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# Thermodynamic Analysis of Actual Vapour Compression System with R12 and Its Eco-Friendly Alternatives Refrigerants

Vijay Singh Bisht[1], A.K.Pratihar[2]
[1](Assistant Professor Mechanical Engineering Department, Uttaranchal University, Dehradun, Uttarakhand, India),
[2](Professor Mechanical Engineering Department, College of Technology G.B.P.U.A.T, Pantnagar, Uttarakhand India)

***ABSTRACT***
This paper presents a theoretical performance study of a vapour compression refrigeration system with refrigerants R-12, R134a and R1234yf. A computational model based on energy first law analysis is presented for the investigation of the effects of evaporating temperatures, degree of subcooling, dead state temperatures and effectiveness of the liquid vapour heat exchanger on the relative capacity change index, coefficient of performance of the vapour compression refrigeration cycle. RCI (relative capacity change index) of the system is highest for R1234yf and with increase in degree of subcooling; R1234yf has the highest percentage increase in COP. The total compressor work requirement for system is highest with R134a. R1234yf is the only refrigerants of all the refrigerants used in present work that satisfy MAC directive (2006/40/EG) because of GWP value less than 150. From these results, it is indicated that R1234yf is the refrigerant for future.
***KEYWORDS***:- COP, Subcooling, LVHE, Pressure drop ,RCI.

## I. INTRODUCTION

Refrigerants are essential working substances used in refrigeration systems. The performance of refrigeration system largely depends upon the characteristics of the refrigerants. Besides performance issues, there are environmental issues concerning the use of refrigerants. In last few decades, it was discovered that some refrigerants cause ozone layer depletion and global warming, which is a serious hazard to environment. Ozone layer depletion (ODP) and global warming potential (GWP) have become one of the most important global issues. The Montreal protocol (UNEP, 1997) states the phasing out of CFC’s and HCFC’s as refrigerants that deplete the ozone layer (ODP). The Kyoto protocol (UNFCC, 2011) encouraged promotion of plans for sustainable development and reduction of global warming potential (GWP) including the regulations of HCFCs. Chlorofluorocarbons (CFCs) are the refrigerants which were responsible for both the environmental problems. Ozone layer depletion problem has been almost solved by replacing chlorofluorocarbons (CFCs) by hydro fluorocarbons (HFCs), hydrocarbon (HCs) and some natural refrigerants. However, problem of global warming is still associated with some newer refrigerants.

R12 refrigerant was widely used for domestic refrigeration which has been replaced by R134a, which is a HFC having zero ozone depletion potential (ODP). But, R134a causes global warming with a global warming potential (GWP) of 1300. This means that the emission of 1 kg of R134a is equivalent to 1300 kg of $CO_2$. R134a is stable in atmosphere for long time and has atmospheric life time of 13 years. Many investigations have been conducted in the research into substitutes for CFC12 and CFC22. Simulation of vapour compression cycle using R134a and R12 **[1].** A comparison of the performance of HFC134a and CFC12 is presented using COP (and compressor power) as a criterion for the same cooling load. Results indicate that the COP for HFC 134a is slightly (about3%) lower than that for a CFC 12 system**.** An experimental study on the application of a mixture of propane, butane, and isobutene to replace HFC134a in a domestic refrigerator. The results showed that a 60%/40% propane/butane mixture was the most appropriate alternative refrigerant has presented **[2] .** Theoretical analysis of vapour compression refrigeration system with R502, R404A and R507A has presented **[3].** The results showed that R507A was better substitute to R502 than R404A. An experimental performance of R1234yf and R1234ze as drop in replacement for R134a in domestic refrigerators has presented **[4].** It is shown that R-134a and R-1234yf have similar energy consumptions and capacities in both refrigerators tested, thus R-1234yf would make a good drop-in replacement for R-134a in domestic refrigeration. A review of next generation refrigerants , the refrigerant selection criteria for the new generation is based on low GWP value suitability, safety, and materials compatibility **[5].** According to National Aeronautics and Space Administration (NASA), due to global warming the following future trends are very likely to occur **[6].**

- Contraction of snow cover areas, increased thaw in permafrost regions, decrease in sea ice extent.
- Increased frequency of hot extremes, heat waves and heavy precipitation.
- Increase in tropical cyclone intensity.
- Precipitation increases in high latitudes.
- Precipitation decreases in subtropical land regions.

