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Effect of Nano-Fluids on Heat Exchanger Efficiency: A Comprehensive Review

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Abstract: Heat exchangers are an integral part of any thermal system that finds wide applications in a wide spectrum of industrial applications. Major determinants of the system's performance include thermal efficiency, operating parameters, and compatibility between working fluids. The use of nanofluids as a working fluid has proven to be an effective way to enhance heat exchanger efficiency. This paper investigates the impact of nanofluids on improving heat exchanger efficiency by improving their thermal characteristics. It contains the largest part of the overview of existing literature, an analysis of the processes of heat transfer, and an assessment of their performance in various applications. This research tries to find important factors that govern efficiency and also locate the insufficiencies of existing works so that it may guide further improvements in this regard. The findings are expected to provide ample insight into the optimization of heat exchanger performance with nanofluids and to guide future research and development work.
Keywords: Nanofluids, Heat Exchangers, Efficiency, Nusselt number, Nanoparticles, Convection

I. INTRODUCTION

There have been great strides in the design and development of heat exchangers, following the rapid increase in demand for better thermal management by industries. In fact, these are the prime pieces of equipment in most systems related to power generation, chemical processing, HVAC, and automotive applications. Improvement in the ability of heat transfer in such systems will be key to better performance in total, which in turn results in lowering energy consumption and reducing the environmental load. It becomes even more imperative to come up with new heat transfer mechanisms with growing energy needs globally. These days, nanofluids are considered one of the most revolutionary and promising methods of HTE intensification. Nanofluids are specially designed liquid classes that contain nanoparticles in the 1–100 nm size range dispersed in a base liquid medium. These nanoparticles may consist of metals, oxides, carbides, or other forms of carbon, including graphene. The introduction of the said nanoparticles significantly enhanced the thermophysical properties of the base fluid, especially its thermal conductivity. With their high thermal conductivities, these nanofluids could prosper at better convective heat transfer rates, hence becoming very effective in all forms of heat-exchanger configurations. The current research work will attempt to present an overall critical review of the recent status of the application of nanofluids in applications for heat exchangers. Attention will be given to many types of heat exchangers of different geometries, namely, shell and tube, plate, and double-pipe heat exchangers, which are commonly used in industries.

This study reviews the enhancement mechanisms of convective heat transfer with nanofluids and complements the review of literature by focusing on one of the most important parameters: the Nusselt number and the overall heat transfer coefficient. This is an interesting case because a clear insight into these processes is necessary to improve the design and performance of heat exchangers based on nanofluids. In addition, the current work expands the assessment to cover nanofluids of various kinds: Cu, Al2O3, and SiC.[4] One group of operating conditions, varying at each Reynolds number and nanoparticle volume fraction, is studied to determine the variability in the parameters due to heat transfer performance[5]. The effectiveness of the thermal efficiency of nanofluids is further detailed through the concentration of nanoparticles, base fluid characteristics, and the impacts of temperature. Other possible impacts include ambient conditions such as magnetic fields and porous media that are associated with nanofluid-transport mechanisms. Besides this performance evaluation, the current study also attempts to find and fill out the gap existing in the literature. Therefore, although much progress has been made in the area, several challenges or possible concerns of nanofluid stability, sedimentation, and fouling, as well as the tradeoffs between the benefits of heat transfer enhancement and an increase in pressure drop, still remain. This work will point out possible future directions of research to fill the gaps and further improve our understanding of their use in heat exchangers. By pinpointing such gaps in research, this paper envisions benefiting the development of more effective and dependable heat transfer systems that could practically turn upside down the present trend of thermal management in several sectors.

There are broader implications of this study that deal with various applications where the effective transfer of heat plays a very critical role. Such efficiency in capturing and delivering solar energy is paramount in solar thermal systems to further effectiveness and reduce costs. Likewise, accurate temperature control in healthcare equipment may ensure both the functionality and safety of processes like hyperthermia treatment. This paper has attempted to delineate some critical perspectives on possible future developments in heat transfer technology by thoroughly assessing its importance in a variety of nanofluid applications.

