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Experimental and Computational Investigation of Air Flow on a Hybrid Heat Sink

Macha Bhargav[1], SK. Meeravali[2], Lakshmi Tulasi Chavali[3], M. Suresh Kumar[4]
[1]M.Tech. Scholar, [2]Assistant Professor, [3]Professor, [4]Associate Professor, Department of Mechanical Engineering, St. Ann's College of Engineering & Technology, Chirala, Andhra Pradesh, India

Abstract: ***Polymer-based heat exchangers can offer lower mass, corrosion resistance and manufacturing flexibility compared with conventional metallic designs, but the low thermal conductivity of unfilled polymers limits heat rejection. This study experimentally and computationally evaluates a hybrid finned-tube heat sink made from reprocessed high-density polyethylene (HDPE) reinforced with multi-walled carbon nanotubes (MWCNTs) and boron nitride (BN). Three fin materials were compared: neat HDPE, HDPE with 4% MWCNT and 2% BN, and HDPE with 6% MWCNT and 2% BN. Thermal conductivity was measured using the composite-wall method, and the fabricated heat sink was tested in an air–water loop at air-side Reynolds numbers of approximately 2,000–40,000. The reported thermal conductivities were 0.581, 0.86 and 1.18 W m^{-1} K^{-1}, respectively. The higher-filled composite also produced the highest plotted heat-transfer rate and overall heat-transfer coefficient across the investigated Reynolds-number range. A three-dimensional steady-state ANSYS Fluent model was used to examine temperature distribution in a representative fin under a 65 °C heating condition and 26 °C room temperature. The computed temperature fields were qualitatively consistent with the observed material trend. The results indicate that hybrid MWCNT/BN reinforcement can improve the thermal response of reprocessed HDPE fins under the tested conditions. Further work should quantify uncertainty, repeatability, mechanical durability and model-to-experiment error before design-level performance claims are made.***

Keywords: polymer composite; hybrid heat sink; high-density polyethylene; multi-walled carbon nanotubes; boron nitride; forced convection; ANSYS Fluent.

I. INTRODUCTION

Heat sinks and compact heat exchangers are widely used to remove heat from electronic, electrical and industrial systems. Copper and aluminium have high thermal conductivity, but their mass, cost, corrosion behavior, and fabrication requirements can be limiting in certain applications. Polymer heat exchangers offer potential advantages in weight, chemical resistance, geometric flexibility, and manufacturing cost; however, the low thermal conductivity of neat polymers can restrict heat transfer from the tube or base to the extended surface [1–4].

Thermally conductive polymer composites address this limitation by incorporating fillers into a polymer matrix. Carbon nanotubes can provide conductive pathways when dispersion and contact between fillers are sufficient, while boron nitride is an electrically insulating ceramic filler with relatively high thermal conductivity. A hybrid filler system may therefore alter the effective heat-conduction network within the matrix [5–8]. The resulting heat-sink performance, however, depends not only on bulk conductivity but also on filler distribution, fin geometry, contact resistance and air-side convection.

The present work investigates a finned-tube heat sink using reprocessed HDPE as the matrix and MWCNT/BN as hybrid reinforcement. The study combines material-level conductivity measurements, forced-air experimental evaluation and three-dimensional numerical simulation. Its purpose is to compare the tested formulations under the reported laboratory conditions rather than to claim a universally optimal polymer heat sink.

II. BACKGROUND AND RESEARCH MOTIVATION

Prior work on polymer heat exchangers has considered applications such as HVAC, condensing boilers, automotive radiators and compact cooling systems. Reviews by Cevallos et al. and Chen et al. describe the potential of polymeric exchangers while emphasizing the trade-off between low material conductivity and advantages such as corrosion resistance and reduced mass [1,2]. Studies of polymer hollow-fibre and finned-tube systems have examined geometry, flow arrangement, and air-side heat transfer as means of compensating for material limitations [3,4].

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Research on polymer nanocomposites shows that filler type, loading, particle morphology and dispersion influence thermal conductivity. Carbon-based fillers, including MWCNTs, may create conductive networks; BN is used as a thermally conductive, electrically insulating filler. The benefit of combining fillers is not automatic: agglomeration, interfacial resistance and processing-induced orientation can affect the measured property [5–8]. For a finned-tube heat sink, conductivity measured through the plate may not fully represent in-plane conduction along the fin, which is particularly important for spreading heat away from the tube interface.

