Proceedings of the
International Conference on Mechanical Engineering and Renewable Energy 2017
(ICMERE2017) 18 – 20 December, 2017, Chittagong, Bangladesh

ICMERE2017-PI-408

IR-REVERSIBILITY ANALYSIS OF A SPLIT TYPE AIRCONDITIONER USING R600a AS REFRIGERANT

M.A. Razzaq[1*], M.M. Khan[2] and J.U. Ahamed[3]

[1,2,3] Department of Mechanical Engineering, Chittagong University of Engineering and Technology, Chittagong-4349, Bangladesh
razzaqrazcuet@gmail.com*, mzamanmehedi@gmai.com and jamal293@yahoo.com

Abstract- *In this experimental work, ir-reversibility of vapor compression air conditioning system with R600a as refrigerant was investigated using second law of thermodynamics. Polyol-ester (POE) oil was used as the lubricant in the split type air-conditioner of capacity of 1TR for the exergetic analysis. The amount of energy consumed by the compressor of the air-conditioner for R600a refrigerant was evaluated and a comparison was shown with R22. An exergetic analysis of this process was summarized to evaluate the amount of exergy destroyed by the air-conditioner components such as compressor, condenser and evaporator. It was found that maximum exergy loss occurs in the compressor portion, which was approximately 50% of total exergy loss and expansion device showed the lowest exergetic destruction. Exergy efficiency for R600a was varied from 10% to 16% for different evaporator temperature. Total exergy loss was decreased with the increase of evaporator temperature significantly. Whereas, total exergy losses were increased with the increase in condensing temperature for a given evaporator and ambient temperature. REPPROP 7 software was used to determine the properties of the refrigerants.*

Keywords: Air-conditioner, Exergy, Ir-reversibility, Exergy destruction and REPROP 7

1. INTRODUCTION

The Exergy of a system at a certain thermodynamic state is the *maximum* amount of work that can be obtained when the system moves from that particular state to a state of equilibrium with the surroundings. The thermodynamic quantity of exergy, which can be used to assess and improve energy systems, can also help better understand the benefits of utilizing “green” energy by providing more useful and meaningful information than energy alone. Exergy identifies the areas of efficiency improvements and reductions in thermodynamic losses attributable to “green” technologies. Unlike energy, exergy is not subject to a conservation law (except for ideal processes). A system in complete equilibrium with its environment does not have any exergy. The exergy of a system increases the more as it deviates from the environment.

It is reported that the vapor compression refrigeration systems release large amount of heat to the surroundings. As a result of difference in temperatures between the system and the surroundings, irreversibility takes place. This irreversibility degrades the performances of the system components. Losses in a component should be measured to improve the performance of the whole system. The losses in the cycle need to be evaluated considering individual thermodynamic processes that make up the cycle. In evaluating the efficiency of the vapor compression refrigeration system, the most commonly used term is the coefficient of performance (COP), which is related to the first law of thermodynamics. But the first law of thermodynamics does not distinguish between heat and work. It cannot be used to identify the sources of thermodynamic losses in a thermodynamic cycle. The first law gives no information on how, where, and how much the system performance is degraded. On the other hand, second law of thermodynamics can be used to identify and quantify the thermodynamic losses in a cycle. Using the concept of irreversibility, thermodynamic losses (i.e., exergy losses) in vapor compression refrigeration cycle can be measured.

Hydrocarbons can be used in the existing air-conditioning equipment as a replacement for the conventional refrigerants and are compatible with mineral or synthetic oil. In some cases, no changes in the hardware configuration of the equipment are needed. Hydrocarbons are environmentally friendly and found to have zero ozone depletion potential (ODP) and lower global warming potential (GWP) too. Hydrocarbons are cheaper than R-22 and easily available. Most of the hydrocarbons offer good miscibility with mineral oils and good compatibility with common materials employed in the air-conditioning equipment. The Kyoto Protocol [1] encourages the reduction of GWP including the regulations of hydro fluorocarbons. Table 1 represents the physical and environmental data for selected refrigerants. From the table it is clear that R600a (isobutene) refrigerants have the zero ODP and lowest GWP.

