Exergy and performance analyses of impact subcooling for vapor compression refrigeration system utilizing eco-friendly refrigerants

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Abstract. In the present paper, performance and exergy analysis for a vapor compression refrigeration system (VCRS) operating with eco-friendly refrigerants such as R1234ze and R1234yf are tested under different operation conditions to change the recently worked refrigerants R-134a. An analysis through performance and exergy is performed to guide the thermodynamic improvement for the VCRS. Additionally, a comprehensive study is conducted to examine the effects of subcooling temperature on performance and exergy destruction in all components of the VCRS. The exergy destruction of the compressors, condenser, evaporator and expansion device were calculated to obtain the exergy efficiencies. For simulation and analysis the VCRS, Engineering Equation Solver (EES) software program was utilized to obtain the thermodynamics refrigerant properties in which the system operates with the highest eco-friendly, energy and exergy performance is developed the VCRS to determine the most suitable alternative refrigerant to replace the R134a. The results indicate that the refrigerant R1234yf showed the greatest COP enhancement 16.7% due to subcooling, followed by R1234ze 14% and R134a 12.8% under the same operating conditions.

1. Introduction
The detection of the ozone hole and global warming potential (GWP), its possibly destructive effect on people health combined with the discovering of the high critical power of these refrigerants on the ozone layer [1], have determined the global community to find explanations to solve these problems. The Montreal Protocol recognized the limits for the decrease of the CFCs and HCFCs [2]. The refrigeration manufacturers have industrialized the HFCs as a suitable alternative, with focus to the refrigerant R134a. However, the R134a generally used in the VCRS were categorized as greenhouse gases because of their GWP.

Therefore, those refrigerants should be replaced with safe and eco-friendly refrigerants in an environmental approach and the performance can also be enhanced so as to conform to the international environmental. The refrigerants group HFO-1234yf and HFO-1234ze (Hydrofluorooolefins- HFOs) are classified as small values GWP of 7, as they reduce the environmental effect. The properties characterization of three selected refrigerants (R134a, R1234ze and R1234fy) is specified in Table 1. Many researchers examined both the refrigerants R1234ze and R1234fy as a strong alternative to R134a [3-6]. Ansari et al. [7] described the exergy and performance analysis of R1234ze and R1234yf in VCRS with heat exchanger between liquid-vapor. The results show that the condenser has higher efficiency value while the heat exchanger has lower efficiency in VCRS. Ozgur
et al. [8] performed thermal and exergy investigation for VCRS. According to the results, the refrigerant R1234yf is best suitable as an alternative to R134a.

Some review papers referring to exergy and thermal inquiry are important for the use of power ability alternatives for a selection of refrigeration and air conditioning systems. The classical methods of performance analysis depend on the thermodynamics laws, such as the First Law of Thermodynamics (changes in energy quality during the thermodynamics process). However, the first law of thermodynamics does not take into consideration the effect of the environment properties around the VCRS and does not describe the entropy generation and irreversibility of the thermodynamics processes within the VCRS. Exergy is a comparative method defined as the maximum useful work available from the VCRS, when its state is carried to the dead state [9-10]. Hence, the exergy investigation is a more sensible scale of the performance combined with environmental aspects for all thermodynamics process for VCRS.

As seen in the literature review obtained, a lot of the research studied tended to focus on the analysis of the thermodynamic performance for VCRS. Additionally, far too little attention has been paid to examine the effect of subcooling temperature and second law efficiency on the performance and exergy destruction of VCRS components. In this study, the coefficient of performance (COP) and exergy analysis for VCRS with impact of subcooling temperature utilizing eco-friends refrigerant R1234ze and R1234yf as an alternative to R134a was accomplished for different conditions.

| Refrigerants | Chemical Name       | Critical temperature [°C] | Critical pressure [kPa] | Boiling temperature [°C] | ODP | GWP Per 100 year |
|--------------|---------------------|---------------------------|-------------------------|--------------------------|-----|------------------|
| R-134a       | Tetrafluoroethane   | 101.06                    | 41000                   | -26.07                   | 0   | 1430             |
| R1234yf      | Hydrofluoroolefins  | 109                       | 34000                   | -29.4                    | 0   | 4                |
| R1234ze      | Hydrofluoroolefins  | 101                       | 36000                   | -19                      | 0   | 7                |

2. Description of VCRS

The VCRS consisted of several major components: compressor, condenser, evaporator and expansion device. The pressure-enthalpy diagram of the simple VCRS depicts (see figure 1). The sub-cooler is useful to the VCRS for improving system performance by increasing the degree of subcooling, as shown in figure 2.

