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Research Article

Energy-efficient refrigeration: The role of TiO_2 nanoparticles in R600a/R290 refrigerant blends

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ABSTRACT

Analysis on the need for sustainable and energy-efficient cooling mechanisms has fuelled a drive towards developing sustainable vapor compression refrigeration (VCR) systems. Experimental advancement of VCR systems is accomplished using Titanium dioxide (TiO_2) nanoparticles, which are widely known for their high coefficient of performance (COP) and operational efficiency. This research studied the influence of TiO_2 nanoparticles poised in mineral oil on a VCR system utilizing a refrigerant mixture of R600a and R290 (60:40 mass ratio). The COP of the cooling system whenever nanoparticles were implemented and when they were not measured with the capillary tube lengths being 8, 10, 12, and 14 feet through pull-down and performance test, respectively. The outcomes show that the adding of nanoparticles can raise the heat transfer rates in the evaporator and condenser, resulting in a macrophenomenon with a maximum COP enhancement of 8% at 10 foot for the capillary length. More to the point, the nano refrigerant at this optimum length proved superior over the conventional R600a/R290 in system performance (7.1% increase) and compressor power consumption (7.14% decrease). Longer capillary tubes (12 and 14 feet) were not as effective, which led to increased power consumption and less refrigeration effect. The work identified challenges as well with nanoparticle dispersion and compressor lubricant compatibility. This paper presents a pathway to sustainable refrigeration by enhancing energy efficiency and operational performance through the optimization of the length of capillaries, which play a important role in the operation of nanoparticle-augmented VCR systems.

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INTRODUCTION

The Vapor Compression Refrigeration systems are the oldest and utmost used refrigeration systems globally that power a majority of the domestic refrigerators, air conditioners, industrial chillers, etc. These systems work on a four-part, closed-loop cycle: A compressor, condenser, expansion valve, and evaporator. The refrigerant moves

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between these two stages, changing from a gaseous to a liquid state in the process; this allows it to absorb heat from cooled spaces and dumps it outside. VCR systems are acclaimed for their reliability and high coefficient of performance, yet conventional refrigerants, such as hydrofluorocarbons (HFCs), significantly contribute to global warming owing to their elevated levels of greenhouse gas emissions. This has prompted research into traditional eco-friendly alternatives — natural refrigerants (hydrocarbons like R600a and R290, for example) — and advanced modifications to improve efficiency. Nanorefrigerants, created through the dispersion of nanoparticles (such as TiO_2, Al_2O_3, carbon nanotubes) in the fundamental refrigerants or lubricants, domain us with disruptive possibilities for VCR systems. These nanoparticles improve evaporator and condenser efficiency by increasing thermal conductivity and heat transfer rates. Research shows that nanorefrigerants increase COP of the system as much as 12%, lower the work on the compressor, and reduce energy consumption. The article will present the performance between pure refrigerant and TiO_2-R600a blends where TiO_2 blended with R600a has demonstrated higher cooling performance. Nevertheless, obstacles to general adoption, such as nanoparticle agglomeration, long-term stability and interactions between materials in the system, remain. Current work is aimed at fine-tuning the optimal concentration of these nanoparticles, getting them to disperse evenly, and overcoming safety and cost barriers, Saylor said, which would be needed to realize the vision of sustainable, high-efficiency cooling.

The rising threat of climate change has increased scrutiny on refrigerants, especially their contribution to global warming. Abas et al. [1] assessing and selecting natural refrigerants versus synthetic refrigerants based not only on operational performance but also environmental sustainability. Their analysis highlights the need for eco-friendly alternatives that do not trade performance for ecological impact. They contend that regulatory frameworks and technological innovation will be the two biggest drivers of a transition to a lower greenhouse gas emission refrigeration system. Further building on these results, Alawi et al. nanorefrigerants and nanolubricants in cooling revolution [2]. They show that nanoparticles increase thermal conductivity and energy efficiency in refrigeration systems, leading to unprecedented levels of performance with a lower environmental impact. This study agrees with Sanukrishna and Prakash [3] as they performed experimental validation on the improved thermal and rheological traits of TiO_2-PAG nanolubricants that can enhance the heat transfer process as well as reduce mechanical wear together with surface damage. Sharif et al. [4] As indicated by, all these benefits of nanorefrigerantsare further supported by innovative mechanics like the augmented heat exchange capability and energy savings. Meanwhile, Aberoumand et al. [5] shows silver-based nanofluids density, thermal conductivity, and specific heat properties provide outperformed thermophysical properties than classical fluids for heat transfer applications. Although we have made progress, there are still challenges. Some researchers, such as Alawi and Sidik [6], point out the long-term stability of CuO/R134a nanorefrigerants is limited, and more studies need to be conducted for the material compatibility. Azmi et al. There is a written work on the adding of TiO_2 and SiO_2 nanofluids to turbulent flow improved the heat exchange capacity, but its application on the real refrigeration systems still scarce. [7,8]. Gao et al. [9] investigated the alternative of high-GWP refrigerants in the cold chain in China and indicated an evident trend towards the natural and low-GWP replacements, due to environmental regulation and environment concern. Zhang et al. [10] experimentally determined and modelled the thermal conductivity of nanorefrigerants at low volume fractions and found that even small amounts of added nanoparticles substantially enhance the thermal behaviour, which results in an increase of heat transfer effectiveness. In addition, to these results, Kumar et al. [11] experimented using nanocomposites in VCR systems with optimized capillary tube lengths and nano-enhanced lubricants and found that they could enhance the COP and compressor power consumption. Overall, these studies allow the development of the eco-friendly and energy-saving VCR system designs based on refrigerant elimination and nanotechnology incorporation.

