International Journal of Current Engineering and Technology
ISSN 2277 - 4106

Available at http://inpressco.com/category/ijcet

Research Article

First Law and Second Law Analysis of Mechanical Vapour Compression Refrigeration System using Refrigerants CFC12, R134a and R290

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Accepted 10 March 2014, Available online 01 April 2014, **Special Issue-3, (April 2014)**

Abstract

Thermodynamic analysis of an ideal vapour compression refrigeration system is done in this paper using refrigerants as CFC12, R134a and R290. This analysis is done by developing a mathematical model. A FORTRAN code is developed to solve the mathematical problems. Various parameters computed in this papers are compressor power, coefficient of performance of the system, total exergy loss, mass flow rate and exergy efficiency. The investigation is done within the evaporator range of 0ºC to -20ºC and condenser temperature of 30ºC to 40ºC. It is found from this investigation that performances of these two alternative refrigerants has slightly lower than the CFC refrigerant. So those two refrigerants can be used as a replacement for CFC12 in short term basis.

Keywords: *alternative refrigerants, CFC12, R134a, R290, exergy, COP.*

1. Introduction

Refrigerant is a substance which is used as a working substance in refrigeration system to move heat from lower temperature to higher temperature to get cooling effect. Midgley discovered halogenated hydrocarbon refrigerants having favorable thermodynamic properties. But these halogenated hydrocarbon refrigerants attack the atmospheric stratosphere and destroy ozone layer. With the discovery of ozone hole in stratosphere as stated by Molina and Rowland (Molina and Rowland, 1974) and the Montreal protocols (Paul, *et al* 2013), the CFC and HCFC refrigerants are to be phased out due to their higher global worming potential (GWP) and higher ozone depletion potential (ODP). For these reasons, recently ODP and GWP plays a vital role in the development of new environment friendly alternative refrigerants other than CFC and HCFC refrigerants for their higher ODP and GWP. So, develop countries stopped production of CFC and HCFC refrigerants and looking for alternative environment friendly refrigerants. So, HC and HFC refrigerants with zero ODP and low GWP are considered for long term purpose. Although the ODP of some HFCs is zero, their GWP related to the greenhouse effect is large. On the other hand, HC refrigerants have a flammability issue, which restricts the usage in existing systems. However this flammability issue can be avoided by blending HC refrigerants with HFC refrigerants. It is also found that an HC/HFC mixture makes a very good solution with mineral oil and contribution to global warming of HC/HFC mixture is very low due to very low GWP (about one third of HFC) and hence HFC134a is found to be most suitable alternative refrigerant for CFC12. Refrigerant HFC134a has very similar thermodynamic properties such as molecular weight, critical temperature, boiling point as CFC12 are shown in table 1 with zero ODP and less GWP as compared to CFC12 are shown in table 2 (Calm and Hourahan, 2001). This gave confidence to the researchers to consider HFC134a as a suitable replacement to CFC12 for short term basis.

Hammad and Alsaad (Hammad and Alsaad, 1999) investigated on domestic refrigerator using LPG (24.4% propane, 56.4% butane and 17.2 % iso-butane) as refrigerant. They concluded that this is the environment friendly refrigerant mixture and that can replace CFC12 in domestic refrigerator. Jung et al. (Jung, *et al*, 1996) investigated on domestic refrigerator using propane and iso-butane as a refrigerant mixture and found that mass fraction range of 0.2 to 0.6 of propane increase the COP up to 2.3% compared to CFC12. Mani and Selladurai (Mani and Selladurai, 2008) experimented on vapour compression refrigeration system using new refrigerant mixture of propane and iso-butane for substitution of CFC12 and R134a. They found that this mixture had a refrigeration capacity 19.9% to 50.1 % higher than R12 and 28.6% to 87.2% higher than R134a and COP improved by 3.9% to 25.1% than R12 at lower evaporator temperature and 11.8% to 17.6% at higher temperature. Chen and Prasad (Chen and Prasad, 1999) theoretically analyzed vapour compression refrigeration system using R134a and CFC12 as refrigerants and reported that the COP for R134a is slightly (3%) lower than the CFC12.