Therefore, search for better alternatives which have zero ozone depletion potential (ODP) and zero or lower global warming potential (GWP) is still on. R1234yf is a new refrigerant which has lower global warming potential than R134a. R1234yf has global warming potential (GWP) of 4, so it satisfy MAC Directive (GWP below 150) passed in July 2006 **[7].** R1234yf has nearly similar value of molecular weight and normal boiling point, making R1234yf a good replacement of R134a.Vapour pressure is very critical property when considering replacement capability of a refrigerant in vapour compression system. The vapour pressure of both the refrigerants is nearly similar. An experimental analysis of the internal heat exchanger influence on a vapour compression system performance working with R1234yf as a drop-in replacement for R134a have presented **[8].**

It was concluded that in R1234yf drop-in substitute for R134a, the introduction of an internal heat exchanger would reduce the decrease in the cooling capacity and COP between 2-6%, almost compensating these reductions cause by using R1234yf as drop-in replacement for R134a with an internal heat exchanger for high compression ratios.

The main characteristics of R12 and its alternatives are given in Table 1.

**Table 1** Characteristics of R12 and its alternative refrigerants [5,7]

| **Characteristics** | **R12** | **R134a** | **R1234yf** |
|---|---|---|---|
| **Chemical Formula** | $CF_2Cl_2$ | $CF_3CH_2F$ | $C_3F_4H_2$ |
| **Molecular weight** | 120.92 | 102.03 | 114.04 |
| **Boiling point (˚C)** | -29.75 | -26.07 | -29.03 |
| **Ozone Depletion Potential (ODP)** | 1 | 0 | 0 |
| **Global warming Potential (GWP)** | 10,900 | 1300 | 4 |
| **Atmospheric Life Time** | 100(Years) | 13(Years) | 11(days) |

### 2.1 Thermodynamic Analysis of Vapour Compression System

The vapour compression system used in present analysis has been shown in figure 1

#### 2.1.1 Assumptions

Following assumptions have been taken in the analysis:

1. The system is at steady state condition. All processes are steady flow processes.
2. Changes in kinetic and potential energy in analysis of all the components of system.
3. There is no heat in-leak to the system.
4. Pressure losses in pipelines are neglected

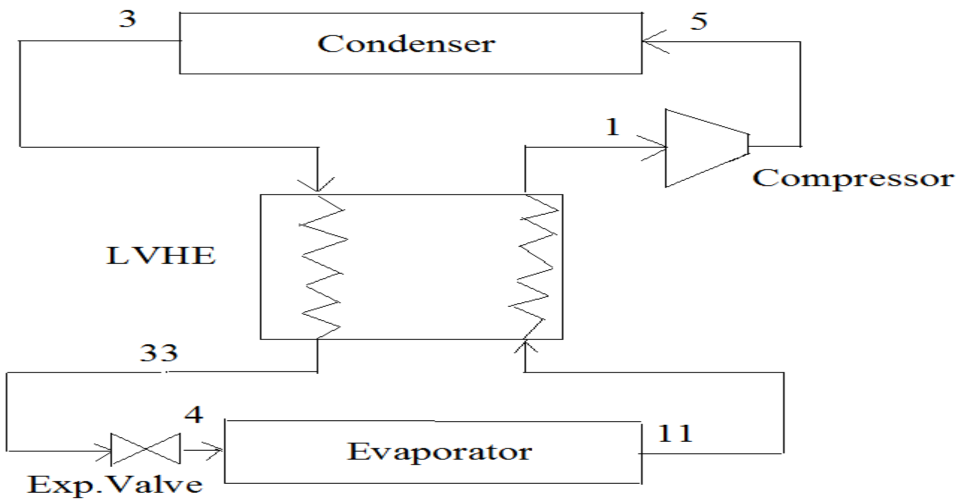


**Fig. 2.1** Schematic diagram of actual vapour compression system with liquid vapour heat exchanger

Thermodynamic cycle of actual vapour compression system on p-h coordinates has been shown in Figure 2.2.

