INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 12, Issue 3, 2021 pp.139-148
Journal homepage: www.IJEE.IEEFoundation.org

An analysis of alternative refrigerants to optimise the performance of a vapour compression refrigeration cycle

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Received 8 Sep. 2021; Received in revised form 21 Nov. 2021; Accepted 18 Dec. 2021; Available online 28 Dec. 2021

Abstract
This paper investigates the performance of alternative refrigerants with low Global Warming Potential and zero Ozone Depletion Potential. The application here is the working fluid in vapour compression refrigeration cycles. A vapour compression refrigeration cycle model was developed in MATLAB and tested with refrigerants R1234ze(E), R134a, R32, R407C and ECP410a. The performance of each refrigerant was analysed against the baseline refrigerant R134a using cooling capacity, coefficient of performance, Carnot coefficient of performance and compressor power as the performance parameters. The results show that the cooling capacity of the vapour compression refrigeration cycle can be successfully optimized by 159.44% with ECP410a, 70.28% with R32 and 5.96% with R407C. The tests also demonstrated that an increase in coefficient of performance of 28.05% with ECP410a, 217.92% with R32 and 32.21% with R407C can be achieved. Whereas the results showed that the use of R1234ze(E) yielded a decrease in performance of -9.52% for cooling capacity and -16.10% for coefficient of performance. It was also determined that the use of R32 could yield a decrease in compressor power by 46.50%.

Keywords: Refrigerants; Vapour Compression Refrigeration Cycle; Azeotropic; Low Global Warming Potential; Zero Ozone Depletion Potential; MATLAB; CoolProp.

1. Introduction

Global refrigerant consumption is on the rise as the markets for room air conditioners and industrial refrigeration are rapidly increasing and automotive vehicles are becoming more sophisticated [1, 2]. In 2015 R. Agarwal et al conducted a study on global refrigerant consumption and determined that 4345kt was consumed annually, emitting 861kt of CO_2 emissions per year [3].

The releasing of CO_2 emissions and the potent greenhouse gases associated with the use of HFC refrigerants is contributing to 13% of man-made global warming [4]. This alarming statistic has led to mass research to find refrigerants with low Global Warming Potential (GWP) and zero Ozone Depletion Potential (ODP). Fourth generation refrigerants with these characteristics are being investigated when acting as the working fluid in Vapour Compression Refrigeration Cycles (VCRC) but recent research indicates that potential for synthesis of the current fourth generation refrigerants is unlikely, therefore new compositions must be investigated [5].

The VCRC are the most common cycle found in air conditioning systems and equates to almost 80% of the industrial refrigeration sector [6]. The physical model of the cycle comprises of; a compressor, condenser, expansion valve and evaporator connected by a PVC pipe to transport the working fluid.

Enhancement of a vapour compression refrigeration cycle using refrigerants with attractive thermophysical properties offers a promising way to increase the cooling capacity and efficiency of the system. Past research has focused on improving the VCRC's cooling capacity and COP using altered fluid selection [4], [7, 8]. This research has spanned four decades with the first notable findings coming from E Wali's work, using CFC refrigerants [9].

The aim of this study was to conduct a performance analysis using a numerical model, to optimise a vapour compression refrigeration cycle's cooling capacity and COP, using a selection of alternative refrigerants. The performance of the conceptual cooling system was analysed using cooling capacity, COP, and compressor power as the performance indicators.

Four alternative refrigerants with low GWP and zero ODP were selected using the criteria outlined by Kilicarslan and Müller [10]. Their performance was analysed against the baseline refrigerant R134a. Some of the first investigations into using refrigerant mixtures to improve VCRC performance was conducted by Jung et al, who used their work to find alternative refrigerants for R22. Seven of these blends contained R1270 in their composition. The results showed that the highest COP could be achieved with a composition containing 45% R1270, 40% R290, 15% DME followed by a composition containing R1270 and 20% R290. Finding alternatives to R22 was progressed 15 years later by Joudi et al [11], who determined that the refrigerant R407C performed closest to R22 in terms of COP, cooling capacity and power consumption, followed by R410a.

Further research into refrigerants containing R1270 in its composition, was conducted by Cox et al [4]. This work focused on finding azeotropic and near azeotropic refrigerant blends with low GWP and zero ODP to increase their cooling capacity and COP. It was determined that the azeotropic blend of 75% R1270 and 25% R161, termed ECP410a was the most suitable for domestic and industrial air conditioning systems, increasing the cooling COP of the refrigerant 6-10% compared to its predecessor R410a [4]. Whilst the results from this paper are promising, since its development in 2008 there has been no analysis conducted to determine the performance of ECP410a when acting as the working fluid in a VCRC model.

