THERMODYNAMIC ANALYSIS OF ACTUAL VAPOUR COMPRESSION SYSTEM WITH R22 AND ITS ECO-FRIENDLY ALTERNATIVES REFRIGERANTS

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ABSTRACT

This paper presents a theoretical performance study of a vapour compression refrigeration system with refrigerants R-22, R407C and R410A. A computational model based on energy and exergy 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, exergetic efficiency and exergy destruction ratio of the vapour compression refrigeration cycle. RCI (relative capacity change index) of the system is highest for R410A and with increase in degree of subcooling; R410A has the highest percentage increase in COP. Exergetic efficiency of system using R410A is close to that of R22 system. The optimum temperature range for evaporator for all three refrigerants at which exergetic efficiency is maximum and EDR is minimum at this condenser temperature 40 ˚C is -30 to -35 ˚C. The R22 system performance is most affected by pressure drops. At higher degree of subcooling, performance of R410A improves. Performance of R410A is better than that R407C is evident from the results of thermodynamic analysis.

Keywords*: *EDR, Exergetic Efficiency,* 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

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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.

R22 refrigerant was mainly used in air conditioners and deep freezers etc. R22 has ozone depletion potential (ODP) of 0.034. The global warming potential (GWP) of R22 is 1700 and atmospheric life time of 12 years. The replacements of R22 are R407C and 410A having zero ozone depletion potential. Although, R22 has very low ozone depletion potential but high global warming potential. The replacements of R22 are R407C and 410A. The GWP of R407C and R410A are 1600 and 2000 respectively. Since both the refrigerants are blends are unstable and have negligible atmosphere life time. Therefore, search for better alternatives which have zero ozone depletion potential (ODP) and zero or lower global warming potential (GWP) and having low atmospheric life time is still on.

The main characteristics of R22 and its alternative are given in Table 2

Table 2 Characteristics of R22 and Its Alternative Refrigerants [1]

Characteristics	**R22**	**R407C**	**R410A**
Chemical Formula	$CHClF_2$	CH_3CHF_2	$C_3F_4H_2$
Molecular weight (g/mol)	120.92	66.05	114.04
Boiling point (˚C)	-40.8	-43.63	-51.36
Ozone Depletion Potential (ODP)	0.034	0	0
Global warming Potential (GWP)	17,80	1700	2000
Safety Group	$\mathbf{A_1}$	$\mathbf{A_1}$	$\mathbf{A_1}$

A computational model based on the exergy analysis was presented on vapor compression refrigeration cycle**[2].** It was found that the evaporating and condensing temperatures have strong effects on the exergy losses in the evaporator and condenser and on the second law of efficiency and COP of the cycle but little effects on the exergy losses in the compressor and the expansion valve. **[3]** A comparative exergetic analysis on R22 and its substitution R407C had carried out . The overall exergetic performance of the plant working with R22 was consistently better than that of its candidate substitute.

Theoretical analysis of vapour compression refrigeration system with R502, R404A and R507A **[4].** This study presented a detailed exergy analysis of an actual vapour compression refrigeration (VCR) cycle. The results revealed that R507A was better substitute to R502 than R404A. An experimental evaluation of R22 and R407C evaporative heat transfer coefficients in a vapour compression plant **[5].** The experimental conditions under

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which heat transfer coefficients were determined reflect a typical working situation for small l-scale refrigeration systems. The heat flux ranged from 1.9 to 9.1 kW/m^2 and the mass flux was varied from 30 to 140 kg/m^{2}s. An experimental evaluation is performed on a single-stage vapour compression plant using three different working fluids, R134a, R407Cand R22. This fact was transferred to the COP, obtaining a smaller value of the COP using R22 than using R407C for high compression ratios **[6].** had presented effect of evaporator temperature on vapor compression refrigeration system **[7].** This study presented comparable evaluation of R600a (isobutane), R290 (propane), R134a, R22, for R410A, and R32 an optimized finned-tube evaporator, and analyses the evaporator effect on the system coefficient of performance (COP). From literature review, it concludes that there is need of thermodynamic analysis of alternative refrigerants to R22. Find out parameters that enhance system performance while using alternative refrigerants.