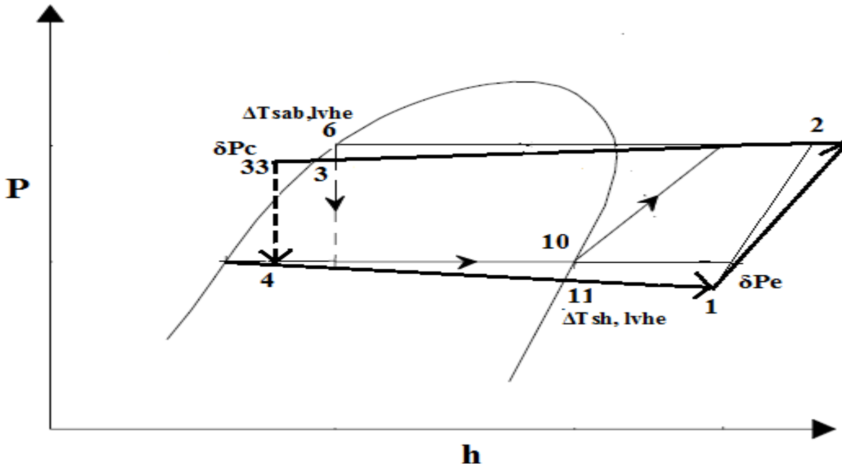


Fig. 2.2 p-h diagram showing subcooling and superheating

**2.1.2 Governing equations**

Energy balance equation for compressor

$$\dot{E}_{in} = \dot{E}_{out} \quad (2.1)$$

$$\dot{w}_{1-2} = \dot{m}\,(h_2 - h_1) \quad (2.2)$$

Compressor isentropic or adiabatic efficiency: It is ratio of isentropic work to the actual measure input power.

$$\eta_{comp,isen} = \frac{h_2 - h_1}{h_5 - h_1} \quad (2.3)$$

$$h_5 = \frac{h_2 - h_1}{\eta_{comp,isen}} + h_1 \quad (2.4)$$

$$\dot{w}_{comp} = \dot{m}_r (h_5 - h_1) \quad (2.5)$$

Energy balance equation for condenser

$$\dot{m}\,h_3 + \dot{Q}_C = \dot{m}\,h_5 \quad (2.6)$$

$$\dot{Q}_C = \dot{m}\,h_5 - \dot{m}\,h_3 \quad (2.7)$$

Energy balance equation for LVHE

Since the mass flow rate of liquid and vapour is the same, we get from the energy balance of the heat exchanger.

$$Q_n = h_1 - h_{11} = h_3 - h_{33} \quad (2.8)$$

The effectiveness of lvhe is the ratio of the actual to maximum possible heat transfer rates. In our system effectiveness is given as

$$\varepsilon = \frac{T_1 - T_{11}}{T_3 - T_{11}} \quad (2.9)$$

The effect of a liquid-suction heat exchanger on refrigeration capacity can be evaluated in terms of RCI **[9].**

Relative capacity change index (RCI) is percentage increase in refrigeration capacity when using liquid vapour heat exchanger.

$$RCI = \left(\frac{(h_{11} - h_{33}) - (h_{11} - h_3)}{(h_{11} - h_3)}\right) \times 100 \quad (2.10)$$

$Q_e$ is refrigerating effect, given as

$$Q_e = h_1 - h_4 \quad (2.11)$$

$$\dot{Q}_{rc} = \dot{m} \times Q_e \quad (2.12)$$

Energy balance in expansion valve

$$\dot{m}\,h_{33} = \dot{m}\,h_4 \quad (2.13)$$

Expansion valve is essentially an isenthalpic (i.e., constant enthalpy) device.

$$h_{33} = h_4 \quad (2.14)$$

Energy balance equation for evaporator

$$\dot{m}\,h_4 + \dot{Q}_{rc} = \dot{m}\,h_{11} \quad (2.15)$$

$$\dot{Q}_{rc} = \dot{m}\,h_{11} - \dot{m}\,h_4 \quad (2.16)$$

Where, $\dot{Q}_{rc}$ is refrigerating capacity, $\eta_c$ is isentropic efficiency of compressor, $\dot{w}_{comp}$ is work done by compressor.

The performance of vapour compression refrigeration system can be predicted in terms of coefficient of performance (COP), which is defined as the ratio of net refrigerating effect produced by the refrigerator to the work done by the compressor. The ideal COP of vapour compression cycle is dependent on the properties of the refrigerant.

COP is expressed as

$$COP = \frac{\dot{Q}_{rc}}{\dot{w}_{comp}} \quad (2.17)$$

The present work is validated Arora and Kaushik, (2008) carried out theoretical analysis of vapour compression refrigeration system with R502, R404A and R507A.The present computational model developed for carrying out the energy analysis of the system using Engineering Equation Solver software (Klein and Alvarado, 2012). The present computational model system using the same assumptions and conditions give the same result as by Arora and Kaushik, (2008) **[3].**

## II. Result and discussions

A computer program has been developed depending upon the requirements of engineering equation solver (EES). The equations are written in the equation window of EES in the FORTRAN LANGUAGE. EES solves these equations itself on giving 'calculate' command **[10].**

Computational model developed for carrying out the energy analysis of the system using Engineering Equation Solver software (Klein and Alvarado, 2012) was solved to get the desired results. Various operating conditions assumed for analysis have been listed in section 4.1 and results have been presented in the subsequent sections

**3.1 Operating conditions assumed for analysis of R12 and its alternatives**

For thermodynamic analysis of vapour compression system following data has been assumed.

