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Efficiency Evaluation and Environmental Impact of Various Ecofriendly Single-Refrigerants as Alternatives to Replace R134a in Mechanical Vapor Compression Refrigeration Machine

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Abstract: *This study focuses on energy performance investigation and environmental impact analysis of various single-refrigerants (R1234yf, R1234ze, R161 and R13I1) as possible alternatives to high global warming potential refrigerant R134a. To reach this objective, a numerical model is developed to evaluate and compare the cycle performance parameters of the single-refrigerants considered in this work with R134a, like cooling capacity, coefficient of performance, volumetric refrigerating capacity and the pressure ratio. The comparison was made at evaporating temperatures (Te) ranging from (-10 to 10 °C) and the constant condensation temperature (Tc) of 50 °C. The results proved that the application of R161 exhibited a higher of COP, cooling capacity, volumetric refrigerating capacity, as well as lower pressure ratio compared with R134a, which confirms that it could be a good suitable substitute for the R134a in terms of cycle performances and environmental protection.*
Keywords: Single-Refrigerants, Environmental Impact, Vapor compression system, Energy efficiency, Volumetric refrigerating capacity

Résumé : *Cette étude se concentre sur l'étude de la performance énergétique et l'analyse de l'impact environnemental de divers réfrigérants pure (R1234yf, R1234ze, R161 et R13I1) comme alternatives possibles au réfrigérant R134a qui a un potentiel de réchauffement global élevé. Pour atteindre cet objectif, un modèle numérique est développé pour évaluer et comparer les paramètres de performance du cycle des réfrigérantes pures considérées dans ce travail avec le R134a, comme la capacité de refroidissement, le coefficient de performance, la capacité de réfrigération volumétrique et le rapport de pression. La comparaison a été faite à des températures d'évaporation (Te) allant de (-10 à 10 °C) et à une température de condensation constante (Tc) de 50 °C. Les résultats ont prouvé que l'application du R161 présentait un COP, une capacité de refroidissement, une capacité de réfrigération volumétrique plus élevés, ainsi qu'un rapport de pression inférieur par rapport au R134a, ce qui confirme qu'il pourrait être un bon substitut approprié au R134a en termes de performances de cycle et protection environnementale.*
Mots-clés : Réfrigérants pure, Impact environnemental, Système de compression de vapeur, Efficacité énergétique, Capacité frigorifique volumétrique,

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Introduction

Most refrigeration and air-conditioning systems in the refrigeration engineering are based on the mechanical vapor compression refrigeration cycles, which depend on the performance of refrigerants that are safe, chemically stable, have good thermodynamic and thermo-physical properties. Chlorofluorocarbons (CFCs) and hydro-chlorofluorocarbons (HCFCs) have been applied extensively as refrigerants in these systems from 1930s, as a result of their outstanding thermodynamic, thermo-physical and safety properties. These refrigerants largely replaced the toxic sulphur dioxide and ammonia, the less cyclically efficient carbon dioxide, and the flammable hydrocarbons (R600a, R290) used earlier in the century ((H. Pham et al, 2010), (B.O. Bolaji et al, 2012)). Since 1987, refrigerants are experiencing new constraints due to global environmental concerns. These chlorine containing fluorinated hydrocarbon refrigerants (CFCs and HCFCs) was found to diffuse up into the stratosphere. The chlorine content of the refrigerants was the principal cause of destruction of the stratospheric ozone, which absorbs the sun's high-energy ultraviolet rays and protects both humans and other living things from exposure to ultraviolet radiation. The hazard is represented by the refrigerant ozone depletion potential (ODP) number ((J.T.McMullan, 2002), (M. Padilla et al, 2010), (K. Kim et al, 2011)). The protection of stratospheric ozone under the Montreal Protocol has led to the phase-down of CFCs and HCFCs. CFCs have been banned in the industrial field and especially the refrigeration industry all over the world since 2010. HCFCs, despite their low ODP, have been banned from equipment of refrigeration as of 1 January 2010, and they will also be phased out internationally, in the developed countries by 2024, in the developing countries by 2030. Many chemicals have been considered as alternative refrigerants over the decades and the selection of replacement refrigerants has been encouraged to avoid the shortcomings of the previous ones CFCs and HCFCs, which were the two most used groups of refrigerants, were replaced in most applications with refrigerant R134a (HFC), due to their zero ODP, which is appealing ((T. Sivasakthivel, 2011), (B.O. Bolaji, 2012)). However, the refrigerant R134a have come under scrutiny for their contribution to greenhouse gases. While they were entirely harmless to the ozone layer, they did have large global warming potential (GWP) and are regulated by the international Kyoto Protocol (1997) (WT. Tsai, 2013). It is known that halocarbons (CFCs, HCFCs and HFCs) accounted for 12% of the radiative forcing produced by the increased levels of globally mixed long-lived greenhouse gases from 1750 to 2009. Due to the phase-out of CFCs, their atmospheric concentrations are diminishing, while those of HCFCs and HFCs are increasing speedily (G. Saviano et al, 2018).

