International Journal of Automotive and Mechanical Engineering
ISSN: 2229-8649 (Print); ISSN: 2180-1606 (Online);
Volume 14, Issue 2 pp. 4125-4139 June 2017

DOI: https://doi.org/10.15282/ijame.14.2.2017.2.0331

Performance and exergetic investigation of a domestic split air conditioner using blends of R22 and R290

M.F. Raiyan[1], J.U. Ahamed[1*], M.M. Rahman[2] and M.A. Salam[1]

[1]Department of Mechanical Engineering, Chittagong University of Engineering and Technology, Chittagong-4349, Bangladesh
[1*]Phone: +8801720-641636, +88031-714935; Fax: +88031-714910
[*]Email: jamal293@yahoo.com
[2]Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600, Pekan, Malaysia
Email: mustafizur@ump.edu.my

ABSTRACT

In this article, the mechanical performance and exergy of a one-ton split type air conditioning system by using the mixture of two different refrigerants of different proportions have been investigated. It has become necessary to find an alternative of Chlorodifluoromethane (R22) as it has high ODP (Ozone Depletion Potential) and GWP (Global Warming Potential). Propane (R290) has a lower ODP and GWP and in this project, it was considered with R22 for making different blends. Here, two different mixtures of R22 and R290 (respectively), were prepared and denoted as X_6 and X_7. After conducting a test run for several hours, evaporator temperature, condenser temperature, compressor suction and discharge pressure, and enthalpy at different points (obtained from REFPROP) were measured. By using experimentally obtained data, power consumption and Coefficient of Performance (COP) were calculated for different refrigerants. Different characteristic graphs were drawn establishing relation among various parameters. It was found that during the same observation period, the mixture X_6 and X_7 consumed less electric power than R22. Moreover, the COP was also found to be higher for X_6 and X_7 than that of R22. Finally, total exergy destruction in all components was calculated for different refrigerants and comparative analysis was made.

Keywords: Power consumption, coefficient of performance, R22; R290; exergy.

INTRODUCTION

Globally, R22 is used as a refrigerant in most air conditioning systems for its suitable properties such as stability, non-toxicity, non-flammability [1-4] and good thermodynamic properties [5]. The general cause of ozone layer depletion is that Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs) which are a large class of chlorine containing chemicals, migrate to the stratosphere where they react with the ozone [6]. Many investigations have been conducted so far to observe the impact of chlorine-based refrigerants. These researches included a study on CFC generation and its use as well as a recommendation for phasing out the harmful refrigerant [7]. Besides, its emission, environmental impact, and concentration in the atmosphere due to leakage were also studied [8-11]. The partially halogenated HCFCs are bound to be prohibited in the near future. Researchers are working to identify alternative refrigerants which will be less harmful and hazardous to the protective ozone layer. Researches have already shown that hydrocarbons are a good alternative to existing refrigerants. As the search for alternative refrigerants are going on around the world, the current research work aims to investigate the performance as well as exergy of a domestic air conditioning system by using R290 in different proportions with the existing R22. Due to the temperature difference between the system and surroundings, irreversibility takes place. This irreversibility degrades the performance 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. The most commonly used term for evaluating the performance of a vapour compression cycle is the coefficient of performance (COP), which is related to the first law of thermodynamics [3, 12]. However, the first law of thermodynamics fails to distinguish between heat and work. It is unable 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, the second law of thermodynamics can be used to measure degradation of available work. By using the idea of irreversibility, thermodynamic losses can be measured. These losses are also called exergy loss. It is the maximum amount of work produced by a system as it comes to the equilibrium of a reference temperature [13-16].

Many investigations have been conducted so far to study the performance of air conditioning systems by using different types of refrigerants [17-21]. Arora et al. [5] carried out an investigation of actual vapour compression refrigeration cycle in terms of COP, energy destruction and energy efficiency for R22, R407C and R410A by developing a computational model. The results showed that COP and energy efficiency for R22 were higher in comparison to R407C and R410A. It was concluded that R410A is a better alternative compared to R407C with high coefficient of performance and low energy destruction ratio when considering refrigeration applications. For air conditioning application, R407A is a better option than R410A. Ramu et al. [22] has theoretically assessed R22 and the mixtures composed of R32, R125, and 600a as alternative refrigerants. The energy performance assessment of the air conditioner was made for three different condensing temperatures such as 35, 45, and 55°C with evaporator temperatures between −10 and 10°C. The assessment was made in terms of standard energy performance parameters such as COP, compressor power consumption, compressor discharge temperature, and volumetric cooling capacity (VCC). Navarro et al. [23] observed the performance and oil circulation rate of commercial reciprocating compressors of different capacities working with propane (R290) as a refrigerant. This experimental investigation included five R407C positive displacement hermetic reciprocating compressors, covering different capacities, displacement, stroke-to-bore ratios and number of cylinders, which have been characterized using propane as refrigerant by means of a specifically designed characterization test rig. In a study on heat pump performance by Park et al. [24], R170/R290 mixture was used in an attempt to substitute R22. It was observed that for R170/R290 mixture, the COP decreases and the capacity increases with an increase in the amount of R170. The mixture of R170/R290 (by mass, 4:96) shows a similar capacity and COP as those of R22. From the study, it was concluded that R170/R290 mixture is a good long term ‘drop-in’ candidate from the viewpoint of energy efficiency and greenhouse warming to replace R22 in residential air-conditioners and heat pumps [25]. Palm [26] reviewed on hydrocarbons as refrigerants in small heat pumps and refrigeration systems. A major point was found from the review and it was revealed that using hydrocarbons will result in COP equals to, or higher than those of similar HFC systems. It was also shown that components suitable for hydrocarbon systems are available in the market, even though the number of large-size hermetic compressors is limited.

