

ANALYSIS OF VAPOUR COMPRESSION REFRIGERATION SYSTEM USING R134a AND CuO NANOPARTICLES:

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Abstract : Vapour Compression Refrigeration Systems (VCRS) are widely used for domestic, commercial, and industrial cooling applications. The increasing demand for energy-efficient refrigeration has encouraged the development of advanced cooling technologies. R134a is commonly used because of its good thermodynamic properties and zero ozone depletion potential; however, its relatively high global warming potential and energy consumption remain important concerns. The present project investigates the performance of a vapour compression refrigeration system using R134a with CuO nanoparticles. CuO nanoparticles have high thermal conductivity and can enhance the heat-transfer characteristics of the refrigerant, thereby improving heat transfer in the evaporator and condenser. The addition of CuO nanoparticles can increase cooling capacity and refrigeration effect while reducing compressor power consumption.

The performance of the system is evaluated using parameters such as coefficient of performance (COP), cooling capacity, compressor work, and energy consumption. A comparative analysis of conventional R134a and CuO–R134a nanorefrigerant is considered to determine the effect of nanoparticles on system performance. The influence of nanoparticle concentration and operating conditions is also examined. Suitable CuO concentration is essential to achieve improved performance without causing agglomeration, sedimentation, or excessive viscosity. The use of CuO nanoparticles has shown promising potential for improving the COP and thermal performance of VCR systems. The study aims to identify suitable operating conditions for achieving higher efficiency and improved cooling performance. Overall, CuO-enhanced R134a can be a promising approach for improving the energy efficiency of conventional refrigeration systems, although further experimental investigation is required to determine the optimum nanoparticle concentration, long-term stability, and practical applicability of the nanorefrigerant.

Keywords : Vapour Compression Refrigeration System (VCRS), R134a, CuO Nanoparticles, Nanorefrigerant, Cooling Capacity, Refrigeration Effect, Compressor Work, Coefficient of Performance (COP), Heat Transfer, Energy Efficiency.

IndexTerms - Component,formatting,style,styling,insert.

INTRODUCTION

Vapour Compression Refrigeration Systems (VCRS) are widely used in domestic, commercial, and industrial applications such as refrigerators, air conditioners, cold storage, and industrial cooling. A conventional VCR system consists of four main components: compressor, condenser, expansion device, and evaporator. During operation, the refrigerant undergoes compression, condensation, expansion, and evaporation to remove heat from a low-temperature region and reject it to the surroundings. The performance of the system is commonly evaluated using parameters such as cooling capacity, refrigeration effect, compressor power, operating pressure, temperature, and coefficient of performance (COP).

R134a has been widely used as a refrigerant because of its favourable thermodynamic properties, chemical stability, and compatibility with refrigeration components. Although R134a has zero ozone depletion potential (ODP), it has a relatively high global warming potential (GWP), which creates environmental concerns. Therefore, improving the energy efficiency and thermal performance of R134a-based refrigeration systems has become an important area of research. Reducing compressor power consumption and increasing cooling capacity can improve the overall efficiency of the refrigeration system.

Nanotechnology provides a promising approach for improving the thermal performance of refrigeration systems through the use of nanorefrigerants and nanolubricants. Nanoparticles have a very small size and a large surface-area-to-volume ratio, which can enhance the thermal conductivity and heat-transfer characteristics of the working fluid. Among various nanoparticles, Copper Oxide (CuO) has attracted considerable attention because of its favourable thermal properties, availability, and good heat-transfer capability.

The addition of CuO nanoparticles to R134a can enhance heat transfer in the evaporator and condenser, which may increase the refrigeration effect and cooling capacity. CuO nanoparticles may also improve the lubrication characteristics of the compressor, reducing friction and potentially decreasing compressor power consumption. These improvements can contribute to an increase in the coefficient of performance (COP) and overall energy efficiency of the refrigeration system.

However, the performance of CuO-based nanorefrigerants depends on several factors, including nanoparticle concentration, particle size, dispersion stability, refrigerant charge, operating pressure, and evaporator and condenser temperatures. Excessive nanoparticle concentration may result in agglomeration, sedimentation, increased viscosity, pressure drop, and higher compressor power consumption. Therefore, selecting an appropriate concentration of CuO nanoparticles is essential to achieve improved heat transfer and system performance without causing operational problems.

The present project focuses on the analysis of a Vapour Compression Refrigeration System using R134a and CuO nanoparticles. The performance of the CuO-enhanced R134a system is compared with that of the conventional R134a system under suitable operating conditions. Important parameters such as cooling capacity, refrigeration effect, compressor work, power consumption, operating pressure, temperature, and coefficient of performance (COP) are considered for evaluating system performance.

The main objective of this study is to determine the effect of CuO nanoparticles on the thermal performance and energy efficiency of an R134a-based VCR system. The study aims to identify suitable operating conditions and nanoparticle concentration for achieving higher cooling capacity, improved COP, and reduced energy consumption. The investigation can contribute to the development of more efficient and environmentally improved refrigeration systems using nanotechnology.

2. THERMODYNAMIC CYCLE & SYSTEM SETUP

2.1 Vapour Compression Refrigeration Cycle

The vapour compression refrigeration system (VCRS) is one of the most widely used refrigeration systems for domestic, commercial and industrial cooling applications. The system operates by transferring heat from a low-temperature region to a high-temperature surrounding with the help of mechanical work supplied to the compressor. In the present study, R134a is considered as the base refrigerant and CuO nanoparticles are incorporated to investigate their influence on the thermal and performance characteristics of the refrigeration system.