II ANALYSIS OF VAPOUR COMPRESSION SYSTEM

The vapour compression system used in present analysis has been shown in figure 2.1.

2.1 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.

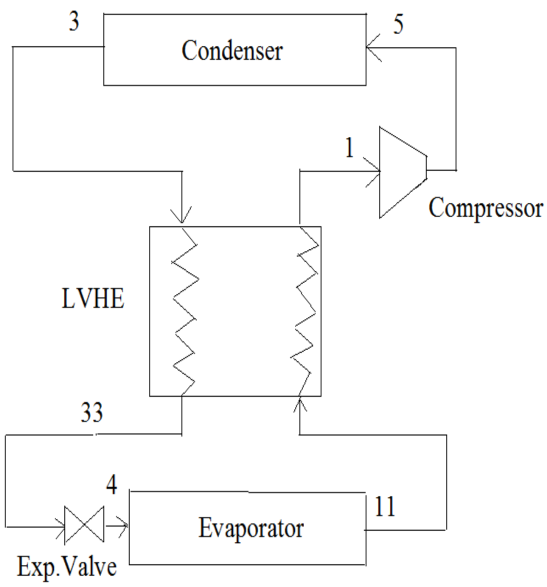

Figure 2.1 Showing Vapour Compression Systems with Liquid Vapour Heat Exchanger

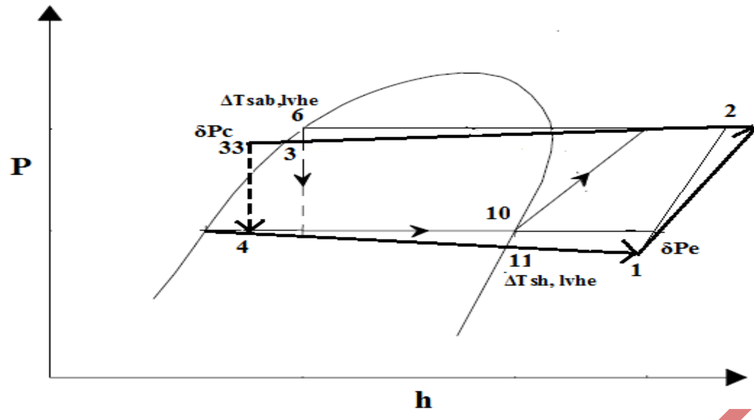

Fig.2.2 p-h Diagram of Vapour Compression System with Liquid Vapour Heat Exchanger

2.2 First Law Analysis of Vapour Compression System

$$\dot{E}_{in} = \dot{E}_{out} \tag{2.1}$$

Energy balance equation for compressor

$$\dot{m}\,h_1 + \dot{w}_{1-2} = \dot{m}\,h_2 \tag{2.2}$$

$$\dot{w}_{1-2} = \dot{m}\,(h_2 - h_1) \tag{2.3}$$

$$\eta_{comp,isen} = \frac{h_2 - h_1}{h_5 - h_1} \tag{2.4}$$

$$h_5 = \frac{h_2 - h_1}{\eta_{comp,isen}} + h_1 \tag{2.5}$$

$$\dot{w}_{comp\ actual} = \dot{m}_r(h_5 - h_1) \tag{2.6}$$

Energy balance equation for condenser

$$\dot{Q}_C = \dot{m}\,h_5 - \dot{m}\,h_3 \tag{2.7}$$

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.

$$Q_n = h_1 - h_{11} = h_3 - h_{33} \tag{2.8}$$

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

$$\varepsilon = \frac{T_1 - T_{11}}{T_3 - T_{11}} \tag{2.9}$$

The effect of a liquid-suction heat exchanger on refrigeration capacity can be evaluated in terms of RCI **[8].**