1. Mass flow rate of refrigerant: 1kg/sec.
2. Degree of sub cooling of liquid refrigerant in LVHE ($\Delta T_{sub,lvhe}$ : 5˚C).
3. Isentropic efficiency of compressor ( $\eta_{comp}$ ) :75%.
4. Difference between evaporator and space temperature ($T_R$-$T_E$): 15˚C.
5. Effectiveness of liquid vapour heat exchanger ε= 0.8.
6. Evaporator temperature -30˚C to 0˚C in steps of 5.
7. Condenser temperature: 35˚C and 50˚C.
8. Pressure drop in evaporator $\delta P_e$: 20 kPa.
9. Pressure drop in condenser $\delta P_c$:10 kPa.
10. Dead state temperature ($T_0$) = 25 ˚C.
11. It is presumed that pressure drop in liquid vapour heat exchanger (LVHE) is negligible.

**3.2.1 Effect of evaporator temperature on compressor work and refrigerating effect at condenser temperature 50˚ C**

Evaporator temperature varies from -30˚C to 0˚C is shown in fig. 3.1. The condenser temperature is fixed to 50˚C. As the evaporator temperature increases from -30˚C to 0˚C, the value of compressor work decreases and refrigerating effect increases for all refrigerants. R134a has highest value of compressor work. R12 has minimum value of compressor work. R134a also has highest value of refrigerating effect at evaporator temperature equal to 0˚C.

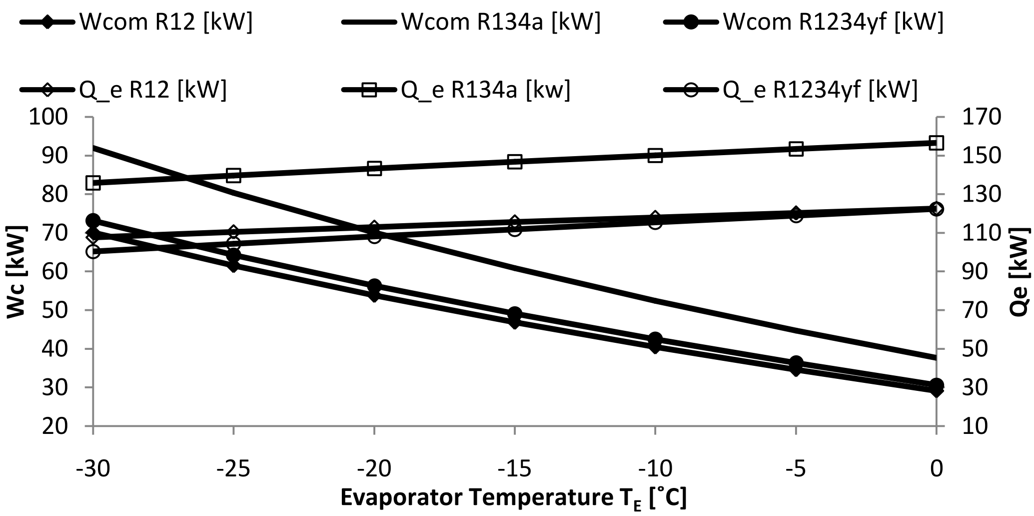


Fig.3.1 Variation of compressor work & refrigerating effect with evaporator temperature

This result trend can be explained from the fact that with increase in evaporator temperature refrigerating effect increases, there is decrease in specific volume of suction vapour. There is decrease in pressure ratio. With decrease in pressure ratio there is increase in the volumetric efficiency. There is decrease in compressor work due to decrease in pressure ratio.

