The Effect of Eco-friendly Refrigerants on Performance of Vapor Compression Refrigeration System with Dedicated Mechanical Subcooling

Naushad Ahmad Ansari, Akhilesh Arora, Samsher and K. Manjunath

Abstract   The demand for high-performance refrigeration systems with eco-friendly refrigerants is increasing due to global warming. In this article, the thermodynamic analysis of a vapor compression refrigeration system with dedicated mechanical subcooling using eco-friendly refrigerants R1243zf, R1233zd(E) is carried out and their performance is compared with refrigerant R134a. The parameters like COP and exergetic efficiency of the system is computed. The effects of subcooling temperature, condenser temperature, evaporator temperature, compressor efficiency, and effectiveness of heat exchanger are also investigated and discussed. The performance of the system can be directly related to subcooling temperature. There is an optimum value of subcooling temperature predicted for the system in this article. In the study, it is observed that low GWP refrigerant R1233zd(E) is a better-performing refrigerant than R134a, whereas R1243zf is also a low GWP refrigerant which has slightly lower COP and exergetic efficiency than R134a.

Keywords   COP · Exergetic efficiency · Subcooling · Eco-friendly

Nomenclature

COP   Coefficient of performance

N. A. Ansari (✉) · A. Arora · Samsher
Mechanical Engineering Department, Delhi Technological University,
Bawana Road, Delhi 110042, India
e-mail: naushad.nsr@gmail.com

A. Arora
e-mail: akhilesharora@dce.ac.in

Samsher
e-mail: samsher@dce.ac.in

K. Manjunath
Mechanical Engineering, Ch. B. P. Government Engineering College, Jaffarpur,
Delhi 110073, India
e-mail: manjukmys@gmail.com

GWP   Global warming potential
ODP   Ozone depletion level
Q Heat transfer (kW)
W Work transfer (kW)
h Enthalpy (kJ/kg)
T Temperature (°C)
P Pressure (kPa)
η Efficiency
$\dot{m}$ Mass flow rate (kg/s)
ε Effectiveness
EP   Exergy in product (kW)

Subscripts

Comp   Compressor
r   Refrigerant
ex   Exergetic
0   Ambient states
scc   Subcooling refrigeration cycle

1   Introduction

A dedicated mechanical subcooling vapor compression refrigeration cycle consists of two vapor compression cycle where subcooling of refrigerant of main compression cycle at the exit of the condenser improves the performance of the system, thus saving the high-grade electrical energy which also contributes to a clean environment. It is accomplished by adding a small subcooler cycle with the main cycle and thus forming a system known as dedicated mechanical subcooling vapor compression refrigeration cycle. Apart from ozone depletion potential (ODP), the global warming potential has also become a very important criterion for the refrigerants to be used in the refrigeration and air-conditioning applications. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) were to be phased out due to their ODP and GWP problems when Montreal Protocol on January 1, 1989, came into force [1, 2]. Hydrofluorocarbons (HFCs) like R134a have zero ODP but due to significantly high GWP needs to be replaced by low GWP refrigerants [3]. All HFCs and other greenhouse gases have to be curbed under Kyoto Protocol agreement which was proposed in December, 1997, and enforced on February 16, 2005. The next-generation refrigerants, hydrochlorofluoroolefins (HCFOs) like R1233zd(E) and hydrofluoroolefins (HFOs) like R1243zf, can become a good alternative due to their very low GWP.

Thornton et al. [4] in their research predicted that the performance of overall dedicated subcooling cycle depended upon the optimum subcooling temperature and the

Table 1 Properties of refrigerants [12, 13]

Name	Atmospheric life	ODP	Solubility in water	Critical temperature	GWP	Boiling point
R-134a	14 years	0	0.11% by weight at 77 °F or 25 °C	252 °F or 122 °C	1200	−14.9 °F or −26.1 °C
R-1233zd(E)	26 days	0	0.19% by weight at 20 °C	439.6 K or 166.6 °C	1	66 °F or 19 °C
R-1243zf	11 days	0	0.33% by weight at 95 °C	222 °F or 105.5 °C	4	−13.3 °F or −25.2 °C

