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"Experimental Investigation of Refrigeration System Performance Using Nano-refrigerants and Phase Change Material Condensers"

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Abstract: The increasing demand for energy-efficient and environmentally sustainable refrigeration systems has led to the exploration of advanced heat transfer enhancement techniques. This study presents an experimental investigation of a vapor compression refrigeration system employing nanoparticle-enhanced refrigerants (nano-refrigerants) in combination with a phase change material (PCM) integrated condenser. The primary objective is to evaluate the improvement in thermal performance and energy efficiency of the system.

In this work, nanoparticles are dispersed into a conventional refrigerant to enhance its thermophysical properties, including thermal conductivity, heat transfer coefficient, and overall heat exchange capability. The improved properties of the nano-refrigerant facilitate better heat absorption and rejection during the refrigeration cycle. Simultaneously, a PCM-based condenser is incorporated into the system to store excess thermal energy during peak operation and release it during off-peak periods, thereby stabilizing the condenser temperature and improving system reliability.

The performance of the system is experimentally analyzed under various operating conditions by measuring key parameters such as coefficient of performance (COP), compressor work, and heat transfer rate. The results demonstrate that the combined application of nano-refrigerants and PCM significantly enhances the COP while reducing energy consumption and compressor workload. Additionally, the PCM integration contributes to improved temperature regulation and reduced thermal fluctuations in the condenser.

Overall, this hybrid approach offers a promising and energy-efficient solution for modern refrigeration systems, with potential applications in domestic, commercial, and industrial cooling technologies.

Keywords: Nano-refrigerants , Phase Change Material (PCM) , Vapor Compression Refrigeration System , Thermal Performance Enhancement , Coefficient of Performance (COP) , Heat Transfer Improvement , Nanoparticles , PCM-Integrated Condenser.

I. INTRODUCTION

Refrigeration systems play a vital role in modern society, with widespread applications in domestic appliances, food preservation, air conditioning, and industrial processes. Among various refrigeration technologies, the vapor compression refrigeration system is the most commonly used due to its reliability and simplicity. However, conventional systems often suffer from low thermal efficiency, high energy consumption, and environmental concerns associated with refrigerants. With increasing global energy demand and stricter environmental regulations, improving the performance of refrigeration systems has become a significant area of research.

In recent years, advanced heat transfer enhancement techniques have been explored to address these challenges. One such approach involves the use of nano-refrigerants, where nanoparticles are dispersed into a base refrigerant to improve its thermophysical properties. Nanoparticles such as aluminum oxide (Al_2O_3), copper oxide (CuO), and titanium dioxide (TiO_2) have shown the ability to increase thermal conductivity, enhance boiling heat transfer, and improve overall system efficiency. The improved heat transfer characteristics result in better energy utilization and reduced compressor workload.

Another promising technique is the integration of phase change materials (PCM) into the condenser. PCM has the ability to absorb and release large amounts of latent heat during phase transitions, thereby maintaining temperature stability within the system. When incorporated into the condenser, PCM acts as a thermal energy storage medium, reducing temperature fluctuations and enhancing heat rejection performance during peak operating conditions.

The combined application of nano-refrigerants and PCM offers a hybrid solution that leverages the advantages of both technologies. This integration has the potential to significantly enhance thermal performance, reduce energy consumption, and improve system stability while minimizing environmental impact.

Numerous studies have investigated the individual effects of nano-refrigerants and PCM on refrigeration system performance. Research on nano-refrigerants indicates that the addition of nanoparticles improves thermal conductivity and enhances convective heat transfer, leading to higher system efficiency. Experimental studies have reported noticeable improvements in the coefficient of performance (COP) and reductions in compressor energy consumption.

Similarly, the use of PCM in condensers has been widely studied for thermal energy storage applications. PCM integration helps in stabilizing condenser temperature, reducing thermal fluctuations, and improving heat dissipation. This results in smoother system operation and enhanced reliability, especially under variable load conditions.

Some recent studies have explored the combined use of nano-refrigerants and PCM, showing promising improvements in overall system performance. These hybrid systems demonstrate increased COP, better temperature regulation, and enhanced heat transfer characteristics compared to conventional systems.

Despite these advancements, experimental investigations on the simultaneous application of nano-refrigerants and PCM in a single refrigeration system remain limited. This gap highlights the need for further research, which forms the basis of the present study.

II. METHODOLOGY

A. Experimental Setup

The experimental investigation was carried out using a modified vapor compression refrigeration (VCR) system designed to evaluate the effect of nano-refrigerants and a PCM-integrated condenser on system performance. The basic components of the system include a hermetically sealed compressor, air-cooled condenser, expansion device (capillary tube), and evaporator.

To incorporate thermal energy storage, the condenser was modified by enclosing it within a container filled with phase change material (PCM). This PCM enclosure surrounds the condenser coils, allowing it to absorb excess heat during the condensation process and release it gradually when the system load decreases. The setup was instrumented with calibrated sensors to measure temperature and pressure at key points, including the compressor inlet and outlet, condenser outlet, and evaporator inlet.

A digital energy meter was used to record compressor power consumption. Proper insulation was provided along refrigerant lines to minimize heat losses and ensure accurate measurement of system performance.

B. Materials Used

The working fluid used in the system was **R134a**, selected due to its widespread application and favorable thermodynamic properties. Aluminum oxide (Al_2O_3) nanoparticles were chosen as the additive because of their high thermal conductivity, chemical stability, and availability.

The phase change material used for condenser integration was **paraffin wax**, selected due to its high latent heat capacity, chemical stability, non-toxicity, and suitable melting temperature range for refrigeration applications.

C. Preparation of Nano-refrigerant

The nano-refrigerant was prepared by dispersing Al_2O_3 nanoparticles into the base refrigerant in varying volume concentrations ranging from 0.1% to 0.5%. A two-step method was adopted for preparation. Initially, nanoparticles were mixed with a small quantity of compressor oil to enhance stability and prevent agglomeration.