Advantages and problems including their solutions were provided by Xuanfei [27] while using only R290 as the sole substitute of R22. Necessary measures were taken according to the thermo-physical properties of R290 to minimize the risk. It was seen that the photochemical smog produced by R290 was relatively lower than other hydrocarbons which are considered as prospective alternatives of R22. Greco et al. [28] exhibited the results of an experimental study with a smooth, horizontal, stainless steel tube on pressure drop during horizontal flow boiling of refrigerants R22, R507, R404A, R134a, R407C and R410A. The steel tube (6mm dia.) was uniformly heated by Joule effect with constant evaporating pressure of 7.0 bar varying the mass flux in the range 280–1,080 kg/m^2 s. The experimental comparison showed that the pressure drop of R22 was significantly higher compared to all the other fluids. The results were compared against well-known pressure drop prediction methods. Farraj et al. [29] investigated the performance of a one-ton split air conditioning unit designed to use R22 as a refrigerant. They used Liquefied Petroleum Gas Mixture (LPGM) of 30% propane, R290 and 70% butane, R600, (weight ratio) for the replacement of CFCs and HCFCs like R22. For powering the air conditioning unit, a photo voltaic array of 12 modules was used. The voltaic array generated power with the help of an electric generator. Considering the changes of evaporation temperature and condensing temperature, they compared COP, cooling capacity, power consumption of the compressor, heat rejection, and mass flow rate of refrigerant and found that LPGM has a lower COP than R22 but has a higher refrigeration effect, lower mass rate of flow, lower compressor exit temperature, and lower power consumption.

Experimental investigation of domestic refrigerator with hydrocarbons (isobutene and butane) and their energy as well as exergy analysis were performed by Ahamed et al. [30]. They arrived at the results that energy efficiency ratio of hydrocarbons is comparable with R134a but exergy efficiency and sustainability index of hydrocarbons are much higher than that of R134a at considered evaporator temperature. It was also found that compressors showed the highest system defect (69%) among components of considered system. Jabaraj et al. [31] analysed the possibility of using R407C/R290/R600a refrigerant mixture as a substitute for R22 in a window air conditioner and to evolve an optimal composition for the mixture. The experiments for the mixtures containing 10, 15, 20, and 25% R290/R600a blend (by weight) in R407C were referred as M10, M15, M20, and M25, respectively. Among the mixtures, M20 was characterized with maximum refrigeration capacity. It was observed that the improvement in refrigeration capacity of M20 mixture was 9.54 to 12.76% higher than R22 at various condenser inlet air temperatures. It was also observed that among the mixtures, M20 had the lowest power consumption which is 1.25 to 1.45% higher than R22. Exergy analysis of a heat pump using water and air was done by Cakir et al. [32]. They found the highest compressor exergy efficiency while running the system in water to air mode. In that experiment, exergy analysis of all the components was performed using four different modes (water to water, air to water, air to air, and water to air). Superiority of R413A over R12 from an exergetic point of view was investigated by Padilla et al. [33]. Parameters and factors affecting the performance of both refrigerants were evaluated using an exergy analysis. 12 tests (six for each refrigerant) were carried out in a controlled environment during the selected cooling process from evaporator outlet temperature from 15°C to 10°C. The evaporator and condenser air-flows were modified to simulate different evaporator cooling loads and condensers ventilation loads. The overall energy and exergy performance of the system working with R413A was consistently better than that of R12. The main aims of this article were to investigate the mechanical performance by calculating power consumption, COP, pressure ratio, refrigerating effect as well as thermodynamic performance evaluation based on 2nd law analysis (exergy analysis). Condenser temperature and evaporator temperature were recorded with high precision as exergy loss depends on them [34].