cycle extreme temperatures, i.e., condenser and evaporator temperature. She et al. [5] predicted a 67.67% higher COP of a subcooling system compared to the conventional refrigeration system under same operating conditions. Qureshi and Zubair [6] described exclusively different models of subcooling. Qureshi and Zubair [7] investigated the subcooling model using different refrigerants and showed that R134a is the best-performing refrigerant in main and subcooling cycle. Khan and Zubair [8] investigated an integrated subcooling refrigeration system and predicted that optimum subcooling temperature was approximately arithmetic mean temperature of evaporator and condenser temperature. Qureshi et al. [9] analyzed the mechanical subcooling system and predicted 21% increase in exergetic efficiency compared to the conventional compression refrigeration cycle. Pottker and Hrnjak [10] theoretically analyzed the subcooling system using different refrigerants. Dai et al. [11] analyzed a transcritical CO_2 refrigeration subcooling system and found that maximum rate of increase in COP is to be 43.8% and concluded that discharge pressure and subcooling temperature influenced the subcooling cycle more significantly than other parameters. Lai [12] predicted that R1243zf is a potential refrigerant to replace R134a in a refrigeration system. Miyoshi et al. [13] developed a centrifugal chiller using R1233zd(E) as a refrigerant and predicted it to be a good replacement of R134a as a better-performing refrigerant in chillers.

The objective of this article is to investigate the performance of low GWP refrigerants in a dedicated mechanical subcooling refrigeration cycle which is promising and energy efficient as recorded by the researchers. The properties of the refrigerants used for the analysis are provided in Table 1.
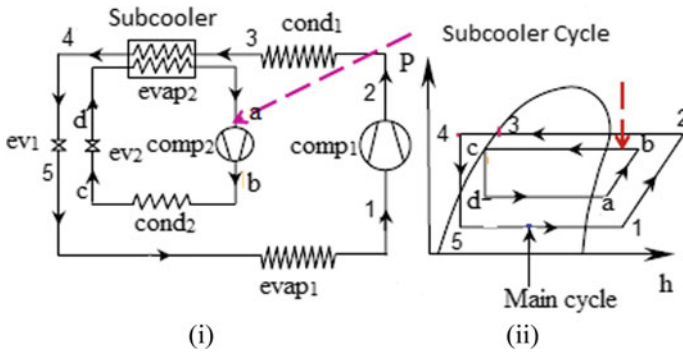
Fig. 1 (i) Schematic diagram of dedicated subcooling compression system and (ii) pressure enthalpy diagram of the system

2 Description of the Dedicated Subcooling Refrigeration System

Figure 1 shows the schematic diagram of the subcooling system where (i) represents the flow diagram and (ii) represents the pressure–enthalpy phase diagram. Points 1–2–3–4–5 is related to the main cycle of dedicated subcooling compression system, and points a–b–c–d is related to smaller cycle termed as subcooler cycle which is coupled with the main cycle at the exit of main cycle condenser (cond1). Compressed refrigerant (1–2) in the main cycle compressor (comp1) passes through cond1 (2–3) releasing heat to the atmosphere. It enters into the subcooler where heat is absorbed by the evaporator (evap2) of the subcooler cycle, or subcooling of the refrigerant takes place. It passes through the expansion valve (ev1) (4–5) of main cycle throttled to low pressure and then passes through the evaporator (evap1) of the main cycle attaining the desired objective of cooling by absorbing the heat from the space to be cooled before entering into comp1 and thus completing the cycle. In the subcooler cycle, which also functions like a conventional vapor compression cycle, the refrigerant is compressed to high pressure (a–b) in compressor (comp2) of the subcooler cycle enters into condenser (cond2) releasing heat to ambient (b–c) before throttling (c–d) to low pressure in expansion valve (ev2) and thereafter enters into the evaporator (evap2) (d–a) of the subcooler cycle where it absorbs heat of main cycle refrigerant acting as a heat exchanger. The refrigerant of the subcooler cycle then enters into comp2 thus completing the cycle.

