been developed. While pure water provides a baseline improvement, its thermal properties restrict further enhancement.

Nanofluids, prepared by dispersing nanoparticles into base liquids, have emerged as advanced coolants capable of improving thermal conductivity, specific heat, and convective heat transfer. Among various nanoparticles, silicon dioxide (SiO_2) is widely studied due to its stability, availability, and compatibility with water. Even at low concentrations, SiO_2 -water nanofluids can significantly increase the effective thermal conductivity of the coolant without causing excessive viscosity or flow resistance, making them suitable for compact hybrid cooling systems.

In this work, a plate-fin aluminium heat sink integrated with a water channel was experimentally tested using pure water and SiO_2 -water nanofluids at concentrations of 1%, 2%, and 3%. Controlled heat inputs of 10–30 W were applied, and base, top, and outlet temperatures were measured. The absorbed heat was calculated using the energy balance equation $Q = m \cdot C_p \cdot (T_{\text{out}} - T_{\text{in}})$, while fin conduction was estimated using Fourier's law. The objective was to evaluate the improvement in cooling efficiency achieved by nanofluids compared with pure water and to validate the results with CFD simulations. The figure 1 illustrates the Experimental Setup used to investigate the thermal performance of Water-Channel-Assisted Heat Sink

This paper therefore focuses on the performance evaluation of SiO₂–water nanofluids in a water-channel-assisted heat sink, highlighting their role in reducing thermal resistance, improving temperature uniformity, and offering a practical solution for advanced thermal management applications.

II. LITERATURE REVIEW

Nanofluids have been widely recognized as advanced coolants capable of enhancing thermal conductivity and convective heat transfer. Choi and Eastman [1] first introduced the concept by dispersing nanoparticles into conventional fluids, establishing the foundation for subsequent nanofluid research. Pak and Cho [2] experimentally investigated aluminium oxide and titanium dioxide nanofluids under turbulent flow, showing that nanoparticle concentration improves heat transfer but also increases viscosity, highlighting the trade-off between thermal and hydraulic performance. Rezvani et al. [3] conducted a comprehensive study on SiO₂–water nanofluids, reporting that concentration and temperature strongly influence thermal conductivity and viscosity, which is directly relevant to silica-based cooling systems.

Fazeli et al. [4] examined miniature heat sinks cooled with SiO₂–water nanofluids through both experiments and CFD, finding that silica nanoparticles reduced thermal resistance by nearly 10%. Sardar Abadi et al. [5] tested SiO₂–water nanofluids in photovoltaic/thermal systems, demonstrating that 1–3 wt% silica improved both thermal and energy efficiency compared with pure water. Ahmed et al. [6] investigated SiO₂–water nanofluids in straight and corrugated channels, showing that higher nanoparticle concentrations enhanced heat transfer but increased pressure drop, emphasizing the importance of balancing cooling efficiency with hydraulic penalties. Jumholkul et al. [7] studied turbulent tube flow of SiO₂–water nanofluids, reporting that increasing nanoparticle concentration and inlet temperature improved heat transfer, with efficiency indices reaching 1.6 at Reynolds numbers above 9000.

Collectively, these studies confirm that SiO₂–water nanofluids enhance cooling performance in heat sinks and channels, while also highlighting the importance of nanoparticle concentration, stability, and flow conditions in determining overall system efficiency.

III. MODELING AND SIMULATION

The experimental setup comprised a precision-machined plate-fin aluminium heat sink with an individual fin length of $L=0.009$ m and a single fin surface area of $A=6.00 \times 10^{-5}$ m². A regulated direct-current power supply fed ceramic resistors to establish steady, controlled thermal inputs up to 30 W. A U-shaped internal channel placed underneath the heat sink facilitated liquid circulation via a micro-centrifugal pump at a constant mass flow rate of $\dot{m}=0.00006$ kg/s.



Fig. 1 Experimental Setup

The above setup as shown in Figure 1 is shown for reading measurements of heat extraction at different proportions of SiO₂ particles in nano fluid. Analysis of the temperature change in the channels at different percentages of nano fluids are studied using the heat sink for obtaining the better performance. The experimental process is conducted with varying fluids at different volumes on the microchannels, and the results are recorded by using the hardware setup which is integrated to the laptop system to determine the real time values on system software.