METHODS AND MATERIALS

A one-ton split type air conditioner was used for this experiment with R22 as the main refrigerant. The setup was instrumented with pressure gauges (P) and K-type digital thermocouples (T). Two thermocouples (ranging between −20°C and 200°C) were placed at the inlet and outlet of the compressor in order to measure temperature of the working fluid along with two pressure gauges for measuring inlet and outlet pressure. Two types of pressure gauges were used. The low-pressure gauge with three-way valve has a range of 0 to 220 psi and high-pressure gauge can measure from 0 to 500 psi. Another thermocouple was placed at the outlet of condenser for recording temperature in that position. Finally, the instrumentation of the setup was completed by placing a pressure and a temperature measuring device in between expansion valve and evaporator inlet. A precision multimeter (±0.5% accuracy) recorded current consumption in ampere along with main power line voltage. Ambient condition was recorded with a room thermometer and a digital hygrometer recorded relative humidity, dry bulb, and wet bulb temperature. Major components and complete instrumentation of the setup is illustrated in Figure 1.

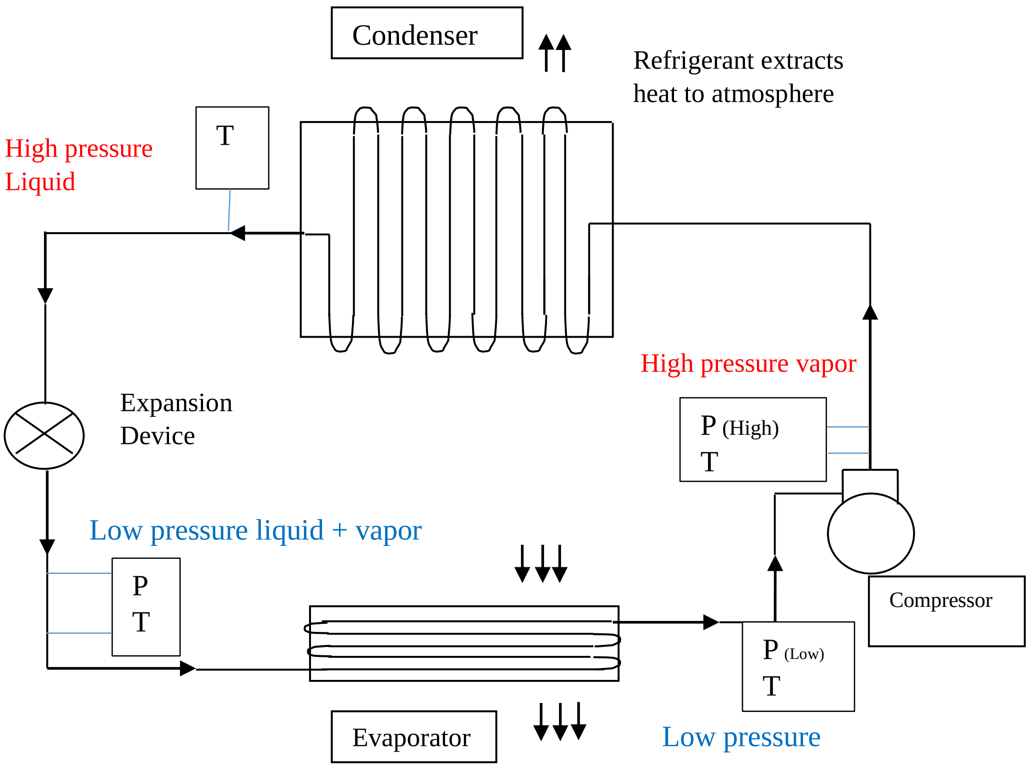

Figure 1. Schematic diagram of experimental setup.

The system can be charged with a total amount of 700 gm refrigerant. During the first test run, the air conditioner was operated solely by using R22. After collecting experimental data (power consumption, pressure and temperature), the system was evacuated for charging with new refrigerants prepared from the blend of R22 and R290. A vacuum pump was used to remove all refrigerants from the closed loop. Two different blends were prepared. The first blend (X_6) had the ratio of R22 (595 gm) and R290 (105 gm) as (85:15) by weight. For the blend X_7, the amount was 630 gm and 60 gm, respectively for R22 and R290. A digital weight scale was used for accurately maintaining the weight of the refrigerants. Figure 2 illustrates the charging of refrigerants into the system.

Figure 2. Experimental setup in laboratory and refrigerant charging system.

MATHEMATICAL MODELLING AND DATA COLLECTION

For calculating coefficient of performance (COP), pressure ratio, power consumption, refrigerating effect and exergy, several governing equations were used.

Governing Equations

Vapour-compression refrigeration system uses a circulating liquid refrigerant as the medium which absorbs and removes heat from the space to be cooled and subsequently rejects that heat outside. REFPROP 7 software was used to determine different thermo-physical properties of the mixtures (in this case Enthalpy) based on experimentally collected data (pressure and temperature) at different points.

The actual coefficient of performance is an important parameter and it can be calculated by using Eq. (1).

$$(COP)_{actual} = \frac{h_1 - h_4}{h_2 - h_1} \tag{1}$$

where,

$h_1 - h_4$ = Refrigerating effect; $h_2 - h_1$ = Compression work.

