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# Performance Investigation of Expander-Compressor Unit in Vapor Compression Refrigeration System Using Alternative Refrigerants

Naushad A. Ansari[*1], Akhilesh Arora[2], Samsher[3], Manjunath K[4]
*[1, 2, 3] Department of Mechanical Engineering,Delhi Technologial University, Shahbad Daulatpur,Main Bawana Road, Delhi-42, India,*
*[4]Mechanical Engineering,Ch. Brahm Prakash Govt. Engineering College, Jaffarpur, Delhi-73, India.*
*Corresponding Author: Naushad A. Ansari*

***Abstract:*** *Efficient refrigeration system using eco friendly refrigerants are of great importance with the growing application of it. It has been investigated that using expanders in vapor compression refrigeration system (VCRS) in place of conventional VCRS is a viable option to improve the energy efficiencies of refrigeration systems. Advancement in technology also supports the idea to manufacture and integrate expanders into practical VCRS. The present research focuses on analyzing the performance of eco friendly refrigerants in such a system. In the study four refrigerants namely R134a, R1233zd(E), R423a and R1243zf are considered in a expander based VCRS and the thermodynamic analysis is of the system using these refrigerants are done. R134a is taken as a base refrigerant to compare the outcome of other three refrigerants in the system. The COP of the VCRS is found to be in following order R1233zd(E), R134a, R423a and R1243zf where R1233zd(E) has the largest value of COP and R1233zf has the lowest value. Exergetic efficiency also shows a similar trend for these refrigerants when used in expander based VCRS. Although R1233zd(E) gives better results but the difference in the performance of other two alternative refrigerants is not large when compared with R134a. Thus, making them potential replacement of R134a due their very low global warming potential (GWP).*

***Keywords:*** *Alternative Refrigerants, COP, Expander, Refrigeration System, Exergetic efficiency.*

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## I. Introduction

Refrigeration and air conditioning technology is widely used in industrial, commercial and residential applications. Due to economic growth, population growth and improved living standards the annual energy consumption behavior and demand is steadily increasing. Presently, major demands of cooling and heating applications are met out by the conventional vapor compression systems. For the facilities such as lighting, heating and air conditioning related to building provisions, annual energy consumption of 40% of world annual energy demand was reported (Omer, 2008). Air conditioning and refrigeration applications consumed about 15% of the electrical energy worldwide as reported by Coulomb (2006). Air conditioning and refrigeration system operates mostly on electrical energy which are produced from fossil fuels thus, releases green house gases accounting for 80% of the total green house gases released from the system and rest is from refrigerants releasing into the atmosphere (International Institute of refrigeration, 2004). Therefore, it is very important to study and employ a refrigeration system which is energy efficient and uses environmentally friendly refrigerants as well.

