Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.14744/thermal.0000000

Research Article

Enhancing VCRS performance: A study of R134a and refrigerant blends with spiral condensers and series evaporators

Sourabh KULKARNI[1,*], Shriramshastri CHAVALI[1], Shruti VEDPATHAK[1,2]

[1]*Department of Mechanical Engineering, Faculty of Engineering Technology, D Y Patil University Ambi, Maharashtra, 410507, India*
[2]*Department of Mechanical Engineering, Dr D Y Patil University Institute of Technology, Pimpri, Maharashtra, 411018, India*

ARTICLE INFO

Article history
Received: 13 June 2024
Revised: 29 October 2024
Accepted: 31 October 2024

Keywords:
R134a; Refrigerant Blends; Series Evaporator Arrangement; Spiral Condenser; Vapor Compression Refrigeration System (VCRS)

ABSTRACT

The purpose of this work will be the improve the vapour compression refrigeration system, taking into account the usage of environmentally friendly refrigerants. This is important because the alternative solution for achieving a minimal invasion into the environment with maximum energy efficiency is urgently needed. The method used here, namely, system redesigns with spiral condensers and series evaporators, was validated using CoolPack software. Major outcomes are that the coefficient of performance is increased by 77% and power consumption is reduced by 19% when a spiral condenser is used instead of the conventional systems. The hydrocarbon blends of propane and isobutane were found to be possible substitutes for R134a, and using nanofluids of Al_2O_3 or ZnO was shown to increase the coefficient of performance up to 137%. The research does not only add a source of enhancing literature but also provides a practical framework for developing more sustainable and ef ficient refrigeration technologies.

Cite this article as: Kulkarni S, Chavali S, Vedpathak S. Enhancing VCRS performance: A study of R134a and refrigerant blends with spiral condensers and series evaporators. J Ther Eng 2025;11(5):1–15.

INTRODUCTION

Energy conservation is indeed a challenging concern today, especially in systems like refrigeration, where efficiency and sustainability are paramount. The VCRS serves a critical role in maintaining suitable environments and preserving perishable goods. It achieves this by leveraging fundamental thermodynamic principles to efficiently transfer heat from low-temperature spaces to high-temperature ones. Comprising components like compressors, condensers, expansion valves, and evaporators, the VCRS operates in a continuous cycle involving compression, condensation, expansion, and evaporation processes. Each component works sequentially to circulate refrigerant, facilitating the transfer of heat.

Also in the past few years, the pressure to have safe environmental and energy-efficient refrigeration systems has motivated a lot of research into alternative refrigerants, recovery of waste heat, and innovative system modifications. For instance, illustrated the possibility of using

***Corresponding author.**
*E-mail address: sourabhkdypu@gmail.com

This paper was recommended for publication in revised form by Editor-in-Chief Ahmet Selim Dalkılıç

Published by Yıldız Technical University Press, İstanbul, Turkey

hydrocarbon blends as a substitute to HFC-134a, in that they carry out the task with a significantly lower environmental footprint [1, 2]. More research indicates that the utilization of water-cooled condensers enhances COP by up to 13.4% as alternative refrigerants utilize this, yet their system modification provides considerable performance enhancements in energy efficiency [2]. Furthermore, applied the humidification-dehumidification desalination process, incorporating waste heat recovery, where such configurations improve COP to 7.6 and, in addition, produce distillate water [3].

Despite this, Investigated and found that although mixtures of R290 and R600a in any ratio increase refrigeration effects, there is not much knowledge regarding their performance when combined with highly advanced condenser designs like spiral condensers [4]. Another potential area is nanofluids by using Al_2O_3 and ZnO wherein primary experiments exhibit increased heat transfer and efficiency, but which has not been tested under different combinations with environmentally friendly refrigerants under modified VCRS configurations. These developments are taken one step further by incorporating spiral condenser design and nanofluids in the process, thus an integrated assessment of the interactions on system performance and operational conditions is provided. This helps bridge the essential gap that exists within the literature and helps advance the development of next-generation sustainable refrigeration technologies.

The choice of refrigerant is also critical towards efficiency and to a greater extent in terms of its environmental impact. Though widely used, the use of HFC Refrigerant R134a calls for alternatives due to its high GWP. Promising alternatives are R290, also known as Propane, and R600a known as Isobutene. These alternatives have low ODP and GWP values in addition to favourable properties in thermodynamics. Alternative development in this line provides paths towards improving the sustainability as well as efficiency of refrigeration systems with less environmental harm. Other factors that the research identified are replacement alternatives necessitated due to its GWP being higher which raises concern about environmental degradation, particularly as an alternative to HCFC and HFCs, respectively [5]. For example, exergy analysis was conducted on eighteen refrigerants in the form of an assessment incorporating elements of environmental safety from multistage multi-evaporator vapour compression refrigeration systems that were modelled on Simulink. Results have shown that the exergy loss has been mainly contributed to by compressors, followed by condensers, evaporators, and expansion devices. Environmentally friendly refrigerants, such as R 1234ze (E) and R1234yf, have performed quite well compared to conventional options [6]. The VCRS has mostly been preferred in lots of applications because of its excellent COP and Refrigeration Effectiveness. Despite the favourable thermodynamic properties of HFCs like R134a, their significant GWP has propelled the search for eco-friendly alternatives that offer augmented COP, effectual heat transfer, with lower values of GWP and ODP. Investigation suggests that mixed refrigeration systems or blends incorporating Nanofluids and R134a can enhance thermal efficiency and overall system performance.

An exergy analysis under AHRI standard conditions compared refrigerants like R12, R134a, R1234yf, and R600a, finding R600a to have superior performance and the lowest TEWI, while CO_2 emerged as a promising alternative due to its affordability and non-toxicity [7]. For very low-temperature applications below -50°C, (Mota-Babiloni et al., 2023) The study explored pure fluid combinations and refrigerants like R-469A for temperatures below -80°C, suggesting a trade-off between environmental concerns and flammability. Five new refrigerants (R440A, R451A, R445A, R444A, and R441A) with GWP below 150 were also investigated, with R440A as well as R451A showing superior thermal characteristics to COP and like R134a, making them eco-friendly substitutes despite flammability concerns [8]. Research Confirms that using environmentally friendly refrigerants like propane and isobutane blends can significantly enhance the system's performance while dropping environmental effects [9].

The European gas regulations have necessitated the replacement of refrigerants with higher GWP, particularly affecting standalone systems using R134a. Alternatives studied include R600a, R290, as well as CO_2, with commercial beverage cooler tests showing significant energy reductions with these refrigerants, except for R1234yf [10]. Global warming concerns drive the necessity to decrease GHG (greenhouse gas emissions) as well as fossil fuel use, making low GWP refrigerants crucial, especially in heat pumps for waste heat recovery. However, there is a lack of performance analysis and application guidelines for these refrigerants in heat pumps, prompting a study of 17 refrigerants with lower GWP. Moreover, guidelines for utilizing refrigerants in heat pumps are provided [11]. Additionally, experimental investigations on household refrigerators using HC mixtures (R290/R600a) and R436A using different capillary tube lengths and refrigerant charges showed that R436A could achieve design temperatures of -15°C, making it a viable R134a substitute [12]. Studies mandated by the Kyoto Protocol also confirmed that R290 and R600a mixtures offer low energy consumption and higher COP, presenting them as promising alternatives to R134a [13].