A conventional vapour compression refrigeration cycle consists of four main components: compressor, condenser, expansion device and evaporator. The refrigerant continuously circulates through these components and undergoes a series of thermodynamic processes. The four basic processes of the ideal cycle are compression, condensation, expansion and evaporation.

The sequence of the refrigeration cycle is:

Compressor → Condenser → Expansion Device → Evaporator → Compressor

The four thermodynamic processes are described below.

2.1.1 Process 1–2: Isentropic Compression

At state 1, the refrigerant leaves the evaporator as low-pressure vapour and enters the compressor. The compressor increases the pressure and temperature of the refrigerant by supplying mechanical work. In an ideal refrigeration cycle, the compression process is considered isentropic.

The specific compressor work is given by:

$$W_c = h_2 - h_1$$

where,

W_c = specific compressor work, kJ/kg

h_1 = enthalpy of refrigerant at compressor inlet, kJ/kg

h_2 = enthalpy of refrigerant at compressor outlet, kJ/kg

In an actual refrigeration system, the compression process is not perfectly isentropic because of mechanical losses, heat transfer and internal irreversibilities.

2.1.2 Process 2–3: Constant Pressure Condensation

The high-pressure and high-temperature refrigerant vapour leaving the compressor enters the condenser. The refrigerant rejects heat to the surrounding environment through the condenser walls and changes from vapour to liquid.

Ideally, this heat rejection occurs approximately at constant pressure.

The heat rejected in the condenser is given by:

$$Q_H = \dot{m} (h_2 - h_3)$$

where,

Q_H = heat rejected by the condenser, kW

$\dot{m}$ = refrigerant mass flow rate, kg/s

h_3 = enthalpy of refrigerant at condenser outlet, kJ/kg

The effectiveness of the condenser directly affects the condensing pressure and temperature and consequently influences the overall performance of the refrigeration system.

2.1.3 Process 3–4: Isenthalpic Expansion

The high-pressure liquid refrigerant leaving the condenser passes through the expansion device. The expansion device may be a capillary tube, thermostatic expansion valve or another suitable throttling device.

During this process, the pressure of the refrigerant decreases rapidly. The expansion process is assumed to be isenthalpic, meaning that the enthalpy remains approximately constant.

Therefore:

$$h_3 = h_4$$

where,

h_4 = enthalpy of refrigerant at the outlet of the expansion device, kJ/kg.

After expansion, the refrigerant enters the evaporator as a low-pressure liquid-vapour mixture.

2.1.4 Process 4–1: Constant Pressure Evaporation

The low-pressure refrigerant mixture enters the evaporator and absorbs heat from the refrigerated space. During this process, the refrigerant changes from a liquid-vapour mixture into vapour.

The refrigeration effect is given by:

$$Q_L = \dot{m} (h_1 - h_4)$$

where,

Q_L = refrigeration capacity, kW

$\dot{m}$ = refrigerant mass flow rate, kg/s

h_1 = enthalpy at evaporator outlet, kJ/kg

h_4 = enthalpy at evaporator inlet, kJ/kg

The evaporator is therefore responsible for extracting heat from the space or medium that needs to be cooled.

2.2 Coefficient of Performance

The coefficient of performance (COP) is the most important performance parameter of a refrigeration system. It represents the ratio of useful refrigeration effect obtained to the work supplied to the compressor.

The COP of the vapour compression refrigeration system is expressed as:

$$COP = Q_L / W_c$$

For an ideal vapour compression refrigeration cycle:

$$COP = (h_1 - h_4) / (h_2 - h_1)$$

A higher COP indicates better refrigeration performance because a greater amount of cooling is produced for a given amount of compressor work.

In the present study, the COP of the conventional R134a system is compared with the COP obtained after incorporating CuO nanoparticles under comparable operating conditions.

2.3 System Setup

The experimental vapour compression refrigeration system consists of four major components: compressor, condenser, expansion device and evaporator. These components are connected in a closed refrigerant circuit.

The basic arrangement of the system is:

$$\text{Compressor} \rightarrow \text{Condenser} \rightarrow \text{Expansion Device} \rightarrow \text{Evaporator} \rightarrow \text{Compressor}$$

R134a is used as the base refrigerant. CuO nanoparticles are incorporated according to the selected experimental methodology in order to investigate their influence on heat transfer and refrigeration performance.

The major components of the system are described below.

2.3.1 Compressor

The compressor is the main power-consuming component of the refrigeration system. It draws low-pressure refrigerant vapour from the evaporator and compresses it to a high-pressure and high-temperature state before delivering it to the condenser.

The compressor work has a direct effect on the COP of the system. Therefore, any increase in compressor power caused by excessive pressure drop or viscosity should be considered while evaluating the benefit of CuO nanoparticles.

2.3.2 Condenser

The condenser receives high-pressure and high-temperature refrigerant vapour from the compressor. Heat is rejected from the refrigerant to the surrounding atmosphere through the condenser.

During condensation, the refrigerant changes from high-temperature vapour to high-pressure liquid. Improved heat transfer in the condenser can help reduce the condensing temperature and improve system performance under suitable operating conditions.

2.3.3 Expansion Device

The expansion device reduces the pressure of the liquid refrigerant before it enters the evaporator. The sudden reduction in pressure results in partial vaporisation of the refrigerant.

