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# Irreversibility analysis of three stage vapour compression refrigeration systems with flash-intercooler using eco-friendly new refrigerants (R134a, R1234yf, R1234ze, R227ea and R245fa)

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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]. 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 [2], so that second law thermodynamic analysis is the advanced approach for thermodynamic analysis which gives an additional practical view of the processes [3-5]. The utility of second law analysis on vapour compression refrigeration systems is well defined because it gives the idea 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 [6].Xuan and Chen [7] 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. [8] 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.It was observed that mass flow rate is greatly affected by change in

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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 [9] also focused on the replacement of R12 with R410a and conducted experimental investigation of medium temperature vapour compression refrigeration cycles and carried out thermodynamic analysis. The comparison was made of heat transfer and pressure drop characteristics and found that the R410a gives best thermodynamic performances among R404a. Han et al. [10] carried out experimental investigation under different working conditions and their results revealed that there could be replacement of R407c in vapour compression refrigeration system having rotor compressor with mixture of R32/R125/R161 showing higher first law performance in terms of COP and less pressure ratio along with slightly high discharge compressor temperature without any modification in the existing design. Cabello et al [11] had studied about the effect of operating parameters on COP, work input and cooling capacity of single-stage vapour compression refrigeration system. There is great influence on energetic parameters due change in suction pressure, condensing and evaporating temperatures. With exergetic efficiency 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].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 [2], so exergetic analysis is the advanced approach for thermodynamic analysis which gives an additional practical view of the processes [3-5]. The utility of second law analysis on vapour compression refrigeration systems is well defined because it gives the idea for improvements in efficiency due to modifications in existing design in terms of reducing exergy destructions in the components. In addition to this second law analysis also provides new thought for development in the existing system [6].Xuan and Chen [7] presented in this manuscript about the replacement of R502 by mixture of HFC-161.Through experimental study it was 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.[8] effect of condensing pressure, evaporating pressure and degree of superheating was experimentally investigated on single stage vapour compression refrigeration system using R22, R134a and R407C.It was observed that 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.Spatz and Motta [9] focused on replacement of R12 with R410a through experimental investigation of medium temperature vapour compression refrigeration cycles. In terms of thermodynamic analysis, comparison of heat transfer and pressure drop characteristics, R410a gives best performance among R12, R404a and R290a.Han et al.[10]under different working conditions experimental results revealed that there could be replacement of R407C in vapour compression refrigeration system having rotor compressor with mixture of R32/R125/R161 showing higher COP, less pressure ratio and slightly high discharge compressor temperature without any modification in the same system. Cabello et al [11] had studied about the effect of operating parameters on COP, work input and cooling capacity of single-stage vapour Getu and Bansal [12] had optimized the design and operating parameters of like condensing temperature, sub cooling 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 [13] through experimental investigation of domestic refrigerator they arrived on conclusions that under different environmental temperatures COP of system using mixture of R290 and R600a in the ratio of 45.2: 54.8 by weight showing up to 3.6% greater than same system using R134a, also discharge temperature of compressor with mixture of R290 and R600a is lower in the range of 8.5-13.4K than same compressor with R134a.Padilla et al [14]exergy analysis of domestic vapour compression refrigeration system with R12 and R413a was done. They concluded that performance in terms of power consumption, irreversibility and exergy efficiency of R413A is better than R12.The impact on second law efficiency (exergetic efficiency) with change in temperature of low, intermediate and high temperature evaporator of three systems. As variation in second law efficiency is reciprocal to coefficient of performance. 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 [1].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 [2], so exergetic analysis is the advanced approach for thermodynamic analysis which gives an additional practical view of the processes [3-5]. The utility of second law analysis on vapour compression refrigeration systems is well defined because it gives the idea for improvements in efficiency due to modifications in existing design in terms of reducing exergy destructions in the components. In addition to this second law analysis also provides new thought for development in the existing system [6].Xuan and Chen [7] presented in this manuscript about the replacement of R502 by mixture of HFC-161.Through experimental study it was 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.[8] effect of condensing pressure, evaporating pressure and degree of superheating was experimentally investigated on single stage vapour compression refrigeration system using R22, R134a and R407C.It was observed that 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 In this paper great emphasis put on saving of energy and using of ecofriendly refrigerants due to increase of energy crises, global warming anddepletion 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 evaporators at different temperatures 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 than R407C.Spatz and Motta [9]focused on replacement of R12 with R410a through experimental investigation of medium temperature vapour compression refrigeration cycles. In terms of thermodynamic analysis, comparison of heat transfer and pressure drop characteristics, R410a gives best performance among R12, R404a and R290a.Han et al. [10]under different working conditions experimental results revealed that there could be replacement of R407C in vapour compression refrigeration system having rotor compressor with mixture of R32/R125/R161 showing higher COP, less pressure ratio and slightly high discharge compressor temperature without any modification in the same system. Cabello et al [11] had studied about the effect of operating parameters on COP, work input and cooling capacity of single-stage vapour compression refrigeration system.