Similarly, parallel works on alternative refrigerants show compromises between performance [12] evaluated for R290/R600a blends and safety, mainly flammability confinements [13]. Pendyala et al. [14] and Colombo et al. [15] discuss efficiency improvements with novel refrigerant blends but highlight the need for economic and life cycle assessments. Recent advances demonstrate the potential of nanotechnology. Bi et al. [16] report a 3.6% enhancement in the efficiency of domestic refrigerators using TiO_2-R600a nano-refrigerants, whereas Adelekan et al. [17] which yield a 12% enhancement in COP using 15 nm TiO_2 nanoparticles. Vamshi et al. The first trimming algorithms were based on the work of, e.g., Chen et al. [18] and Sheikholeslami et al. Boiling heat transfer and system reliability are enhanced via the use of nanoparticles as reported in multiple studies [19]. Babarinde et al. [20] reviewed the application of nanorefrigerants for improving thermal and energy performance and focused on the dispersion of nanoparticles and system compatibility issues. Said et al. [21] presented a detailed review on the use and modes of action of nano-refrigerants and nano-lubricants, focusing on their influence on heat transfer enhancement and related operating issues. Yousif et al. [22] through an experiment proved the beneficial effect of TiO_2 and Al_2O_3 nanoparticles on the performance of VCR systems and supported that with their use can be realized the energy-saving refrigeration technology. Similarly, Al-Tajer et al. [23] studied the heat transfer of nanofluid in the elliptic tubing and circle tubing and found that the nanofluid has much higher thermal conductance compared to the traditional fluid. Katoch et al. [24]

conducted performance studies of nano-refrigerants using MATLAB-Simulink, the results are consistent with the conclusion that optimum nano-concentration gives higher values of COP. Barza et al. [25] conducted experimental studies on a nanorefrigerant system (R-134a + ZrO_2) and found an increase in the steady state performance, thereby confirming the practical implementation of nanofluids in conventional refrigeration systems. Also, Zhang and Zhou [26] underlined the importance of incorporating big data analytics into electric mobility solutions, indirectly favouring predictive maintenance and optimization in thermodynamic systems such as refrigeration. Taken all together, these studies provide precious insights for the continuous growth of energy-efficient, green, and high-performance refrigeration technology using nanotechnology and state-of-the-art computational tactics. Secop (2018) emphasized the practicality of using R600a and R290 refrigerants in small hermetic systems, underlining their environmental advantages and safe application when proper handling and design protocols are followed [27]. Demir et al. [28] (2018) provided an in-depth overview of titanium dioxide (TiO_2) nanoparticles, discussing their synthesis methods, structural characteristics, and applicability in thermal systems due to their high surface area and thermal stability. In the context of lubrication, Siddiqui et al. [29] (2013) examined the properties of mineral oil and highlighted its relevance in improving mechanical performance and reducing wear in thermal machinery. Leong et al. [30] (2006) introduced a thermal conductivity model for nanofluids, showing the significance of the interfacial layer formed between nanoparticles and base fluids in enhancing heat transfer. Mohamad (2024) extended this application by demonstrating the improved heat transfer in flat-plate solar collectors when TiO_2-based nanofluids were utilized, indicating clear efficiency gains over traditional fluids [31]. Similarly, Qader et al. [32] (2023) numerically analyzed heat transfer in circular pipes with porous media, revealing enhanced thermal distribution and energy effectiveness through optimized fluid flow paths. In another related work, Qader et al. (2023) further demonstrated the improved effectiveness of double-pipe heat exchangers by integrating porous media and TiO_2 nanofluids, validated through CFD simulations, confirming the superior heat transfer characteristics of nanoparticle-enhanced working fluids [33]. Shaik et al. [34] carried out a comprehensive study on the application of low-GWP refrigerants to enhance domestic refrigerator performance. Their investigation highlighted that refrigerants such as R1234yf and R152a not only reduce environmental impact but also maintain acceptable thermal and energy performance levels when compared to conventional HFC-134a. Pardo-Cely et al. [35] explored the influence of refrigerant charge variation on the energy efficiency and cooling behavior of domestic refrigerators. The study concluded that both overcharging and undercharging significantly affect the system's coefficient of performance and energy consumption, underscoring the critical role of optimal refrigerant charge for efficient operation.

Summary of Literature and Scope of Work

The existing literature establishes the benefits of using natural refrigerants and nanorefrigerants in VCR systems to enhance energy efficiency and reduce environmental impact. However, gaps remain in experimental validation, particularly regarding optimal nanoparticle concentrations, long-term stability, and real-world applicability. This study addresses these gaps by experimentally comparing the performance of pure R600a and TiO_2-R600a nanorefrigerant blends, focusing on improving thermal performance while resolving issues like nanoparticle agglomeration and compatibility. The work is novel in its practical approach and aims to bridge the gap between theoretical research and sustainable, high-efficiency refrigeration system implementation.