The expansion process is considered approximately isenthalpic, and therefore:

$$h_3 = h_4$$

The expansion device also controls the refrigerant flow entering the evaporator.

2.3.4 Evaporator

The evaporator is the component where useful refrigeration is produced. The low-pressure refrigerant absorbs heat from the refrigerated space or cooling medium and evaporates.

The amount of heat absorbed by the refrigerant determines the refrigeration capacity of the system.

2.3.5 R134a Refrigerant

R134a is a hydrofluorocarbon refrigerant that has been widely used in refrigeration and air-conditioning applications. In the present analysis, R134a is considered as the base refrigerant for evaluating the influence of CuO nanoparticles on refrigeration-system performance.

The thermodynamic properties of R134a, including pressure, temperature and enthalpy, are required for determining the performance parameters of the refrigeration cycle.

2.3.6 CuO Nanoparticles

Copper oxide (CuO) nanoparticles are incorporated into the refrigeration system to enhance the thermal characteristics of the working fluid. CuO has comparatively high thermal conductivity and can influence the heat-transfer behaviour of the refrigerant/lubricant mixture.

The addition of CuO nanoparticles may improve heat transfer through mechanisms such as increased effective thermal conductivity, modification of the thermal boundary layer and enhanced microscale energy transport.

However, the concentration of CuO nanoparticles must be controlled. Excessive nanoparticle concentration may increase viscosity, pressure drop and the possibility of particle agglomeration. Therefore, the optimum concentration is an important factor in determining the overall performance of the refrigeration system.

2.4 Thermodynamic States of the System

The four important thermodynamic states of the vapour compression refrigeration cycle are summarized below.

State 1: Refrigerant at the outlet of the evaporator and inlet of the compressor. The refrigerant is generally in the vapour state.

State 2: Refrigerant at the outlet of the compressor and inlet of the condenser. The refrigerant is at high pressure and high temperature.

State 3: Refrigerant at the outlet of the condenser and inlet of the expansion device. The refrigerant is generally in the liquid state.

State 4: Refrigerant at the outlet of the expansion device and inlet of the evaporator. The refrigerant is generally a low-pressure liquid-vapour mixture.

The enthalpy values at these four states are used to determine the refrigeration effect, compressor work, condenser heat rejection and coefficient of performance.

2.5 Energy Balance of the Refrigeration Cycle

For a complete refrigeration cycle, the energy balance can be expressed as:

$$Q_H = Q_L + W_c$$

where,

Q_H = heat rejected by the condenser

Q_L = heat absorbed in the evaporator

W_c = work supplied to the compressor

This relationship represents the basic energy conservation principle for the refrigeration cycle.

The energy balance can also be used as a check on the accuracy of experimental calculations.

2.6 Effect of CuO Nanoparticles on the System

The addition of CuO nanoparticles is expected to influence the thermal and flow characteristics of the refrigeration system. The primary objective is to improve heat transfer in the evaporator and condenser.

The possible effects of CuO nanoparticles include:

Increase in effective thermal conductivity.

Improvement in heat-transfer characteristics.

Possible increase in refrigeration capacity.

Possible improvement in coefficient of performance.

Modification of refrigerant/lubricant viscosity.

Possible increase in pressure drop at higher concentrations.

Possibility of nanoparticle agglomeration at unsuitable concentrations.

Therefore, the performance of the system depends not only on the presence of CuO nanoparticles but also on their concentration, particle size, dispersion stability, operating conditions and compatibility with the refrigeration system.

The main objective of the experimental analysis is therefore to determine whether the addition of CuO nanoparticles provides a measurable improvement in refrigeration performance compared with the conventional R134a system.

3. Experimental setup

The experimental setup of the vapour compression refrigeration system is shown in Fig. 4. The main components of the refrigeration system are a 1/3 HP hermetic reciprocating compressor, condenser, evaporator, thermal expansion valve (TEV), and a Coriolis mass flow meter. Measurement locations for pressure, temperature, refrigerant mass flow rate, and compressor power are shown in Fig. 4.

Ten T-type thermocouples were installed at different locations of the system. Six pressure transducers were installed at the inlets and outlets of the evaporator, condenser, and compressor. An R134a TEV was used instead of a capillary tube. The TEV eliminates the requirement of a fixed capillary tube length and controls the refrigerant entering the evaporator based on the sensed exit temperature and pressure.

A sight glass was installed at the condenser exit to observe the refrigerant condition before entering the TEV. A pressure switch was also installed to provide high-pressure protection. Counter-flow heat exchangers were used for the evaporator and condenser. The coiled evaporator and condenser were immersed in an ethylene glycol bath and water bath, respectively.

The ethylene glycol bath and water bath were circulated at a constant flow rate of 8.73 L/min using a feed pump. The ethylene glycol bath temperatures were maintained at 13, 5, 0, -8, and -13 °C, corresponding to evaporation temperatures of 0, -5, -10, -15, and -20 °C, respectively. The condensation temperature was maintained at a constant 32 °C.

The refrigerant copper pipes, condenser water bath container, and evaporator ethylene glycol bath container were insulated. R134a was used as the refrigerant with POE base oil and POE/CuO nanolubricant.

