Exergy Performance Assessment of R152A as Possible Alternative to R134A in A Domestic Refrigeration System

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Abstract- *In this work, the exergy performance assessment of a domestic refrigeration system has been theoretically assessed with R152a as an alternative refrigerant to R134a. The exergy performance assessment of the refrigerator was made for three condensing temperatures 40oC, 50oC and 60oC with evaporator temperatures between -30oC and 5oC.The assessment was made in terms of standard exergy performance parameters such as exergetic efficiency, exergy destructions, efficiency defect, exergy performance coefficient and EDR in the system. The overall efficiency defect in the refrigeration cycle working with R152a is consistently better than that of R134a. It has also been found that at higher evaporating temperatures, the exergy losses are minimal for the refrigerants in the four components. The results indicate that the exergetic efficiency for R152a is higher in comparison with R134a. The results confirmed that the new refrigerant is an Exergy efficient and environment friendly alternative to R134a in domestic refrigerators.*

Keywords- R134a, R152a, domestic refrigeration system, exergy performance

I. INTRODUCTION

For the past half century, chlorofluorocarbons (CFCs) have been used extensively in the field of refrigeration due to their favorable characteristics. In particular, CFC12 has been predominantly used for small refrigeration units including domestic refrigerator/freezers.

Thermodynamic processes in refrigeration systems release large amount of heat to the environment. heat transfer between the system and the surroundings environment takes place at a finite temperature difference. Which is a major source of irreversibility for the cycle. Irreversibility causes the system performance to degrade. The losses in the cycle need to evaluate considering individual thermodynamic processes that makeup the cycle. First law analysis is still the most commonly used method in the analysis of thermal systems. The first law is only concerned with the conservation of energy and it gives no information on how? Where? And how much the system performance is degraded. Exergy analysis is powerful tool to design, optimization and performance evaluation of energy systems. The principle and methodologies of exergy analysis are well established. An exergy analysis is usually aimed to determine the maximum performance of the system and identify the energy destruction. Identifying the main sites of exergy destruction shows the direction for potential improvements an important of exergy analysis for the systems that consume work such as refrigeration, liquefaction of gases and distillation of water is finding the minimum work required for the certain desired results.

An examination of thermodynamic principles reveals that the current focus on exergy conservation as a strategy is at best incomplete and at worst wholly incorrect. As it is converted from one form to another, energy is neither lost nor destroyed, it does however, lose a certain quality which can be described as its ability to do work. Since it is the ability of energy to do work which gives energy its value to society. We should strive to conserve available work (Exergy) not energy.

An exergy analysis or second law analysis is a very powerful way of optimizing complex thermodynamic systems. In vapour compression refrigeration cycle an exergy analysis can be used to identify which components of the system are responsible for irreversibity or lost work and developments can then be directed at those components.

II. LITERATURE REVIEW

Since the advent of the Montreal Protocol, as the CFC12 has high ODP and GWP the refrigeration industry has been trying to find out the best substitutes for ozone depleting substances.[1] For a past decade, HFC134a has been used to replace CFC12 used in refrigerators and automobile air conditioners. HFC134a has such favorable characteristics as zero ozone depleting potential (ODP), non-flammability, stability, and similar vapor pressure to that of CFC12. A recent survey, however, showed that the performance of HFC134a in refrigerators with a proper compressor and lubricant is quite comparable to that of CFC12. In 1997 the Kyoto protocol was agreed by many nations calling for the reduction in emissions of greenhouse gases including HFCs.[2] Since the Global warming potential (GWP) of HFC134a is relatively high (GWP1300) and also expensive, the production and use of HFC134a will be terminated in the near future. The research and development in the field of Refrigeration and Air-Conditioning apply to the use of natural refrigerants is not only associated with the need to preserve the environment itself, but also has g reat importance in the latent need for enhanced efficiency energy equipment. Such a feature is observed in Decision XIX/6 of the Montreal Protocol.