The specific motivation here is to connect the material-level conductivity trend with the heat-transfer behaviour of a fabricated assembly. The study compares three formulations using a common experimental arrangement and uses ANSYS Fluent to visualize the temperature distribution within a representative fin. The work is therefore an experimental comparison supported by numerical interpretation; it does not establish a new heat-transfer correlation or a validated predictive model for all operating conditions.

Research objectives

- Prepare and compare neat HDPE and two hybrid MWCNT/BN-reinforced HDPE formulations.
- Measure the thermal conductivity of the prepared plates using the reported composite-wall arrangement.
- Evaluate average heat-transfer rate and overall heat-transfer coefficient as air-side Reynolds number increases.
- Examine temperature distribution in a representative fin using a three-dimensional steady-state ANSYS Fluent model.

III. MATERIALS AND EXPERIMENTAL METHODOLOGY

A. *Materials and formulations*

Reprocessed high-density polyethylene was used as the continuous matrix. The two reinforced materials contained MWCNT and BN at the nominal loadings reported in the thesis. The comparison set comprised (i) neat HDPE, (ii) 4% MWCNT + 2% BN in HDPE and (iii) 6% MWCNT + 2% BN in HDPE. The thesis reports 99% purity for the MWCNT powder and 98% purity for the BN powder. Because the source thesis uses percentage notation inconsistently in some places, the percentages are retained here as reported; the basis (mass or volume fraction) should be stated explicitly in a final journal submission [9-10].

Table 1. Formulations used in the experimental investigation.

Formulation	Nominal composition	Role in comparison
F1	HDPE	Unfilled reference material
F2	4% MWCNT + 2% BN / HDPE	Intermediate hybrid-filler loading
F3	6% MWCNT + 2% BN / HDPE	Higher MWCNT loading with BN

Table 1 defines the three material cases compared in this study. Neat HDPE serves as the reference, while the two reinforced formulations allow the effect of increasing MWCNT content at a fixed nominal BN loading to be examined. The percentage basis should be confirmed from the original preparation records before journal submission.

B. *Heat-sink assembly and test loop*

The polymeric fins were fabricated using a machined die and assembled around copper tubes to form a finned-tube heat sink. The experimental loop comprised a duct and blower on the air side, a heated water tank and pump on the water side, flow-control valves, thermocouples and a manometer. Heated water supplied energy through the copper tubes while air flowed across the fin array. The thesis describes water-inlet temperature settings from 30 °C to 75 °C and air-side Reynolds numbers spanning approximately 2,000–40,000.

Figure 1. Fabricated hybrid finned-tube heat sink (source: supplied thesis)

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C. Experimental procedure and measurements

For each test condition, the water loop was operated to establish the selected inlet temperature and the blower was used to set the air-side flow condition. The thesis describes full-, half-, and quarter-valve-opening settings. Temperature readings were recorded at the air inlet and outlet and at the water inlet and outlet; manometer readings were used to characterize the air-side pressure difference. The copper pipes outside the duct were insulated as described in the experimental procedure. Measurements were then used to calculate thermal conductivity, heat-transfer rate and overall heat-transfer coefficient.

Figure 2. Experimental test rig used for the air–water heat-transfer investigation (source: supplied thesis)

D. Thermal conductivity measurement

Thermal conductivity was evaluated using a composite-wall arrangement based on the temperature gradient across the prepared plate. For one-dimensional conduction through a homogeneous layer, the Fourier relation can be written as

$$\mathbf{Q = k\,A\,(T_1 - T_2) / L}$$

where Q is the heat-transfer rate, k is thermal conductivity, A is the effective area normal to heat flow, L is the specimen thickness, and $T_1 - T_2$ is the measured temperature difference across the specimen. The actual composite-wall calculation follows the layer arrangement and measurements described in the thesis. In interpreting the results, the direction of measurement matters: the reported plate conductivity should not be assumed to equal the in-plane conductivity of a fin without additional evidence.