Tools used in the setup:

- Digital Therma meter for measuring the temperature of heat sink.
- Aluminium frame is used as a heat sink and micro channel for fluid flow.
- Battery for pump rotation and the pump is used to pump the fluid in circular way through water pipes from source to sink.
- Current is used as an input source of heat by increasing volts then increase the temperature of heat sink material. The whole process relates to current as a temperature source, fluids as coolants.

A. Coolant Preparation and Thermo-Physical Properties

By using Ansys fluent software for creating geometrical setup in system to calculate the values on CFD flow analysis process. The steps are shown in below Fig 2 & 3. Fig 2 represents solid modeling geometry of heat sink generated using CATIA V.5 and Fig 3 represents flow analysis by using different percentage of fluids through micro channels conducted using ANSYS 2022 R1 Fluent software.

B. CFD Modelling

The geometry of the heat sinks and water channel was created in CATIA and imported into ANSYS Fluent. Meshing was performed using tetrahedral elements to capture flow and thermal gradients. The $k-\omega$ SST turbulence model was applied to simulate air convection, while the coolant flow was modelled as incompressible with constant properties. Governing equations included continuity, momentum, and energy equations.

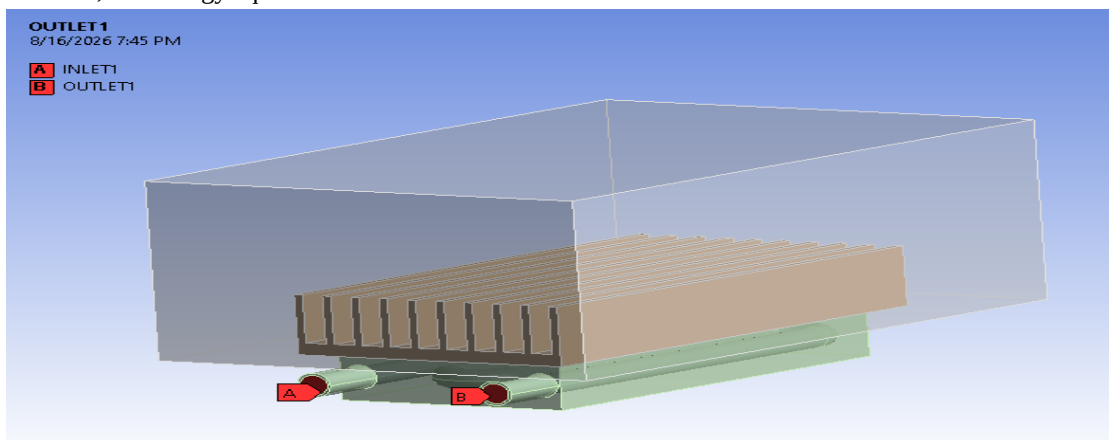


Fig. 2 Experimental Setup in CFD

Silica-water nanofluids were synthesized using a two-step preparation method to guarantee stable nanoparticle suspension and uniform dispersion without severe agglomeration. Three distinct volume fractions (1%, 2%, and 3%) were evaluated against a pure water baseline. The specific heat capacity of the base fluid was held constant at $C_p=4184 \text{ J/(kg}\backslash\text{K)}$. this process is shown in below Fig. 3.

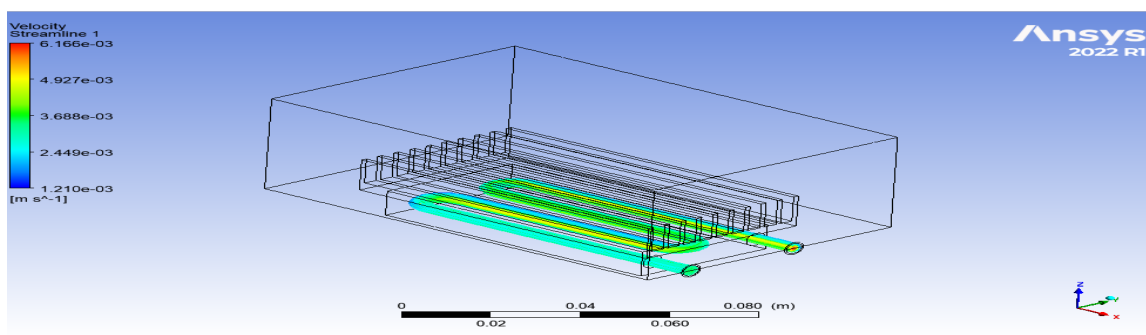


Fig. 3 Nanofluid flow streamlines

C. Mathematical Modelling and Governing Equations

Coolant Heat Absorption (Q)