An exergy analysis is usually aimed to determine the maximum performance of the system and identify the sites of exergy destruction. Exergy analysis of a complex system can be performed by analyzing the components of the system separately. Identifying the main sites of exergy destruction shows the direction for potential improvements [3].Therefore, exergy analysis identifies the margin available to design more efficient energy systems by reducing inefficiencies. Exergy analysis permits many of the shortcomings of energy analysis to be overcome. Exergy analysis is useful in identifying the causes, locations and magnitudes of process inefficiencies. There has been little analysis about exergy for vapour compression refrigeration using R152a.

B.O.Bolagi, M.A.Akintunde, and T.O.Falade investigated experimentally the performance of three zero ODP HFC refrigerants (R32, R134a and R152a) in a vapour compression refrigerator and compared the results obtained. The results show that the COP of R152a was 2.5% higher than that of R134a and 14.7% higher than that of R32 [4].

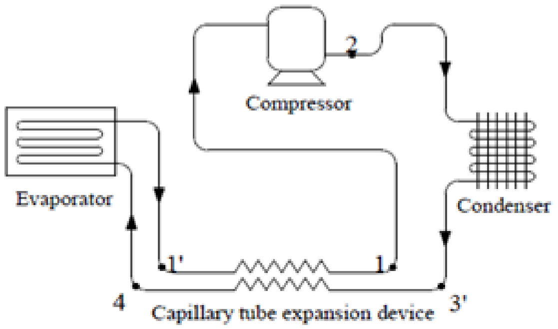
B.O.Bolagi et al. investigated theoretically the energy performance of two zero ODP refrigerants (R152a and R600a) in a vapour compression refrigeration system as alternative to R134a and compared the results obtained. The results showed that the vapour pressure and specific volume of R152a are very close to those of R134a. R152a emerged as the most energy efficient with average Power Per Ton of Refrigeration (PPTR) of 10.6% less than that of R134a.The average COPs obtained for R152a and R600a were 13.4% higher and 5.4% lower than that of R134a, respectively. Generally, R152a performed better as R134a substitute in that it has the lowest PPTR, highest thermal conductivity, refrigerating effect, VRC and COP[5].

Bolaji.B.O.(2010) Conducted an experimental study on the exergetic performance of a domestic Refrigerator using two environment friendly Refrigerants R134a and R152a as alternative to R12.The results obtained showed that the average COP of R152a was very close to that of R12 with only 1.4% reduction, while 18.2% reduction was obtained for R134a in comparison with that of R12[6]. J.U.Ahamed etl (2010) conducted a comparative study on thermodynamic performance of R600 and R600a as refrigerant. This study shows that the exergy efficiency is higher for butane compared to that of isobutene and R134a as refrigerant [7].Limited researches have been performed on exergy analysis of the vapour compression refrigeration system using R152a. It is found that the refrigerant has greater advantage on the basis of energy and other environmental impacts. Now it has become necessary to know the exergy performance as well as energy performance of the low GWP refrigerant compared to existing refrigerant R134a.

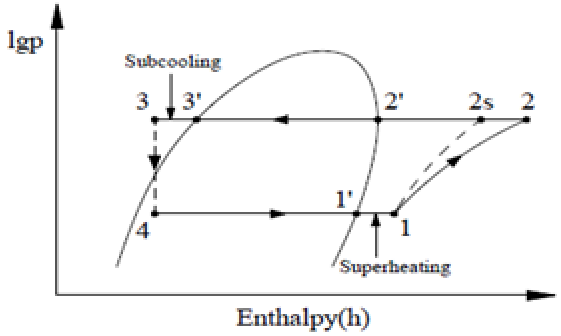
The literature survey is based on the study of R134a replacement and exergetic analysis. Most of the performance analysis of refrigeration system is investigated using an energy approach based on the first law of thermodynamics (i.e. by means of coefficient of performance). The energy analysis deals with only quantity of energy and it does not give the information that how, where and how much the performance of the system degrade. Thus, modern approach to process analysis required to use the exergy analysis which provides the more realistic view of the process.