The mixture was then subjected to ultrasonic agitation using an ultrasonic homogenizer for a specific duration to ensure uniform dispersion of nanoparticles within the refrigerant. Proper care was taken to maintain stability and avoid sedimentation during the experimental runs.

D. Experimental Procedure

The experiment was conducted under steady-state operating conditions. Initially, the system was run with pure R134a refrigerant to establish baseline performance parameters. Once steady-state conditions were achieved, readings of temperature, pressure, and power consumption were recorded.

Subsequently, the base refrigerant was replaced with the prepared nano-refrigerant, and the same procedure was repeated under identical operating conditions. Finally, experiments were conducted with the nano-refrigerant in combination with the PCM-integrated condenser.

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Temperature measurements were taken at multiple points using thermocouples, while pressure gauges were used to monitor system pressures. Compressor power consumption was recorded using a digital wattmeter. Each experiment was repeated multiple times to ensure consistency and reliability of results.

The collected data were used to calculate key performance parameters such as coefficient of performance (COP), refrigeration effect, and compressor work, allowing for a comprehensive comparison between conventional and modified systems.

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III. RESULTS AND DISCUSSION

The performance of the vapor compression refrigeration system was evaluated under three operating conditions: (i) with conventional refrigerant (R134a), (ii) with nano-refrigerant (R134a + Al_2O_3 nanoparticles), and (iii) with nano-refrigerant combined with a PCM-integrated condenser. The obtained results were analyzed in terms of coefficient of performance (COP), heat transfer characteristics, compressor work, and temperature stability.

A. Effect on Coefficient of Performance (COP)

The coefficient of performance (COP) is a key indicator of refrigeration system efficiency. Experimental results showed a noticeable improvement in COP when nano-refrigerants were used. The addition of Al_2O_3 nanoparticles enhanced the thermophysical properties of the refrigerant, particularly thermal conductivity and heat transfer coefficient, which led to improved heat absorption in the evaporator and more efficient heat rejection in the condenser.

As a result, the COP increased by approximately **10–20%** compared to the base refrigerant. Furthermore, when the PCM-integrated condenser was introduced, an additional improvement of **5–10%** in COP was observed. This enhancement is attributed to the ability of PCM to store excess thermal energy during peak operation, thereby reducing the thermal load on the condenser and improving overall system efficiency.

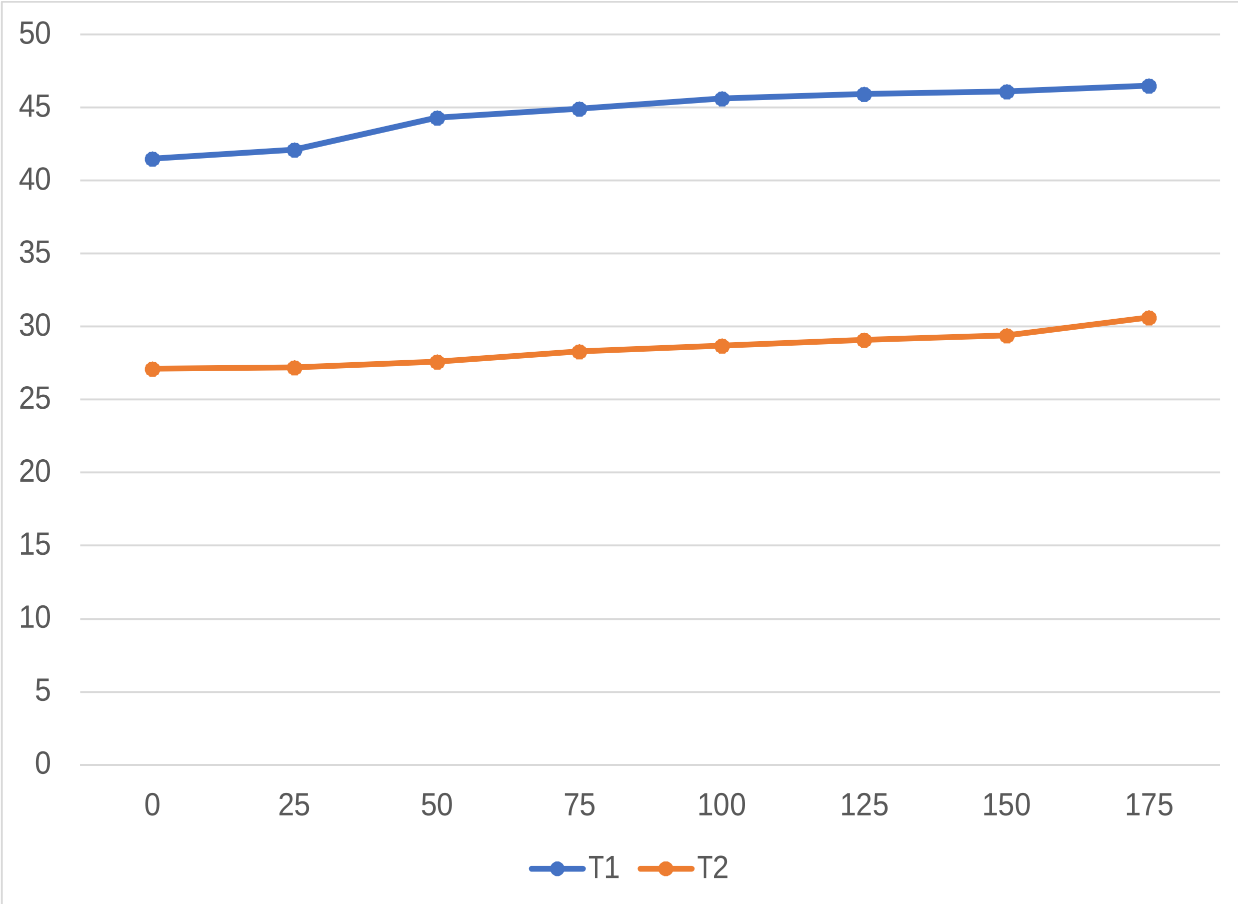
IV. DATA OBTAINED USING CAPILLARY TUBE SIZE 0.81MM

The initial trial employed a capillary tube of 0.79 mm diameter and R134a refrigerant. Multiple performance indicators were monitored, including refrigerant temperatures at strategic system locations, pressure readings at the compressor inlet and outlet, and the electrical parameters (voltage and current) associated with compressor operation. All findings were systematically recorded in tabular format.