Development of an Energy-Efficient Design for a Low-Volume VCRS Model Using R290, R600a, and R1234yf. Environmental and thermos-economic analyses based on COP and exergy efficiency parameters reveal that R290 is the most viable substitute for R134a, showing that its operational costs represent almost 75% of the total costs with the Kyoto Protocol requirement to phase out R134a, a 28:72 weight ratio of R134a and LPG is being considered, showing that it performs better with a higher COP and lower compressor discharge temperatures than R134a alone [14]. Compatibility with mineral oil lubricant is also satisfactory.

Besides, Performance study of various refrigerant mixtures in cascade refrigeration cycles revealed that the R134a/R170 has maximum COP and lowest mass flow rate. Further, the performance increased at a higher temperature of the evaporator with the pair of [15, 16].

The exergy analysis of the VCRS was performed to look for losses at different levels, as well as specifically in refrigerants R134a, R12, and R22, and their impact on evaporator temperature. The use of RefProp software was carried out to compare some parameters, like energetic efficiency and irreversibility, to predict the effects of more elevated evaporator temperatures on exergy loss and second-law efficiency, with the latter showing that R134a experienced the highest exergy loss [17]. The introduction of Al2O3 nanoparticles in VCRS without any retrofitting has been shown to enhance thermal performance with less energy consumption due to the high thermal conductivity and low viscosity of nanoparticles. Another requirement suggested in this study is the choice of more efficient materials for the compressor during the inclusion of nano-refrigerants [18]. Further investigation of R449A as a coolant in commercial refrigeration systems through EES analysis and simulation found that its addition had a significant effect on raising the performance of the system. Also, an indication of a reduction in greenhouse gas emissions up to 40.4% was shown by R290 [19]. The application of nano refrigerants and nano lubricants increased the heat transfer efficiency and COP and lowered energy consumption; however, more effort should be dedicated to their application [20].

Various approaches, including experimental and analytical methods, have been explored by researchers to provide insights into the selection of expansion devices for different refrigerants. Additionally, Enhancing COP in VCRS systems has been studied by incorporating SiO2 nanoparticles mixed with POE oil nano lubricant and modifying condenser designs, such as using spiral condensers with increased surface area compared to conventional designs [21]. Studies have demonstrated that increasing nanoparticle concentration improves COP. Furthermore, assessing the performance of two-evaporator VCRS systems with different arrangements (series and parallel) has shown that series arrangements yield higher COP ranges due to optimal cooling achieved with refrigerant R134a [22]. Modifications in evaporator design through fin installations have also been explored, comparing the use of Hydrocarbon (HC) refrigerants with R134a. Integration of HC-R134a has been found advantageous, reducing time to reach the similar refrigeration effect, increasing COP, as well as reducing consumption of power [23]. Owing to features like low GWP and enhanced heat transfer rates.

Findings from Indicate that the optimal selection of the working fluid does affect the system's performance [24]. The blend of R134a with nanofluids enhances cold production by improving heat transfer efficiency, leading to greater cooling capacity. It also reduces compressor power consumption by lowering the compressor's workload, resulting in decreased electrical energy use and improved energy efficiency. Previous studies independently investigated the interplay of design parameter modifications and the impact of using different refrigerant mixtures on VCRS performance.

The current investigation introduces innovative VCRS redesign with spiral condensers and series evaporators, which has greatly improved the enhancement of energy efficiency and thus reduces environmental impact by using eco-friendly refrigerants. However, the existing knowledge gaps in the current literature even show how low-GWP refrigerants and nanofluids have not been explored suitably within any VCRS configurations. This research emphasizes the dual importance of thermal performance and environmental impact, advocating for the implementation of a series arrangement of evaporators and spiral condenser configurations to enhance system efficiency. Such configurations hold promises for sustainable refrigeration applications, offering

Table 1. Based on the Selection of Eco-Friendly Refrigerants

Study	Refrigerants Examined	Methodology	Key Findings	COP Improvement	Environmental Impact
[25]	R152a, R1234yf, R134a	Experimental, oil-free VCR system	R1234yf is like R134a in temperature/pressure but lower COP as well as cooling capacity by 16% and 11% correspondingly.	Decrease in COP for R1234yf by 16%	R152a is promising but flammable
[26]	R290/R600a mixtures	Experimental on variable speed hermetic compressors	COP increased by 10-20% over R600a depending on mixture composition and conditions.	10-20% greater than R600a	Enhanced performance with proper mix ratios
[27]	R32, R1234yf, R1234ze(E), R290 vs. R134a	Dynamic model using Modelica	COP changes: +8% (R32), -12% (R1234yf), -3% (R1234ze(E)), -5% (R290) compared to R134a.	COP increases with R32, decreases with others	Significant system charge reduction for R32, R1234yf, R1234ze(E), R290

Table 2. Based on the Effect of Mixing Nanofluids with Primary Refrigerant

Study	Nanoparticle Type	Working Fluid	Methodology	Key Findings	Performance Improvement
[28]	Al_2O_3	R134a	Thermal analysis	Improved heat transfer with Al_2O_3 nanoparticles in R134a refrigerant.	Enhanced heat transfer
[18]	Al_2O_3	R134a	Experimental, no system retrofit	Al_2O_3 nano refrigerant outperformed conventional mixture, achieving faster cooling and improved energy consumption.	Faster cooling, improved energy consumption
[29]	Al_2O_3	R134a, R600a	Experimental, varying nanoparticle concentration	Adding 0.1 wt% of R600a-Al_2O_3, decreased evaporator pressure, cuts consumption of power by 28.7%, with an increase in COP by 37.2%.	Increased COP, reduced power consumption.

Table 3. Based on the Effect of Modifications in the Design of VCRS

Study	Focus	Methodology	Key Findings
[21]	Expansion devices performance	Analysis	The straight capillary tube demonstrated a greater mass flow rate, while the Thermostatic expansion valve improved flow control.
[30]	Transient mathematical models for VCRS	Simulation, experimental validation	Mathematical models can improve domestic refrigeration system design by manufacturers.

both feasibility and adaptability in addressing the pressing challenges of energy conservation and environmental sustainability. This work demonstrates a remarkable 77% enhancement in COP and a 19% reduction in power consumption relative to traditional systems for the proposed configuration. The results set up a new benchmark for the design of VCRSs and opened doors to further research concerning sustainable refrigeration technologies.

MATERIALS AND METHODS

In the section on materials and methods, the study focuses on the specification of components, the experimental parameter selection, along with the setup of the experimental apparatus.