Theoretically, coefficient of performance can be measured by Eq. (2) which can be derived when the evaporator and condenser temperatures are known.

$$(COP)_{theoretical} = \frac{T_{evaporator}}{T_{condenser} - T_{evaporator}} \tag{2}$$

Pressure ratio is an important parameter during the investigation of an air conditioning system. It is the ratio of compressor outlet (P_c) to the inlet pressure (P_e). In other words, it is the ratio of condenser pressure to evaporator pressure. High compression ratio indicates that compressor has to work more to lift the pressure for a given mass flow rate. It can be expressed as,

$$P_r = \frac{P_c}{P_e} \tag{3}$$

Mathematical formulation for exergy analysis in different components can be arranged in the following way:
Exergy content of pure substances at any state is given by,

$$\psi = (h_i - h_o) - T_o(s_i - s_o) \tag{4}$$

Where, h_0 and s_0 are the enthalpy and entropy values of working fluid at the environmental temperature (T_0), which ultimately forms the energy sink for irreversible and reversible process.
The general availability loss in each component is given by,

$$\Delta\psi = \sum m_i\psi_i - \sum m_E\psi_E - Q\left(1 - \frac{T_0}{T_i}\right) - W \tag{5}$$

The first term on the right-hand side is the sum of exergy input and second term is sum of exergy output while the third term is energy of heat Q, which was being transferred at a constant temperature, T.

The availability balances for the four processes on an input/output product basis are as follows:

Compressor: $$\psi_1 = \psi_2 - \sum q_i\left(1 - \frac{T_0}{T_i}\right) - W_{in} + I_{com} \tag{6}$$

Condenser: $$\psi_2 = \psi_3 - \sum q_i\left(1 - \frac{T_0}{T_i}\right) + I_{cond} \tag{7}$$

Expansion valve: $$\psi_3 = \psi_4 + I_{exp} \tag{8}$$

Evaporator: $$\psi_4 = \psi_1 - \sum q_i\left(1 - \frac{T_0}{T_i}\right) + I_{eva} \tag{9}$$

Total exergy destruction in the system,

$$I_{total} = I_{cond} + I_{exp} + I_{evap} + I_{comp} \tag{10}$$

here, W stands for work input by the electric motor. Muhamad and Darus [35] also performed exergy analysis of an air conditioning system by using the similar mathematical model.

RESULTS AND DISCUSSION

Power consumption comparison among three different refrigerants are shown graphically in Figure 3. It is apparent that power consumption depends on atmospheric temperature. In this experiment, ambient temperature was fluctuated with environmental condition and manual steps were not taken to control it so that the precise result and exact impact of environmental temperature can be studied. According to the observed data, the power consumption for the HC blends was less than R22. With an increase in ambient temperature, evaporator needs to be cooled more than the usual time. This is why the compressor work also increased which gave rise to power consumption. Power consumption was calculated for each refrigerant with respect to ambient temperature. At 28°C, total power consumption was in the lowest position whereas it was found to be the highest at 32°C for all refrigerants and R22 almost consumed 0.8 kWh of power. From the graphical representation, it can be seen that with the rise of ambient temperature, power consumption increased and later decreased as the ambient temperature slowly dropped in the afternoon. In all cases, the blends X_6 and X_7 consumed less power than R22. Devotta et al. [36] also found that for air conditioners, 12.4 to 13.5% energy consumption is reduced using R290 instead of R22. Investigation made by Sekhar et al. [37] observed reduction in energy consumption by 4–11% while using R290 and R600 as a mixture.

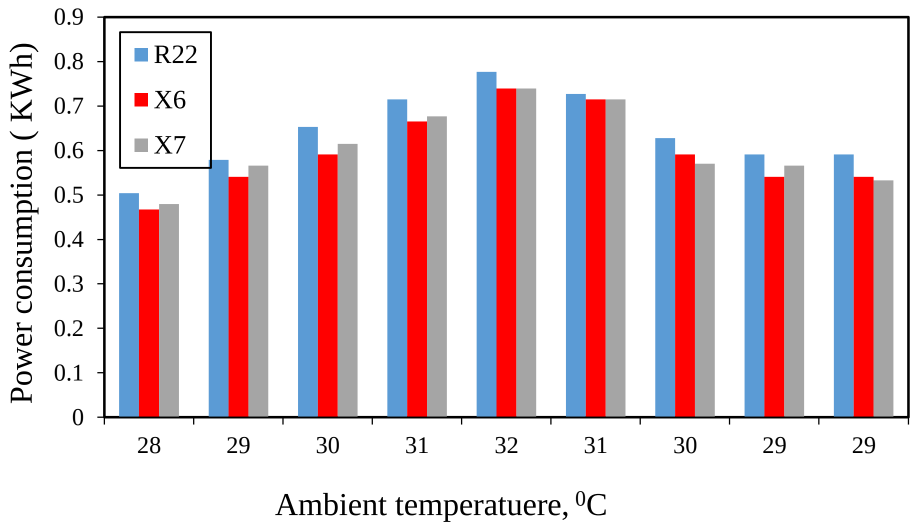

Figure 3. Variations of power consumptions using R22, X_6 and X_7 at different ambient temperatures.

