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Experimental Performance Evaluation of a Vapor Compression Refrigeration System Using CuO–SiO_2–MnO_2 Nanoparticle-Enhanced R134a Refrigerant with Different Capillary Tube Diameters

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Abstract: Improving the energy efficiency of vapor compression refrigeration systems (VCRS) is essential due to rising energy demand and environmental concerns associated with conventional refrigerants. This experimental study investigates the performance enhancement of a VCRS using nanoparticle-enhanced R134a refrigerant and different capillary tube diameters. Copper oxide (CuO), silicon dioxide (SiO_2), and manganese dioxide (MnO_2) nanoparticles were dispersed individually and in hybrid combinations within 100 g of R134a to form nano-refrigerants. Experiments were conducted using two capillary tube diameters, 0.81 mm and 1.14 mm, under controlled ambient conditions ranging from 30°C to 31.6°C. Key performance parameters such as refrigerant temperatures at various system locations, suction and discharge pressures, compressor and evaporator power consumption, and coefficient of performance (COP) were evaluated at regular time intervals. The results indicate a noticeable improvement in thermal performance with the addition of nanoparticles. For the 0.81 mm capillary tube, the COP increased from 1.50 for pure R134a to 1.80 with CuO–SiO_2 nano-refrigerant. In the case of the 1.14 mm capillary tube, the hybrid CuO–SiO_2–MnO_2 nano-refrigerant achieved the highest COP of 2.04–2.21, representing a significant enhancement compared to the base refrigerant. The study demonstrates that the combined effect of optimized capillary tube diameter and hybrid nanoparticles improves heat transfer characteristics, reduces compressor power consumption, and enhances overall system efficiency. These findings highlight the potential of nanoparticle-based refrigerants as an effective approach for improving the performance of small-scale refrigeration applications.
Keywords: Vapor Compression Refrigeration System; Nano-Refrigerant; R134a; CuO Nanoparticles; SiO_2 Nanoparticles; MnO_2 Nanoparticles; Capillary Tube Diameter; Coefficient of Performance (CoP).

I. INTRODUCTION

Refrigeration systems are vital across numerous sectors, including food preservation, healthcare, and industrial processes. Their efficiency is critical not only for lowering energy consumption but also for minimizing environmental impacts. Conventional refrigerants like hydrofluorocarbons (HFCs) have raised environmental concerns due to their high global warming potential (GWP) and ozone depletion potential (ODP). Consequently, it is essential to explore alternative methods that improve refrigeration efficiency while promoting sustainability. One promising approach involves the integration of nanoparticles into refrigerants and the use of phase change materials (PCMs) within condenser systems. Nanoparticles possess unique thermal characteristics that can enhance heat transfer and alter the phase behavior of refrigerants. Likewise, PCMs can absorb and release significant amounts of latent heat during phase transitions, thereby moderating temperature fluctuations and lowering energy consumption.

A. Nanoparticles and nanofluids

Nanoparticles and nanofluids have emerged as promising materials in thermal management and other fields:

1) Nanoparticles: Particles sized 1–100 nm with high surface area-to-volume ratios and unique properties. Synthesized from metals, metal oxides, polymers, and carbon materials through various methods.

2) Nanofluids: Suspensions of nanoparticles in base fluids like water or oil, enhancing thermal conductivity, viscosity, and heat capacity. This makes them excellent for heat transfer applications.

Common nanoparticles include metals (silver, copper), metal oxides (alumina, titania), carbon-based materials (graphene, CNTs), and polymers.

Research focuses on optimizing dispersion, stability, and thermal properties to maximize heat transfer efficiency.