The refrigerant charge was initially varied from 170 to 250 g in four equal increments to determine the optimum refrigerant charge. Between each charge, the system was evacuated for 15 min using a vacuum pump. It was observed that a higher refrigerant charge increased the compressor discharge pressure. Based on the discharge pressure, refrigeration effect, compressor work, and coefficient of performance (COP), the optimum refrigerant charge was determined to be 190 g. Therefore, 190 g of R134a was used for all experiments.

A base study was first conducted using pure POE oil and then compared with the POE/CuO nanolubricant. Since the evaporation process starts at the evaporator inlet, the inlet temperature of the evaporator was considered as the evaporation temperature. Each experimental run was repeated three times, and the average values were used for the analysis. The repeatability of the experimental data was within $\pm 3\%$.

The inlet evaporation temperatures were maintained with an allowable deviation of ± 1 °C, while the superheat degree was fixed at 6 °C. The measurements were recorded after the system reached steady-state conditions following 30 min of operation.

The measured variables were recorded using LabVIEW 2019 version 19.0 at a sampling rate of 3.33 mHz. REFPROP 9.5 was used to obtain the thermodynamic properties of R134a.

The experiments were conducted in Pretoria, South Africa, with an average ambient temperature of 20 °C and 55% relative humidity. The laboratory ambient conditions were maintained using an air-conditioning system. The experimental procedure followed in this study is presented in Fig. 5.

The heat absorbed or rejected by the refrigerant in the evaporator and condenser is calculated using:

$$Q_{ref} = (\dot{m} \Delta h)_{ref}$$

The heat transfer to or from the ethylene glycol and water baths is calculated using:

$$Q_{eg} = (\dot{m} C_p \Delta T)_{eg}$$

$$Q_w = (\dot{m} C_p \Delta T)_w$$

where $\dot{m}$ is the mass flow rate of the working fluid, Δh is the change in enthalpy of the refrigerant across the evaporator or condenser, C_p is the specific heat capacity, and ΔT is the temperature difference between the inlet and outlet of the ethylene glycol and water baths.

The refrigeration effect and compressor work were calculated using:

$$Q_{evap} = h_o - h_i$$

$$W_{comp} = h_o - h_i$$

where h_i and h_o represent the inlet and outlet enthalpy, respectively. The condenser outlet enthalpy was considered as the inlet enthalpy of the evaporator.

The coefficient of performance (COP) of the refrigeration system was calculated using:

$$COP = Q_{evap} / W_{comp}$$

4. MATHEMATICAL FORMULATION & CALCULATION FRAMEWORK

3.1 Thermodynamic Analysis

The performance of the vapour compression refrigeration system using R134a and CuO nanoparticles is evaluated using the thermodynamic properties of the refrigerant at different points of the refrigeration cycle. The important parameters considered for the analysis are refrigeration capacity, compressor work, heat rejection, coefficient of performance and percentage improvement in performance.

The four principal thermodynamic states considered in the analysis are:

State 1: Compressor inlet / evaporator outlet

State 2: Compressor outlet / condenser inlet

State 3: Condenser outlet / expansion device inlet

State 4: Expansion device outlet / evaporator inlet

The enthalpy values corresponding to these states are used for calculating the performance of the refrigeration system.

4.2 Refrigeration Effect

The refrigeration effect represents the amount of heat absorbed by the refrigerant in the evaporator.

The specific refrigeration effect is calculated as:

$$q_L = h_1 - h_4$$

where,

q_L = specific refrigeration effect, kJ/kg

h_1 = enthalpy of refrigerant at evaporator outlet, kJ/kg

h_4 = enthalpy of refrigerant at evaporator inlet, kJ/kg

The total refrigeration capacity is calculated using:

$$Q_L = \dot{m} (h_1 - h_4)$$

where,

Q_L = refrigeration capacity, kW

$\dot{m}$ = refrigerant mass flow rate, kg/s

A higher refrigeration capacity indicates that the system is capable of absorbing a greater amount of heat from the refrigerated space per unit time.

4.3 Compressor Work

The compressor supplies the mechanical work required to circulate and compress the refrigerant.

The specific compressor work is given by:

$$w_c = h_2 - h_1$$

where,

w_c = specific compressor work, kJ/kg

h_2 = enthalpy of refrigerant at compressor outlet, kJ/kg

h_1 = enthalpy of refrigerant at compressor inlet, kJ/kg

The theoretical compressor power can be calculated using:

$$W_c = \dot{m} (h_2 - h_1)$$

In an experimental system, the actual electrical power consumed by the compressor can also be measured using a wattmeter or power meter.

The measured compressor power is particularly important because the actual system contains mechanical, electrical and thermodynamic losses.

4.4 Heat Rejection in Condenser

The heat rejected by the refrigerant in the condenser is calculated from the enthalpy difference between the compressor outlet and condenser outlet.

The heat rejection rate is:

$$Q_H = \dot{m} (h_2 - h_3)$$

where,

Q_H = condenser heat rejection rate, kW

h_2 = enthalpy at condenser inlet, kJ/kg

h_3 = enthalpy at condenser outlet, kJ/kg

The condenser must reject both the heat absorbed in the evaporator and the work supplied to the compressor.

Therefore, the overall energy balance of the refrigeration cycle is:

$$Q_H = Q_L + W_c$$

This equation provides an important check for the thermodynamic consistency of the calculated results.

4.5 Expansion Process

The expansion process occurs through the expansion device. The refrigerant undergoes a pressure reduction before entering the evaporator.