Commonly when investigating VCRC performance using altered refrigerant selection, researchers have used experimental techniques and mathematical models, comparing the results against a baseline refrigerant [7], [12-14]. Li et al [14] modelled a 0.64mm microchannel tube and analysed the heat transfer coefficient results produced by R1234ze(E), R32 and R134a, determining that the use of R32 would increase the performance of the VCRC.

A numerical model of the VCRC was developed in MATLAB and validated against a manual calculation using refrigerant R134a as the baseline fluid. Analysing a systems performance using theoretical models is a crucial stage in the development process and is known to have a profoundly positive impact on the design optimization of the refrigeration system, pre-fabrication [15]. Many past research works have successfully used dynamic simulation models and theoretical models built in MATLAB to research a refrigeration system's performance [14-18].

There were several assumptions made during this calculation. Each component within the system is assumed to be analysed as a control volume at steady state. It was assumed that there were no pressure drops which occurred across the evaporator or condenser. The compressor operates isentropically with an efficiency of 80% [19]. The refrigerant undergoes a throttling process as it passes through the expansion valve. It was assumed that kinetic and potential energy are negligible. It was also assumed that the refrigerant enters the compressor as a saturated vapour and leaves the condenser as a liquid.

2. Methodology

2.1 The VCRC

A model of the VCRC was developed in MATLAB (R2020b), using equations 1, 4, 5 & 6 shown below. This methodology followed work carried out by Mba et al [17], which successfully optimized a refrigeration system's performance using MATLAB.

The VCRC operates under a reverse Rankine cycle. The waste heat is rejected from the system to an external area known as the hot reservoir (T_H) and heat is extracted from the cold reservoir (T_C) creating a cooling effect for the selected space.

Figure 1 presents a T-s diagram for the VCRC and shows the four processes the refrigerant undergoes during the cycle. Each of these processes are described by a set of equations (1-4).

The diagram below (Figure 1) presents the saturation vapour curve of the fluid, the area to the left of the curve denotes the subcooled region and the area to the right denotes the superheated region. Each saturation curve is unique for different refrigerants because of their differing compositions, this causes a variation in cooling capacity under the same operating conditions [18].

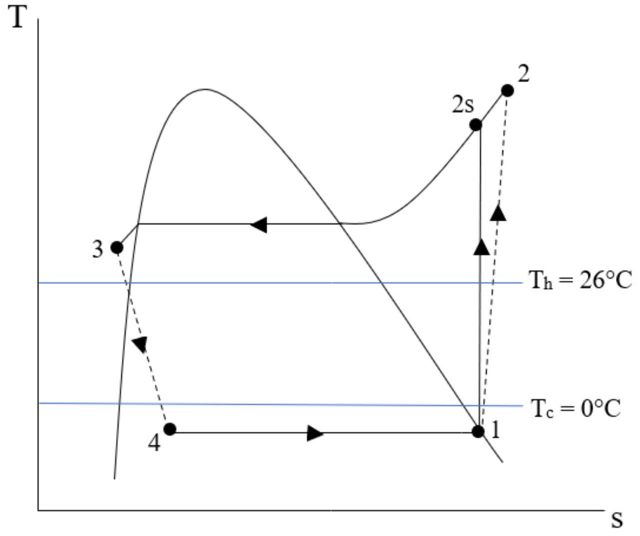

Figure 1. T-s diagram showing the four processes of the VCRC.

State 1-2s

Equation 1 was used as a performance parameter in this paper to calculate the power required to isentropically compress the refrigerant from state 1-2s. The theoretical model of the VCRC assumes that this is an adiabatic process.

$$W_c = \dot{m}(h_{2s} - h_1) \tag{1}$$

where W_c is the compressor power (kW), $\dot{m}$ is the mass flow rate (kg/s), h_{2s} is the enthalpy at state 2s (kJ/kg), h_1 is the enthalpy at state 1 (kJ/kg).

State 2-3

Equation 2 describes the isothermal heat rejection to the cooler surroundings as the refrigerant passes through the condenser and condenses into a subcooled liquid. This equation was not used as a performance parameter in this paper.

$$Q_{out} = \dot{m}(h_2 - h_3) \tag{2}$$

where Q_{out} is the heat energy rejected from the cycle (kW), $\dot{m}$ is the mass flow rate (kg/s), h_2 is the enthalpy at state 2 (kJ/kg), h_3 is the enthalpy at state 3 (kJ/kg).