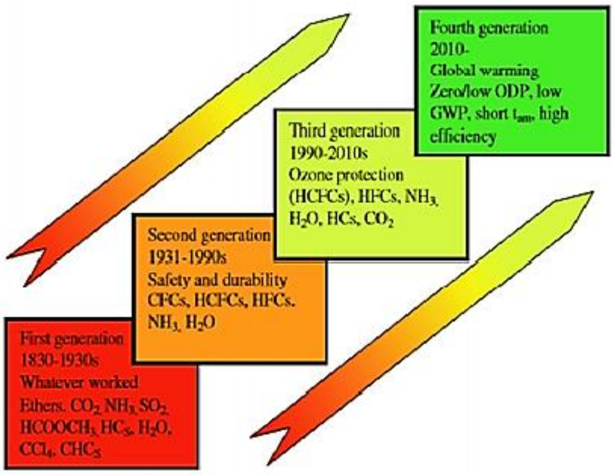

Figure (1): Evolution of refrigerants

The global concern about the increasing impact of mankind on the warming of our atmosphere has forced the refrigeration industry to begin searching for alternatives with a lower GWP. The researchers have to revisit the use of long-term alternative refrigerants that are favorable for the environment. The current search for environmentally friendly refrigerants is driven by the recent approval of increasingly restrictive regulations that limit the use of substances with high global warming potential (GWP), and the need to maintain high process efficiencies.

On the other hand, there is a renewed interest in the use of single-refrigerants (R1234yf, R1234ze, R161 and R13I1) as the working fluids in the thermodynamic systems. Where we can see that those fluids has excellent thermo-physical properties (M. Mohanraj et al, 2011), good safety and negligible environmental impact [Zero Ozone Depletion Potential, Low Global Warming Potential] (G. Saviano et al, 2018), so it is considered as an alternative refrigerants. Considering the increasing restrictions imposed by the international Montreal and Kyoto protocols, the refrigerants can be selected as possible new working fluids in the mechanical vapor compression refrigeration system and can be recommended as a good candidate for replacing the above working fluids and especially the R134a (HFC) synthetic refrigerant which has a typical GWP of 1430 (G. Saviano et al, 2018) and widely used in refrigeration engineering.

The purpose of this study is to investigate and evaluate theoretically the thermodynamic performances of the mechanical vapor compression refrigeration system using the ecofriendly refrigerants (R1234yf, R1234ze, R161 and R13I1) as a new working fluid and compare it with the traditional R134a fluid which has high performances, where we will study the cycle performance parameters of each fluids under the same given operating conditions. Additionally, the environmental impact, are also examined.

1. Cycle Description and Refrigerants Selection

1.1. Mechanical Vapor Compression Refrigeration System

The mechanical vapor compression refrigeration system is the most commonly used among all refrigeration systems. In this system, the refrigerant is mentioned in the state of liquid and vapor. It must readily evaporate and condense or change alternately between the vapor and liquid phase without leaving the system. Fig.2 illustrates the main components of the mechanical vapor compression refrigeration system (B.O. Bolaji, 2015), namely compressor, condenser, expansion device, and evaporator.

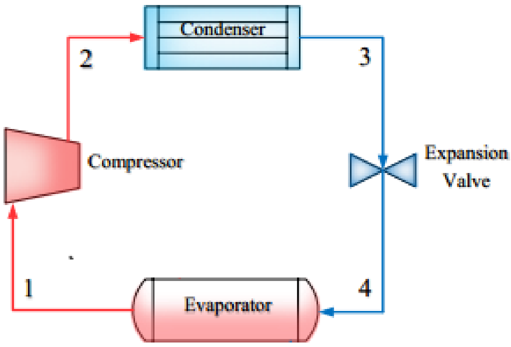

Figure (2): Schematic of mechanical vapor compression refrigeration system

The refrigerant vapor at low temperature and low pressure enters the compressor (state 1) where it is compressed to high temperature and high pressure (Fig.3). The high temperature refrigerant vapor then enters the condenser (state 2) where it is condensed to high pressure liquid. The high pressure liquid refrigerant then enters into the expansion valve (state 3) where its pressure is decreased. Ultimately the liquid refrigerant will attain lower temperature. This low temperature liquid refrigerant absorbs the latent heat from the evaporator (state 4) undergoes phase change to vapor state and produce cold (B.O. Bolaji et al, 2017).

