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Exergy analysis of VCR System working with refrigerants R-134a & Hydrocarbon

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Abstract – This paper discusses about an exergy analysis of a Vapour Compression Refrigeration System working with the refrigerants R-134a and HC (a mixture of R-290/R-600a). The objective of this paper is to find out the Exergy Analysis, Exergetic Efficiency, Exergy Destruction Ratio (EDR), Co-efficient of Performance and 2nd law efficiency for all the major components of a VCRS viz. Compressor, Condenser, Expander and Evaporator. The purpose of this work is to carry out an exergy analysis of a domestic VCRS working on R-134a with Hydrocarbon as an alternative to enhance its performance. The VCRS performance will be checked with reference to evaporator temperature on COP, Exergetic efficiency and EDR. Due to prevention of GWP (Global Warming Potential), Hydrocarbon and R-134a are used as refrigerant to give better results for domestic operation.

***Keywords** - COP, EDR, Exergic efficiency, Exergetic loss, , Hydrocarbon and R-134a.*

I. INTRODUCTION

Among various refrigeration systems, the vapour compression refrigeration system is the most suitable system from the commercial as well as domestic point of view. This is the most useful & reliable form of refrigeration system. In this system the working fluids are R134a and Hydrocarbons. Objective of this work is to bring out an exergy analysis of a VCRS with air as well as water cooled condenser under Hydrocarbon refrigerant as a substitute for R-134a on the working of a domestic VCRS which is best suited with R-134a.The performance of these two refrigerants were examined by an exergy analysis. The effect of evaporator temperature on the coefficient of performance, exergy loss, exergic efficiency and exergy destruction ratio in all major components of the VCRS for R-134a &Hydrocarbons mixture will be experimentally evaluated. For 180 litres of cooling load capacity and maximum COP of the VCRS, the length of capillary tube is fixed to 3.5m. Now a days most of the energy are wasted in cooling and air conditioning in industrial as well as for domestic sector. Use of refrigerants in cooling and air conditioning increases global warming and are responsible for ozone layer depletion. Basic requirements of ideal refrigerants are having good physical and chemical properties by which refrigerants should be non-toxic, non-flammable and have low boiling point. Chlorofluorocarbon (CFC) and Hydro-Chlorofluorocarbons (HCFCs) are in practice since many decades and they contain large amount of chlorine as well as global warming potential and ozone layer depletion potential, due to which these kinds of refrigerants are almost prohibited. The refrigerants used in this work are eco-friendly, harmless to ozone layer and global warming.

II. LITERATURE REVIEW

Mukul Kumar et al. [1] studied the working of a simple VCRS using two different refrigerants namely R134a and Hydrocarbon. They used exergy analysis as an instrument for designing and performance evaluation of a VCRS. In analysis it was observed that COP and Exergy efficiency of VCRS using Hydrocarbon as a refrigerant. Also R134a is best according to zero ODP and low GWP have better performance than Hydrocarbon.

Niraj Kumar Mahato et al. [2] studied the working of a VCRS using two different refrigerants mainly R134a and Hydrocarbon employing two different types of condenser cooling such as air cooled and water cooled. The result shows that the refrigeration system performance gets improved in water cooled condenser with Hydrocarbon as a refrigerant.

Sattar et al. [3] studied the working of a domestic refrigerator with R-134a as a refrigerant by replacing R-134a with Hydrocarbon. A study on condenser temperature, evaporator temperature, COP, work of compression heat rejection ratio and refrigerating effect was done. It was found that the energy consumptions were 3% and 2% less when isobutene and butanes were used in place of R-134a in refrigerator. It was shown that the energy consumption and COP of domestic refrigerator was high when Hydrocarbons were used as arefrigerant in place of R-134a.

Nawaz khan et al. [4] studied an exergy analysis of a VCRS using R12, R22, and R134a as refrigerants. They developed relations for total exergy destruction in the system, the

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overall exergetic efficiency of the system and exergy destruction ratio related to exergetic efficiency. They further formulated an expression for COP of VCRS. Experimental results show that the COP and exergetic efficiency of R12 are better than that of R22 and R134a. The EDR of R-134a is higher than that of R-122 & R-22. For all refrigerants, COP and exergy efficiency increases with increase in degree of sub-cooling.

