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ENERGY, EXERGY AND SUSTAINABILITY ANALYSIS OF TWO-STAGE VAPOUR COMPRESSION REFRIGERATION SYSTEM

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ABSTRACT

In this paper comparative analysis of R152a, R600, R600a, R410a, R290, R1234yf, R404a and R134a as refrigerants in two stage vapour compression refrigeration system has been done on the basis of energetic and exergetic performance. Performance parameters such as entropy generations, COP, exergetic efficiency, sustainability index were investigated at different ambient condition. It was found that both energy and exergy efficiencies of R134a is 8.97% and 5.38% lower than R152a and R600 respectively at -50 ºC evaporating and 45 ºC condensing temperatures. It was also observed that Irreversibility was minimal at higher evaporating temperatures and condenser was responsible for highest irreversibility or losses in two stage vapour compression refrigeration system. Sustainability index for R152a (1.96) was highest compared to other refrigerants.

INTRODUCTION

Refrigeration technology based on the principle of rejection of heat to the surrounding at higher temperature and absorption of heat at low temperature evaporator [1], expansion valve, condenser and compressor are the main four components of single stage vapour compression system. Vapour compression refrigeration systems consume large amount of electricity. This difficulty can be removed by improve the performance parameters of system. Coefficient of performance and exergetic efficiency are main two parameters to calculate the performance of refrigeration systems. Coefficient of performance can be enhanced either by minimizing power consumption of compressor or increasing of refrigeration effect. Refrigeration effect can be increased by adoption of multi-stage throttling .On the other hand power consumption of compressor can be enhanced by incorporation of multi-stage compression and flash chamber. Collective effect of these two factors improves overall performance of vapour compression system. It is presented that irreversibility in system components take place due to large temperature difference between system and surrounding. In order to improve the system performance Irreversibility should be measured in the cycle because Exergy losses are responsible for degradation of system performance .Coefficient of performance is commonly used to calculate the performance of vapour compression system but COP provides no information regarding thermodynamic losses in the system components. Using exergy analysis one can be quantify the exergy losses in vapour compression refrigeration systems. Exergy losses increase with increasing of temperature difference between systems and surrounding. Exergy is the available or useful energy and loss of energy means loss of exergy in the system. Exergy losses are useful to improve the performance of system and better utilization of energy input given to the system which is beneficial for environmental conditions and economics of energy technologies. Utilization of green energy can be increased by this method [2-4].

In past decades, refrigerants such as R12, R02, R22 etc. used in vapour compression refrigeration system responsible for increasing of global warming and ozone depletion potential. An international society named Montreal protocol discussed and signed on the refrigerants having higher global warming and ozone depletion potential values for all countries. In order to control the emission of greenhouse gases one more committee was formed named as Kyto protocol [5]. After 90's a program was ran to phase out the higher GWP and ODP refrigerants (CFC and HCFC) for the purpose of environmental problems. To replace "old" refrigerants with "new" refrigerants lots of researches has been carried out [6-11]. Selladurai and Saravanakumar [12] evaluated performance parameters such as COP and exergetic efficiency with R290/R600 hydrocarbon mixture on a domestic refrigerator designed to work with R134a and observed that performance of same system is higher with R290/R600a hydrocarbon mixture compared to R134a. In their analysis condenser, expansion valve and evaporator showing lower exergy destruction compared to compressor. Reddy et al. [13] presented theoretical analysis of R134a, R143a, R152a, R404A, R410A, R502 and R507A in vapour compression refrigeration system and effect on coefficient of performance and second law efficiency with variation of superheating of evaporator outlet, evaporator temperature and degree of subcooling at condenser outlet, vapour liquid heat exchanger effectiveness and degree of condenser temperature was discussed. They reported that COP and exergetic efficiency significantly affected with change of evaporator and condenser temperatures and also observed that R134a and R407C show highest and lowest performance in all respect. Kumar et al. [14] carried out energy and exergy analysis of single stage vapour compression refrigeration system using R11 and R12 as working fluids. Evaluation in terms of COP, exergetic efficiency and exergy losses in different components (compressor, evaporator, expansion valve and condenser) was done. Cornelissen[15] proposed that non-renewable energy sources are useful for minimizing the irreversibility of the system for sustainable development of systems. He also observed that emissions of gases put adverse effect on environmental conditions. In Nikolaidis and Probert [16]' study, effect of condenser and evaporator temperatures on two-stage vapour compression refrigeration system using R22 was studied and suggested that there is requirement to optimize the condenser and evaporator conditions.

