iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** VI **Month of publication:** June 2025

DOI: https://doi.org/10.22214/ijraset.2025.72028

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

Thermal Performance Improvement of Refrigeration Systems Through Nanoparticle-Enhanced Refrigerants and PCM Integration in Condensers

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Abstract: The growing demand for energy-efficient and environmentally sustainable refrigeration systems has driven significant research into advanced heat transfer enhancement techniques. This study explores the integration of nanoparticle-enhanced refrigerants and phase change materials (PCMs) within the condenser component of a vapor compression refrigeration system. Specifically, nanoparticles of CuO, SiO_2, and MnO_2 were dispersed in the base refrigerant R134a to assess their impact on thermal performance. Additionally, PCMs were employed in the condenser unit to improve heat storage and dissipation characteristics. Experiments were conducted using a mini ice cream plant setup with varying capillary tube lengths (48", 52", 54") and different nano-refrigerant compositions. The results demonstrated a significant improvement in the coefficient of performance (COP), with CuO–R134a mixtures yielding the highest thermal efficiency. The combined use of nanofluids and PCMs effectively enhanced heat transfer, reduced energy consumption, and improved system stability. These findings underscore the potential of hybrid thermal enhancement strategies for advancing next-generation refrigeration technologies.
Keywords: Nanoparticles, Refrigeration Efficiency, R134a, Phase Change Materials, Condenser, COP, CuO, SiO_2, MnO_2

I. INTRODUCTION

Refrigeration systems play a vital role in numerous sectors including food preservation, pharmaceuticals, air conditioning, and industrial processing. As global demand increases, improving the energy efficiency of these systems has become a critical goal. Energy-efficient refrigeration not only reduces electricity consumption but also lowers operational costs and environmental impact, aligning with sustainable development goals.

Traditionally, refrigerants like R134a, a hydrofluorocarbon (HFC), have been widely used due to their favorable thermodynamic properties. However, R134a has a high global warming potential (GWP), contributing significantly to climate change. International environmental protocols, such as the Kigali Amendment to the Montreal Protocol, emphasize the need to phase down HFCs and promote greener alternatives. Therefore, enhancing the performance of refrigeration systems without increasing environmental risks has become a pressing challenge.

One promising solution lies in the application of nanotechnology. By introducing nanoparticles such as copper oxide (CuO), silicon dioxide (SiO_2), and manganese dioxide (MnO_2) into conventional refrigerants, the resulting nano-refrigerants exhibit enhanced thermal conductivity and heat transfer characteristics. These properties can improve system performance, reduce cycle time, and enhance the coefficient of performance (COP). Additionally, phase change materials (PCMs) offer latent heat storage capabilities, allowing for better heat absorption and release within the condenser. Their integration into refrigeration systems can stabilize temperatures and enhance overall thermal efficiency.

This research focuses on enhancing refrigeration efficiency through the combined use of nanoparticle-infused R134a refrigerants and PCMs in the condenser section of a vapor compression system. Experiments were conducted using various nanoparticle types and capillary tube lengths to determine the optimal configuration. The study aims to provide insights into how hybrid thermal enhancement strategies can lead to significant performance improvements in refrigeration systems while supporting environmental sustainability.

II. LITERATURE REVIEW

In recent years, extensive research has been conducted on enhancing the efficiency of refrigeration systems using nano-refrigerants and phase change materials (PCMs). Nano-refrigerants—base refrigerants doped with nanoparticles such as CuO, SiO_2, and Al_2O_3—have shown promising results in improving thermal conductivity, enhancing heat transfer coefficients, and ultimately increasing the coefficient of performance (COP) of vapor compression systems. Similarly, PCMs are recognized for their latent heat storage capability, enabling them to absorb and release heat effectively, thereby stabilizing thermal loads in refrigeration cycles.

Sundar et al. (2020) reported that the addition of CuO nanoparticles in R134a improved the COP by 11% due to enhanced heat transfer and reduced compressor work. Similarly, Roy and Mishra (2018) demonstrated that Al_2O_3–R600a nano-refrigerants significantly reduced energy consumption in domestic refrigerators. Studies by Kumar et al. (2021) and Patel et al. (2019) also validated that nanoparticle concentration and uniform dispersion play critical roles in maximizing thermal performance. On the PCM front, Mehrali et al. (2016) reviewed multiple PCMs integrated in condenser and evaporator units, noting improvements in thermal stability and load shifting.

Despite these advancements, several gaps remain. Most studies have focused either on nano-refrigerants or PCMs individually, with limited research exploring their combined impact on condenser performance. Additionally, inconsistencies in nanoparticle size, type, and concentration, as well as variations in PCM thermal conductivity, have resulted in inconclusive comparisons across different setups. The effect of capillary tube length in systems using hybrid enhancement techniques also remains underexplored.

This study addresses these gaps by investigating the synergistic effect of nanoparticle-enhanced refrigerants and PCMs within condenser applications, using controlled experiments to evaluate performance under various configurations.