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

Q_e is refrigerating effect, given as

$$Q_e = h_1 - h_4 \tag{2.11}$$

$$\dot{Q}_{rc} = \dot{m} \times Q_e \tag{2.12}$$

Energy balance in expansion valve

$$\dot{m}\,h_{33} = \dot{m}\,h_4 \tag{2.13}$$

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Energy balance equation for evaporator

$$\dot{m}\, h_4 + \dot{Q}_{rc} = \dot{m}\, h_{11} \qquad (2.14)$$

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

Where, $\dot{Q}_{rc}$ is refrigerating capacity, η_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),

$$COP = \frac{Q_{rc}}{W_{comp}} \qquad (2.16)$$

2.3 Second Law Analysis of Vapour Compression System

Assuming same assumption as in first law analysis

Exergy balance on a control volume gives

$$\dot{E}x_{in} - \dot{E}x_{out} - \dot{E}x_{dest,in-out} = 0 \qquad (2.17)$$

Exergy balance equation for compressor

$$\dot{E}x_{dest,1-5} = \dot{E}x_{in} - \dot{E}x_{out} \qquad (2.18)$$

Exergy destruction in compressor gives

$$\dot{E}x_{dest\ compressor} = \dot{m}(T_0(S_5 - S_1)) \qquad (2.19)$$

Exergy balance in condenser gives

$$\dot{E}x_{dest\ condenser} = = \dot{m}(h_5 - T_0 \times S_5) - \dot{m}(h_3 - T_0 \times S_3) \qquad (2.20)$$

Exergy balance in expansion valve

$$\dot{E}x_{dest,33-4} = \dot{m}[h_{33} - h_4 - T_0(s_{33} - s_4)] \qquad (2.21)$$

Exergy balance in evaporator

$$\dot{E}x_{dest,4-11} = \dot{E}x_4 - \dot{E}x_{11} - \left[-\dot{Q}_{RC}\left(1 - \frac{T_r}{T_0}\right)\right] \qquad (2.22)$$

Exergy balance in liquid vapour heat exchanger

$$Ex_{dest\ lvhe} = \dot{m}((h_3 - h_{33} + h_{11} - h_1) - T_0(s_3 - s_{33} + s_1 - s_{11}) \qquad (2.23)$$

Total exergy destruction in the system is

$$\sum \dot{E}d_1 = ex_{dest\ comp} + ex_{dest\ evap} + ex_{dest\ cond} + ex_{dest\ throttle\ valve} + ex_{dest\ lvhe} \qquad (2.24)$$

The thermal exergy loss in a component is given by

$$\sum \dot{E}L_1 = Q_I\left(1 - \frac{T_0}{T_I}\right) \qquad (2.25)$$

Where $\dot{Q}_1$ is the heat rejected by the Ith component and T_I is the temperature at the boundary of the Ith component. Thermal exergy loss rate is related to external irreversibility which takes place because of temperature difference between the control volume and the immediate surroundings.

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Exergetic efficiency: In general case exergetic efficiency is defined as the ratio of exergy recovered to the exergy supplied.

$$\eta_{ex} = \frac{\text{Exergy recovered}}{\text{Exergy supplied}}$$

When we apply exergy rate balance in the system then, we get

$$\dot{E}F = \dot{E}P + \sum \dot{E}D_i + \sum \dot{E}L_i \quad (2.26)$$

$\dot{E}F$ = the exergy rate at which fuel is supplied, in actual vapour compression system it is equal to compressor work input w_c.

EP= the exergy rate of product, in case of vapour compression refrigeration system, the product is the exergy of the heat abstracted in to the evaporator from the space to be cooled at temperature T_r,

$$\dot{E}P = \dot{Q}_{rc} \left| \left(1 - \frac{T_0}{T_r}\right) \right| \quad (2.27)$$

$$\eta_{ex} = \frac{\dot{E}P}{\dot{E}F} \quad (2.28)$$

$$\eta_{ex} = \frac{\dot{Q}_{rc} \left| \left(1 - \frac{T_0}{T_r}\right) \right|}{w_c} \quad (2.29)$$

Both the equation of exergetic efficiency will give the same result

Exergy destruction ratio (EDR)

EDR is related to exergetic efficiency as shown in equation below:

$$EDR = \frac{1}{\eta_{ex}} - 1 \quad (2.30)$$

The present work is validated from the work of 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 and exergy 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).

III RESULT AND DISCUSSIONS

A computer program has been developed depending upon the requirements of engineering equation solver (EES)[9]. The equations are written in the equation window of EES in the FORTRAN LANGUAGE. Computational model developed for carrying out the energy and exergy analysis of the system using Engineering Equation Solver software (Klein and Alvarado, 2012) was solved to get the desired results

3.1 Operating conditions assumed for analysis of R22 and its alternatives

For thermodynamic analysis of vapour compression system with R22 and its eco-friendly alternatives following data is assumed listed below.