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Richardson and Butterworth (Richardson and Butterworth, 1995) experimentally investigated the performance of hydrocarbon refrigerants in a hermetic vapour compression refrigeration system and came to the conclusion that propane and propane/isobutane mixtures can be used in an unmodified CFC12 system and can achieved better COPs than CFC12 under the same operating conditions. They found that around 50% propane and 50% isobutene mixture not only just give the similar saturation characteristics but also gives a better COP when proportion of propane is increased. They also mentioned that hydrocarbon refrigerants have a flammability issue, they can be safely used in hermetic vapour compression refrigeration

The aim of this study is to investigate the performance of vapour compression refrigeration systems using R134a, CFC12 and R290 as refrigerants based on energy and exergy concept. Various parameters like COP, compressor power, exergy loss, mass flow rate of refrigerant, exergy efficiency are computed and compared in this work.

Table. 1 Properties of Different Refrigerants

Refrigerant	Molecular weight(wt)	Critical temperature (°C)	Boiling Point (°C)
R134a	102.03	101.1	-26.5
R152a	66.05	113.3	-24
R600a	58.12	134.7	-11.6
R600	58.12	152	-0.5
R290	44.1	96.7	-42.1
R717	17.03	132.3	-33.3
R744	44.01	31.1	-78.4
R507	98.9	70.9	-47.1
R12	120.93	112	-29.79
R22	86.47	96.2	-40.8
R11	137.37	23.7	198
R143A	84.04	-47.3	72.9
R718	18.02	100	373

2. Mathematical formulation

Figure 1 shows the p-h diagram of a complete ideal vapour compression refrigeration system. Various calculations are done based on this system using different refrigerants. COP of vapour compression refrigeration system is a very important criterion for performance analysis. It represents the refrigeration effect per unit compressor work.

$$COP = \frac{\text{Refrigeration Effect}}{\text{Compressor Work}} = \frac{Q}{W} \quad (1)$$

where Q is the refrigeration effect and W is the compressor work.
The compressor work, W can be expressed as

$$W = \dot{m}(h_2 - h_1) \quad (2)$$

where $(h_2 - h_1)$ is the difference of enthalpy which includes the effect of compressor efficiency and $\dot{m}$ is the mass flow rate of the refrigerants which can be expressed as

$$\dot{m} = \frac{Q}{(h_1 - h_4)} \quad (3)$$

where $(h_1 - h_4)$ is the difference of enthalpy in the cycle.

Exergy or availability of a system is the maximum obtainable work output from the system. So exergy loss is the very important criterion to evaluate the thermodynamic performance of the vapour compression refrigeration system. System performance improved if exergy loss is less. For that reason it is our aim to minimize the exergy loss to improve the system thermodynamically. The exergy can be expressed following Chen and Prasad (Chen and Prasad, 1999) as

$$e = (h - h_0) - T_0(s - s_0) \quad (4)$$

where kinetic and potential energy are excluded.
The exergy loss can be calculated by calculating exergy loss in each component of the system. Exergy loss in compressor can be expressed as

$$\Delta e_w = (h_1 - h_2) + T_0(s_2 - s_1) + w \quad (5)$$

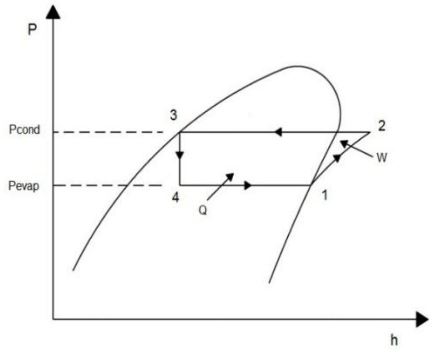

Fig. 1. Ideal vapour compression refrigeration cycle in p-h diagram

Exergy loss in condenser can be expressed as

$$\Delta e_c = (h_2 - h_3) + T_0(s_3 - s_2) \quad (6)$$

Exergy loss in expansion valve can be expressed as

$$\Delta e_v = (h_3 - h_4) + T_0(s_4 - s_3) \quad (7)$$

Table. 2 Refrigerants and their ODP and GWP values

Refrigerant	ODP	GWP
R-12 (CFC)	0.9	3
R-22 HCFC	0.05	0.34
R-134a (HFC)	0	0.29
R-717 (NH_3)	0	0
R-744 (CO_2)	0	0
R-290 propane	0	<0.03
R-600 (butane)	0	<0.03
R-718 (H_2O)	0	0
R-728 (air)	0	0