This study presents a novel experimental evaluation of TiO_2-R600a nanorefrigerant blends in Vapor Compression Refrigeration systems, distinguishing itself from previous research by focusing on the optimal nanoparticle concentration for enhanced cooling performance and energy efficiency. Unlike prior studies that are largely theoretical or simulation-based, this work offers practical insights by directly comparing pure and blended refrigerants, addressing key challenges such as nanoparticle dispersion, agglomeration, and long-term stability. By bridging the gap between laboratory findings and real-world application, the study contributes to the extension of sustainable, high-performance, and ecologically friendly refrigeration equipment.

MATERIALS AND METHODS

A variable capillary configuration has been expertly set up to effectively evaluate the performance of the two refrigerants simultaneously being analyzed in this vapor compression refrigeration (VCR) system. The experimental apparatus is a high quality hermetic air compressor combined with an accurately designed set of capillary tubes as shown in Figure1, which the thermal static load is simulated with. A computerized evaporator was included to impose variable static thermal loads for precise control of cooling. Measurement points were selected for the data attainment system to measure the performance of the refrigerant systems as a whole. All system valves were closed tightly to avoid any leakages when the experiment started.

An 8-foot capillary tube was first soldered in place and the entire refrigeration circuit was evacuated with a vacuum pump to get rid of all moisture and non-condensable gases as well. The system was then evacuated until the vacuum conditions with 60:40 mass ratio of R600a and R290 were obtained. The refrigerant charge was closely controlled to obtain accurate and repeatable charging between episodes. On charging the device was actuated by opening the capillary tube valve. The bimetallic strip on the evaporator was moved into place at its maximum to effect maximum heat exchange and an evaporators temperature set point was chosen. Timer1 was started at the same time. Temperature was supervised with a digital indicator and the time duration of each one-degree Celsius drop in temperature was registered. This process was repeated until the evaporator reached the target lower temperature. From the base mix, tests were performed, with and without inclusion of lubricant dispersions of TiO_2 nanoparticles, under different values of condensers temperatures. During both tests, key parameters were recorded: compressor inlet and outlet pressures, evaporator and condenser temperatures, sub-cooling and superheating.

In addition, to check the cooling performance of the system, 7 liters of water was in the evaporator chamber, and the time taken to achieve a desired temperature drop was recorded with an accuracy of one second. The lengths of the capillary tubes were varied (8 ft, 10 ft, 12 ft, and 14 ft) in a systematic manner to determine the optimum refrigerant distribution and the performance of the system. This well-designed procedure yielded strong, reproducible and all-around assessment of VCR system performance through refrigerant combination and capillary tube arrangement, offering a new insight into the nanomaterial influence on system efficiency with optimization consideration. The properties of refrigerants are enlisted in table 1.

The properties of R600a (isobutane) and R290 (propane) listed in the table make them highly suitable for use as a refrigerant blend due to their complementary characteristics. R600a has a higher boiling point (-11.7°C) compared to R290 (-42.1°C), which allows the blend to balance evaporation and condensation temperatures, enhancing system performance across different operating conditions. The higher latent heat of vaporization of R290 (426 kJ/kg) compared to R600a (367 kJ/kg) contributes to improved cooling capacity and heat absorption.

If we move to environmentally friendly options, both refrigerants have a zero Ozone Depletion Potential (ODP) and a very low Global Warming Potential (GWP) of around 3. R600a (135°C) critical temperature is also higher than R290 (96.7°C) thus, R600a shows higher stability in high temperature–high pressure surroundings compared with R290. The results from the literature indicate that the combined thermophysical properties of these refrigerants are beneficial for energy-efficient, low power consumption, and better performance, which makes the mixture an attractive solution for sustainable and high-performance refrigeration systems. The R600a/R290 (60:40) blend is selected because it combines high energy efficiency, environmental friendliness, improved heat transfer, reduced operational pressure, and better compatibility for small-capacity vapor compression systems. Using pure R290 could lead to very high system pressures, which might be risky. Mixing it with R600a lowers the overall system pressure compared to pure R290, making the system safer without sacrificing too much performance.

TiO_2 nanoparticles were prepared by chemical vapor deposition with high purity and uniform particles size. The nanoparticles were dispersed into compressor lubricating oil with continuous magnetic stirring for 72h to achieve a stable and uniform dispersion. This TiO_2 containing lubricant so obtained was mixed with a refrigerant mixture containing R600a and R290 and charged in the VCR system. During operation, the compressor with a hermetic enclosure circulated the refrigerant-lubricant blend, providing a dispersion of the nanoparticles in a refrigerant flow. Such integration led to better heat transfer on evaporator and condenser side, and thus the VCR system achieved overall better performance. The physical properties of TiO_2 nanoparticles and mineral oil used in the compressor are listed in table 2.