**3.2.2 Effect of evaporator temperature on compressor work and refrigerating effect at condenser temperature 35 ˚C.**

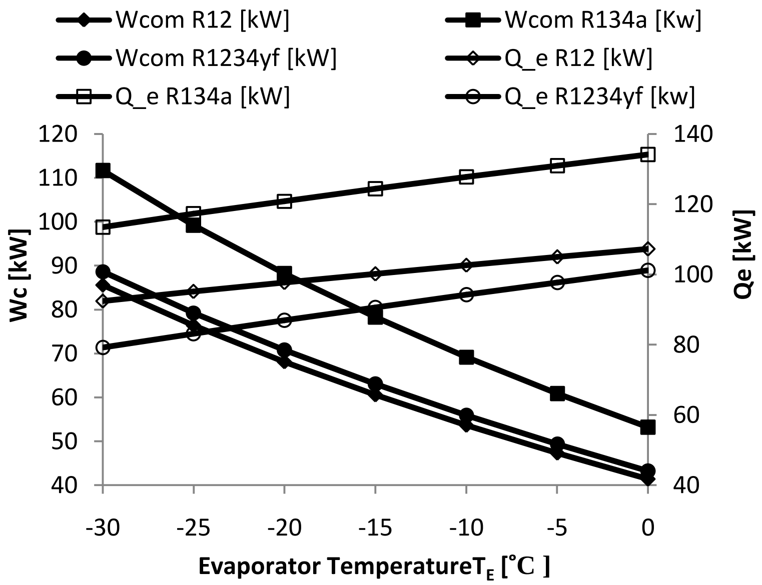


Fig 3.2 compressor work & refrigerating effect with evaporator temperature

Fig.3.2 shows variation of compressor work with evaporator temperature. Evaporator temperature varies from -30˚C to 0˚C. The condenser temperature is fixed to 35˚C. As the evaporator temperature increases from -30˚C to 0˚C the value of compressor work decreases for all refrigerants. R134a has highest value of compressor work. R12 has minimum value of compressor work. Fig.4.4 shows variation of refrigerating effect with evaporator temperature. R134a also has highest value of refrigerating effect at evaporator temperature equal to 0˚C. R1234yf has lowest value of refrigerating effect at evaporator temperature 0˚C. The performance of refrigerants would be clearer from their COP values. All the refrigerants are performed well at 35 ˚C than 50˚C condenser temperature.

This result trend can be explained from the fact that with increase in evaporator temperature refrigerating effect increases, there is decrease in specific volume of suction vapour. There is decrease in pressure ratio. With decrease in pressure ratio there is increase in the volumetric efficiency. There is decrease in compressor work due to decrease in pressure ratio.

### 3.2.3 Effect of evaporator temperature on COP of the system

For all three refrigerants with increase in evaporator temperature, the COP value increases as shown in Fig. 3.3. At 50˚C condenser temperature and -30˚C evaporator temperature all the refrigerants have lowest value of COP. The percentage increase in value of COP from 0˚C and 30˚C is the highest for R1234yf that is about 162.23%. The percentage increase in value of COP from 0˚C and 30˚C for R12 and R134a are 140% and 148% respectively. R12 has highest value of COP but still the performance or percentage increase in COP value is least in all three refrigerants.

At 35˚C condenser temperature and -30˚C evaporator temperature the refrigerants have minimum value of COP. The percentage increase in value of COP from 0˚C and 30˚C is highest for R1234yf is about 190.6%. The percentage increase in value of COP from 0˚C and 30˚C for R12 and R134a are 173.5% and 181.5%.R12 has highest value of COP but still the performance or percentage increase in COP value is least in all three refrigerants.

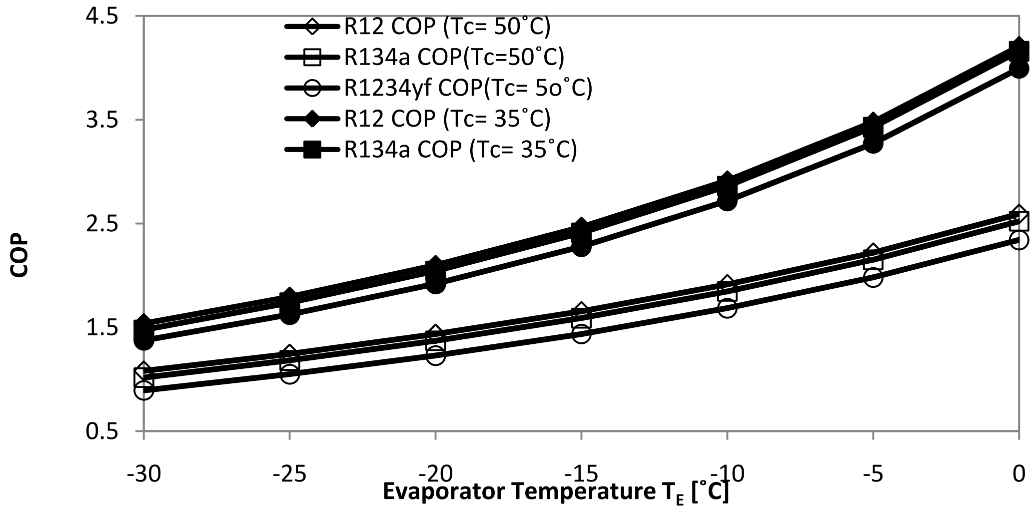


Fig. 3.3 Variation in COP with evaporator temperature

This result trend can be explained from the fact that with increase in evaporator temperature, the pressure ratio across the compressor reduces causing compressor work to reduce and cooling capacity increases because of increase in refrigerating effect. The combined effect of these two factors is to enhance the overall COP. R12 presents the highest COP among all the refrigerants corresponding to condenser temperatures considered 50˚C and 35˚C.