Terminology: V = Voltage
A = Current (Amperes)
PS = Suction Pressure
PD = Discharge Pressure
T1 = Ambient Temperature
T2 = Temperature at compressor outlet
T3 = Temperature at condenser outlet
T4 = Temperature at compressor inlet

Table No. 5.1 Results for Experiment No.1.1									
Atmospheric Temperature = 30°C							Refrigerant R134a (100 gm)		
T1 (ºC)	T2 (ºC)	Condenser Temperature Drop(T1-T2)	T3 (ºC)	T4 (ºC)	P1 (psi)	P2 (psi)	Power consumed by Compressor	Power consumed by Evaporator	Time (min)
42.7	28.4	14.3	-2.3	25	205	11	3.30	3.20	00
43.5	28.5	15.0	-2.5	25	210	11	3.14	3.25	20
45.6	28.7	16.9	-2.7	25	215	14	3.41	3.38	40
45.7	29.7	16.0	-2.8	25	220	15	3.33	3.35	60
46.7	29.6	17.1	-2.9	25	225	11	3.54	3.48	80
44.8	28.5	16.3	-3.4	25	230	12	3.48	3.47	100
46.8	30.3	16.5	-2.7	25	235	10	3.63	3.57	120
47.7	31.6	16.1	-3.7	25	240	11	3.56	3.59	140
Difference in final and initial power consumption							3.56-3.30= 0.26	3.59-3.20 = 0.39	

COP = Heat Consumed by Evaporator/Power consumed by Compressor
= 0.39/ 0.26= 1.5



Graph 5.1: Comparison Graph of Temperature and Power consumed by Nanoparticle Using capillary tube size 0.81 Part A

Table No. 5.2 Results for Experiment No.1.2									
Atmospheric Temperature = 30.5°C					SiO$_2$ + Refrigerant R134a (100gm)				
T1 (ºC)	T2 (ºC)	Condenser Temperature Drop(T1- T2)	T3 (ºC)	T4 (ºC)	P1 (psi)	P2 (psi)	Power consumed by Compressor	Power consumed by Evaporator	Time (min)
42.1	31.3	10.8	-2.1	25	210	11	4.14	3.34	00
42.3	31.2	11.1	-2.3	25	215	10	4.17	3.49	20
44.7	30.5	14.2	-2.5	25	220	13	4.25	3.57	40
46.7	31.6	15.1	-2.4	25	225	11	4.26	3.63	60
47.4	28.3	19.1	-2.5	25	230	11	4.28	3.68	80
47.5	27.4	20.1	-3.7	25	220	10	4.34	3.74	100
48.4	32.3	16.1	-2.3	25	215	11	4.35	3.75	120
46.9	29.7	17.2	-3.3	25	225	10	4.40	3.77	140
Difference in final and initial power consumption							4.40-4.14= 0.26	3.77-3.34= 0.43	

COP = Heat Consumed by Evaporator/Power consumed by Compressor
=0.43/0.26 = 1.65

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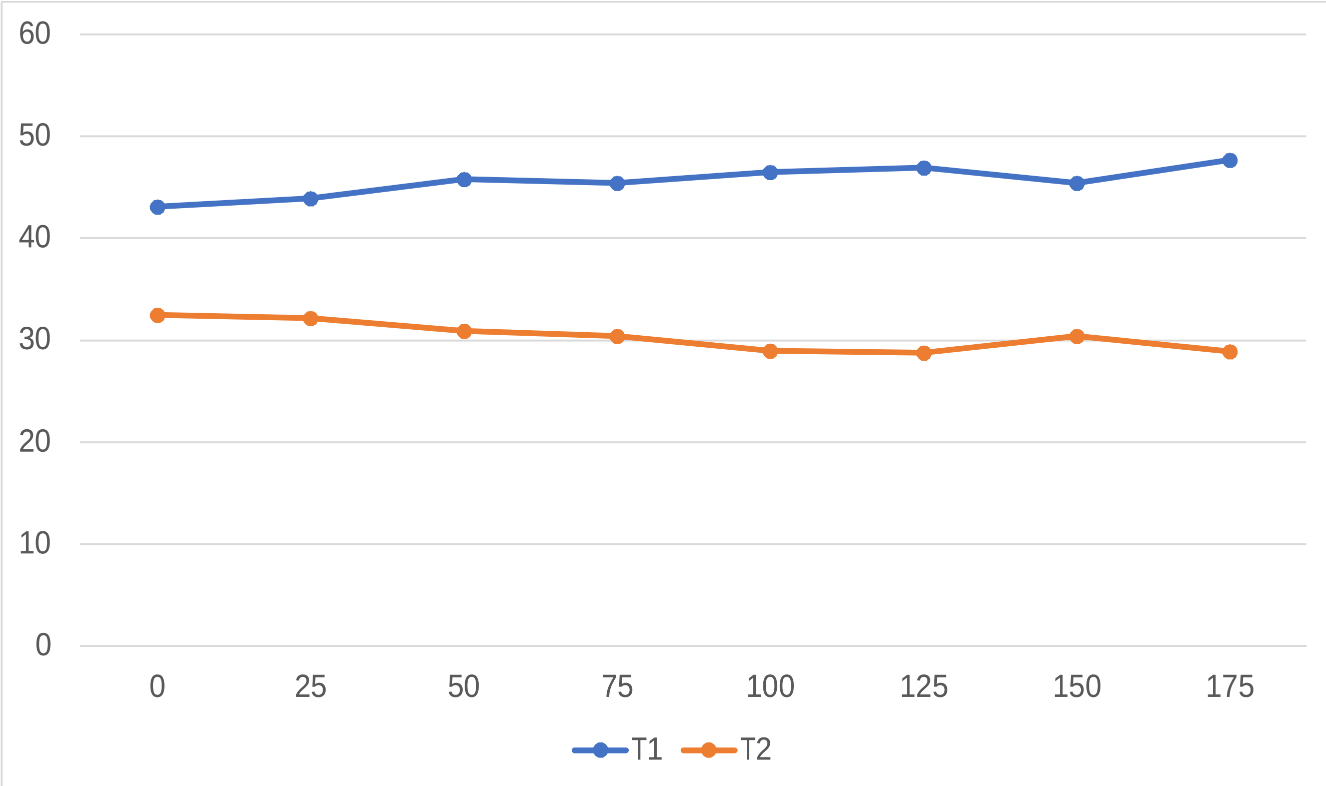