II. LITERATURE REVIEW

Nanofluids are nanoparticles dispersed in base conventional fluids and have shown immense interest over the past decade because of their enhanced thermal characteristics and potential for heat transfer applications. The basic definitions related to this work are nanofluid, thermal conductivity, heat transfer enhancement, Nusselt number, and pressure drop. The new classes of advanced nanofluids with exciting applications range from automotive cooling and electronics thermal management to renewable energy systems, which until recent times were not feasible because of the continuous improvement in this field. In the review, the available studies on using nanofluids to enhance heat-transfer efficiency are synthesized, clearly explaining the facilitating mechanisms towards enhanced performance, the influence of a number of factors that can affect enhancements, and the highlights in the literature. The current chapter extensively analyzes the impacts of nanoparticle concentration, base fluid composition, flow conditions, and geometric parameters on heat transfer performance, with the final conclusion presenting a general critical analysis and recommendations for future research.

A. Effect of Nanoparticle Concentration

Empirical studies confirmed that, with the presence of nanoparticles, the thermal properties of a fluid can be changed significantly. The addition of copper nanoparticles to base fluids, namely ethylene glycol, propylene glycol, and water, showed that an enhancement in the Nusselt number could reach up to 14.9% at a nanoparticle volume fraction of 1%. In addition, with nanofluids, one of the major research issues has been the development of stable suspensions at higher volume fractions, where it is attempted to achieve the maximum thermal conductivity enhancement with the suspension being stable and not resulting in a significant rise in viscosity. In the same vein, it has been reported that an increase in the concentration of alumina nanoparticles is associated with a high improvement in heat transfer rate, up to 8666.47 watts, with optimum taking place at a volumetric concentration of 0.53%[2]. It is worthwhile noting that high nanoparticle volume concentrations are often associated with high-pressure drops, particularly from studies involving SiO2 and Ag nanofluids[3]. Further research efforts can explore the optimization of nanoparticle size and morphology to reduce the pressure drop challenges while maintaining or enhancing thermal performance.

B. Based Fluid Composition

Another important performance determinant of nanofluids is the selection of the base fluid. An ethylene-glycol-base nanofluid presents relatively more enhancement to thermal heat transfer compared to its water-based counterparts. The reason for this enhanced performance is the basic thermal conductivity of ethylene glycol and lower values for the nanoparticle-enhanced suspension, which makes it effective for heat transfer[1]. The fluid mixture of 5% EG, 5% PG, and 90% W also demonstrates significantly enhanced performance in heat transfer with increased volume percentages of nanoparticles and inlet temperature. Recent studies on this line have looked into eco-friendly base fluids, namely plant-based oils, as a sustainable alternative that could still maintain competitive thermal performance relative to petroleum-derived synthetic oils[1].

C. Flow conditions and geometric considerations

All these configurations have been found to influence nanofluids' heat transfer rates depending on the flow—a counterflow or a parallel flow. Basically, counterflow can give higher transfer rates compared to parallel. The change in the flow pattern allows nanoparticles to have a dynamic interaction with the flow field, hence optimizing the efficiency of heat transfer. Highly optimized performance depends on the design of the exchanger. Inclination of the sidewall angles provides huge optimization in the trapezoidal geometries through, inter alia, the realization of some additional benefits of the interaction of the aspect ratios.

Our results showed that small geometric modifications enhanced thermal transport properties in the nanofluids thanks to a recently acquired detailed understanding made possible through computations in fluid dynamics.

D. Hybrid Nanofluids in Porous Media

This took the already one step further in thermal conduction, with hybrid nanofluids normally involving aggregates composed of two or more types of nanoparticles exhibiting strong inter-particle interactions of thermal characteristics. These multicomponent properties endow the hybrid nanofluid with the possibility of tailoring its thermal conductivities, viscosities, and specific heat to allow for characteristics of heat transfer within porous media.

Other significant improvements were the increase in area for heat exchange and the improvement in fluid mixing. This combination has shown exceptional efficiency in applications that require outstanding heat performance, for example, miniature heat exchangers in miniaturized environments.

More than that, magnetic fields can control thermal performance and subsequently manipulate some characteristics due to the magnetic effects mentioned. Implementation of electromagnetic fields with hybrid nanofluids has opened up new mechanisms for controlled heat transfer in advanced engineering applications.