Figure 1 demonstrates the thermodynamic cycle of the vapor compression refrigeration system Ph relation for the given cycle is shown. At point 1, the refrigerant leaves the evaporators in the form of low-pressure vapour and goes into the Compressor where it gets compressed to the high-pressure stage (point 2) Increasing the temperature as well as the pressure of the refrigerant (work input, Wk). The high-pressure vapour proceeds into the Condenser. In this component, at point 3, it surrenders the heat Qk and condenses to a high-pressure liquid. Such condensation lowers the temperature but keeps on keeping the pressure at

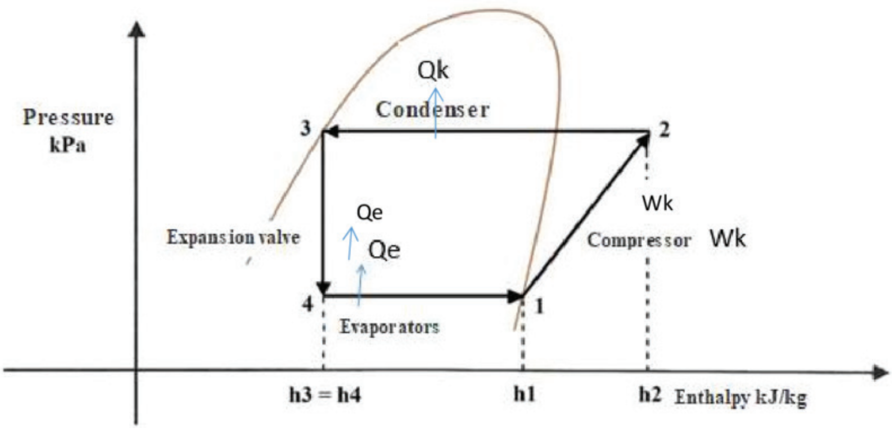

Figure 1. Thermodynamic Cycle.

hand. The refrigerant which has condensed flows through the expansion valve where, from point 3, it drops to point 4, decreasing in both pressure and temperature, thus making a low-pressure liquid-vapor mixture. It is at point 4 that the refrigerant passes into the Evaporators, wherein it absorbs heat Qe from the surroundings and evaporates completely to revert into a gaseous condition. It is at this step that the system derives its needed heat from the surroundings, hence affording the cooling needed to operate the system. This cycle repeats as the refrigerant reintroduces itself into the compressor. The energy exchange processes that take place at every stage of the cycle are manifest in the diagram, and the figure well represents the thermodynamic transformations important for efficient cooling in the modified VCRS configuration. The Coefficient of Performance (COP) evaluates the system's performance for vapor compression refrigeration as:

$$COP = \frac{Refrigerating\ Effect}{Work\ Done} = \frac{h_1 - h_4}{h_2 - h_1} \quad (1)$$

Compressor Selection and Mathematical Modelling

The compressor's scientific model incorporates measurements of thermodynamic processes which refers to the quantification of key parameters such as pressure, temperature, enthalpy, and mass flow rate within the compressor's operation. These measurements are crucial for accurately modelling work done during the compression cycle and energy exchanges that occur around this component. The compressor's fundamental equation includes W_{c0} (*in kJ/kg*) (Work required for a compressor), which is power consumption throughout the compression phase.

Work required for a compressor,

$$W_{c0} = h_2 - h_1 \quad (2)$$

Where it denotes enthalpy h_1 at the compressor intake and enthalpy h_2 at the compressor exit. These equations give a framework for modelling compressors considering numerous aspects such as refrigerant type, operating circumstances, etc. The hermetically sealed compressor employed in this study project was an Emerson 0.32 HP (Model No. KCN415LAG-BXX) compressor with a voltage of 230V/50HZ.

Condenser Selection and Mathematical Modelling

Heat rejection and energy exchange with this component are included in the mathematical modelling of the condenser. Qc, or the heat forbidden by the condenser during the condensation process, is the fundamental equation for a condenser.

Heat rejected Q_c (kW) in condenser,

$$Q_c = m\,(h_2 - h_3) \quad (3)$$

The enthalpy at the condenser intake (h2) is identical to the refrigerant's mass flow rate (m), whereas at the condenser exit (h3). The condenser's efficacy (ε) is determined as the ratio of actual to maximal heat transfer. These equations serve as a foundation for modelling condensers using various factors such as refrigerant type and mass flow rate, as well as providing insight for analysis and optimization of the system. Table 4 provides the characteristics of the condensers used for the study setting.

Expansion Device Selection and Mathematical Modelling

Measuring variations in enthalpy and pressure during expansion is part of the mathematical modelling of expansion devices. The isenthalpic expansion mechanism is crucial to the fundamental equation for expansion.

$$h_3 = h_4 \quad (4)$$

The expansion device's intake enthalpy is h_3, whereas the exit enthalpy is h_4. This equation may be used to calculate the performance of an expansion device, taking into account elements such as efficiency, operating conditions, as well as refrigerant. In the study, an expansion device selected is a capillary tube employed in the system. Capillary tubes have tiny internal diameters and are made with copper for varied lengths depending on the purpose. The capillary tube utilized in this configuration has a diameter of 2 mm.

Evaporator Selection and Mathematical Modelling

Evaporator's mathematical modelling comprises an examination of the heat absorption mechanism along with

Table 4. Choice of parameters for Air Cooled condenser

Parameters	Fins	Spiral Condenser
Material	MS (Mild Steel)	Copper
Length	9 m	7m
Diameter	0.005 m	0.007 m
No. of Turns	10	5
Thermal Conductivity	50 W/m·K	385 W/m·K
Corrosion Resistance	Lower, prone to rust	Higher, resistant to corrosion
Heat Transfer Efficiency	Lower efficiency	Higher efficiency

energy interactions around it. As per the first rule of thermodynamics, the following fundamental equation governs the behaviour of the evaporator,

Absorbed heat Q_e (kW) in the evaporator,

$$Q_e = \dot{m}\,(h1 - h4) \quad (5)$$

Where h1 refers to the enthalpy at the evaporator outlet (compressor intake) and h4 refers to the enthalpy at the evaporator inlet (expansion valve outlet), and m is the refrigerant's mass flow rate. Moreover, the efficacy (εevap) of the evaporator displays how much heat is transferred compared to how much is transferred at its highest. In the modelling of the evaporator's performance, the above equations are essential, since they consider crucial factors like refrigerant properties, heat transfer efficiency, and mass flow rate. The wood evaporator used for this experiment has an internal coiling built with a 7 mm tube diameter. Inside insulation prevents heat loss to the surroundings. A series configuration of evaporators further ensures identical cooling capacity across both.

Assortment of Additional Components

Suction pressure is measured using WIKA pressure gauges that have an overall range of 150 psi to -30 psi, and discharge pressure is measured using pressure gauges with an overall range of 300 psi and 0 psi. It employed two 500 W heaters in addition to a glass tube rotameter device for measuring the flow rate of fluid or gas. The rotameter with a capacity of 0.50 LPH to 50 LPH is used in this configuration. To ensure operational safety, an excess load cut-off mechanism was supplied to the compressor. At different locations, RTD sensors were employed for temperature measurement. A blend of R290 propane-R600a isobutane refrigerant was utilized. The desirable characteristics like High critical temperature with Low Freezing / Boiling point are important for any refrigerant. The boiling point and critical temperature of R134a are -26°C and 101°C, respectively whereas these values are -11.7 °C and 134.98°C for Isobutane R600 and -42.1°C and 96.7°C for Propane. These values indicate that isobutane and propane show critical temperature features with desirable Boiling points. The molecular weights of R134a R290 and R600a are 102.03 g/mol, 44.1 g/mol, and 58.12 g/mol respectively. Reciprocating compressors benefit from lower molecular weights because it reduce compressor size. Due to the lower molecular weight, Propane and Isobutane are more ideal than R134a. According to global safety standards (IEC/EN 60335-2-24), the limit of maximum refrigerant charge for household appliances is 150 gm which resembles about 360 g of typical refrigerants.

