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Thermodynamic performance analysis of two stage vapour compression refrigeration systems with flash-intercooler using eco-friendly new refrigerants (R134a, R1234yf, R1234ze, R227ea and R152a)

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Abstract

In this paper, comparison between three vapour compression refrigeration systems (i.e.System-1: Three stage compression with multiple expansion valves and water coolers and System-2: Three stage compression with multiple expansion valves and flash inter cooling chambers in parallel and System-3: Three stage compression with multiple expansion valves and flash inter cooling chambers in series)using environmental friendly refrigerants on the basis of energetic and exergetic approach have been made. It has been observed that for all selected new eco-friendly refrigerants, energy and exergetic efficiency of system-2 is lower than system-1 and sytem-3.The best performance using R134a was observed in system-3. For all Vapour compression refrigeration systems R227ea showed lowest thermal performance in terms of COP, second law efficiency whereas performances of R134a is better in comparison of other selected refrigerants 2.Thermodynamic second law performance of R134ze is less than R1234yf . Since R134a is easily available and also gives better thermodynamic performances, therefore R134a may also be used for practical applications without taking of any safety precautions.

Key words: Irreversibility Computation, VCRS, Energy-Exergy Analysis**,** Thermodynamics of Refrigeration systems

1. Introduction

Nowadays most of the energy utilize in cooling and air conditioning in industrial as well as for domestic applications, in addition to energy consumption, using of refrigerants in cooling and air conditioning having high GWP and ODP which are responsible for increasing global warming and ozone depletion. The primary requirements of ideal refrigerants are having good physical and chemical properties. Due to good physical and chemical properties such as non-corrosiveness, non-toxicity, non- flammability, low boiling point, Chlorofluorocarbons (CFCs) have been used over the last many decades, but hydro-chlorofluorocarbons (HCFCs) and Chlorofluorocarbons (CFCs) having large amount of chlorine content as well as high global warming potential and ozone depletion potential, so after 90s refrigerants under these categories these kinds of refrigerants are almost prohibited [1]. This paper mainly deals with the impact on second law efficiency in terms of exergetic efficiency with change in temperature of low, intermediate and high temperature evaporator of three systems.. It is also observed that second law efficiency decrease with increase in evaporator temperature. R134a and R227ea have maximum and minimum second law efficiency for both systems similar to performance evaluation in terms of energetic efficiency. It was also found that temperature variation in low and intermediate evaporator put great impact on second law efficiency in comparison with temperature evaporator, for all three systems.

2. Literature Review

Most of the study has been carried out for the performance evaluation of vapour compression refrigeration system using energetic analysis, but with the help of first law analysis irreversibility destruction or losses in components of system unable to determined [1], so that second law thermodynamic analysis is the advanced approach for thermodynamic analysis which gives an additional practical view of the processes. The utility of second law analysis on vapour compression refrigeration systems is well defined because it gives the idea