B. Objectives of Experiment

The experiment is designed to systematically develop and evaluate nano-refrigerants by incorporating varying concentrations of copper oxide (CuO), silicon dioxide (SiO_2), and manganese dioxide (MnO_2) nanoparticles into the R-134a refrigerant. The key objectives of this experimental investigation are as follows:

1) Formulation of Nano-Refrigerants: To prepare stable CuO–SiO_2–MnO_2/R-134a nanofluid mixtures with different nanoparticle concentrations, ensuring homogeneous dispersion and minimal agglomeration.
2) Thermal Performance Analysis: To quantify the enhancement in thermal conductivity resulting from nanoparticle inclusion, thereby assessing their impact on the heat transfer potential of the base refrigerant.
3) Experimental Evaluation: To conduct performance testing using a controlled heat exchanger setup, evaluating metrics such as refrigerating effect, coefficient of performance (COP), and heat transfer coefficients under operational conditions.
4) Stability Assessment: To monitor and evaluate the physical and chemical stability of the formulated nano-refrigerants over time, including sedimentation behavior and possible chemical interactions with system materials.

C. 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:

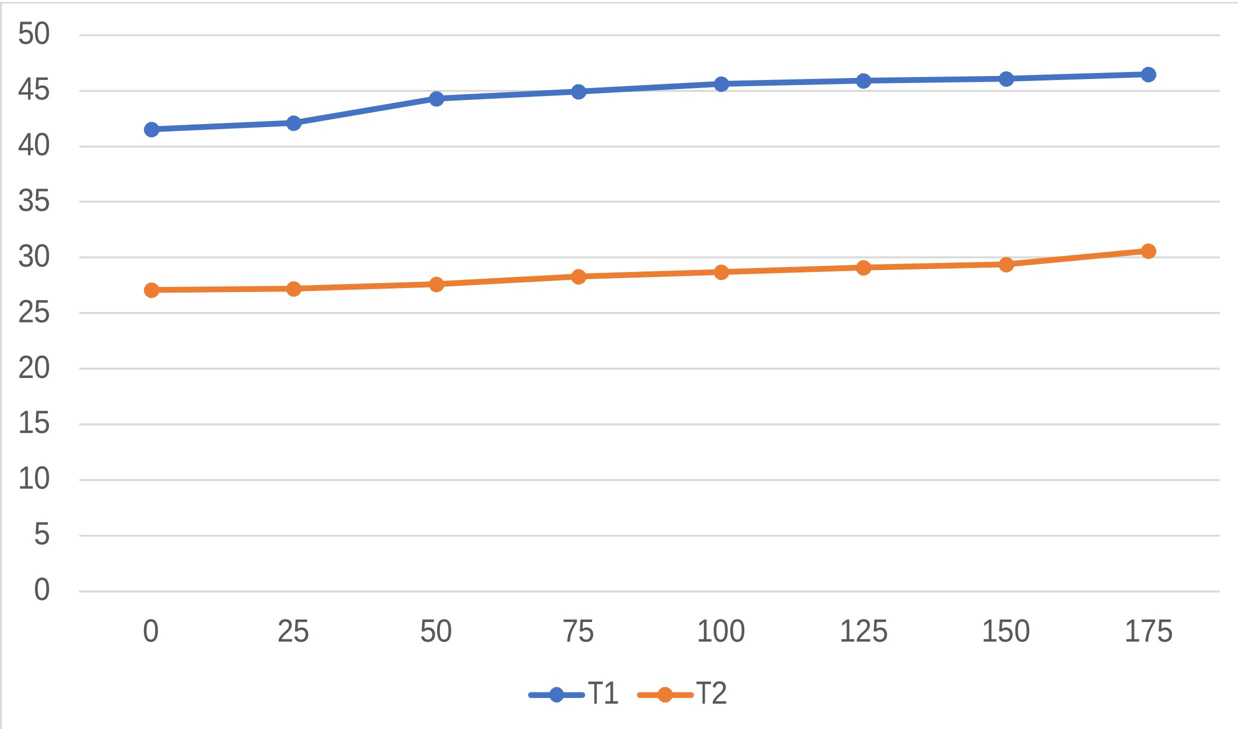
V = Voltage
A = Current (Amperes)
PS = Suction Pressure
PD = Discharge Pressure
T1 = Ambient Temperature
T2 = Temperature at compressor outlet
T3 = Temperature at condenser outlet
T4 = Temperature at compressor inlet

