THEORETICAL EXERGY AND SECOND LAW ANALYSIS OF VAPOUR COMPRESSION REFRIGERATION SYSTEM WITH REFRIGERANTS OF LOW AND HIGH GLOBAL WARMING POTENTIAL

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ABSTRACT

The paper contains exergy analysis and comparison of performance parameters based on second law of thermodynamics. Investigation is conducted by calculating Co-efficient of performance, Second law efficiency, total exergy destruction, exergy efficiency and Exergy Destruction Ratio for refrigerants like R134a, R404a, R502 and R507 with low Global warming Potential refrigerants like R290, R600a, R1270 and mixture of R290 & R600a. Theoretical study is carried out for evaporator temperature and condenser temperature of -10°C and 40°C respectively. Results obtained indicate that low GWP refrigerants are better than current refrigerants when analyzed in context of second law of thermodynamics.

Keywords: Exergy Analysis, Energy Analysis, Second Law Analysis, Low GWP Refrigerants, Vapour Compression Refrigeration System

INTRODUCTION

Selection of refrigerants for a refrigeration device depends on many factors like operating temperature range, pressure ratio, toxicity, chemical stability etc. However the criterion, over past few years has shifted to Ozone Depletion Potential (ODP) and GWP. As discussed (United Nations Montreal protocol, 1987) refrigerants with Chlorofluorocarbon (CFC) and Hydro chlorofluorocarbon (HCFC) were proposed to phase out as they had high ODP. Their replacements were sought in the form of Hydro fluorocarbon (HFC), but they were found to have high GWP. Thus seen in context of environment, zero ODP and low GWP refrigerants are need of the hour. Exergy in place of energy is used for analysis as it shows the degradation of energy value and helps in minimization of entropy generation. Various researchers have suggested different low GWP refrigerants as replacements for CFC, HCFC and HFC. Chaudhari et al. used R290 as a replacement for R22 and found that the COP value obtained for R290 was very close to that of R22. (Agrawal, N., 2017.) tested zeotropic blend of R290 and R600a in domestic refrigerator as a substitute to R134a and found Structure zeotropic blend was better in context of COP and compressor power. In other study Gill J.et al. carried energy analysis of VCR system with mixture of R134a and LPG and found the COP of mixture was higher. Apart from this some researchers like Paula de et al. used exergy investigation for checking the feasibility of hydrocarbons. (Arora A., 2011). carried exergy analysis and concluded that R507A is a better choice to replace R502 against R404a . In another study Joibari et.al., conducted exergy analysis for a domestic

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refrigerator with R600a and it was concluded that charge required for R600a was 66% less than R134a. There are many studies which analyzed alternate refrigerants based on environment and energetic approach . However in the presented work authors have done exergy analysis of VCR system and calculated various performance parameters and compared the results obtained for different refrigerants. On basis of literature survey the researchers have presented the results of studies in which parameters like COP, Exergy destruction, Exergy efficiency, second law efficiency and Exergy destruction ratio (EDR). They are calculated and their variation with ambient temperature (To) and evaporator temperature (Te) is studied.R600a is found to be the best replacement of R134a in terms of COP, second law efficiency and exergy destruction ratio. Other hydrocarbons like R290 and R1270 have performance close to R134a but are far better in ODP and GWP.

ENERGY ANALYSIS & EXERGY ANALYSIS

VCR cycle schematic is represent in figure 1. Its p-h and T-S plots are shown in figure 2 and figure 3 respectively. The plots represent that compression is not isentropic. The compressor efficiency is considered 80 % (Anta et al.2019)