Figure 1. Simple VCRS.
3. Performance and exergy modelling
Both the first and second law of thermodynamics are applied to estimate the performance and exergy of compressor, condenser, evaporator and expansion device.

The following several assumptions were made for the performance and exergy analyses:
- Neglected pressure drop evaporator and condenser.
- Steady state.
- Neglected change in the kinetic and potential energy for VCRS.
- The dead state conditions are temperature $T_o=27{^{\circ}}C$ and pressure $P_o=100kpa$.
- The cooling capacity equal 2 Ton.
- The condenser temperature 50 $^{\circ}C$.
- The evaporator temperature -10 $^{\circ}C$.
- The subcooling temperature range 1–10 $^{\circ}C$.
- The superheating temperature 5 $^{\circ}C$.

The performance, exergy destructions and efficiencies of VCRS with subcooling can be determined by Equations (1-20), and without subcooling they can be determined by Equations (1a-20a). State points 1–2–3–4–5-6-7 are related to the main cycle of VCRS, Table 2 showing the exergy state for all points.

| State  | Exergy (kJ/kg) |
|--------|----------------|
| Point [0] | $\psi = h_0 - (T_0 S_0)$ |
| Point [1] | $\psi = h_1 - (T_0 S_1) - \psi_0$ |
| Point [2] | $\psi = h_2 - (T_0 S_2) - \psi_0$ |
| Point [3] | $\psi = h_3 - (T_0 S_3) - \psi_0$ |
| Point [4] | $\psi = h_4 - (T_0 S_4) - \psi_0$ |
| Point [5] | $\psi = h_5 - (T_0 S_5) - \psi_0$ |
| Point [6] | $\psi = h_6 - (T_0 S_6) - \psi_0$ |
| Point [7] | $\psi = h_7 - (T_0 S_7) - \psi_0$ |
4. Equations and Mathematical

4.1 Compressor

The compressor power and work can be calculated as [12-13]

\[ \dot{W}_{\text{sub}} = m_{\text{sub}} (h_2 - h_1) \]  
\[ \dot{W} = \dot{m}(h_2 - h_1) \]  
\[ W = \dot{m}(h_2 - h_1). \]  

The compression ratio equal:

\[ CR = p_{\text{cond}} (P_{\text{evap}})^{-1}. \]  

The isotropic compressor efficiency as follows:

\[ \eta_c = (h_{2s} - h_1)(h_2 - h_1)^{-1}. \]  

The empirical efficiency is calculated as:

\[ \eta_c = 1 - 0.05CR. \]  

The rate of destruction exergy of the compressor is calculated as follows:

\[ \psi_{\text{dest,comp,sub}} = \dot{m}_{\text{sub}} T_0 (S_2 - S_1) \]  
\[ \psi_{\text{dest,comp}} = \dot{m} T_0 (S_2 - S_1). \]  

The exergy efficiency is calculated as:

\[ \eta_{\text{dest,comp}} = \psi_2 - \psi_1(W)^{-1}. \]  

4.2 Condenser

The rate of heat rejected in the condenser can be calculated as:

\[ \dot{Q}_{\text{cond,sub}} = \dot{m}_{\text{sub}} (h_2 - h_4) \]  
\[ \dot{Q}_{\text{cond}} = \dot{m}(h_2 - h_4). \]  

The rate of exergy destruction and efficiency of the condenser:

\[ \psi_{\text{dest,cond,sub}} = T_0 \dot{S}_{\text{gen,cond,sub}} \]  
\[ \psi_{\text{dest,cond}} = T_0 \dot{S}_{\text{gen,cond}}. \]  

The rate of entropy generation:

\[ \dot{S}_{\text{gen,sub}} = \dot{m}_{\text{sub}} [(S_2 - S_4) + \dot{Q}_{\text{cond,sub}} (T_{\text{cond}})^{-1}] \]  
\[ \dot{S}_{\text{gen}} = \dot{m} [(S_2 - S_4) + \dot{Q}_{\text{cond}} T_{\text{cond}}^{-1}]. \]  