Synthetic refrigerant lubricating oils like glycols, chloroformates, and alkylbenzenes—have shown exceptional reliability in refrigeration applications. Since CFCs were back in the day utilized as refrigerants in systems (like R12 and R13), mineral oil or alkylbenzene were also used as lubricants in CFC refrigerants, and HCFCs (like R22). In recent years, the use of CFC and HCFC refrigerants has rightly declined due to their detrimental effect on the ozone layer. Consequently, HFC refrigerants, including R23, R32, R134a, and others, have surged in popularity within

Table 1. Properties of R600a and R290 [Ref-27]

Property	*R600a (Isobutane)*	*R290 (Propane)*
Chemical Formula	C_4H_{10}	C_3H_8
Molecular Weight	58.12 g/mol	44.10 g/mol
Boiling Point	-11.7°C	-42.1°C
Critical Temperature	135°C	96.7°C
Critical Pressure	3.64 MPa	4.25 MPa
Latent Heat of Vaporization	367 kJ/kg	426 kJ/kg
ODP (Ozone Depletion Potential)	0	0
GWP (Global Warming Potential)	~3	~3

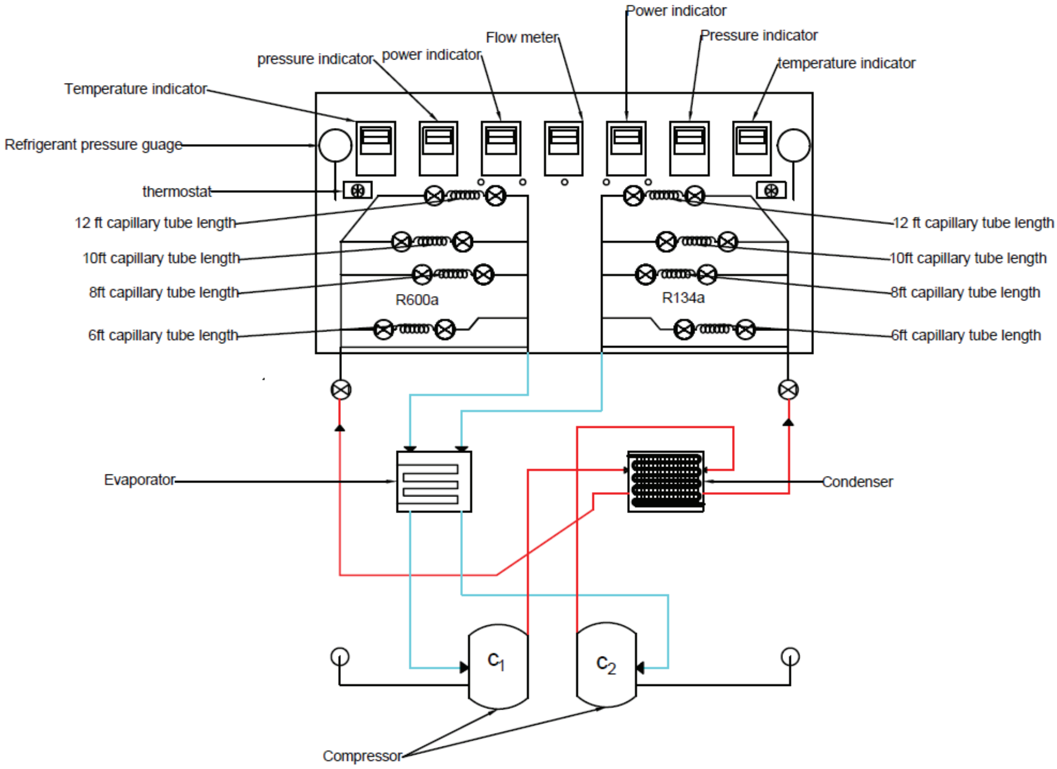

Figure 1. Computerized vapour Compression refrigeration system.

Table 2. Properties of TiO_2 nanoparticles and Mineral Oil [Ref-28 & 29]

Property	*TiO_2 Nanoparticles*	*Mineral Oil*
Appearance	White powder	Clear liquid
Density	3.9 g/cm^3	0.85–0.90 g/cm^3
Particle Size	20–100 nm	-
Molecular Weight	79.9 g/mol (TiO_2)	Varies with type (typically around 300-500 g/mol)
Viscosity	-	30–50 cSt (at 40°C)
Boiling Point	Sublimation point ~1800°C	300–350°C
Melting Point	1850°C	-
Thermal Conductivity	8.4 W/m K	0.12 W/m K
Specific Heat Capacity	~0.71 J/g·K	~2.0 J/g·K

Figure 2. Injection of Nanoparticles to mineral oil.

HVAC systems, utilizing polyol esters (POE) as lubricants. However, it is crucial to recognize that POE has a significant drawback because it absorbs moisture at a much higher rate than mineral-based oils. Therefore, strict adherence to proper handling procedures is essential to minimize moisture exposure. To effectively combat this issue, one should always opt for metal containers over plastic ones to prevent moisture ingress.