FIGURE1:
VAPOUR COMPRESSION REFRIGERATION CYCLE

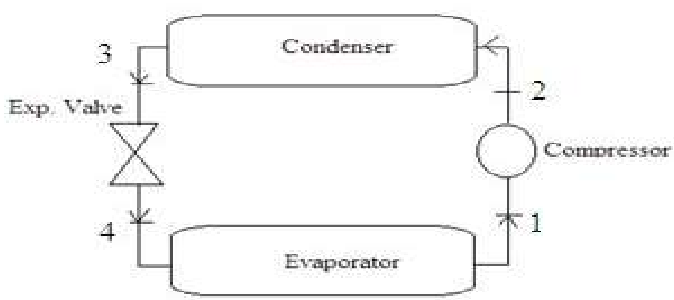

FIGURE 2:
PRESSURE V/S ENTHALPY DIAGRAM OF VCR CYCLE WITH IRREVERSIBLE COMPRESSION

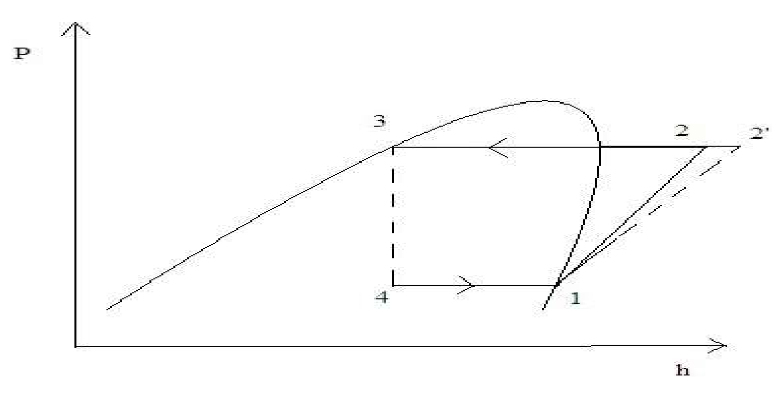

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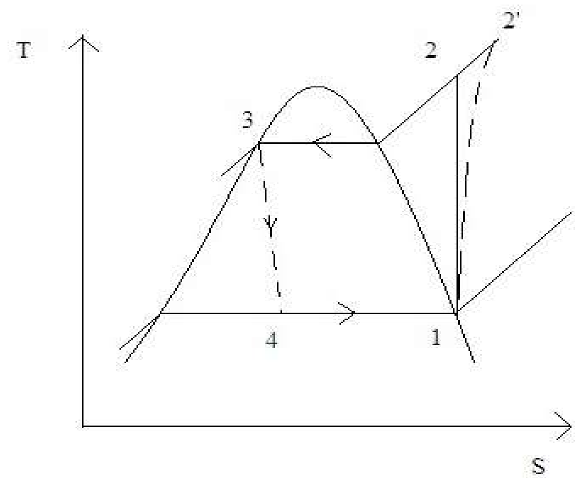
FIGURE 3:
TEMPERATURE ENTROPY DIAGRAM OF VAPOUR COMPRESSION CYCLE WITH IRREVERSIBLE COMPRESSION



NOMENCLATURE	
Variable	**Description[a]**
COP	Coefficient of performance
EDR	Exergy destruction ratio
E*xd*	Exergy Destruction (Watt)
GWP	Global Warming Potential
H	Specific Enthalpy ($kJkg^{-1}$)
M	Mass flow rate in kgs^{-1}
ODP	Ozone depletion Potential
Q	Heat transfer in (kW)
S	Specific Entropy ($KJKg^{-1}K^{-1}$)
T	Temperature (K)
VCR	Vapour compression Refrigeration
η_X	Exergy Efficiency (%)
η_{II}	Second Law Efficiency (%)
Ψ	Availability
Subscript	
C	Compressor
C	Condenser
E	Evaporator
O	Dead state

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ENERGY ANALYSIS

By applying Steady flow Energy Equation (SFEE) on each component of VCR cycle individually, the energy balance equations are deduced as

a. Work consumed in compressor (Wc)

$$Wc = m\ (h_1 - h_{2'}) \tag{1}$$

b. Heat rejected in Condenser (Q_c)

$$Q_c = m\ (h_{2'} - h_3) \tag{2}$$

c. For Expansion Valve

$$h_3 = h_4 \tag{3}$$

d. Heat absorbed in Evaporator (Q_e)

$$Q_e = m\ (h_1 - h_4) \tag{4}$$

Performance measure of a VCR system is given by COP which is given as ratio of refrigeration effect produced for given work input.

$$COP = Q_e/W_c \tag{5}$$

EXERGY ANALYSIS

Exergy destruction (E_{xd}) for various components is calculated from the following equations (Dincer 2010)