Victor et al (2008) presented a study on automobile air-conditioning based on vapor compression refrigeration cycle with R134a as refrigerant incorporating an expander and a thermostatic expansion valve and predicted reasonable gains in cycle performance. Alison et al (2013) did an economic analysis based on thermodynamic investigation by installing expanders to refrigeration systems to address the financial problem. Their importance was air conditioning systems of medium scale having a refrigerating load of 5270 W while the ambient temperature of 35 °C, evaporating temperature of 7.2 °C and the condensing temperature of 54.4 °C was considered. Various refrigerants, like R22, $NH_3$, R32, R404A, $CO_2$, R134a, R1234yf, R410A, R438A and R407C were considered in the study and it was found that by installing expander in vapor compression system 1 to 4 MWh of energy could be saved in a span of 8 years. A payback period of less than 5 years for most of these refrigerants was estimated with an exception of $CO_2$ and R404A whose pay back periods were suggested to be less than 1 and 3 years respectively. Xiaohui et al (2014) presented the study of vapor compression system where the expander work recovered during the expansion process was also employed for subcooling of the proposed system. They predicted a higher COP of the system while using refrigerants R12, R32, R22, R134a, R41, R717, R507A, R404A and R744 in the main cycle. A COP increment of 17.2% was computed by them for R744 as working fluid in the cycle. J. W. Thornton et al (1992) studied a dedicated mechanical subcooling model of vapor compression system with R12 as refrigerant and predicted an optimum subcooling evaporator temperature to be -1.11$^0$C (considered ambient temperature and main cycle evaporator temperature were 26.67$^0$C and -28.90C respectively) for all ranges of ambient and main cycle evaporator temperature. Bingchun et al (2009) in their experimental investigation of a transcritical $CO_2$ vapor compression cycle aimed on the design improvements within expander related to its leakage and frictional losses showed the increase in volumetric efficiency from 17% to 30% and the improvement of isentropic efficiency from 9% to 23% resulting in COP increment of 14.2% compared to conventional throttling cycle. Bjorn (2007) presented a study by comparing properties of hydrocarbons, namely propane, propene and isobutane with R134a, R22 and ammonia and predicted the higher performance of hydrocarbons over R134a and R22 in vapor compare system. Hoseong et al (2016) developed a model to evaluate the life cycle climate performance to understand the environmental impact of various space heating and cooling methods adopted in residential buildings with the focus on severe climate change affecting the mankind globally. They have evaluated five cycle options along with seven refrigerants of low GWP for air conditioning applications.

Ken Shaun Yap et al (2018) proposed a maximum increment of COP by 36.6% with $CO_2$ as working fluid in a basic vapor compression system using a novel cross vane type expander and compressor as a single unit. They investigated that the average difference of net power input to the system between theoretical model and experimental model was 10.5% and concluded that largest power loss of 81.2% of the total loss was due to end-face friction. Seyoung et al (2018) in their review article explored various options for household refrigerator technologies with concern on energy efficiency and ecofriendly refrigerants discussed about dual evaporator cycle, expansion loss recovery options, ejector and expander cycles including current cycle options.

This study presents the performance analysis of an expander based VCRS among the various methods proposed by researchers to improve the energy efficiency of the system replacing the conventional throttling based VCRS. This idea was initially reported by Lorentzen (1994) to increase the COP of $CO_2$ refrigeration system. It was further applied to conventional R134a and R22 systems where the COP of the system increased up to 15% as reported by Robinson et al (1998). The focus in the present study is to analyze the thermodynamic performance using ecofriendly refrigerants namely, R1233zd(E), R423a and R1243zf based on R134a performance in the expander based VCRS and to compare it with conventional VCRS.

## II. Description of the Expander Vapor Compression Refrigeration System

Figure 1 shows the schematic diagram of expander VCRS where expander is coupled with compressor in such a way that net work of the cycle is saved by utilizing work of expansion. Processes of compression (1-2) and expansion (3-4) are isentropic. The compressed refrigerant at high pressure enters into condenser from 2-3 and thereafter it enters into expander resulting in work output to be utilized by the system. After isentropic expansion from 3-4, the low-pressure refrigerant enters into evaporator from 4-1 producing the desired cooling and thus completing the cycle. The same processes are shown on T-s diagram in figure 2.