For experimentation, four cases were recognized and attained with the aid of valves as below.

- Conventional VCRS (Expansion Device, Evaporator I, Compressor, as well as Condenser)
- Traditional VCRS with evaporators in series (Evaporator I, Compressor, Evaporator II, Expansion Device and Spiral Condenser)
- Expansion Device, Compressor, Evaporator I, and Spiral Condenser comprise the VCRS utilizing a spiral condenser.
- Utilizing a spiral condenser, VCRS is set up in series with the spiral condenser, compressor, evaporator I, expansion device, and evaporator II. The configurations were made with the aid of valves.

This section gives a summary of the experimental methods, selection of materials, fabrication, and testing methods used in this research work. In this section, we outline the specifications of the components chosen for the experimental investigation of the VCRS system. The setup includes a condenser, evaporator, capillary tube, compressor, pressure gauges, refrigerant, and rotameter. The design of the VCRS system is done by considering some standard parameters. From the literature review following parameters were selected for experimentation purposes. Following are short description of the Specifications of components of the Vapor Compression Refrigeration System.

Condenser

Evaporator

In this experimental setup, the evaporator is constructed from wood, with a copper tube coiled inside having a diameter of 7mm. Insulation has been incorporated within the evaporator to shield it from ambient heat sources. The fact that all evaporators have the same cooling capacity is notable.

Compressor

A compressor is a mechanical device that boosts gas pressure by decreasing volume, facilitating refrigerant circulation. The setup employed a 0.32 hp hermetically sealed (230V/50Hz) compressor (Emerson model KCN415LAG - BXX).

Table 5. Specifications of Fin-type condenser

Parameter	Specifications
Coil Diameter	5 mm
Coil Length	9 mm
Coil Material	Mild Steel
Number of turns	10

Table 6. Specifications of Spiral type condenser

Parameter	Specifications
Coil Diameter	7 mm
Coil Length	7 mm
Coil Material	Copper
Number of turns	5

Capillary Tube

The capillary tube, a key throttling device in refrigeration, comprises a copper tube with a small internal diameter. It's lengthy and coiled to save space, with a 2mm diameter in this setup.

Pressure Gauges

Pressure gauges are vital for measuring fluid pressure in diverse applications. In this study, gauges with a range of 150 psi to -30 psi monitor suction pressure from the compressor, while track discharge pressure ranging from 300 psi to 0 psi.

Refrigerant

Refrigerants facilitate heat transfer in heat cycles. This study employs R134a (Tetra Fluro ethane) due to its widespread use, well-documented thermodynamic properties, and relevance as an industry standard, allowing for effective comparison with alternative refrigerant blends in the study with specific properties such as the critical pressure and temperature, as well as boiling and freezing point.

Rotameter

In this experiment, a glass tube calibrated for 0.50 to 50 Lph serves as the rotameter, which measures fluid or gas flow rates.

Nanofluid Preparation

Al_2O_3 nanoparticles were used for this research work and specifications were taken from the research work. Nanofluid preparation is an important step for experimental study. Nanofluid can be prepared by single-step method. The initial stage in the experimental study is to prepare Nano-oil for lubrication. Nanofluids may be produced using a one-step technique. In this method nanopowder of Al_2O_3 is taken and mixed with POE oil in the required proportion and after that kept in an ultrasonic vibrator for 7-8 hours.

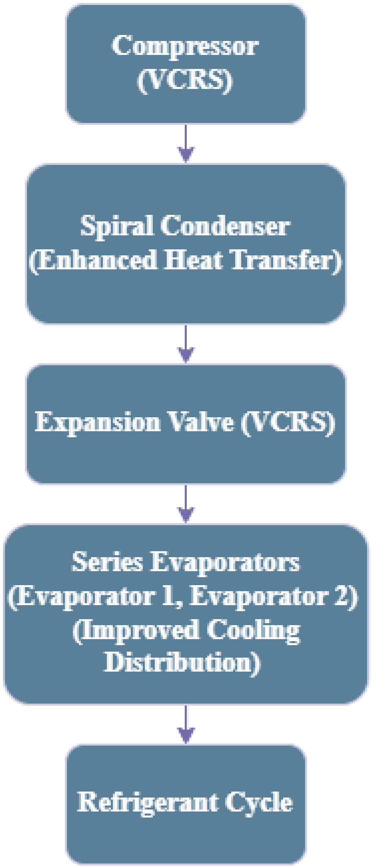

Figure 3. Modified VCRS Configuration (with Spiral Condenser and Series Evaporators)

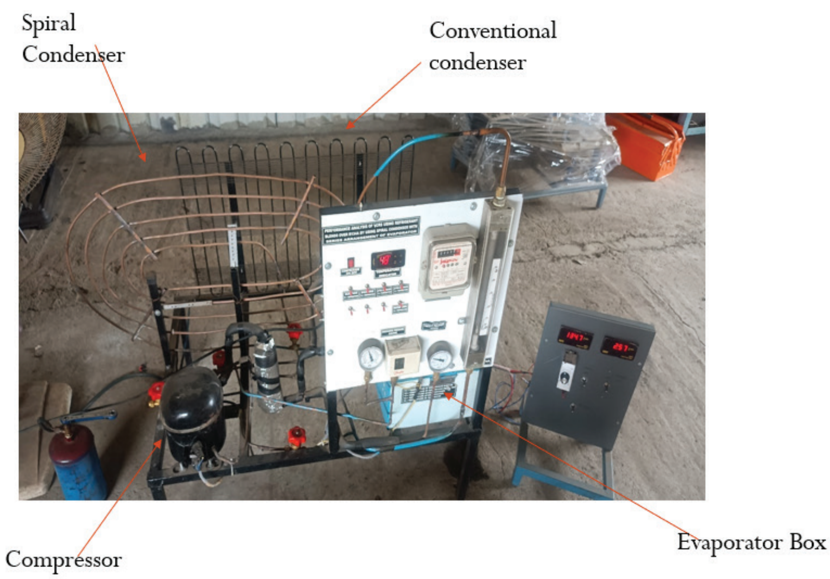

Figure 2. Experimental Set-Up.

As indicated in Figure 2, four cases are considered with distinct refrigerant blends in each case. A pure refrigerant R134a was used in Case 1 as a baseline. In Case 2, the nanofluid Al_2O_3 is blended with R134a to measure the impact of the nanofluid on the system performance and heat transfer effectiveness. The third and fourth cases presented a Propane-Isobutane mixture in diverse proportions for potential use as an alternative refrigerant. For all the cases, a set of experiments was run, with the results reported in tabular form, showing what was obtained in terms of performance metrics such as cooling capacity, COP, and EER.