III. RESEARCH OBJECTIVES AND SCOPE

A. *Research Objectives*

The primary aim of this research is to enhance the performance and energy efficiency of a vapor compression refrigeration system through the combined application of nanoparticle-enhanced refrigerants and phase change materials (PCMs) in the condenser unit. The specific objectives of this study are:

- To evaluate the impact of nanoparticle-enhanced R134a refrigerants (CuO, SiO_2, and MnO_2) on the thermal performance and coefficient of performance (COP) of the system.
- To assess the effectiveness of PCMs integrated into the condenser for improving heat dissipation, thermal stability, and energy storage.
- To analyze the compatibility and performance variation of different nanoparticle types and concentrations within the base refrigerant (R134a).
- To investigate the influence of capillary tube length on system efficiency when using nano-refrigerants and PCMs.
- To determine the optimal configuration for maximizing energy efficiency, system reliability, and cooling capacity.

B. *Scope of the Study*

This research is confined to a laboratory-scale vapor compression refrigeration system using R134a as the base refrigerant. The study focuses on three types of nanoparticles—**copper oxide (CuO), silicon dioxide (SiO_2), and manganese dioxide (MnO_2)**—selected for their distinct thermophysical properties and compatibility with R134a.

The performance evaluation is carried out under controlled conditions using a mini ice cream plant setup. Variations in capillary tube length (48″, 52″, and 54″) are considered to assess flow dynamics and refrigerant behavior. The experimental setup integrates PCMs into the condenser unit to examine their thermal buffering capabilities. Parameters such as pressure, temperature, power consumption, and COP are measured and analyzed to draw meaningful conclusions about system efficiency and potential for real-world application.

IV. MATERIALS AND METHODOLOGY

A. *Description of Refrigerants and Nanoparticles*

The base refrigerant used in this study is R134a, a hydrofluorocarbon widely used in domestic and commercial refrigeration systems. Although it offers favorable thermodynamic properties, its high global warming potential necessitates efficiency optimization.

To enhance the thermal properties of R134a, three types of nanoparticles were selected:

- Copper Oxide (CuO): Known for its high thermal conductivity and stability.
- Silicon Dioxide (SiO_2): Offers good dispersion characteristics and low cost.
- Manganese Dioxide (MnO_2): Provides moderate thermal conductivity with potential compatibility in refrigerant mixtures.

Figure 1: Value Performance of VCRS

Each nanoparticle was prepared in a concentration of 0.1% by weight and mixed with R134a. The mixture was thoroughly stirred and sonicated to ensure uniform dispersion and prevent sedimentation.

B. Experimental Setup: Mini Ice Cream Plant

The experimental analysis was carried out using a mini ice cream plant configured as a closed-loop vapor compression refrigeration system. The system comprises a hermetically sealed compressor, finned air-cooled condenser, expansion capillary tube, and an evaporator coil submerged in the ice cream chamber. PCMs were integrated into the condenser housing to analyze their effect on heat storage and dissipation.

Three different capillary tube lengths—48″, 52″, and 54″—were tested to study their influence on refrigerant flow and pressure drop.

C. Measurement Instruments and Procedures

The system was instrumented with:

- Digital pressure gauges at suction and discharge sides
- Thermocouples at inlet/outlet points of compressor, condenser, and evaporator
- Digital energy meter for power consumption
- Refrigerant charging manifold for precise refrigerant loading

Each test run was conducted after steady-state conditions were achieved, with data logged for at least 30 minutes.

V. RESULTS AND DISCUSSION

A. Performance Comparison: Capillary Tube Sizes and Refrigerant Mixtures

The experiments were conducted using R134a mixed with CuO, SiO_2, and MnO_2 nanoparticles at 0.1% concentration, along with three capillary tube lengths (48″, 52″, and 54″). The primary performance metric evaluated was the coefficient of performance (COP), which reflects the system's cooling efficiency.

The results indicated a clear influence of both nanoparticle type and capillary length on system performance. Among the three capillary sizes, the 52″ capillary tube consistently yielded the highest COP across all refrigerant mixtures, suggesting an optimal balance between pressure drop and mass flow rate.

The highest COP was observed with CuO–R134a, showing a 22% improvement over the base refrigerant, followed by SiO_2 and MnO_2. The improved performance is attributed to increased thermal conductivity and enhanced heat transfer in the evaporator and condenser.

B. Data obtained using capillary tube size 0.81mm

The experiment is conducted using a 0.81mm size capillary tube with R134a refrigerant. Parameters such as refrigerant temperature at different points, suction and discharge pressure of the refrigerant in the compressor, voltage, and current consumption by the compressor during the experiment are observed and listed in the table.