## 2. Energy and exergy analysis

For carrying out energetic and exergetic analysis, computational models of system-1 and system-2 has been developed and impact of chosen refrigerants on these systems has been analyzed using EES [15].In this investigation following assumptions are made:

1. Load on the low, intermediate and high temperature evaporator is 10TR,
2. Dead state temperature (T0 ): $25^0$C
3. Difference between evaporator and space temperature (Tr-Te):$5^0$C.
4. Adiabatic efficiency of compressor: 76%.
5. Dead state enthalpy (Φ0) and entropy (s0) of the refrigerants have been calculated corresponding to the dead state temperature (T0) of $25^0$ C.
6. Variation in kinetic and potential energy is negligible.
7. Expansion process is adiabatic
8. Temperature of low, intermediate and high temperature evaporators are -$10^0$C, $0^0$C and $10^0$C respectively.
9. Condenser temperature : $50^0$C
10. Degree of sub cooling : $10^0$

### 2.1 Thermodynamic Analysis

First law of thermodynamic gives the idea of energy balance of system.

$$\dot{m}_{c1} = \dot{m}_{e1} = \frac{\dot{Q}_{e1}}{(\Phi_1 - \Phi_{10})} \quad (1)$$

$$\dot{m}_{e2} = \frac{\dot{Q}_{e2}}{(\Phi_3 - \Phi_9)} \quad (2)$$

$$\dot{m}_{f1} = \frac{\dot{m}_{c1}(\Phi_2 - \Phi_3)}{(\Phi_3 - \Phi_9)} \quad (3)$$

$$\dot{m}_{c2} = \dot{m}_{c1} + \dot{m}_{e2} + \dot{m}_{f1} \quad (4)$$

$$\dot{m}_{e3} = \frac{\dot{Q}_{e3}}{(\Phi_5 - \Phi_8)} \quad (5)$$

$$\dot{m}_{f2} = \frac{\dot{m}_{c2}(\Phi_4 - \Phi_5)}{(\Phi_5 - \Phi_8)} \quad (6)$$

$$\dot{m}_{c3} = \dot{m}_{c2} + \dot{m}_{e3} + \dot{m}_{f2} \quad (7)$$

*Energy consumption for sytem-1*

$$P_{c1} = \frac{\dot{m}_{c1}(\Phi_2 - \Phi_1)}{60} \quad (8)$$

$$P_{c2} = \frac{\dot{m}_{c2}(\Phi_4 - \Phi_3)}{60} \quad (9)$$

$$P_{c3} = \frac{\dot{m}_{c3}(\Phi_6 - \Phi_5)}{60} \quad (10)$$

*Energetic efficiency of system-1*

$$\text{COP} = \frac{\dot{Q}_e}{P_c * 60} \quad (11)$$

### *2.2 Rate of exergy loss due to irreversibility$(T_o\dot{S}_{gen})$ in various components of system-1*

The 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 [12].