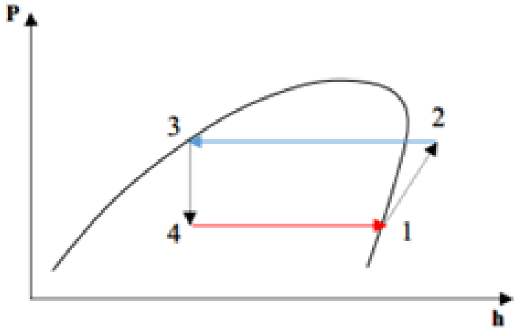

Figure (3): Pressure-enthalpy (P-h) chart of mechanical vapor compression refrigeration system

1.2. Single-Refrigerants

Refrigerant selection is very important, since it directly influences on the environment (ozone depleting potential and global warming potential) and performances of the Vapor compression refrigeration system such as coefficient of performance. The choice of the working fluid is a complex problem, because that do not meet modern environmental requirements.

Recently,single-refrigerants (R1234yf, R1234ze, R161 and R13I1) attract attention due to their thermo-physical properties, zero ozone depleting potential (ODP) and low global warming potential (GWP). Table 1 shows the fundamental thermodynamic and environmental properties of the inspected refrigerants ((G. Saviano et al, 2018), (M. Mohanraj et al, 2011), (J.M. Calm, 2008), (J.M. Calm, 2011)).

Table (1): Environmental characteristics and physical properties of investigated refrigerants

Refrigerant	*Molecular formula*	*Tc [K]*	*Pc [MPa]*	*GWP*	*ODP*
R1234yf	$C_2H_2F_4$	367.85	3.3823	4	0
R1234ze	$C_2H_2F_4$	382.52	3.6349	6	0
R161	C_2H_5F	375.25	5.040	12	0
R13I1	CF_3I	396.44	3.95	0	0
R134a	$C_2H_2F_4$	374.30	4.06	1430	0

As we can see from the table, the single-refrigerants (R1234yf, R1234ze, R161 and R13I1) exhibits a GWP lower than 1430 ,which allows us to say that the single-refrigerants can be recommended as the replacing refrigerant in terms of environmental protection of R134a which has high global warming potential (GWP=1430).
The simulation of the mechanical vapor compression refrigeration system operation using the above single-refrigerants will be discussed in the next section.

2. Assumptions and Energy Analysis

2.1. Assumptions

For the sake of simplification of the thermodynamic analysis of the mechanical vapor compression refrigeration system, the following assumptions were made:

- The single-refrigerants at the evaporator and the condenser outlet is in saturation conditions;
- The pressure loss is negligible in the condenser, the evaporator and the pipes;
- The variations in kinetic and potential energy are not considerable;
- The transformations in the heat exchangers are isobaric process (*P*= constant);
- The compression in the compressor is isentropic process (*s*= constant);
- The flow through in the expansion valve is isenthalpic process.

According to the above considerations, the equations for the main components of the mechanical vapor compression refrigeration system can be obtained.The mathematical model of the system will be discussed in the next section.

2.2. Energy Analysis Models

The mathematical computations used for the evaluation of thermodynamic performance characteristics of mechanical vapor compression refrigeration system are listed below :

The heat absorbed by the single-refrigerant is calculated as:

$$Q_{evap} = \left(h_1 - h_4\right) \qquad (1)$$

The work input to compressor is calculated by:

$$W_{comp} = \left(h_2 - h_1\right) \qquad (2)$$

The flow of the single-refrigerant in the expansion valve from point 3 to point 4 is isenthalpic (h= constant). Therefore,

$$h_3 = h_4 \qquad (3)$$

The volumetric refrigeration capacity (VRC) is computed by:

$$VRC = \rho_1 Q_{evap} \qquad (4)$$

The coefficient of performance of the mechanical vapor compression refrigeration system is determined by the following relation:

$$COP = Q_{evap} / W_{comp} \qquad (5)$$

In order to verify the cycle performance parameters of single-refrigerants (R1234yf, R1234ze, R161 and R13I1) and the refrigerant R134a, a simulation program written in MATLAB is constructed to compute the performances of the single-refrigerants.The flow chart of computational procedure is shown in Fig.4.