Nawaz Khan et al. [5] studied the working of VCRS for four different configurations with four different refrigerants. The four configurations were simple VCRS multiple VCRS with flash chamber, multiple VCRS with water inter cooler and liquid sub-cooler and multiple VCRS with flash intercooler and multiple expansion valve. The four refrigerants were R-12, R-134a, R-407 and R-717. It was found that the refrigerant R717 has highest COP for simple VCRS, multiple compression system with flash chamber and MCRS with flash intercooling & multiple expression valve followed by the R12 in simple VCRS, R134a in MCRS with flash chamber and R407 in MCRS with flash intercooling and multi expression valve but in MCRS with water intercooler and liquid sub-cooler the highest COP is of R12 followed by R717.

Wongwises et al. [6] studied the working of a VCRS with different refrigerants like Hydrocarbon (A mixture of Propane/Butane in ratio 60/40%) and R134a. It was found that energy consumption was lower in the case of Hydrocarbon refrigerant than R-134a. This was due to the fact that the saturation temperature of Hydrocarbon and the latent heat of vaporization of Hydrocarbon are higher than that of R-134a. So this causes less energy destruction and suitable for replacement of R-134a on the basis of 2^{nd} law efficiency.

Selladurai et al. [7] studied the working of a domestic VCRS with refrigerants R-134a and R290/R600a. It was found that R290/R600a mixture showed higher COP and exergetic efficiency than R-134a. In this study it was also found that the highest irreversibility was in compressor compared to condenser, expansion valve and evaporator.

Mastani Joybari et al. [8] studied the working of a domestic VCRS designed to use 145g of R134a as a refrigerant. The refrigerant R134a was replaced by R600a and 60g of R600a showed same result as in the case of 145g of R134a. The result showed the economical advantages and reduces the risk of flammability of Hydrocarbon mixture.

Baskaran et al. [9] studied the working of a VCRS with various eco-friendly refrigerants. The performance was compared on the basis of COP, pressure ratio and environmental aspects such as ozone layer depletion and global warming. It was noted that R-170 is most suitable alternative for R-1324a. The COP of the system enhances with rise in evaporating temperature for constant condensing temperature.

Reddy et al. [10] studied the working of a VCRS with refrigerants R134a, R143a, R152a, R404a, R502 and R507a using numerical analysis. They discussed the effect of evaporator temperature, degree of sub-cooling at condenser temperature on COP and exergetic efficiency. It was found that evaporator and condenser temperature have significant effect on both COP and energetic efficiency and also found that R-134a has the better performance while R407c has poor performance in all respect.

Bolaji et al. [11] studied the working of a VCRS with refrigerants R12, R134a and R152a. It was found that R152a refrigerant best suited for as an alternative for R134a.

Bilal et al. [12] studied the performance degradation of a VCRS due to fouling for various applications. Two sets of refrigerants such as R-134a & R410a, R-407c & R-717 and R-404a &R-290 were considered depending upon the assumption and their properties.

Said et al. [13] studied the working of a VCRS with refrigerants R-123, R-134a, R-11 and R-12 theoretically. For a specific amount of desired exergy, more compression work was required for R-123 and R-134a than R-11 and R-12. This difference was not very significant at high evaporation temperatures and hence R-123 and R-134a should not be excluded as alternative refrigerants. Also an optimum evaporation temperature for each condensation temperature was found for maximum exergic efficiency.

Qureshi et al. [14] studied the working of a VCRS due to fouling using three eco-friendly refrigerants R-134a, R-410a and R-407c. It was found that the first law efficiency in terms of COP and second law efficiency in terms of exergetic efficiency using R-134a gives best result in all the cases.

Ahamed et al. [15] studied the working of a domestic refrigerator with Hydrocarbons (butane & isobutene) as refrigerants. It was found that energy efficiency ratio of Hydrocarbons are comparable with R-134a at considered evaporator temperature but exergy efficiency and sustainability index of hydrocarbons are much higher than that of R-134a. It was also found that compressor showed highest system defect (69%) among considered components in the system.