State 3-4

$$h_4 = h_3 \tag{3}$$

where h_4 is the enthalpy at state 4 (kJ/kg), h_3 is the enthalpy at state 3 (kJ/kg).
The refrigerant undergoes an irreversible adiabatic expansion as it passes through the expansion valve. There is no work done on the system and theoretically no heat transfer therefore, enthalpy between state 3 and 4 remains constant.

State 4 to 1

$$Q_{in} = \dot{m}(h_1 - h_4) \tag{4}$$

where Q_{in} is the cooling capacity (kW), $\dot{m}$ is the mass flow rate (kg/s), h_1 is the enthalpy at state 1 (kJ/kg), h_4 is the enthalpy at state 4 (kJ/kg).

Equation 4 describes the isothermal heat absorption process as the refrigerant passes through the evaporator, creating a cooling effect for the external space.

The cooling capacity (Q_{in}) was used as a performance parameter in this paper to measure the change in performance of the VCRC between the test refrigerant and the base line refrigerant.

The remaining performance parameters used in this paper are COP (Equation 5) and the Carnot COP (Equation 6).

$$\beta = \frac{Q_{in}}{W_c} = \frac{h_1 - h_4}{h_2 - h_1} \tag{5}$$

The COP (5) was used to calculate the ratio of useful cooling (Qin) to the compressor power input (Wc). Achieving a high COP is desirable as it means that the system has a high efficiency and as a result will generate lower operating costs.

$$\beta_{max} = \frac{T_C}{T_C - T_H} \tag{6}$$

The Carnot COP (6) represents the maximum theoretical COP achievable by a refrigeration cycle, operating between T_C and T_H. The Carnot COP was compared with the COP to analyse the performance of the VCRC. Riffe [17] performed a study on the relationship between the Carnot Cycle and the actual VCRC and determined that the Carnot COP does not set a limit for the maximum COP a refrigeration system can achieve. This means that theoretically a refrigerant can achieve a COP which exceeds the Carnot COP for that VCRC.

2.2 The manual calculation

The manual calculation was performed using R134a as the working fluid, this refrigerant was later used as a baseline to compare with four more refrigerants. Equations 1-6 were used to generate values for the four VCRC processes and Qin, β, βmax and W_c were used as the performance parameters.

Table 1 shows the input conditions used to solve the equations described above. All quantities are measured in SI Units.

Table 1. Input conditions for the manual calculation.

Symbol	Definition	Value	Units
T_1	Temperature at state 1	263	K
T_3	Temperature at state 3	303	K
P_2	Pressure at state 2	9e5	Pa
$\dot{m}$	Mass flow rate of the refrigerant	0.08	Kg/s
$\eta_{compressor}$	Efficiency of the compressor	0.8	No dimension

2.3 Development and Validation of the Numerical Model in MATLAB

MATLAB was used in this paper to develop and validate a numerical model of the VCRC. The methodology follows previous successful research which used MATLAB to analyse the performance of refrigeration systems [20].

To generate the thermodynamic properties of each refrigerant, CoolProp was used within the MATLAB software.

CoolProp has been used for fluid modelling within refrigeration systems in many research works [21-25]. The fluid modelling is based on the Helmholtz energy formulations (Equations 7 and 8) to construct the equation of state.

$$\frac{h}{RT} = \frac{u}{RT} + \frac{p}{\rho RT} \tag{7}$$

where h is enthalpy (kJ/kg), R is the ideal gas constant (J/mol.K), T is the temperature (K), p is the pressure (Pa), ρ is the density (kg/m^3).

$$\frac{s}{R} = \tau\left[\left(\frac{\partial\alpha^0}{\partial\tau}\right) + \left(\frac{\partial\alpha^r}{\partial\tau}\right)_\delta\right] - \alpha^0 - \alpha^r \tag{8}$$

where s is entropy (kJ/kg.K), R is the ideal gas constant (J/mol.K), τ is the time constant (s), ∂ is a partial derivative, α^0 is the ideal gas contribution, α^r is the residual helmoltz energy contribution and δ is a functional derivative.

Each of the four processes of the cycle were described in MATLAB to calculate the enthalpy, entropy, temperature, and pressure at each state. CoolProp was used by the MATLAB script to provide the required parameters. Refrigerant R134a was used first to validate the model against the manual calculation and its performance used as a baseline to compare against the other four refrigerants.