Table No. 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	

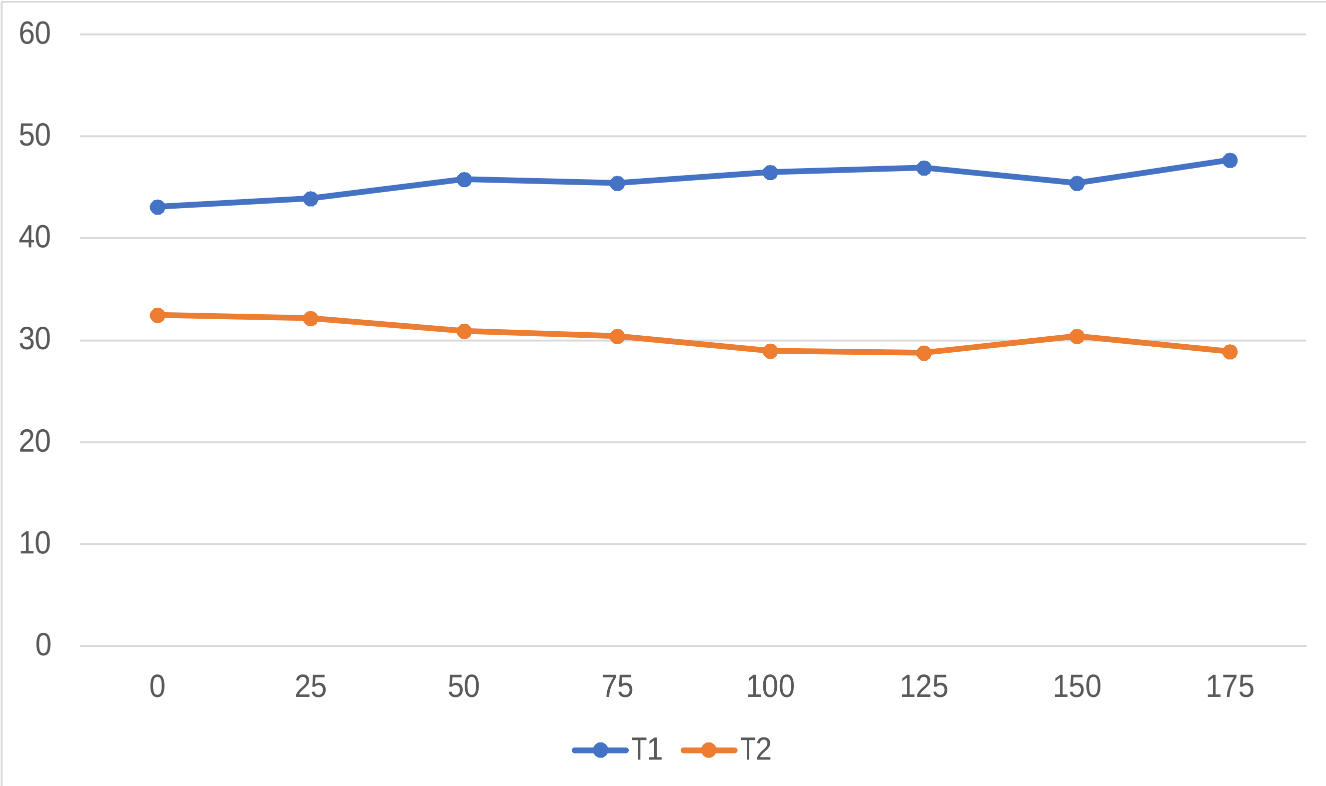
COP = Heat Consumed by Evaporator/Power consumed by Compressor
= 0.39/ 0.26= 1.5