**Effect of subcooling on relative capacity change index of system with different refrigerants**

Fig. 3.4 shows variation in percentage change in refrigerating capacity value or RCI values of refrigerants R12, R134a and R1234yf for different values of $\Delta T_{subcooling}$ ranging from 1˚ C to 10˚ C. RCI increases for all refrigerants with increase in degree of subcooling.

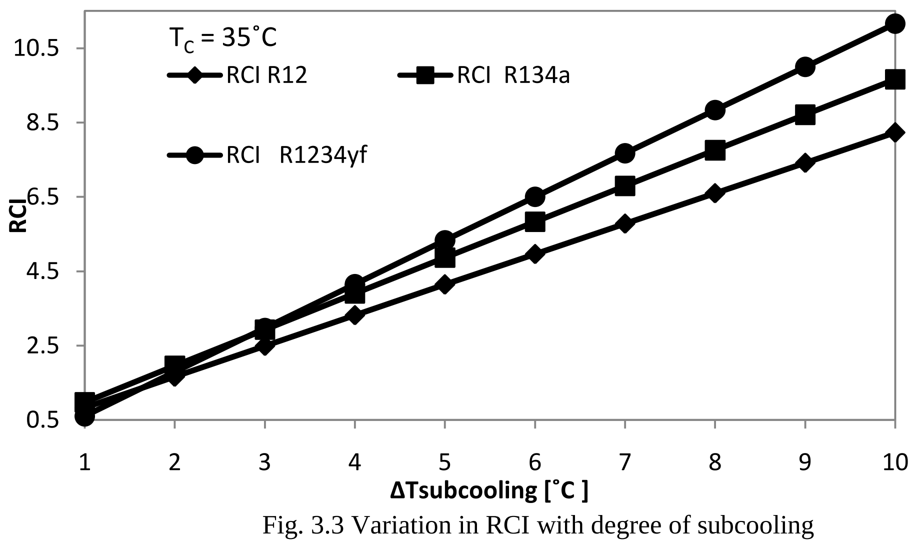


Fig. 3.3 Variation in RCI with degree of subcooling

The RCI value shows how much subcooling in the liquid vapour heat exchanger is effective in increasing refrigerating capacity.

The RCI is the lowest at 1˚ C subcooling and the highest at 10˚ C subcooling for R1234yf. All refrigerants have the minimum value of RCI at $\Delta T_{subcooling}$ a 1˚ C. R134a has the percentage change in refrigerating capacity value greater than R12 at both $\Delta T_{subcooling}$ 1˚C and $\Delta T_{subcooling}$ 10˚C. R1234yf has the highest percentage increase in value of RCI with increase in degree of subcooling. Liquid vapour heat exchanger is most beneficial for R1234yf.

**Effect of subcooling on cop of system working with different refrigerants**

Fig. 3.5 shows variation of COP with increase in$\Delta T_{subcooling}$ . As$\Delta T_{subcooling}$ increases, the COP value of all refrigerants increases. At $\Delta T_{subcooling}$ 1˚C, all the three refrigerants have their lowest value of COP. At $\Delta T_{subcooling}$ 10˚C, all the three refrigerants have their highest value of their COP. With increase in $\Delta T_{subcooling}$ from 1˚ C to 10˚ C the percentage increase in value of COP is the highest for R1234yf is 10.4876 %. R134a have percentage increase in COP of 8.589%. R12 has lowest percentage increase in COP of 7.34 %. This result indicate that R1234yf could perform better at higher value of $\Delta T_{subcooling}$ .

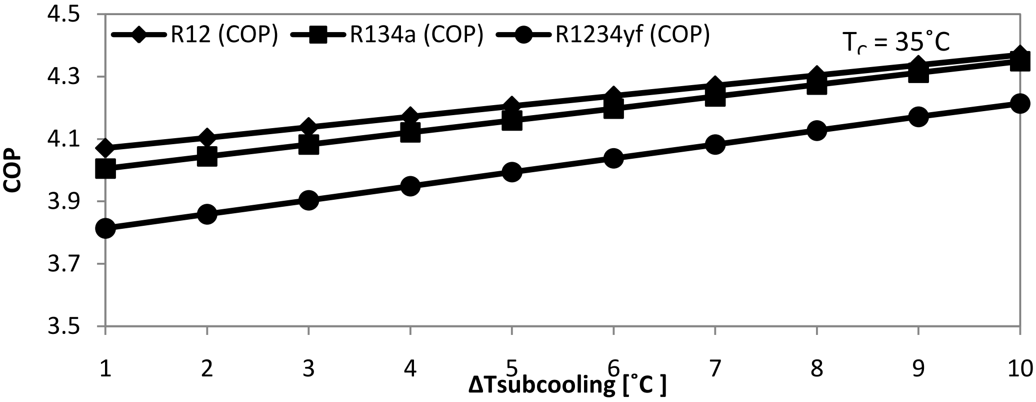


Fig.3.4 Variation in values of COP of system with degree of subcooling

This trend can be explained, as there is increase in degree of subcooling, consequently specific refrigerating effect increases causing cooling capacity to increase. While the compressors work, remain constant. The COP of system increases with degree of subcooling in liquid vapour heat exchanger.