Table 1: Physical and environmental properties of refrigerants.

Refrigerant	Boiling point (˚C)	Critical Temperature (˚C)	ODP	GWP
R-14	-127.9	-45.56	0	7390
R-12	-29.8	112	1	10900
R-11	-23.71	197.96	1	4750
R-502	-45.56	82.2	0	1300
R-13	-81.48	28.85	10	14400
R-404A	-46.5	72.1	0	3922
R-507	-46.7	70.9	0	3900
R-600a	-11.7	134.7	0	3

Fatouh and Kafafy [2] evaluated the possibility of using HCs mixtures as working fluid to replace R134a in domestic refrigerators. In their simulation analysis, the performance characteristics of domestic refrigerators were predicted for various working fluids such as R134a, propane, commercial butane, and propane/isobutane/n-butane mixtures with various propane mass fractions. They found that pure butane has low COP and high operating pressures. J.U. Ahamed et. al. [3] investigated experimentally the influence of HC refrigerants on a vapor compression refrigeration system based on exergetic performance. They concluded that exergy loss for butane and isobutene was lesser than that of the refrigerant R134a. For higher evaporating temperature exergy loss was decreased for all refrigerants. Exergy efficiency was also higher for butane compared to that of isobutene and R-134a as refrigerants. Exergy loss in the compressor was higher than that in the other parts of the system i.e. up to 69% of the total exergy loss occurs in the compressor. Reddy *et al.* [4] studied numerically on a vapor compression refrigeration system using R134a, R143a, R152a, R404A, R410A, R502 and R507A and reported the influence of evaporator temperature, degree of sub-cooling at condenser outlet, superheating of evaporator outlet, vapor liquid heat exchanger effectiveness and degree of condenser temperature on COP and exergetic efficiency. They concluded that evaporator and condenser temperature have significant effect on both COP and exergetic efficiency and also found that R134a has the better performance while R407C has poor performance in all respect. Venkataiah *et al.* [5] presented the simulation of a 1.5-ton capacity room air conditioning system with some selected refrigerants having their suitability as alternative refrigerants to R22 for air conditioning system. The refrigerants with zero Ozone depletion potential refrigerants R22, R134a, R404A, R407C, R410A, R507A, R290 and R600a considered their analysis. They used COOLPACK software for the analysis of thermodynamic properties. The analysis mainly focused on obtaining results of parameters like heat rejection rate, mass flow rate of refrigerant, displacement volume, power input, discharge temperature, COP, saturation pressure and pressures ratio with fixed condenser temperature and with variable evaporator temperatures. Arcaklioglu et al. [6] calculated rational efficiency and component based irreversibility ratios of a cooling system depending on the second law of thermodynamics using HFC and HC-based pure refrigerants, such as, R32, R125, R134a, R143a, R152a, R290, R600a and their binary and ternary mixtures, along with R12, R22 and R502 (i.e. CFCs). Park and Jung [7] have investigated thermodynamic performance of two pure HCs and seven mixtures composed of propylene (R1270), propane (R290), HFC152a and dimethyl ether (RE170) as an alternative to R22 in residential air conditioners. They have made some tests and results have showed that the COP of these mixtures is up to 5.7% higher than that of R22. Said and Ismail [8] assessed the theoretical performances of R123, R134a, R11 and R12 as coolants. It was established that for a specific amount of desired exergy, more compression work is required for R123 and R134a than R11 and R12. The differences are not very significant at high evaporation temperatures and hence R123 and R134a should not be excluded as alternative coolants. Also, in their study they obtained an optimum evaporation temperature for each condensation temperature, which yields the highest exergetic efficiency. Aprea and Renno [9] studied experimentally, the performance of a commercial vapour compression refrigeration plant, generally adopted for preservation of foodstuff, using R22 and its candidate substitute (R417A) as working fluids. The working of the plant was regulated by on/off cycles of the compressor, operating at the nominal frequency of 50 Hz, imposed by the classical thermostatic control. The reported result indicated that the substitute refrigerant (R417A), which is a non-azeotropic mixture and non-ozone depleting, can serve as a long term replacement for R22; it can be used in new and existing direct expansion R22 systems using traditional R22 lubricants. Also in their analysis, the best exergetic performances of R22 in comparison with those of R417A were determined in terms of the coefficient of performance, exergetic efficiency and exergy destroyed in the plant components. Khalid [10] studied the performance analysis of R22 and its substitute refrigerant mixtures R407C, R410A and R417A on the basis of first law. It was found that the COP of R417A is 12% higher than R22, but for R407C and R410A, COP is 5% lowered as compared to R22, and R417A can be used in existing system without any modification.
There is no general rule governing the selection of refrigerants, however there are of course the five classic criteria and those are:

- Thermos-physical properties
- Technological
- Economic aspects
- Safety
- Environmental factors

No refrigerant is ideal, but the desirable characteristics of "ideal" refrigerants are considered to be:

- Normal boiling point below 0°C
- Non-flammable
- Non-toxic
- Easily detectable in case of leakage
- Stable under operating conditions

- Easy to recycle after use
- Relatively large area for heat evaporation
- Relatively inexpensive to produce
- Low environmental impacts in case of accidental venting
- Low gas flow rate per unit of cooling at compressor

Though ideal refrigerant doesn't exist, we required to compare our refrigerant with these ideal characteristics. If a refrigerant has some properties close to these ideal characteristics is appropriate for our experimental work. This work aims at increasing COP and exergy efficiency (EE), and decreasing the ir-reversibility at different components and total ir-reversibility of the air-conditioner. In this work, COP, ir-reversibility at the process that make the cycle, total ir-reversibility and EE are reported compared for different operating condition of the condenser and the evaporator using R600a refrigerant.

2. MATERIALS AND METHODS

2.1 Description of Experimental Setup and Instrumentation

Figure 1 represents the schematic diagram of the experimental setup. A split type air-conditioner was used in the experimental process and the compressor was hermitically sealed. The experimental setup consists of compressor, condenser, expansion valve and evaporator. The lubricating oil used was Polyol-ester (POE) oil. Refrigerants was charged through the inlet port. A mega digital electronic scale was used to measure the weight of the refrigerant accurately. Approximately 700gm of the refrigerant was used for the experimental analysis. In this test rig a split-type air conditioner was installed. The main loop of the system under study consists of five basic components (compressor, evaporator, condenser, capillary tubes and liquid line filter-drier) as shown in Figure 1.

The experimental setup was located in a closed psychometric loop. To measure the inlet and outlet temperature of the compressor two digital thermometer was installed. The other two thermometer was used to measure the inlet and outlet temperature of condenser and evaporator respectively. The HIOKI True-RMS Clamp Meter was used to measure the power consumption by the compressor. It was used to read the voltage (volt), currents (amp), resistance and continuity which need to calculate the power (kW) that had been consumed by the air-conditioner unit during running with different refrigerants.

Precision thermometer with an accuracy of ±0.01˚C is used to measure the room temperature. To know the condition of the room a hygrometer is set in the room to detect the atmospheric condition i.e. relative humidity, dry bulb and wet bulb temperature. In this experiment suction and discharge temperature is important. The air conditioner was instrumented with two pressure gauges at the inlet and outlet of the compressor.

The power consumption and the readings of the temperature sensor and pressure gauge are taken within some intervals during day time. Data was taken for three days for different ambient temperatures.

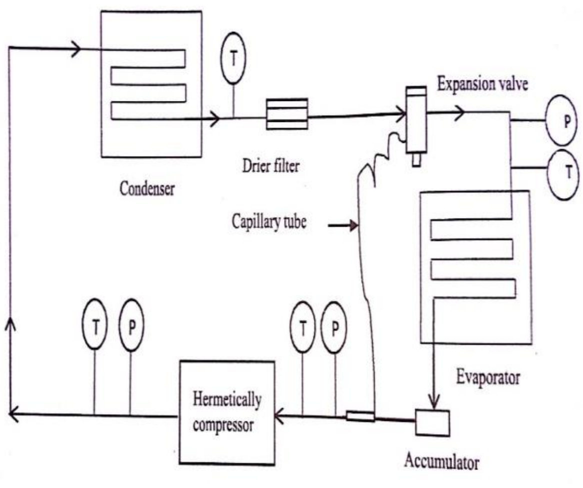


Fig. 1: Schematic diagram of experimental setup.