Graph 1: Comparison Graph of Temperature and Power consumed by Nanoparticle Using capillary tube size 0.81 Part A

Table No. 2 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	31.3	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



Graph 2: Comparison Graph of Temperature and Power consumed by Nanoparticle Using capillary tube size 0.81 Part B

Table No. 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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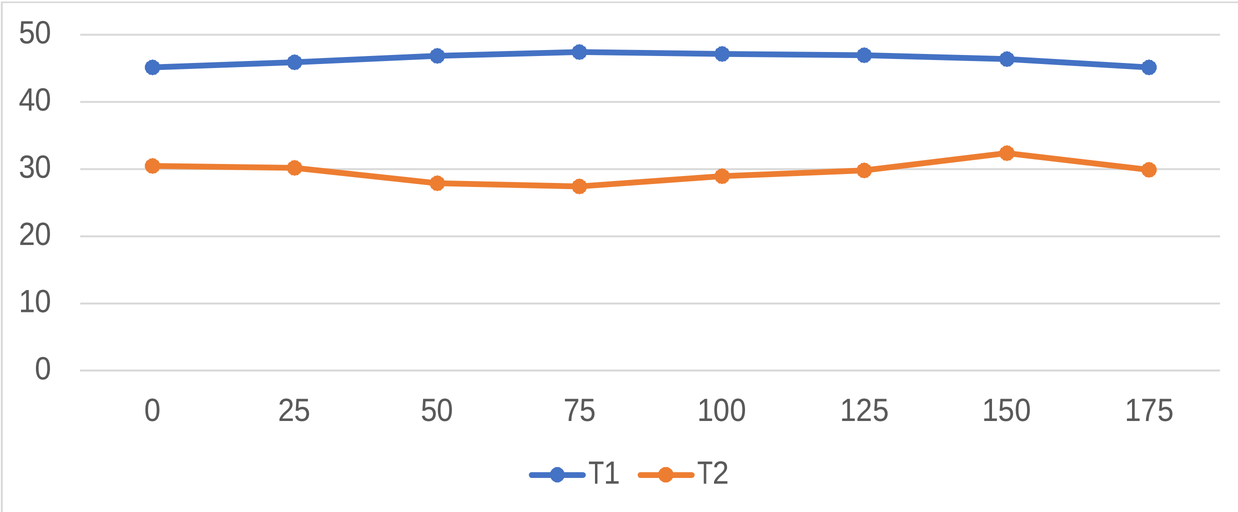


Graph 3 Comparison Graph of Temperature and Power consumed by Nanoparticle Using capillary tube size 0.81 Part C