E. Thermal Efficiency and Pumping Power

Much higher mass flow rates of air and coolant usually result in much better thermal performance. Therefore, it is of utmost importance to optimize such flowrates through the system so that they directly affect the rate of heat transfer and energy efficiency of the device. Nanofluids increase the cooling capacity relative to base fluids and, therefore, decrease the input power required in the pumping system. For instance, Cu-based nanofluids showed a lower power requirement at the fuel-pumping stage compared to SiC, Al2O3, and TiO2 nanofluids. Thus, the development of low-viscosity nanofluids with high thermal conductivity has become a research topic of interest in enabling high heat transfer efficiency and reducing energy consumption.[4]

The enhancement of heat transfer in heat exchangers using nanofluids has been the subject of extensive research over the years. Various studies have investigated the impact of different nanofluids on the thermal performance of heat exchangers.

Barai et al. (2024) conducted the study on the performance, especially on heat transfer, of nanofluids in heat exchangers, where boosting up thermal conductivity and diminution in thermal boundary layer thickness act as prime modes for the performance development of heat exchangers using nanofluids. These increase the operational efficiency of the heat exchangers. They thus concluded that the great potential of nanofluids, especially those containing high thermal-conductivity nanoparticles, is significant.[10]

Almurtaji et al. (2024) studied the impact of nanofluids on heat exchangers' thermal hydraulic performance. The experimental investigation focused specifically on the influences of nanoparticle concentration and size hose independent heat transfer pressure drop characteristics. It was concluded that,, despite much promising improvement in heat transfer, it is essential to control the resultant pressure drop so that the excess leadss to unnecessary energy consumption in pumping.[11]

Ali and Salam (2024) gave a review of the the syntheses, stabilities, thermophysical properties, and heat transfer mechanisms of nanofluids. They indicated that the aspect of the nanofluid on which the the reliability of heat transfer efficiency depended was stability. The authors further discussed different developed ways of preparing stable nanofluids and the the influence of those methods on the evaluation of heat exchanger performance.[12]

Bhosale et al. (2024) experimentally and numerically surveyed possible augmentations by the use of nanofluids in heat transfer augmentation of heat exchangers. In general, the addition of nanoparticles enhances the performance of the base fluid, mainly increasing the heat transfer rate in turbulent flow conditions. But particular results of performance depend basically on type and distribution.[13]

On the performance of the heat exchanger through the use of nanofluids, Maghrabiea et al. (2024) went further to investigate. Several other studies were conducted on different geometries of the heat exchanger using different types of nanofluids. The authors concluded that the heat exchanger efficiency could be improved with the use of nanofluids, particularly when the need for highly rated heat transfer requirements arises.[14]

Aiding this enhancement in heat transfer rates is the presence of nanoparticles in the nanofluids involved, most of which possess a higher thermal conductivity than conventional fluids. The applications of nanofluid have increased in industries over the last few years due to the requirement for advanced cooling processes to achieve better performance in computing, energy, and transport. A number of studies have shown that, in general, nanofluids play an appreciably excellent role in heat transfer, especially with metallic nanoparticles, respectively, in round or radial geometries. However, a number of issues, including sedimentation, erosion, and fouling, have not been put into rigorous discussion in the literature with further experimental validation and exploration. In this light, the present studies can foresee a considerable improvement in understanding the long-term stability and behavior of nanofluids and the different materials that will be used for their wide industrial use.

This review also recognized an increase in such studies after 2012, and this indicates frankly the mounting interest in the discipline of heat exchangers because of nanofluids. This bibliometric review shows that most of these studies have international research community front-runners in India, Iran, and China, among others, and they particularly cover fields like engineering, physics, and chemical engineering[6]. The extension of the need arises with much study going on towards the different mechanisms that enhance heat transfer using nanofluids for new developments and optimization of flow parameters in the study of mechanisms at the atomic level and the effect on particle size. The gaps identified in existing literature would be of importance to experimental and numerical studies, leading to optimization of nanofluid performance for different end uses. One emerging trend is that machine learning and artificial intelligence are applied in the formulation of nanofluids in ways that optimize their performance and predict their behavior under alternative operating conditions.