Many researchers carried out researches on different proportion of hydrocarbons as working fluid in vapour compression refrigeration systems. Fatouh and Kafafy [17] suggested to replace R134a with hydrocarbon mixtures such as propane, propane/isobutane/n-butane mixtures, butane, and various propane mass fractions in domestic refrigerator. Pure butane showed high operating pressures and low coefficient of performance among considered refrigerants. Wongwises et al. [18] did experimental investigation on automotive air-conditioners with isobutene, propane, butane and suggested to replace R134a with these hydrocarbon mixtures. They observed that mixture of propane 50%, butane 40%, and isobutane 10% was best hydrocarbon mixture to replace R134a. Jung et al. [19], Arcaklioglu [20], and Arcaklioglu et al. [21] suggested to use of pure hydrocarbon instead of their mixtures due variation in condenser and evaporator temperature during phase changing at constant pressure. These changes in condenser and evaporator temperature cause for problem in vapour compression refrigeration cycle. Liedenfrost et al. [22] investigated freon as refrigerant on the performance of a refrigeration cycle

Through above literature, it was found that energy, exergy and sustainable analysis of single stage vapour compression refrigeration systems have been done. But no literature contributed for energy and exergy analysis of two-stage vapour compression refrigeration system. Present works analyze the system in terms of energy and exergy efficiencies and explain the effect of exergy losses on two-stage vapour compression refrigeration system with hydrocarbons and R134a.

MATHEMATICAL CALCULATIONS

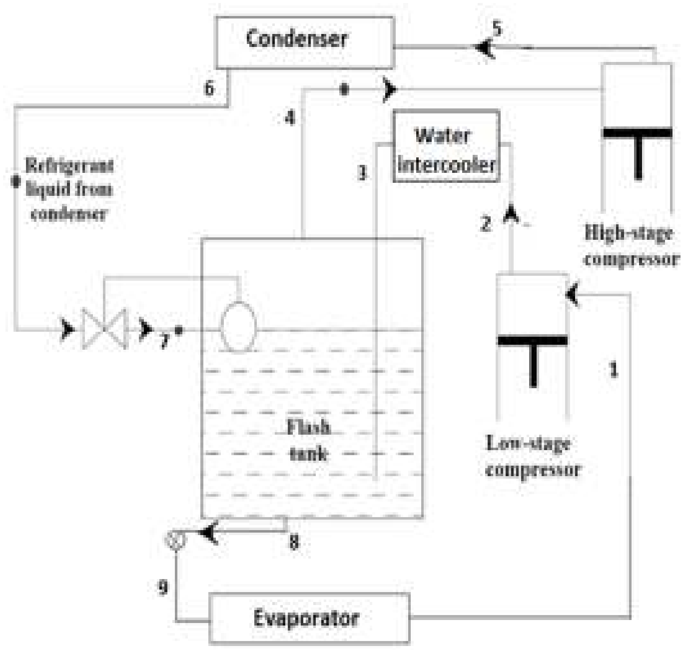

FIG.1 SCHEMATIC DIAGRAM OF TWO-STAGE VAPOUR COMPRESSION REFRIGERATION SYSTEM

Some mathematical calculations are required to analyze the two-stage vapour compression refrigeration system based on energy and exergy method. Two stage vapour compression refrigeration system consist of low and high pressure compressor, condenser, evaporator, expansion valves, water-intercooler and flash chamber. Energy and exergy efficiencies are different for different refrigerants for same system. Following assumptions are taken for thermodynamic analysis of the system:

- ✓ Temperature and pressure losses are not considered.
- ✓ All components are running under steady state conditions.
- ✓ Energy and exergy losses due to potential and kinetic energy are neglected.
- ✓ Mechanical efficiencies of low and high pressure compressors are assumed to be 80%.