As shown in Figure 3 the configuration and order of the redesigned Vapor Compression Refrigeration System, with high-capacity components that will enhance performance. A Compressor leads off where it compresses the refrigerant and begins the cycle. Then it passes through a Spiral Condenser. This is among the major improvements suggested to maximize the heat transfer efficiency compared to traditional condensers. This condenser absorbs the heat inside so that the refrigerant cools down and, therefore, proceeds to the next stage. The cooled refrigerant then passes over into the Expansion Valve from the condenser, where, due to the dropping pressure, it becomes cold. The refrigerant remains in this lower pressure and cooler state for subsequent steps in the process to work properly and efficiently in cooling. Then, there's a series of Evaporators: Evaporator 1 and Evaporator 2, following one another. This arrangement offers better cooling distribution across the area and optimal energy usage. This is because the respective evaporators draw heat out of the space, which in turn lowers the temperature of the target area. The cycle ends with the refrigerant returning to the compressor, thus maintaining the continuous flow of the system with maximum efficiency. A revised design that is now the spiral condenser and series evaporators thus tries to cool the system in an attempt to enhance the efficiency of the overall system.

RESULTS AND DISCUSSION

This section details the validation of experimental results by comparing them with simulations from Cool Pack Software, focusing on various refrigerant blends and parameters across different cases. In this economic investigation, the improved VCRS system is also discussed with the Payback Period. Using Cool Pack software, the results validation is performed indicating decent promise with below 10% variance. The COP of the normal VCRS is 2.25, as shown in Table 7, which also presents the percentage improvements in COP compared to normal VCRS for different arrangements.

Table 7. COP Improvement for Different Arrangements

Arrangement	COP	Percentage Improvement Compared to Normal VCRS
Spiral VCRS	3.08	(3.08-2.25)/2.25= 0.36 (36%)
Normal with Series	3.52	(3.52-2.25)/2.25= 0.56 (56%)
Spiral with Series	4	(4-2.25)/2.25= 0.77 (77%)
Evaporators in series and spiral condenser using R134a together with nanofluid	5.33	(5.33-2.25)/2.25= 1.37 (137%)

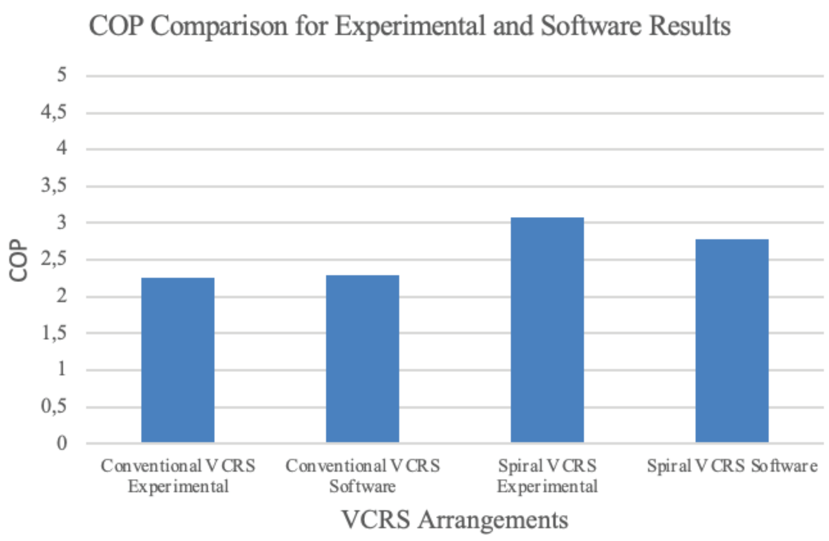

Figure 4. COP Comparison for Experimental and Software Results.

The COP result of both conventional and spiral VCRS configurations is plotted on a graph against experimental and software-simulated values. A slightly higher COP, 2.4, is given by the simulation result as compared to the value of 2.2 yielded by the experimental result for conventional VCRS. In the spiral configuration, experimental COP is enhanced considerably to a level of about 3.4, while in the simulation result, it is somewhat lower at 3.0. It was noted that the VCRS spiral configuration yielded a tremendous increase in efficiency over the conventional type configuration. The matching of the experimental and software results confirms the improvement of the spiral condenser and series evaporator design on system performance, and this was particularly obvious for the spiral configuration. A comparison of different refrigerants based on environmental parameters is carried out. According to a United Nations Environment Program study with a decrease of 1% ozone layer, there will be an increase in 2% chances of skin cancer. Intergovernmental Panel on Climate Change (IPCC) has reported biosphere has already warmed up to 1oc and in the next century there will be a rise of about 4°C due to human interference in the global climate.

As shown in Figure 4 the Comparison of Results for Change of system design including Spiral condenser as well as In-Series Evaporators using refrigerant R134a, Al203 Nanofluid along with R134a and using Propane Isobutane blend experiments were conducted and results obtained are tabulated. For reference Results and discussion for Case A] Using R134a are given below. There are various ways to enhance heat transfer and improve the coefficient of performance in VCRS. From past research, it has been found that with the use of a spiral condenser and series evaporator arrangement, there is an enhancement in heat transfer. For this research effect of combining these two parameters is discussed.

Impact on COP

Considering practical applications of the VCRS system there are requirements where simultaneous cooling is required for more than one compartment. Also, a spiral condenser has a high heat transfer coefficient and a compact size, providing a beneficial heat exchange area that improves the coefficient of performance. There is no earlier study reported to find an effect on performance with a combination of parameters which was studied in this research and discussed. Condenser design modifications can have a significant effect on COP. As the condenser plays a crucial role in heat rejection with its optimal design substantial COP improvement can be observed. With innovations in the design of condensers, COP enhancement can be achieved. The spiral condenser has a distinct design from the conventional straight tube condenser and has various advantageous features like increased efficiency and compact design. Also, with the use of a spiral condenser which has increased surface area and because refrigerant will get a longer path to flow more heat exchange will take place. Due to this enhanced heat transfer more condensation or subcooling is achieved resulting in increased COP.

Also, from this research experimental results graph, it is visible that with system modifications, design COP is increased. There is almost a 36% enhancement in COP with the use of a spiral condenser over a conventional condenser and an almost 77% increase in COP utilizing a spiral condenser in a series arrangement. The application of a series arrangement of evaporators has multiple advantages, including efficiency enhancement and ease of varying loads. In the series arrangement, as refrigerant passes one after another, it allows correct cooling distribution. Also, the series arrangement allows the activation of one or more individual evaporators based on thermal requirements. With this arrangement, energy savings as per application temperature control are achieved. From Fig. 5, it

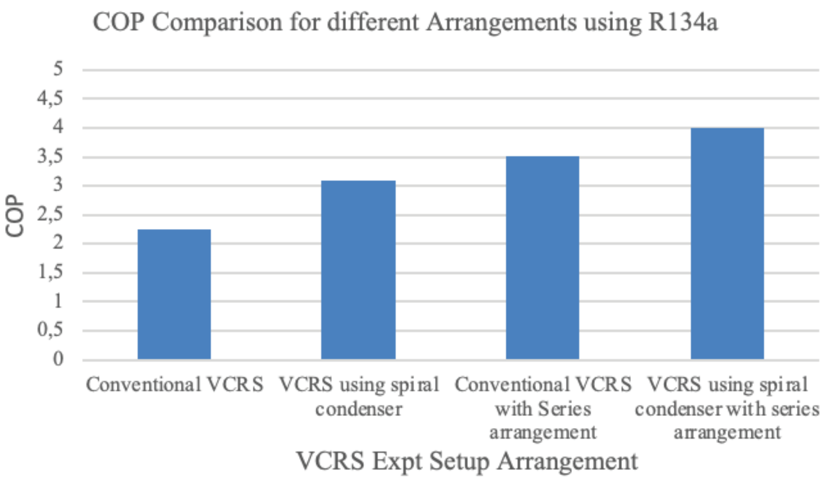

Figure 5. COP Comparison for different Arrangements using R134a.

can be seen that with the use of the series arrangement of evaporators over a conventional VCRS system with a single evaporator, COP increased up to 55%, and when the series system was incorporated along with the series arrangement, it improved by up to 77%. So, with the use of both factor combinations, COP is enhanced.