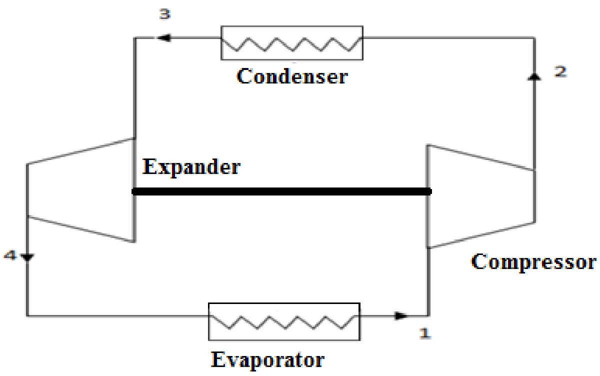


**Figure 1: Schematic diagram of expander compression refrigeration system**.

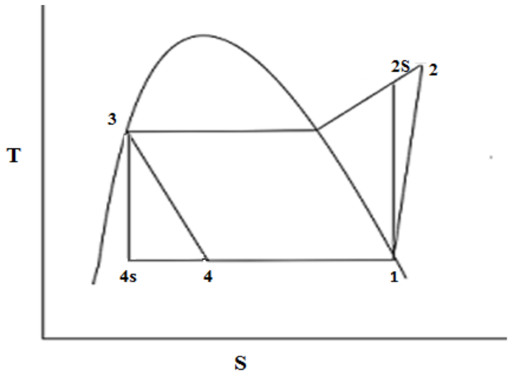


**Figure 2: T-s diagram of expander VCRS**

## III. Thermodynamic Analysis of Vicars

The energy and exergy analysis of VCRS is performed by developing a code using EES software developed by S. A. Klien (2005). Principle of energy conservation and exergy balance is assumed for the analysis. The code has been validated by comparing the results with Bjorn Palm (2007). The predicted values of parameters by Bjorn Palm (2007) viz. theoretical COP and pressure ratio for R134a in a expansion valve VCRS were 3.06 and 7.66 respectively (condenser temperature= $40^0$C, evaporator temperature= $-20^0$C with isentropic compression) whereas the corresponding parameters obtained for R134a in the present study are 3.064 and 7.658 for same constant parameters. The error is negligible and adequate to be validated.

### 3.1. *Energy balance*

Pressure across the compressor and expander is defined as the pressure ratio between condenser pressure to the evaporator pressure ($P_r = P_c/P_e$).

The energy balance equation for the expansion valve VCRS system is given by:

$$\dot{Q}_e = \dot{m}_r(h1 - h4) \quad (1)$$

$$\dot{W}_{comp} = \dot{m}_r(h2 - h1) \quad (2)$$

$$COP_{ev} = \dot{Q}_e/\dot{W}_{comp} \quad (3)$$

The energy balance equation for the system in figure 1 is given by:

$$\dot{W}_{exp} = \dot{m}_r(h3 - h4_{exp}) \quad (4)$$

$$\dot{W}_{net} = \dot{W}_{comp} - \dot{W}_{exp} \quad (5)$$

Net work is given as the difference of compressor and expander work

$$\dot{Q}_{e,exp} = \dot{m}_r(h1 - h4_{exp}) \quad (6)$$

$$COP = \dot{Q}_{e,exp}/\dot{W}_{net} \quad (7)$$

$$COP\% = (COP - COP_{ev})/COP \quad (8)$$

Where, $\dot{Q}_e$ is the cooling capacity of the expansion valve VCRS, $\dot{m}_r$ is the mass flow rate of refrigerant in kg/s, $\dot{W}_{comp}$ is the compressor work, $COP_{ev}$ is the coefficient of performance of expansion valve VCRS, $\dot{W}_{exp}$ is the expander work, $\dot{W}_{net}$ is the net work transfer to the system, $COP$ is the coefficient of performance of the expander VCRS, $\dot{Q}_{e,exp}$ is the cooling capacity of expander VCRS and $h$ is the enthalpy.

### 3.2. *Exergy balance*

Exergy Balance for the expansion valve VCRS system is given by:

$$\dot{EP}_{ev} = \dot{Q}_e(1 - (T_0/T_r) \quad (9)$$

$$\eta_{\_ex,ev} = \dot{EP}/\dot{W}_{comp} \quad (10)$$

Exergy Balance for the expander VCRS system is given by:

$$\dot{EP}_{exp} = \dot{Q}_{e,exp}(1 - (T_0/T_r)) \quad (11)$$

$$\eta_{-ex} = \dot{EP}_{exp}/\dot{W}_{net} \quad (12)$$

Where, $\dot{EP}_{ev}$ is the exergy rate of product in the expansion valve VCRS, $\dot{EP}_{exp}$ is the exergy rate of product in expander VCRS, $\eta_{\_ex,ev}$ is the exergetic efficiency of expansion valve VCRS, $\eta_{\_ex}$ is the exergetic efficiency of expander VCRS. $T_0$ is the ambient temperature and $T_r$ is refrigerant temperature.