A performance evaluation of the VCRC was conducted using equations 1, 4-6. The results were used to validate the model against the manual calculation.

2.4 Selection and testing of different refrigerants

This section addresses the need to investigate the performance of refrigerants with low GWP and zero ODP in a VCRC. The following criteria in Table 2 was chosen to identify a selection of 'ideal' refrigerants for use in VCRC.

A summary of the refrigerant's fundamental characteristics is shown below in Table 3.

Table 2. Criteria for refrigerant selection.

Performance	**Safety**	**Environmental**	**Cost**
High critical temperature	Non- Toxic	Zero ODP	Low cost
Low normal boiling point	Low flammability	Low GWP	

Table 3. Refrigerant's fundamental characteristics.

Characteristics	R134a	R1234ze(E)	R32	R407C	ECP410a
Composition [% mass]	100%	100%	100%	23% R32 25% R125 52% R134a	25% R161 75% R1270
Molecular Weight [kg/kmol]	102.03	114	52.0	86.2	43.6
Normal Boiling Point [°C]	-26.4	-19.3	-51.7	-43.7	-49.2
Critical Temperature [°C]	101.1	109.4	78.1	86.0	94.9
ASHRAE Safety Class	A1	A2L	A2	A1	A3
GWP	1430	6	675	1600	~7
ODP	0	0	0	0	0
Ref	[26, 27]	[26, 28]	[29, 30]	[31, 32]	[4]

The four additional refrigerants were analysed in MATLAB using the same mathematical model and input conditions as R134a. R134ze(E), R32 and R407C used the same code written for R134a.

ECP410a used different code to develop the mathematical model as the interaction parameters for 75% R1270 and 25% R161 were not available in CoolProp.

The mixture modelling performed in CoolProp is derived from the work of Lemmon et al [33-37]. CoolProp uses information from the excess Helmholtz energy term and the reducing function for each pair of components in the mixture, to construct an equation of state.

The code for ECP410a was developed first by setting own binary parameters for the mixture using the 'set mixture binary pair data function' in CoolProp. The Boolean configuration variable was then set by changing the function "*overwrite binary interaction*" to true.

A parameter designated "AbstractState" was then constructed for R1270 and R161 using the low-level interfact and conventional root finding. An instance of the multi fluid mixture model was created with the binary interaction parameters 75% R1270 and 25% R161. The mole fractions were then applied, and a pressure-temperature flash calculation was performed using the temperature at state 2s as 314K and the pressure at state 2 as 9e5 Pa, to internally calculate density specific entropy at state 2 and specific enthalpy at state 2s.

Once the AbstractState was constructed the interaction parameters were set by calling the ‘set binary interaction double’ and ‘get binary interaction double’ functions in CoolProp. Solving the thermodynamic properties at states 1, 2, 3 and 4 the performance parameters were calculated using the same script as the previous refrigerants.

3. Results and Discussion

The reviewed literature indicated that there is a need for more investigation into the optimisation of the VCRC cooling capacity and COP, using alternative refrigerants with low GWP and zero ODP. A model of the VCRC was developed and analysed using MATLAB and CoolProp. Five separate simulations were carried out using R134a, R1234ze(E), R32, R407C and ECP410a as the working fluids and their performance was analysed against the baseline refrigerant R134a.

3.1 Cooling Capacity

The cooling capacities (Equation 4) produced by the tested refrigerants are presented below in Figure 2. A stated in section 2.2, the input conditions were the same throughout each test. The data was generated by the theoretical model of the VCRC built in MATLAB.

