Advances in Automobile Engineering

Gohel and Kapadia, Adv Automob Eng 2016, 5:1
DOI: 10.4172/2167-7670.1000129

Research Article Open Access

Thermodynamic Cycle Analysis of Mobile Air Conditioning System Using Hfo-1234yf as an Alternative Replacement of Hfc-134a

Gohel JV[1]* and Kapadia R[2]

[1]*Mechanical Engineering Department, Aditya Silver Oak Institute of Technology, Ahmedabad, India*
[2]*Mechanical Engineering Department, SVMIT College, Bharuch, India*

Abstract

This paper presents thermodynamic cycle analysis of mobile air conditioning system using HFO1234yf as alternative replacement for HFC-134a. Under a wide range of working conditions (Varying Condensing temperature, Evaporating temperature, Sub cooling and sub heating with Internal heat exchanger (IHX) and without internal heat exchanger) on simple vapor compression system, we compare the energy performance of both refrigerants - R134a and HFO1234yf.

Result shows that without using an Internal heat exchanger, At lower condensing temperature (35°C), Mass flow rate increases about 27-32%, refrigerating effect decreases 22-25%, co mpressor work increases 4-6% and COP decreases about 3-5%.

While at higher condensing temperature (55°C), mass flow rate increases about 35-42%, refrigerating capacity decreases 27-30%, and compressor work increases 8-13% and COP decreases 7-10%.

Using an internal heat exchanger (IHX), these differences in the energy performance are significantly reduced.

At lower condensing temperature (35°C), mass flow rate decreases about 18-22%, refrigerating capacity decreases 15-18%, compressor work increases 1-3% and COP decreases about 2-3% and

At higher condensing temperature (55°C), mass flow rate decreases 23-28%, refrigerating capacity decreases 18-22%, compressor work increases 5-8% and COP decreases about 4-7%.

The energy performance parameters of HFO1234yf are close to those obtained with HFC-134a at Low condensing temperature and making use of an IHX. Even though the values of performance parameters for HFO1234yf are smaller than that of HFC-134a, but difference is small so it can be a good alternative to HFC-134a because of its environmental friendly properties with introducing IHX.

Keywords: Thermodynamic analysis; Drop-in; R134a; HFO-1234yf; COP; Compressor work; Refrigerating capacity; Heat exchanger

Nomenclature

COP - Coefficient of performance

C_p- Specific heat (kJ/kg K)

h -Specific enthalpy (kJ/kg)

m_{ref}- Mass flow rate (kg/s)

Q_o- Cooling Capacity (kW)

T - Temperature (°C)

subscripts

h5 -Specific enthalpy at evaporator inlet

h6- Specific enthalpy at evaporator outlet

h1 - Specific enthalpy at compressor discharge

ref- Refrigerant

Introduction

Montreal Protocol (UNEP, 1987) was adopted by many nations to begin the phase out of both Chlorofluoro carbons(CFCs) and Hydro Chloro fluoro carbons (HCFCs)due to their ozone depleting potential (ODP). Hydro fluorocarbons (HFCs) were developed as long term alternative to substitute CFCs and HCFCs as they were non ozone depleting, but have large global warming potential (GWP). In 1997, HFCs were considered as greenhouse gases and currently they are target compounds for greenhouse gases emission reduction under the Kyoto Protocol (GCRP, 1997). In this way, the growing international concern over relatively high GWP refrigerants has motivated the study of low GWP alternatives for HFCs in vapor compression systems [1-5].

Today mobile air-conditioning system in passenger car contains a refrigerant, paying a major contribution to increasing the greenhouse effect andabout 30% of the worldwide emissions of hydro fluorocarbons arise from mobile air-conditioning systems. One of those refrigerants is R134a, with a GWP of 1430, extensively used in car air conditioning (banned in Europe for new mobile air conditioners according to Directive, 2006/ 40/EC). Thus, air conditioning systems of vehicles (passenger cars with a maximum of 8 seats and commercial vehicles with a gross weight limit of up to 3.5 tons), for which type approval is issued within the EU starting from 01.01.2011, may not be filled

***Corresponding author:** Gohel JV, Head of the Department, Mechanical Engineering Department, Aditya Silver Oak Institute of Technology, Ahmedabad, India, Tel: 079 6604 6304; E-mail: jigneshgohel.me@socet.edu.in

Received January 14, 2016; **Accepted** February 27, 2016; **Published** March 03, 2016

Citation: Gohel JV, Kapadia R (2016) Thermodynamic Cycle Analysis of Mobile Air Conditioning System Using Hfo-1234yf as an Alternative Replacement of Hfc-134a. Adv Automob Eng 5: 129 doi:10.4172/2167-7670.1000129

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anymore with R134a [6-11]. Starting from 01.01.2017, vehicles filled with R134a cannot be initially type-approved anymore. However, the use of R134a shall be further permitted for service and maintenance work on already existing R134a systems [12].