The X_6 and X_7 mixtures were prepared in REFPROP 7 in order to find enthalpies at different points. From Equation (1), COP at different evaporator temperatures have been calculated for R22, X_6 and X_7. The compressor's suction and discharge pressures were different for independent refrigerants. Though they slightly deviated from each other, these deviations significantly affected the evaporator temperature and overall cooling performance. As the condensation and boiling temperature (saturation temperature) of a refrigerant rose with pressure, the heat rejection capability also improved at the same time. A graphical study between compressor's suction pressure i.e. evaporator pressure and COP is depicted in Figure 4.

The COP of the split air conditioner using R22 as a refrigerant is considered as standard and the COP of X_6 and X_7 were compared. The COP against evaporator temperature is plotted for mixture X_6, X_7, and R22 at 29°C ambient temperature. The result is displayed in Figure 5 showing a progressive increase in COP as the evaporating temperature increased. The increase in COP with an increase in evaporator temperature was steady with a moderate slope for R22. The mixtures (X_6 and X_7) have higher latent heat of vaporization than that of R22. Hence, they absorbed more heat from the controlled room. Park et al. [38] found that COP varies with the types of the refrigerants and their properties. The researchers also investigated the energy performance of R22, R290, and R1270. According to their results, R290 had the best performance. In this experiment, mixture X_6 exhibited a 3.45% rise in COP than R22 and the rise in COP for mixture X_7 was found to be 2.30% higher than that of R22. Mean evaporator temperature varied in between 6.5 to 12.5°C for R22 and it was between 9 to 13°C and 7.5 to 12.9°C for X_6 and X_7, respectively.

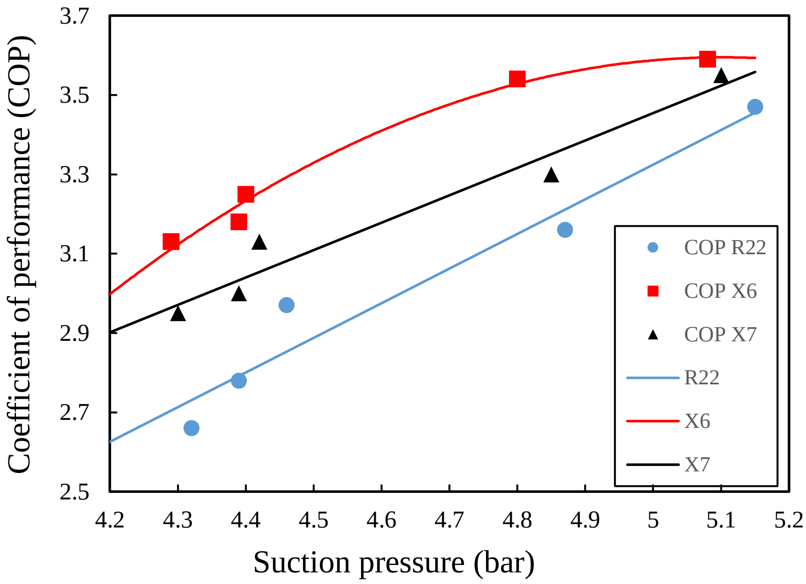

Figure 4. Variation in COP with evaporator pressure.

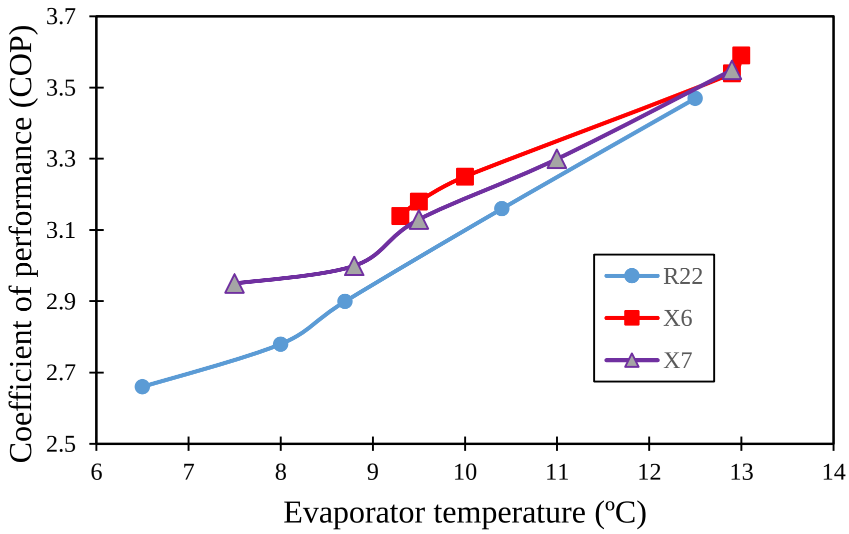

Figure 5. Change in COP with evaporator temperature.