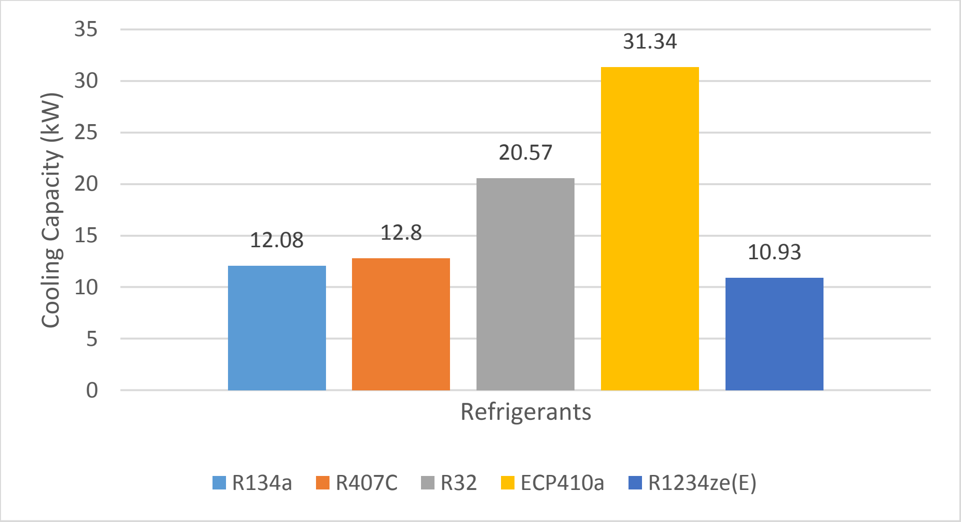

Figure 2. Graph comparing the cooling capacities of the tested refrigerants.

Figure 2 shows that refrigerants R32, R407C and ECP410a were successful in increasing the cooling capacity of the VCRC, compared with the baseline refrigerant R134a.

ECP410a produced the highest cooling capacity out of the refrigerants at 31.34kW, increasing 159.4% from the baseline refrigerant R134a. The large increase in performance and the low GWP and zero ODP characteristics make this refrigerant an attractive alternative to R134a. This result also supports Cox et al [4] who concluded that ECP410a would produce a high cooling capacity.

R32 produced the second highest cooling capacity at 20.57kW, increasing 70.3% from R134a. This result comes from the decreased compressor power and high COP (outlined in sections X). This result supports Li and Hrnjack’s previous work [14] who determined that the high heat transfer coefficient compared with R134a and R1234ze(E) would yield an increase in performance.

R407C produced a cooling capacity of 12.8kW, only 5.96% higher than R134a. It is predicted that the zeotropic nature of the refrigerant caused a temperature glide across the evaporator and as such yielded a large decrease in cooling capacity. This result supports Nowak and Zyczkowski [38] who found that the temperature glide exhibited at a pressure between 8-10bar would yield a negative reduction in performance.

R1234ze(E) was tested as a low GWP alternative to R134a. This refrigerant yielded a reduction of -9.52% in cooling capacity compared with R134a, performing the worst out of the five refrigerants. Past research has shown that the cooling capacity of R123ze(E) could be increased to the same result as R134a with the implementation of a compressor with a higher displacement [13] making it a more viable environmentally friendly alternative to R134a. Table 4 presents the percentage change in cooling capacity from the baseline refrigerant R134a.

Table 4. Refrigerant Cooling Capacities.

Refrigerant	Cooling Capacity (kW)	% Change from R134a
R134a		0
R407C	12.8	+5.96
R32	20.57	+70.28
ECP410a	31.34	+159.44
R1234ze(E)	10.93	-9.52

3.2 COP

The COP (Equation 5) results for each of the tested refrigerants are presented below in Figure 3.

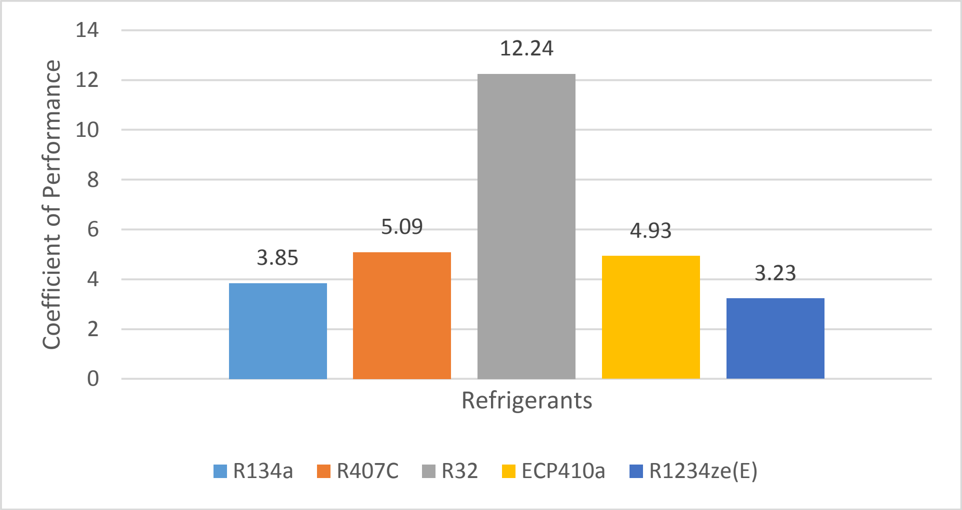

Figure 3. A graph comparing the COP of each of the tested refrigerants.