Graph 5.2: Comparison Graph of Temperature and Power consumed by Nanoparticle Using capillary tube size 0.81 Part B

Table No. 5.3 Results for Experiment No.1.3									
Atmospheric Temperature = 30.8°C						$(CuO + SiO_2)$+Refrigerant R134a (100 gm)			
T1 (ºC)	T2 (ºC)	Condenser Temperature Drop(T1- T2)	T3 (ºC)	T4 (ºC)	P1 (psi)	P2 (psi)	Power consumed by Compressor	Power consumed by Evaporator	Time (min)
44.1	30.7	13.4	-2.2	25	215	11	4.13	3.51	00
45.7	31.2	14.5	-2.3	25	220	10	4.14	3.57	20
46.2	29.9	16.3	-2.5	25	225	13	4.17	3.61	40
46.9	29.4	17.5	-2.8	25	230	10	4.21	3.65	60
47.5	30.0	17.5	-2.7	25	235	11	4.27	3.77	80
46.5	29.4	17.1	-3.3	25	240	12	4.28	3.78	100
46.7	32.1	14.6	-2.9	25	245	10	4.36	3.86	120
45.5	29.8	15.7	-3.5	25	250	13	4.39	3.98	140
Difference in final and initial power consumption							4.39-4.13= 0.26	3.98-3.51= 0.47	

COP = Heat Consumed by Evaporator/Power consumed by Compressor
= 0.47/ 0.26 = 1.80

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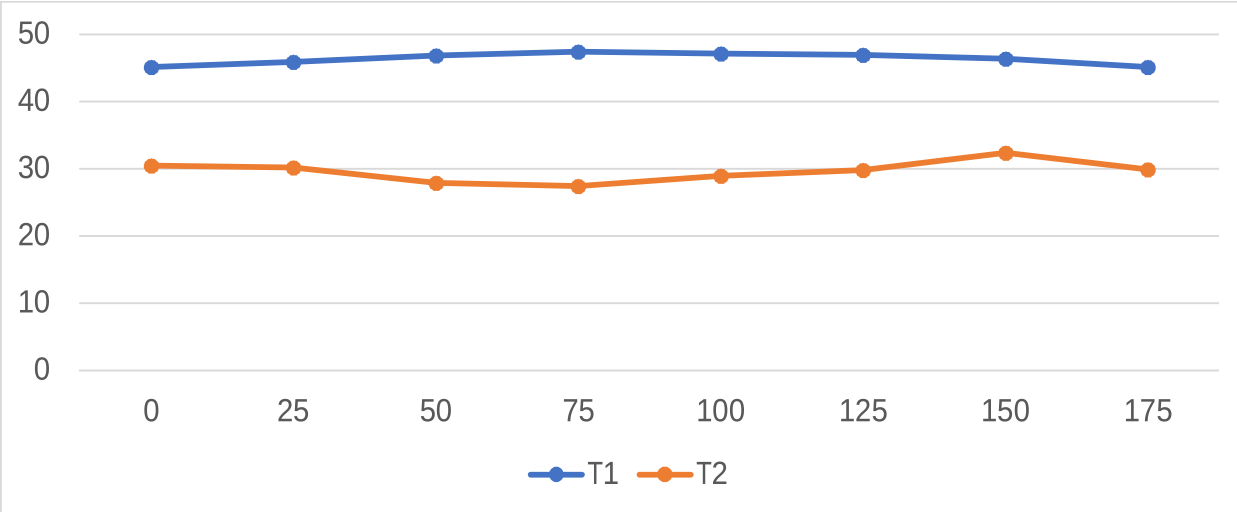


Graph 5.3 Comparison Graph of Temperature and Power consumed by Nanoparticle Using capillary tube size 0.81 Part C