Dalkilic et al. [16] studied the working of a VCRS with R-12 & R-22 as refrigerants with various non-azeotropic mixed refrigerants. It was found that HC 290/HC 600a (40/60 by weight %) and HC 290/HC1270 (20/80 by weight %) are suitable alternatives for R-12& R-22 respectively.

Mohanraj et al. [17] studied the performance of a domestic refrigerator working on R-134a as a refrigerant with a mixture of R-290 and R600a in different environmental temperatures. It was found that mixture of R-290 and R-600a in the ratio (45.2):(54.8) by weight shown up to 3.6% greater COP than R-134a. Also the discharge temperature of compressor with Hydrocarbon was lower in the range of 8.5-13.425 K, than same compressor with R-134a.

Jwo et al. [18] studied the working of a domestic refrigerator working on R-134a as a refrigerant with Hydrocarbon (a mixture of R-290 and R-600a 50/50 by weight %). It was found that the refrigerating effect get

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improved with Hydrocarbon than R-134a. Also the total power consumption was reduced by 4.4% and mass of refrigerant by 40%.

Mani et al. [19] studied the working of VCRS with refrigerant mixture of R-290/R600a in place of R-12 and R-134a. It was found that the refrigerant mixture of R290/R600a had 28.6-87.2% higher refrigerating capacity than R-134a.

Fatouh et al. [20] studied the performance of a VCRS working on R-134a with a mixture of Propane/Isobutene/n-Butane. It was found that refrigerant mixture containing 60% Propane gives same result as with refrigerant R-134a without any system modification.

Cabello et al. [21] studied the effect of condensing pressure, evaporating pressure and degree of superheating on single stage VCRS using R-22, R-134a and R-407c as a refrigerant. It was reported that mass flow rate is highly influenced by change in suction conditions of compressor resulting in refrigeration capacity. Further it was also found that for higher compression ratio, R-22 gives lower COP than R-407c.

Ashford et al. [22] studied the issue of GWP related with R134a and found that GWP of HFC refrigerants are more prominent than CFC refrigerants. This issue could be relieved by thermal storage using secondary refrigerants or phase change materials for domestic refrigerators.

Halimic et al. [23] studied the working of a VCRS with on R-12, R-401a, R-290 and R-134a for replacement of R-12. It was found that R-134a can replace R-12 without any system modification but from green house impact R-290 is a better substitute for R-12.

Lee et al. [24] studied the working of a domestic VCRS working on R-12 and R-134a with R-600a. It was found that COP of the system gets improved with R-600a than R-12 and R-134a.

III. SYSTEM DESCRIPTION

In a vapour compression system fundamental processessuch as compression, condensation, expansion and evaporation are completed in a cycle. For this, there are components like

I. Compressor
II. Condenser
III. Expansion valve

IV. Evaporator

The low temperature and pressure refrigerant vapour (state '1') enters the "Compressor", where it is compressed isentropically resulting in high temperature and pressure of refrigerant at exit (state '2'). The refrigerant vapour from exit of compressor enters into the condenser, where it is condensed to high pressure liquid (state '3') and is collected in a "receiver tank". From receiver tank it passes through an expansion valve, where refrigerant is throttled down to a lower pressure and has a low temperature (state '4'). After this refrigerant finally passes on to evaporator, from where it extracts heat from the surrounding and vaporizes to low pressure vapour (state '1').