Exergy destruction in Compressor

$$E_{xd\ 1\text{-}2} = m\ T_o\ (s_2 - s_1) \tag{6}$$

Exergy destruction in Condenser

$$E_{xd\ 2\text{-}3} = m\ T_o\ (s_3 - s_2 + q_C/T_c) \tag{7}$$

Exergy destruction in Expansion Valve

$$E_{xd\ 3\text{-}4} = m\ T_o\ (s_4 - s_3) \tag{8}$$

Exergy destruction in Evaporator

$$E_{xd\ 4\text{-}1} = m\ To\ (s_1 - s_4 - q_e/T_e) \tag{9}$$

Total exergy destruction ($E_{xd\ total}$) is the sum of exergy destroyed in different components. It is given by the equation

$$E_{xd\ total} = E_{xd\ 1\text{-}2} + E_{xd\ 2\text{-}3} + E_{xd\ 3\text{-}4} + E_{xd\ 4\text{-}1} \tag{10}$$

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Second law efficiency (η_{II}) shows how close is the system's actual performance to Carnot's performance.

$$\eta_{II} = \frac{COPactual}{COPcarnot} \tag{11}$$

One more second law parameter is exergy efficiency (η_X) which is stated as ratio of exergy of heat absorbed in evaporator to compressor work [3]

$$\eta_X = \frac{\Psi 1 - \Psi 4}{Wc} \tag{12}$$

Where $\Psi = (h - h_o) - T_0(s\text{-}s_0)$

Ψ is the availability of the system. Another parameter is EDR which is the ratio of total exergy destroyed in system to product's exergy (Arora, A., 2008) .

$$EDR = \frac{1}{\eta_X} - 1 \tag{13}$$

RESULTS AND DISCUSSION

Assumptions made for computation of results are mentioned below.

- Mass flow of refrigerant per second (m): 0.00256 kgs^{-1}
- Isentropic efficiency of compressor: 80 %
- Evaporator temperature in Kelvin (Te): 263
- Condenser temperature (Tc) in Kelvin: 313
- Dead state temperature (To) in Kelvin: 303

On the basis of equations mentioned above from (1) to (13), parameters like COP, total exergy destruction, exergy efficiency , Second law efficiency and Exergy destruction ratio are calculated. Results are shown in Table 2 and can be seen from figure 4 to figure 14. Table 1 represents a comparison of physical and environmental properties. COP of the System for various refrigerants is presented in Figure 4. It is observed from figure that R600a has the highest COP among all the refrigerants taken into consideration and its value is 3.453 % more than commonly used refrigerant R134a. Other hydrocarbon refrigerants like R1270 and R290 also have COP close to that obtained for R134a. Refrigerants studied (Arora A., 2011). R404a, R502 and R507 have COP less than that of R134a by 12.374% , 6.419 % and 12.693 % respectively. Total exergy destruction for different refrigerants is present in Figure 5. It is observed that total exergy destruction ($E_{xd\ total}$) is maximum for mixture of R290 & R600a. Total exergy destruction in case of R600a is more than R134a by 62.5 %. However, this is compensated by negligible GWP of R600a (GWP = 3) against R134a (GWP = 1300). For R404 total exergy destroyed is more than that for R134a by 0.615 %.

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Second law efficiency for various refrigerants is given in figure6. It is noted that highest II law efficiency is obtained for R600a and it has higher second law efficiency than R134a by 3.51% and its EDR is lesser by 6.96 %. This can be evaluated from equation 11. Exergy Efficiency obtained for different refrigerants can be observed from figure7. Highest exergy efficiency is obtained for refrigerant R404a whereas least value is obtained for mixture of R290 and R600a. Second law efficiency of R290 and R1270 is less than that of R134a by 1.673 % and 1.98 % respectively.

EDR of R290 is higher than R134a by 3.594 % whereas EDR of R1270 is higher than R134a by 4.313 %. Hydrocarbon mixture (R290 and R (600a 50 % by each mass) obtained COP and II law efficiency less than R134a by 28.75 %. The EDR is higher than R134a.
COP and II law efficiency variation with evaporator temperature are presented in figure8 and figure 9 respectively. It is clear that both COP and II law efficiency increase with evaporator temperature.