3 Energy and Exergy Analysis of the System

The energy and exergy analysis is carried out by considering the principle of mass conservation, energy conservation, and exergy conservation.

$$W_{comp1} = \dot{m}_r(h_2 - h_1) \tag{1}$$

$$W_{comp2} = \dot{m}_r(h_b - h_a) \tag{2}$$

$$COP_s = Q_e/W_{comp1} \tag{3}$$

where COP_s is the simple compression cycle COP.

$$\Delta T_{sub} = T_3 - T_4 = \delta_{sc} \tag{4}$$

The effectiveness of the subcooler is defined as:

$$\epsilon_{subcooler} = (T_3 - T_4)/(T_3 - T_d) \tag{5}$$

$$Q_e = \dot{m}_r(h_1 - h_5) \tag{6}$$

$$W_{comp} = W_{comp1} + W_{comp2} \tag{7}$$

$$COP_{scc} = Q_e/(W_{comp1} + W_{comp2}) \tag{8}$$

where COP_{scc} is subcooling compression refrigeration cycle COP.
The exergy in product is defined as:

$$EP_{scc} = Q_e(1 - (T_0/T_r)) \tag{9}$$

Therefore, exergetic efficiency of the subcooling cycle is given by:

$$\eta_{ex} = EP_{scc}/W_{comp} \tag{10}$$

3.1 Model Validation

Yilmaz et al. [14] carried an analytical and numerical analysis of a subcooling cycle using R134a as refrigerant in main and subcooler cycle. They calculated the maximum increase of COP up to 30% at an optimum subcooling temperature of 35.5 °C ($T_c = 60$ °C, $T_e = -20$ °C, $\eta_{comp} = 0.80$) (assumed effectiveness of heat exchanger to be 5 °C less than maximum temperature). In the present study, the maximum increase of 32% in COP is calculated at an optimum temperature of 35.75 °C with the same input conditions. The small variation in result falls within the acceptable limit. Miyoshi et al. [13] calculated the theoretical COP of a simple vapor compression refrigeration system as 6.93 ($T_c = 38$ °C, $T_e = 6$ °C, $\eta_{comp} = 0.90$) with refrigerant R1233zd(E). In the present study, COP of the simple vapor compression

system is calculated as 6.922 using R1233zd(E) and the same input parameters. The calculated value is fit for validation of results.

4 Results and Discussion

The energy and exergy analysis of the subcooling refrigeration system is carried out by developing a computational model using engineering equation solver (EES) [15]. In the subcooling system, similar pairs of each refrigerant are considered to access the performance; e.g., R1233zd(E) is assumed in main cycle and subcooler cycle, and same is true for R134a and R1243zf. Compressor efficiency of main cycle and subcooler cycle are assumed to be same. Other assumptions for calculation are as follows:

Refrigeration capacity	50 kW
Isentropic efficiency of the compressor	0.65
Evaporator temperature	−35 to 10 °C
Condenser temperature	32 to 55 °C
Subcooling temperature	2 to 37 °C
Effectiveness of subcooler	0.8.

Further, dead state temperature and pressure are considered to be atmospheric, i.e., 25 °C and 1.01324 bar. Enthalpy and entropy reference for the refrigerants are calculated corresponding to dead state temperature. It is assumed that there is no heat loss or pressure drop in other components and connecting lines. The difference between evaporator temperature and space to be cooled is assumed as 5 °C.