D. Data obtained by using capillary tube size 1.14mm.

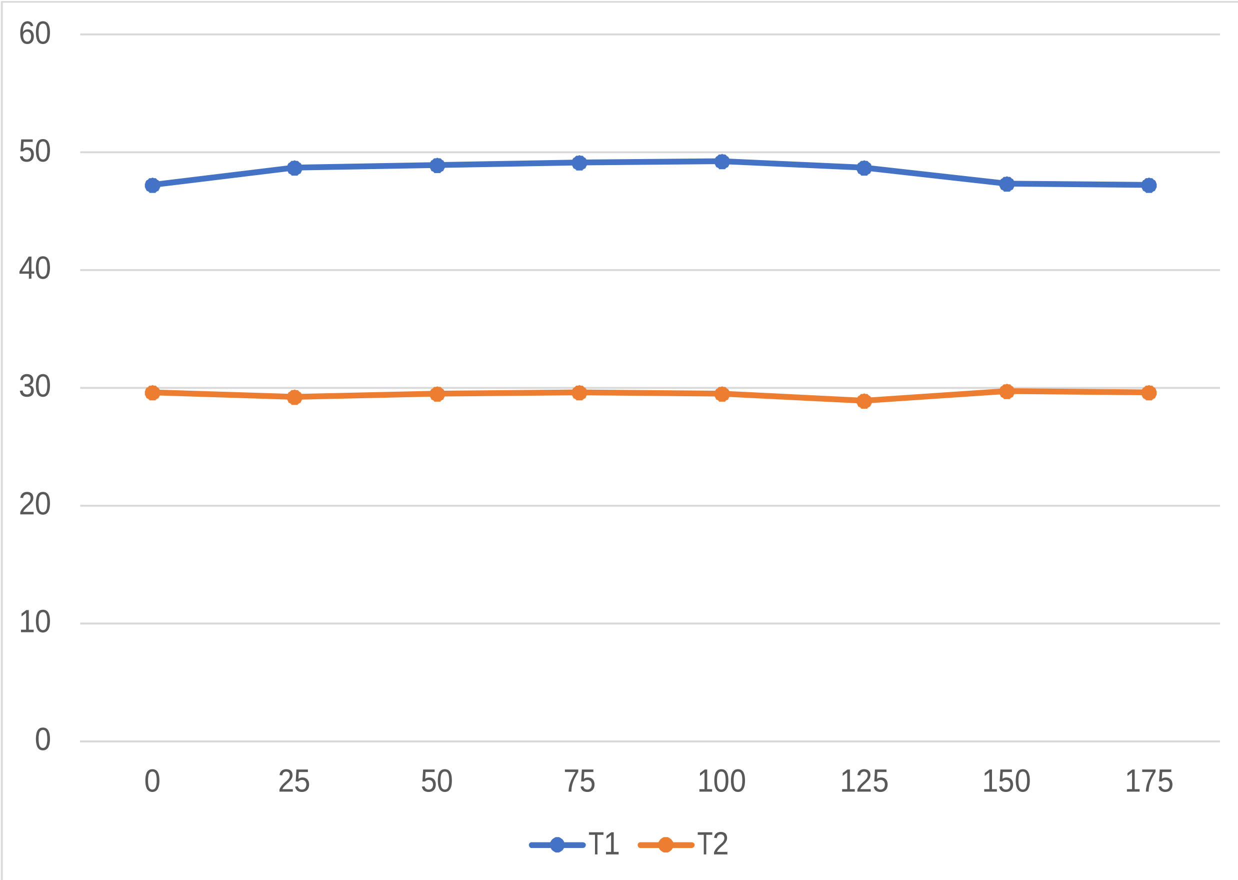
In the second trial, a 1.12 mm diameter capillary tube was used with the same refrigerant (R134a). The same set of parameters was recorded to ensure consistency in comparison. This included refrigerant temperature readings at various stages, compressor pressure measurements, and power consumption metrics.

T6= 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. 4 Results for Experiment No.2.1

Atmospheric Temperature = 30°C					Refrigerant R134a (100gm)				
T1 (ºC)	T2 (ºC)	Condenser Temperature Drop(T1- T2)	T3 (ºC)	T4 (ºC)	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	