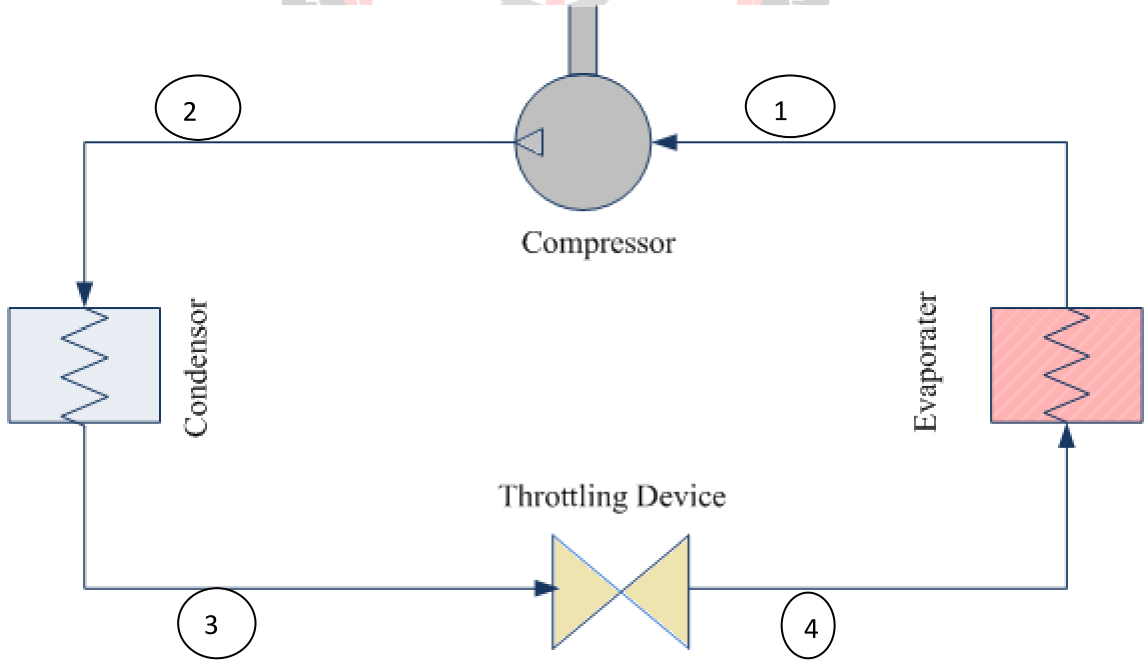

Fig.1: Flow diagram of VCRS.

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PROPERTIES OF REFRIGERANT

These properties are used for exergy analysis:-

S.NO	Property	R-134a	R-290	R-600a
1.	Chemical formula	CH_2FCF_3	Propane $CH_3CH_2CH_3$	Isobutane $(CH_3)_2CHCHF_3$
2.	Molar Mass (kg/K-mol)	102.03	44.9	58.12
3.	Critical Point Temp. T_c (^0C)	101.06	96.67	134.98
4.	Critical Pressure P_c (bar)	40.593	4.24	3.66
5.	Critical Density (Kg/ m^3)	511.9	220	221
6.	Boiling Point	-26.074	-42.2	-11.80
7.	ODP	0	0	0

V. THERMODYNAMICS OF VCRS

A. The exergy analysis is based on following assumptions:

1. Load on the evaporator at low, intermediate and high temperature is 1 TR.
2. We assume that dead state temperature (T_0) = 25^0C .
3. Adiabatic or mechanical efficiency of the compressor is about 80%.
4. In this system dead state enthalpy (h_0) and dead state entropy (S_0) have been evaluated at the dead state temperature (T_0), i.e. $T_o = 25^0C$.
5. Mechanical energy, i.e. kinetic and potential energy in the system are negligible.
6. Expansion process in the expansion valve or throttle valve is adiabatic.
7. No pressure loss in pipeline of the system.
8. Temperature difference between evaporator and space is about 10^0C .
9. For finding the value of enthalpy, entropy etc, steady state operation is considered.
10. Refrigerants are ecofriendly in terms of GWP and ODP.