2.2 Mathematical Formulation

Mathematical formulation for exergy analysis in different components can be arranged in the following way,

Specific ir-reversibility at any state is given by

$$\psi_i = (h_i - h_0) - T_0 (s_i - s_0) \quad (1)$$

For evaporator,

$$I_{ev} = \dot{m}\,[(\psi_4 - \psi_1) + Q_{ev}\left(1 - \frac{T_0}{T_{ev}}\right)$$
$$= \dot{m}[(h_4 - h_1) - T_0 (s_4 - s_1)] + Q_{ev}\left(1 - \frac{T_0}{T_{ev}}\right) \quad (2)$$

For compressor, Compressor work

$$W_c = \dot{m}(h_2 - h_1) \quad (3)$$

Electrical power,

$$W_{el} = \frac{W_c}{\eta_{mech} \times \eta_{el}} \quad (4)$$

Thus,

$$I_{comp} = \dot{m}[(\psi_1 - \psi_2) + W_{el}$$
$$= \dot{m}[(h_1 - h_2) - T_0 (s_1 - s_2)] + W_{el} \quad (5)$$

For condenser,

$$Q_{cond} = \dot{m}(h_2 - h_3) \quad (6)$$

$$I_{cond} = \dot{m}[(\psi_2 - \psi_3) + Q_{cond}\left(1 - \frac{T_0}{T_{cond}}\right)$$
$$= \dot{m}(h_2 - h_3) - T_0 (s_2 - s_3) + Q_{cond}\left(1 - \frac{T_0}{T_{cond}}\right) \quad (7)$$

In expansion device,

$$I_{exp} = \dot{m}T_0[(\psi_4 - \psi_3) \quad (8)$$

Total Ir-reversibility,

$$I_{total} = I_{ev} + I_{comp} + I_{cond} + I_{exp} \quad (9)$$

Exergetic efficiency,

$$\eta_{exergy} = \frac{\psi_4 - \psi_1}{W_{el}}$$
$$= \frac{(h_4 - h_1) - T_0 (s_4 - s_1)}{W_{el}} \quad (10)$$

Here h and s represents enthalpy and entropy of the vapor compression cycle at different condition of the refrigerants. The enthalpy and entropy of the refrigerants was determined at different temperature and pressure using REPPROP 7 package software. Figure 2 shows the p-h diagram of the vapor compression system used for the air conditioner.

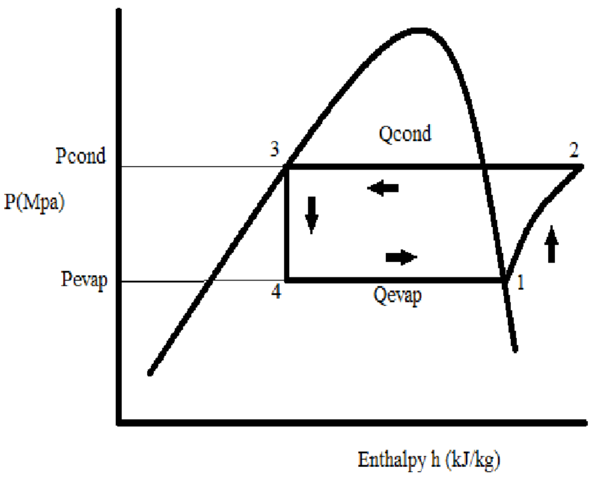


Fig. 2: P-h diagram of a VCR system

3. Results and Discussion

3.1 Power Consumption

Data was collected for three consecutive days and for three different temperatures. Data was taken for a twenty minute time interval. Power consumption was varied with day time because the outside or ambient temperature changed with different day. Data was collected for R22 and R600a refrigerants. The variation of power consumption is represented in the Figure 3. It is observed from the figure that, power consumption is higher for R22 refrigerants for different ambient temperature.