For an ideal throttling process, the enthalpy remains constant:

$$h_3 = h_4$$

Therefore, the enthalpy at the outlet of the expansion device is approximately equal to the enthalpy at its inlet.

During expansion, a portion of the liquid refrigerant flashes into vapour due to the pressure reduction. The resulting low-pressure mixture then enters the evaporator.

4.6 Coefficient of Performance

The coefficient of performance (COP) is the primary performance parameter used to evaluate the efficiency of a refrigeration system.

COP is defined as the ratio of refrigeration effect to compressor work.

$$\text{COP} = Q_L / W_c$$

For the ideal vapour compression refrigeration cycle:

$$\text{COP} = (h_1 - h_4) / (h_2 - h_1)$$

A higher COP indicates better system performance because more useful cooling is obtained for a given amount of compressor work. The COP of the conventional R134a system is compared with the COP of the CuO-assisted system under similar operating conditions.

4.7 Percentage Improvement in COP

The percentage improvement in COP after incorporating CuO nanoparticles is calculated using:

$$\text{Percentage improvement in COP} = [(COP_{CuO} - COP_{R134a}) / COP_{R134a}] \times 100$$

where,

COP_{CuO} = coefficient of performance of the system using CuO nanoparticles

COP_{R134a} = coefficient of performance of the conventional R134a system

A positive value indicates an improvement in COP after incorporating CuO nanoparticles.

3.8 Percentage Change in Refrigeration Capacity

The percentage change in refrigeration capacity can be calculated as:

$$\text{Percentage change in } Q_L = [(Q_{L,CuO} - Q_{L,R134a}) / Q_{L,R134a}] \times 100$$

where,

$Q_{L,CuO}$ = refrigeration capacity with CuO nanoparticles

$Q_{L,R134a}$ = refrigeration capacity of the conventional R134a system

This parameter is used to determine whether the addition of CuO nanoparticles increases the cooling capacity of the refrigeration system.

4.8 Percentage Change in Compressor Power

The change in compressor power is an important parameter because an increase in cooling capacity is beneficial only if it does not result in an excessive increase in power consumption.

The percentage change in compressor power is calculated as:

$$\text{Percentage change in compressor power} = [(W_{CuO} - W_{R134a}) / W_{R134a}] \times 100$$

where,

W_{CuO} = compressor power with CuO nanoparticles

WR134a = compressor power of the conventional R134a system

A reduction in compressor power together with an increase in refrigeration capacity would result in a significant improvement in system COP.

4.9 Effectiveness of CuO Nanoparticles

The performance improvement obtained from CuO nanoparticles depends on their concentration and dispersion within the working fluid. At an appropriate concentration, CuO nanoparticles can improve thermal transport by increasing the effective thermal conductivity of the working medium and modifying the heat-transfer behaviour.

The major mechanisms responsible for the possible improvement include:

1. Enhanced Thermal Conductivity

CuO nanoparticles possess higher thermal conductivity than the base fluid. Their addition can increase the effective thermal conductivity of the refrigerant/lubricant mixture and improve heat transport.

2. Improved Heat Transfer

The presence of nanoparticles can modify the thermal boundary layer near the heat-transfer surface. This can improve heat transfer in both the evaporator and condenser.

3. Microscale Mixing

Brownian motion of nanoparticles can contribute to microscale movement within the fluid. This may enhance energy transport under suitable operating conditions.

4. Modification of Thermal Boundary Layer

Nanoparticles can disturb the thermal boundary layer and potentially reduce thermal resistance between the working fluid and heat-transfer surface.

5. Effect of Nanoparticle Concentration

The concentration of CuO nanoparticles has a significant effect on system performance. A suitable concentration may improve heat transfer, whereas an excessive concentration can increase viscosity and pressure drop.

3.11 Effect of Nanoparticle Concentration on Performance

The effect of CuO concentration cannot be considered purely linear. At low concentrations, the addition of nanoparticles may provide beneficial thermal effects without causing significant flow resistance.

As the concentration increases, the effective thermal conductivity may continue to increase; however, viscosity and particle interactions may also increase.

Therefore, an optimum concentration may exist at which the combined effect of heat-transfer enhancement and flow resistance produces the highest COP.

The relationship can be summarized as:

Low CuO concentration → Limited heat-transfer enhancement

Optimum CuO concentration → Maximum overall performance

High CuO concentration → Increased viscosity/agglomeration/pressure drop and possible reduction in performance

4.10 Pressure Ratio

The pressure ratio of the compressor is an important operating parameter and is defined as:

Pressure ratio = Discharge pressure / Suction pressure

A higher pressure ratio generally results in greater compressor work and can reduce the COP of the refrigeration system.

Therefore, the effect of CuO nanoparticles should also be analysed with respect to suction pressure, discharge pressure and pressure ratio.

4.11 Uncertainty and Experimental Accuracy

Experimental measurements are affected by uncertainties in temperature, pressure, mass-flow rate and electrical power measurements. Therefore, the accuracy of the measuring instruments should be considered when evaluating the experimental results.

The major sources of experimental uncertainty include:

1. Temperature measurement error

Errors may occur because of sensor accuracy, sensor placement and thermal contact.

2. Pressure measurement error

Pressure gauges or pressure transducers may introduce measurement uncertainty.

3. Power measurement error

Variations in supply voltage and measurement accuracy can affect the calculated compressor power.