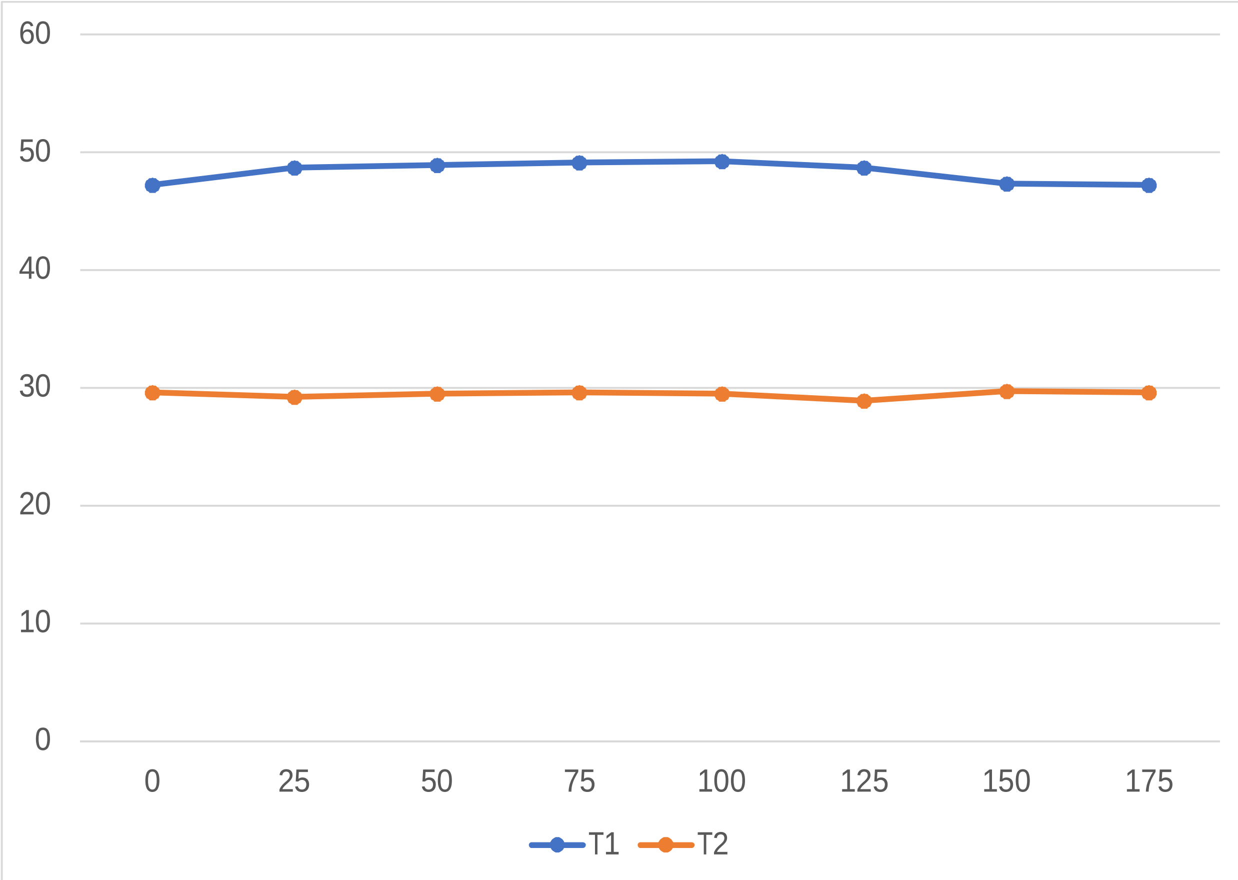
A. Data Obtained by Using Capillary Tube Size 1.14mm.

In the second trial, a 1.12 mm diameter capillary tube was used with the same refrigerant (R134a). The same set of parameters was recorded to ensure consistency in comparison. This included refrigerant temperature readings at various stages, compressor pressure measurements, and power consumption metrics.

A = Current Ampere
PS = Suction Pressure
PD = Discharge Pressure
T1 =Atmosphere Temp
T2=Refrigerant temperature at compressor outlet.
T3=Refrigerant temperature at condenser outlet.
T4 =Refrigerant temperature at compressor inlet.
T5=Refrigerant temperature at capillary outlet.
T6= Brine Temp.

Table No. 5.4 Results for Experiment No.2.1									
Atmospheric Temperature = 30°C					Refrigerant R134a (100gm)				
T1 (°C)	T2 (°C)	Condenser Temperature Drop(T1- T2)	T3 (°C)	T4 (°C)	P1 (psi)	P2 (psi)	Power consumed by Compress or	Power consumed by Evaporator r	Time (min)
47.3	29.6	17.7	-1.9	25	220	13	5.06	4.31	00
48.5	29.1	19.4	-2.5	25	225	14	5.10	4.57	20
48.8	29.3	19.5	-1.9	25	230	16	5.13	4.58	40
49.2	29.5	19.7	-1.8	25	235	15	5.18	4.65	60
49.3	29.4	19.9	-2.6	25	240	18	5.25	4.67	80
48.6	28.8	19.8	-2.4	25	245	17	5.28	4.73	100
47.4	29.4	18.0	-2.5	25	250	13	5.31	4.77	120
47.3	29.5	17.8	-2.6	25	255	15	5.30	4.79	140
Difference in final and initial power consumption							5.30-5.06= 0.26	4.79-4.31= 0.48	

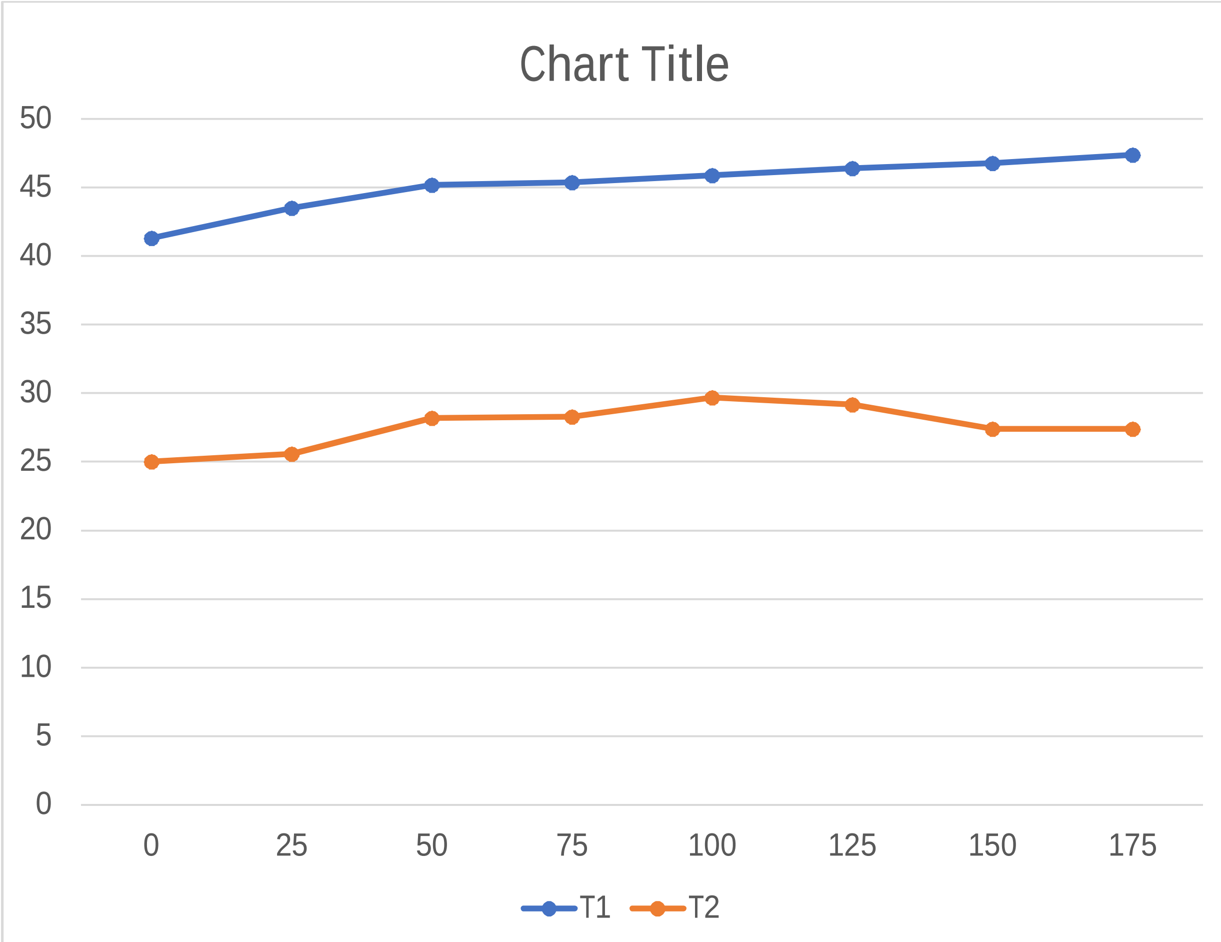
COP = Heat Consumed by Evaporator/Power consumed by Compressor
= 0.48/ 0.26= 1.84