RESULTS AND DISCUSSION

The Tests were conducted on a vapor compression refrigeration system setup using R600a and R290 as the operational fluid, systematically evaluating varied lengths of capillary tubes set at 8, 10, 12, and 14 feet. These experiments were effectively repeated with R600a and R290 combined with 0.1% TiO_2 powder in 300 ml of lube oil. TiO_2 nanoparticles were selected for their exceptional thermal conductivity (ranging from 4 to 11.8 W/m K), proven safety, accessibility, and chemical stability, making them an ideal choice for nanofluids preparation. For the 8-foot capillary tube, critical parameters were meticulously recorded, including the inlet temperature of the compressor (T_1), exit temperature of the compressor (T_2), exit temperature of the condenser (T_3), exit temperature of the evaporator (T_4), thermal load temperature in the evaporator (T_5), delivery pressure (P_d), suction pressure (P_s), and work input to the compressor.

To evaluate the enhancement in thermal conductivity of 300 mL lubricating mineral oil when 0.1% TiO_2 nanoparticles (by volume) are added, use the Maxwell-Garnett effective medium theory. This model estimations the thermal conductivity of nanofluids established on nanoparticle concentration and properties. Process flow chart is shown in figure3.

"Maxwell-Garnett equation for thermal conductivity of nanofluids [30]"

$$k_{\text{eff}} = k_{\text{oil}} \left(\frac{k_{\text{TiO}_2} + 2k_{\text{oil}} + 2\phi(k_{\text{TiO}_2} - k_{\text{oil}})}{k_{\text{TiO}_2} + 2k_{\text{oil}} - \phi(k_{\text{TiO}_2} - k_{\text{oil}})} \right) \quad (1)$$

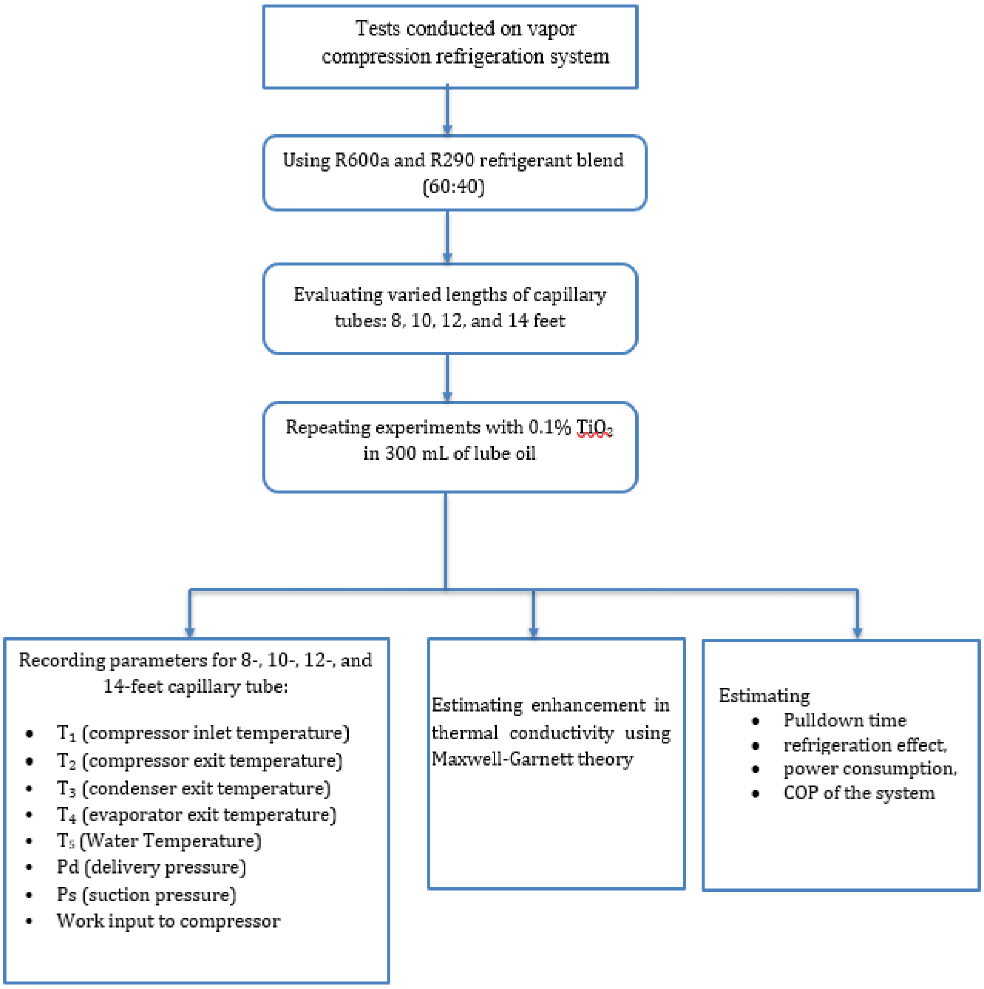

Figure 3. Process flow chart.

Where, k_{eff} is effective thermal conductivity W/m-K; k_{TiO_2} is thermal conductivity of Titanium dioxide W/m-K; k_{TiO_2} is thermal conductivity of mineral oil W/m-K, ϕ = volume fraction of nano particles.