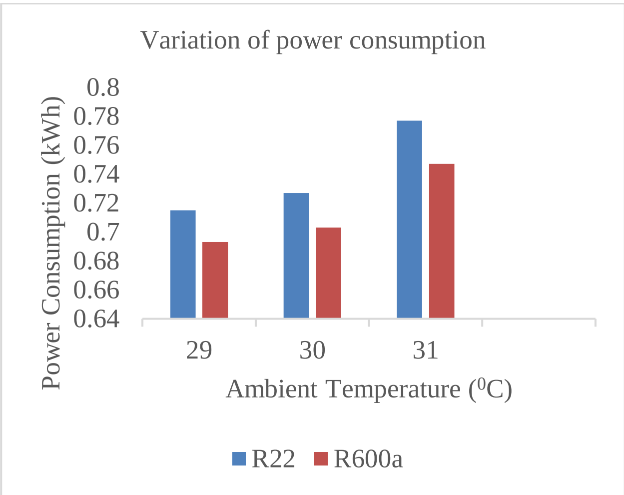


Fig. 3: Variation of power consumptions

3.2 Coefficient of Performance

The average COP for different environmental condition was compared for R22 and R600a refrigerants. It was found that, COP increased up-to 184% for R600a refrigerant compared with R22. Figure 4 shows a graphical presentation of the COP of the refrigerants. It was also found that, COP decreased with the increase of ambient temperature. Table 2 shows the variation of COP with the ambient temperature.

3.3 Ir-reversibility at the process

Total ir-reversibility at the process is the summation of total ir-reversibility occurred in the components of the air-conditioner. Figure 5 shows the ir-reversibility occurred in the different components of the air-conditioner for different ambient temperature. From the figure, it can be concluded that, compressor is the highest exergy destroying components in the air-conditioner unit. Ir-reversibility destruction is minimum for the expansion device for the air-conditioner. In the compressor, ir-reversibility was maximum at an ambient temperature of 31^0C.

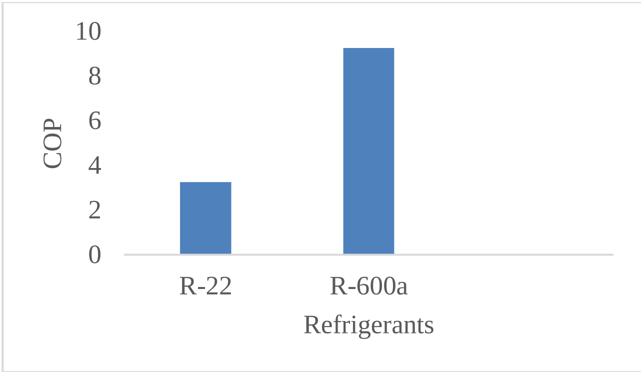


Fig. 4: Variation of COP

Table 2: Average COP for different ambient temperature

Date	Ambient temperature (^{0})	Average COP	COP decreased, %
Day 1	31	9.26	
Day 2	30	11.75	26%
Day 3	29	10.56	14%

The variation of total exergy associated with different evaporator temperature in the process is illustrated in Figure 6 (a), (b) and (c) for different ambient temperature. In every case, total exergy decreased as the increment of evaporator temperature. Exergy efficiency (EE) denotes the exergetic performance of the system. Figure 7 (a), (b) and (c) shows the variation of EE with the evaporator temperature for different ambient temperature. From the Fig.7, it is apparent that, EE decreased with the change of evaporator temperature for every ambient temperature. Figure 5 indicates that compressor destroys maximum amount of exergy which is about 50% of the total exergy of the process. Expansion device destroys minimum amount of exergy comparing with other components in the air-conditioner.

Table 3 shows the percentage of exergy destroyed in the compressor section for different ambient temperature. As the ambient temperature decreases, contribution of compressor to the total exergy reduced as the total exergy.