The study builds on existing research on the use of nanofluids in automotive cooling systems, where the superior thermal properties of nanofluids have been shown to enhance heat transfer rates. Previous studies have demonstrated that nanofluids can improve the efficiency of radiators, leading to smaller and more efficient designs. The literature review emphasizes the benefits of using nanofluids, such as higher heat transfer rates and reduced radiator sizes. However, it also highlights the need for further research on the effects of different nanoparticle concentrations, transient analysis, and the optimization of radiator designs. The study contributes to the literature by providing detailed CFD analysis results, supporting the potential of nanofluids in automotive applications while suggesting areas for further exploration.[7]

The study reviews the growing interest in green synthesis methods for preparing nanofluids, which offer environmentally friendly alternatives to conventional methods. Previous research has highlighted the enhanced heat transfer capabilities of nanofluids in helical coil heat exchangers, with a focus on the effects of nanoparticle concentration and Reynolds number. The literature review acknowledges the benefits of using silver nanofluids, such as higher thermal conductivity and improved heat transfer rates. However, it also points out the challenges of increased friction factors and the need for further research on optimizing nanoparticle concentrations, long-term stability, and the effects of different nanofluids. The study adds to the existing literature by providing experimental data on the thermal performance of green synthesis silver nanofluids, offering insights into their potential applications in heat exchangers.[8]

The study reviews existing research on the thermal conductivity and heat transfer coefficients of nanofluids, noting that while they generally offer better thermal properties than base fluids, the efficiency gains are often limited to 10-40%. Previous studies have explored the price-performance ratios of different nanofluids, with carbon-based nanofluids showing slightly better performance despite their higher cost. The literature review highlights the ongoing debate about the economic viability of nanofluids, with most research concluding that their high cost limits their widespread adoption. The study contributes to this discussion by introducing the Efficiency-Price Index (EPI) and analyzing the economic feasibility of nanofluids in various applications. It also identifies gaps in the literature, such as the need for standardized experimental methods and the development of cost-effective nanofluids, to make them more practical for broader industrial use.[9]

The study presents a comprehensive review of the thermal and fluid flow performance of nanofluids in compact heat exchangers (CHXs), emphasizing their potential to enhance energy efficiency in heat transfer applications. With the increasing demand for miniaturized, cost-effective, and sustainable thermal systems, CHXs have become crucial across various industries, including automotive, aerospace, and renewable energy. However, the conventional thermal fluids often limit their performance under extreme thermal loads. Nanofluids, introduced by dispersing metallic or non-metallic nanoparticles into base fluids, offer a promising solution by significantly improving heat transfer characteristics while maintaining manageable pressure drops. The review highlights both experimental and numerical investigations conducted on different types of CHXs, such as single-tube, shell and tube, micro heat sinks, and plate heat exchangers, utilizing various nanofluids like Al_2O_3, TiO_2, graphene, and carbon nanotubes. Key findings indicate that nanofluids consistently enhance heat transfer coefficients (HTCs) compared to base fluids, with improvements strongly influenced by nanoparticle type, concentration, Reynolds number, and flow regime. However, challenges such as increased pressure drop, nanoparticle sedimentation, and potential corrosion demand further study. The numerical studies, predominantly employing finite volume methods with assumptions of steady-state, incompressible, and Newtonian flow, corroborate experimental results but reveal gaps in accurately modeling thermophysical properties, especially under varying thermal conditions. The review underscores the need for systematic experimental validation, reliable thermophysical property databases, and careful consideration of environmental and health impacts of nanofluids. It calls for future research to focus on optimizing nanofluid formulations, exploring diverse HX geometries, and balancing thermal performance with energy efficiency and sustainability, to unlock the full potential of nanofluids in compact heat exchangers.[21]

Nanofluids (NFs) are advanced heat transfer fluids (HTFs) created by dispersing nanoparticles (NPs) into a base fluid (BF), significantly improving thermal conductivity and heat transfer performance. While their energy efficiency benefits have been widely acknowledged, the environmental impacts (EIs) of NFs remain underexplored. NFs' EIs are influenced by the type and loading of NPs, with non-toxic, naturally occurring NPs in water-based NFs showing the lowest EIs. The production methods for NPs and NFs also affect their EIs, with simpler synthesis routes reducing chemical and energy usage. Despite their potential in energy savings and reduced carbon emissions, a comprehensive evaluation of their environmental and toxicity impacts is necessary to promote sustainable use.[25]