Exergy loss in evaporator can be expressed as

$$\Delta e_e = (h_4 - h_1)\frac{T_0}{T_r} + T_0(s_1 - s_4) \quad (8)$$

And the total exergy loss can be expressed as

$$\Delta E = \dot{m}(\Delta e_w + \Delta e_c + \Delta e_v + \Delta e_e) \quad (9)$$

Exergetic efficiency can be expressed as

$$\eta_{II} = \frac{Q\left|\left(1 - \frac{T_0}{T_r}\right)\right|}{W_C} \quad (10)$$

3. Results and discussion

Compressor power, COP, total exergy loss, mass flow rate and exergetic efficiency obtained from the simulation of actual vapour compression refrigeration system using CFC12, R134a and R290 as refrigerants are shown in figures 2-11. A FORTRAN code is developed for doing the whole calculation for this simulation program.

In this computation following input datas are assumed

Condenser Temperature, T_c = 30ºC to 40ºC
Evaporator Temperature, T_e = 0ºC to -20ºC
Refrigeration Effect, Q = 1 kW
Compressor Efficiency, η = 0.7
Cold Room Temperature, T_r = 0ºC
Surrounding Temperature, T_0 = 25ºC

Figure 2 and figure 3 show the variation of compressor power with evaporator temperature at constant condenser temperature of 303K and 313K respectively.

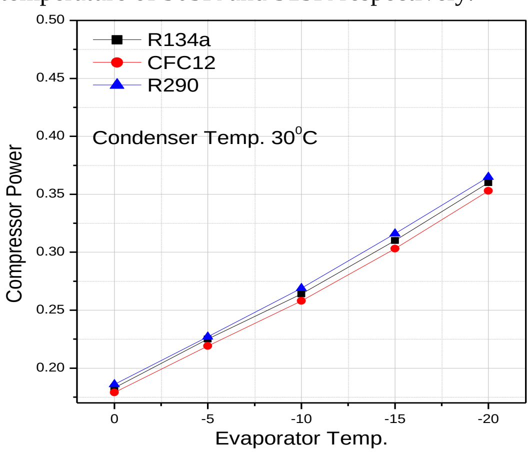

Fig. 2 Variation of compressor power with evaporator temperature of different refrigerants at condenser temperature of 30°C

It is seen from the figures that with the decrease in evaporator temperature compressor power increases for refrigerant CFC12 and similar trend were found for R134a and R290 also. It is also seen from the figures that compressor power requirement for CFC12 is less and that for R290 is maximum for all evaporator temperature for both 303K and 313K condenser temperatures. This is because of the different specific volume of different refrigerants used in the work. As specific volume of CFC12 is low the compressor power requirement is low and high for R290 because of its high specific volume of vapour. Power requirement for refrigerant R134a is slightly higher than CFC12 and lower than R290. Maximum difference obtains between compressor power of CFC12 and R134a is 3.3% at condenser temperature of 40ºC. Compressor power difference between R134 and R290 at condenser temperature of 30ºC is 1.8% and it increases to 2.1% for the condenser temperature of 40ºC.

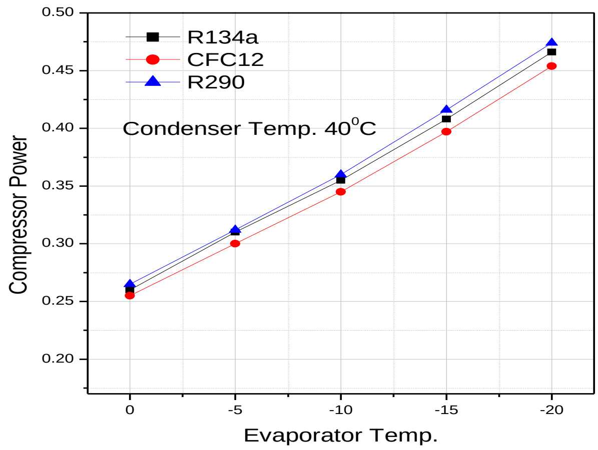

Fig. 3 Variation of compressor power with evaporator temperature of different refrigerants at condenser temperature of 40°C