*Exergy at any state is given as*

$$X = (\Phi - \Phi_0) - T_0(s - s_0) \quad (12)$$

*Compressors*

$$\left(T_o\dot{S}_{gen}\right)_{c1} = \dot{W}_{c1} + \dot{m}_{c1}(X_2 - X_1) \quad (13)$$
$$(T_o\dot{S}_{gen})_{c2} = \dot{W}_{c2} + \dot{m}_{c2}(X_4 - X_3) \quad (14)$$
$$(T_o\dot{S}_{gen})_{c3} = \dot{W}_{c3} + \dot{m}_{c3}(X_6 - X_5) \quad (15)$$
$$\dot{\Psi}_c = (T_o\dot{S}_{gen})_{c1} + (T_o\dot{S}_{gen})_{c2} + (T_o\dot{S}_{gen})_{c3} \quad (16)$$

*Evaporators*

$$(T_o\dot{S}_{gen})_{e1} = \dot{m}_{e1}(X_1 - X_{10}) - \dot{Q}_{e1}\left(1 - \frac{T_0}{T_{r1}}\right) \quad (17)$$
$$\left(T_o\dot{S}_{gen}\right)_{e2} = \dot{m}_{e2}(X_3 - X_9) - \dot{Q}_{e2}\left(1 - \frac{T_0}{T_{r2}}\right) \quad (18)$$
$$(T_o\dot{S}_{gen})_{e3} = \dot{m}_{e3}(X_5 - X_8) - \dot{Q}_{e3}\left(1 - \frac{T_0}{T_{r3}}\right) \quad (19)$$
$$\dot{\Psi}_e = (T_o\dot{S}_{gen})_{e1} + (T_o\dot{S}_{gen})_{e2} + (T_o\dot{S}_{gen})_{e3} \quad (20)$$

*Condenser*

$$\dot{\Psi}_{cond} = \left(T_o\dot{S}_{gen}\right)_{cond} = \dot{m}_{c3}(X_6 - X_7) - \dot{Q}_e\left(1 - \frac{T_0}{T_r}\right) \quad (21)$$
$$(T_o\dot{S}_{gen})_{tv1} = \dot{m}_{e1}(X_{77} - X_{10}) \quad (22)$$
$$\left(T_o\dot{S}_{gen}\right)_{tv2} = (\dot{m}_{e2} + \dot{m}_{f1})(X_{77} - X_9) \quad (23)$$
$$(T_o\dot{S}_{gen})_{tv3} = (\dot{m}_{e3} + \dot{m}_{f2})(X_{77} - X_8) \quad (24)$$
$$\dot{\Psi}_{tv} = (T_o\dot{S}_{gen})_{tv1} + (T_o\dot{S}_{gen})_{tv2} + (T_o\dot{S}_{gen})_{tv3} \quad (25)$$

*Liquid subcooler*

$$\dot{\Psi}_{lsc} = (T_o\dot{S}_{gen})_{sc} = \dot{m}_{c3}(X_7 - X_{77}) \quad (26)$$

*Flash intercoolers*

$$(T_o\dot{S}_{gen})_{f1} = \dot{m}_{f1}(X_9 - X_3) + \dot{m}_{c1}(X_2 - X_3) \quad (27)$$
$$(T_o\dot{S}_{gen})_{f2} = \dot{m}_{f2}(X_8 - X_5) + \dot{m}_{c1}(X_4 - X_5) \quad (28)$$
$$\dot{\Psi}_f = (T_o\dot{S}_{gen})_{f1} + (T_o\dot{S}_{gen})_{f2} \quad (29)$$
$$\sum \dot{\Psi}_k = \dot{\Psi}_e + \dot{\Psi}_c + \dot{\Psi}_{cond} + \dot{\Psi}_{tv} + \dot{\Psi}_{lsc} + \dot{\Psi}_f \quad (30)$$
$$\dot{m}_{c1'} = \dot{m}_{e1'} = \frac{\dot{Q}_{e1'}}{(\Phi_{1'} - \Phi_{12'})} \quad (31)$$
$$\dot{m}_{e2'} = \frac{\dot{Q}_{e2'}}{(\Phi_{3'} - \Phi_{10'})} + \dot{m}_{c1'}\left(\frac{x_{10'}}{1 - x_{10'}}\right) \quad (32)$$
$$\dot{m}_{f1'} = \frac{\dot{m}_{c1'}(\Phi_{2'} - \Phi_{3'})}{(\Phi_{3'} - \Phi_{10'})} \quad (33)$$
$$\dot{m}_{c2'} = \dot{m}_{c1'} + \dot{m}_{e2'} + \dot{m}_{f1'} \quad (34)$$
$$\dot{m}_{e3'} = \frac{\dot{Q}_{e3'}}{(\Phi_{5'} - \Phi_{8'})} + \dot{m}_{c2'}\left(\frac{x_{8'}}{1 - x_{8'}}\right) \quad (35)$$
$$\dot{m}_{f2'} = \frac{\dot{m}_{c2'}(\Phi_{4'} - \Phi_{5'})}{(\Phi_{5'} - \Phi_{8'})} \quad (36)$$