**4.2.6 Effect of liquid vapour heat exchanger effectiveness on cop of the system**

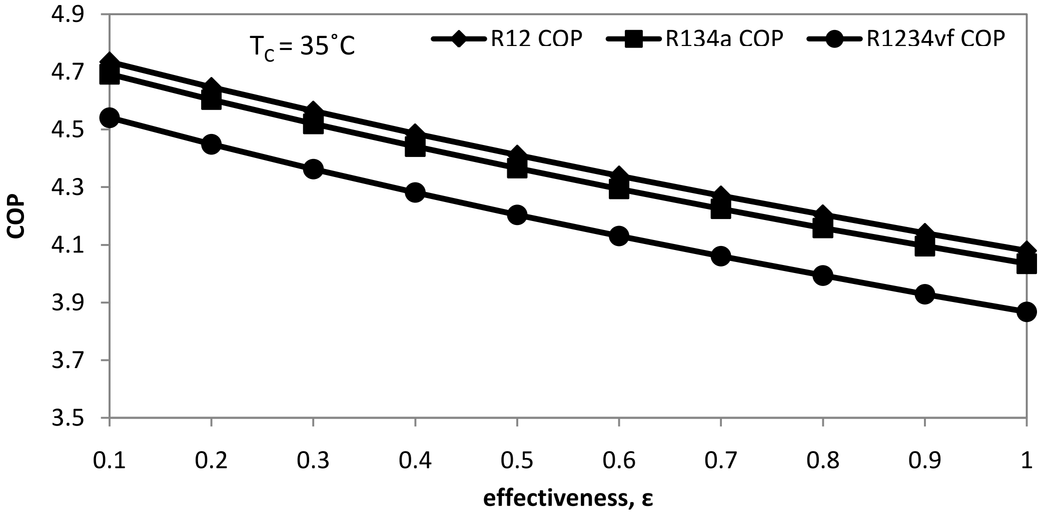


**Fig. 3.5** Variation in value of COP of system with effectiveness of liquid vapour heat exchanger

Fig. 3.6 shows the variation in COP of system with effectiveness of liquid vapour heat exchanger. For all three refrigerants, the value of COP decreases with increase in effectiveness of the liquid vapour heat exchanger. The percentage decrease in value of COP for R12, R134a andR1234yf are 13.8%, 14.02% and 14.82 %.

This trend of results can be explained from the fact that with the increase in effectiveness of LVHE, first there is increase in degree of subcooling, consequently specific refrigerating effect increases causing cooling capacity to increase. Second, there is superheating of suction vapour, which causes isentropic compression to happen along the isentropes having reduced slope, and thus increase in compressor work is observed. The positive effect of increase in cooling capacity is heavily negated by increase in compressor work hence combined effect is such that it causes a decrease in COP of the overall system.

**3.2.10 Variation in the COP of the system with and without pressure drop in the evaporator and condenser.**

Fig. 3.6 shows variation in COP with and without pressure drop in the evaporator and condenser at $T_C$ = 50˚C. Pressure drop is most harmful for R12. The percentage decrease in the value of COP is 5.57 %. The percentage decrease in COP is the lowest in R134a. The percentage decrease for R1234yf is 5.56%.

Fig. 3.7 shows variation in COP with and without pressure drop in the evaporator and condenser at $T_C$ = 35˚C. Pressure drop is most harmful for R12 as percentage decrease in the value of COP is 6.986 %. The percentage decrease in COP value is the lowest for R134a. The percentage decrease for R1234yf is 6.81%.