Substitute the thermal conductivity values of TiO_2 and Mineral oil from table 2 in the equation 1

$$k_{eff} = 0.12\left(\frac{8.4 + 2(0.12) + 2(0.001)(8.4 - 0.12)}{8.4 + 2(0.12) - 0.001(8.4 - 0.12)}\right)$$

$$k_{eff} = 0.12(8.631728.65656) = 0.12 \times 1.00288 = 0.12035$$

The thermal conductivity of mineral oil is enhanced by 0.29% with 0.1% TiO_2 nanoparticles added to the mineral oil.

Additionally, pulldown time was precisely documented in seconds. This rigorous approach was consistently applied across all tested lengths of capillary tubes, including 10 feet, 12 feet, and 14 feet. The results for the refrigerant R600a and R290 without nanoparticles are clearly shown in Table 3, while Table 4 gives the detailed findings when nanoparticles were injected. These results underscore the significant impact of TiO_2 nanoparticles on system performance, highlighting their value in refrigeration technology advancements.

The size of the capillary tube, denoted L, is measured in feet and is integral to system performance, and, the temperatures are reported in °C for accuracy. Pressures are measured in kg/cm², work input to the compressor is measured in watts, and pulldown time is measured in

Table 3. Experimental Observations at variable length of capillary tubes for R600a and R290

L (ft)	T_1 (°C)	T_2 (°C)	T_3 (°C)	T_4 (°C)	T_5 (°C)	P_s (kg/cm²)	P_d (kg/cm²)	*Power (W)*	*Time (sec)*
8	20.7	46.5	44.2	10.9	5	4.27	8.59	253	1469
10	19	47.1	42.3	7.3	5	3.64	7.76	243	1266
12	19.1	50.2	44.6	6.5	5	3.47	5.1	253	1121
14	19.7	51.7	46	6.2	5	3.79	8.14	243	1187

Table 4. Experimental Observations at variable lengths of capillary tubes for R600a and R290 with TiO_2

L (ft)	T_1 (°C)	T_2 (°C)	T_3 (°C)	T_4 (°C)	T_5 (°C)	P_s (kg/cm²)	P_d (kg/cm²)	*Power (W)*	*Time (sec)*
8	23.0	42.1	40.6	16.8	05	4.46	8.12	234	1321
10	8.25	23.0	45.6	11.8	05	4.11	8.25	234	1170
12	23.6	49.9	47.5	11.6	05	3.93	8.38	243	1084
14	29.6	51.9	49.2	10.8	05	3.72	8.39	243	1110

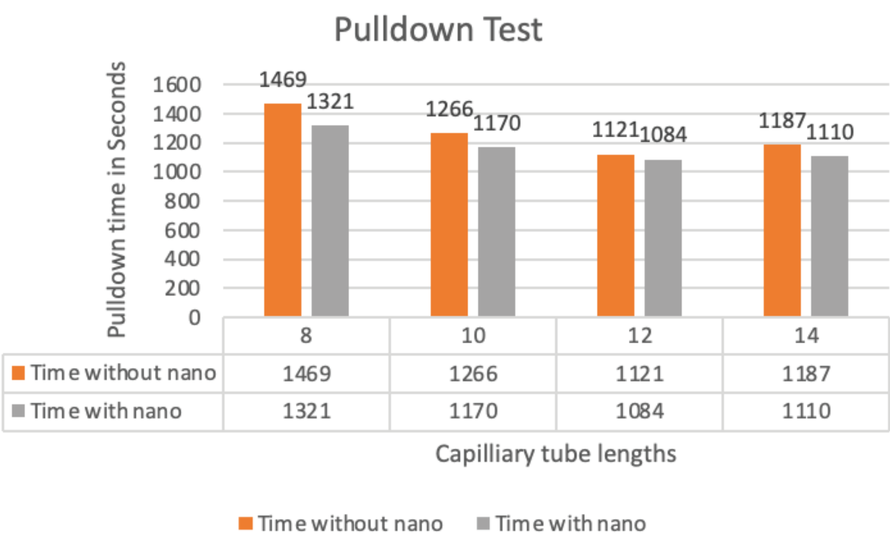

Figure 4. Pulldown time for the drop in temperature with and without nano particles.

seconds to determine efficiency. For this study, a evaporator, which has a thermal load of 7 litre of water at hydrogenated evaporator temperature (T_5) was used. The COP is calculated through several observations performed with R600a and R290 as the fluid used. The detailed methodology allows for a complete analysis of the effectiveness of the vapor compression refrigeration system under various conditions, demonstrating the possibility of further optimization and reduction of operating costs.

The pulldown test results, illustrated in Figure 4, compare cooling durations required to achieve a target temperature of 20^0C drop across varying capillary tube lengths, with and without nanoparticle-enhanced refrigerant. Shorter tubes exhibited the most pronounced efficiency gains when nanoparticles were introduced. For example, the 8-unit tube reduced pulldown time from 1469 seconds to 1321 seconds—a 10.1% improvement. While nanoparticle integration consistently lowered cooling times, its efficacy diminished as tube length increased. The 12-unit tube demonstrated only a 3.3% reduction, indicating that nanoparticle benefits are inversely proportional to capillary length. This trend underscores the technology's stronger impact in compact systems.