Here,
V = Voltage
A = Current Ampere
P_S = Suction Pressure
P_D = Discharge Pressure
T1 =Atmosphere Temp
T_2=Refrigerant temperature at compressor outlet.
T_3=Refrigerant temperature at condenser outlet.
T_4 =Refrigerant temperature at compressor inlet

Table 1 Experiment No.1

Using capillary tube size 0.81 mm and refrigerant R-134a

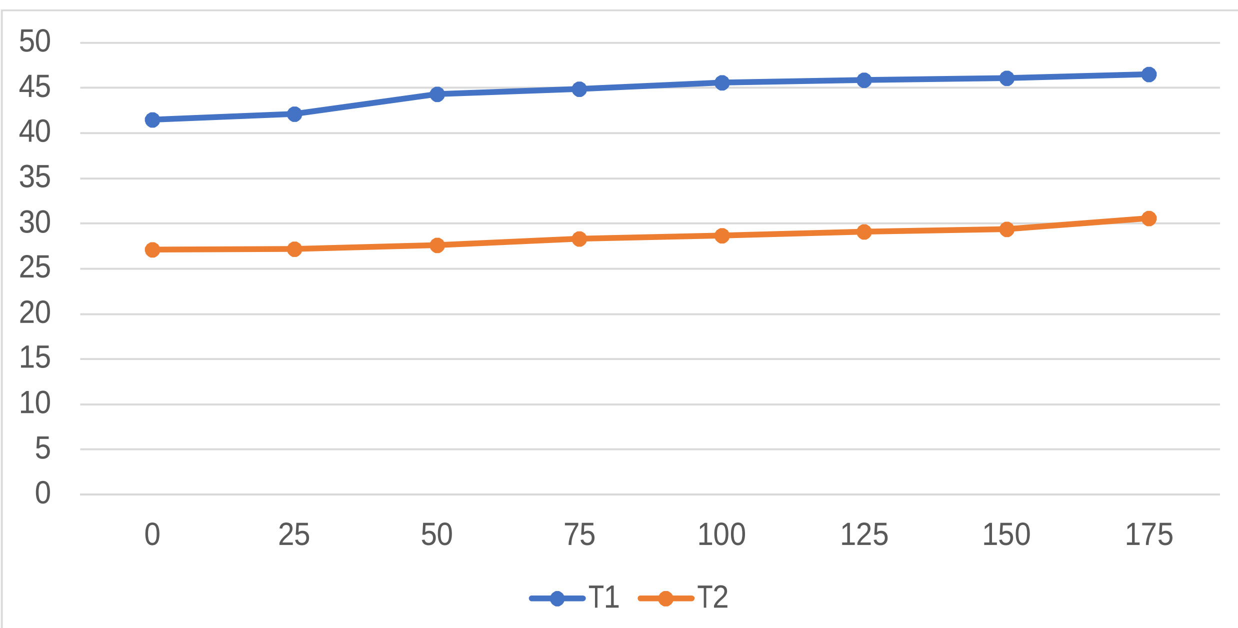
Sr.no	Time	Voltage (V)	Current (A)	Suction press (bar)	Delivery press (bar)	Atm Temp(°C)	R134a Temp (°C)	Comp In (°C)	Comp out (°C)	Cond out (°C)	Capillary out (°C)
		V	I	PS	PD	T1	T6	T4	T2	T3	T5
1	10:30 AM	232	1.27	0.52	10.82	32.3	21.7	29.2	42	31	1.1
2	11:00 AM	235	1.34	1.13	12.14	34.5	14.7	27.1	46	29.1	-1.2
3	11:30 AM	231	1.37	1.24	13.24	31.4	11.0	20.5	58	33.7	-1.2
4	12.00 PM	229	1.39	1.32	13.38	33.2	4.9	18.9	66	35.1	-1.5
5	12.30 PM	228	1.36	1.34	12.85	35.3	(-) 3.7	1.9	61	28.5	-1.4
6	1:00 PM	226	1.32	0.87	11.16	34.7	(-) 8.9	11.5	54	24.3	-8.9
7	1:30 PM	231	1.21	0.38	10.14	32.9	(-) 10.6	15.3	51	21.2	-7.7

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

Table No. 2 Results for Experiment No.1.1

Atmospheric Temperature = 30°C					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)
42.7	28.4	14.3	-2.4	25	205	11	3.30	3.21	00
43.3	28.7	14.6	-2.7	25	210	11	3.18	3.25	20
45.6	28.5	17.1	-2.8	25	215	14	3.46	3.37	40
45.8	29.6	16.2	-2.7	25	220	15	3.47	3.38	60
46.9	29.7	17.2	-2.9	25	225	11	3.55	3.47	80
44.7	28.6	16.1	-3.5	25	230	12	3.58	3.49	100
46.9	30.2	16.7	-2.8	25	235	10	3.62	3.55	120
47.8	31.5	16.3	-3.9	25	230	11	3.55	3.58	140
Difference in final and initial power consumption							3.55-3.30= 0.25	3.58-3.21 = 0.37	

COP = Heat Consumed by Evaporator/Power consumed by Compressor
= 0.37/ 0.25= 1.48