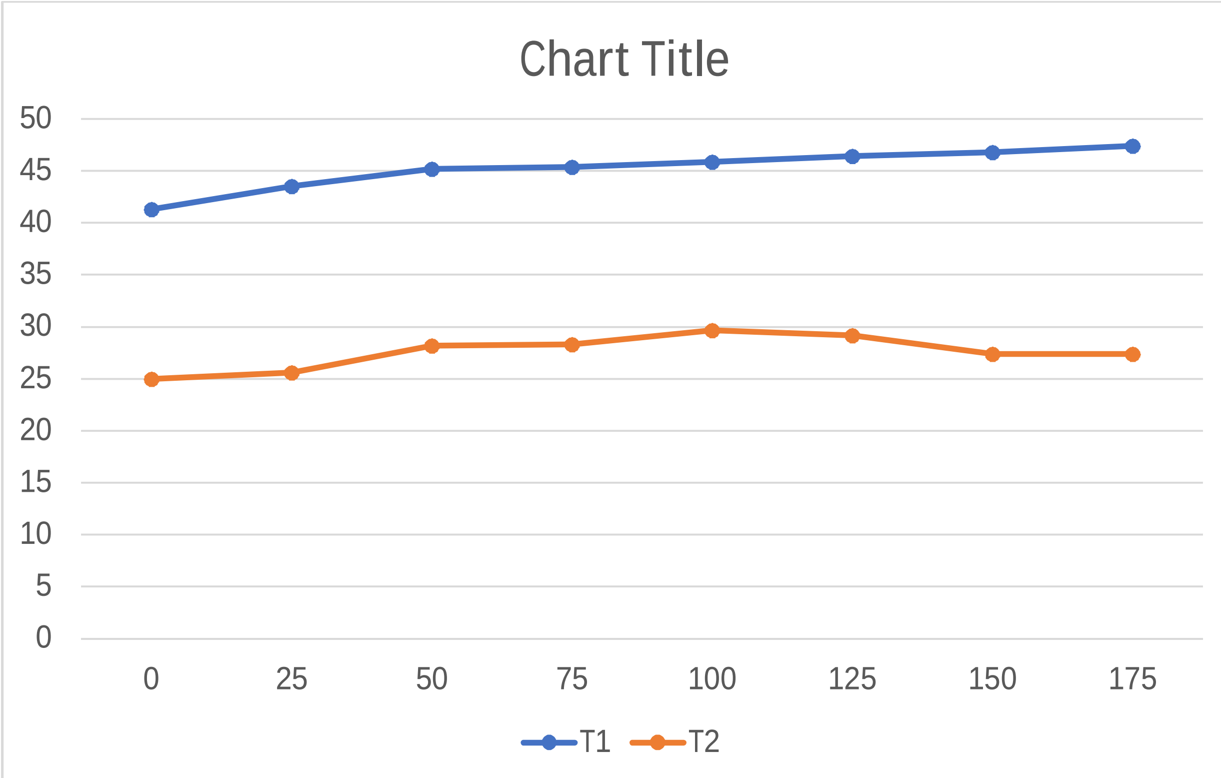
COP = Heat Consumed by Evaporator/Power consumed by Compresso
= 0.48/ 0.26= 1.84



Graph 4: Comparison Graph of Temperature and Power consumed by Nanoparticle Using capillary tube size 1.14 Part A

Table No. 5 Results for Experiment No.2.2									
Atmospheric Temperature = 31.6°C					SiO_2 Nanoparticles + 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)
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: Comparison Graph of Temperature and Power consumed by Nanoparticle Using capillary tube size 1.14 Part B