The effectiveness of vapor compression refrigeration systems is quantified using the Coefficient of Performance, calculated as the ratio of refrigeration effect (heat absorbed in the evaporator) to compressor work input. Mathematically, this is calculated by using equation (2):

Coefficient of Performance

$$(C.O.P) = \frac{Refrigeration\ effect}{Work\ done} = \frac{m\ Cp\ \Delta T/time}{Power\ Supplid\ to\ Compressor} \quad (2)$$

Where m = water to be cooled in kg.

C_p = Specific heat of water = 4.180 $\frac{kJ}{kg\ K}$

$\Delta T/time$ = drop in temperature with respective time

The cooling effect quantifies the refrigeration output generated in the evaporator, expressed in watts, while the power expenditure on the compressor can be directly monitored using a wattmeter, also measured in watts. By calculating the ratio of these two parameters, we can derive an accurate coefficient of performance for the refrigeration system. The investigational results obtained with R600a and R290 as refrigerants—both with and without the integration of nanoparticles—are compiled in Table 5. This table showcases findings for changing sizes of capillary tubes (8, 10, 12, and 14 feet). The data not only highlights the system's efficiency under different conditions but also emphasizes the potential enhancements in performance

Table 5. COP at various capillary tube lengths.

Length of Capillary tube	*COP of R600a & R290*	*COP of R600a & R290with TiO_2*
8	1.57	1.69
10	2.05	2.09
12	2.11	2.15
14	2.02	2.17

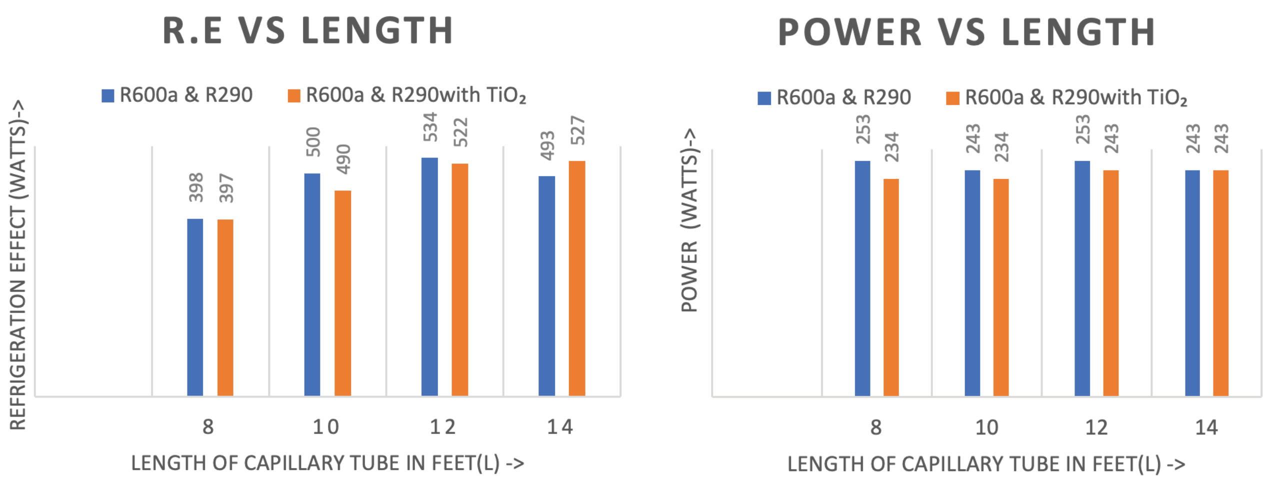

Figure 5. R.E and Power vs capillary length for (R600a & R290) and (R600a & R290 with TiO_2)

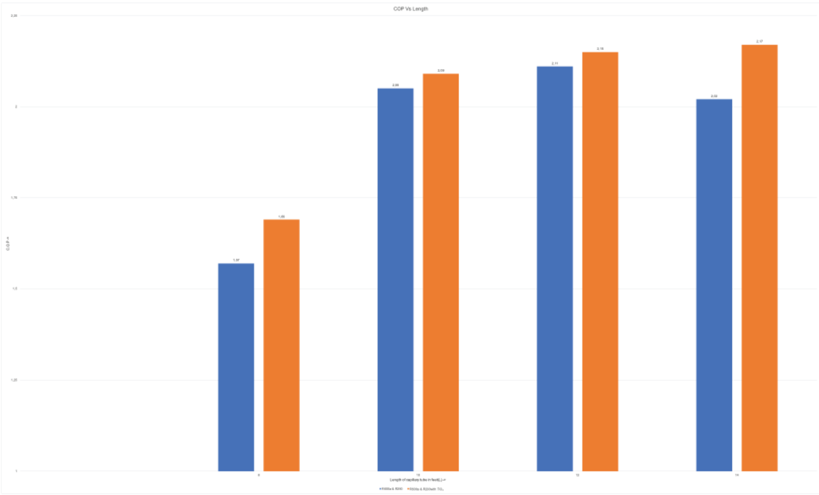

Figure 6. VCR system COP vs capillary length of (R600a & R290) and (R600a & R290 with TiO_2).

due to the incorporation of TiO_2 nanoparticles, contributing valuable insights for further advancements in refrigeration technology.