TABLE 1
PHYSICAL PROPERTIES AND ENVIRONMENTAL PROPERTIES OF CONSIDERED REFRIGERANTS

Property	R134a	R290	R600a	R1270	R404a	R502	R507
GWP	1300	3	4	2	3949	4786	3986
Critical temperature (T_{cr})	101.06	96.74	134.66	91.06	72.04	81.51	70.62
Critical Pressure (P_{cr})	40.59	42.51	36.29	45.55	37.28	40.16	37.04
Safety Group	A1	A3	A3	A3	A1	A1	A1

TABLE 2
PERFORMANCE PARAMETERS FOR VARIOUS REFRIGERANTS

Refrigerant	COP	II law Efficiency (%)	Total Exergy destruction (Watt)	Exergy Efficiency (%)	EDR
R134a	3.226	61.295	40.664	48.941	1.0433
R290	3.172	60.269	79.922	48.058	1.0808
R290+R600a	2.2985	43.672	215.874	14.961	5.6840
R600a	3.3374	63.448	66.117	50.746	0.9706
R1270	3.1622	60.08	82.829	47.884	1.0883
R404a	2.8268	53.71	40.91407	68.26	0.4650
R502	3.0189	57.3935	33.5741	45.772	1.1840
R507	2.8165	53.5472	39.8129	42.6976	1.3421

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FIGURE 4:
COP FOR VARIOUS REFRIGERANTS