The study investigates the thermal performance of a double-pipe helical heat exchanger through experimental evaluation. Two heat exchangers of different inner tube sizes were tested under varying flow rates and configurations (parallel and counterflow). The research focused on calculating overall heat transfer coefficients and determining heat transfer coefficients for the inner tube and annulus using Wilson plots. Nusselt numbers for both regions were derived and compared with existing literature and numerical data. While the experimental results for the larger heat exchanger aligned well with numerical predictions, discrepancies were observed for the smaller coil, likely due to limitations in the Wilson plot method. The findings largely validated previous numerical studies, demonstrating the enhanced heat transfer capabilities of helical configurations, particularly in counterflow setups.[47]

The study investigates the impact of SiO_2 nanoparticles on the performance of a double-pipe heat exchanger operating under countercurrent flow conditions. The research focuses on key parameters such as viscosity, friction factor, and heat transfer coefficient of SiO_2/water nanofluids at various nanoparticle concentrations (0.2–2%) and particle sizes (25–50 nm). The experimental results show that the viscosity of nanofluids increases with higher nanoparticle concentrations due to the distribution of SiO_2 particles within the base fluid. Conversely, viscosity decreases with an increase in fluid temperature. The friction factor also rises with increasing nanoparticle concentration and decreases as particle size increases, with the smaller 25 nm particles causing a higher friction factor than the 50 nm particles, attributed to greater nanoparticle agglomeration. The heat transfer coefficient was significantly enhanced, increasing by up to 75% at a 2% weight fraction and 30°C. This improvement is more pronounced with smaller particles due to their larger surface area, which promotes efficient heat transfer. The study highlights the potential of SiO_2 nanofluids to optimize heat exchanger performance by improving thermal conductivity and heat transfer rates while noting the trade-offs associated with increased viscosity and pressure drop. These findings are consistent with previous research on nanofluids, underscoring their value in enhancing heat transfer efficiency in industrial applications.[51]

The study focuses on enhancing heat transfer in a double-pipe heat exchanger (DTHE) through the use of nanofluids and passive techniques involving a spiral spring insert. The research explores various nanofluids, including TiO_2, BeO, ZnO, and CuO, with water and ethylene glycol as base fluids, aiming to improve thermal conductivity and overall heat transfer performance. Numerical simulations, conducted using ANSYS 15.0 and the finite volume method, examine the thermal and flow behavior of these nanofluids under different Reynolds numbers (ranging from 1,000 to 10,000). Results demonstrate that the insertion of twisted tape with rectangular cuts significantly enhances heat transfer by increasing turbulence and surface contact. The study confirms that the heat transfer rate and Nusselt number rise with increasing nanoparticle concentration and Reynolds number, while also noting a corresponding increase in pressure drop. Among the nanofluids analyzed, CuO-based nanofluids outperform others, delivering superior heat transfer at higher Reynolds numbers. The findings align well with existing literature, showcasing nanofluids as a promising solution for improving heat exchanger efficiency in various industrial applications.[52]

Suspensions of solid particles in liquids have long been recognized for their potential to enhance heat transfer due to the superior thermal conductivities of solid particles compared to traditional heat-transfer fluids like water or ethylene glycol. Early research in this area mostly focused on suspensions with relatively large particles, from millimeter to micrometer in size, which indeed improved thermal conductivity but faced significant issues. These larger particles tended to settle out quickly, causing instability and clogging, especially problematic in small channels. Magnetic colloids, which use ferromagnetic nanoparticles, were a notable exception due to their stability from small particle size.

The advent of nanotechnology introduced a new solution with "nanofluids," which are suspensions of nanoparticles in the range of approximately 10–40 nm. These fluids have shown remarkable stability, even when left undisturbed for extended periods, and demonstrate significantly enhanced thermal conductivity. For example, Al_2O_3 nanoparticles with a 13 nm diameter at a 4.3% volume fraction increased water's thermal conductivity by 30%, a much greater effect than seen with larger particles. Cu nanofluids have shown even more dramatic results, with just a 0.3% volume fraction of 10 nm Cu nanoparticles raising thermal conductivity by up to 40%.