Two stage vapour compression refrigeration system and its P-H plot shown in Figure 1 and Figure 2 respectively. Exergy, energy and sustainability analysis can be done as follow:

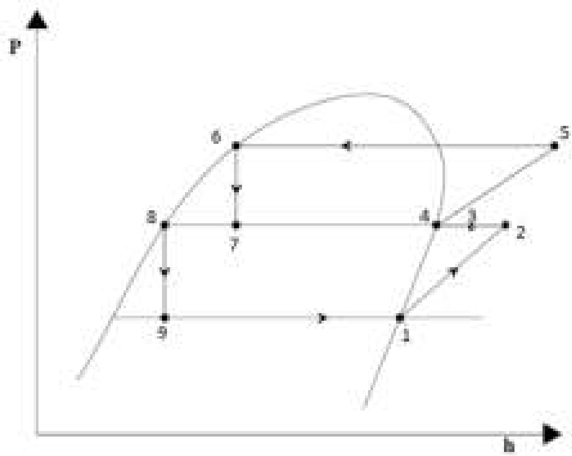

FIG.2 PRESSURE ENTHALPY DIAGRAM OF TWO-STAGE VAPOUR COMPRESSION REFRIGERATION SYSTEM

Exergy at any point, $EX = (h - h_{amb}) - T_{amb}(s - s_{amb})$ (1)

For high and low temperature compressors

$$\left(T_{amb}\dot{S}_{gen}\right)_{HP} = \dot{W_{HP}} + m_{HP}((h_1 - h_2) - T_{amb}(s_1 - s_2)) \quad (2)$$

$$\left(T_{amb}\dot{S}_{gen}\right)_{LP} = \dot{W_{LP}} + m_{LP}((h_4 - h_5) - T_{amb}(s_4 - s_5)) \quad (3)$$

For evaporator

$$\left(T_{amb}\dot{S}_{gen}\right)_{Evap} = \dot{m}_{LP}((h_9 - h_1) - T_{amb}(s_9 - s_1)) + Q\left(1 - \frac{T_{amb}}{T_L}\right) \quad (4)$$

For condenser

$$\left(T_{amb}\dot{S}_{gen}\right)_{Cond} = \dot{m}_{HP}((h_5 - h_6) - T_{amb}(s_5 - s_6)) - Q_{Cond}\left(1 - \frac{T_{amb}}{T_H}\right) \quad (5)$$

For expansion valves

$$\left(T_{amb}\dot{S}_{gen}\right)_{EV} = \dot{m}_{HP}((h_6 - h_7) - T_{amb}(s_6 - s_7)) + \dot{m}_{LP}((h_8 - h_9) - T_{amb}(s_8 - s_9)) \quad (6)$$

For water-intercooler

$$\left(T_{amb}\dot{S}_{gen}\right)_{WI} = \dot{m}_{LP}((h_2 - h_3) - T_{amb}(s_2 - s_3)) \quad (7)$$

For flash chamber

$$\left(T_{amb}\dot{S}_{gen}\right)_{FC} = \dot{m}_{LP}((h_3 - h_4) - T_{amb}(s_3 - s_4)) + (\dot{m}_{HP}h_7 - \dot{m}_{LP}h_8) - T_{amb}(\dot{m}_{HP}s_7 - \dot{m}_{LP}s_8) \quad (8)$$

Exergetic efficiency

$$\eta_{ex} = \frac{Q\left(1 - \frac{T_{amb}}{T_L}\right)}{W_{LP} + W_{HP}} \quad (9)$$

Coefficient of Performance (COP)

$$COP = \frac{\dot{m}_{LP}((h_1 - h_9)}{W_{LP} + W_{HP}} \quad (10)$$

Sustainability index (SI)

$$SI = \frac{1}{1 - \eta_{ex}} \quad (11)$$

Total entropy generation

$$\left(T_{amb}\dot{S}_{gen}\right)_{TOTAL} = \Sigma\left(T_o\dot{S}_{gen}\right)_{HP} + \left(T_o\dot{S}_{gen}\right)_{LP} + \left(T_o\dot{S}_{gen}\right)_{Evap} + \left(T_o\dot{S}_{gen}\right)_{Cond} + \left(T_o\dot{S}_{gen}\right)_{EV} + \left(T_o\dot{S}_{gen}\right)_{WI} + \left(T_o\dot{S}_{gen}\right)_{FC} \quad (12)$$