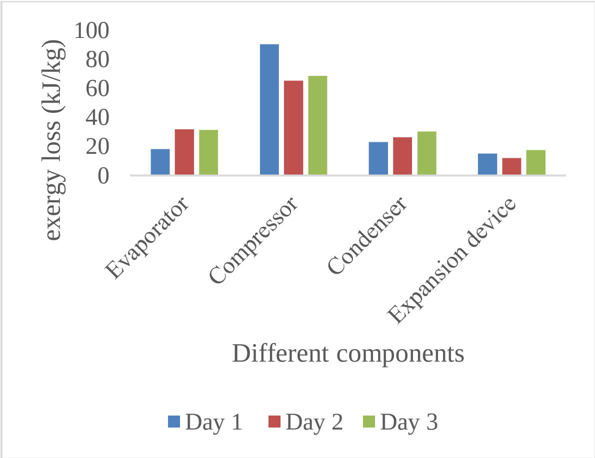
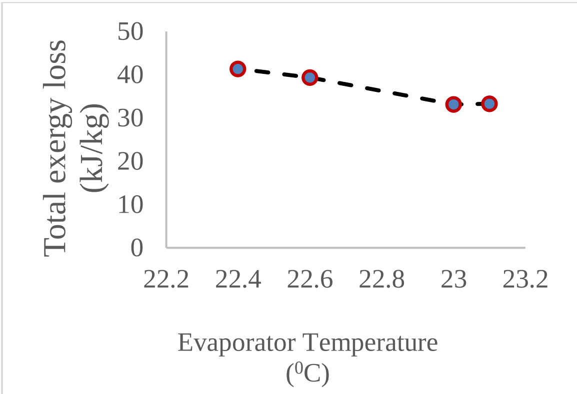
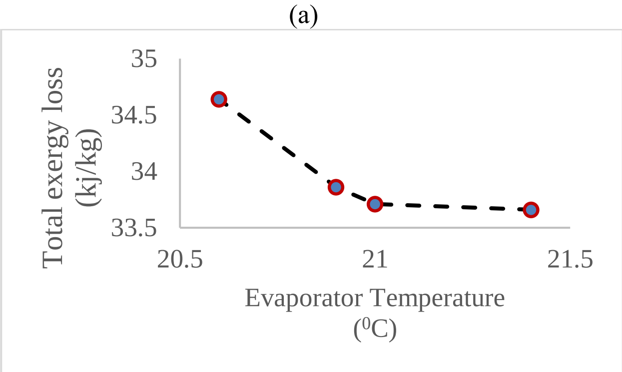


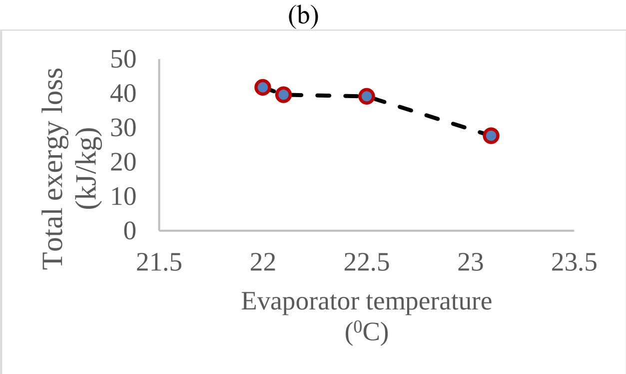
Fig. 5: Variation of exergy loss for different components of a refrigerating system in different ambient temperature.



(a)

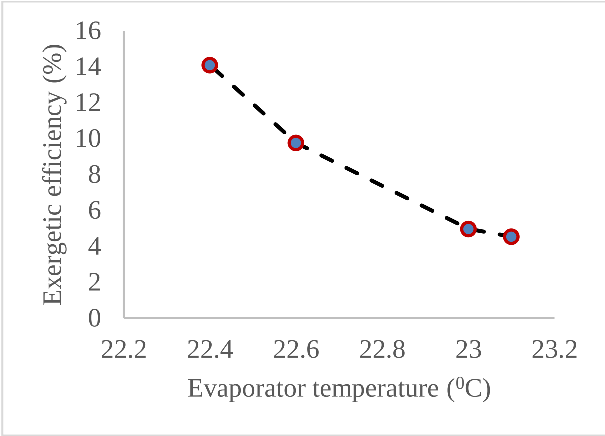


(b)