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for improvements in efficiency due to modifications in existing design in terms of reducing exergy destructions in the components. The second law exergetic analysis also provides new thought for development in the existing system. Bolaji B.O. et.al.[2] explained the utility of natural refrigerants as the ideal, environmentally friendly refrigerants and suggested ultimate solution for the problems of ozone depletion and global warming and concluded that the HFC refrigerants are currently the leading replacement for CFC and HCFC refrigerants in refrigeration and air-conditioning systems. However, they are equally foreign to nature like CFCs and HCFCs, consequently, strong basis for the need to embrace the use of natural refrigerants as replacement for the halocarbon refrigerants was provided and also analysed the potentials of various natural refrigerants in terms of their areas of application in the field of refrigeration and air-conditioning because natural refrigerants are hydrocarbons and their mixtures are miscible with both mineral oil used in R12 and polyol ester oils used in R134a systems with exception of ammonia and are fully compatible with all materials traditionally used in refrigeration systems and concluded that the natural refrigerants are the most suitable long time alternatives in refrigeration and air-conditioning systems. Nikolaidis and Probert [3] explained the utility of system optimization by using exergy analysis to investigate the behaviour of two stage compound compression cycle with flash intercooling using R-22 as refrigerant by varying the condenser saturation temperature and evaporator saturation temperature from 298 to 308 K and 238 to 228 K respectively and determined the effect of temperature change in condenser and evaporator on plants irreversibility rate and concluded that the changes in the temperatures of condenser and evaporator significantly effecting the plants overall irreversibility. Qureshi and Zubair [4] computed the performance degradation due to fouling occurred in the vapor compression systems for various applications using three ecofriendly refrigerants (i.e.R-134a, R-410A and R-407C. and found that the first law efficiency in terms of COP and second law efficiency in terms of exergetic efficiency using R-134a gives best performances in the all cases. Xuan and Chen [5] presented explained about the replacement of R502 by mixture of HFC-161 and found that mixture of HFC-161 gives same and higher performance than R404a at lower and higher evaporative temperature respectively on the vapour compression refrigeration system designed for R404a.Cabello et al.[6] considered the effect of condensing pressure, evaporating pressure and degree of superheating experimentally on the single stage vapour compression refrigeration system using R22, R134a and R407c and found that the mass flow rate is greatly affected by change in suction conditions of compressor in results on refrigeration capacity because refrigeration capacity depended on mass flow rate through evaporator. It was also found that for higher compression ratio R22 gives lower COP than R407C. similarly Spatz and Motta [7] mainly focused on the replacement of R12 with R410a by conducting experiment on vapour compression refrigeration systems for medium temperature and carried out thermodynamic analysis. The comparison was made of heat transfer and pressure drop characteristics and observed that the R410a gives best thermodynamic performances among R404a. Han et al. [8] carried out experimental studies on vapour compression refrigeration systems under different working conditions and their experimental results revealed that there could be replacement of R407c in vapour compression refrigeration system without any modification in the existing design.

Getu and Bansal [9] had optimized the design and operating parameters of like condensing temperature, subcooling temperature, evaporating temperature, superheating temperature and temperature difference in cascade heat exchanger R744-R717 cascade refrigeration system. A regression analysis was also done to obtain optimum thermodynamic parameters of same system.

Mohanraj et al [10] concluded 3.6% greater thermodynamic performance by using mixture of R290 and R600a in the ratio of 45.2: 54.8 by weight through experimental investigation on same domestic refrigeration system under different environmental temperatures COP of system using R134a. Padilla et al [11] carried out exergy analysis of domestic vapour compression refrigeration system using R134a and concluded that thermal performances in terms of power consumption, irreversibility and exergy efficiency of R134A is better than R12.

3. Energy and exergy analysis

For carrying out energetic and exergetic analysis, computational models of system-1 to system-3 have been developed and impact of chosen refrigerants on these systems has been analyzed on the saving of energy and due to increase of energy crises, global warming and depletion of ozone layer.. The work input required running the vapour compression refrigeration system reduced by using compound compression and further decreased by flash intercooling between compressors. COP of system can also be enhanced by compressing the refrigerant very close to the saturation line this can be achieved by compressing the refrigerants in more stages with intermediate intercoolers. The refrigeration effect can be increase by maintaining the condition of refrigerants in more liquid stage at the entrance of evaporator which can be achieved by expanding the refrigerant very close to the liquid line. The expansion can be brought close to the liquid line by sub cooling the refrigerant and removing the flashed vapours by incorporating the flash chamber in the working cycle. The evaporator size can be reduced because unwanted vapours formed are removed before the liquid refrigerant enters in the evaporator. Multi-stage vapour compression with flash intercooler and individual throttle valves (system-1), three compressors arranged in compound compression, individual throttle valves, condenser and evaporator (system-2)and Multiple evaporator at constant temperature with compound compression, flash intercooler and multiple throttle valves and system-3 consists of three compressors arranged in compound compression, multiple throttle valves, condenser and evaporator

In this investigation following assumptions are made:

1. Load on the low, intermediate and high temperature evaporator is 10TR,
2. Dead state temperature (T0): 25^0C
3. Difference between evaporator and space temperature is 5 ^{0}C.
4. Adiabatic efficiency of compressor: 80%.
5. Dead state enthalpy (Φ0) and entropy (s0) of the refrigerants have been calculated corresponding to the dead state temperature (T0) of 298K.
6. Variation in kinetic and potential energy is negligible.
7. Expansion process is adiabatic
8. Temperature of evaporator is 0^0C respectively.
9. Condenser temperature : 50^0C
10. Degree of sub cooling : 10^0C

3.1 Thermodynamic Analysis

First law of thermodynamic gives the idea of energy balance of system while concept of exergy was given by second law of thermodynamics, which always decreases due to thermodynamic irreversibility. Exergy is defined as the measure of usefulness, quality or potential of a stream to cause change and an effective measure of the potential of a substance to impact the environment.