Table No. 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

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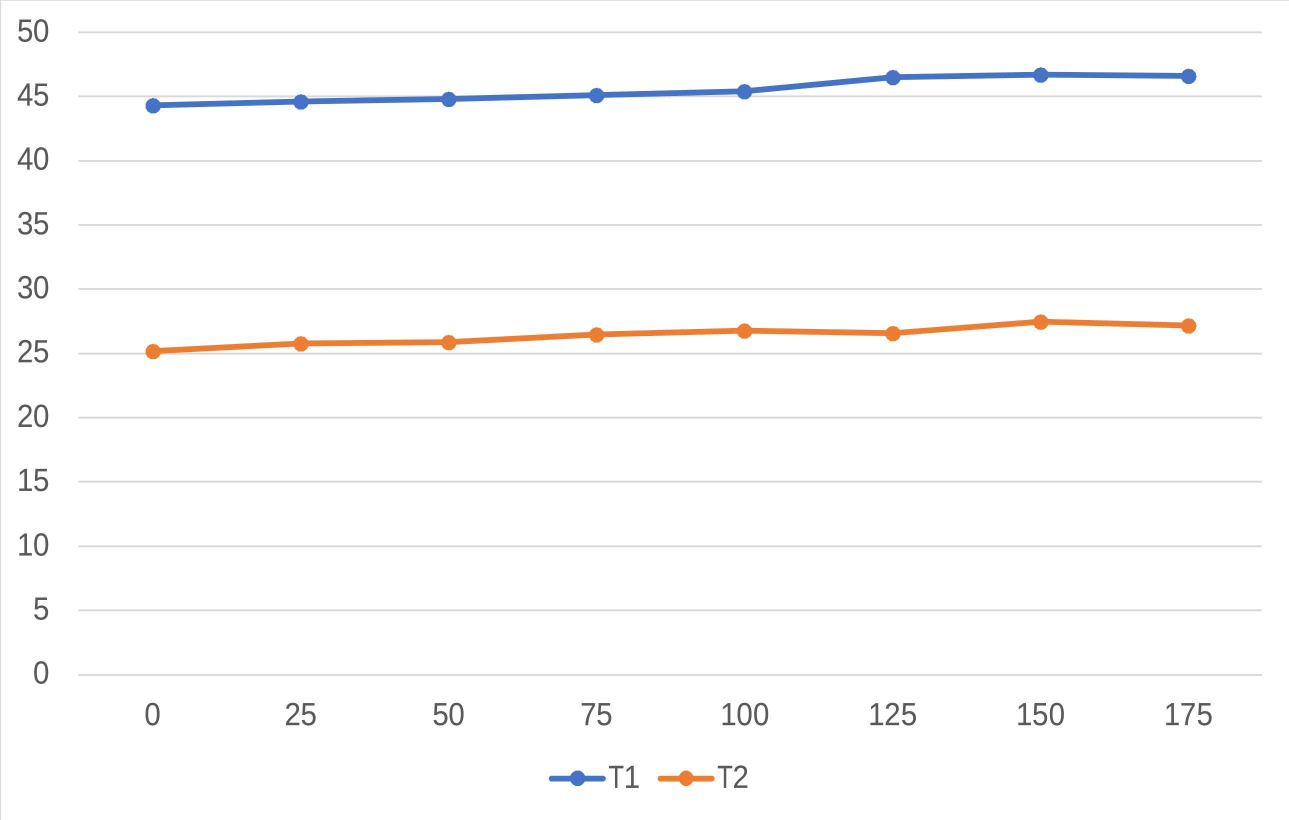

Graph 6: Comparison Graph of Temperature and Power consumed by Nanoparticle Using capillary tube size 1.14 Part C

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 evaporatorPower consumed by compressor\text

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

COP=Power consumed by compressorHeat absorbed by evaporator

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

II. CONCLUSION

The experiments conducted using capillary tubes of varying diameters and refrigerants enhanced with different nanoparticles provide meaningful insights into the operational performance of mini ice cream plants. The collected and analyzed data form a strong foundation for evaluating how capillary tube dimensions and nanoparticle-infused refrigerants influence energy efficiency and thermal performance.

In Experiment No. 1, a 0.81 mm capillary tube was used with various nanoparticle-infused refrigerants, while Experiment No. 2 employed a 1.14 mm tube with similar refrigerant compositions. Experiment No. 2.3 incorporated a combination of CuO, SiO_2, and MnO_2 nanoparticles. The observed Coefficient of Performance (COP) across these studies ranged between 1.48 and 2.21, indicating varying degrees of thermal efficiency, with higher COP values reflecting better performance.

III. FUTURE SCOPES

The study opens several promising research directions for improving Vapor Compression Refrigeration Systems (VCRS) using nanoparticles and optimized capillary tube dimensions:

Broader Nanomaterial Exploration: Beyond CuO, SiO_2, and MnO_2, future studies can investigate other nanoparticles with distinct thermal properties to further enhance heat transfer capabilities.

Optimal Nanoparticle Concentration: Research should focus on identifying ideal nanoparticle concentrations that maximize performance without causing issues such as fluid viscosity increase or particle agglomeration.