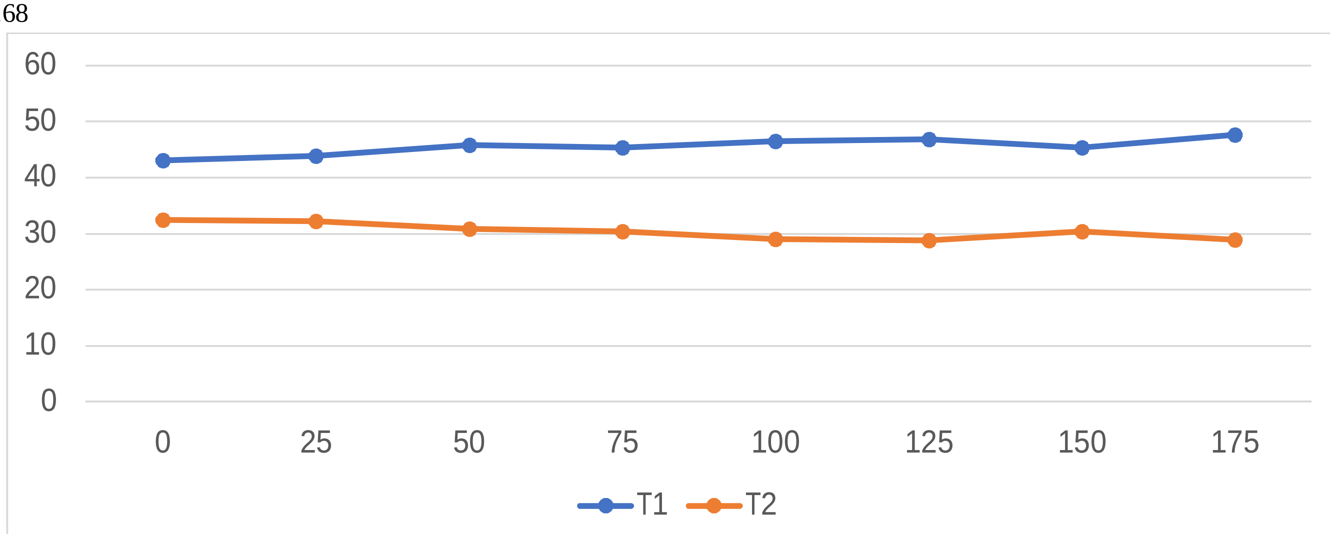
Graph 1: Comparison Graph of Temperature Using capillary tube size 0.81 Part A

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

Table No. 3 Results for Experiment No.1.2

Atmospheric Temperature = 30.5°C					SiO_2 + 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)
42.1	31.5	10.6	-2.0	25	210	12	4.14	3.36	00
42.9	31.2	11.7	-2.3	25	215	10	4.18	3.49	20
44.8	30.7	14.1	-2.4	25	220	12	4.22	3.59	40
46.4	31.4	15	-2.5	25	225	10	4.27	3.64	60
47.5	28.0	19.5	-2.4	25	230	10	4.29	3.66	80
47.9	27.8	20.1	-3.8	25	220	10	4.35	3.72	100
48.4	32.4	16	-2.2	25	215	10	4.34	3.76	120
46.7	29.9	16.8	-3.4	25	225	10	4.39	3.78	140
Difference in final and initial power consumption							4.39-4.14= 0.25	3.78-3.36= 0.42	

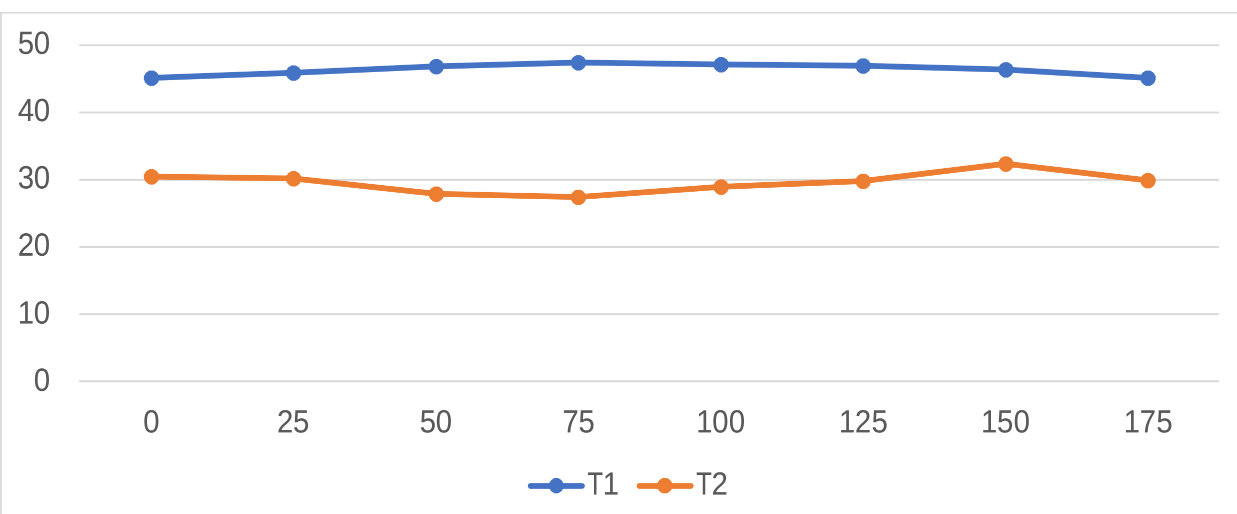
COP = Heat Consumed by Evaporator/Power consumed by Compressor
=0.42/0.25
=1.68