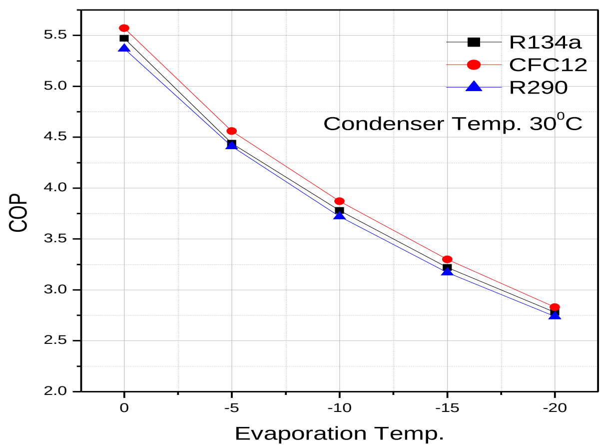

Fig. 4 Variation of COP with evaporator temperature of different refrigerants at condenser temperature of 30°C

Figure 4 and figure 5 show the comparisons between coefficient of performance (COP) against evaporator temperature at constant condenser temperature of 303K and 313K respectively. Specific heat of vaporization of refrigerants plays a significant role for determining the overall COP of the vapour compression refrigeration system. It is seen from the figures that when evaporator temperature decreases, compressor power increases and refrigeration effect decreases though specific heat of vaporization increases with the decrease in evaporator temperature. As a result, overall COP decreases. CFC12 shows the maximum COP among all the refrigerants. Maximum difference obtained between COPs of CFC12 and R134a is 3% at the higher condenser temperature of 40ºC. The difference in COP of CFC12 and R134a is 1.8% at 30ºC condenser temperature and this difference increases to 2.7% at 40ºC condenser temperature.

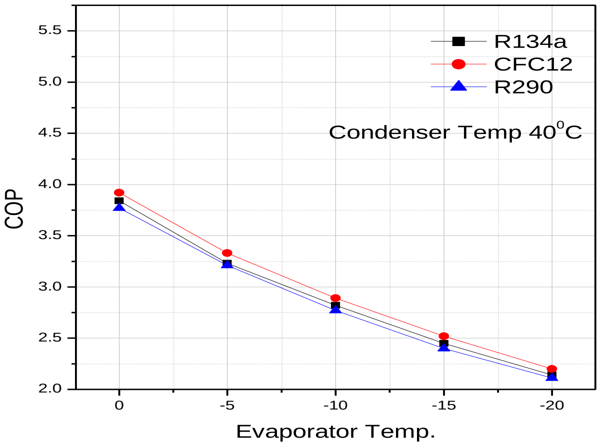

Fig. 5 Variation of COP with evaporator temperature of different refrigerants at condenser temperature of 40°C

Figure 6 and figure 7 show the effect of evaporator temperature on total exergy loss at constant condenser temperature of 303K and 313K respectively. It is seen from the figures that as the evaporator temperature decreases total exergy loss increases. Similar trend is found for all three refrigerants. It is found that the total exergy loss increases due to the loss in compressor and evaporator. The loss in the components increases when evaporator temperature decreases. As total exergy loss is the sum of all the losses in the components, total exergy loss also increases. For all the cases, exergy loss increases with the decrease of evaporator temperature. It is seen from the figures that loss of exergy is minimum for refrigerant CFC12 and maximum for refrigerant R290. Total exergy loss increases when R134a is used other than CFC12. Maximum increase in total exergy loss is about 4.4% for the condenser temperature of 40ºC.

The variation of mass flow rate of the refrigerants with evaporator temperature have been shown in figure 8 and figure 9 for condenser temperature of 303K and 313K respectively. It is seen from the figures that mass flow rate requirement, to achieve same cooling effect, increases with decrease in evaporator temperature for all the refrigerants due to decrease in refrigeration effect with the decrease in evaporator temperature. It is seen from the figures that mass flow rate requirement for refrigerant CFC12 is maximum for its lower latent heat of vaporization and that for refrigerant R290 is minimum due to higher latent heat of vaporization to achieve the same refrigeration effect. It is also observed that mass flow requirement is also increased for increase in condenser temperature.