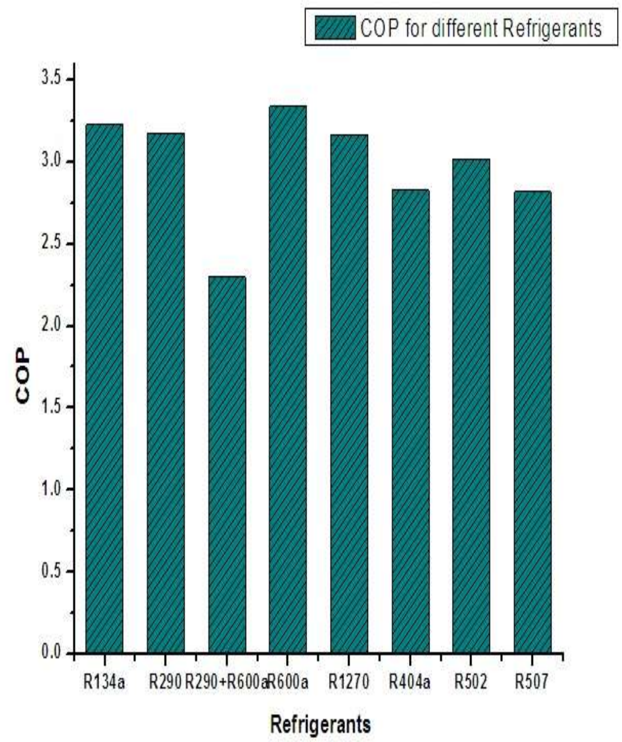

FIGURE 5:
TOTAL EXERGY DESTRUCTION FOR VARIOUS REFRIGERANTS

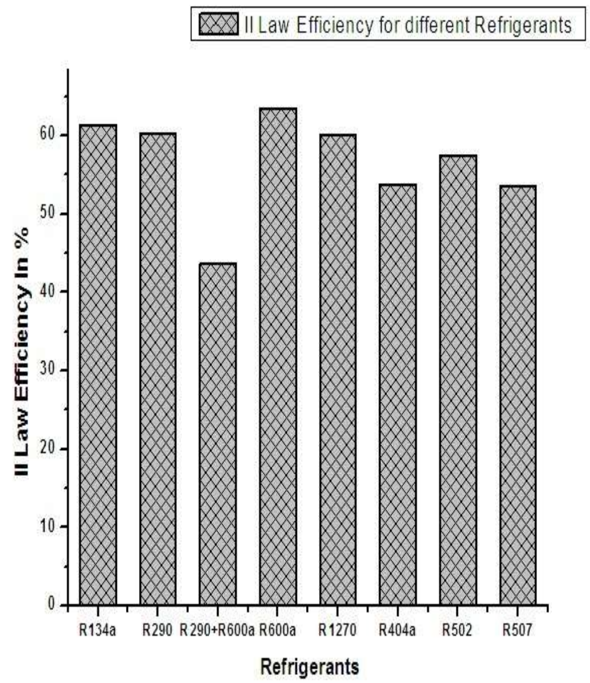

FIGURE 6:
II LAW EFFICIENCY FOR VARIOUS REFRIGERANTS

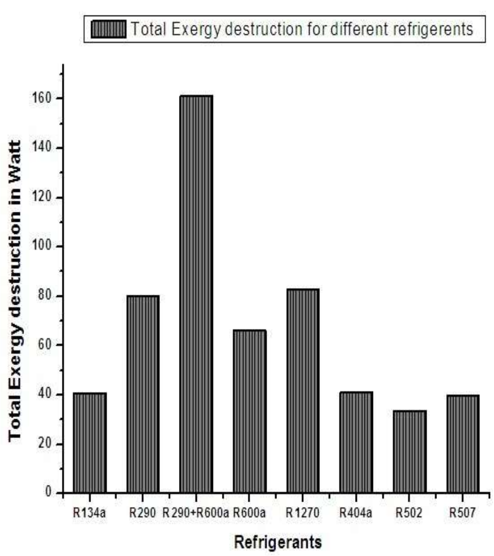

FIGURE 7:
EXERGY EFFICIENCY FOR VARIOUS REFRIGERANTS

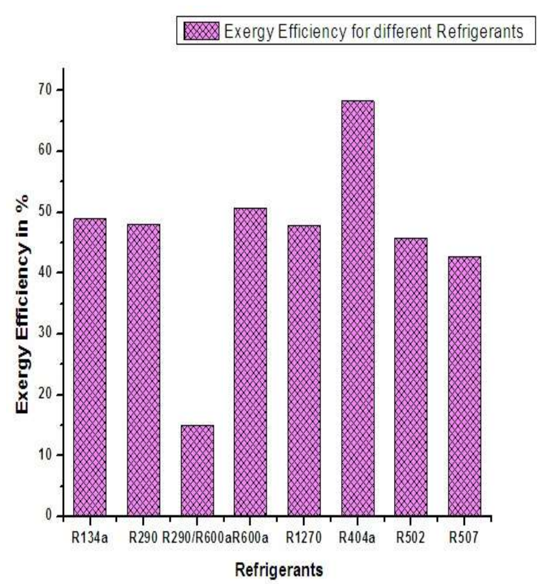

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**FIGURE 8:
COP VARIATION WITH
EVAPORATOR TEMPERATURE**

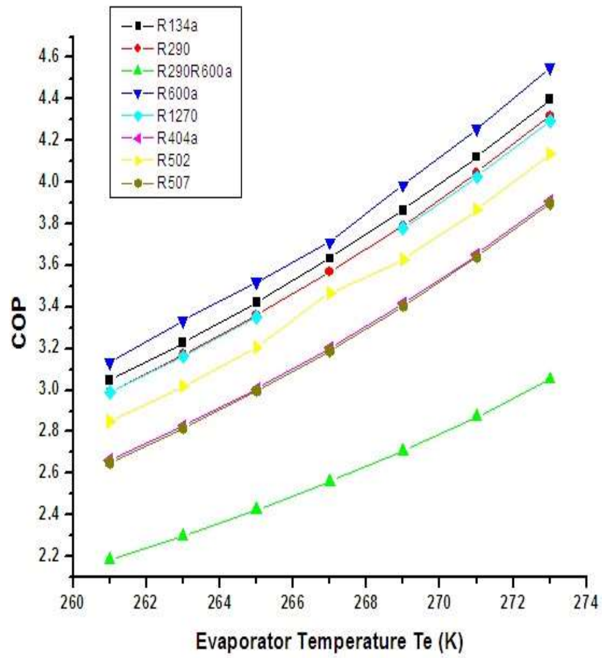