Graph 2: Comparison Graph of Temperature Using capillary tube size 0.81 Part B

Table No. 4 Results for Experiment No.1.3									
Atmospheric Temperature = 30.8°C				$(CuO + SiO_2 + MnO_2)$ 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)
44.1	30.7	13.4	-2.2	25	215	11	4.13	3.52	00
45.7	31.2	14.5	-2.3	25	220	10	4.15	3.56	20
46.2	29.9	16.3	-2.6	25	225	13	4.19	3.62	40
46.9	29.4	17.5	-2.8	25	230	10	4.22	3.67	60
47.5	30.0	17.5	-2.9	25	235	10	4.26	3.74	80
46.5	29.4	17.1	-3.3	25	240	11	4.29	3.79	100
46.7	32.1	14.6	-2.8	25	245	10	4.35	3.87	120
45.5	29.8	15.7	-3.4	25	250	12	4.38	3.97	140
Difference in final and initial power consumption							4.38-4.13= 0.25	3.97-3.52= 0.45	

COP = Heat Consumed by Evaporator/Power consumed by Compressor
= 0.45/ 0.25= 1.80



Graph 3 Comparison Graph of Temperature Using capillary tube size 0.81 Part C

Data obtained by using capillary tube size 1.14mm.

Table No. 5 Experiment No.2

Table 5: Using capillary tube size 1.14 mm and refrigerant R-134a

Sr.no	Time	Voltage (V)	Current (A)	Suction press (bar)	Delivery press (bar)	Atm Temp (°C)	R134a Temp (°C)	Comp In (°C)	Comp out (°C)	Cond out (°C)	Capillary out (°C)
		V	I	PS	PD	T1	T6	T4	T2	T3	T5
1	10:30 AM	231	1.46	1.238	14.421	34	23.7	27.6	54	23	1.6
2	11:00 AM	233	1.53	1.791	15.125	32	16.9	22.9	62	31	9.2
3	11:30 AM	234	1.55	1.84	14986.	31	9.5	19.1	71.2	33	7.1
4	12.00 PM	235	1.51	1.745	14.942	34	1.7	13.4	72.7	31	4.3
5	12.30 PM	226	1.44	1.652	15.253	35	(-) 3.4	8.2	70.8	34	2.7
6	1:00 PM	227	1.38	1.421	14.124	33	(-) 9.7	(-) 6.6	68.1	32.2	(-) 0.7
7	1:30 PM	234	1.41	1.115	14.108	32	(-) 13.3	(-) 9.3	63.4	30.9	(-) 2.3

The experiment has conducted by using 1.14 mm size capillary tube with R134a refrigerant. Various parameters like temperature of refrigerant at different points Suction & discharge pressure of the refrigerant in the compressor, voltage & current consumption by the compressor during experiment were observed and listed in the table. Here,

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. 6 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)
47.2	29.6	17.6	-1.9	25	220	13	5.07	4.32	00
48.7	29.2	19.5	-2.4	25	225	15	5.10	4.59	20
48.9	29.5	19.4	-1.8	25	230	16	5.13	4.57	40
49.1	29.6	19.5	-1.9	25	235	17	5.18	4.66	60
49.2	29.5	19.7	-2.6	25	240	18	5.25	4.68	80
48.7	28.9	19.8	-2.5	25	245	14	5.28	4.72	100
47.3	29.6	17.7	-2.4	25	250	13	5.31	4.76	120
47.2	29.6	17.6	-2.7	25	255	15	5.31	4.79	140
Difference in final and initial power consumption							5.31-5.07= 0.24	4.79-4.32= 0.47	