The exergy efficiency is calculated as:

\[ \eta_{\text{dest,cond,sub}} = \dot{Q}_{\text{cond,sub}} (1 - T_0 (T_{\text{cond}})^{-1})(\dot{m}_{\text{sub}} [(h_2 - h_4 - T_0 (S_2 - S_4))]^{-1}. \]
\[ \eta_{\text{dest,cond}} = Q_{\text{cond,sub}} \left(1 - T_0 \left(\frac{T_{\text{cond}}}{T_0}\right)^{\frac{1}{\gamma}}\right) \left[m\left(\frac{h_2 - h_3 - T_0(S_2 - S_3)}{S_2 - S_3}\right)\right]^{-1}. \]  \hspace{1cm} (10a)

### 4.3 Expansion device

The throttling process is constant enthalpy, where for subcooling cycle \( h_4 = h_5 \) and for no subcooling \( h_3 = h_7 \). The rate of exergy destruction and efficiency of the throttling can be determined from:

\[ \psi_{\text{dest,exp,sub}} = m_{\text{sub}} T_0 \left(\frac{S_5}{S_4}\right) \]  \hspace{1cm} (11)

\[ \psi_{\text{dest,exp}} = m T_0 \left(\frac{S_7}{S_3}\right) \]  \hspace{1cm} (11a)

\[ \eta_{\text{dest,exp,sub}} = -\psi_4 \left(\psi_{\text{dest,exp,sub}}\right)^{-1} \]  \hspace{1cm} (12)

\[ \eta_{\text{dest,exp}} = -\psi_3 \left(\psi_{\text{dest,exp}}\right)^{-1}. \]  \hspace{1cm} (12a)

### 4.4 Evaporator

The refrigeration effect can be calculated as:

\[ Q_{\text{evap,sub}} = (h_6 - h_5) \]  \hspace{1cm} (13)

\[ Q_{\text{evap}} = (h_6 - h_7) \]  \hspace{1cm} (13a)

The refrigeration capacity can be expressed as:

\[ \dot{Q}_{\text{evap}} = m_{\text{sub}} (h_6 - h_5) \]  \hspace{1cm} (14)

\[ \dot{Q}_{\text{evap}} = m (h_6 - h_7) \]  \hspace{1cm} (14a)

where the system capacity equal 7.032kW

The rate of exergy destruction of the evaporator is the following [14-15]:

\[ \psi_{\text{dest,evap,sub}} = T_0 \dot{S}_{\text{gen, evaporator}} \]  \hspace{1cm} (15)

\[ \psi_{\text{dest,evap}} = T_0 \dot{S}_{\text{gen, evaporator}} \]  \hspace{1cm} (15a)

The entropy generation in the evaporator can be expressed as:

\[ \dot{S}_{\text{gen, sub}} = (S_6 - S_5) - \left(Q_{\text{evap}} \left(T_{\text{evap}}\right)^{-1}\right) \]  \hspace{1cm} (16)

\[ \dot{S}_{\text{gen}} = (S_6 - S_7) - \left(Q_{\text{evap}} \left(T_{\text{evap}}\right)^{-1}\right) \]  \hspace{1cm} (16a)

The exergy efficiency can be expressed as:

\[ \eta_{\text{dest,evap,sub}} = Q_{\text{evap}} \left(T_0 - T_{\text{evap}}\right) \left(T_{\text{evap}}\right)^{-1} \left((h_5 - h_6) - T_0(S_5 - S_6)\right)^{-1} \]  \hspace{1cm} (17)

\[ \eta_{\text{dest,evap}} = Q_{\text{evap}} \left(T_0 - T_{\text{evap}}\right) \left(T_{\text{evap}}\right)^{-1} \left((h_7 - h_6) - T_0(S_7 - S_6)\right)^{-1} \]  \hspace{1cm} (17a)

### 4.5 COP and total exergy destruction

Is defined as the amount of cooling effect per unit work provided. The COP can be determined from:

\[ \text{COP}_{\text{sub}} = \frac{\dot{Q}_{\text{evap}}}{\dot{W}_{\text{sub}}} \]  \hspace{1cm} (18)
4.6 Total exergy destruction