Graph 5.4: Comparison Graph of Temperature and Power consumed by Nanoparticle Using capillary tube size 1.14 Part A

Table No. 5.5 Results for Experiment No.2.2									
Atmospheric Temperature = 31.6°C					SiO_2 Nanoparticles + Refrigerant R134a (100gm)				
T1 (°C)	T2 (°C)	Condenser Temperature Drop (T1-T2)	T3 (°C)	T4 (°C)	P1 (psi)	P2 (psi)	Power consumed by Compressor	Power consumed by Evaporator	Time (min)
41.6	25.2	16.4	0.7	25	225	17	4.53	4.10	00
43.8	25.4	18.4	0.8	25	230	20	4.57	4.18	20
45.6	28.6	17.0	0.9	25	235	22	4.61	4.17	40
45.8	28.7	17.1	-0.7	25	240	18	4.60	4.18	60
45.9	29.5	16.4	-1.6	25	245	17	4.62	4.24	80
46.7	29.2	17.5	-1.5	25	250	14	4.72	4.35	100
46.8	27.6	19.2	-2.8	25	255	15	4.75	4.47	120
47.9	27.8	20.1	-2.7	25	260	17	4.79	4.59	140
Difference in final and initial power consumption							4.79-4.53= 0.26	4.59-4.10= 0.49	

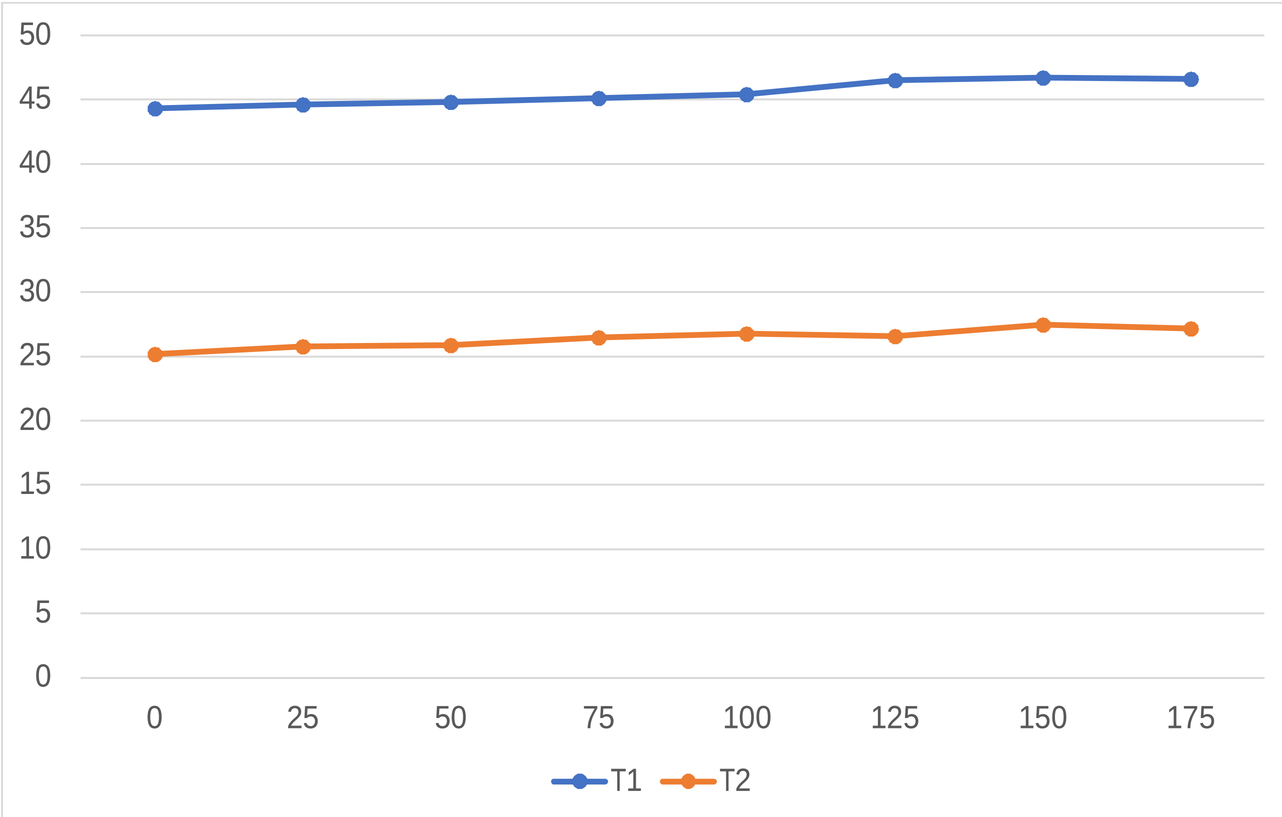
COP = Heat Consumed by Evaporator/Power consumed by Compressor
= 0.49/ 0.26= 1.88