Exergy at any state is given as

$$X = (\Phi - \Phi_0) - T_0(s - s_0) \quad (1)$$

Compressors

$$\left(T_o\dot{S}_{gen}\right)_{c1} = \dot{W}_{c1} + \dot{m}_{c1}(X_2 - X_1) \quad (2)$$
$$(T_o\dot{S}_{gen})_{c2} = \dot{W}_{c2} + \dot{m}_{c2}(X_4 - X_3) \quad (3)$$
$$(T_o\dot{S}_{gen})_{c3} = \dot{W}_{c3} + \dot{m}_{c3}(X_6 - X_5 \quad (4)$$
$$\dot{\Psi}_c = (T_o\dot{S}_{gen})_{c1} + (T_o\dot{S}_{gen})_{c2} + (T_o\dot{S}_{gen})_{c3} \quad (5)$$

Evaporators

$$(T_o\dot{S}_{gen})_{e1} = \dot{m}_{e1}(X_1 - X_{10}) - \dot{Q}_{e1}\left(1 - \frac{T_0}{T_{r1}}\right) \quad (6)$$
$$\dot{\Psi}_e = (T_o\dot{S}_{gen})_{e1} \quad (7)$$

Condenser

$$\dot{\Psi}_{cond} = \left(T_o\dot{S}_{gen}\right)_{cond} = \dot{m}_{c3}(X_6 - X_7) - \dot{Q}_e\left(1 - \frac{T_0}{T_r}\right) \quad (8)$$

Throttle Valves

$$(T_o\dot{S}_{gen})_{tv1} = \dot{m}_{e1}(X_{77} - X_{10}) \quad (9)$$
$$\left(T_o\dot{S}_{gen}\right)_{tv2} = (\dot{m}_{e1} + \dot{m}_{f1})(X_{77} - X_9) \quad (10)$$
$$(T_o\dot{S}_{gen})_{tv3} = (\dot{m}_{e1} + \dot{m}_{f2})(X_{77} - X_8) \quad (11)$$
$$\dot{\Psi}_{tv} = (T_o\dot{S}_{gen})_{tv1} + (T_o\dot{S}_{gen})_{tv2} + (T_o\dot{S}_{gen})_{tv3} \quad (12)$$

Liquid subcooler

$$\dot{\Psi}_{lsc} = (T_o\dot{S}_{gen})_{sc} = \dot{m}_{c3}(X_7 - X_{77}) \quad (13)$$

Flash intercoolers

$$(T_o\dot{S}_{gen})_{f1} = \dot{m}_{f1}(X_9 - X_3) + \dot{m}_{c1}(X_2 - X_3) \quad (14)$$
$$(T_o\dot{S}_{gen})_{f2} = \dot{m}_{f2}(X_8 - X_5) + \dot{m}_{c1}(X_4 - X_5) \quad (15)$$
$$\dot{\Psi}_f = (T_o\dot{S}_{gen})_{f1} + (T_o\dot{S}_{gen})_{f2} \quad (16)$$

Total irreversibility destruction in system-1

$$\sum \dot{\Psi}_k = \dot{\Psi}_e + \dot{\Psi}_c + \dot{\Psi}_{cond} + \dot{\Psi}_{tv} + \dot{\Psi}_{lsc} + \dot{\Psi}_f \quad (17)$$
$$\dot{m}_{f1'} = \frac{\dot{m}_{c1'}(\Phi_{2'} - \Phi_{3'})}{(\Phi_{3'} - \Phi_{10'})} \quad (18)$$
$$\dot{m}_{c2'} = \dot{m}_{c1'} + \dot{m}_{f1'} \quad (19)$$
$$\dot{m}_{c2'} = \frac{\dot{Q}_{e1'}}{(\Phi_{5'} - \Phi_{8'})} + \dot{m}_{c2'}\left(\frac{x_{8'}}{1 - x_{8'}}\right) \quad (20)$$
$$\dot{m}_{f2'} = \frac{\dot{m}_{c2'}(\Phi_{4'} - \Phi_{5'})}{(\Phi_{5'} - \Phi_{8'})} \quad (21)$$