*Power required for running the compressors*

$$P_{c1'} = \frac{\dot{m}_{c1'}(\Phi_{2'} - \Phi_{1'})}{60} \quad (37)$$
$$P_{c2'} = \frac{\dot{m}_{c2'}(\Phi_{4'} - \Phi_{3'})}{60} \quad (38)$$
$$P_{c3'} = \frac{\dot{m}_{c3'}(\Phi_{6'} - \Phi_{5'})}{60} \quad (39)$$
$$\text{Energetic efficiency} = \frac{\dot{Q}_{e'}}{P_{c'} * 60} \quad (40)$$

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

$$(T_o\dot{S}_{gen})_{c1'} = \dot{W}_{c1'} + \dot{m}_{c1'}(X_{2'} - X_{1'}) \quad (41)$$
$$(T_o\dot{S}_{gen})_{c2'} = \dot{W}_{c2'} + \dot{m}_{c2'}(X_{4'} - X_{3'}) \quad (42)$$
$$(T_o\dot{S}_{gen})_{c3'} = \dot{W}_{c3'} + \dot{m}_{c3'}(X_{6'} - X_{5'}) \quad (43)$$
$$\dot{\Psi}_{c'} = (T_o\dot{S}_{gen})_{c1'} + (T_o\dot{S}_{gen})_{c2'} + (T_o\dot{S}_{gen})_{c3'} \quad (44)$$

*Evaporators*

$$\left(T_o\dot{S}_{gen}\right)_{e1'} = \dot{m}_{e1'}(X_{1'} - X_{12'} - \dot{Q}_{e1'}\left(1 - \frac{T_0}{T_{r1'}}\right) \quad (45)$$
$$\left(T_o\dot{S}_{gen}\right)_{e2'} = \dot{m}_{e2'}(X_{3'} - X_{10'}) - \dot{Q}_{e2'}\left(1 - \frac{T_0}{T_{r2'}}\right) \quad (46)$$
$$\left(T_o\dot{S}_{gen}\right)_{e3'} = \dot{m}_{e3'}(X_{5'} - X_{8'}) - \dot{Q}_{e3'}\left(1 - \frac{T_0}{T_{r3'}}\right) \quad (47)$$
$$\dot{\Psi}_{e'} = (T_o\dot{S}_{gen})_{e1'} + (T_o\dot{S}_{gen})_{e2'} + (T_o\dot{S}_{gen})_{e3'} \quad (48)$$

*Condenser*

$$\dot{\Psi}_{cond'} = \left(T_o\dot{S}_{gen}\right)_{cond'} = \dot{m}_{c3'}(X_{6'} - X_{7'}) - \dot{Q}_{e'}\left(1 - \frac{T_0}{T_{r'}}\right) \quad (49)$$