Graph 5.5: Comparison Graph of Temperature and Power consumed by Nanoparticle Using capillary tube size 1.14 Part B

Table No. 5.6 Results for Experiment No.2.3									
Atmospheric Temperature = 30.4°C			($CuO + SiO_2$+Mno2) Nanoparticle + Refrigerant R134a (100 gm)						
T1 (°C)	T2 (°C)	Condenser Temperature Drop(T1-T2)	T3 (°C)	T4 (°C)	P1 (psi)	P2 (psi)	Power consumed by Compressor	Power consumed by Evaporator	Time (min)
44.7	25.3	19.4	-1.2	25	230	16	6.43	7.11	00
44.7	25.8	18.9	-1.5	25	235	17	6.49	7.27	20
44.8	25.6	19.2	-1.9	25	240	15	6.53	7.34	40
45.5	26.6	18.9	-1.7	25	245	17	6.54	7.33	60
45.8	26.5	19.3	-1.8	25	250	13	6.61	7.36	80
46.8	26.4	20.4	-1.5	25	255	15	6.65	7.45	100
46.7	27.3	19.4	-1.6	25	260	11	6.70	7.44	120
46.9	27.2	19.7	-1.7	25	265	12	6.69	7.64	140
Difference in final and initial power consumption							6.69-6.43= 0.26	7.64-7.11= 0.53	

COP = Heat Consumed by Evaporator/Power consumed by Compressor
= 0.53/ 0.26= 2.04



Graph 5.6: Comparison Graph of Temperature and Power consumed by Nanoparticle Using capillary tube size 1.14 Part C

Table 5.8 presents the experimental results for Experiment No. 2.3, where a mixture of CuO, SiO_2, and MnO_2 nanoparticles was added to 100 grams of R134a refrigerant. The ambient temperature during the trial was maintained at 30.4°C.

Recorded parameters include:

Temperatures at multiple key points (T1 to T4)

Suction and discharge pressures (P1 and P2)

Condenser temperature drop (T1 − T2)

Power consumed by the compressor and evaporator

Time intervals (measured every 20 minutes)

The Coefficient of Performance (COP) was calculated using:

COP=Heat absorbed by evaporator Power consumed by compressor\text

{COP} = {Heat absorbed by evaporator} {Power consumed by compressor}}

COP=Power consumed by compressor Heat absorbed by evaporator

In this setup, the COP was found to be 2.21, indicating a relatively efficient thermal performance under nanoparticle-enhanced conditions.

V. SUMMARY

This series of experiments highlights the influence of both capillary tube diameter and nanoparticle additives on the thermal performance and energy efficiency of mini-scale refrigeration systems. The findings support the potential for further optimization through careful selection of physical system parameters and innovative refrigerant formulations.

A. Heat Transfer Enhancement

The use of nano-refrigerants significantly improved heat transfer performance within the system. The presence of nanoparticles increased the effective thermal conductivity of the refrigerant, leading to enhanced convective heat transfer in both the evaporator and condenser.

In addition, the PCM integrated into the condenser acted as a thermal buffer. During operation, PCM absorbed excess heat released by the refrigerant during condensation, thereby reducing the temperature of the condenser surface. This resulted in improved heat rejection and prevented overheating under high-load conditions. The combined effect of nanorefrigerants and PCM led to a more efficient and stable heat transfer process.

B. Compressor Work

A reduction in compressor work was observed with the use of nanorefrigerants and PCM integration. Due to improved heat transfer characteristics, the refrigerant required less energy for compression to achieve the desired cooling effect. The enhanced heat dissipation in the condenser reduced the discharge pressure, thereby lowering the compressor load.

Experimental results indicated a measurable decrease in power consumption when compared to the conventional system. This reduction in compressor work directly contributes to improved energy efficiency and lower operating costs.

C. Temperature Stability

Temperature stability is an important factor in maintaining consistent system performance. The integration of PCM within the condenser significantly improved temperature regulation. During peak operating conditions, PCM absorbed excess heat by undergoing a phase change, which helped maintain a nearly constant temperature in the condenser.

This thermal buffering effect reduced temperature fluctuations and ensured smoother system operation under varying load conditions. As a result, the system exhibited improved reliability and consistent performance over extended periods of operation.

D. Advantages of the Proposed System

The integration of nanoparticle-enhanced refrigerants and phase change material (PCM) within the refrigeration system offers several significant advantages over conventional systems. These benefits contribute to improved performance, cost-effectiveness, and sustainability.

E. Improved Energy Efficiency

One of the primary advantages of the proposed system is the substantial improvement in energy efficiency. The inclusion of nanoparticles enhances the thermal conductivity and heat transfer characteristics of the refrigerant, enabling faster heat absorption and rejection.

Additionally, the PCM-integrated condenser helps in storing excess thermal energy and releasing it gradually, thereby reducing the thermal load on the system. This combined effect results in a higher coefficient of performance (COP), meaning more cooling is achieved per unit of energy consumed.

F. Reduced Operational Cost

The enhanced energy efficiency directly leads to lower power consumption, which in turn reduces operational costs. The decrease in compressor workload minimizes electricity usage during system operation. Over time, this reduction in energy consumption translates into significant cost savings, especially in large-scale or continuous refrigeration applications such as industrial cooling and commercial refrigeration systems.

G. Enhanced System Lifespan

The proposed system also contributes to increased durability and longer operational life. The improved heat transfer reduces excessive thermal stress on key components such as the compressor and condenser. Additionally, the PCM helps in maintaining stable operating temperatures, preventing overheating and frequent cycling of the system. These factors reduce wear and tear on mechanical components, resulting in fewer breakdowns and lower maintenance requirements.