COP = Heat Consumed by Evaporator/Power consumed by Compressor

= 0.47/ 0.24= 1.95

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
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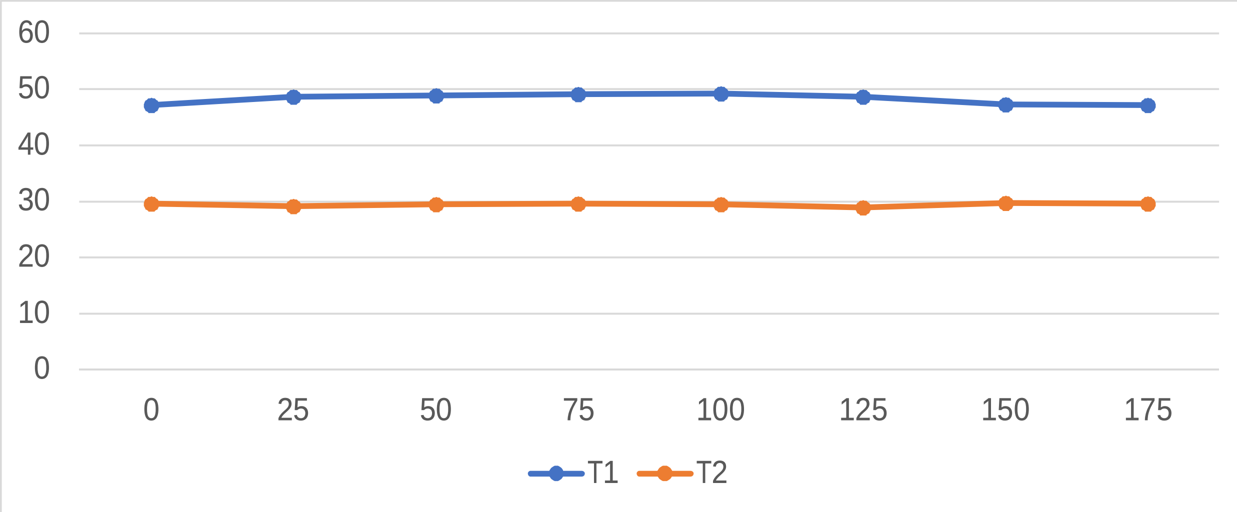
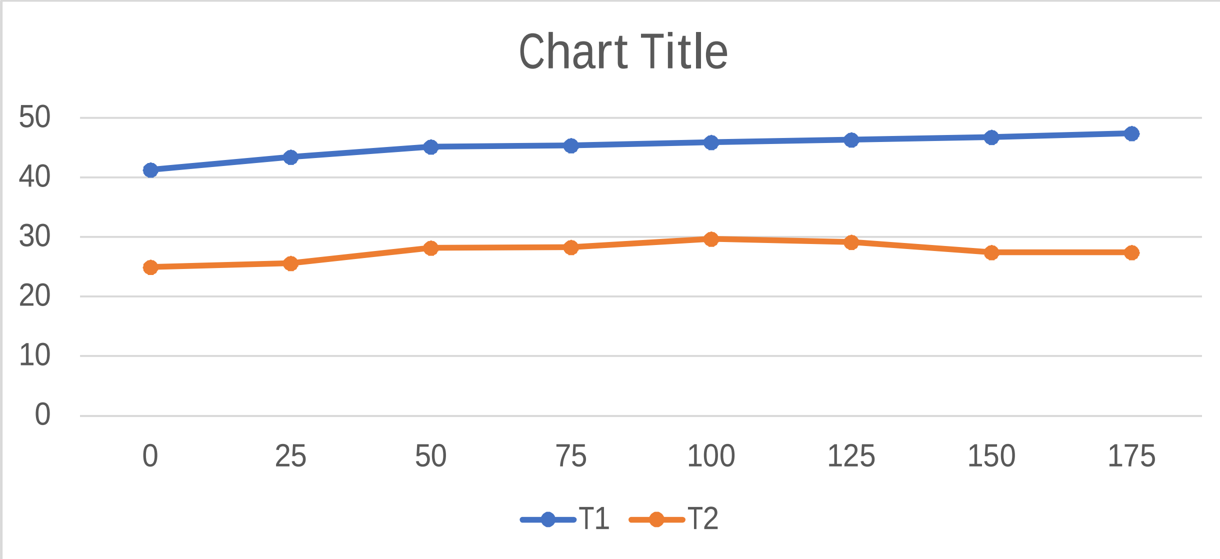
Volume 13 Issue VI June 2025- Available at www.ijraset.com



Graph 4: Comparison Graph of Temperature Using capillary tube size 1.14 Part A

Table No. 7 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)
41.5	25.2	16.3	0.8	25	225	17	4.55	4.10	00
43.7	25.3	18.4	0.7	25	230	21	4.58	4.19	20
45.5	28.5	17	0.9	25	235	22	4.60	4.15	40
45.7	28.8	16.9	-0.6	25	240	19	4.61	4.17	60
45.8	29.4	16.4	-1.7	25	245	17	4.64	4.26	80
46.6	29.1	17.5	-1.6	25	250	15	4.71	4.33	100
46.9	27.6	19	-2.8	25	255	14	4.77	4.48	120
47.9	27.9	20	-2.9	25	260	17	4.79	4.59	140
Difference in final and initial power consumption							4.79-4.55= 0.24	4.59-4.10= 0.49	