Power required for running the compressors

$$P_{c1'} = \frac{\dot{m}_{c1'}(\Phi_{2'} - \Phi_{1'})}{60} \quad (22)$$
$$P_{c2'} = \frac{\dot{m}_{c2'}(\Phi_{4'} - \Phi_{3'})}{60} \quad (23)$$
$$P_{c3'} = \frac{\dot{m}_{c3'}(\Phi_{6'} - \Phi_{5'})}{60} \quad (24)$$
$$\text{Energetic efficiency} = \frac{\dot{Q}_{e'}}{P_{c'} * 60} \quad (25)$$

3.2 Rate of exergy loss due to irreversibilties ($T_o\dot{S}_{gen}$) in various components of system-2

Compressors

$$(T_o\dot{S}_{gen})_{c1'} = \dot{W}_{c1'} + \dot{m}_{c1'}(X_{2'} - X_{1'}) \quad (26)$$
$$(T_o\dot{S}_{gen})_{c2'} = \dot{W}_{c2'} + \dot{m}_{c2'}(X_{4'} - X_{3'}) \quad (27)$$
$$(T_o\dot{S}_{gen})_{c3'} = \dot{W}_{c3'} + \dot{m}_{c3'}(X_{6'} - X_{5'}) \quad (28)$$
$$\dot{\Psi}_{c'} = (T_o\dot{S}_{gen})_{c1'} + (T_o\dot{S}_{gen})_{c2'} + (T_o\dot{S}_{gen})_{c3'} \quad (29)$$

Evaporator

$$\left(T_o\dot{S}_{gen}\right)_{e1'} = \dot{m}_{e1'}(X_{1'} - X_{12'} - \dot{Q}_{e1'}\left(1 - \frac{T_0}{T_{r1'}}\right) \quad (30)$$
$$\dot{\Psi}_{e'} = (T_o\dot{S}_{gen})_{e1'} \quad (31)$$

Condenser

$$\dot{\Psi}_{cond'} = (T_o\dot{S}_{gen})_{cond'} \dot{m}_{c3'}(X_{6'} - X_{7'}) - \dot{Q}_{e'}\left(1 - \frac{T_o}{T_{r'}}\right) \quad (32)$$

Throttle Valves

$$(T_o\dot{S}_{gen})_{tv1'} = \dot{m}_{e1'}(X_{11'} - X_{12'}) \quad (33)$$
$$(T_o\dot{S}_{gen})_{tv2'} = \dot{m}_{c2'}(X_{9'} - X_{10'}) \quad (34)$$
$$(T_o\dot{S}_{gen})_{tv3'} = \dot{m}_{c3'}(X_{77'} - X_{8'}) \quad (35)$$
$$\dot{\Psi}_{tv'} = (T_o\dot{S}_{gen})_{tv1'} + (T_o\dot{S}_{gen})_{tv2'} + (T_o\dot{S}_{gen})_{tv3'} \quad (36)$$

Liquid subcooler

$$\dot{\Psi}_{lsc'} = (T_o\dot{S}_{gen})_{lsc'} = \dot{m}_{c3'}(X_{7'} - X_{77'} \quad (37)$$

Flash intercoolers

$$(T_o\dot{S}_{gen})_{f1'} = \dot{m}_{f1'}(X_{10'} - X_{3'}) + \dot{m}_{c1'}(X_{2'} - X_{3'}) \quad (38)$$
$$(T_o\dot{S}_{gen})_{f2'} = \dot{m}_{f2'}(X_{8'} - X_{5'}) + \dot{m}_{c2'}(X_{4'} - X_{5'}) \quad (39)$$

$$\dot{\Psi}_{f'} = (T_o\dot{S}_{gen})_{f1'} + (T_o\dot{S}_{gen})_{f2'} \quad (40)$$

Total irreversibility destruction in system-1

$$\sum \dot{\Psi}_{k'} = \dot{\Psi}_{e'} + \dot{\Psi}_{c'} + \dot{\Psi}_{cond'} + \dot{\Psi}_{tv'} + \dot{\Psi}_{lsc'} + \dot{\Psi}_{f'} \quad (41)$$