Thermodynamic analysis

A schematic diagram of a vapor compression refrigeration cycle used in domestic refrigerators and its pressure enthalpy diagram with liquid sub cooling and vapor superheating are depicted in the in Fig. 1 a and b, respectively. The domestic refrigerators are using capillary tube expansion device. Processes, 1-2, 2-3, 3-4 and 4-1 represent the various processes such as compression, condensation, expansion and evaporation, respectively. Processes 1-1′, and 3-3′ represent the superheating and sub-cooling processes, respectively. Points 1, 2, 3 and 4 represent the thermodynamic state of the refrigerant at compressor inlet (superheated vapor at evaporator pressure), compressor outlet (superheated vapor at condenser pressure), condenser outlet (sub cooled liquid at condenser pressure) and two phase fluid at evaporator pressure. The performance of the system is theoretically assessed in terms of exergy aspects based on the second law of thermodynamics.



shematic diagram of refrigerator cycle



Pressure- Enthalpy Diagram

The following assumptions are made based on the preliminary experiments with 180 liter domestic refrigerator using R134a.

i The compressor isentropic efficiency (η_{ise}) and volumetric efficiency (η_{vol}) are 0.75,
ii The compressor mechanical and motor efficiency are 0.85.
iii Compressor speed (N) is assumed as 2800 rpm,
iv Compressor stroke volume (V_{dis}) is 5 cm^3/rev.
v Sub cooling and super heating are 5°C.

The super heating and sub cooling take place in the evaporator and in the condenser, respectively and in the capillary tube.

The property values obtained from REFPROP have been used for predicting the performance of the refrigerator.

Mathematical formulation for exergy analysis in different components can be arranged in the following way. [8

Coefficient of performance (COP)

COP is defined as the ratio of refrigeration effect to the compressor work for the VCR cycle.

$$\mathrm{COP} = \frac{Refrigeration\ Effect}{Compressor\ work} \quad (1)$$

$$= Q_L/W$$

Isentropic efficiency,

$$\eta_{comp.} = \frac{W_{isen}}{W} = \frac{h_{2s}-h_1}{h_2-h_1} \quad (2)$$

Compressor:

$$\dot{E}_{x_{in}} - \dot{E}_{x_{out}} - \dot{E}_{x_{dest,1-2}} = 0$$
$$\dot{E}_{x_{dest,1-2}} = \dot{E}_{x_{in}} - \dot{E}_{x_{out}}$$
$$\dot{E}_{x_{dest,1-2}} = \dot{W} + \dot{E}_{x_1} - \dot{E}_{x_2}$$
$$\dot{E}_{x_{dest,1-2}} = \dot{W} - \Delta\dot{E}_{x_{12}}$$
$$\dot{E}_{x_{dest1-2}} = \dot{W} + m[(h_1 - h_2) - T_0(s_1 - s_2)]$$

(or)

$$\dot{E}_{x_{dest1-2}} = T_0\dot{s}_{gen_{1-2}} = \dot{m}T_0(s_2 - s_1)$$
$$\eta_{ex,comp} = \frac{W_{rev}}{W} = 1 - \frac{\dot{E}_{x_{dest,1-2}}}{W} \quad (3)$$

Condenser:

$$\dot{E}_{x_{dest,2-3}} = \dot{E}_{x_{in}} - \dot{E}_{x_{out}}$$
$$\dot{E}_{x_{dest,2-3}} = \left(\dot{E}_{x_2} - \dot{E}_{x_3}\right) - \dot{E}_{x_{QH}}$$
$$= \dot{m}[(h_2 - h_3) - T_0(s_2 - s_3)] - \dot{Q}_H\left(1 - \frac{T_0}{T_H}\right)$$

(or)

$$\dot{E}_{x_{dest,2-3}} = T_0\dot{S}_{ger_{2-3}} = \dot{m}T_0\left(s_3 - s_2 + \frac{q_H}{T_H}\right)$$
$$\eta_{ex,cond} = \frac{E_{x_{QH}}}{E_{x_2} - E_{x_3}} = \frac{Q_H\left(1 - \frac{T_0}{T_H}\right)}{m[h_2 - h_3 - T_0(s_2 - s_3)]}$$
$$\eta_{ex,cond} = 1 - \frac{\dot{E}_{x_{dest2-3}}}{\dot{E}_{x_2} - \dot{E}_{x_3}} \quad (4)$$