*Throttle Valves*

$$(T_o\dot{S}_{gen})_{tv1'} = \dot{m}_{e1'}(X_{11'} - X_{12'}) \quad (50)$$
$$\left(T_o\dot{S}_{gen}\right)_{tv2'} = \dot{m}_{c2'}(X_{9'} - X_{10'}) \quad (51)$$
$$(T_o\dot{S}_{gen})_{tv3'} = \dot{m}_{c3'}(X_{77'} - X_{8'}) \quad (52)$$
$$\dot{\Psi}_{tv'} = (T_o\dot{S}_{gen})_{tv1'} + (T_o\dot{S}_{gen})_{tv2'} + (T_o\dot{S}_{gen})_{tv3'} \quad (53)$$

*Liquid subcooler*

$$\dot{\Psi}_{lsc'} = (T_o\dot{S}_{gen})_{lsc'} = \dot{m}_{c3'}(X_{7'} - X_{77'}) \quad (54)$$

*Flash intercoolers*

$$(T_o\dot{S}_{gen})_{f1'} = \dot{m}_{f1'}(X_{10'} - X_{3'}) + \dot{m}_{c1'}(X_{2'} - X_{3'}) \quad (55)$$

$$(T_o\dot{S}_{gen})_{f2'} = \dot{m}_{f2'}(X_{8'} - X_{5'}) + \dot{m}_{c2'}(X_{4'} - X_{5'}) \quad (56)$$

$$\dot{\Psi}_{f'} = (T_o\dot{S}_{gen})_{f1'} + (T_o\dot{S}_{gen})_{f2'} \quad (57)$$

*Total irreversibility destruction in system-1*

$$\sum \dot{\Psi}_{k'} = \dot{\Psi}_{e'} + \dot{\Psi}_{c'} + \dot{\Psi}_{cond'} + \dot{\Psi}_{tv'} + \dot{\Psi}_{lsc'} + \dot{\Psi}_{f'} \quad (58)$$

*2.4* Exergetic efficiency

$$\text{Exergetic efficiency} = \frac{\text{Exergy of cooling load of evaporators}}{\text{Compressors work}} = \frac{\dot{EP}}{\dot{W}} \quad (59)$$

$$\text{Exergetic efficiency of system} - 1 = \frac{(\dot{Q}_{e1}+\dot{Q}_{e2}+\dot{Q}_{e3}) - T_o\left(\frac{\dot{Q}_{e1}}{T_{r1}}+\frac{\dot{Q}_{e2}}{T_{r2}}+\frac{\dot{Q}_{e3}}{T_{r3}}\right)}{P_c * 60} \quad (60)$$

$$\text{Rational efficiency of system} - 2 = \frac{(\dot{Q}_{e1'}+\dot{Q}_{e2'}+\dot{Q}_{e3'}) - T_o\left(\frac{\dot{Q}_{e1'}}{T_{r1'}}+\frac{\dot{Q}_{e2'}}{T_{r2'}}+\frac{\dot{Q}_{e3'}}{T_{r3'}}\right)}{P_{c'} * 60} \quad (61)$$

## 3. Result and Discussion

The effect of various ecofriendly refrigerants with coefficient of performance for considered refrigerants of system-1 and system-2 is shown by Table-1 to Table-5 respectively.

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

| Refrigerant | System-1 Three stage Compression with multiple expansion Valves and water coolers | System-2 Three stage Compression with multiple expansion Valves and flash inter cooling Chambers in parallel | System-3 Three stage Compression with multiple expansion Valves and flash inter cooling Chambers in series |
|---|---|---|---|
| R134a | 2.754 | 2.65 | 3.275 |
| R1234yf | 2.293 | 2.256 | 3.005 |
| R1234ze | 2.412 | 2.373 | 3.116 |
| R227ea | 1.882 | 1.951 | 2.956 |
| R245fa | 2.355 | 2.367 | 3.228 |

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

| Refrigerant | System-1 Three stage Compression with multiple expansion Valves and water coolers | System-2 Three stage Compression with multiple expansion Valves and flash inter cooling Chambers in parallel | System-3 Three stage Compression with multiple expansion Valves and flash inter cooling Chambers in series |
|---|---|---|---|
| R134a | 0.3658 | 0.3520 | 0.4351 |
| R1234yf | 0.3313 | 0.3259 | 0.4342 |
| R1234ze | 0.2425 | 0.2387 | 0.3134 |
| R227ea | 0.1657 | 0.1717 | 0.2603 |
| R245fa | 0.2025 | 0.1987 | 0.2734 |