## IV. Results and Discussion

Following constant input and ambient parameters are considered for the analysis:-

1. Cooling capacity ($\dot{Q}_e$) : 10 kW
2. Isentropic efficiency of compressor ($\eta_{comp}$) : 50-100 %
3. Isentropic efficiency of expander ($\eta_{exp}$) : 0-100%
4. Evaporator temperature ($T_e$) : 10°C to -30°C
5. Condenser temperature ($T_c$) : $30^0$C-55°C
6. Ambient temperature ($T_o$) : $25^0$C

The difference between refrigerant temperature ($T_r$) and space to be cooled is taken as $5^0$C.

### 4.1. *Effect of condenser temperature*

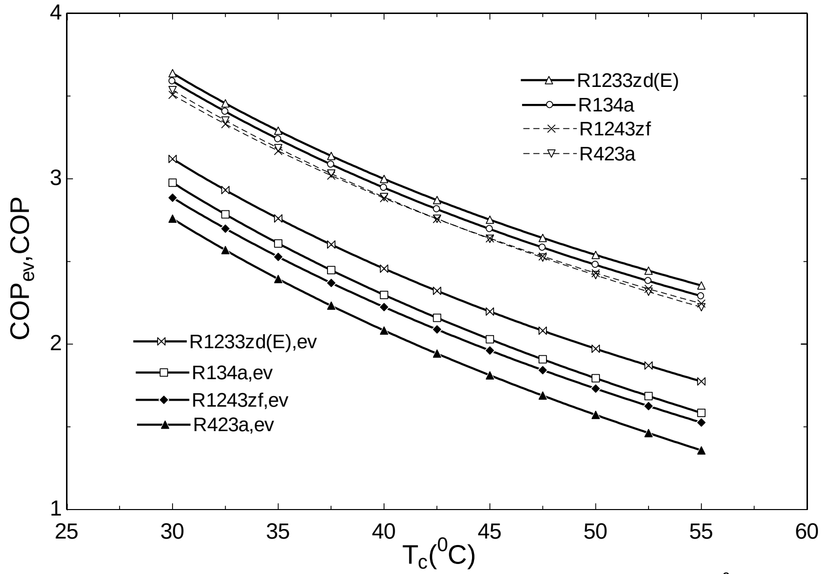


**Figure 3: Variation of COP$_{ev}$ & COP v/s condenser temperature (T$_e$= -20$^0$C, η$_{comp}$= 0.75%)**

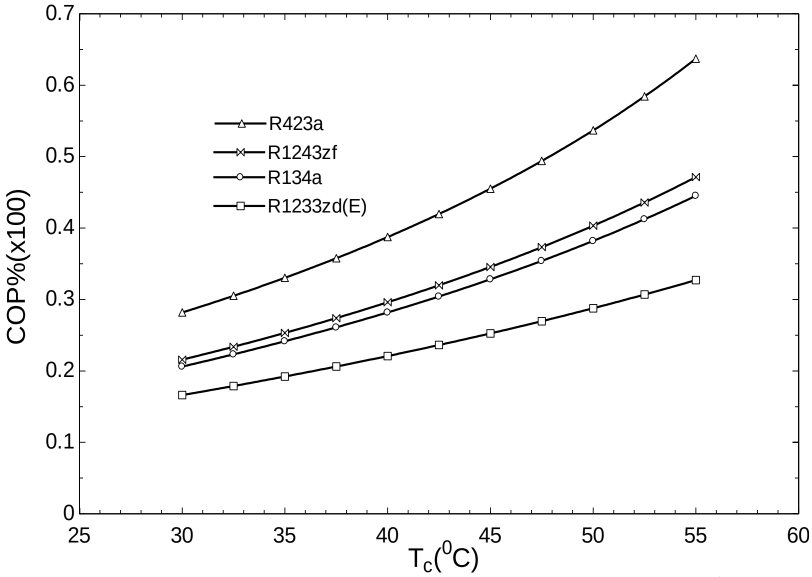


**Figure 4: Percentage change in COP v/s condenser temperature (T$_e$= -20$^0$C, η$_{comp}$= 0.75%)**

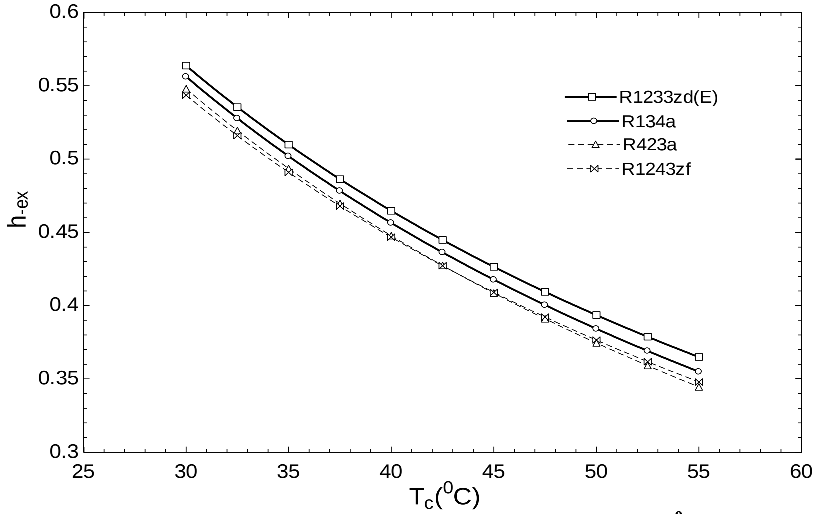


**Figure 5: Exergetic efficiency v/s condenser temperature ($T_e$= -20$^0$C, $\eta_{comp}$= 0.75%)**

Figure 3 shows the effect of condenser temperature on $COP_{ev}$ (coefficient of performance of VCRS with expansion valve) and COP (coefficient of performance of VCRS with expander) of the refrigerants, namely R1233zd(E), R134a, R423a and R1243zf. It is observed that R1233zd(E) has the higher COP at various range of condenser temperature followed by R134a and R1243zf. COP