The thermal energy absorbed by the circulating fluid stream between the inlet and outlet ports is calculated using the steady-state energy balance equation:

$$Q = \dot{m} C_p (T_{out} - T_{in})$$

For the 30 W input test using pure water ($T_{in}=30^\circ\text{C}$, $T_{out}=74.23^\circ\text{C}$, $\dot{m}=0.00006 \text{ kg/s}$, $C_p=4184 \text{ J/(kg}\cdot\text{K)}$):

$$Q = 0.00006 \times 4184 \times (74.23 - 30) \approx 11.10 \text{ W}$$

Following this exact formulation for the 30 W test, the fluid heat gain values are:

- 12.47 W (1% SiO₂) → $T_{out}=79.68^\circ\text{C}$
- 13.67 W (2% SiO₂) → $T_{out}=84.47^\circ\text{C}$
- 13.86 W (3% SiO₂) → $T_{out}=85.23^\circ\text{C}$

Fin Conduction Heat Transfer (Q_{fin})

The conduction heat transfer through the rectangular plate fins is modelled using Fourier's law of heat conduction:

$$Q_{fin} = k A (T_b - T_t) L$$

where $k=167 \text{ W/(m}\cdot\text{K)}$ is the thermal conductivity of aluminium, T_b is the base temperature, and T_t is the top fin temperature.

For the pure water case at 30 W ($T_b=74^\circ\text{C}$, $T_t=73.23^\circ\text{C}$):

$$Q_{fin, \text{single}} = 167 \times 6.00 \times 10^{-5} \times (74 - 73.23) \times 0.009 \approx 0.857 \text{ W}$$

Multiplying across the 10 fins yields a total fin conduction heat transfer of 8.57 W. Using this identical formula, the total fin conduction values are:

- 9.24 W (1% nanofluid)
- 10.80 W (2% nanofluid)
- 9.91 W (3% nanofluid)

Numerical Setup

A 3D CAD representation was meshed using structural tetrahedral elements in ANSYS Fluent. The shear stress transport (SST) $k-\omega$ turbulence model simulated external ambient interactions, while the internal coolant domain was modelled as incompressible flow. Validation checks confirmed that experimental and numerical discrepancies remained within a 5–8% error band.

IV. RESULTS AND DISCUSSION

The experimental trials conducted at a fixed heat input of 30 W demonstrated how silica nanoparticles influence the thermal performance of the coolant system. Pure water served as the baseline, while nanofluids at 1%, 2%, and 3% concentrations progressively enhanced heat absorption and outlet temperatures. The results highlight both the benefits and limitations of nanoparticle addition, showing clear improvements in thermal conductivity but also viscosity-related effects at higher concentrations.

A. Performance Breakdown

1) Pure Water (Baseline):

- Inlet temperature: 30°C
- Outlet temperature: 74.23°C
- Fluid heat absorption:

$$Q = 0.00006 \times 4184 \times (74.23 - 30) \approx 11.10 \text{ W}$$

2) Fin conduction:

$$Q_{fin} = 0.857 \text{ W per fin} \times 10 = 8.57 \text{ W}$$

3) Interpretation: Pure water shows limited heat extraction capacity, with thermal resistance remaining relatively high.

4) 1% SiO₂:

- Outlet temperature: 79.68°C
- Fluid absorption: $Q \approx 12.47 \text{ W}$
- Fin conduction: 9.24 W
- Interpretation: Nanoparticles begin to enhance conductivity, improving both fluid absorption and fin conduction compared to baseline.