Exergetic efficiency

$$= \frac{\text{Exergy of cooling load of evaporators}}{\text{Compressors work}} = \frac{\dot{EP}}{\dot{W}} \quad (42)$$

Exergetic efficiency of system

$$= \frac{(\dot{Q}_{e1}) - T_o\left(\frac{\dot{Q}_{e1}}{T_{r1}} + \right)}{P_c * 60} \quad (43)$$

4. Result and Discussions

The effect of various ecofriendly refrigerants with coefficient of performance for considered refrigerants of system-1 to system-3 is shown by Table-1 to Table-8 respectively. The first law efficiency in terms of COP of system-1 using R227ea is higher than HFC-134a, HFO-1234yf & HFO1234ze, However R1234ze gives better COP than using R134a, however lowest first law performance in terms of COP was observed by using R1234yf in the system-1.Similarly in case of system-2, R-1234ze gives higher COP than using all ecofriendly refrigerants. R134a in system-2 has higher COP than R1234yf. Therefore R1234ze is best alternative for replacing R134a in system1 and System-2. For system-3, the COP Using R1234ze is higher than by using R227ea and R134a.

Table-1: First Law efficiency in terms of COP of various Refrigeration Systems of 35 kW cooling capacity

Refrigerant	System-1 Two stage compression with water inter cooler and liquid sub cooler	System-2 Two stage compression with water intercooler, liquid sub cooler and liquid flash chamber	System-3 Two stage vapour compression with water intercooler liquid sub cooler and flash intercooler
R134a	2.866	3.08	3.086
R1234yf	2.551	2.796	2.782
R1234ze	3.078	3.157	3.159
R227ea	3.098	3.134	3.137
R152a	3.016	3.134	3.152

However, and lower first law performance in terms of COP was observed by using HFO-1234yf. Hence HFO-1234ze can be a good ‘replacement of HFC-134a at higher value of evaporator temperature and HFO-1234yf can be a good replacement lower value of evaporator temperature after certain modification.

Table-2 shows the comparison between three vapour compression refrigeration systems. It was observed that second law efficiency of system -3 is higher than system -1 however, by using R134a is higher than other ecofriendly refrigerants however first law efficiency in terms of COP and exergetic efficiency of HFC-134a is more than R134yf and HFO1234ze. Hence HFO-1234yf can be a good replacement of HFC-134a at lower value of evaporator temperature and HFO-1234ze can be a good replacement of HFC-134a at lower value of evaporator temperature after certain modification Table-3 &Table-4 show the higher exergy destruction ratio in terms of exergy of fuel in terms of power required for running all systems by using R234zebut lower than by using R-227ea. In case of all (three), systems using R134a, the system -3 gives lowest EDR and system-1 gives higher EDR while second system has lower EDR than system1 and higher than system-3.

Table-2: Second Law efficiency in terms of Exergetic Efficiency of various Refrigeration Systems of 35 kW cooling capacity

Refrigerant	System-1 Two stage compression with water inter cooler and liquid sub cooler	System-2 Two stage compression with water intercooler, liquid sub cooler and liquid flash chamber	System-3 Vapour compression with water intercooler liquid sub cooler and flash intercooler
R134a	0.3833	0.4091	0.4099
R1234yf	0.3686	0.4040	0.4020
R1234ze	0.3095	0.3175	0.3177
R227ea	0.2727	0.2760	0.2762
R152a	0.3676	0.382	0.3841

Table-3: Exergy Destruction Ratio based on exergy input of various Refrigeration Systems of 35 kW cooling capacity

Refrigerant	System-1 Two stage compression with water inter cooler and liquid sub cooler	System-2 Two stage compression with water intercooler, liquid sub cooler and liquid flash chamber	System-3 Two stage vapour compression with water intercooler liquid sub cooler and flash intercooler
R134a	0.6167	0.5909	0.5901
R1234yf	0.6314	0.5960	0.5980
R1234ze	0.6905	0.6825	0.6823
R227ea	0.7273	0.7240	0.7238
R152a	0.6324	0.6180	0.6158

Table-4: Exergy Destruction Ratio based on exergy output of various Refrigeration Systems of 35 kW cooling capacity