The data shows the impact of TiO_2 nanoparticles in the compressor lubricating oil on the performance of a vapour compression refrigeration system for various capillary tube lengths under a 20°C temperature drop. The addition of TiO_2 constantly enhances the system performance across all capillary tube lengths. For an 8 cm capillary, the performance improves from 1.57 to 1.69. Similarly, at 10 cm and 12 cm capillary lengths, the performance increases from 2.05 to 2.09 and from 2.11 to 2.15, respectively. The most significant improvement is observed at 14 cm, where performance rises from 2.02 to 2.17. This indicates that the incorporation of TiO_2 nanoparticles enhances heat transfer and improves the overall efficiency of the refrigerant blend system.

The power given to the compressor has an inverse relationship with the coefficient of performance (COP), which is directly proportional to the cooling effect. Using a nano refrigerant instead of the traditional R600a and R290 refrigerants results in an 8.7% enhancement in COP at 8- foot capillary.

As the Capillary length rises from 8 to 14 feet the percentage increase in COP value increases at for refrigerant added nano particles as compared to without nanoparticles. The increase in COP with the addition of TiO_2 nanoparticles is primarily due to improved thermal and flow properties of the refrigerant-lubricant mixture. Enhanced thermal conductivity facilitates more efficient heat transfer in the evaporator and condenser, boosting the refrigeration effect. Nanoparticles also modify the refrigerant's thermophysical properties, reducing viscosity and minimizing pressure drops, thereby improving flow characteristics. This enhancement leads to reduced compressor power consumption, particularly notable at the 10-foot capillary length. Additionally, the increased surface area provided by the nanoparticles further optimizes heat absorption and dissipation, contributing to overall system efficiency and performance. Figure 5 shows the refrigeration effect and energy consumption with respect to variable capillary tube lengths and Figure 6 shows the performance variations with respect to variable capillaries.

This study offers practical and timely insights for improving the energy efficiency of vapor compression refrigeration (VCR) systems, which are widely used in everyday applications like home refrigerators, air conditioners, and industrial cooling. By combining a low-impact refrigerant blend (R600a/R290) with TiO_2 nanoparticles, we've shown that it's possible to enhance system performance—achieving a higher COP and reducing power consumption. These findings not only support the development of more sustainable cooling technologies but also provide a useful reference for engineers, researchers, and industry professionals looking to optimize refrigeration systems in a more environmentally responsible way.

CONCLUSION

The investigational study revealed the remarkable impact of nanoparticles suspended in mineral oil on the working of a vapor compression refrigeration system, exploring capillary lengths of 8 feet, 10 feet, 12 feet, and 14 feet. The addition of nanoparticles significantly enhanced the thermal properties of the refrigerant, leading to a remarkable increase in heat transfer rates within the evaporator. Key findings illuminated the following insights:

- ➢ At a 10-foot capillary length, the refrigeration effect produced by the nano refrigerant soared, surpassing that of normal R600a and R290; yet this enhancement gracefully tapered as capillary length increased.

- Power consumption by the compressor saw an impressive decrease of 7.14% at the 10-foot capillary length with the incorporation of nanoparticles, while power demands rose with the 12-foot and 14-foot lengths.
- The system's overall performance achieved a noteworthy 7.1% increase with nanoparticles at the 10-foot length, demonstrating potential yet declining performance for the lengths beyond.
- These findings suggest that a capillary tube length of 10 feet stands as the ideal choice when harnessing nanoparticles in lubricating oil, leading to the enhancement of the coefficient of performance (COP) in refrigeration systems.

Summary The performance of a vapor compression refrigeration system using nanoparticulate mixtures suspended in mineral oil was analyzed to evaluate the impact of varying capillary tube lengths. Specifically, the study examined two-phase refrigerant flow transitions in capillary tubes measuring 8, 10, 12, and 14 feet in length. The results demonstrate how different tube lengths significantly affect the system's overall performance. Using nanoparticles not only improved the thermal characteristics of the refrigerant, thus attaining increased rates of heat transport. Under the most favorable conditions of 10 ft capillary length, the system was able to achieve a coefficient performance of about 7.1% higher and reduce compressor power consumption by 7.14% compared to standard refrigerants R600a and R290. Performance improvement diminished as the length of a capillary rise above 10 feet, confirming that a capillary should be no longer than 10 feet to maximize efficiency with nanoparticle-lubricated refrigerants.

Future scope of work: There is room for future improvements which can be a potential work. Future research can explore the performance of Vapor Compression Refrigeration (VCR) systems using different mass ratios of refrigerants, both with and without the addition of nanoparticles, to determine the optimal blend for maximizing efficiency, stability, and cooling capacity under varying operating conditions. Evaluation of other nanoparticles and working on different percentages will help to find better combinations for enhanced thermal properties. Long-term stability studies for dispersion and potential wear on compressor components are necessary to evaluate reliability. Moreover, the applicability of this technology will be extended to the performance assessment of advanced refrigerant blends, different capillary tube materials and diameters, as well as the energy efficiency analysis over varying load conditions. These directions will continue to build advances for more energy-efficient sustainable refrigeration and air-conditioning systems.

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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