RESULTS AND DISCUSSION

In this discussion effect of change of evaporator and condenser temperature on performance parameters like coefficient of performance, exergy loss, exergetic efficiency and sustainability index was studied for considered refrigerants

Change of coefficient of performance with change in evaporating temperature for considered refrigerants

As cleared from Table.1 that coefficient of performance of R134a is 4.2-8.9% and 3.6-5.3% lower than R152a and R600 respectively or in other words R134a consumes more electricity than R152a and R600.Ambient condition play an important role in electricity consumption of vapour compression refrigeration systems because higher the temperature difference between system and surrounding higher will be compressor work that's why COP of vapour compression refrigeration system increase with increase in evaporator temperature and decrease with decrease in evaporator temperature.

TABLE 1.VARIATION OF COP AT DIFFERENT EVAPORATING TEMPERATURE FOR DIFFERENT REFRIGERANTS

T_{Evap} (°C)	R152a	R600	R134a	R600a	R410a	R290	R1234yf	R404a
-50	1.457	1.409	1.337	1.33	1.314	1.303	1.197	1.123
-45	1.59	1.54	1.466	1.458	1.437	1.429	1.321	1.24
-40	1.74	1.689	1.611	1.603	1.576	1.571	1.461	1.371
-35	1.911	1.857	1.775	1.767	1.732	1.733	1.62	1.521
-30	2.105	2.05	1.964	1.956	1.91	1.917	1.802	1.691
-25	2.328	2.273	2.181	2.175	2.115	2.129	2.013	1.887
-20	2.587	2.533	2.433	2.429	2.351	2.376	2.259	2.115
-15	2.89	2.838	2.73	2.729	2.627	2.666	2.548	2.383
-10	3.251	3.202	3.083	3.086	2.955	3.01	2.894	2.702
-5	3.686	3.641	3.509	3.519	3.348	3.425	3.312	3.086
0	4.219	4.182	4.033	4.052	3.831	3.936	3.827	3.558
5	4.889	4.863	4.691	4.723	4.436	4.578	4.476	4.151

COP of considered system with R152a, R600 ,R134a ,R600a ,R290 ,R410a,R1234yf and R404a varied between 1.45-4.88,1.40-4.86,1.33-4.69,1.33-4.72,1.30-4.57,1.31-4.43,1.30-4.47 and 1.12-4.15 respectively between -50 oC to 5 oC evaporator temperature.

Change of exergy loss with change in evaporating temperature for considered refrigerants

As shown in Fig. 3 exergy destructions or exergy losses decreases with increase of evaporator temperature. This is because that if evaporating temperature decreases the heat exchange between working fluid entered into the evaporator tubes and space being cooled also decreases, which finally decrease the cooling effect and therefore exergy destruction increases. Among selected refrigerants R404a (6.02-30.83 KW) and R152a (4.94-22.06 KW) shows higher and lower exergy loss for selected evaporator temperature range respectively. It was also observed that flash chamber, compressor, condenser, expansion valve, water-intercooler and evaporator are in increasing order of exergy loss for different refrigerants.

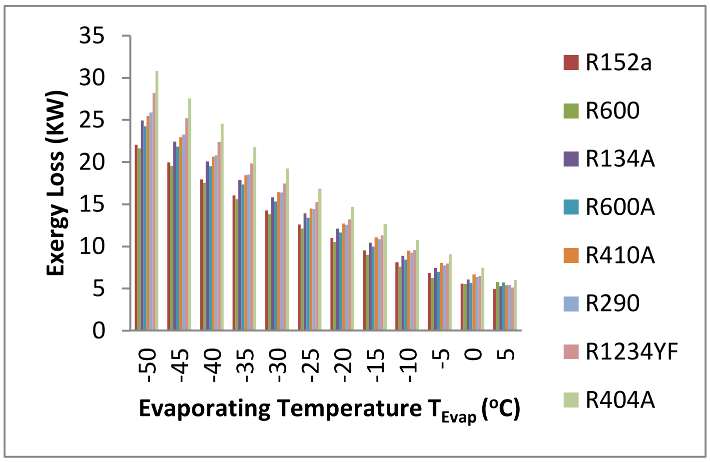

FIG 3.VARIATION OF EXERGY LOSS (KW) AT DIFFERENT EVAPORATING TEMPERATURE FOR DIFFERENT REFRIGERANTS

Change of exergy loss with change in evaporating temperature for R152a as working fluid