Within our study, considerable enhancement in COP is attained with spiral condenser configurations and series evaporators that amount to about 77% more than the conventional systems. Interestingly, this is greater than that envisaged by the COP improvement realized [2] When using water-cooled condensers, with a marked performance configuration. More recently, [31] demonstrated that the incorporation of nanofluids like CuO, ZnO, and Al_2O_3 in the R22 refrigerant has enhanced the thermal performance of the air conditioning systems highly. The novel application is then extended into this study by incorporating nanofluids, in the shape of Al_2O_3. This results in a COP improvement of 137% compared with a performance benchmark that was previously indicated as substantially out of bounds. Also, the reductions in power consumption experienced with our proposed design are higher than those for the work reported [3], proving the effectiveness of our system design in this regard.

Impact on Power Consumption (Wc)

Modification of the VCRS system using a spiral condenser has a noticeable impact on power consumption. As a spiral condenser has a coiled structure, the heat transfer rate is enhanced, which results in enhanced condensation and reduced temperature at the expansion valve inlet. This results in the compressor working at a low-pressure head and using less power to maintain the required cooling effect. This ultimately results in enhanced performance and an energy-efficient system. In industrial applications where energy conservation is of prime importance, spiral condensers can be used. From the graph, results reveal that with the using a spiral condenser over a conventional condenser, power consumption is reduced by 19%, whereas, with the use of a spiral condenser over a conventional system along with a series arrangement, there is a decline in consumption of 15%.

Impact on Net Refrigeration Effect (RE)

A spiral condenser allows improved heat dissipation, resulting in the low-pressure temperature of refrigerant before entering the expansion valve. Hence refrigerant-entreating evaporators already have low-temperature benefits in absorbing more heat from refrigerated compartments/evaporators. Thus, with the implementation of a spiral condenser, the refrigeration effect is enhanced. Also, the series arrangement optimizes the heat transfer process, allowing for greater cooling efficiency and the ability to maintain lower temperatures within the system. Figure 7, illustrates that including a spiral condenser, there is a 17% rise in the net refrigeration effect, while a spiral condenser used in combination with a series arrangement, is almost doubled.

Economic analysis of the modified VCRS system (payback period).

The time taken for all cash inflows identical to the early investment is known as the payback period. It shows when the experiment has recouped its early expenses. The payback period is the early investment or yearly inflow of net Cash. The outcome reflects how many years are needed to break even on the investment.

As shown in Table 9 and Table 10, modification cost refers to the expenses incurred when making changes or

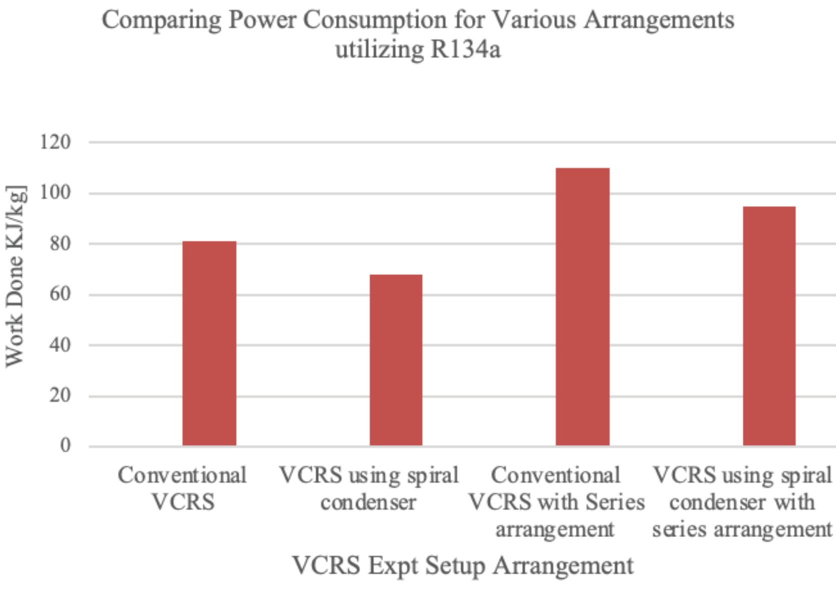

Figure 6. Impact on power consumption using evaporators in series including a spiral condenser and R134a.

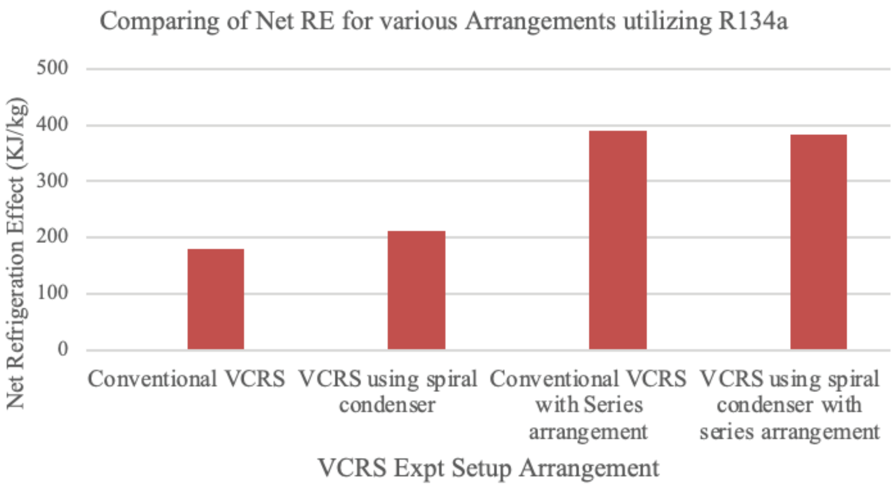

Figure 7. Comparing Net Refrigeration Impact with various arrangements utilizing R134a.

upgrades to an existing system (e.g., the modification cost increase of spiral conder over conventional fins type is 1000 Rs.), and 0 means no change in cost and 2200 means increase in cost with the use of nanofluid. It is in INR.

Future Scope of the Work

Future research could emphasize growing the study to embrace a comprehensive range of refrigerants and nanofluids to further understand their impact on VCRS performance. Investigations could explore alternative low-GWP refrigerants and advanced nanofluids to enhance energy efficiency while minimizing environmental impact. Additionally, incorporating varying operating conditions and load profiles could provide a more comprehensive assessment of system performance across different scenarios. This would help identify optimal configurations and materials for specific applications, enhancing the adaptability and sustainability of VCRS technology.

Integrating real-time monitoring and control systems using IoT and machine learning could optimize VCRS performance dynamically. Future studies could investigate the implementation of smart controls and predictive maintenance strategies to improve efficiency and reduce operational costs. By leveraging advanced data analytics and real-time feedback, it may be possible to fine-tune system operations and extend the lifespan of components.