of R423a is minimum in case of expansion valve VCRS at the different condenser temperatures but for expander VCRS COP of R423a is slightly higher than COP of R1243zf at low condenser temperature and becomes equal to the COP of R1243zf at 43$^0$C condenser temperature and at higher condenser temperature COP of R423a is slightly lower than R1243zf. In figure 5, a similar trend is observed where exergetic efficiency of R1233zd(E) is higher compared to other fluids with a maximum value of 56.37% and minimum value of 36.49% for expander VCRS. Exergetic efficiency of R134a varies from 35.40% to 55.62%. Exergetic efficiency of R423a and R1243zf falls in the range of 34.45% to 54.79% and 34.79% to 54.35% respectively which shows a different pattern of variation unlike COP. The exergetic efficiency of these two refrigerants becomes equal also at 43$^0$C condenser temperature. The comparison of expander VCRS performance at the given condition can be observed from the maximum values of COP which is 3.589, 3.536, 3.508 and 3.638 for R134a, R423a, R1243zf and R1233zd(E) respectively.

Figure 4 shows another important phenomenon where it can be observed that gain in COP of an expander VCRS over expansion valve VCRS is maximum for R423a (28.18%-63.72%) followed by R1243zf(21.58%-47.14%) and R134a(20.61%-44.52%) whereas the minimum gain belongs to R1233zd(E)(16.62%-32.71%).