The total exergy destruction in the VCRS can be calculated by:

\[
\psi_{\text{dest total sub}} = \psi_{\text{dest comp sub}} + \psi_{\text{dest cond sub}} + \psi_{\text{dest exp sub}} + \psi_{\text{dest evap sub}}.
\]  

(19)

4.7 The total efficiency

The total efficiency in the VCRS can be expressed as:

\[
\eta_{\text{dest total sub}} = \eta_{\text{dest comp sub}} + \eta_{\text{dest cond sub}} + \eta_{\text{dest exp sub}} \eta_{\text{dest evap sub}}.
\]  

(20)

Figure 3. Flow chart of EES.
4.8 The second law efficiency
The second law efficiency in the VCRS can be expressed as:
\[
\eta_{SL} = \frac{COP_{carnot}}{COP} \quad (21)
\]
\[
COP_{carnot} = \frac{T_L}{T_H - T_L} \quad (21a)
\]

4.9 COP enhancement
The enhancement in COP for the VCRS can be expressed as:
\[
COP_N = (COP_{sub} - COP) COP^{-1} \quad (22)
\]

4.10 The condenser and evaporator improvement
For evaporator
\[
Q_{evap,N} = (Q_{evap,sun} - Q_{evap}) Q_{evap}^{-1} \quad (23)
\]
For condenser
\[
Q_{cond,N} = (Q_{cond,sun} - Q_{cond}) Q_{cond}^{-1} \quad (24)
\]

The performance and exergy equations were solved and simulated by EES software package program. EES function information was applied to determine the refrigerants thermodynamic properties of R123fy, R234ze and R134a. The figure 3 shows the flow chart solution procedures.

5. Results and Discussion
The use of sections to divide the text of the paper is optional and left as a decision for the author. Where the author wishes to divide the paper into sections, the formatting shown in Table 2 should be used.

5.1 Validations:
To evaluate the accuracy of the results for the present research, the effect of the evaporation temperature on COP for R-134a is validated with the data from Jian et al. [16], as shown in figure4. The prediction of COP in the present study is a little higher than that of the recorded results. The deviation between the compression results was because of the assumed constant thermal properties.

![Figure 4. Comparison of COP between the present studies with other results at various T_{evap.}](image_url)
Overall, the results for the present research have achieved good agreement with the experimental reading.

5.2 Effect of subcooling temperature on COP
When the refrigerant is sub-cooled before it enters the expansion device, the refrigerating effect and COP are increased. Because the vapor of refrigerant entering the compressor and the work of compression is the equivalent for subcooling and simple VCRS. This means that the increase in refrigerating effect is achieved without increasing the power of the compressor. From figure 5 (a)-(c) shows the COP as a function of the subcooling temperature for R134a, R1234yf and R1234ze with fixed refrigeration capacity at 2 Ton. It can be seen that the maximize COP was achieved with subcooling 10°C for all refrigerants. However, the properties of R134a, R1234yf and R1234ze affect the COP increase. Inside among of refrigerants, R1234yf showed the greatest COP improvement 16.7% due to subcooling, followed by R1234ze 14% and R134a 12.8% under the same operating conditions.

5.3 Effect of subcooling temperature on the heat of condenser and evaporator
In the figure 6 (a)-(c) explores the influence of subcooling temperature on the heat rejection in the condenser and refrigeration effect. In addition, the comparison of the refrigeration effect and heat reject in condenser of simple VCRS with the refrigeration effect (Q_{evap}) and heat reject (Q_{cond}) of subcooling VCRS. As the subcooling temperature increases, the outlet temperature from condenser will be lower to T_4(T_4=T_{cond} - T_{sub}). It should be noted that the refrigeration effect increases with the increase in subcooling temperature for all three refrigerants. For R134a, Q_{evap} improvement is recorded as 7.4%, and it is 5.8% for R1234ze, finally 2.9% for R1234yf under same operation conditions. This VCRS with R134a has the highest heat reject in condenser for condenser and evaporator temperature 50°C, -10°C (see figure 6 (a)). Moreover, the incensement in the Q_N is very small for all three refrigerants. It should be considered nearly constant within this subcooling temperature range evaluated. This result can also be observed in the work of Pottker et al. [17].