E. Heat-transfer calculations

The heat-transfer rate on a fluid side is commonly evaluated from the mass-flow rate and the measured temperature change:

$$\mathbf{Q = \dot{m}\,c_p\,(T_out - T_in)}$$

where $\dot{m}$ is the fluid mass-flow rate and c_p is its specific heat capacity. The overall heat-transfer coefficient is obtained using the heat-transfer rate, area and log-mean temperature difference (LMTD):

$$\mathbf{Q = U\,A\,\Delta T_lm}$$

The reported overall coefficient and heat-transfer rate are compared as functions of air-side Reynolds number. The analysis is descriptive: uncertainty intervals and repeated-trial statistics were not sufficiently documented in the supplied thesis to support a formal significance test.

F. Numerical model

ANSYS Fluent was used to examine heat diffusion in a three-dimensional single-fin domain. The thesis reports a steady-state solver and an energy model, with the heater set to 65 °C and the surrounding room at 26 °C. The stated flow assumptions include steady, incompressible behaviour, with an RNG k–ε turbulence model identified in the presentation materials. The computational results are used to compare temperature fields among the three materials. A quantitative validation metric, grid-independence study and a detailed error comparison against measured temperatures are not reported clearly enough to claim a fully validated CFD model.

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IV. RESULTS AND DISCUSSION

A. *Thermal conductivity*

The measured conductivity increases with increasing hybrid filler loading. The thesis reports 0.581 W m^{-1} K^{-1} for the neat HDPE plate, 0.86 W m^{-1} K^{-1} for the 4% MWCNT + 2% BN formulation and 1.18 W m^{-1} K^{-1} for the 6% MWCNT + 2% BN formulation. Relative to the neat-HDPE value, these correspond to approximate increases of 48% and 103%, respectively. The higher-filled material therefore exhibited about twice the reported conductivity of the unfilled plate.

Table 2. Thermal conductivity of the tested HDPE-based formulations.

Material	Thermal conductivity (W m^{-1} K^{-1})	Change relative to HDPE
HDPE	0.581	Reference
4% MWCNT + 2% BN / HDPE	0.86	≈48% higher
6% MWCNT + 2% BN / HDPE	1.18	≈103% higher

As summarized in Table 2, the reported conductivity increases from 0.581 W m^{-1} K^{-1} for neat HDPE to 0.86 and 1.18 W m^{-1} K^{-1} for the reinforced formulations. These correspond to approximate increases of 48% and 103% relative to the HDPE reference, respectively. The comparison indicates a material property improvement under the reported measurement method; repeatability and uncertainty should be included if replicate measurements are available.

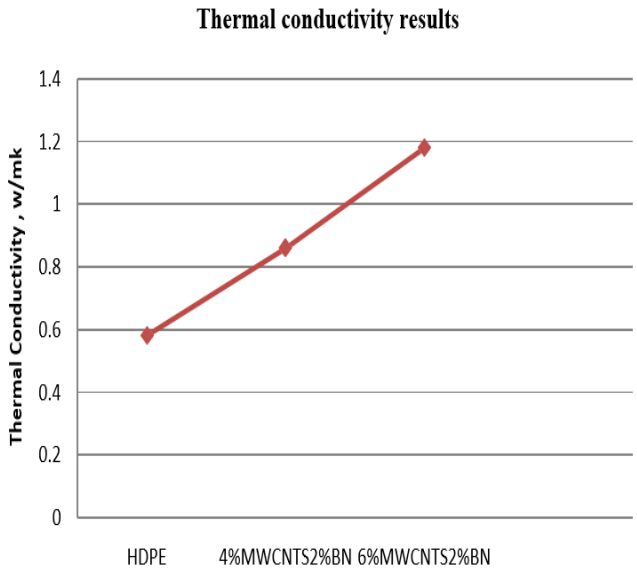

Figure 4. Thermal conductivity reported for the three polymer-composite formulations (original thesis plot)

The trend is consistent with the expected role of conductive fillers in providing additional heat-transfer pathways through a polymer matrix. The measured increase should nevertheless be interpreted as a result for the specific specimens and test method. Dispersion quality, filler orientation, interfacial thermal resistance and specimen-to-specimen variability can affect the effective property. Since no uncertainty bars are shown in the source plot, the magnitude of repeatability cannot be assessed from the figure alone.