### 4.2. *Effect of evaporator temperature*

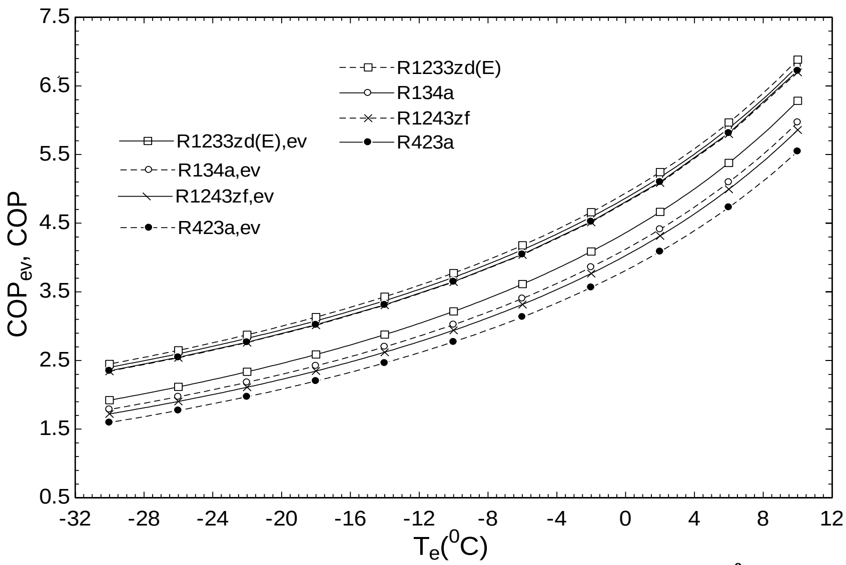


**Figure 6: Variation of $COP_{ev}$ & COP v/s evaporator temperature ($T_c$= 40$^0$C, $\eta_{comp}$= 0.75%)**

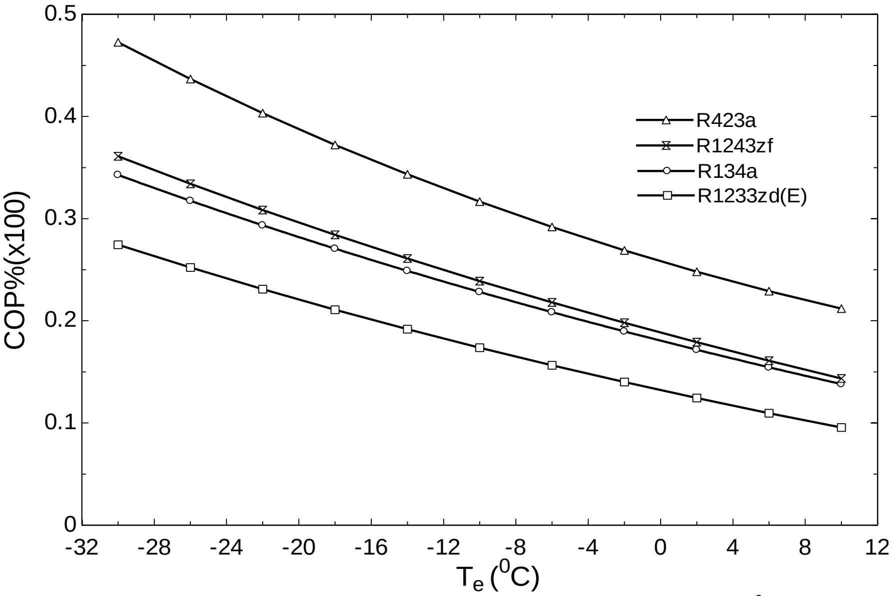


**Figure 7: Percentage change in COP v/s evaporator temperature ($T_c$= 40$^0$C, $\eta_{comp}$= 0.75%)**

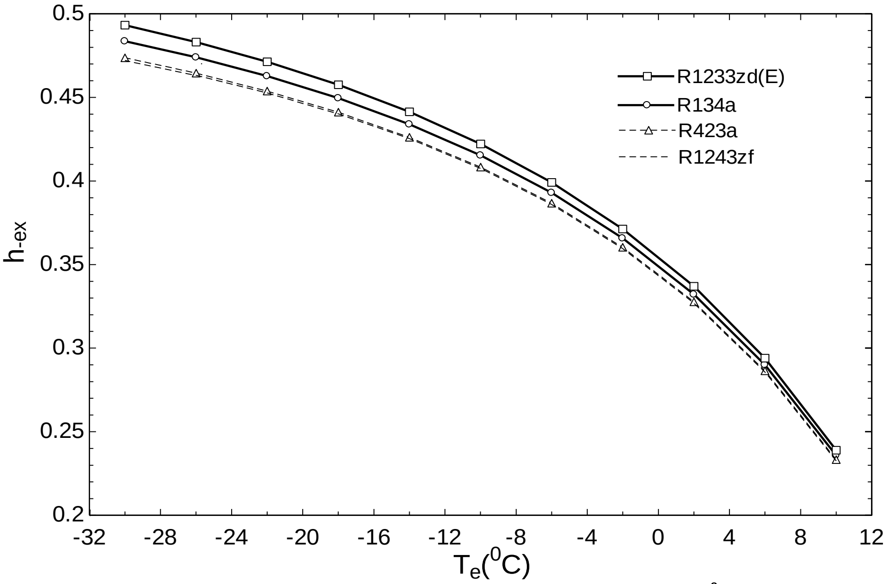


**Figure 8: Exergetic efficiency v/s evaporator temperature ($T_c$= 40$^0$C, $\eta_{comp}$= 0.75%)**

Figure 6 shows the effect of evaporator temperature on $COP_{ev}$ of expansion valve VCRS and COP of expander VCRS. It is observed that there is a large gain in COP of expander VCRS for the refrigerants considered in the study. However, the difference in the COP variation of these refrigerants at different evaporator temperature is small which can be listed in the descending order as R1233zd(E), R134a, R1243zf and R423a accordingly. The minimum and maximum value of COP of these refrigerants are given as 2.448 to 6.883 for R1233zd(E), 2.4 to 6.793 for R134a, 2.343 to 6.699 for R1243zf and 2.35 to 6.722 for R423a. It is observed that COP of R423a betters slightly the COP of R1243zf at higher evaporator temperature. In figure 8 it is observed that the trend of variation in exergetic efficiency is similar to COP variation for these refrigerants. However, the curve of exergetic efficiency converges at higher evaporator temperature and it is wider at low evaporator temperature except for R423a and R1243zf where the difference in exergetic efficiency of these two is negligibly small. The different range of exergetic efficiency of these refrigerants are R1233zd(E) (23.89% to 49.32%), R134a (23.57% to 48.36%), R1243zf (23.25% to 47.21%) and R423a (22.33% to 47.36%).

Figure 7 shows the percentage change in COP of expander VCRS over the COP of expansion valve VCRS. It is observed that percent change in COP of R423a is maximum followed by R1243zf and R134a respectively whereas it minimum for R1233zd(E). The minimum and maximum range of exergetic efficiency observed is given by 9.546% to 27.45% for R1233zd(E), 13.81% to 34.28% for R134a, 14.35% to 36.09% for R1243zf and 21.2% to 47.25% for R423a.