The input data assumed is given below:

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 (η_{comp}) :75%.

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4. Difference between evaporator and space temperature (T_R-T_e): 15 ℃.
5. Effectiveness of liquid vapour heat exchanger ε= 0.8.
6. Evaporator temperature -50˚C to 0˚C in steps of 5.
7. Condenser temperature: 40˚C.
8. Pressure drop in evaporator δP_e: 20 kPa
9. Pressure drop in condenser δP_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.

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

Fig. 3.1 shows variation in RCI of system with of refrigerants R22, R407C and R410A for different values of $\Delta T_{subcooling}$ ranging from 1˚ C to 10˚ C.The RCI value is the highest for R410A. R407C has the lowest value at $\Delta T_{subcooling}$of 1˚ C and R410A has highest value at $\Delta T_{subcooling}$10˚ C.For R410Apercentage change in refrigerating capacity value is greater than other two refrigerants. Liquid vapour heat exchanger is most beneficial for R410A.

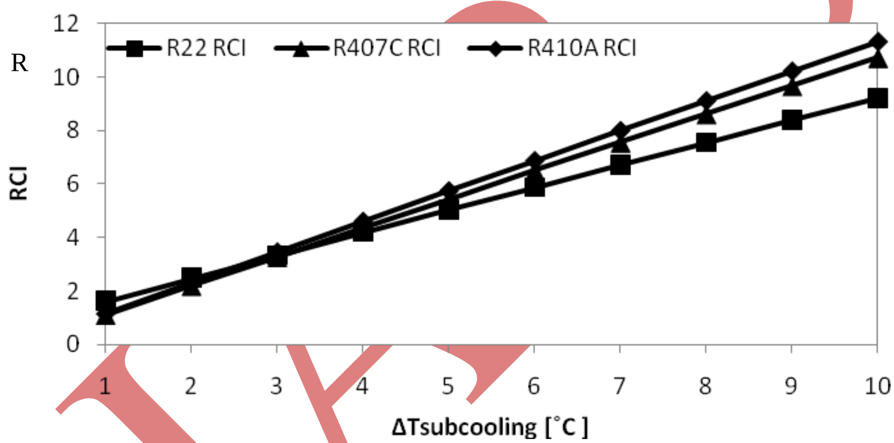

Fig.3.1 Variation of RCI of Refrigerants with Degree of Subcooling

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

For all three refrigerants with increase in evaporator temperature the COP increases as shown in Fig. 3.2. R22 has highest value of COP but the percentage increase in COP value is least among all three refrigerants.

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. R22 gives highest COP among all the refrigerants corresponding to condenser temperatures considered. R410A shows better COP than R407C at both temperature 50˚C and 40˚C.

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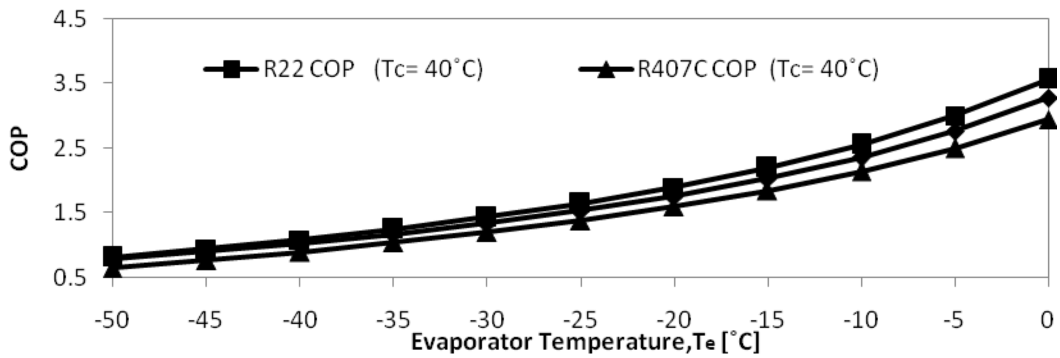