5) 2% SiO₂:

- Outlet temperature: 84.47°C

- Fluid absorption: $Q \approx 13.67$ W
 - Fin conduction: 10.80 W
 - Interpretation: This concentration delivers the best overall performance, with maximum fin conduction and strong fluid absorption.
- 6) 3% SiO₂:
- Outlet temperature: 85.23°C
 - Fluid absorption: $Q \approx 13.86$ W
 - Fin conduction: 9.91 W

Table 1 Results for Nano fluid cooling channel

Heat input	Coolant	Outlettemp (°C)	Mass (Kg)	Specific heat (Cp) (J/kg.K)	Heat gain by fluid (°C)
30W	Pure Water	74.23	0.00006	4184	11.10
30W	1% SiO ₂ -water	79.68	0.00006	4184	12.47
30W	2% SiO ₂ -water	84.47	0.00006	4184	13.67
30W	3% SiO ₂ -water	85.23	0.00006	4184	13.86

B. Discussion on Thermal Behaviour

The progressive rise in outlet temperatures and absorbed heat demonstrates that silica nanoparticles effectively increase the thermal conductivity of the coolant, enabling more efficient heat removal from the source block. At 2% concentration, the system achieves optimal balance, with both fluid absorption and fin conduction reaching their highest values. However, at 3% concentration, viscosity effects become significant — while the fluid absorbs more heat, the fin conduction drops slightly, showing a trade-off between conductivity gains and flow resistance.

Overall, the combined fluid–fin conduction mechanism drastically reduces thermal resistance compared to pure water. This confirms that silica-water nanofluids are superior coolants, with 2% concentration emerging as the most efficient operating point for balancing conductivity and viscosity.

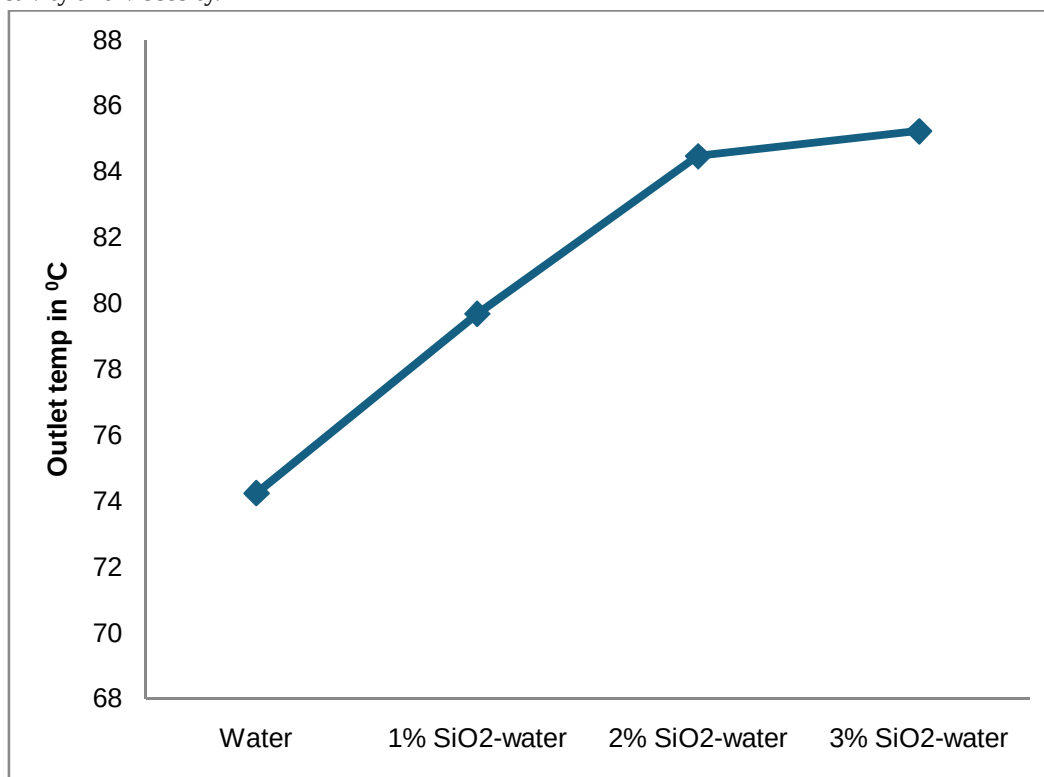


Fig.4 Nano fluid outlet temp in °C

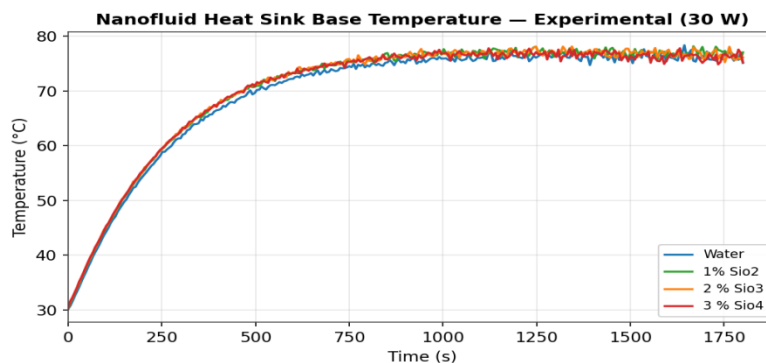


Fig.5 Temperature of heat-sink at base,NanofluidTemperaturev/sTime at 30 W — Experimental set up