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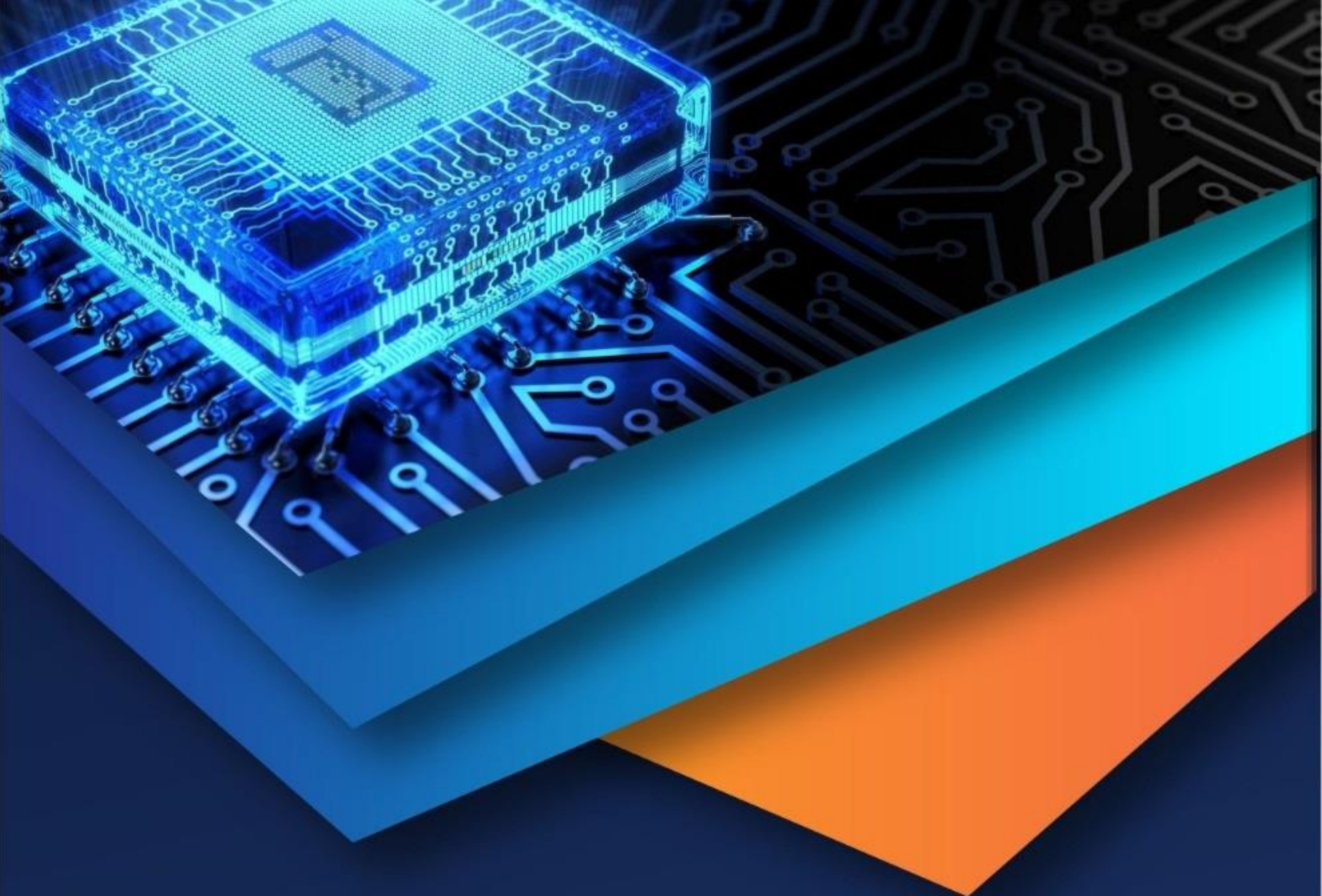

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