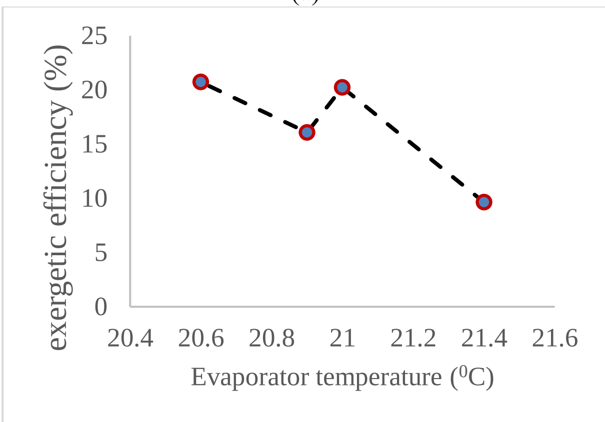


(c)

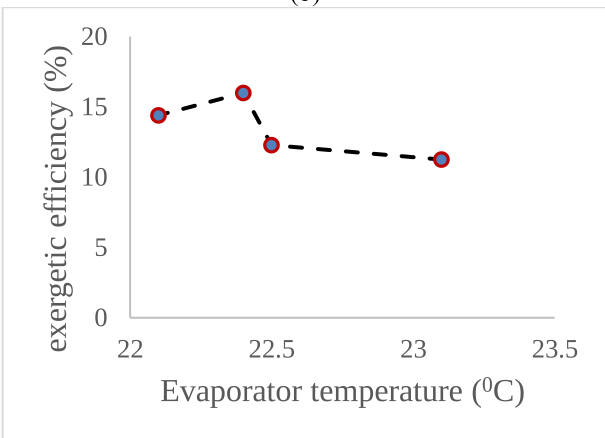
Fig. 6: Variation in total exergy loss with evaporator temperature for ambient temperature of (a) 31^{0}C (b) 30^{0}C and (c) 29^{0}C.



(a)



(b)



(c)

Fig. 7: Variation of exergetic efficiency with evaporator temperature for ambient temperature of (a) 31^{0}C (b) 30^{0}C and (c) 29^{0}C.

Table 3: Percent of exergy loss in compressor

Ambient temperature	Total exergy loss (kJ/kg)	Compressor exergy loss (kJ/kg)	Contribution of compressor (%)
31	147.1	90.49	61.33%
30	135.42	65.42	48.3%

29	148	68.47	47%

4. Conclusion

In this study an ideal vapor-compression refrigeration system is considered for performance comparison of R600a in different ambient temperature. Hydrocarbon is considered as the most suitable refrigerant for air conditioners due to its zero ODP, low GWP and availability. Although hydrocarbons and their mixtures have some flammability problems, but they have better energy performance (COP) and high cooling capacity as well as exergy efficiency compared to the CFC/HCFC refrigerants. HC mixtures are miscible with both mineral oil and synthetic lubricants. From this research work, the following conclusion can be summarized:

- Energy consumption rate for R600a is much lower than R22
- The COP is increased with the increase of evaporator temperatures for any ambient temperature. It is observed that a small fluctuation is occurred in COP for different ambient temperatures.
- Total ir-reversibility are decreased with the increase of evaporator temperature significantly.
- Total exergy losses increase with the increase in condensing temperature for a given evaporator and ambient temperature.
- Exergy efficiency decreases with increase in evaporator temperature at any given ambient temperature.
- Most exergetic components of a refrigerating system is compressor and minimum exergy loss happen in expansion device. Over 50% exergy loss occur in compressor for R600a.

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6. NOMINCLATURE

Symbol	Meaning	Unit
T_0	Ambient temperature	^0C
h	Enthalpy	kJ/kg
s	Entropy	kJ/K
$\dot{m}$	Mass flow rate	kg/s
P	Pressure	bar
Ψ	Specific exergy	
Q_{cond}	Condenser refrigeration capacity	kW
Q_{ev}	Evaporator refrigeration capacity	kW
η_{exe}	Exergy efficiency	%
I_{ev}	Evaporator ir-reversibility	kJ/kg
I_{comp}	Compressor ir-reversibility	kJ/kg
I_{cond}	Condenser ir-reversibility	kJ/kg
I_{exp}	Expansion device ir-reversibility	kJ/kg
I_{total}	Total ir-reversibility	kJ/kg