B. *Average heat-transfer rate*

The thesis plots average heat-transfer rate against air-side Reynolds number over a range from approximately 2,000 to 40,000. All three material curves rise as Reynolds number increases, indicating greater heat transfer under the higher-flow conditions investigated. The 6% MWCNT + 2% BN composite produces the highest curve, while neat HDPE produces the lowest. The source text reports that, near Re ≈ 2,000, the difference between the highest and lowest heat-transfer cases is approximately 0.027 kW.

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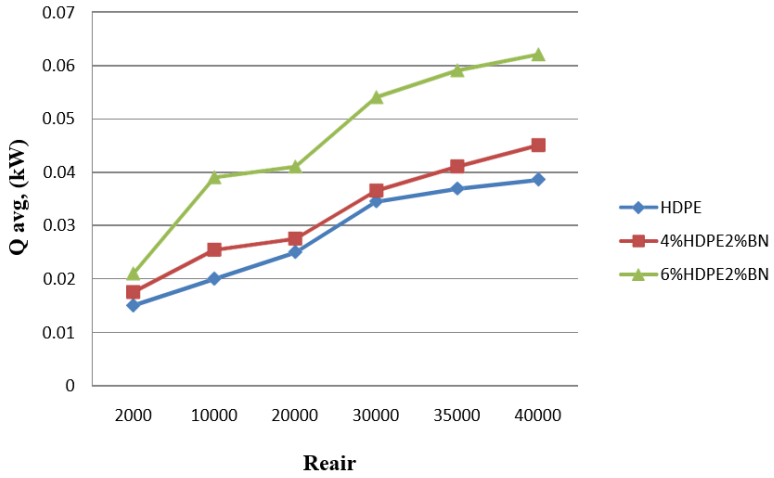

Figure 5. Average heat-transfer rate versus air-side Reynolds number (source thesis plot)

C. Overall heat-transfer coefficient

The overall heat-transfer coefficient also increases with air-side Reynolds number for all three formulations. The higher-filled composite yields the largest plotted values over the investigated range, followed by the intermediate formulation and neat HDPE. This ordering agrees with the conductivity measurements and the heat-transfer-rate curves. The trend suggests that the improved solid-side conduction associated with the reinforced materials contributes to better overall performance under the tested arrangement; however, the measured overall coefficient also reflects air-side convection, water-side convection, geometry and contact resistances.

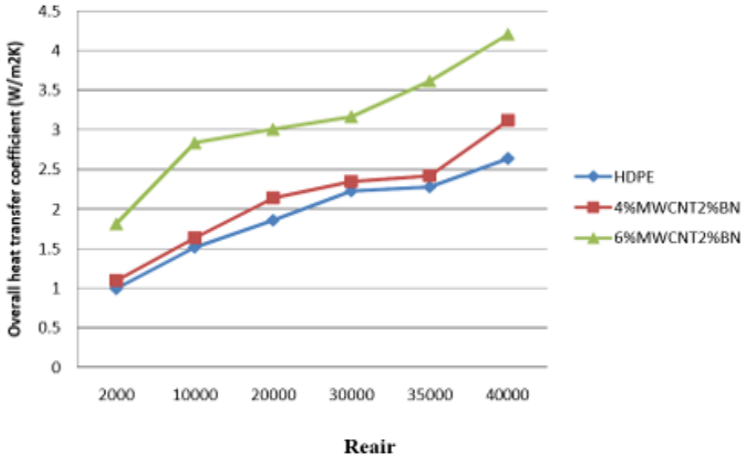

Figure 6. Overall heat-transfer coefficient versus air-side Reynolds number (source thesis plot)

The original thesis conclusion reports percentage improvements for heat-transfer rate and overall coefficient. Because the narrative and plotted values do not provide a fully auditable point-by-point calculation of every percentage, this manuscript emphasizes the observed ordering and flow dependence rather than presenting the reported maximum percentage increases as independently verified quantities. The exact test-point values, uncertainty and calculation basis should be checked against the raw experimental records before submission.