Refrigeration effect (RE) of a vapour compression system is defined as the difference in enthalpy between evaporator inlet and outlet which can be mathematically expressed as $(h_1 - h_4)$. To observe the variation of RE along with evaporator temperature, a graph was plotted in Figure 6. At higher evaporator temperature, the enthalpy of the refrigerant is higher. Therefore, the refrigerating effect in the evaporator is higher. At the same time, it is not possible to maintain constant condenser temperature thus, the trends are not in a straight line. Figure 6 shows the variation of refrigerating effect with evaporating for refrigerant R22, X_6, and X_7. Refrigerating effect in the evaporator depends not only on evaporator temperature but also refrigerant types. It was observed that the hydrocarbon mixtures had a higher refrigerating effect than R22 as the mixture contains higher latent heat of vaporisation hence it created higher refrigerating effect. Cooling capacity also increased with the use of hydrocarbons. Higher refrigerating effect indicates higher cooling capacity of the refrigerant. It also enhances the energy performance of the vapour compression system. Refrigerating effect of R22 varied between 120 KJ/kg to 140 KJ/kg whereas for the blends (X_6 and X_7), it varied between a short range of 135 KJ/kg to 142 KJ/kg. In all cases, the blend refrigerants gave more refrigerating effect than R22. Alternative refrigerants including R290 mixture also exhibited better refrigerating effect than R22 in an experimental investigation performed by Dalkilic et al. [39]. Refrigerating effect also increased with evaporator temperature in their research.

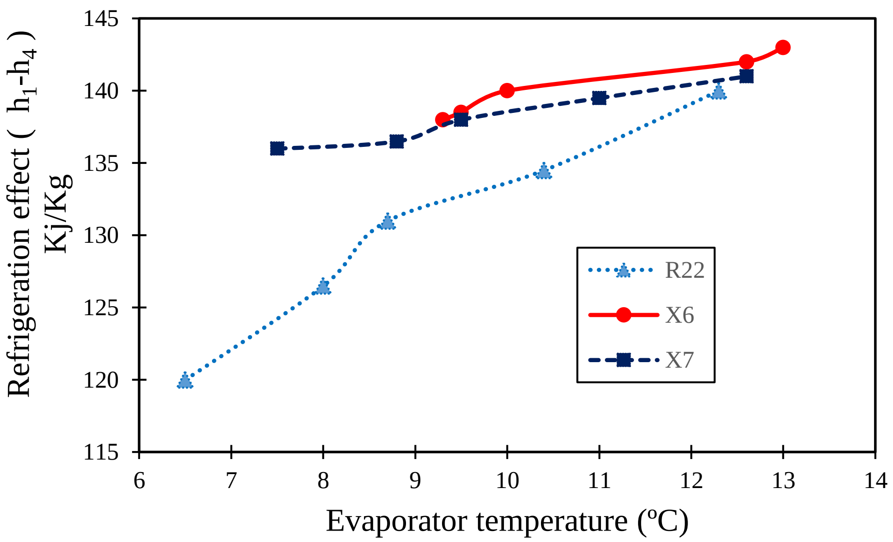

Figure 6. Change in refrigerating effect with respect to evaporator temperature.

From Eq. (3), different pressure ratio for different refrigerants were calculated. Pressure ratio is not only an important factor for choosing alternative refrigerant but also indicates the required size of the compressor [40]. Pressure ratio and compressor power consumption have a close relation with each other. Power consumption seems to increase gradually with the increase in pressure ratio. During the operation of R22, power consumption was found to be higher than others. The relation between pressure ratio and power consumption is given in Figure 7.

Effect of Mean Evaporator Temperature

Total exergy loss was obtained by Eq. (10). Figure 8 describes the variations in exergy losses with different mean evaporating temperature for different refrigerants. Exergy losses for different evaporating temperature for both the refrigerants at ambient temperature 24°C are described in Figure 8. For the refrigerant R22, the exergy losses are higher at every evaporating temperature than that of the refrigerant X_7. Blend X_6 experienced maximum exergy loss during the experiment. The downward trend shows the decrease in exergy loss with an increase in evaporator temperature. According to the obtained data and plotted graph, it can be seen that blend X_7 has better exergetic efficiency than R22 based on thermodynamic analysis.