4.1 *Effect of Condenser Temperature*

Figure 2 explores the effect of condenser temperature on coefficient of the performance of the system and also reveals the comparison of the performance of simple vapor compression refrigeration system (COP_s) with the performance of subcooling vapor compression refrigeration system (COP_{scc}). As the condenser temperature decreases, COP of both the system increases, while COP of subcooling system always remains greater than COP of simple compression system, but there is a distinct pattern of increase. COP of R1233zd(E) in subcooling compression cycle is 13.5% higher and 23.31% higher at condenser temperature of 32 and 55 °C, respectively, corresponding to simple compression cycle. Similarly, R134a shows a higher COP increase by 15.35 and 31% and R1243zf shows 15.9 and 33.13% increase for same condenser temperatures compared to simple compression system. Thus, R1233zd(E) is better-performing refrigerant followed by R134a and R1243zf. COP of R1243zf is slightly lower than R134a, but due to very low GWP of 4 and very small life cycle, it can offset the R134a as a preferred refrigerant. Also, the improvement in COP
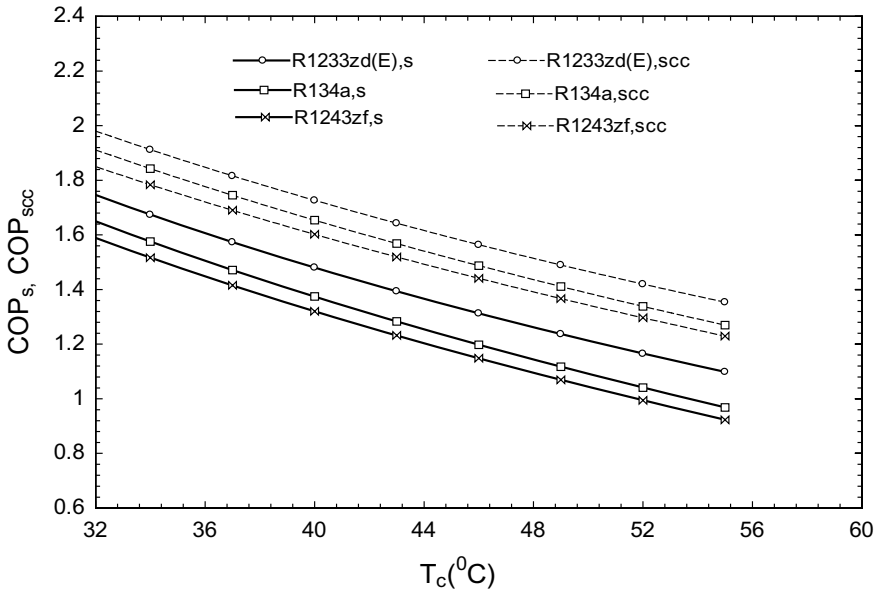
Fig. 2 Condenser temperature versus simple compression refrigeration cycle COP and subcooling compression cycle COP ($T_e = -35\ ^\circ C$, $\delta_{sc} = 30\ ^\circ C$)

of R1243zf is significantly better than the corresponding improvement of COP of other two refrigerants for high condenser temperature when it is used in subcooling compression cycle.

4.2 Effect of Evaporator Temperature

Figure 3 presents the effect of evaporator temperature on COP and exergetic efficiency of the subcooling cycle. COP increases with the increase in evaporator temperature, but it is observed that COP of subcooling cycle is improving compared to simple compression cycle. For 1233zd(E), COP improvement is recorded as 1.64% at 10 °C evaporator temperature, and it is 20.85% at −35 °C evaporator temperature. The similar pattern of improvement in COP and exergetic efficiency is observed for R1324a and R1243zf, where R1243zf shows the highest improvement of 28.64% in COP at −35 °C evaporator temperature. R1233zd(E) has the maximum COP of 3.948 and minimum COP of 1.466 at $T_e = 10\ ^\circ C$ and −35 °C, respectively. The corresponding COP of R134a is 3.677 (maximum) and 1.386 (minimum) and for R1243zf is 3.611 (maximum) and 1.343 (minimum) at same evaporator temperatures. The highest exergetic efficiency 33.28% is recorded for R1233zd(E) followed by 31.44% for R134a and 30.46% for R1243zf. At higher evaporator temperature,
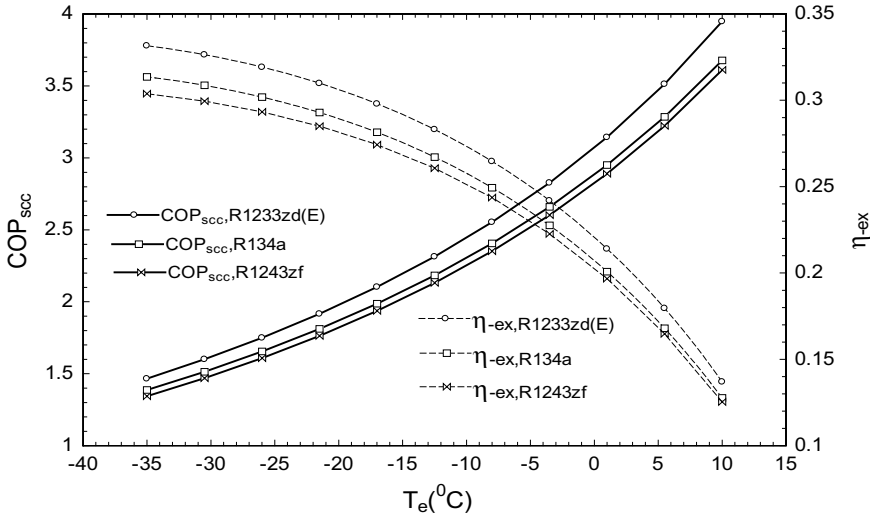
Fig. 3 Evaporator temperature versus COP and exergetic efficiency of subcooling compression refrigeration cycle (T_c = 50 °C, δ_{sc} = 30 °C)