**FIGURE 10:
EXERGY EFFICIENCY WITH
AMBIENT TEMPERATURE**

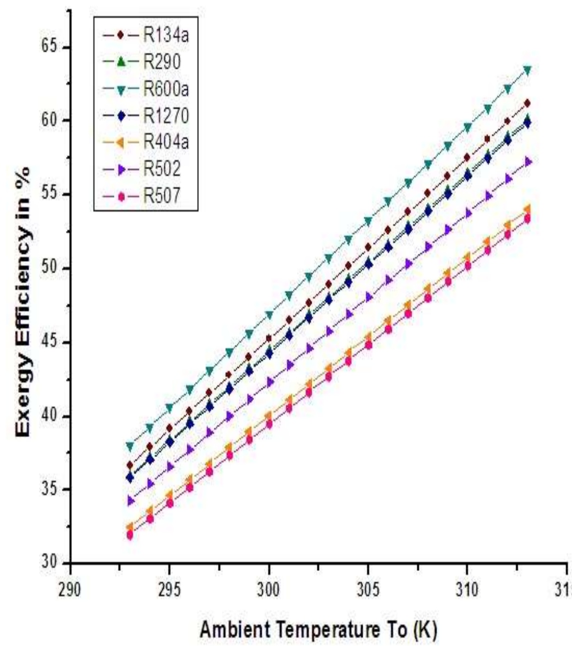

**FIGURE 9:
II LAW EFFICIENCY WITH
EVAPORATOR TEMPERATURE**

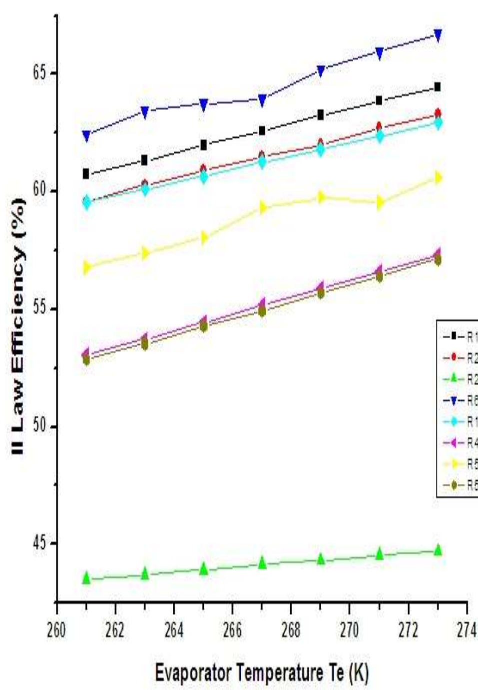

**FIGURE 11:
EXERGY DESTRUCTION IN
COMPRESSOR WITH TO**

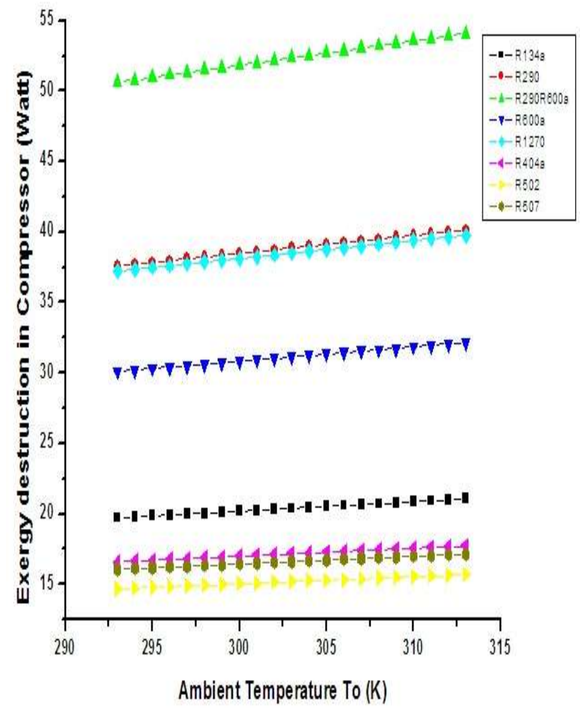

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FIGURE 12:
EXERGY DESTRUCTION IN CONDENSER WITH TO

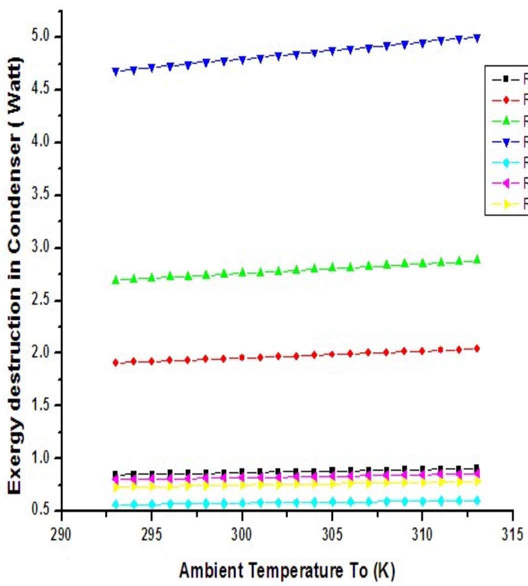
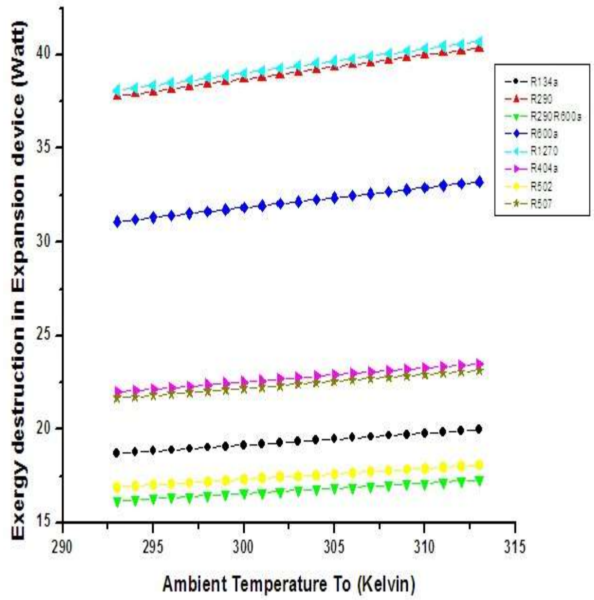