4. Mass-flow measurement error

Any uncertainty in refrigerant mass-flow rate directly affects the calculated refrigeration capacity.

5. Nanoparticle concentration error

Incorrect measurement or dispersion of CuO nanoparticles can affect the repeatability of experimental results.

Therefore, repeated measurements should preferably be taken under the same operating conditions to improve the reliability of the final results.

4.12 Performance Comparison

The performance of the conventional R134a system and the CuO-assisted R134a system should be compared using the following parameters:

1. Refrigeration capacity
2. Compressor power consumption
3. COP
4. Evaporator temperature
5. Condenser temperature
6. Suction pressure
7. Discharge pressure
8. Pressure ratio
9. CuO nanoparticle concentration

The final comparison should be based on experimental measurements or reliable published data. Numerical performance improvements should not be assumed without supporting experimental or literature evidence.

4.13 Summary of Mathematical Analysis

The mathematical analysis provides a systematic method for evaluating the effect of CuO nanoparticles on the performance of the R134a vapour compression refrigeration system.

The most important performance relationship is:

$$\text{COP} = \text{Refrigeration Capacity} / \text{Compressor Power}$$

Therefore, the addition of CuO nanoparticles can be considered beneficial when it produces an increase in refrigeration capacity and/or a reduction in compressor power, resulting in an overall increase in COP.

The calculated thermodynamic parameters are subsequently used for graphical representation and comparative analysis of the conventional R134a system and the CuO-assisted refrigeration system.

5. LITERATURE RESULTS & COMPARATIVE ANALYSIS

Several experimental, numerical and theoretical investigations have been carried out to evaluate the effect of CuO nanoparticles on the performance of R134a-based vapour compression refrigeration systems. The reported studies mainly investigate cooling capacity, heat-transfer characteristics, compressor power consumption and coefficient of performance (COP).

The literature indicates that CuO nanoparticles can improve the thermal transport characteristics of the refrigerant or refrigerant-lubricant mixture under suitable conditions. However, the magnitude of improvement depends strongly on nanoparticle concentration, particle size, dispersion method, lubricant type, refrigerant charge and operating conditions.

Therefore, the performance improvement obtained from CuO nanoparticles should not be considered as a fixed value for every refrigeration system.

5.2 Experimental Results Reported for R134a–CuO Systems

One important experimental investigation by Ande, Koppala and Hadi studied a vapour compression refrigeration system using pure R134a and R134a containing CuO nanoparticles. The study used a CuO concentration of 1.6% and compared the performance of the nanorefrigerant with conventional R134a. The reported actual COP increased from 3.0 for R134a to 3.5 for CuO–R134a, while compressor power consumption decreased from approximately 1.16 kW to 1.00 kW. The authors reported an increase of approximately 16.66% in COP and a reduction of approximately 13.79% in power consumption.

Another experimental study comparing R134a, CuO-based nanorefrigerant and SiO₂-based nanorefrigerant reported that the maximum COP for the investigated CuO system occurred at a CuO concentration of 0.5 g. The study also reported improved cooling speed and reduced power consumption over the tested concentration range. Research on CuO nanoparticles dispersed in POE lubricant has also reported improvements in refrigeration-system performance. Such studies consider CuO as a nanolubricant, where the nanoparticles can influence both heat transfer and compressor lubrication characteristics.

5.3 Consolidated Literature Comparison

Study Investigation /	Working System	CuO Condition	Main Observation
Ande, Koppala & Hadi (2018)	R134a VCRS	1.6% CuO	COP increased from 3.0 to 3.5; compressor power decreased from 1.16 kW to 1.00 kW
Kaushik & Sharma (2022)	R134a VCRS	Different CuO concentrations	Maximum COP reported at 0.5 g CuO in the investigated range
Ramanjaneyulu (2022)	R134a VCRS with POE nanolubricant	0.1–0.3% CuO	Improvement in refrigeration performance reported with CuO nanolubricant
CuO evaporating heat-transfer investigation	R134a/CuO	0.05–1% CuO	Heat-transfer coefficient increased with concentration up to an optimum value and then decreased
CuO/CeO ₂ hybrid investigation	R134a-based system	CuO/CeO ₂ mixture	Numerical investigation indicated potential performance improvement

The results show that CuO can provide performance enhancement, but the optimum concentration is system-dependent. Experimental results should therefore be compared only when the operating conditions and measurement methods are reasonably similar.

5.4 Comparative Performance of Conventional R134a and CuO–R134a

The conventional R134a system acts as the reference system. The addition of CuO nanoparticles modifies the thermophysical and heat-transfer behaviour of the working fluid. The principal comparison parameters are:

1. Cooling Capacity

The cooling capacity represents the rate at which heat is absorbed by the evaporator. Improvement in evaporator heat transfer can increase the refrigeration effect under suitable conditions.

2. Compressor Power

Compressor power represents the energy required to circulate and compress the refrigerant. A reduction in compressor power directly contributes to an increase in COP.

3. Coefficient of Performance

COP is calculated as:

$$\text{COP} = Q_L / W_c$$

An increase in cooling capacity combined with unchanged or reduced compressor power results in higher COP.

4. Heat-Transfer Characteristics

CuO nanoparticles can increase effective thermal conductivity and modify the heat-transfer behaviour of the working fluid. Investigations have reported enhanced heat-transfer coefficients over specific CuO concentration ranges.