Refrigerant	System-1 Two stage compression with water inter cooler and liquid sub cooler	System-2 Two stage compression with water intercooler, liquid sub cooler and liquid flash chamber	System-3 Vapour compression with water intercooler liquid sub cooler and flash intercooler
R134a	1.734	1.373	1.35
R1234yf	2.018	1.391	1.379
R1234ze	3.123	2.133	2.128
R227ea	5.036	2.618	2.615
R152a	1.720	1,580	1.557

Table-5: Exergy input of various Refrigeration Systems

Refrigerant	System-1 Two stage compression with water inter cooler and liquid sub cooler	System-2 Two stage compression with water intercooler, liquid sub cooler and liquid flash chamber	System-3 Vapour compression with water intercooler liquid sub cooler and flash intercooler
R134a	12.13	11.37	17.01
R1234yf	13.72	12.52	18.87
R1234ze	11.37	11.09	16.62
R227ea	11.30	11.17	16.73
R152a	14.51	11.60	16.65

Table-6: Power required (kW) to run the compressor-1for all vapour compression refrigeration systems of 35 kW cooling capacity

Refrigerant	System-1 Two stage compression with water inter cooler and liquid sub cooler	System-2 Two stage Compression with multiple expansion Valves and flash inter cooling Chambers in parallel	System-3 Vapour compression with water intercooler liquid sub cooler and flash intercooler
R134a	5.455	4.816	7.224
R1234yf	6.177	5.218	7.828
R1234ze	5.288	5.043	7.565
R227ea	5.409	5.297	7.946
R245fa	5.251	4.87	7.305

The irreversibility analysis of systems, the exergy destruction Ratio based on exergy of fuel in terms of total power and exergy destruction Ratio based on exergy of products are shown in Table-3 to Table-4 respectively. However the exergy of fuel in terms of total power required to run all system are shown in Table-5 respectively. It was observed that the exergy destruction ratio of system-3 is lower than system-1. Table-6 and Table-7 are showing the power required to run all compressors in all system using five ecofriendly refrigerants.

Table-7: *Power required (kW) to run the compressor-2for all vapour compression refrigeration systems of 35 kWCooling capacity*

Refrigerant	System-1 Two stage compression with water inter cooler and liquid sub cooler	System-2 Two stage compression with water intercooler, liquid sub cooler and liquid flash chamber	System-3 Vapour compression with water intercooler liquid sub cooler and flash intercooler
R134a	6.674	6.65	9.791
R1234yf	7.545	7.302	11.05
R1234ze	6.084	6.044	9.056
R227ea	5.890	5.869	8.789
R152a	6.354	6.299	9.351

5. Conclusions and Recommendations

Thermodynamic energy-exergy analysis of multi-stage vapour compression refrigerator and flash intercooler with individual or multiple throttle valves have been done in terms of COP, second law efficiency and irreversibility destruction ratio based on exergy of fuel and Exergy destruction based on exergy of product and following conclusions have been made

1. The total power required to run sytem using R1234yf is more than using R134a while R134a required more power than using R1234yf in case of all systems. Similarly, the same trends also observed in case of power required to run the second compressor in all systems. However compressor-1 required more power by using R234ze by replacing R134a
2. Three VCR systems (system-1 to system-3) were analyzed analytically and it was observed that COP (energetic efficiency) of system-3 is higher than system-2. The COP of all systems increases with increase in evaporator temperature for chosen refrigerants. It was also observed that R134a shows better thermodynamic performances in terms of COP and exergetic efficiency and R-227ea gives low first law performance in term of COP and second law efficiency in terms of exergetic efficiency for all systems.
3. From the irreversibility point of view, or exergy destruction based on exergy of fuel or exergy of output, the system-1 was found worst Total efficiency defect is more for HFO-1234yf followed by HFO-1234ze and HFC-134a, but the difference is small.
4. Increase in ambient state temperature has a positive effect on exergetic efficiency and EDR, i.e. EDR reduces and exergetic efficiency increases.HFO1234ze gives lesser values of exergetic efficiency whereas HFO-1234yf gives lower values of thermal performances values.
5. First law performance in terms of COP and second law exergetic performance of system-3 is higher than system-2for selected new ecofriendly refrigerants.
6. For all vapour compressor refrigeration systemsR227ea shows minimum thermal performance in terms of COP, second law efficiency.
7. System 1 also gives higher thermodynamic performance than system-2 and lower than system-3.

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