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

| Refrigerant | System-1 Three stage Compression with multiple expansion Valves and water coolers | System-2 Three stage Compression with multiple expansion Valves and flash inter cooling Chambers in parallel | System-3 Three stage Compression with multiple expansion Valves and flash inter cooling Chambers in series |
|---|---|---|---|
| R134a | 0.6342 | 0.6480 | 0.5649 |
| R1234yf | 0.6687 | 0.6741 | 0.5658 |
| R1234ze | 0.7575 | 0.7613 | 0.6866 |
| R227ea | 0.8343 | 0.8383 | 0.7397 |
| R245fa | 0.7925 | 0.8013 | 0.7266 |

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

| Refrigerant | System-1 Three stage Compression with multiple expansion Valves and water coolers | System-2 Three stage Compression with multiple expansion Valves and flash inter cooling Chambers in parallel | System-3 |
|---|---|---|---|
| R134a | 1.734 | 1.832 | 1.222 |
| R1234yf | 2.018 | 2.068 | 1.229 |
| R1234ze | 3.123 | 3.189 | 2.081 |
| R227ea | 5.036 | 4.823 | 2.692 |
| R245fa | 3.93 | 4.0 | 2.29 |

*Table-5: Exergy input of various Refrigeration Systems*

| Refrigerant | System-1 Three stage Compression with multiple expansion Valves and water coolers | System-2 Three stage Compression with multiple expansion Valves and flash inter cooling Chambers in parallel | System-3 Three stage Compression with multiple expansion Valves and flash inter cooling Chambers in series |
|---|---|---|---|
| R134a | 12.71 | 13.21 | 10.69 |
| R1234yf | 15.26 | 15.52 | 11.65 |
| R1234ze | 14.51 | 14.75 | 11.23 |
| R227ea | 18.6 | 17.94 | 11.84 |
| R245fa | 14.51 | 14.78 | 10.84 |

Both systems (system-1& system-2) were analytically analyzed and it was observed that COP (energetic efficiency) of system-3 is higher than system-2The 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. The irreversibility analysis of systems, the exergy destruction Ratio based on exergy of fuel in terms of total power and also 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 the system are shown in Table-5 respectively. It was observed that the exergy destruction ratio of system-3 is lower than system-1. Tabl-6 to Table-8 are showing the power required to run all compressors in all system using five ecofriendly refrigerants.

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

| Refrigerant | System-1 Three stage Compression with multiple expansion Valves and water coolers | System-2 Three stage Compression with multiple expansion Valves and flash inter cooling Chambers in parallel | System-3 Three stage Compression with multiple expansion Valves and flash inter cooling Chambers in series |
|---|---|---|---|
| R134a | 4.892 | 4.892 | 3.433 |
| R1234yf | 5.906 | 5.906 | 3.686 |
| R1234ze | 5.602 | 5.602 | 3.565 |
| R227ea | 7.246 | 7.246 | 3.687 |
| R245fa | 5.75 | 5.75 | 3.44 |

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

| Refrigera nt | System-1 Three stage Compression with multiple expansion Valves and water coolers | System-2 Three stage Compression with multiple expansion Valves and flash inter cooling Chambers in parallel | System-3 Three stage Compression with multiple expansion Valves and flash inter cooling Chambers in series |
|---|---|---|---|
| R134a | 4.957 | 5.195 | 4.307 |
| R1234yf | 5.943 | 6.081 | 4.711 |
| R1234ze | 5.655 | 5.777 | 4.542 |
| R227ea | 7.208 | 6.938 | 4.813 |
| R245fa | 5.778 | 5.762 | 4.388 |