Expansion valve:

$$\dot{E}_{x_{dest3-4}} = \dot{E}_{x_{in}} - \dot{E}_{x_{out}}$$
$$\dot{E}_{x_{dest3-4}} = \dot{E}_{x_3} - \dot{E}_{x_4} = \dot{m}[(h_3 - h_4) - T_0(s_3 - s_4)]$$
$$\dot{E}_{x_{dest,3-4}} = T_0\dot{S}_{gen_{3-4}} = \dot{m}T_0(s_4 - s_3)$$
$$\eta_{exp.valve} = 1 - \frac{E_{x_{dest,3-4}}}{E_{x_3} - E_{x_4}} \quad (5)$$

Evaporator:

$$\dot{E}_{x_{dest,4-1}} = \dot{E}_{x_{in}} - \dot{E}_{x_{out}}$$
$$\dot{E}_{x_{dest.4-1}} = -\dot{E}_{x_{QL}} + \dot{E}_{x_4} - \dot{E}_{x_1}$$
$$\dot{E}_{x_{dest,4-1}} = \left(\dot{E}_{x_4} - \dot{E}_{x_1}\right) - E_{x_{QL}}$$

$$= \dot{m}[(h_4 - h_1) - T_0(s_4 - s_1)] - [-Q_L(1 - \frac{T_0}{T_L})]$$

$$= \dot{m}[(h_4 - h_1) - T_0(s_4 - s_1)] + Q_L(1 - \frac{T_0}{T_L})$$

(Or)

$$\dot{E}_{x_{dest,4-1}} = T_0\dot{S}_{gen,4-1} = \dot{m}T_0\left(s_1 - s_4 - \frac{q_L}{T_L}\right)$$

$$\eta_{exs.\ Evp.} = \frac{E_{xQL}}{E_{x_4} - E_{x_1}} = \frac{-Q_L(1-\frac{T_0}{T_L})}{\dot{m}[(h_4-h_1)-T_0(s_4-s_1)]}$$

$$= 1 - \frac{E_{x,dest4-1}}{E_{x_4} - E_{x_1}} \qquad (6)$$

Total exergy destruction in the cycle,

$$\dot{E}_{x_{dest\ total}} = \dot{E}_{x_{dest1-2}} + \dot{E}_{x_{dest2-3}} + \dot{E}_{x_{dest3-4}} + \dot{E}_{x_{dest4-1}}$$

$$\dot{E}_{x_{dest\ total}} = \dot{W} - \dot{E}_{x_{QL}} \qquad (7)$$

$$\dot{E}_{x_{QL}} = -Q_L\left(1 - \frac{T_0}{T_L}\right) \qquad (8)$$

$$\dot{w}_{min} = \dot{E}_{x_{QL}} \qquad (9)$$

The second law efficiency (or exergy efficiency) of cycle

$$\eta_{exergy} = \frac{E_{xQL}}{W} = \frac{W_{min}}{W} = 1 - \frac{E_{x_{dest\ total}}}{W} \qquad (10)$$

Exergetic performance coefficient (EPC)

EPC gives information about the total exergy destruction rate (or loss rate of availability) in order to produce a certain amount of exergy output. The EPC objective function for a VCR system is defined as the ratio of exergy output to the total exergy destruction.

$$EPC = \frac{\varepsilon}{1-\varepsilon} \qquad (11)$$

Exergy Destruction Ratio (EDR)

Exergy Destruction Ratio is the ratio of the total exergy destruction in the system to the exergy in the product.

$$EDR = \frac{ED_{total}}{EP}(or)\left(\frac{1}{\eta_{ex.}} - 1\right) = (\frac{1-\varepsilon}{\varepsilon}) \qquad (12)$$

$$EP = Q_e\left|1 - \frac{T_0}{T_r}\right| \qquad (13)$$

Efficiency Defect

Efficiency defect is defined as the ratio between the exergy flow destroyed in each component and the exergy flow required to sustain the process.