Traditional theories of heat transfer, which treat thermal conductivity using continuum-level equations and focus on properties like particle shape and volume, fail to explain these results fully. They do not account for the unique behavior of heat at the nanoscale, where factors like the particle-liquid interface and particle movement play a role. This study explores possible mechanisms behind the enhanced thermal conductivity of nanofluids, utilizing molecular dynamics simulations to analyze heat transfer at the atomic level. Through these simulations, new insights emerge that suggest how nanoscale interactions can lead to such notable improvements in thermal transport, paving the way for more effective nanofluid designs for heat management.[19]

Although the work reported in this review supports the possibility of nanofluids enhancing thermal transport effectiveness, variances and inconsistencies can be found.

For instance, the sedimentation of nanoparticles at high concentrations is likely to decrease the thermophysical attributes of nanofluids, indicating the need to maintain optimum concentration levels to avoid any degradation in performance. The opening of new frontiers in the development of new stabilization agents and more advanced dispersion techniques could create avenues for this problem in terms of the long-term stability of nanofluids in practical applications. Hybrid nanofluids exhibit better thermal properties compared to their conventional counterparts. The preparation and stability still remain questions about them. Further studies are also needed in the area of how exactly the interaction works between the different kinds of nanoparticles and how to stop agglomeration. A major problem is the pressure drop associated with nanofluids, particularly at high nanoparticle concentrations. The balance can be designed by reducing this using the thermal conductivity and viscosity levels permissible in the design of nanofluid formulations. The literature review emphasizes that significant progress has been made in the development of nanofluids for improving heat transfer characteristics, primarily for achieving improvements in both thermal conductivity and heat transfer coefficients. The adoption of nanofluids in existing thermal management systems thereby offers a solution for increasing energy efficiency and lowering industrial activity effects on the environment. It is pertinent to note here that significant enhancement of heat transfer efficiency is associated with nanoparticle concentration, nature of base fluid, and flow conditions; more particularly, it is affected by geometric parameters. A lot of future research will be necessary to effectively implement this technique in the different heat transfer systems with respect to issues of nanoparticle sedimentation, hybrid nanofluid stability, and pressure losses. Finally, the respective assessments of long-term stability and possible environmental impact are the needed conditions for the wide application of nanofluids. Further research on these issues should focus attention on the economic possibility of using the fluids by analyzing a cost-benefit ratio in application and also research possibilities for large-scale production.

III. CONCLUSION

This article presents a critical review relating to the performance evaluation of heat exchangers with nanofluids, which has arisen due to the augmentation in their thermal efficiency upon the inclusion of nanoparticles. Nanofluids, owing to their higher values of thermophysical properties, have shown great potential in enhancing the heat transfer rate in various geometries of heat exchangers, including shell and tube, plate, and double-pipe heat exchanger geometries. The analysis underlines that this enhancement of thermal conductivity and convective heat transfer coefficients is directly dependent upon the concentration, size, and type of nanoparticles involved.

This review also highlights many challenges considered and that should be surmounted in order to maximize the application of nanofluids in heat exchangers. Sedimentation, stability, pressure drop, and possible fouling are important factors that might weaken the effectiveness of nanofluids in the long term. The trade-off between heat transfer enhancement and the accompanying rise in the required pumping power is a balancing act that must be carefully weighed for energy efficiency benefits not to be nullified by operational costs. It can be summarized from the literature that although much progress has been achieved in the mechanisms of nanofluids for heat transfer enhancement, further investigations are still at their neck and shoulders, especially in nanofluid stability, and also external factors influencing the characteristics, such as a magnetic field, and development of hybrid nanofluids by combining more types of nanoparticles to achieve desired thermal properties. Besides, more empirical studies are required to validate theoretical models that might explore the performance of nanofluids in real-world industrial applications.

Nanofluids open a very promising avenue for the effective enhancement of heat exchangers' efficiency and find wide uses in almost all industries as far as thermal management aspects are concerned.