*Table-8: Power required (kW) to run the compressor-III for all vapour compression refrigeration systems of 35 kW cooling capacity*

| Refrigerant | System-1 Three stage Compression with multiple expansion Valves and water coolers | System-2 Three stage Compression with multiple expansion Valves and flash inter cooling Chambers in parallel | System-3 Three stage Compression with multiple expansion Valves and flash inter cooling Chambers in series |
|---|---|---|---|
| R134a | 2.86 | 3.121 | 2.946 |
| R1234yf | 3.415 | 3.529 | 3.251 |
| R1234ze | 3.257 | 3.369 | 3.124 |
| R227ea | 4.146 | 3.759 | 3.34 |
| R245fa | 3.336 | 3.273 | 3.014 |

## 4. 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. First law performance in terms of COP and second law exergetic performance of system-3 is higher than system-2for selected new ecofriendly refrigerants.
2. For all vapour compressor refrigeration systems R227ea shows minimum thermal performance in terms of COP, second law efficiency.
3. System 1 also gives higher thermodynamic performance than system-2 and lower than system-3.

## References


[1] Camelia Stanciu,Adina Gheorghian,Dorin Stanciu, Alexandru Dobrovicescu(2011)-Exergy analysis and refrigerant effect on the operation and performance limits of a one stage vapour compression refrigeration system,Termotehnia, 36-42.

[2] V. Siva Reddy,N. L. Panwar ,S. C. Kaushik(2011)-Exergetic analysis of a vapour compression refrigeration system with R134a, R143a, R152a, R404A, R407C, R410A, R502 and R507A,Clean Techn Environ Policy,14:47–53.

[3] J.U. Ahamed , R. Saidur, H.H. Masjuki(2011)-A review on exergy analysis of vapor compression refrigeration system, Renewable and Sustainable Energy Reviews,15: 1593–1600.

[4] Szargut D, Petela R, Egzergia(1965),WNT.

[5] Szargut J, Morris D, Steward F(1998)-Exergy analysis of thermal, chemical and metallurgical processes.,New York: Hemisphere Publishing Corporation.

[6] Saidur R, Masjuki HH, Jamaluddin MY(2007)-An application of energy and exergy analysis in residential sector in Malaysia. Energy Policy, 35: 1050–63.

[7] Yongmei Xuan, Guangming Chen. Experimental study on HFC-161 mixture as an alternative refrigerant to R502. Int J Refrigeration. Article in Press.

[8] R.Cabello a, E.Torrella b, J.Navarro-Esbr. Experimental evaluation of a vapour compression plant performance using R134a, R407C and R22 as working fluids. Int J Applied Thermal Engineering.2004; 24:1905-1917.

[9] Mark W. Spatz, Samuel F. Yana Motta. An evaluation of options for replacing HCFC-22 in medium temperature refrigeration systems. Int J Refrigeration.2004; 27:475-483.

[10] X.H. Han, Q. Wang, Z.W. Zhu, G.M. Chen. Cycle performance study on R32/R125/R161 as an alternative refrigerant to R407C. Int J Applied Thermal Engineering.2007; 27:2559-2565.

[11] R. Cabello, J. Navarro-Esbrı, R. Llopis, E. Torrella. Analysis of the variation mechanism in the main energetic parameters in a single-stage vapour compression plant. Int J Applied Thermal Engineering.2007; 27:167-176.

[12] H.M Getu, P.K Bansal. Thermodynamic analysis of an R744-R717 cascade refrigeration system. Int J Refrigeration.2008; 31:45-54.

[13] M. Mohanraj, S. Jayaraj, C. Muraleedharan, P. Chandrasekar.Experimental investigation of R290/R600a mixture as an alternative to R134a in a domestic refrigerator. Int J Thermal Sciences.2009; 48:1036-1042.

[14] M. Padilla, R. Revellin, J. Bonjour. Exergy analysis of R413A as replacement of R12 in a domestic refrigeration system. Int J Energy Conversion and Management.2010; 51:2195-2201.

[15] Klein, S.A., Alvarado, F., 2005. Engineering Equation Solver, Version 7.441. F Chart Software, Middleton, WI.


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