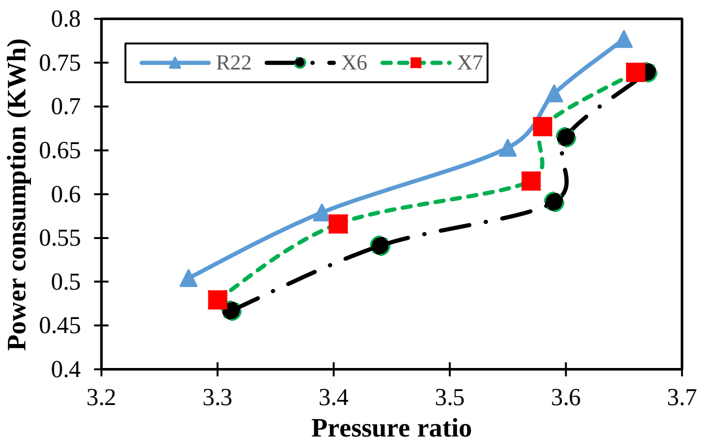

Figure 7. Relationship between power consumption and pressure ratio.

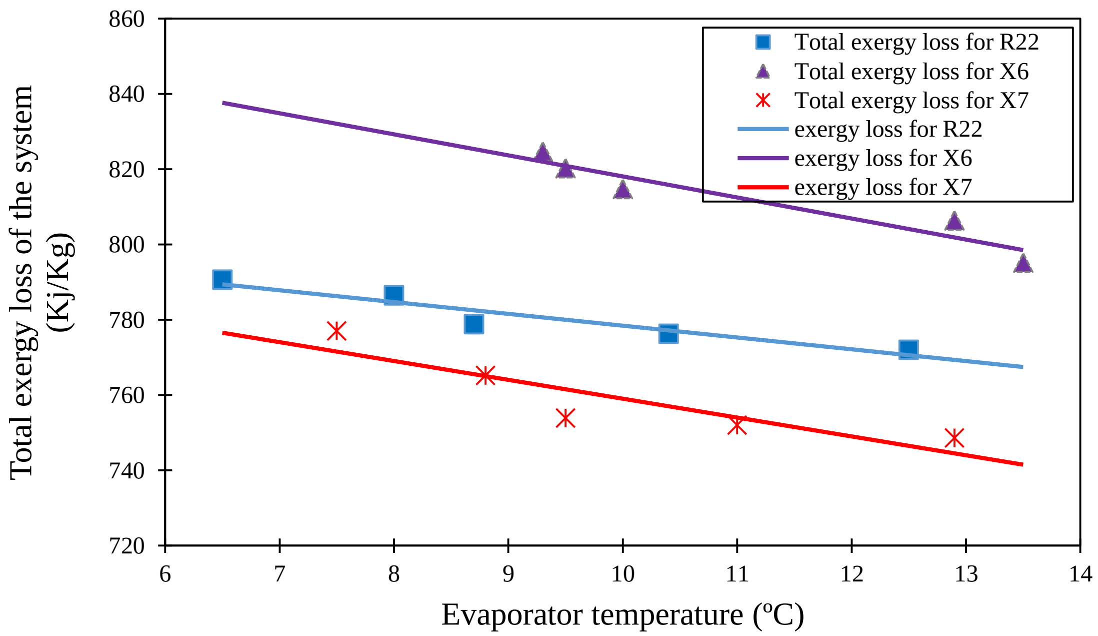

Figure 8. Change in exergy loss with evaporator temperature.

The effect of condenser temperature on exergy loss is given in Figure 9. Exergy loss increased with an increase in condenser temperature. For all refrigerants, total irreversibility rate increased with the increase of condensing temperature. As the difference between ambient and a specific component becomes higher, it increases the possibility of irreversibility and as a result, the net amount of available work is reduced thus giving rise to exergy loss. The difference of the evaporator and ambient temperatures was very small. Thus, changes in exergy losses were mainly dependant on the condensing temperature. Kalaiselvam et al. [41] also found that with the increase of condensing temperature, exergy losses increased and exergy efficiency decreased for all the refrigerants. The effect of condenser is very important when it comes to the energy conservation issue. Even the flow through the condenser can play a crucial role while investigating the performance of an air conditioning system [42]. Bhatkar et al. [43] used R290 with R600a as a drop-in substitute to R134a while using micro channel condenser. Condenser capacity was increased by 185.4% and refrigeration capacity increased by 140.8%. Finally, it was suggested to use the mixture of R290 and R600a (50:50) instead of R134a in conventional automobile and household air conditioning as well as refrigeration system.