$$\delta^i = \frac{\dot{X}_i}{Wc} \qquad (14)$$

$$\Sigma\delta^i = \frac{\Sigma\dot{X}_i}{Wc} = \frac{\dot{X}_i}{Wc}$$

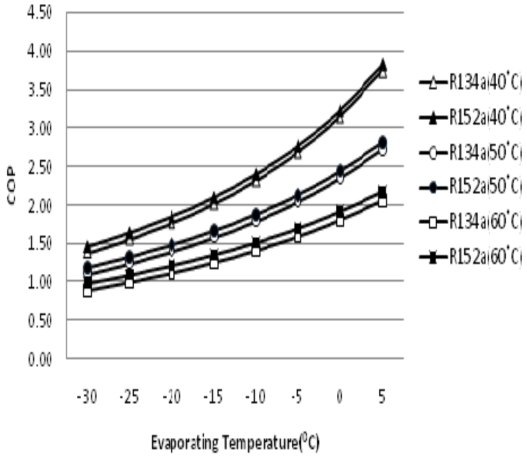
η_x=(1- $\Sigma\dot{X}_i$)*100%

(15)

III. RESULTS AND DISCUSSIONS

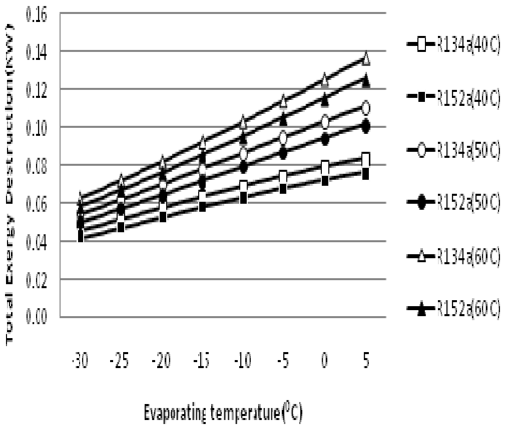
In this section, the exergy performance parameters are calculated from the results for the refrigerants using the different equations (1) - (15) and discussed. The comparison of Co efficient of performance (COP), exergy destruction, exergy efficiency, efficiency defect in different components, Exergy destruction ratio (EDR) and Exergy performance coefficient (EPC) are given below for R134a and R152a.

3.1Variation of Coefficient of performance On Evaporating Temperature



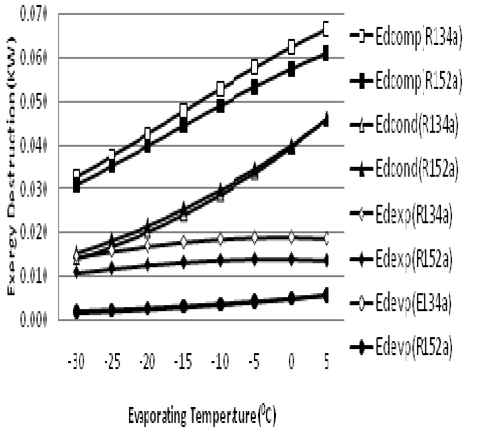
The COP of the two refrigerants is compared in Fig. 2. The COP of R152a is higher than that of R134a by about 3.60%, 5.78% and 8.62% at 40, 50 and 60°C, respectively due to its lower compressor power consumption and higher evaporator capacity. The COP of both R134a and R152a increases by about 132.58-171.51% with an increase in evaporator temperature from −30 to 5°C for the considered range of condensing temperatures.

3.2 Variation of Total Exergy Losses on Evaporating Temperature



Exergy loss increases as the temperature of the evaporator decreases as shown in Figure 3. Among the two refrigerants, R152a exhibits minimum exergy loss. The exergy loss is minimum at higher evaporating temperature, when compared to lower evaporating temperature. The average exergy loss for R152a is 8.15%, 7.82% and 7.30% at 40, 50 and 60°C, respectively lower than that of R134a. The exergy loss of both R134a and R152a decreases by about 80.85-118.49% with an increase in evaporator temperature from −30 to 5°C for the considered range of condensing temperatures

3.3 Variation of Exergy Losses on Evaporating Temperature in Different Components



Exergy losses in the individual components for Refrigerant R152a and R134a are shown in Figure 4 at condensing temperatures 40^{0}C, 50^{0}C and 60^{0}C respectively. Greater portion of exergy losses take place in the compressor. Evaporator has lower exergy losses compared to the other components.