D. Numerical temperature distribution

The ANSYS Fluent results compare temperature fields for neat HDPE, the 4% MWCNT + 2% BN composite and the 6% MWCNT + 2% BN composite. The source figure shows broader and stronger heat spreading for the more conductive formulation, while the neat-HDPE case exhibits a more localized temperature field around the heat-transfer region. The numerical pattern is qualitatively consistent with the experimentally measured increase in thermal conductivity.

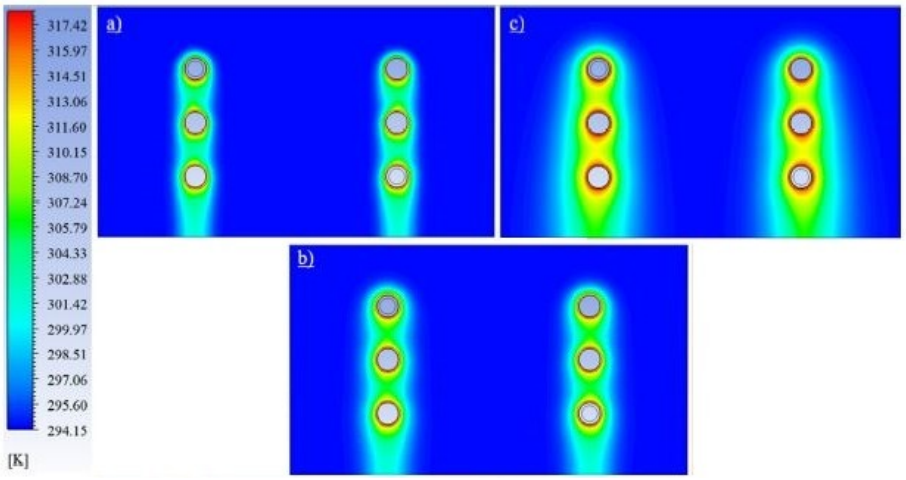

Figure 7. Temperature contours for (a) HDPE, (b) 4% MWCNT + 2% BN / HDPE, and (c) 6% MWCNT + 2% BN / HDPE (source thesis)

The simulation supports interpretation of the spatial temperature distribution, but it should not be taken as quantitative validation without reporting mesh-independence evidence, solver residuals, boundary-condition sensitivity and direct comparison of predicted and measured temperatures. The single-fin model also does not by itself reproduce every flow and contact feature of the complete experimental assembly.

E. Engineering interpretation

Across the three formulations, the material with the highest reported conductivity also provides the highest plotted heat-transfer rate and overall heat-transfer coefficient. This agreement across material testing, assembly-level measurements and numerical temperature fields is the central finding. It indicates that hybrid MWCNT/BN reinforcement is a promising route for improving the thermal response of reprocessed HDPE fins in the tested configuration. The results do not establish that the composite can replace metals in all applications: mechanical strength, long-term thermal cycling, filler cost, processability, ageing and fin-to-tube contact resistance require separate evaluation.

V. CONCLUSIONS

An experimental and computational investigation was conducted on a hybrid finned-tube heat sink fabricated from reprocessed HDPE reinforced with MWCNTs and BN. Three formulations were compared: neat HDPE, 4% MWCNT + 2% BN / HDPE, and 6% MWCNT + 2% BN / HDPE. The main conclusions are as follows.

- The reported thermal conductivity increased from 0.581 W m^{-1} K^{-1} for neat HDPE to 0.86 W m^{-1} K^{-1} and 1.18 W m^{-1} K^{-1} for the two hybrid composites.
- Average heat-transfer rate increased with air-side Reynolds number, and the 6% MWCNT + 2% BN formulation produced the highest curve in the reported range.
- The overall heat-transfer coefficient followed the same qualitative material ordering, with the higher-filled composite giving the largest plotted values.
- The ANSYS Fluent temperature fields qualitatively supported the observed conductivity trend by showing more extensive heat spreading for the higher-conductivity material.