B. Temperature and entropy diagram of a VCR system

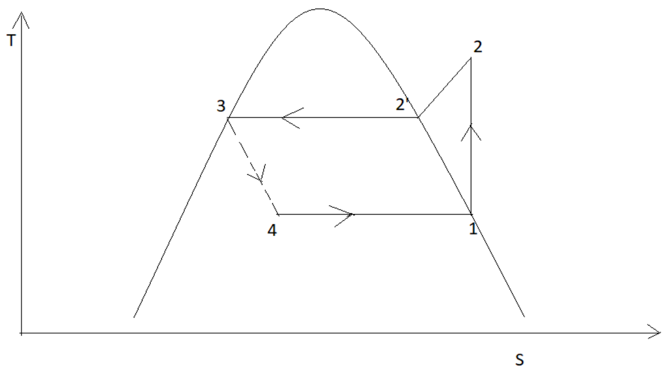

Fig.2: T-S Diagram of VCRS

C. Pressure and entropy diagram of a VCR system

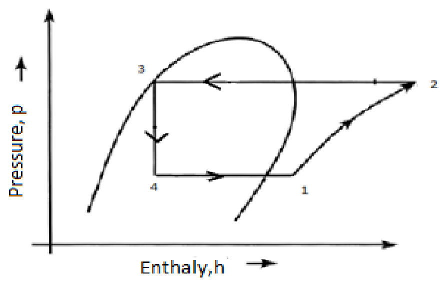

Fig.3- P-H diagram of VCRS

In this diagram,

Process 1-2 Isentropic Compression (Entropy Constant)

Process 2-3 Isobaric heat rejection

Process 3-4 Isenthalpic expansion (Enthalpy Constant)

Process 4-1 Constant pressure heat addition

$$C.O.P = \frac{Q_E}{W_C}$$

$$C.O.P = \frac{h_1 - h_4}{h_2 - h_1} = \frac{h_1 - h_3}{h_2 - h_1} \quad \text{-------------- (1)}$$

D. Exergy analysis of a VCRS

Exergy is the thermodynamic parameter which represents the maximum work which can be obtained by the reversible process until it reaches the thermodynamic equilibrium with surrounding. Exergy analysis or availability is used to find out the

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performance of a thermodynamic system. Although exergy is not conserved, they may be destroyed when we use the experimental data for finding the exergy loss from the experimentation using refrigerants R-134a and Hydrocarbon in order to have a qualitative measurement of the system efficiency.

For the system, component wise exergy balance equation is:-

(a) For compressor :

Compressor work,

$$W_C = m_r(h_2 - h_1)$$

Exergy at inlet, $\lambda_1 = m_r(h_1 - T_0 S_1) + W_c$

Exergy at outlet, $\lambda_2 = m_r(h_2 - T_0 S_2)$

The exergy loss (due to irreversibility) in the compressor

$I_{Comp.} = m_r(h_1 - T_o S_1) - m_r(h_2 - T_o S_2) + m_r(h_2 - h_1)$ -------------------------- (2)

(b) For condenser :

Heat removed at constant pressure in condenser

$$Q_{cond.} = m_r(h_2 - h_3)$$

Exergy at inlet, $\lambda_2 = m_r(h_2 - T_0 S_2)$

Exergy at outlet, $\lambda_3 = m_r(h_3 - T_0 S_3)$

Total exergy loss in condenser:-

$$I_{cond.} = m_r(h_2 - T_0 S_2) - m_r(h_3 - T_0 S_3) - Q_{cond.}(1 - \frac{T_0}{T_3}) \quad \text{------------------ (3)}$$

(c) For expansion valve :

Enthalpy constant during expansion process

So, $h_3 = h_4$

Exergy at inlet, $\lambda_3 = m_r(h_3 - T_0 S_3)$

Exergy at outlet, $\lambda_4 = m_r(h_4 - T_0 S_4)$

Total exergy loss in expansion

$$I_{exp.} = m_r(h_3 - T_0 S_3) - m_r(h_4 - T_0 S_4)$$

$$h_3 = h_4$$

$$I_{exp.} = m_r T_0(S_4 - S_3) \quad \text{--- (4)}$$

(d) For evaporator :

Heat addition at constant pressure in evaporator,

$$Q_{eva.} = m_r(h_1 - h_4)$$

Exergy at inlet, $\lambda_4 = m_r(h_4 - T_0 S_4) + Q_{eva.}(1 - \frac{T_0}{T_4})$

Exergy at outlet, $\lambda_1 = m_r(h_4 - T_0 S \ )$

Total Exergy loss in evaporator

$$I_{eva.} = m_r(h_4 - T_0 S_4) + Q_{eva.}(1 - \frac{T_0}{T_4}) - m_r(h_1 - T_0 S_1) \quad \text{----------- (5)}$$

Overall exergy loss of the system

$$I_{Total} = I_{comp.} + I_{cond.} + I_{exp.} + I_{eva.} \quad \text{-------------------------------------- (6)}$$