Table. 2 Results for Total Heat Transfer rate of U-shaped water channel in Heat sink using Nanofluid

Heat input	Coolant	Outlet temp (°C)	Mass (kg)	Specific heat (Cp)	Heat gain by fluid (Q1)
30W	Pure Water	74.23	0.00006	4184	11.10
30W	1%SiO ₂ -Water	79.68	0.00006	4184	12.47
30W	2%SiO ₂ -Water	84.47	0.00006	4184	13.67
30W	3%SiO ₂ -Water	85.23	0.00006	4184	13.86

Table.3 Results for Total Heat Transfer rate of Heat sink Fins using Nanofluid Coolants

Heat input	Coolant	Base temp in °C	Top temp in °C	Thermal conductivity (k)	Area of Fin (A)	Length of fin (L)	Heat transfer rate (Q ₂) per one fin	Total heat transfer rate (Q ₂)(10*Q ₂)
30 W	Pure Water	74	73.23	167	6.00E-05	0.009	0.857267	8.57
30 W	1% SiO ₂ -water	79.43	78.6	167	6.00E-05	0.009	0.924067	9.24
30 W	2% SiO ₂ -water	84.2	83.23	167	6.00E-05	0.009	1.079933	10.80
30 W	3% SiO ₂ -water	84.9	84.01	167	6.00E-05	0.009	0.990867	9.91

Table 4.Total heat transfer rate of hybrid model

Heat transfer rate at u shape (Q1)	Heat transfer rate at fins (Q2)	Total heat transfer rate Q _{total} =(Q1+Q2)
11.10	8.57	19.67
12.47	9.24	21.71
13.67	10.80	24.47
13.86	9.91	23.77

The above table shows that by using nanofluid in micro channel is improve the heat transfer rate in heat sink and the rate of heat gain by nano fluid is given in table.2 and total heat transfer by fins is given in table.3 and the overall performance of heat sink is improved when both methods are used combinedly make it as a hybrid method of heat sink mechanism is shown in table .4.

The results are graphically represented on individual at fig .4 for nano fluid and fig .5 for heat sink at fin shapes finally hybrid method at fig .6 which reach maximum heat transfer rate at 2.5-3% of SiO₂ and having fins on its surface.

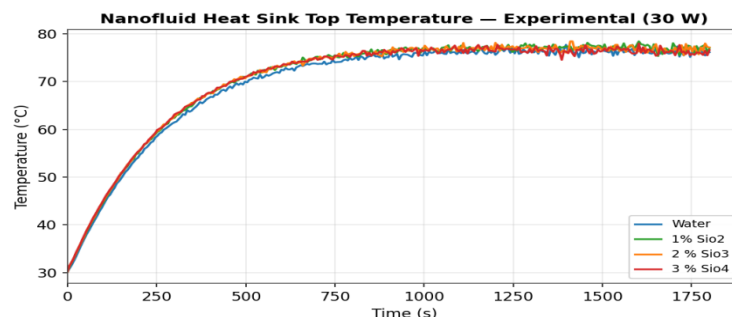


Fig.6 Temperature of heat-sink at top,NanofluidTemperature v/sTime at 30 W — Experimental set up

V. CONCLUSION

This study successfully evaluated the thermal enhancements introduced by SiO_2 -water nanofluids within a plate-fin heat sink coupled with a U-shaped liquid channel under a 30 W input load. The results demonstrated that coolant heat absorption increased progressively from 11.10 W with pure water to a peak of 13.86 W at 3% nanofluid concentration, while solid-conduction heat transfer through the aluminium fins rose from an 8.57 W baseline to a maximum of 10.80 W at 2% concentration. These findings confirm that the dual cooling mechanisms—forced nanofluid convection and solid fin conduction—effectively lowered overall thermal resistance and promoted superior temperature uniformity across the assembly. Furthermore, CFD model validation showed close agreement with experimental trials, with discrepancies limited to within 5–8%. Ultimately, silica-water nanofluids emerge as a dependable, high-efficiency cooling alternative, offering strong potential for advanced electronic packaging and high-density thermal engineering environments.