5. Operating Pressure and Temperature

Suction and discharge pressures and evaporator and condenser temperatures must be monitored because changes in these parameters directly influence compressor work and COP.

5.5 Important Observation from Literature

The literature does not support the assumption that increasing CuO concentration continuously improves refrigeration performance. At lower concentrations, CuO nanoparticles may improve thermal transport without producing a large increase in flow resistance. As concentration increases, viscosity, particle interaction and the possibility of agglomeration may also increase.

Therefore, the expected relationship is:

Low CuO concentration → Limited enhancement

Optimum CuO concentration → Maximum overall performance

Excessive CuO concentration → Possible increase in viscosity, pressure drop and agglomeration

The optimum concentration must therefore be determined experimentally for the particular refrigerant, lubricant and refrigeration system.

6. PARAMETRIC DISCUSSION AND PHYSICAL MECHANISMS

6.1 Effect of CuO Concentration

CuO concentration is one of the most important parameters affecting the performance of a nanorefrigerant system.

At a suitable concentration, CuO nanoparticles can improve thermal transport and heat-transfer behaviour. However, increasing concentration beyond the optimum level may increase viscosity and flow resistance.

Therefore, the influence of CuO concentration should be evaluated by measuring COP, cooling capacity, compressor power and pressure drop simultaneously.

6.2 Effect on Thermal Conductivity

CuO has comparatively high thermal conductivity relative to conventional refrigerant/lubricant fluids. When nanoparticles are appropriately dispersed, they can modify the effective thermal conductivity of the working medium.

Improved thermal conductivity can reduce thermal resistance between the refrigerant and heat-transfer surface.

However, thermal conductivity alone cannot be used to predict the overall refrigeration performance. Viscosity, density, specific heat, particle stability and pressure drop must also be considered.

6.3 Effect on Evaporator Heat Transfer

The evaporator is responsible for absorbing heat from the refrigerated space.

The addition of CuO nanoparticles can potentially improve evaporator heat transfer through:

1. Enhanced effective thermal conductivity
2. Modification of the thermal boundary layer
3. Nanoparticle Brownian motion

4. Increased microscale energy transport

5. Improved interaction between the working fluid and heat-transfer surface

Experimental and numerical investigations of CuO–R134a systems have reported enhancement in evaporating heat-transfer behaviour over specific concentration ranges. However, the improvement becomes concentration-dependent and may decrease after an optimum value.

6.4 Effect on Condenser Heat Transfer

In the condenser, the high-pressure refrigerant rejects heat to the surrounding environment.

Improved heat transfer in the condenser can reduce the required temperature difference between the refrigerant and surroundings. This may reduce condensing temperature and pressure under suitable operating conditions.

A reduction in condensing pressure can decrease the compressor pressure ratio and potentially reduce compressor work.

Therefore, condenser performance is an important factor in determining the overall benefit of CuO nanoparticles.

6.5 Effect on Cooling Capacity

The refrigeration capacity is given by:

$$Q_1 = \dot{m} (h_1 - h_4)$$

Cooling capacity depends on both refrigerant mass-flow rate and the enthalpy difference across the evaporator.

If CuO nanoparticles enhance evaporator heat transfer without causing excessive flow resistance, the refrigeration effect may increase. However, cooling capacity should be determined experimentally rather than assumed to increase simply because nanoparticles have been added.

6.6 Effect on Compressor Power

Compressor power depends on pressure ratio, mass-flow rate, compressor efficiency and refrigerant properties.

CuO nanoparticles may affect compressor power through changes in the refrigerant/lubricant properties and, when used as a nanolubricant, through changes in friction and lubrication characteristics.

An experimental R134a–CuO study reported a reduction in compressor power from approximately 1.16 kW for R134a to 1.00 kW for the tested CuO–R134a condition. This demonstrates the potential benefit, but the reported value should not be treated as a universal reduction for all R134a–CuO systems.

6.7 Effect on COP

COP combines the effects of cooling capacity and compressor work:

$$\text{COP} = Q_1 / W_c$$

An increase in cooling capacity combined with unchanged or reduced compressor power results in higher COP.

The experimental study by Ande et al. reported an actual COP increase from 3.0 for R134a to 3.5 for the investigated CuO–R134a condition.

6.8 Physical Mechanism of Heat-Transfer Enhancement

The possible physical mechanisms associated with CuO nanoparticles include:

1. Increased Effective Thermal Conductivity

The dispersed nanoparticles provide additional pathways for thermal transport.

2. Brownian Motion

Small nanoparticles undergo random motion within the fluid, which can contribute to microscale mixing and energy transport.

3. Thermal Boundary-Layer Modification

Nanoparticle movement can influence the thermal boundary layer near heat-transfer surfaces.

4. Increased Effective Heat-Transfer Area

The large specific surface area associated with nanoscale particles can increase interaction between the nanoparticles and surrounding fluid.

5. Modification of Refrigerant–Surface Interaction

The presence of nanoparticles can modify the local thermal and flow characteristics near the heat-transfer surface.

These mechanisms can act simultaneously, but their relative importance depends on particle size, concentration, flow regime and phase-change conditions.

6.9 Effect of Particle Size

Particle size can influence dispersion stability, thermal transport and flow behaviour.

Smaller nanoparticles generally provide a larger surface-area-to-volume ratio. However, very small particles may also exhibit stronger particle interactions and can require careful dispersion control.

Therefore, particle size should be considered together with concentration rather than as an independent parameter.