3.4 Variation of Exergy Efficiency on Evaporating Temperature

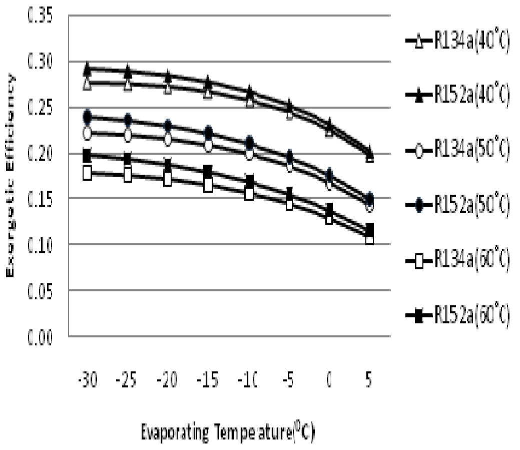


Figure 5 shows the effect of evaporator temperatures on exergetic efficiency (η_{ex}) with increases in evaporator temperature. Exergetic efficiency increases till the optimum evaporator temperature and beyond the optimum temperature decrease. The optimum evaporator is the temperature at which maximum exergetic efficiency is achieved. The increasing and decreasing of exergetic efficiency depends upon the two factors, first factor is the exergy of cooling effects i.e. Q_e (1-(T_o/T_e)). With increase in evaporator temperatures, Q_e increases while the term (1-(T_o/T_e)) reduces. Second factor is the compressor work required by compressor W which decreases with increase in evaporator temperature. The term Q_e and W have positive effect on increase of exergetic efficiency while the term (1-(T_o/T_e)) have negative effect on increase of exergetic efficiency. The combined effect of these two factors, increases exergetic efficiency increases till the optimum evaporator temperature and beyond the optimum temperature decrease. The average exergy efficiency for R152a is 8.15%, 7.82% and 7.30% at 40, 50 and 60°C, respectively higher than that of R134a.The Exergy Efficiency of both R134a and R152a increases by about 40.09-72.28% with an increase in evaporator temperature from −30 to 5°C for the considered range of condensing temperatures

3.5 Variation of Total Exergy Losses on Condensing Temperature

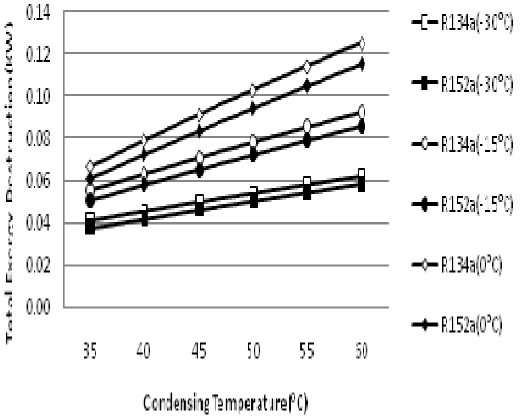
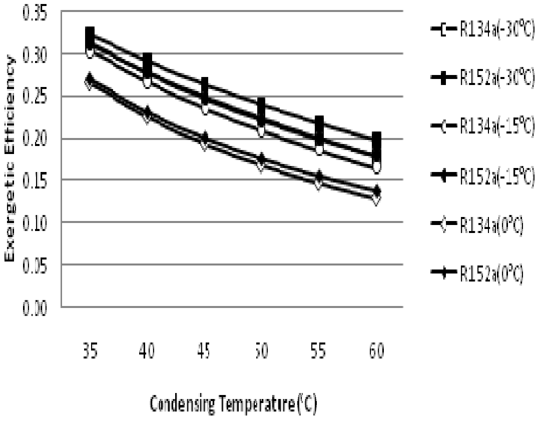