Fig. 4 shows the variation of exergy loss for individual component with change in evaporating temperature with R152a used as working fluid. Behaviors of exergy destruction in different components of two stage vapour compression refrigeration system for rest of refrigerants are also observed similar. Flash chamber responsible for highest and evaporator shows lowest exergy destruction compared to other components. The exergy destruction in the components increase with the decrease of evaporating temperature.Yumrutas et al. [23] observed the effect on exergy loss with change of evaporation and condenser temperature. Khan [24] studied that due to the low expansion process and compressor efficiency most of the irreversible losses occurred in the system. He also found that with increase in difference between evaporator and condenser temperatures exergy losses increases with R12, R134a, R22, and R502 used as refrigerants.

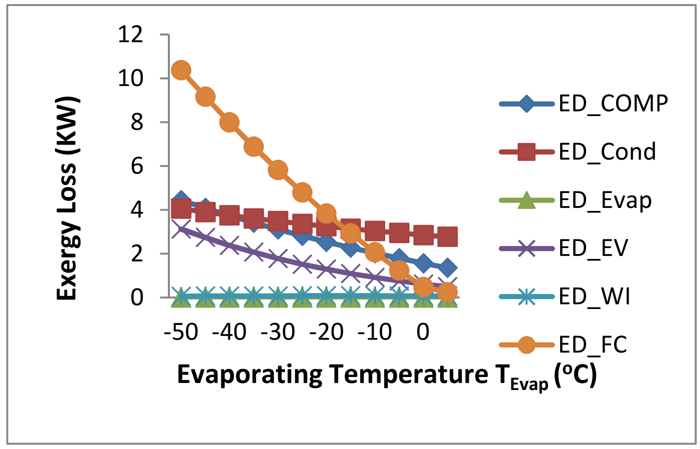

FIG 4.VARIATION OF EXERGY LOSS (KW) AT DIFFERENT EVAPORATING TEMPERATURES FOR R152A

Change of exergy loss with change in condensing temperature for considered refrigerants

It is observed from Fig. 5 that for all considered refrigerants exergy destructions increased with increase of condensing temperature. This is due to increase of temperature difference between condenser and surrounding.

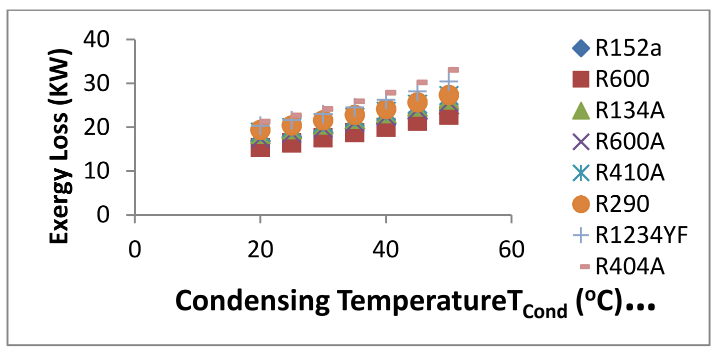

FIG 5.VARIATION OF EXERGY LOSS (KW) AT DIFFERENT CONDENSING TEMPERATURES FOR DIFFERENT REFRIGERANTS

Change of exergetic efficiency with change in evaporating temperature for considered refrigerants

It is found that exergy losses decreases with increase of evaporating temperature for considered refrigerants. Fig. 6 shows that R152a gives highest exergetic efficiency among selected refrigerants. The purpose of condenser to take out the heat produced by compressor in discharge line and carried by refrigerant during cooling effect in evaporator. This heat in refrigerant removed by transferring heat to the wall of condenser tubes due to convection and then transfer of heat due to conduction from tubes wall to surrounding.