exergetic efficiency curve for the three refrigerants converges, and at 10 °C evaporator temperature, R134a and R1243zf have the same exergetic efficiency.

4.3 Effect of Subcooling Temperature

Figures 4 and 5 explore the effect of subcooling temperature on COP and exergetic efficiency. It is observed that COP and exergetic efficiency are improving with the increase in subcooling temperature; it reaches to maximum at an optimum subcooling temperature which is recorded as approximately 31.5 °C for all the three refrigerants considered in the study, and after attaining this peak, COP and exergetic efficiency decrease with the increase in subcooling temperature. The trends of both the COP and exergetic efficiency curves are similar with respect to subcooling temperature. The optimum subcooling temperature is an important parameter to be considered for design conditions of dedicated subcooling system.
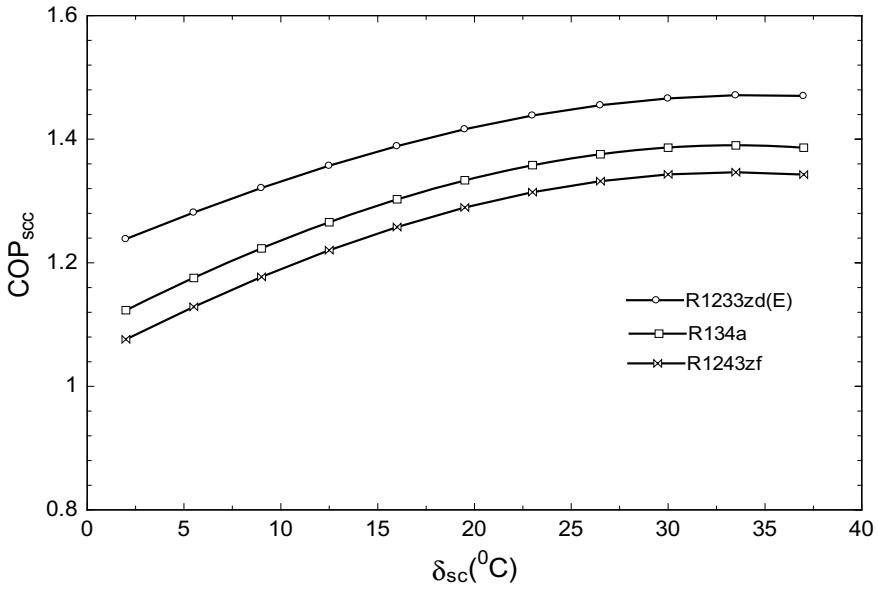
Fig. 4 Subcooling temperature versus subcooling compression refrigeration cycle COP (T_c = 50 °C, $T_e = -35$ °C)