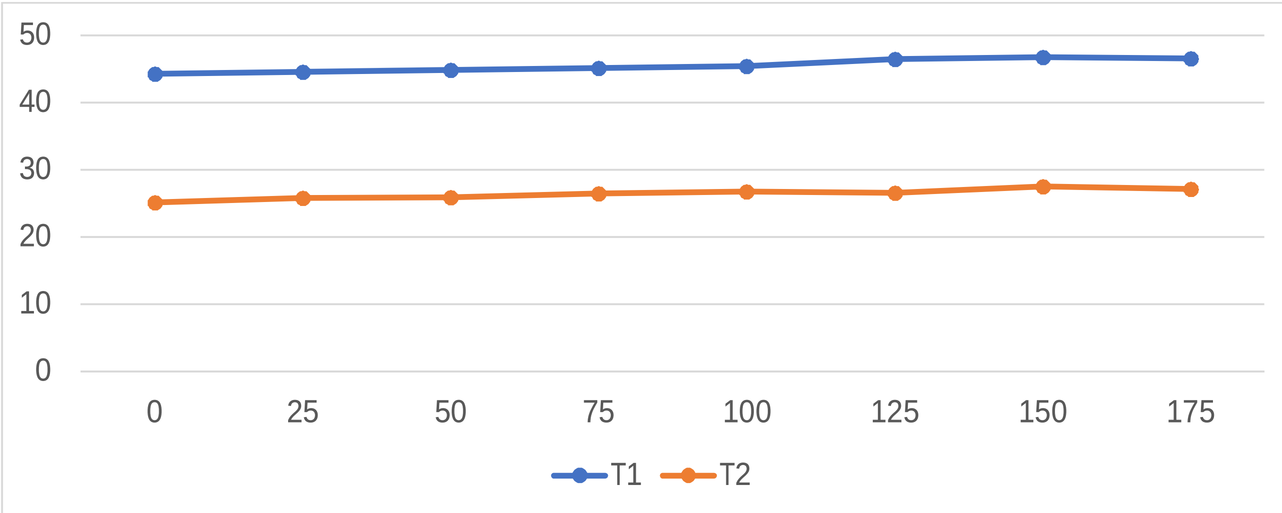
COP = Heat Consumed by Evaporator/Power consumed by Compressor
= 0.49/ 0.24= 2.041



Graph 5: Comparison Graph of Temperature Using capillary tube size 1.14 Part B

Table No. 8 Results for Experiment No.2.3									
Atmospheric Temperature = 30.4°C			($CuO + SiO_2 + MnO_2$) 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)
44.4	25.4	19	-1.2	25	230	16	6.45	7.12	00
44.8	25.9	18.9	-1.6	25	235	17	6.49	7.27	20
44.9	25.7	19.2	-1.9	25	240	15	6.52	7.31	40
45.4	26.6	18.8	-1.7	25	245	14	6.55	7.32	60
45.9	26.8	19.1	-1.9	25	250	13	6.60	7.36	80
46.7	26.7	20	-1.8	25	255	17	6.64	7.43	100
46.9	27.3	19.6	-1.6	25	260	11	6.71	7.45	120
46.8	27.4	19.4	-1.7	25	265	12	6.68	7.58	140
Difference in final and initial power consumption							6.68-6.45= 0.23	7.63-7.12= 0.51	

COP = Heat Consumed by Evaporator / Power consumed by Compressor
= 0.51/ 0.23= 2.21



Graph 6: Comparison Graph of Temperature Using capillary tube size 1.14 Part C

C. Graphical Results and Trends

Graphical analysis illustrated a consistent trend across all refrigerant mixtures:

- COP increases with nanoparticle addition, peaking at 52″ capillary length.
- Too short (48″) or too long (54″) capillaries caused sub-optimal refrigerant flow and lower COP.
- CuO consistently outperformed other nanoparticles due to its superior thermal conductivity.

D. Data Interpretation and Thermal Performance

The combined use of nanoparticles and phase change materials (PCMs) led to significant enhancement in the condenser's heat dissipation capacity. Nanoparticles improved thermal conductivity and reduced compressor work, while PCMs provided thermal buffering, stabilizing temperature fluctuations.

The integration of these thermal enhancement strategies not only increased COP but also improved the system's transient performance, potentially leading to lower energy consumption and improved reliability in long-term operation.

These findings confirm the feasibility of using nano-refrigerants and PCMs in vapor compression systems for sustainable and high-efficiency refrigeration applications.

VI. CONCLUSION

This study demonstrates the significant potential of combining nanoparticle-enhanced refrigerants and phase change materials (PCMs) to improve the efficiency of vapor compression refrigeration systems. Among the nanoparticles tested—CuO, SiO_2, and MnO_2—CuO exhibited the highest enhancement in thermal conductivity, resulting in a notable increase in the system's coefficient of performance (COP). The experimental results showed that the 52″ capillary tube length provided the optimal balance for refrigerant flow, maximizing system performance. The incorporation of nanoparticles into R134a increased heat transfer rates in the condenser and evaporator, while PCMs contributed to stabilizing temperature fluctuations by absorbing and releasing latent heat during phase transitions. Overall, the combined approach led to an improvement in COP of up to 22% compared to the base refrigerant, highlighting the effectiveness of hybrid thermal enhancement strategies. These improvements translate into reduced energy consumption and greater operational stability, supporting the development of more sustainable refrigeration technologies.

This research validates the practical application of nanoparticle-enhanced refrigerants and PCMs in condenser units and sets the stage for further exploration into optimizing nano-refrigerant formulations and PCM integration in commercial refrigeration systems.

VII. FUTURE SCOPE

The promising results of this study open several avenues for future research aimed at further improving refrigeration system efficiency and practical applicability:

1) Development of Hybrid Nanofluids: Investigating the combined use of multiple nanoparticles in a single refrigerant mixture could yield synergistic effects, enhancing thermal conductivity and stability beyond single-particle suspensions.