H. Environmentally Friendly Approach

This hybrid system supports environmental sustainability in multiple ways. Reduced energy consumption leads to lower greenhouse gas emissions associated with power generation. Furthermore, improved system efficiency reduces the overall refrigerant usage and leakage risk.

The use of PCM, which is typically non-toxic and recyclable, also contributes to an eco-friendly design. Altogether, the proposed approach aligns with modern environmental standards and promotes greener refrigeration technologies.

VI. CONCLUSION

This experimental investigation demonstrates the effectiveness of combining nanoparticle-enhanced refrigerants with phase change material (PCM)-integrated condensers in improving the performance of a vapor compression refrigeration system. The results clearly indicate that the addition of nanoparticles enhances the thermophysical properties of the refrigerant, leading to improved heat transfer characteristics and better system efficiency.

The integration of PCM within the condenser further contributes to performance enhancement by acting as a thermal energy storage medium. It absorbs excess heat during peak operation and releases it gradually, which helps in maintaining stable condenser temperatures and reducing thermal fluctuations in the system. As a result, the combined system shows a noticeable improvement in the coefficient of performance (COP), reduced compressor power consumption, and overall better energy utilization.

Overall, the hybrid approach provides a significant improvement over conventional refrigeration systems in terms of efficiency, stability, and sustainability. This study confirms that the simultaneous use of nano-refrigerants and PCM is a promising solution for next-generation energy-efficient refrigeration technologies.

VII. FUTURE SCOPE

Although the present study demonstrates significant performance improvements, further research can be conducted to enhance system efficiency and practical applicability.

One potential area of development is the use of hybrid nanoparticles, such as a combination of Al_2O_3 and CuO or other advanced nanomaterials. These hybrid nanofluids may offer superior thermal conductivity and stability compared to single-particle systems.

Another important direction is the exploration of advanced phase change materials (PCMs) with higher latent heat capacity, improved thermal conductivity, and optimized melting temperatures suitable for refrigeration applications. The use of encapsulated or composite PCMs may further enhance heat storage efficiency.

Additionally, the proposed system can be scaled for large-scale industrial and commercial cooling applications, such as cold storage units, air conditioning systems, and food preservation industries. Long-term performance studies, economic analysis, and environmental impact assessments can also be carried out to validate real-world feasibility.

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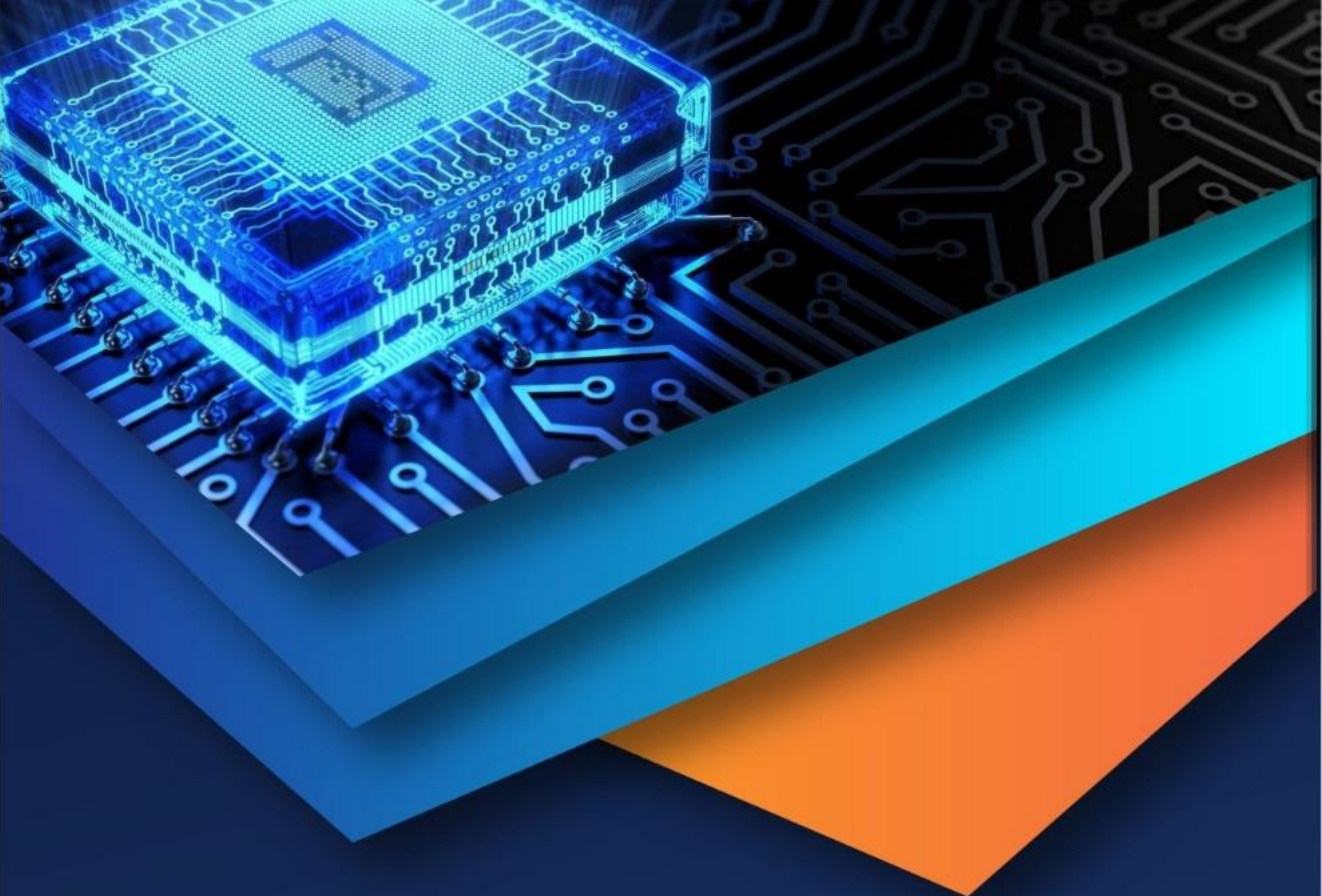

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