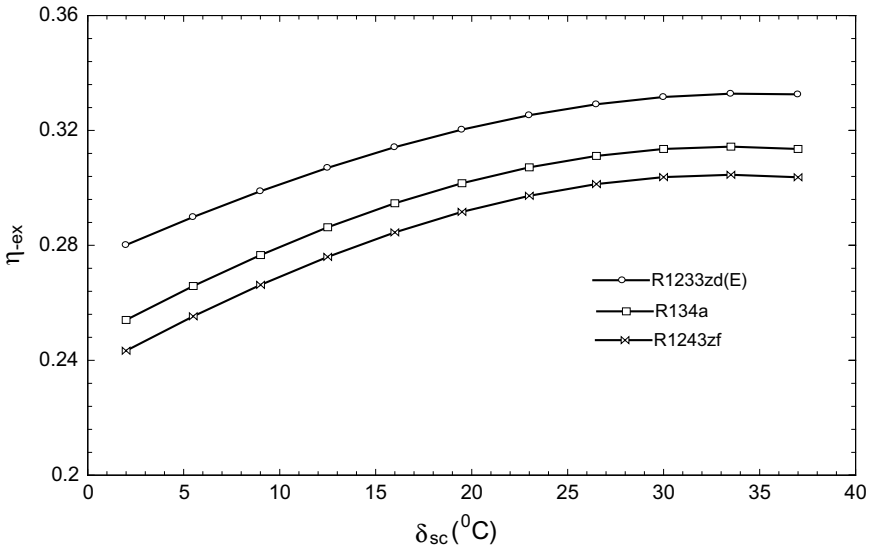**Fig. 5** Subcooling temperature versus exergetic efficiency of subcooling compression refrigeration cycle ($T_c = 50$ °C, $T_e = -35$ °C)
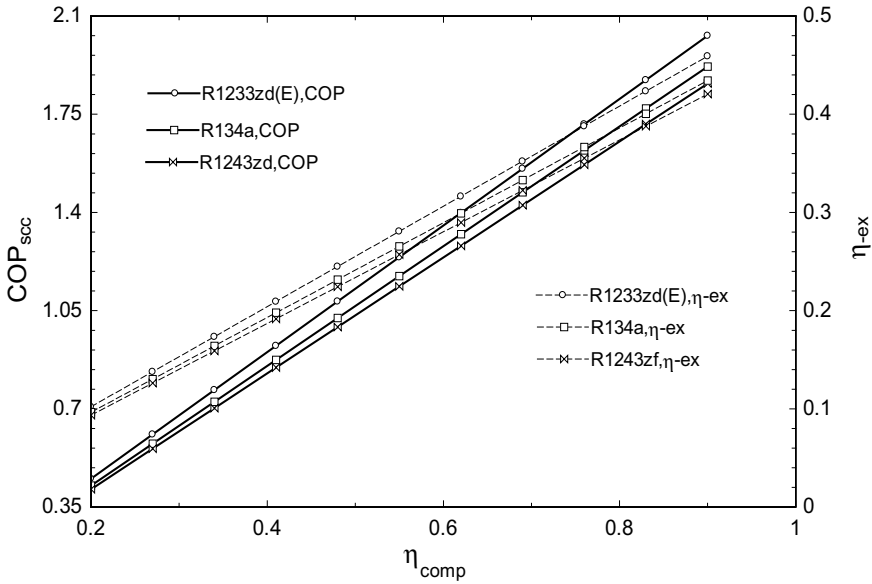
Fig. 6 Compressor efficiency versus COP and exergetic efficiency of subcooling compression refrigeration cycle ($T_c = 50\ °C$, $T_e = -35\ °C$, $\delta_{sc} = 30\ °C$)

4.4 Effect of Compressor Efficiency

Figure 6 shows the effect of compressor efficiency on COP and exergetic efficiency of the system. It is observed that there is a sharp decline in the performance of system with the decrease in compressor efficiency. It is also observed that the COP and exergetic efficiency curves converge for all the three refrigerants with a decrease in compressor efficiency.

4.5 Effect of Subcooler Effectiveness

Figure 7 reveals the effect of subcooler effectiveness on system performance. It is observed that COP and exergetic efficiency decrease with the decrease in effectiveness where the trend of decrease is large at effectiveness values of 0.20–0.60, but thereafter, i.e., beyond 0.60, the effect of subcooler effectiveness is minimal in particular on exergetic efficiency as its curve becomes almost flat, whereas the COP curve smoothens and shows a small increase. The pattern is similar for all the three refrigerants in the study.
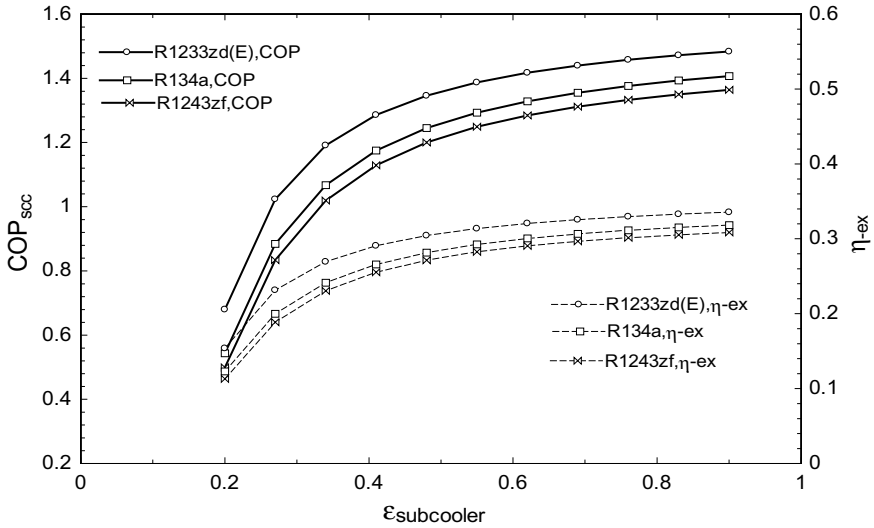
Fig. 7 Effectiveness of subcooler versus COP and exergetic efficiency of subcooling compression refrigeration cycle ($T_c = 50\,°C$, $T_e = -35\,°C$, $\delta_{sc} = 30\,°C$)