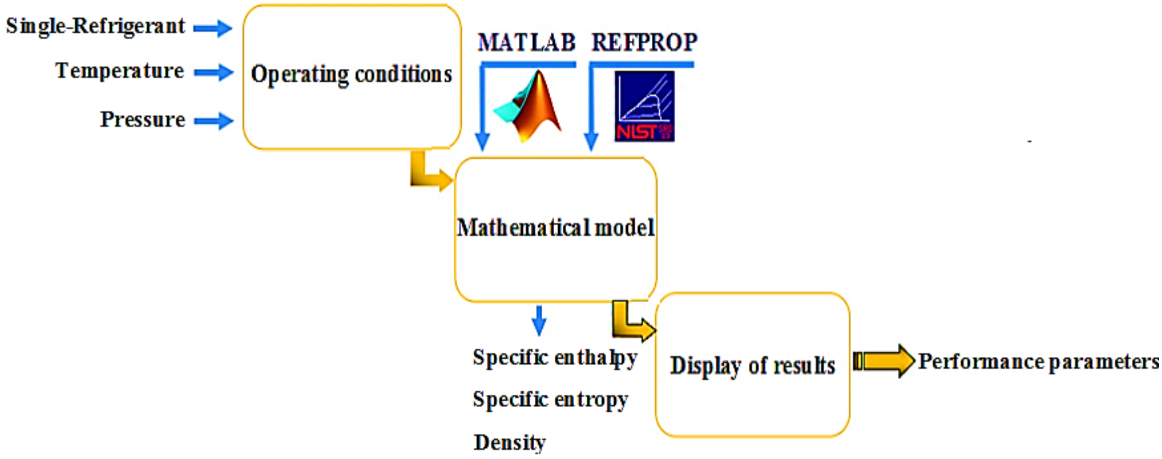

Figure (4): Flow chart of computational procedure

3. Results and Discussion

3.1. Validation

Before presenting the results of the cycle performance parameters of mechanical vapor compression refrigeration system working with various alternative single-refrigerants, a brief discussion on the validation of the simulation program written in MATLAB would be appropriate. The present numerical model is verified with the test results data available of Dalkilic and Wongwises (A.S. Dalkilic and S. Wongwises, 2010) using R22 as refrigerant with the same operating conditions (evaporation temperatures vary from -10 to 10 °C and the constant condensation temperature of 50 °C).

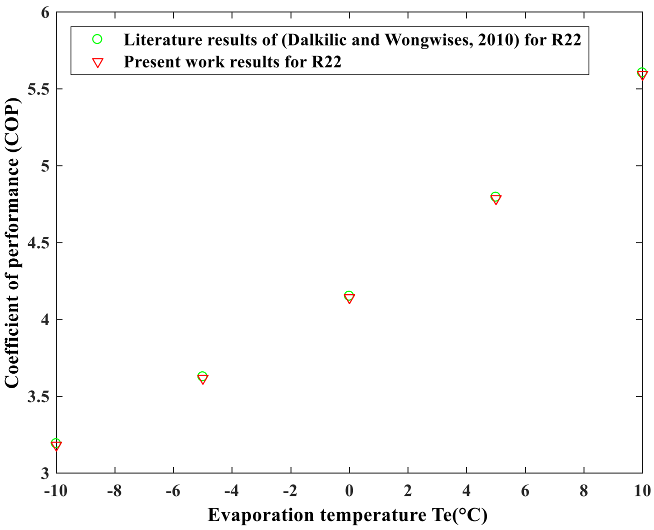

Figure (5): Validation of present program results with (Dalkilic and Wongwises, 2014) results

From the Fig.5, it was observed that present work results of the COP of refrigerant R22 for various evaporator temperatures (-10 to 10 °C) exhibit good agreement with literature results, which confirms the validity of our simulation model.

3.2. Performance Characteristics of Single-Refrigerants

The following section presents the results of the comparative evaluation of single-refrigerants (R1234yf, R1234ze, R161 and R13I1) with R134a in the mechanical vapor compression refrigeration system, where we investigated various performance parameters of single-refrigerants for different evaporator temperatures (-10 to 10 °C).