Table 8. Cost Saving for CASE I and CASE II

Parameter	Cost savings for CASE I System design modified with the usage of in-series evaporators as well as spiral condensers utilizing R134a	Cost savings for CASE II System design modified with the usage of the spiral condenser as well as in-series evaporators utilizing R134a and Al_2O_3 nanofluid	Better Results
Initial Investment	Here an initial Investment will be an extra 6000 Rs.	In this, the initial Investment will be an extra 8200 Rs.	Case I Less Initial Investment
Operating Cost Saving	Cost Savings (%) = 77% × 40% = 30.8% Due to the efficiency enhancement. This indicates a reduction of 30.8% expected in whole operating costs.	Cost Savings (%) =137%×40%=54.8% Due to the efficiency enhancement, this indicates a reduction of 30.8% expected in whole operating costs.	Case 2 More Cost Saving
Energy Consumption Cost	The compressor performs 12 hours daily. Every day, consumption of energy = 3.9 kWh. Monthly consumption = 117 kWh. Yearly cost = 13534 Rs. Modification leads to a 30.8% cost reduction. Yearly savings = 4060 Rs.	The compressor runs 12 hours/day. Daily energy consumption = 3.9 kWh. Monthly consumption = 117 kWh. Monthly cost = 1128 Rs. Yearly cost = 13534 Rs. Modification results in a 54.8% cost reduction. Yearly savings = 7417 Rs.	Case 2 More Yearly Savings.
Payback period	Initial Investment/Annual Net Cash Inflow or saving 6000/4060 = 1.47 ~1.5 Year	Initial Investment/Annual Net Cash Inflow or saving 8200/7417 = 1.1 Year	Case 2 Less Payback Period.

Table 9. Cost of Components for CASE I

Sr. No.	Components	Conventional	Modified	Rise in price
1	Refrigerant	R134a	R134a	0
2	Condenser	Fins type	Spiral	1000
3	Air Heater	I	I and II	1000
4	Evaporator	1	I and II	4000

Table 10. Cost of Components for CASE II

Sr. No.	Component	Conventional	Modified	Increase in Modification Cost
1	Refrigerant	R134a	R134a+Nanofluid	2200
2	Condenser	Fins type	Spiral	1000
3	Air Heater	I	I and II	1000
4	Evaporator	1	I and II	4000

Table 11. Comparison of Refrigerant Blends

R290+R600a	R134a+Al2O3
The blend consists of propane (R290) and isobutane (R600a), both of which are known for their high energy efficiency and efficient heat transfer.	R134a, a stable refrigerant, can enhance heat transfer and system efficiency when combined with Al_2O_3 nanoparticles.
The blend's low GWP and ODP make it ecologically benign, in line with worldwide measures to alleviate climate change besides lessening emissions of greenhouse gas.	R134a, with a high GWP, can be enhanced with Al_2O_3 nanoparticles to improve efficiency, reduce environmental impact, and potentially lower refrigerant charge and leakage.
Propane (R290) and isobutane (R600a) are flammable refrigerants.	R134a, a non-flammable refrigerant with a good safety record, may be safely blended with Al_2O_3 nanoparticles if they are correctly disseminated throughout the refrigerant.
Due to its advantageous thermodynamic features, the R290 and R600a blend often provide great energy efficiency and excellent heat transfer characteristics, allowing for effective VCRS operation.	The addition of Al_2O_3 nanoparticles in R134a is aimed at enhancing its heat transfer capabilities, potentially increasing system efficiency, but its overall efficiency depends on various factors.

Exploring these avenues would contribute to more resilient and efficient refrigeration systems, addressing both economic and environmental challenges in the industry.

CONCLUSION

The study proposed a design for environment-friendly refrigerants, comparing performance with conventional system valve arrangement. The conventional system valve arrangement in a Vapor Compression Refrigeration System (VCRS) typically refers to the standard layout and types of valves used to control the pressure and flow of the refrigerant throughout the system. An arrangement of spiral condensers was employed in addition to in-series evaporators. Outcomes of system validation using the cool pack's software of the base case highlight performance in the allowable (10%) limit.

The major conclusions derived from the study project are as follows.

- The use of spiral condensers and series evaporators boosts the COP (Coefficient of Performance) of VCRS (Vapor Compression Refrigeration System) systems largely. The structure of the spiral condenser lifts the COP by 36% whilst the arrangement of the series evaporator lifts the Coefficient of Performance (COP) by 55%. When both enhancements are combined, they yield an excellent 77% improvement in the Coefficient of Performance (COP).
- Spiral condenser saves 19% of power as compared to conventional condenser existing in the system. If it is taken together with a series arrangement, power

consumption is reduced by 15%. This only suggests a significant betterment of energy efficiency with the new format of the system.

- In residential freezers, one possible replacement for R134a would be a hydrocarbon blend of propane and isobutane.
- Dispersed Al_2O_3 or ZnO outperformed standard working fluid mixtures.
- Redesign of the system including spiral condenser with in-series evaporators using R134a enhanced COP by 77% over conventional VCRS along with a 1.5-year payback period.
- Redesign of the system including spiral condenser with in-series evaporators using R134a along with nanofluid R134a enhanced COP by 137% over conventional VCRS along with a 1.1-year payback period.

This study redesigned a vapour compression refrigeration system, and chances brought about by spiral condensers and series evaporators did inform one of better energy efficiencies and mitigating greenhouse gas emissions with the adoption of low-GWP refrigerants. This means in turn significant value savings and great power efficiency, which will save consumers and companies significantly and will encourage the use of green technologies. Second, and more importantly, the findings of this study can inform manufacturers to develop the following generation refrigeration systems to be flexible in the changing operation, so that it will eventually lead to sustainable commercial and residential applications. It puts at the disposal of stakeholders who are eager to take energy-efficient refrigeration solutions toward practical application the most crucial literature, thus filling the gap between innovative design and practical application in the face of global challenges on climate.

NOMENCLATURE

HFC	Hydrofluorocarbon
GWP	Global Warming Potential
ODP	Ozone Depletion Potential
HCFC	Hydrochlorofluorocarbons
COP	Coefficient of Performance
$\dot{m}$	refrigerant mass flow rate
h	Enthalpy
Qc	Heat rejected in Condenser
Wc	Work Required for the Compressor
VCRS	Vapor Compression Refrigeration System
Qe	Heat absorbed in Evaporator
GWP	Global Warming Potential
TEWI	Total Equivalent Warming Impact
POE	Polyol ester oil
AHRI	Air Conditioning, Heating, & Refrigeration Institute

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.

REFERENCES

[1] Wongwises S, Chimres N. Experimental study of hydrocarbon mixtures to replace HFC-134a in a domestic refrigerator. Energy Convers Manag 2005;46:85-100. [Crossref]

[2] MM. Performance Improvement of VCRS Using Waste Heat Recovery Method. Int J Emerg Trends Eng Res 2020;8:1964-71. [Crossref]

[3] Srithar K, Rajaseenivasan T, Arulmani M, Gnanavel R, Vivar M, Fuentes M. Energy recovery from a vapour compression refrigeration system using humidification dehumidification desalination. Desalination 2018;439:155-61. [Crossref]

[4] Thangavel P, Somasundaram P, Sivakumar T, Kumar CS, Vetriselvan G. Simulation analysis of compression refrigeration cycle with different refrigerants. Int J Eng Innov Technol 2013;2:127-31.