6.10 Effect of Operating Conditions

The performance of CuO–R134a nanorefrigerants depends strongly on operating conditions.

Important operating parameters include:

1. Evaporating temperature
2. Condensing temperature
3. Suction pressure
4. Discharge pressure
5. Refrigerant mass flow rate
6. Compressor operating condition
7. Ambient temperature
8. CuO concentration

Changes in these parameters can significantly affect the measured COP and cooling capacity.

7. PRACTICAL CHALLENGES AND IMPLEMENTATION CONSTRAINTS

Although CuO nanoparticles show potential for improving refrigeration performance, several practical challenges must be considered before commercial implementation.

7.1 Nanoparticle Agglomeration

Nanoparticles can attract each other and form clusters. Agglomeration reduces effective dispersion and may reduce the expected heat-transfer enhancement. A stable and uniform dispersion is therefore essential for repeatable performance.

7.2 Sedimentation and Dispersion Stability

The long-term stability of nanoparticles in the refrigerant or lubricant is an important practical consideration.

Sedimentation can change the effective nanoparticle concentration in different portions of the refrigeration circuit and can cause inconsistent performance.

7.3 Increased Viscosity

Increasing nanoparticle concentration can increase the viscosity of the working fluid.

Higher viscosity can increase frictional losses and pressure drop. Therefore, a concentration that maximizes thermal conductivity may not necessarily provide the highest COP.

7.4 Pressure Drop

The addition of nanoparticles can modify flow resistance.

Excessive pressure drop can increase the required compressor work and may offset the improvement obtained from enhanced heat transfer. Therefore, pressure drop must be considered along with cooling capacity and COP.

7.5 Blockage of Small Flow Passages

Poorly dispersed nanoparticles may accumulate in narrow passages such as capillary tubes or expansion devices.

This can interfere with refrigerant flow and reduce system reliability.

7.6 Compatibility with Lubricant

Compatibility between CuO nanoparticles and the compressor lubricant is important.

The effect of CuO may differ depending on whether the nanoparticles are dispersed directly in the refrigerant or incorporated into a lubricant such as POE or another compressor oil.

7.7 Long-Term Stability

Short-duration experiments cannot fully establish the long-term reliability of a nanorefrigerant system.

Long-term testing should examine:

1. Particle stability
2. Lubricant degradation
3. Compressor wear

4. Pressure-drop variation
5. Heat-transfer performance
6. Refrigerant leakage behaviour
7. Changes in nanoparticle concentration

7.8 Economic Considerations

The use of nanoparticles introduces additional material and preparation costs.

The economic benefit of CuO nanoparticles should therefore be evaluated by comparing:

Initial nanoparticle cost + preparation cost + maintenance cost with Energy savings + improved cooling performance + possible reduction in operating cost.

7.9 Experimental Repeatability

Nanorefrigerant experiments can be sensitive to preparation method, particle dispersion, charging procedure and operating conditions. Therefore, repeated tests under identical conditions are required to establish reliable performance trends.

8. CONCLUSIONS

The present review analyses the performance of a vapour compression refrigeration system using R134a and CuO nanoparticles. The conventional R134a system provides the reference condition, while CuO nanoparticles are considered as a method for modifying the thermal and flow characteristics of the refrigeration working fluid.

The literature indicates that CuO nanoparticles have the potential to improve heat-transfer characteristics in refrigeration systems. Improvements can occur through changes in effective thermal conductivity, thermal boundary-layer behaviour and microscale transport.

Experimental evidence supports the possibility of improved system performance. In one reported R134a–CuO experiment, the actual COP increased from 3.0 for pure R134a to 3.5 for the tested CuO–R134a condition, while compressor power decreased from approximately 1.16 kW to 1.00 kW. The study reported a 16.66% increase in COP and a 13.79% reduction in power consumption. However, the performance of CuO-based nanorefrigerants is strongly dependent on nanoparticle concentration. Increasing concentration does not guarantee continuous improvement because higher concentrations may increase viscosity, pressure drop and agglomeration.

Therefore, an optimum CuO concentration should be identified for each specific refrigeration system rather than assuming a universal optimum value.

The major conclusions of the study are:

1. CuO nanoparticles can potentially enhance heat-transfer characteristics in R134a-based vapour compression refrigeration systems.
2. Improved heat transfer can contribute to increased refrigeration capacity under suitable operating conditions.
3. CuO addition can potentially reduce compressor power consumption, although the result depends on concentration, lubricant and operating conditions.
4. COP can improve when cooling capacity increases without a proportional increase in compressor power.
5. Nanoparticle concentration is a critical parameter and should be optimized experimentally.
6. Excessive concentration can increase viscosity, pressure drop and agglomeration and may reduce the overall benefit.
7. Stable nanoparticle dispersion is essential for reliable and repeatable system operation.
8. Long-term compatibility between CuO nanoparticles, R134a, compressor lubricant and system components requires further investigation.
9. Experimental comparison should be performed under the same evaporating temperature, condensing temperature, refrigerant charge and compressor operating conditions.
10. Further research should focus on long-term stability, optimum concentration, energy efficiency, economic feasibility and practical implementation.

Overall, CuO-enhanced R134a represents a promising approach for improving the thermal performance and energy efficiency of vapour compression refrigeration systems, but its practical application requires careful optimization of nanoparticle concentration, dispersion stability, flow resistance and component compatibility.

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