5.4 Effect of subcooling temperature on heat of condenser and evaporator
The largest value of exergy destruction occurs in the compressor, while the smallest amount occurs in the expansion device and evaporator for all three refrigerant R134a R1234yf and R1234ze. The figure 7 (a)-(c) presents the exergy destruction and total exergy in the all components of the VCRS. The compressor has greater exergy destruction with R1234ze due to high input power consumption and large amount of irreversibility that is created during the compression work process. The evaporator and expansion device have lower exergy destruction in VCRS due to the phase change from liquid to vapor during absorber heat from space in the evaporator and pressure drop in expansion device. The total exergy destruction (3.1kW) in the VCRS with R1234ze is the highest among the refrigerant considered. This due to the large entropy generation and temperature difference that occurs in the condenser and compressor. This result can also be observed in the work De Paula et al. [18]. Note that VCRS with R1234yf and R134a had smaller total exergy destruction values 2.48 kW and 2.7 kW respectively.

5.5 Effect of subcooling temperature on second law and total exergy efficiency
The total exergy efficiency variation with subcooling temperature was compared for three refrigerants as shown in figure 8 (a)-(c). The results show that the VCRS with R134a has the lowest exergy efficiency among all refrigerants. Thus, the exergy efficiency decreases with increasing subcooling temperature, due to increases the irreversible loss in compound of VCRS. This result can also be observed in the work of Fukuda et al. [19]. It should be noted that the second low efficiency increases with the increase in subcooling temperature for all three refrigerants under same operation conditions.
Figure 5. Effect of $T_{\text{sub}}$ on COP and COP$_{N}$ at $T_{\text{evap}} = -10^\circ\text{C}$, $T_{\text{cond}} = 50^\circ\text{C}$ for (a) R134a, (b) R1234fy and (c) R1234ze.
Figure 6. Effect of $T_{sub}$ on heat reject in condenser, heat absorbed in evaporator and $Q_{Nat}T_{evap}=-10\degree C$, $T_{cond}=50\degree C$ for (a) R134a, (b) R1234fy and (c) R1234ze.
Figure 7. Variation of $T_{sub}$ with exergy destruction at various compound of VCRS at $T_{evap} = -10^\circ$C, $T_{cond} = 50^\circ$C for (a) R134a, (b) R1234fy and (c) R1234ze.
Figure 8. Efficiency of total exergy and second law variation with $T_{\text{sub}}$ at $T_{\text{evap}}=-10^\circ\text{C}$, $T_{\text{cond}}=50^\circ\text{C}$ for (a) R134a, (b) R1234fy and (c) R1234ze.
6. Conclusion
A performance and exergy study about the effect of subcooling temperature on VCRS has been presented. The refrigeration effect is strongly dependent on the thermodynamic properties of the refrigerants. In case the refrigerants have great latent heat of vaporization, such as R1234yf, they have a propensity for advantage of the least subcooling temperature. The refrigerant R1234yf showed the greatest COP improvement 16.7% due to subcooling, followed by R1234ze 14% and R134a 12.8% under the same operating conditions. The refrigeration effect increases with the increase in subcooling temperature for all three refrigerants. For R134a, improvement is recorded as 7.4%, and it is 5.8% for R1234ze, finally 2.9% for R1234yf under the same operation conditions. The largest amount of destruction exergy takes place in the compressor, while the smallest happens in the expansion device and in the evaporator for all the three refrigerants R134a, R1234yf and R1234ze. It was found that R1234yf and R134a had smaller total exergy destruction values of 2.48kw and 2.7kw respectively. The refrigerant R134a had the lowest exergy efficiency among all the refrigerants. The exergy efficiency decreases with increasing subcooling temperature, due to increases in the irreversible loss in the compound of VCRS.

Nomenclature

| Symbols | Greek Symbols |
|---------|----------------|
| CR      | Exergy (kW) |
| h       | Exergy destruction |
| m       | Total exergy destruction (kW) |
| s       | Exergy destruction in compressor (kW) |
| T       | Exergy destruction in condenser (kW) |
| To      | Exergy destruction in evaporator (kW) |
| Tsup    | Exergy destruction in expansion (kW) |
| Tsub    | Exergy efficiency (%) |
| P       | Subscripts |
| Pe      | evap |
| Qevap   | cond |
| Qcond   | comp |
| x       | exp |
| W       | gen |
| Wsub    | sub |

Pressures

| Subscripts |
|-----------|
| P          |
| Pe         |

Power

| Subscripts |
|-----------|
| W          |

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