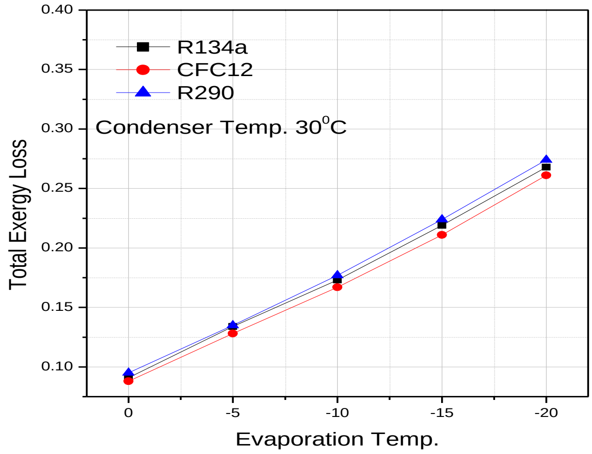

Fig. 6 Variation of total exergy loss with evaporator temperature of different refrigerants at condenser temperature of 30°C

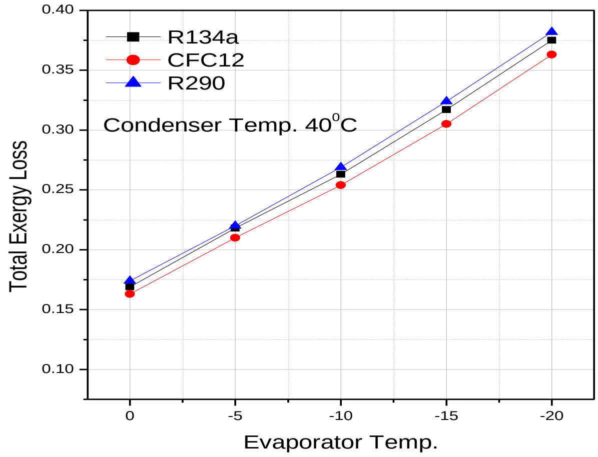

Fig. 7 Variation of total exergy loss with evaporator temperature of different refrigerants at condenser temperature of 40°C

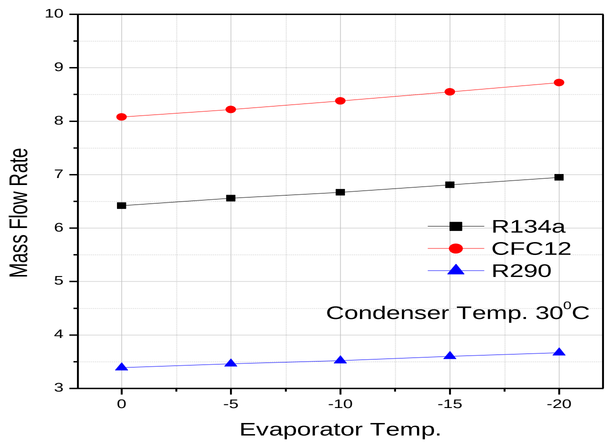

Fig. 8 Variation of mass flow rate with evaporator temperature of different refrigerants at condenser temperature of 30°C

Figure 10 and figure 11 show the variation of exergetic efficiency with evaporation temperature at constant condenser temperature of 303K and 313K respectively.