Exergy Destruction (ED) in the system components:-

Exergy destruction in each component of the cycle is calculated as:-

Exergy destruction in compressor

$$E_{dcomp.} = E_{\lambda 1} + W - E_{\lambda 2}$$

$$E_{dcomp.} = m_r(T_0(S_2 - S_1)) ----------------------------(7)$$

Exergy destruction in condenser

 DOI : 10.35291/2454-9150.2019.0124

$$E_{dcond.} = E_{\lambda 2} - E_{\lambda 3}$$

$$E_{dcond.} = m_r(h_2 - T_0 S_2) - m_r(h_3 - T_0 S_3) - Q_c(1 - \frac{T_0}{T_3}) --------------(8)$$

Exergy destruction in throttle valve-

$$E_{dthrottle} = E_{\lambda 3} - E_{\lambda 4}$$

$$E_{dthrottle} = m_r(h_3 - T_0 S_3) - m_r(h_4 - T_0 S_4) --------------------(9)$$

Exergy destruction in Evaporator -

Total Exergy Destruction

$$\sum E_d = E_{de} + E_{dcomp.} + E_{dcond.} + E_{dthrottle} --------------------(11)$$

Exergetic efficiency

$$\eta_{exergy} = \frac{Q_e}{W_c}(1 - \frac{T_0}{T_e}) ----------------------------(12)$$

Exergy Destruction Ratio (EDR):-

Exergy Destruction Ratio is the ratio of the total exergy destruction in the system to the exergy in the product and it is given by

$$EDR = \frac{ED_{Total}}{EP} \text{ ------------------------------------- } (13)$$

EDR and Exergetic efficiency can be written as:-

$$EDR = \frac{1}{\eta_{Exergy}} - 1 = \frac{ED_{Total}}{EP} \text{ -- } (14)$$

Exergy in the product is given as -

$$ED_{Total} \times \eta_{Exergy} = EP(1 - \eta_{Exergy})$$

$$EP = \frac{ED_{Total} \times \eta_{Exergy}}{(1 - \eta_{Exergy})} \text{ ------------------------ } (15)$$

VI. CONCLUSIONS

- Most of the available literatures discussed about exergy analysis of an air cooled condenser in a VCRS, but there is no discussion about the volume of air flow and speed of air flow on exergy analysis.
- There is no literature available on water cooled condenser in a VCRS working with refrigerants mixed with nano-fluids or nano-particles.
- No discussions are available about the exergy in the product with reference to refrigerants and thermodynamic parameters.
- HC (a mixture of R-290 & R-600a) is most suitable replacement of R-134a from GWP and ODP point of view.
- This work will open a new insight of exergy analysis in terms of mode of cooling, rate of cooling, flow of cooling and nano mixing.

NOMENCLATURE

T_1	Compressor inlet temperature (^0C)
T_2	Compressor exit temperature (^0C)
T_3	Condenser exit temperature (^0C)
T_4	Evaporator inlet temperature (^0C)
T_o	Dead state temperature (^0C)
h	Enthalpy (kJ/kg)
h_1	Specific enthalpy at compressor inlet (kJ/kg)
h_2	Specific enthalpy at compressor exit (kJ/kg)
h_3	Specific enthalpy at condenser exit (kJ/kg)
h_4	Specific enthalpy at evaporator inlet (kJ/kg)
S	Entropy (kJ/kg-K)
S_o	Entropy at dead state (kJ/kg-K)
S_1	Specific entropy at compressor inlet (kJ/kg-K)
S_2	Specific entropy at compressor exit (kJ/kg-K)
S_3	Specific entropy at condenser exit (kJ/kg-K)
S_4	Specific entropy at evaporator inlet (kJ/kg-K)
m_r	Mass flow rate of refrigerant in the system (Kg)
COP	Co-efficient of Performance
Q_E	Refrigerating effect (KJ/S)
W_C	Compressor work (KW)
I	Exergy loss
E_d	Exergy destruction (KW)
η_{exergy}	Exergy Efficiency
EDR	Exergy Destruction Ratio
ED_{total}	Total Exergy Destruction
EP	Exergy in the product
VCRS	Vapor Compression Refrigeration System
MCRS	Multiple Compression Refrigeration System
GWP	Global Warming Potential
ODP	Ozone Depletion Potential
λ	Exergy

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