Fig. 3.2 The variation of COP with evaporator temperature at T_C = 40˚C

3.1.3 Effect of Liquid Vapour Heat Exchanger Effectiveness on COP of the System

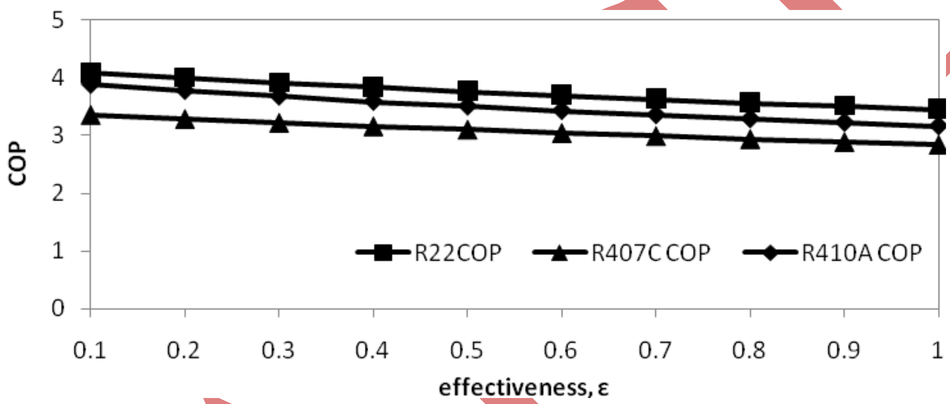

Fig. 3.3 Variation in Value Of COP Of System With Different Refrigerants With Effectiveness Of LVHE

Fig. 3.3 shows the variation in COP with effectiveness of liquid vapour heat exchanger. For all three refrigerants, the value of COP decreases with increase in effectiveness of the LVHE. The percentage decrease in value of COP for R22, R407C and R410A are 15.49%, 15.302% and 18.57 % respectively.

This trend of results can be explained from the fact that with the increase in effectiveness of liquid vapour heat exchanger, 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 isentropic 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 .

3.1.4 Effect of Evaporator Temperature on exergetic efficiency and EDR of the System

At condenser temperature 40˚C, exergetic efficiency first increases, reaches maximum and then decreases with increase in evaporator temperature. This trend is based on two parameters; first one is exergy of cooling effect, i.e. $\dot{Q}_{rc}\left(1-\frac{T_0}{T_R}\right)$and the other compressor work. At condenser temperature of 40˚C $\dot{Q}_{rc}$ and compressor work is dominant over $\left(1-\frac{T_0}{T_R}\right)$ and there is rise in exergetic efficiency at evaporator temperature equal to -30˚C. At this condenser temperature (40˚C) optimum evaporator temperature range is from -30˚C to -35˚C where exergetic efficiency is the highest. At the same time since EDR is inversely proportional to exergetic efficiency, it shows reverse trend. Hence the optimum temperature range for evaporator at this condenser temperature is -30 to -35 ˚C

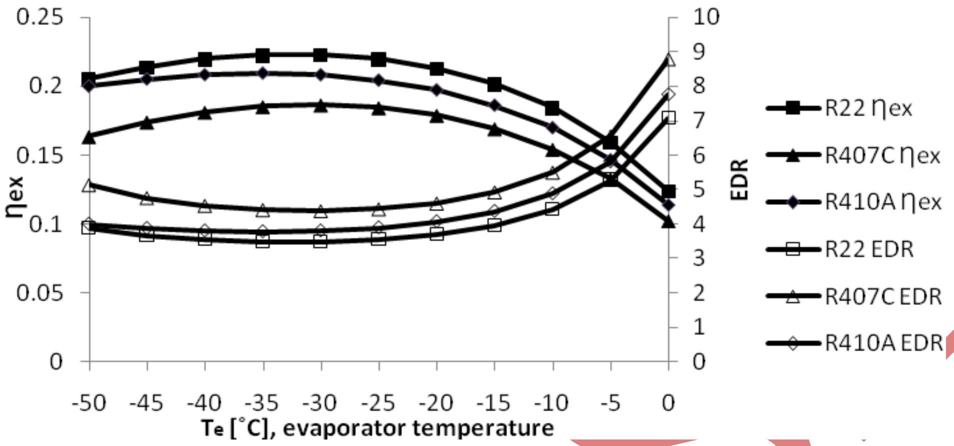

Fig. 3.4 Effect of Evaporator Temperature on Exergetic Efficiency and EDR of the System.