**4.3.** ***Effect of compressor efficiency on COP***

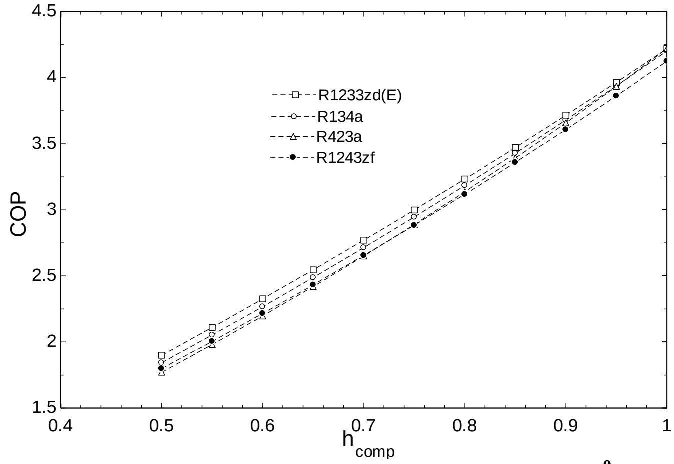


**Figure 9: Variation of COP v/s compressor efficiency ($T_c$= 40$^0$C, $T_e$= -20$^0$C)**

Figure 9 shows the effect of compressor efficiency on the expander VCRS performance and it is observed that compressor efficiency has a significant impact on the COP of the system. It is evaluated that the COP lies in between 1.5-2.0 for each refrigerants at a compressor efficiency of 50% whereas COP value increases to 4-4.5 at 100% compressor efficiency. The trend of COP variation with respect to compressor efficiency for the refrigerants are R1233zd(E), R134a, R423a and R1243zf in descending order. Further, it is observed that COP of R1233zd(E), R134a and R423a converges at higher compressor efficiency.

**4.4.** ***Effect of expander efficiency on COP***

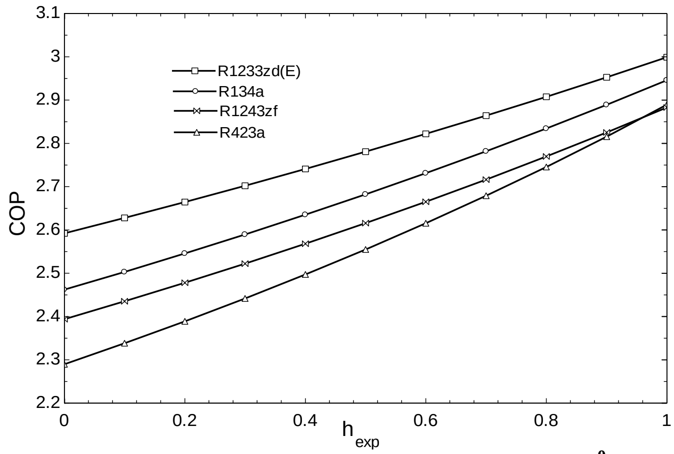


**Figure 10: Variation of COP v/s expandor efficiency ($T_c$= 40$^0$C, $T_e$= -20$^0$C)**

Figure 10 shows the effect of expander efficiency on COP of the refrigerants in the study. It shows that expander efficiency also contributes significantly in performance of VCRS. The COP variation of R423a is large for expander efficiency variation of 0 to 100% whereas the rest of three refrigerants show almost equal variation at different expander efficiency. Further, it is observed that COP of R423a and R1243zf becomes equal at 90%-100% expander efficiency.

## V. Conclusion

This paper presents first law and second law based thermodynamic analysis of a vapor compression refrigeration system based on expansion power recovery by using expander in place of conventional expansion valve with eco friendly refrigerants, namely R134a, R1233zd(E), R423a and R1243zf and the main conclusion can be summarised as follows.

R1233zd(E) scores over other refrigerants with higher COP and higher exergetic efficiency. So, it could be a better alternative to R134a apart from having advantage of very low GWP. It is followed by R134a in terms of performance, R423a and R1243zf have lower COP and exergetic efficiency compared to other two refrigerants but the values are slightly lower than R134a and thus, can be potential substitute of R134a due to very low GWP property.

It is observed that COP of R423a is higher than COP of R1243zf at low condenser temperature but at higher condenser temperature COP of R1243zf becomes greater than the COP of R423a and the point of intersection where COP and exergetic efficiency of both the refrigerants are equal lies at $43^0$C condenser temperature (at $T_e$= $-20^0$C).

COP of the VCRS in the study is compared with conventional expansion valve based VCRS and it is observed that average gain of about 46% of R423a is largest followed by R1243zf with average gain of about 35%. Average gain in COP of R134a and R1233zd(E) is recorded as 33% and 25% respectively.

The effect of compressor efficiency is more dominant than expander efficiency on the COP of the refrigerants in the study. It is observed that COP of the refrigerants become almost three times when compressor efficiency varies from 50% to 100%. The effect of expander efficiency on R423a is more significant as compared to other refrigerants.

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