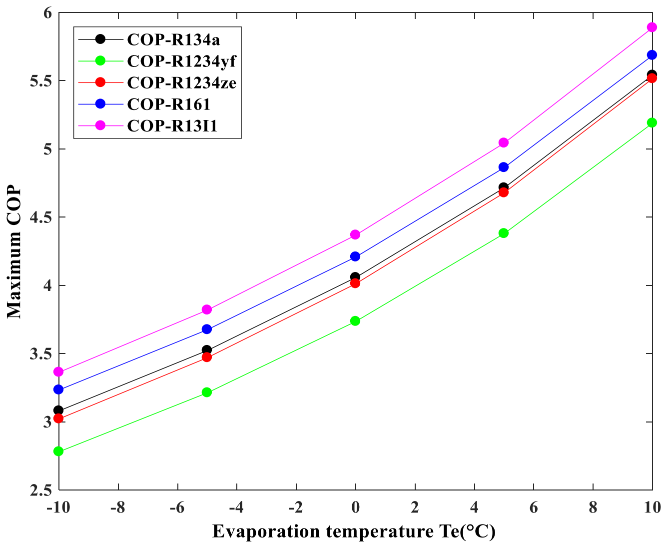

Figure (6): Effect of evaporating temperature on the COP

Fig.6 depict the results of the effect of evaporating temperature (Te) on the coefficient of performance (COP) of the single-refrigerants (R1234yf, R1234ze, R161 and R13I1) and R134a in the mechanical vapor compression refrigeration system. According to the figure, we can see that the coefficient of performance (COP) increases as the evaporating temperature (Te) increases for the constant condensing temperature (Tc) of 50 °C and evaporating temperatures ranging from -10 to 10 °C. The results showed that the COP of the single-refrigerants (R1234yf and R1234ze) lower than that obtained with R134a, while for (R13I1 and R161) the COP is better than the obtained with R134a. When the evaporation temperature increases from -10 to 10 °C, the COP of the booth fluids (R161 and R134a) increases from 3.2333 to 5.6850 and 3.0801 to 5.5402, respectively.

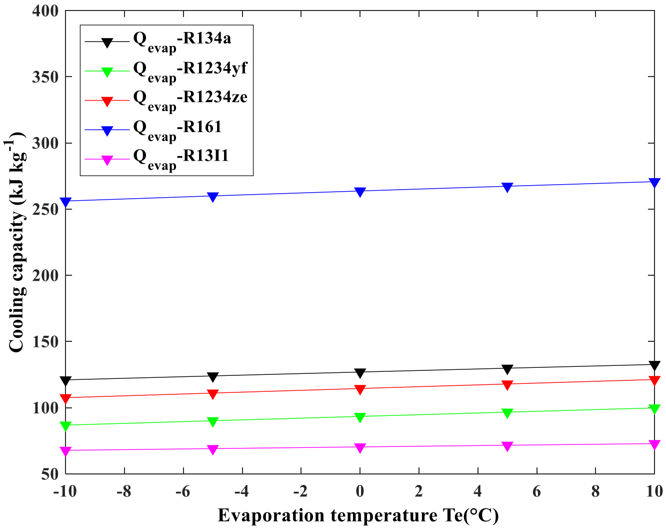

Figure (7): Effect of evaporating temperature on the cooling capacity

The effect of evaporating temperature on the cooling capacity of the single-refrigerants in the mechanical vapor compression refrigeration system is displayed in Fig.7. From this figure, it was noted that an increase in the evaporation temperature leads to an increase in cooling capacity for each fluids. The results showed that the cooling capacity of the single-refrigerant R161 is also higher compared to R134a. When the evaporation temperature increases from (-10 to 10 °C), the cooling capacity of the booth fluids increases from 256.157 to 270.766 kJ/kg and 121.041 to 132.695 kJ/kg, respectively.

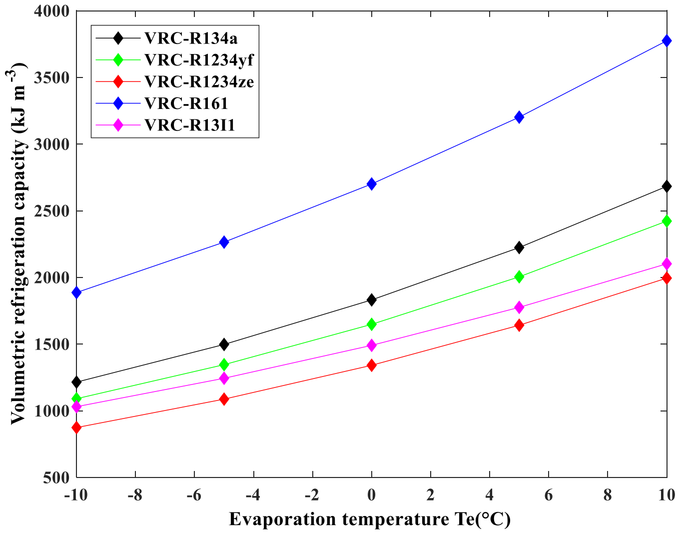

Figure (8): Effect of evaporating temperature on volumetric refrigeration capacity