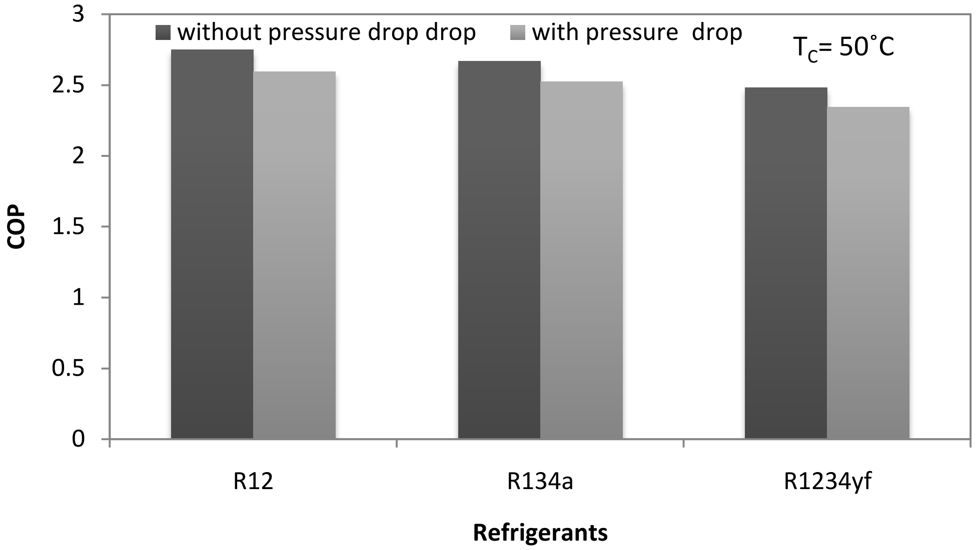


Fig. 3.6 shows variation in COP with and without pressure drop in the evaporator and condenser at $T_C$ = 50˚C.

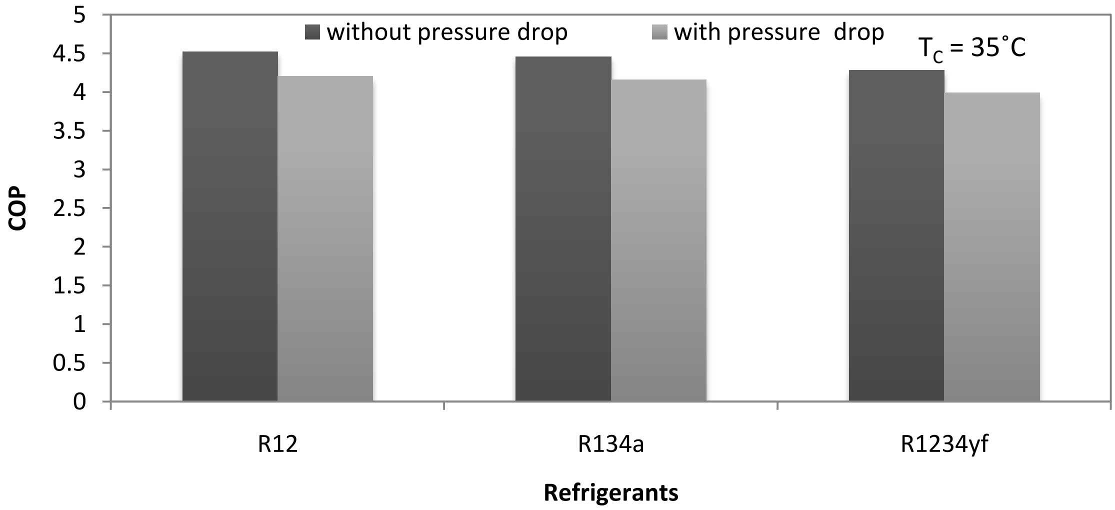


Fig. 3.7 shows variation in COP with and without pressure drop in the evaporator and condenser at $T_C$ = 35˚C.

## Conclusions

1. The compressor power requirement in the system is the highest if R134a is used at both condenser temperatures 50˚C and 35˚C. The compressor power requirement is the minimum in R12 and after it R1234yf.
2. It concludes that the R1234yf could increase the performance of system at higher degree of subcooling. R1234yf has highest value of

relative capacity change index (RCI) of all the three refrigerants.

3. The performance of system with and without pressure drop at both condenser temperatures 50 and 35˚C, at evaporator temperature 0˚C is carried out. The R12 system performance is most affected by pressure drop. COP is decreases with increase in pressure drop. In the descending order of decrease in COP these refrigerants can be arranged as R12, R1234yf and R134a.

Thermodynamic analysis result concluded that R1234yf is good drop in replacement and it has also advantage of lower GWP value than R12 and R134a. R134a system highest work required of all the three refrigerants. With the use of liquid vapour heat exchanger R1234yf has highest value of relative capacity change index (RCI) of all the three refrigerants increases with increase in degree of subcooling system using R1234yf. R1234yf shows the highest percentage increase in COP. R1234yf is the only refrigerants of all the refrigerants used in present work that satisfy MAC directive (2006/40/EG) because of its GWP value less than 150.

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