Figure 6 shows that the exergy losses are increased with the increase of condensing temperature for all the refrigerants. It is obvious because higher the temperature difference between the ambient and the component the higher the exergy losses. Availability of work is also increased. The average exergy loss for R152a is 7.02%, 7.80% and 8.46% at 40, 50 and 60°C, respectively lower than that of R134a. The exergy loss of both R134a and R152a increases by about 53.30-90.34% with an increase in condenser temperature from 35 to 60°C for the considered range of evaporating temperatures

3.6 Variation of Exergy Efficiency on Condensing Temperature



It is observed that with the increase of condensing temperature, irreversibility also increases for all the refrigerants. Variation of exergetic efficiency with condenser temperature for R152a compared with R134a is shown in Fig.7. The average exergy Efficiency for R152a is 6.98%, 5.28% and 3.85% at 40, 50 and 60°C, respectively higher than that of R134a. Exergetic efficiency decreases with increase in condenser temperature. The Exergy efficiency of both R134a and R152a increases by about 63.12-105.98% with an increase in condenser temperature from 35 to 60°C for the considered range of evaporating temperatures

3.7 Variation of Efficiency Defect in Compressor

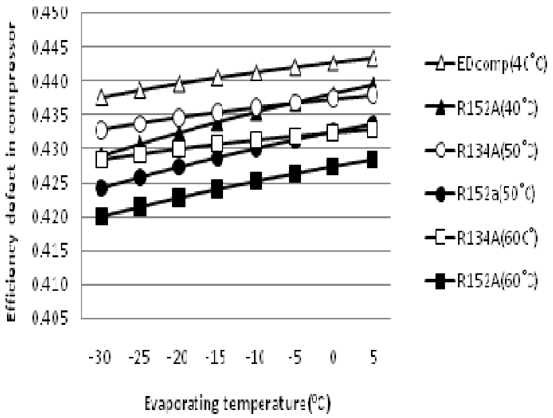


Figure 8 shows the comparison of efficiency defect in compressor for R134a with R152a varying evaporator temperature. As shown in the figure, the efficiency defect in compressor decreases with decrease in evaporator temperature exemption for R134a. The result obtained shows that the average efficiency defect in compressor is 1.41%, 1.48% and 1.50% at 40, 50 and 60°C, respectively lower for R152a respectively in comparison with that of R134a. The Efficiency defect in compressor of both R134a and R152a decreases by about 1.04-2.42% with an increase in evaporator temperature from −30 to 5°C for the considered range of condensing temperatures

3.8Variation of Efficiency Defect in Condenser

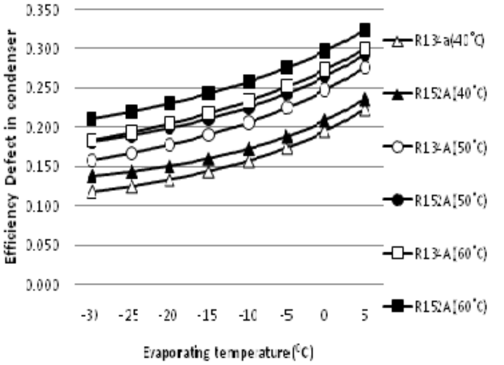


Figure 9 shows the variation of efficiency defect in condenser with evaporator temperature for R134a and R152a. As shown in the figure, efficiency defect in condenser decreases with increase in evaporator temperature. The result obtained showed that the average efficiency defect in condenser is 10.78%, 10.30% and 11.36% at 40, 50 and 60°C, respectively higher for R152a in comparison with that of R134a. The Efficiency defect in condenser of both R134a and R152a increases by about 53.06-90.55% with an increase in evaporator temperature from −30 to 5°C for the considered range of condensing temperatures