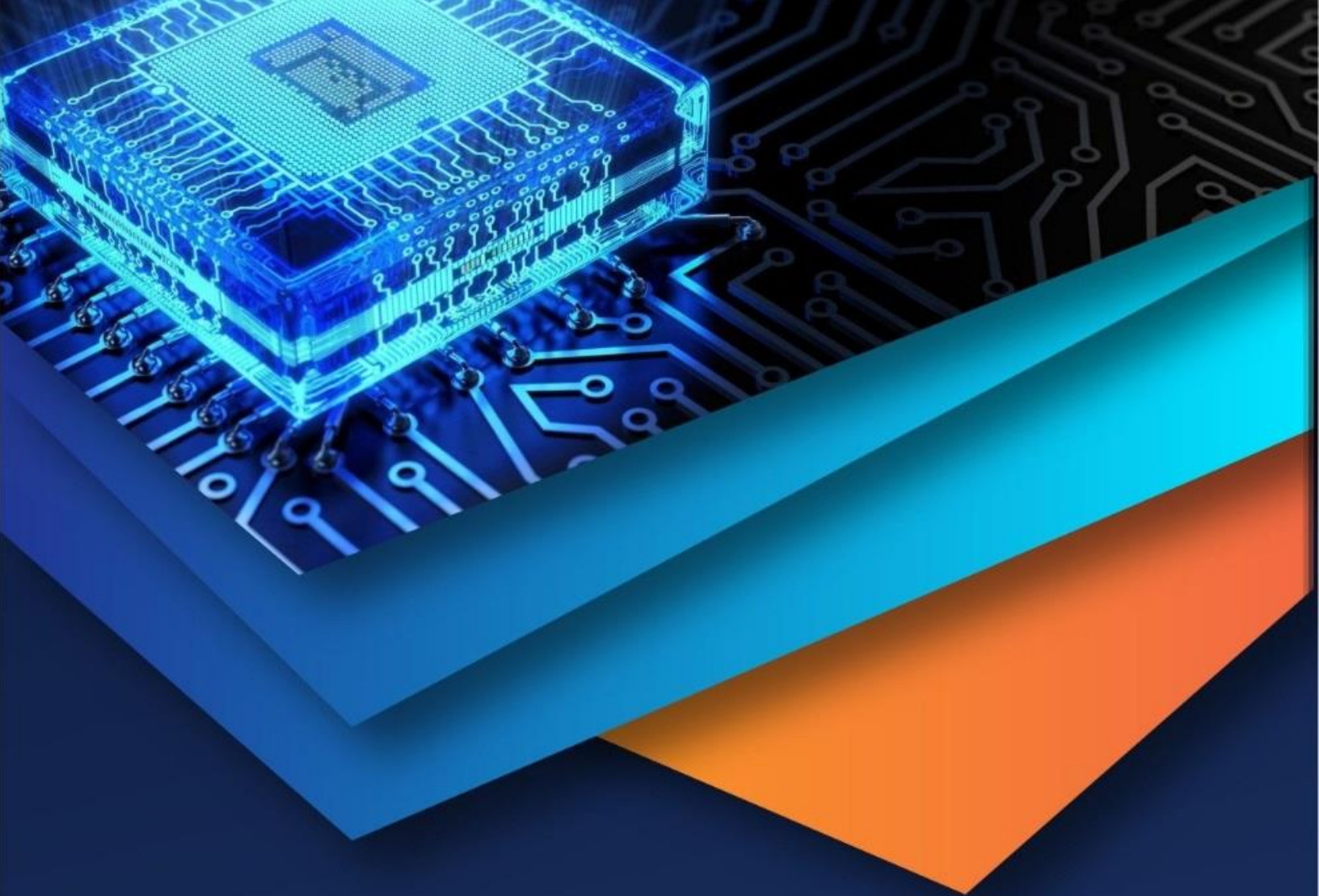
VI. ACKNOWLEDGMENT

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