[5] Malwe PD, Shaikh J, Gawali BS. Exergy assessment of a multistage multi-evaporator vapour compression refrigeration system using eighteen refrigerants. Energy Reports 2022;8:153-62. [Crossref]

[6] Kulkarni S, Chavali S, Dikshit S. A review on analysis of Vapour Compression Refrigeration System (VCRS) for its performance using different eco-friendly refrigerants and nanofluids. Mater Today Proc 2023;72:878-83. [Crossref]

[7] Islam MA, Mitra S, Thu K, Saha BB. Study on thermodynamic and environmental effects of vapour compression refrigeration system employing first to next-generation popular refrigerants. Int J Refrig 2021;131:568-80. [Crossref]

[8] Bolaji BO. Theoretical assessment of new low global warming potential refrigerant mixtures as eco-friendly alternatives in domestic refrigeration systems. Sci African 2020;10:e00632. [Crossref]

[9] Selloum A, Trıkı Z, Engineering YC-J of T, 2021 undefined. Thermodynamic analysis of a solar-driven vapour compression refrigeration system using R1234ze for cooling applications in the Ghardaïa region (Southern Algeria). DergiparkOrgTrA Selloum, Z Trıkı, Y ChıbaJournal Therm Eng 2021•dergiparkOrgTr 2024;10:130-41. [Crossref]

[10] Sánchez D, Andreu-Nácher A, Calleja-Anta D, Llopis R, Cabello R. Energy impact evaluation of different low-GWP alternatives to replace R134a in a beverage cooler. Experimental analysis and optimization for the pure refrigerants R152a, R1234yf, R290, R1270, R600a and R744. Energy Convers Manag 2022;256:115388. [Crossref]

[11] Wu D, Hu B, Wang RZ. Vapor compression heat pumps with pure Low-GWP refrigerants. Renew Sustain Energy Rev 2021;138:110571. [Crossref]

[12] Reddy DVR, Bhramara P, Govindarajulu K. Experimental Evaluation of the Effect of Refrigerant Charge and Capillary Tube Length on the Performance of Household Refrigerator with Different Configurations of R290 and R600a. Mater Today Proc 2018;5:11845-52. [Crossref]

[13] Mohanraj M, Jayaraj S, Muraleedharan C, Chandrasekar P. Experimental investigation of R290/R600a mixture as an alternative to R134a in a domestic refrigerator. Int J Therm Sci 2009;48:1036-42. [Crossref]

[14] de Paula CH, Duarte WM, Rocha TTM, de Oliveira RN, Mendes R de P, Maia AAT. Thermo-economic and environmental analysis of a small capacity vapour compression refrigeration system using R290, R1234yf, and R600a. Int J Refrig 2020;118:250-60. [Crossref]

[15] Gill J, Singh J. Energy analysis of vapour compression refrigeration system using a mixture of R134a and LPG as a refrigerant. Int J Refrig 2017;84:287-99. [Crossref]

[16] Logesh K, Baskar S, Md Azeemudeen M, Reddy BP, Jayanth GVSS. Analysis of Cascade Vapour Refrigeration System with Various Refrigerants. Mater Today Proc 2019;18:4659-64. [Crossref]

[17] Ozair Arshad M, Azam Q, Twaha Irfan Ahmad S, Khan F, Atif Wahid M. Analysis of vapour compression refrigeration system with R-12, R-134a and R-22: An exergy approach. Mater Today Proc 2021;46:6748-52. [Crossref]

[18] Ajayi OO, Ukasoanya DE, Ogbonnaya M, Salawu EY, Okokpujie IP, Akinlabi SA, et al. Investigation of the Effect of R134a/Al2O3 -Nanofluid on the Performance of a Domestic Vapour Compression Refrigeration System. Procedia Manuf 2019;35:112-7. [Crossref]

[19] Giménez-Prades P, Navarro-Esbrí J, Udroiu CM, Mota-Babiloni A. Influence of subcooling in R-449A supermarket refrigeration system and screening of refrigerant mixtures for its energetic and environmental improvement. Appl Therm Eng 2024;236:121787. [Crossref]

[20] Said Z, Rahman SMA, Sohail MA, Bahman AM, Alim MA, Shaik S, et al. Nano-refrigerants and nano-lubricants in refrigeration: Synthesis, mechanisms, applications, and challenges. Appl Therm Eng 2023;233:121211. [Crossref]

[21] Sivaraman N, Vaidyanathan RM, Patel M, Markos M. Performance analysis of refrigerants with various expansion valves in vapour compression refrigeration and air-conditioning system. Mater Today Proc 2021;45:2465-9. [Crossref]

[22] Garg I, Bajpai V. To Study Various Performance Parameters of a Vapor Compression Refrigeration System with Two Evaporators using R-134(a). J Basic Appl Eng Res n.d.;5:268-71.

[23] Subramanian S, Joswa Lazaras IP, Srinivasan S, Sundaresan D, Balakrishnan SK. Performance analysis of fin tube evaporator using various refrigerants. Therm Sci 2020;24:609-12. [Crossref]

[24] Goyal A, Sherwani AF. Optimization of energetic performance and payback period of organic Rankine cycle integrated vapour compression refrigeration system based on exergy, economic, and environmental criteria. J Therm Eng 2023;9:648-58. [Crossref]

[25] Chen X, Liang K, Li Z, Zhao Y, Xu J, Jiang H. Experimental assessment of alternative low global warming potential refrigerants for automotive air conditioners application. Case Stud Therm Eng 2020;22:100800. [Crossref]

[26] Ozsipahi M, Kose HA, Kerpicci H, Gunes H. Experimental study of R290/R600a mixtures in vapour compression refrigeration system. Int J Refrig 2022;133:247-58. [Crossref]

[27] Dhumane R, Ling J, Aute V, Radermacher R. Performance comparison of low GWP refrigerants for a miniature vapour compression system integrated with enhanced phase change material. Appl Therm Eng 2021;182:116160. [Crossref]

[28] Prasad US, Mishra RS, Das RK. Experimental studies of vapour compression refrigeration system with eco-Friendly primary refrigerant and brine mixed with nanoparticles as secondary refrigerant. Mater Today Proc 2021;45:3857-9. [Crossref]

[29] Yogesh Joshi, Dinesh Zanwar, Sandeep Joshi. Performance investigation of vapour compression refrigeration system using R134a and R600a refrigerants and Al_2O_3 nanoparticle-based suspension. Mater Today Proc 2021;44:1511-9. [Crossref]

[30] Gardenghi ÁR, Lacerda JF, Tibiriçá CB, Cabezas-Gómez L. Numerical and experimental study of the

transient behaviour of a domestic vapour compression refrigeration system - Influence of refrigerant charge and ambient temperature. Appl Therm Eng 2021;190:116728. [Crossref]

[31] Vandaarkuzhali S, Xavier JF, Ramadoss R, Jayaseelan V, Sudhakar K. Energy performance of R22 blended with nanofluids in the refrigeration system. J Optoelectron Biomed Mater 2021;13:33-44. [Crossref]