3.1.5 Effect of dead state temperature on exergetic efficiency and EDR of the system

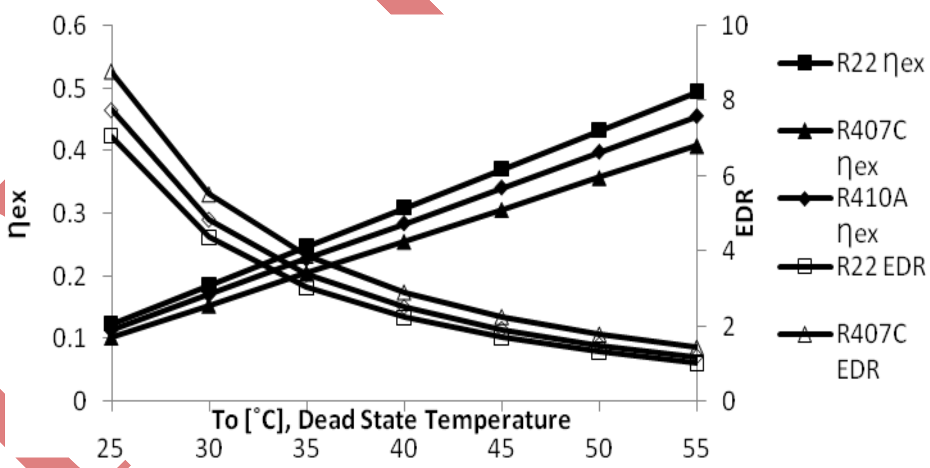

Fig 3.5 Variation in Exergetic Efficiency And EDR With Dead State Temperature

With increase in dead state temperature, term $\left(1-\frac{T_0}{T_r}\right)$ increases while cooling capacity and compressor work remain constant and thus exergetic efficiency increases and EDR reduces. This is justified as exergetic efficiency is inversely proportional to EDR .For a fixed condenser temperature, the increase in dead state temperature causes the irreversibility (due to finite temperature difference) to decrease and hence EDR reduces and exergetic efficiency increases. R407C have lower value of exergetic efficiency and higher value of EDR from both R22 and 410A.

3.1.6 The variation in exergetic efficiency of the system with effectiveness of liquid vapour heat exchanger.

Fig. 3.6 shows the variation in exergetic efficiency of the system with effectiveness of liquid vapour heat exchanger. For all three refrigerants, the value of exergetic efficiency for system decreases with increase in effectiveness of the liquid vapour heat exchanger.

This trend of results can be explained from the fact that with the increase in effectiveness of liquid-vapour heat exchanger, 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.

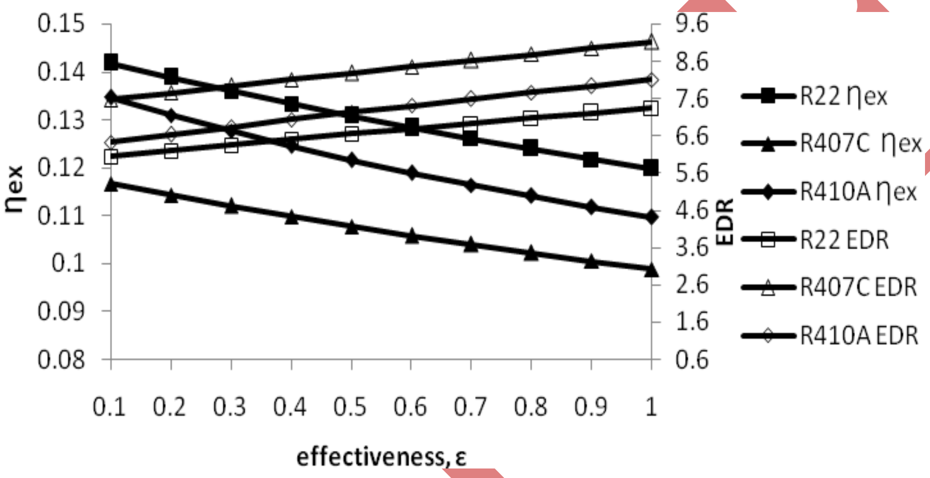

Fig. 3.6 Variation in Exergetic Efficiency of the System with Effectiveness of Liquid Vapour Heat Exchanger