FIGURE 13:
EXERGY DESTRUCTION IN EXPANSION VALVE WITH TO



With increase of 12 °C evaporator temperature high increase in COP is seen in R507 (46.99 %) followed by R600a (45.29%) R502 (45.19 %) and R290 (44.42%). Least increment in COP is for R404a (13.6 %). Similarly for 12 °C rise in evaporator temperature highest increase in II law efficiency is for R507 (8.1%) and least increase is for mixture of R290 & R600a (2.71%).

Exergy efficiency variation of different refrigerants with ambient temperature is shown in figure 10. These variations can be evaluated using equation 12. For increase in ambient temperature by 21°C exergy efficiency increased maximum for R1270 (67%) and least for R404a (66.2%).Further Exergy destruction variation found in Compressor, condenser, Expansion device and evaporator with ambient temperature is shown from figure 11 to figure 14 respectively. On average there is notable increase (6.82%) in the value of exergy destruction of different components of VCR system with increase in temperature of surrounding.

FIGURE 14:
EXERGY DESTRUCTION IN EVAPORATOR WITH TO

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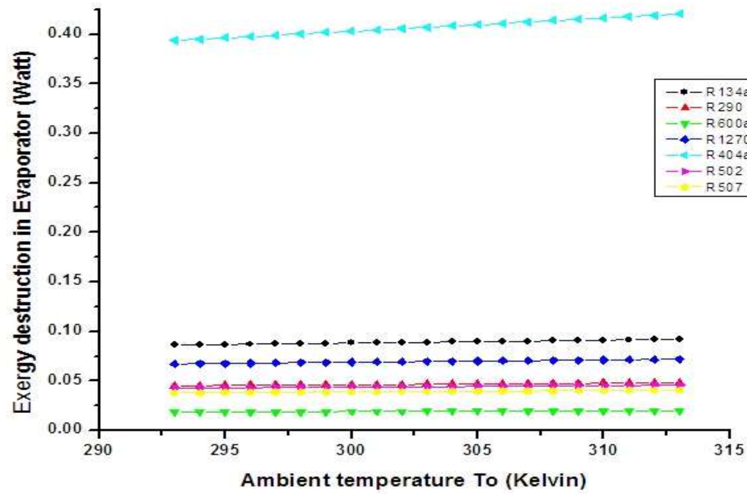

CONCLUSIONS

Based on obtained results for various refrigerants the following conclusions are derived.

- R600a can be considered as best replacement of R134a among all the considered refrigerants. With COP and II law efficiency higher than all other selected refrigerants and exergy destruction ratio less than that of R134a, R600a is the obvious choice.
- Although total exergy destruction is more in R600a than R134a, R404a, R502 and R507, however when seen in context of environmental factors like ODP & GWP and Montreal protocol pure hydrocarbons like R600a, R290 and R1270 can be chosen to be the refrigerants of future.
- COP produced by propane and R1270 is only marginally less than R134a.
- Refrigerants with very less destruction of exergy i.e. R404a (40.914 Watt), R502 (33.574 Watt) and R507 (39.8129 Watt) produced COP less than R134a, R290, R600a and R1270. Further they have very high GWP value, hence are on verge of phasing out.

The pattern of variation of COP with evaporator temperature and exergy efficiency with ambient temperature is similar to the graphs made (Arora, A.,2008) and Chaudhari C.S et al. 2017. It can also be concluded that To has notable effect on exergy destruction.

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