Fig.8 shows the effect of evaporating temperature on the volumetric refrigeration capacity of fluids. As shown in the figure, like the coefficient of performance and cooling capacity, the volumetric refrigeration capacity increases as the evaporator temperature increases for all investigating single-refrigerants.

The volumetric refrigeration capacity indicates the size of compressor required in order to produce a desired cooling effect. From the curves of the variation of the volumetric refrigeration capacity of the single-refrigerants, it was noticed that the maximum volumetric refrigeration capacity of the mechanical vapor compression refrigeration system, which working with the fluid R161 is better than the obtained with R134a.

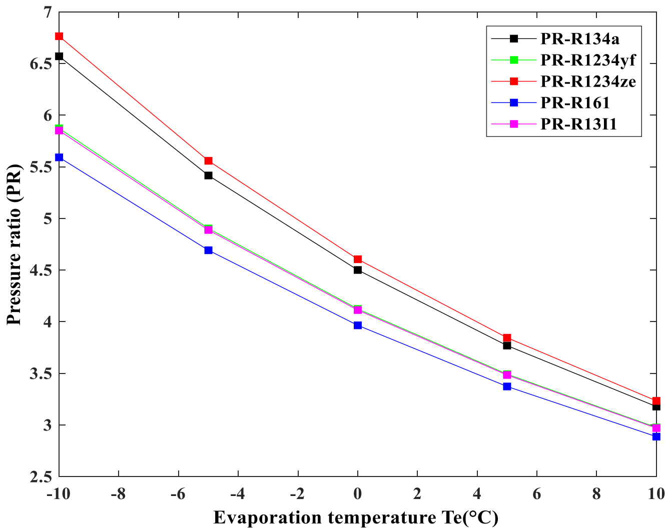

Figure (9): Effect of evaporating temperature on volumetric refrigeration capacity

The variation in the pressure ratio (PR) of single-refrigerants with evaporating temperature is illustrated in Fig.9. From the figure, we can see that the PR of the fluids decreases as the evaporating temperature increases from -10 to 10 °C. The decrease in pressure ratio (PR) for the compressor also improves the efficiency. The PR of the refrigerant R161 tested is found to be lower than R134a under the simulated conditions.

Conclusion

Ozone depletion and global warming are major environmental concerns with serious implications for the future development of the refrigeration-based industries. The discovery of these two major environmental problems has resulted in a series of international treaties demanding a gradual phase out of refrigerant R134a. For this reason, single-refrigerants (R1234yf, R1234ze, R161 and R13I1) have attracted a considerable attention because of their environmentally properties. Therefore, in this study, the performance of these single-refrigerants as alternatives to R134a in mechanical vapor compression refrigeration system was investigated theoretically.
From the results obtained, it is presented that:

- The cooling capacity of the single-refrigerant R161 is higher than R134a;
- The R161 has obvious advantages in terms of volumetric refrigeration capacity compared to R134a;
- The COP of refrigerant R161 is higher than R134a;
- Compared with the R134a, the R161 yielded a GWP lower than R134a (see Table1).
- The pressure ratio (PR) of refrigerant R161 is lower than R134a;

By analyzing the consideration above of single-refrigerants (R1234yf, R1234ze, R161 and R13I1) yields R161 better advantages, which confirms that it could be a good suitable substitute for R134a in mechanical vapor compression refrigeration system.

Nomenclature

List of symbols

h	Specific enthalpy, kJ kg^{-1}
Q	Cooling capacity, kJ kg^{-1}
W	Specific work, kJ kg^{-1}

Greek symbols

ρ	Density, kg m^{-3}

Subscripts

1-4	States of the given system
c	Condensing process
e	Evaporation process
comp	Compressor
evap	Evaporator

Abbreviations

COP	Coefficient of performance
VRC	Volumetric refrigerating capacity
PR	Pressure ratio
GWP	Global warming potential
ODP	Ozone depleting potential
CFC	Chlorofluorocarbons
HCFC	Hydrochlorofluorocarbons
HFC	Hydrofluorocarbons

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