The result shows that the exergetic efficiency of the system decreases when evaporator temperature decreases. Same result obtained for both 30ºC and 40ºC condenser temperature. It is found that we get maximum exergetic efficiency of the system when CFC12 is used as refrigerant and minimum efficiency for R290 as refrigerant, as the total exergy loss of the system is minimum when CFC12 is used and maximum when R290 is used as working fluid. Maximum difference obtains in exergetic efficiency using CFC12 and R134a is 3.1% at 40ºC condenser temperature. The maximum difference obtains for R134a and R290 at condenser temperature of 30ºC is 1.8% and that increased to 2% at condenser temperature of 40ºC

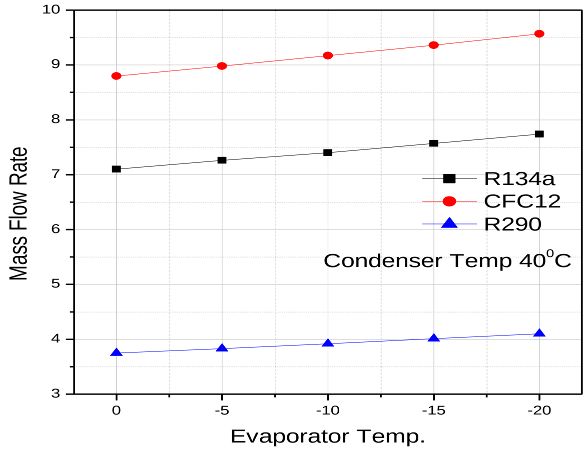

Fig. 9 Variation of mass flow rate with evaporator temperature of different refrigerants at condenser temperature of 40^{o}C

Conclusions

Thermodynamic analysis of mechanical vapour compression refrigeration system has been carried and the following conclusions can be drawn as listed below:

- Compressor power increases with decrease in evaporation temperature and increase in condenser temperature for all three refrigerants. This compressor power for R134a and R290 is very near to that of CFC12.
- COP of the system using R134a and R290 is slightly less than the COP of the system using CFC12. Maximum difference in COP is obtained using R134a is just 3% lower than COP of system using CFC12.
- Exergy loss of the system increases with the decrease in evaporator temperature. Exergy loss of the system increases when R134a and R290 are used other than CFC12.Maximum increase in exergy loss using R134a is 4.4% at condenser temperature of 40ºC.
- Mass flow rate of CFC12 is maximum and mass flow rate of R290 is minimum to achieve same refrigeration effect.
- The exergetic efficiency decreases with decrease in evaporator temperature. Maximum efficiency is achieved by using CFC12 and that differ from the efficiency of system using R134a is 3.1% at condenser temperature of 40ºC.

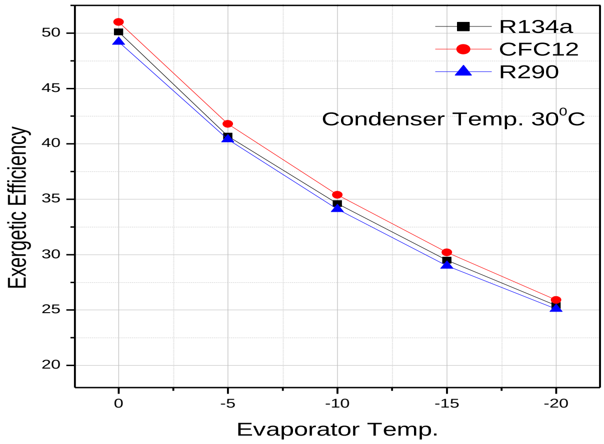

Fig. 10 Variation of exergetic efficiency with evaporator temperature of different refrigerants at condenser temperature of 30^{o}C

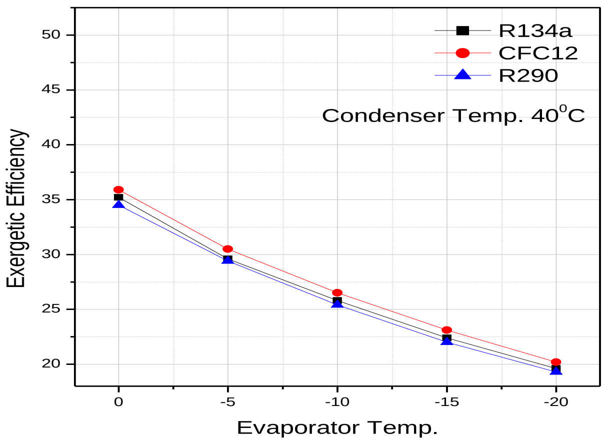

Fig. 11 Variation of exergetic efficiency with evaporator temperature of different refrigerants at condenser temperature of 40^{o}C

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