The realization of this potential calls for continued research to overcome the existing limitations for further optimization in nanofluid formulation and its application to various heat exchanger systems. Further research should fill the gaps in scale-up from laboratory-scale experiments to large-scale industrial-scale implementation in real situations to ensure that nanofluids benefits can be translated into practical energy-efficient solutions for thermal management challenges.

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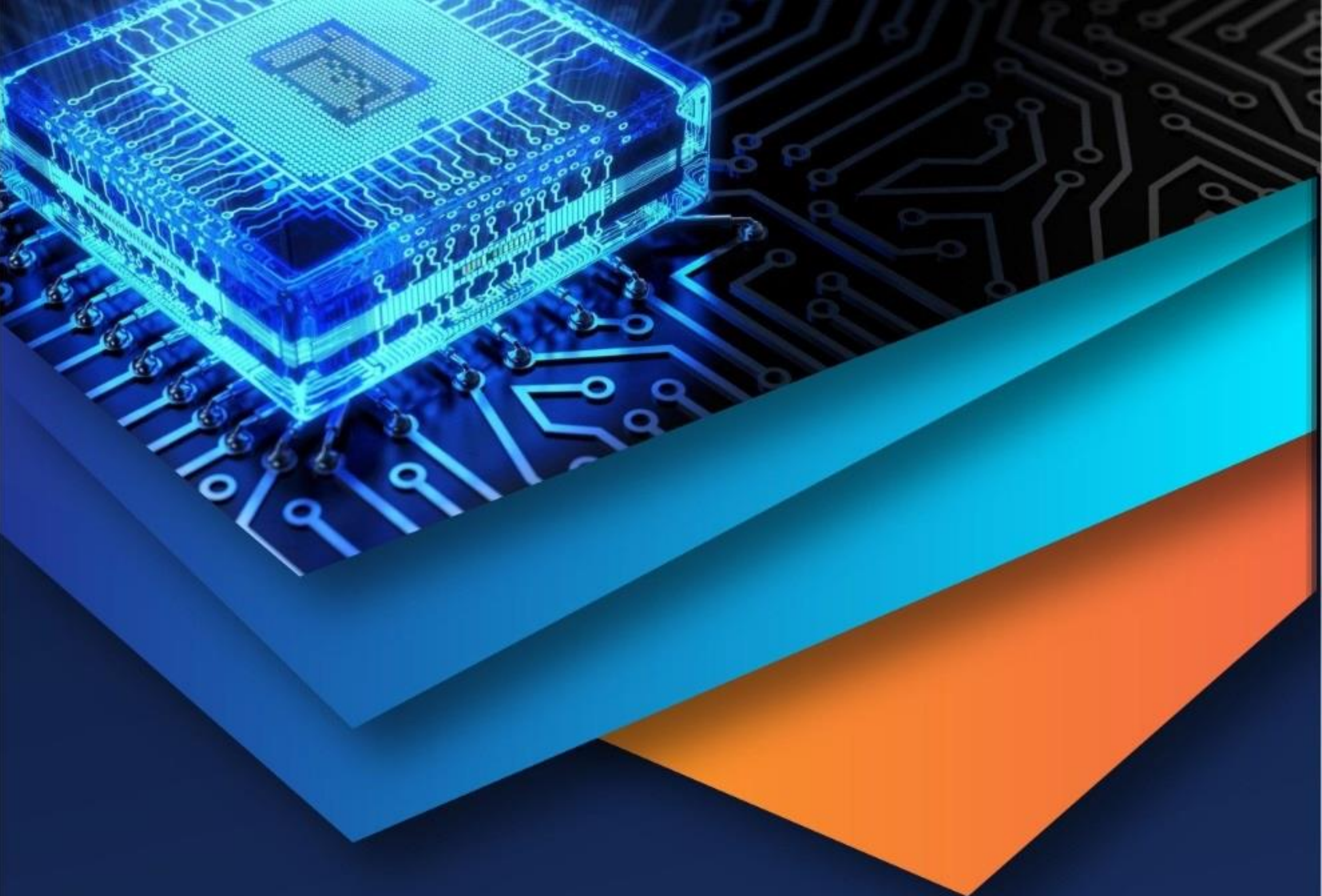

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