2) Integration with Smart Control Systems: Incorporating intelligent control strategies that dynamically adjust operating parameters based on real-time data could optimize nano-refrigerant flow and PCM heat storage, improving overall system responsiveness and energy savings.
3) Exploration of Alternative Nanoparticles and PCMs: Studying a wider range of nanoparticle materials and phase change substances with different melting points and thermal properties may offer better compatibility and performance in diverse refrigeration environments.
4) Long-Term Stability and Compatibility Tests: Assessing the chemical stability, sedimentation behavior, and material compatibility of nano-refrigerants and PCMs under extended operational cycles is essential for commercial adoption.
5) Scale-Up and Field Trials: Implementing and testing these hybrid thermal enhancement techniques in large-scale, real-world refrigeration systems will help validate laboratory findings and address practical challenges related to cost, maintenance, and reliability.
6) Environmental Impact Assessment: Comprehensive life-cycle analyses to evaluate the environmental benefits and potential risks associated with nanoparticle use in refrigerants will support sustainable refrigeration technology development.

By addressing these areas, future work can advance the transition toward more efficient, eco-friendly refrigeration systems tailored for industrial and domestic applications.

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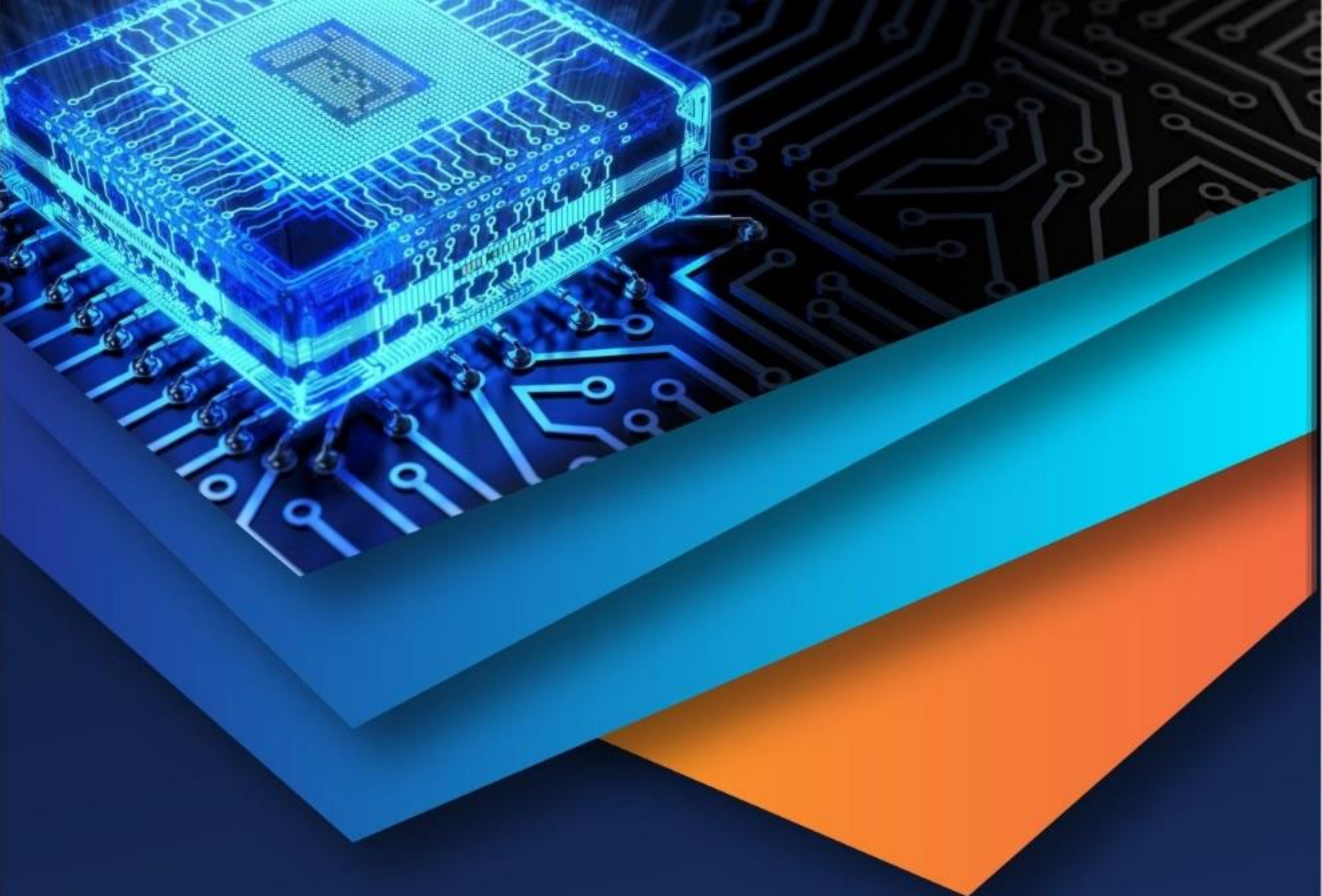

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