The present evidence is limited to the tested specimens, apparatus and reported operating conditions. Further work should document the filler fraction basis and manufacturing protocol, repeat the conductivity and heat-transfer measurements with uncertainty estimates, test mechanical and thermal-cycle durability, and quantify CFD error using measured temperatures and mesh-independence checks. A direct comparison with a metal-fin reference under identical geometry and operating conditions would be needed to establish the practical trade-off between thermal performance, mass and cost.

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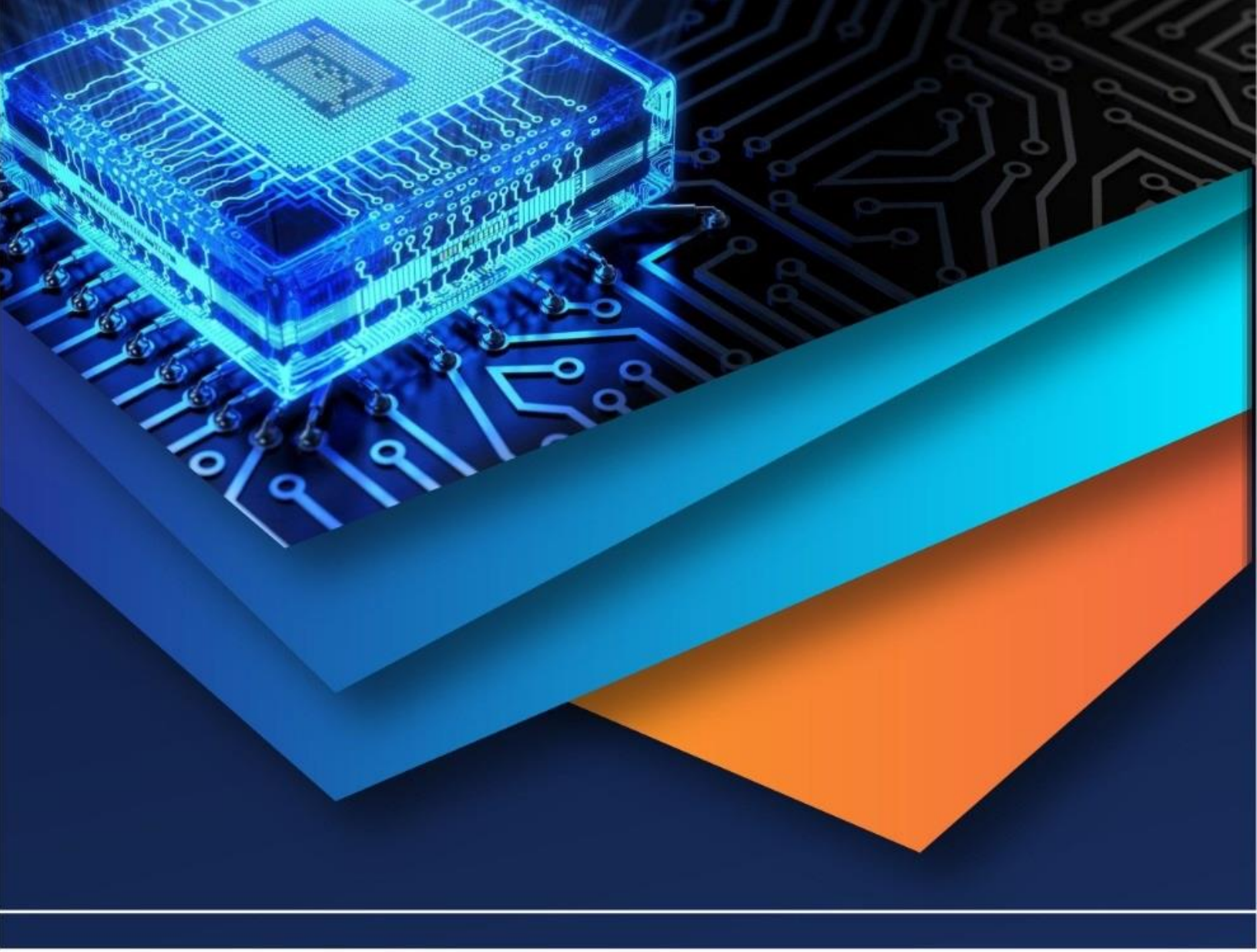

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