Refrigerants R32, R407C and ECP410a yielded a positive increase in COP from the baseline refrigerant R134a.

R32 produced the highest COP out of the five refrigerants at 12.24, increasing 217.9% from the baseline refrigerant R134a. The high COP result demonstrates the relationship between cooling capacity and compressor power and indicates that the VCRC can operate with high efficiency, reducing operating costs.

R407C produced the second highest COP at 5.09, yielding an increase of 32.2% from R134a. This refrigerant has a high critical temperature of -49.2°C and low condenser pressure, resulting in a smaller compressor size. This indicates the reason for the increase in COP despite the low cooling capacity.

ECP410a produced a COP of 4.93, yielding an increase of 28.1% from the baseline refrigerant R134a. This result was low compared to that produced by R32 and indicates that the refrigerant is not extremely effective in increasing the efficiency of the system and would be likely to incur large operating costs.

R1234ze(E) caused a decrease in performance of the system, with the COP falling 16.1% below that of R134a.

Table 5. Refrigerant's COP.

Refrigerant	COP	% Change from R134a
R134a	3.85	0
R407C	5.09	+32.21
R32	12.24	+217.92
ECP410a	4.93	+28.05
R1234ze(E)	3.23	-16.10

3.3 Carnot COP

Table 6 shows the percentage difference between the actual COP and the Carnot COP (Equation 6) of the system using each refrigerant.

Table 6. The percentage difference between the actual COP and the Carnot COP.

Refrigerant	COP	Carnot COP	% Difference
R134a	3.85	10.5	-63.33
R407C	5.09	10.5	-51.52
R32	12.24	10.5	+16.57
ECP410a	4.93	10.5	-53.05
R1234ze(E)	3.23	10.5	-69.24

R32 was the only refrigerant to yield a positive increase of 16.57%. This result was not expected but proved Riffe's theory [39] which states that the Carnot COP does not set a boundary for how well a refrigeration system can perform. The use of R1234ze(E) resulted in a -69.24% difference between the Carnot COP and the actual COP. This result was expected and validated the trend in the decrease in performance of the VCRC when using R1234ze(E), compared with R134a. The increase in COP for both R407C and ECP410a compared with R134a meant that performance of the VCRC moved closer to the theoretical COP limit (Carnot COP). This yielded a difference between the COP and Carnot COP of 51.52% for R407C and 53.05% for ECP410a.

3.4 Compressor Power

Table 7 presents the compressor power (Equation 1) results for each of the five tested refrigerants.

The use of R407C, R32 and R1234ze(E) reduced the compressor power lower than the baseline refrigerant R134a. The largest reduction in compressor power in 46.5% came from R32 with the relationship between COP and cooling capacity indicates the reason for this.

Both ECP410a and R1234ze(E) increased the power required to compress the refrigerant by 102.55% and 7.64% respectively.

Table 7. Compressor Power.

Refrigerant	Compressor Power (kW)	% Change from R134a
R134a	3.14	0
R407C	2.51	-20.06
R32	1.68	-46.50
ECP410a	6.36	+102.55
R1234ze(E)	3.38	+7.64

4. Conclusion

This paper addressed the need for research into the optimisation of a VCRC using new fourth generation refrigerants. The reviewed literature indicated that ECP410a could produce a high cooling capacity [4], but there was little knowledge of its performance in a VCRC model. The results from this paper indicate that the VCRC's performance in terms of cooling capacity and COP can be successfully optimised with the use of R32, R407C and ECP410a. The largest increase in cooling capacity came with the use of ECP410a making it suitable for high ambient temperature applications. However, this refrigerant required the largest compressor size indicating that there will be large operating costs. It is recommended that a further theoretical study be conducted assessing the performance of refrigerant ECP410a with a smaller pressure ratio to try and reduce the compressor power consumption and subsequent compressor size. The aim of this is to improve the economic feasibility of the refrigerant. The use of R32 yielded the highest COP and the smallest compressor power results. The overall effect of these results means that the system size and cost is significantly reduced compared with R134a, making it more economically feasible. Future research could be conducted to try and increase the cooling capacity of R32 by altering the evaporator temperature. This paper performed a theoretical analysis of the VCRC using a mathematical model, therefore, did not analyse the possible degradation of the refrigerant's cooling capacity with increasing ambient temperature. It is recommended that further research be carried out to assess this effect using ECP410a and R32 as the test refrigerants.

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