5 Conclusion

The effect of evaporator temperature and condenser temperature is very significant on the dedicated mechanical subcooling compression refrigeration cycle compared to a simple vapor compression cycle. The performance of subcooling cycle shows more improvement at higher condenser temperature and lower evaporator temperature over the simple compression cycle. Compressor efficiency and effectiveness of subcooler also influence the performance of the system. COP and exergetic efficiency of R1233zd(E) are noticeably higher than R134a, whereas R1243zf has slightly lower COP and exergetic efficiency than R134a. But improvement in the performance of R1243zf at high condenser and low evaporator temperature is more compared to the corresponding improvement of R1233zd(E) and R134a when used in a subcooling compression refrigeration cycle. Therefore, R1233zd(E) and R1243zf are the potential refrigerants to replace R134a.

References

1. IPCC Climate Change (2015) The physical science basis, The working group I
2. United Nations Environmental Programme (1987) Montreal protocol on substances that deplete the ozone layer, Final Act, New York, United Nations
3. IPCC Fourth Assessment Report (2012)

4. Thornton JW, Klein SA, Mitchell JW (1992) Dedicated mechanical subcooling design strategies for supermarket applications. In: International refrigeration and air conditioning conference: paper-11
5. She X, Yin Y, Zhang X (2014) A proposed subcooling method for vapor compression refrigeration cycle based on expansion power recovery. Int J Refrig 43:50–61
6. Qureshi BA, Zubair SM (2013) Mechanical subcooling vapor compression systems: current status and future directions. Int J Refrig 36:2097–2110
7. Qureshi BA, Zubair SM (2012) The effect of refrigerant combinations on performance of a vapor compression refrigeration system with dedicated mechanical subcooling. Int J Refrig 35:47–57
8. Khan JR, Zubair SM (2000) Design and rating of an integrated mechanical subcooling vapor compression refrigeration system. Energy Conv Manage 41:1201–1222
9. Qureshi BA, Inam M, Antar MA, Zubair SM (2013) Experimental energetic analysis of a vapor compression refrigeration system with dedicated mechanical subcooling. Appl Energy 102:1035–1041
10. Pootker G, Hrnjak P (2015) Effect of the condenser subcooling on the performance of vapor compression systems. Int J Refrig 50:156–164
11. Dai B, Liu S, Sun Z, Ma Y (2017) Thermodynamic performance analysis of CO_2 transcritical refrigeration cycle assisted with dedicated mechanical subcooling. Energy Procedia 105:2033–2038
12. Lai NA (2014) Thermodynamic properties of HFO-1243zf and their application in study on a refrigeration cycle. Appl Therm Eng 70(1):1–6
13. Miyoshi N, Suemitsu R, Togano Y, Kanki Y, Hasegawa Y (2016) Centrifugal chiller using HFO-1233zd(E). In: Jraia international symposium: JRAIA2016
14. Yilmaz A, Aktas AE, Erdinc MT, Yilmaz T (2017) Analytical and numerical investigation of a refrigeration cycle integrated with another cycle for subcooling. In: International advanced research & engineering congress, pp 257–263
15. Klein SA, Alvarado F (2017) Engineering equation solver, V10.097. F Chart Software, Middleton, WI