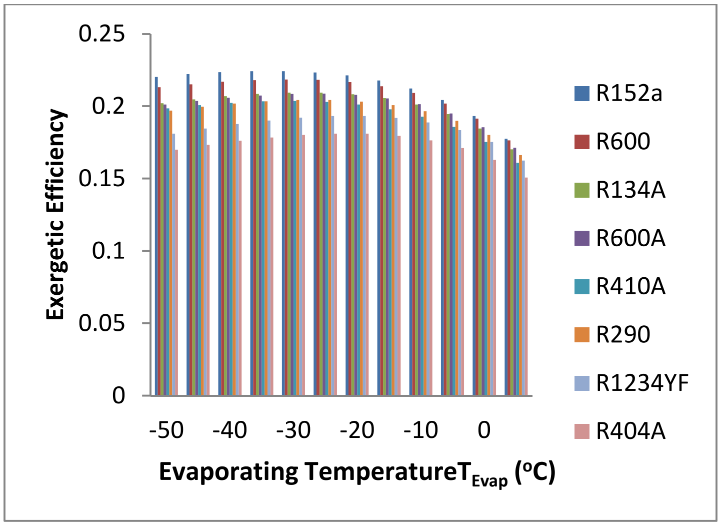

FIG 6. VARIATION OF EXERGETIC EFFICIENCY AT DIFFERENT EVAPORATING TEMPERATURES FOR DIFFERENT REFRIGERANTS

Variation of sustainability index with change in evaporating temperature for considered refrigerants

As shown in Fig. 7 with increase in evaporator temperature sustainability index increases for selected refrigerants. R152a shows higher sustainability index than R134a for selected evaporating temperature range. It is also found that R152a and R600 have higher sustainability index and low impact on surrounding compared to R134a.

CONCLUSIONS AND RECOMMENDATION

Energetic and exergetic analysis of two stage refrigeration system was carried out with different refrigerants and following conclusion and recommendation are presented below:

1. R404a shows lowest performance among selected refrigerants.
2. Exergy destruction for R134a is higher than R152a and R600 but lower than R600a, R410a, R290, R1234yf and R404a.
3. Exergetic and energetic efficiency of R152a is highest among selected refrigerants.
4. Flash chamber responsible for highest exergy destruction for all refrigerants taken under consideration.
5. Sustainability index of the R152a and R600 are higher than that of R134a at every evaporator temperature. It indicates also less environmental impact for hydrocarbons.

However the performance of R152a and R600 is higher than R134a but hydrocarbons are flammable in nature and can be used in limited applications. Therefore R134a recommended for all kind of applications.

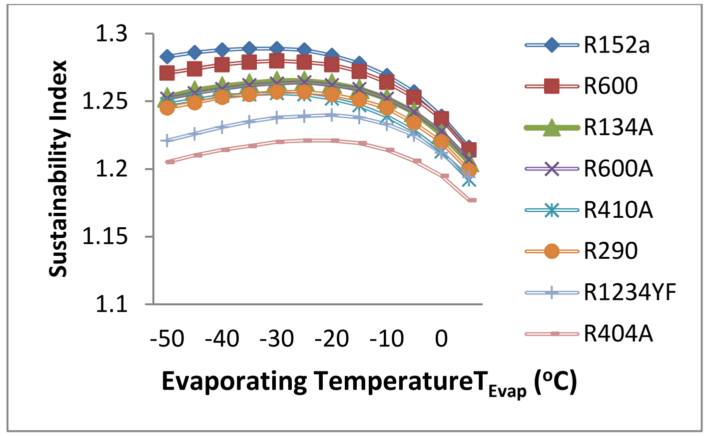

FIG 7. VARIATION OF SUSTAINABILITY INDEX AT DIFFERENT EVAPORATING TEMPERATURES FOR DIFFERENT REFRIGERANTS

NOMENCLATURE

CFC	chlorofluorocarbon	*Subscripts*	
HCFC	hydrochlorofluorocarbon	Evap	evaporator
Q	rate of heat transfer (kW)	Cond	condenser
W	work (kW)	amb	ambient conditions
T	temperature (°C)	WI	water intercooler
s	specific entropy (kJ/kgK)	H	high temperature
h	specific enthalpy(kJ/kg)	L	low temperature
$\dot{S}$	entropy (kJ/s.K)	LP	low pressure
ODP	ozone depletion potential	EV	expansion valve
GWP	global warming potential	gen	generation
m	mass flow rate (kg/s)	HP	high pressure
η	efficiency (non-dimensional)	FC	flash chamber
		ex	exergetic

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