The cooling effect $Q_{rc}\left(1-\frac{T_0}{T_r}\right)$ also has slightly increased in its value, because $\left(1-\frac{T_0}{T_r}\right)$ has no effect of effectiveness, and remain constant. The exergetic efficiency by ratio of cooling effect divides by compressor work of the system. The denominator term has large increase in value than the numerator term $Q_{rc}\left(1-\frac{T_0}{T_r}\right)$ when the effectiveness of the LVHE is increases, hence exergetic efficiency decrease. At the same time since EDR is inversely proportional to exergetic efficiency, it increases with effectiveness.

3.1.6 Variation in the exergetic efficiency of the system with and without pressure drops in the evaporator and condenser

Fig. 3.7 shows the variation in exergetic efficiency of system with and without pressure drops in evaporator and condenser. R22 is the most affected by pressure drops. The percentage decrease in value of exergetic efficiency is the highest for R22 (4.037%). R410A is the least effected by pressure drops. The percentage decrease in value of exergetic efficiency is the lowest for R410A (2.47%).

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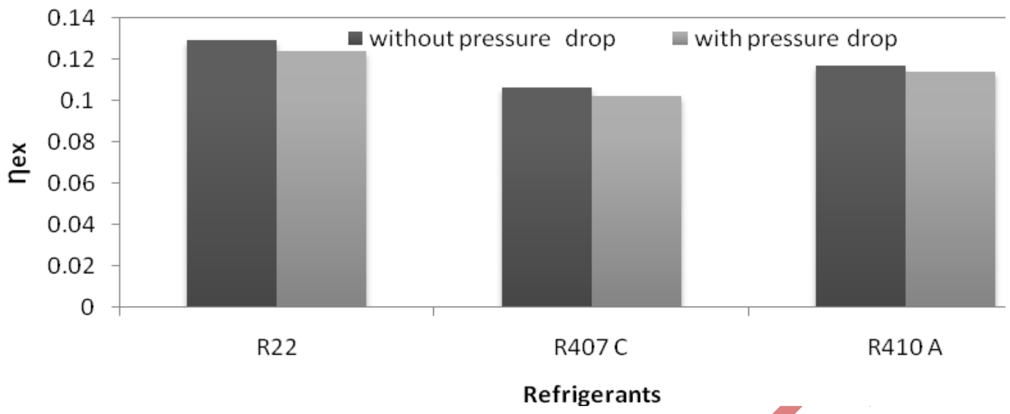

Fig 3.7 Variation in the Exergetic Efficiency of the System with and Without Pressure Drops In the Evaporator and Condenser

IV CONCLUSION

1. The COP of system is the highest for R22.In the descending order of COP v these refrigerants can be arranged as R22, R410A and R407C. The RCI value is the highest for R410A at evaporator temperature 0˚C. In the descending order of RCI these refrigerants can be arranged as R410A, R407C and R22. It is concluded that LVHE is most beneficial for R410A.
2. At fixed condenser temperature of 40˚C, evaporator temperature has been varied from -50˚C to 0˚C. All three refrigerants show highest value of exergetic efficiency of system individually, at evaporator temperature ranging from -35 to -30˚C. It is concluded that this range is the optimum evaporator temperature range for system while using these refrigerants. The exergetic efficiency of system for R22 is the highest. The EDR value is the lowest at optimum evaporator temperature range. In the descending order of exergetic efficiency these refrigerants can be arranged as R22, R410A and R407C.
3. The increase in dead state temperature has positive effect on the exergetic efficiency of system. R22 shows higher value of exergetic efficiency than R410A and R407C. R407C has lowest value of exergetic efficiency of all three refrigerants.
4. Performance of R22 is the most affected by pressure drops in evaporator and condenser.

It is concluded that performance wise R407C and R410A performance are poorer than R22. But at after higher degree of subcooling, performance of R410A improves. Performance of R410A is better than that R407C as evident from the results of thermodynamic analysis is based on both first and second law of thermodynamics.

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