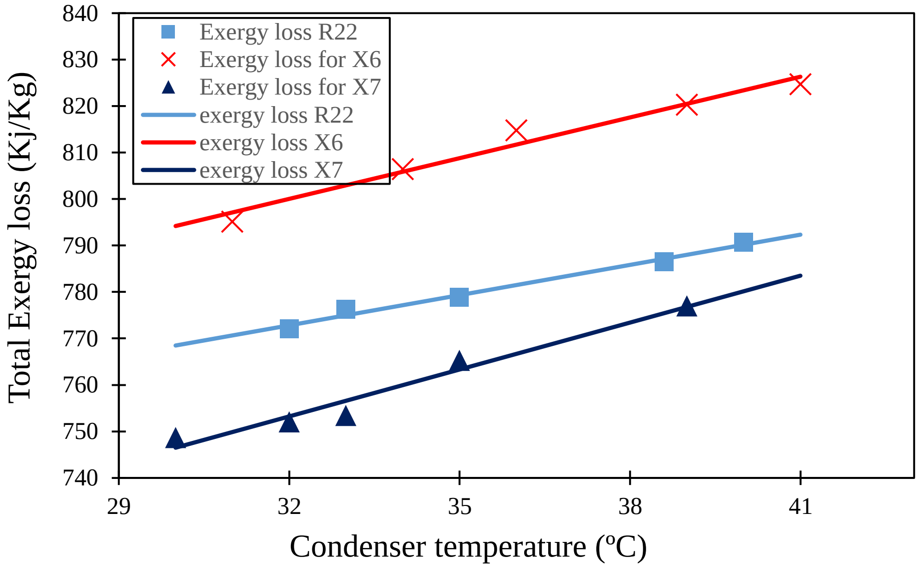

Figure 9. Exergy loss developing with condenser temperature.

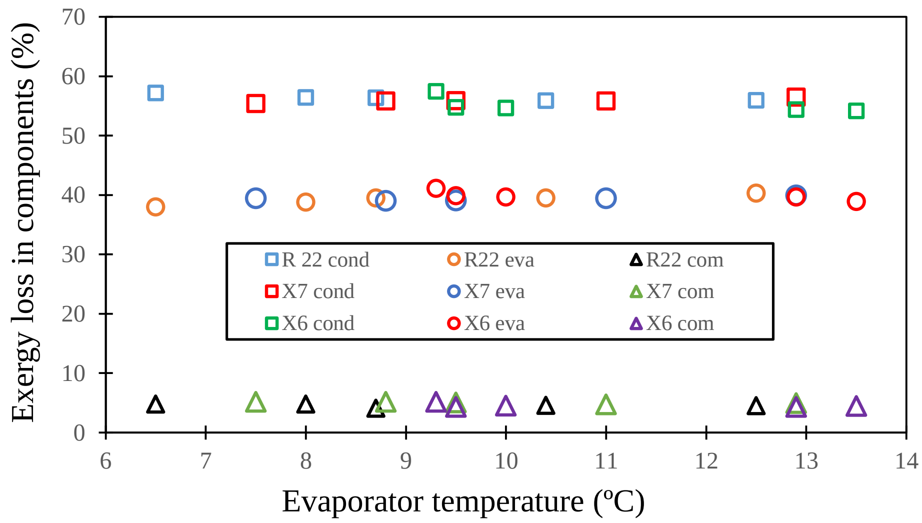

Figure 10. Percentage exergy loss in various components with evaporator temperature.

Exergy destruction depends on evaporator temperature as well as the temperature of other components in the system. The inlet temperature was higher for condenser than other components. Due to higher finite temperature difference, exergy loss in condenser was more significant than compressor, evaporator, and expansion valve. Similar result was found by the investigation made by Singh et al. [44]. Friction pressure drop also gives rises to irreversibility in condenser and evaporator [45]. Condenser and evaporator together account for the majority portion of exergy loss in the cycle with approximately 50% and 40%, respectively. At the capillary tube, the exergy losses seem to be the lowest (almost negligible). Similar results are found from the study of Yumrutas et al. [34] where the highest amount of exergy loss was found in the condenser. A comparative graphical study has been made in Figure 10.

CONCLUSIONS

In this study, a one-ton air conditioner's performance run by R22, X_6, and X_7 have been investigated. Based on the obtained and calculated data as well as graphical illustrations, mixtures prepared by using hydrocarbon (X_6 and X_7) consumed less power than R22. Power consumption of the blend X_6 was 6.37% lower than R22, and X_7 consumed 4.31% less power than that of R22. X_6 has higher coefficient of performance at all conditions than R22 and X_7. Blend X_6 has 3.46% superiority over R22 in terms of COP whereas X_7 showed 2.30% better mechanical performance than R22. The refrigerating effect (RE) of the mixture X_6 is higher than all other refrigerants in this experiment. At 13°C evaporator temperature, X_6 showed the highest cooling capacity which was 142 KJ/kg. COP was found to increase with evaporator temperature for all the refrigerants. With the increase in pressure ratio, power consumption increased gradually. R22 consumed more power than the blends X_6 and X_7 for almost the same pressure ratio. Maximum exergy destruction was found for mixture X_6 which was 5.78% and 4.12% higher than X_7 and R22, respectively. The blend X_7 exhibited least exergy destruction among the three refrigerants which is better from a thermodynamic point of view.

ACKNOWLEDGMENTS

This research was financially supported by Directorate of Research and Extension of Chittagong University of Engineering and Technology (Project number: REC69/731) and conducted in heat engine laboratory under Mechanical Engineering department.

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