3.9 Variation of Efficiency Defect in Expansion Valve

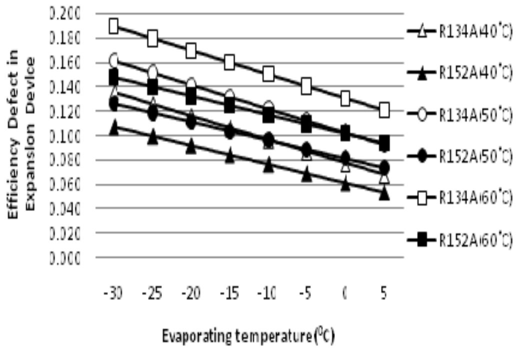


Figure 10 shows the variation of efficiency defect in expansion valve with evaporator temperature for R134a R152a. As revealed in the figure, efficiency defect in expansion valve decreases with increase in evaporator temperature. The result obtained showed that the average efficiency defect in expansion valve is 21.21%, 22.71% and 22.52% at 40, 50 and 60°C, lower for R152a respectively in comparison with that of R134a.The Efficiency defect in Expansion valve of both R134a and R152a increases by about 56.31-100.34% with an increase in evaporator temperature from −30 to 5°C for the considered range of condensing temperatures.

3.10 Variation of Efficiency Defect in Evaporator

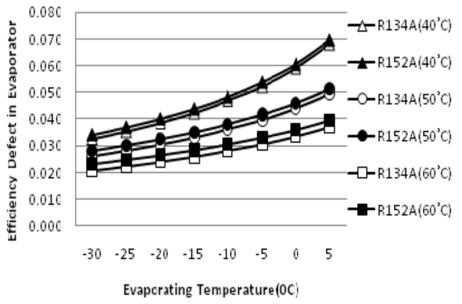


Figure 11 shows the variation of efficiency defect in evaporator with evaporator temperature for R134a and R152a. This figure revealed that the efficiency defect in evaporator decreases with decrease in evaporator temperature. The results obtained showed that the average efficiency defects in evaporator are 5.09%, 7.52% and 10.66% at 40, 50 and 60°C, respectively higher for R152a in comparison with that of R134a. As shown in Fig.12, the overall efficiency defect in evaporator is marginal in comparison with those of other components in the system (Figs.9, 10 and 11). Transferring heat at lower temperature difference can further reduce the efficiency defect in the evaporator .The Efficiency defect in Evaporator of both R134a and R152a increases by about 70.04-109.08% with an increase in evaporator temperature from −30 to 5°C for the considered range of condensing temperatures

3.11 Variation of Exergy Destruction Ratio on Evaporating Temperature

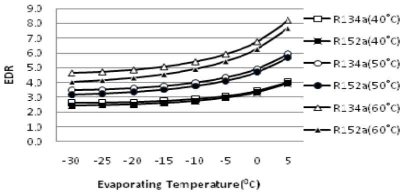


Figure 12 shows the variation of Exergy Destruction Ratio (EDR) with varying evaporator temperature for R134a and R152a. The figure shows that the EDR decreases with increase in evaporator temperature. The trend is similar for all the analyzed refrigerants. The results obtained showed that the average EDR for R152a is 8.15%, 7.82% and 7.30% at 40, 50 and 60°C, respectively lower in comparison to R134a. The Exergy destruction Ratio of both R134a and R152a decreases by about 55.49-90.17% with an increase in evaporator temperature from −30 to 5°C for the considered range of condensing temperatures.

3.12 Variation of Exergy Performance Coefficient on Evaporating Temperature

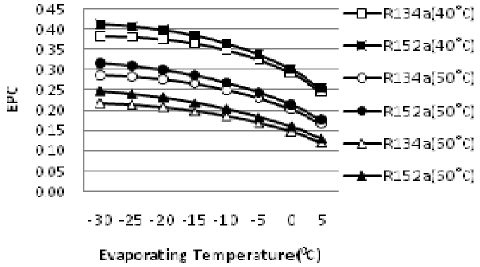


Figure 13 shows the variation of Exergy Performance Coefficient (EPC) with varying evaporator temperature for R134a and R152a. The figure shows that the EPC decreases with increase in evaporator temperature. The results obtained showed that the average EPC for R152a is 4.94%, 7.37% and 10.43% at 40, 50 and 60°C, respectively higher in comparison to R134a. The Exergy Performance Coefficient of both R134a and R152a decreases by about 55.49-90.17% with an increase in evaporator temperature from −30 to 5°C for the considered range of condensing temperatures

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