The main candidates to replace R134a in mobile air conditioning systems are natural refrigerants like ammonia, carbon dioxide, hydrocarbon mixtures - propane (R290), butane (R600) and isobutene (R600a), low GWP HFCs - R32 and R152a; and HFO - specifically R1234yf, developed by Honeywell and DuPont [13-18].

While the Automobile air conditioning (AAC) system provides comfort to the passengers in a vehicle, its operation in a vehicle has two fold impacts on fuel consumption:

(1) Burning extra fuel to power compressor (Major Impact) and

(2) Carrying extra A/C component load in the vehicle

However, using low GWP refrigerants are not the only efficient way to reduce greenhouse gas emissions. In fact it is likely to choose a low GWP refrigerant but still raise total greenhouse gas emissions, when the low GWP refrigerant causes more energy use and fuel consumption then there are larger indirect emissions [19-25]. Therefore in developing the low GWP refrigerants always energy efficiency of the system must be studied and its indirect climate impacts should be considered besides its direct emissions [26,27].

The main disadvantage of the implementation of hydrocarbons mixtures is their flammability (BSI, 2004). For the case of drop-in in domestic refrigeration with medium-class flammability refrigerants, like R152a and R32, the average COP obtained using R152a is higher than the one using R134a, while the average COP of R32 is lower than the one using R134a. R1234yf has been proposed as a replacement for R134a in mobile air conditioning systems (Spatz and Minor, 2008), and its similar thermo physical properties makes R1234yf a good choice to replace R134a in other applications of refrigeration and air conditioning [28-35].

Refrigerant (R1234yf) does not contain chlorine, and therefore its ODP is zero WMO 2007 and its GWP is as low as 4. About security characteristics, R1234yf has low toxicity, similar to R134a, and mild flammability, significantly less than R152a [36-40]. Analyzing other environmental effects of R1234yf, in the case that this refrigerant would be released into the atmosphere, it is almost completely transformed to the persistent trifluoro acetic acid (TFA), and the predicted consequences of some studies of using R1234yf Henne et al., show that future emissions would not cause significant increase in TFA rainwater concentrations.

Reasor et al. evaluated the possibility of R1234yf to be a drop-in replacement for a pre-designed system withR134a or R410A, comparing thermo physical properties and simulating operational conditions. Leck discussed R1234yf, and other new refrigerants developed by DuPont, as replacement for various high-GWP refrigerants. Endoh et al. modified a room air conditioner that had been using R410A to meet the properties of R1234yf, and also evaluated the cycle performance capacity [41]. Okazaki et al. studied the performance of a room air conditioner using R1234yf and R32/ R1234yf mixtures, which was originally designed for R410A, with both the original and modified unit.

Challenges with respect to stationary AC system

- About 30% of the worldwide emissions of hydro fluorocarbons arise from mobile air-conditioning systems.
- Radiation heat from the engine on interior space influences high refrigeration capacity.
- Condenser is installed near the engine and condensation temperature is high which requires new refrigerant to have good heat transfer ability.
- Much vibration occurs on internal piping /hoses and components which results into leakages easily and refrigerant needs to be recharge within 1-2 year.

Thermodynamic Analysis

The aim of this work is to present theoretical study of R1234yf as a drop-in replacement for refrigerant R134a in a vapor compression system in a wide range of working conditions. An energetic characterization with both refrigerants is carried out using as main performance parameters the cooling capacity, the compressor volumetric efficiency, the compressor power consumption, and the COP [42,43]. This theoretical analysis has been done by varying the condensing temperature, the evaporating temperature, the superheating degree and the use of an internal heat exchanger. The results obtained with R134a are taken as baseline for comparison (Figures 1 and 2).

In order to analyze the influence of the operating parameters (evaporating temperature, condensing temperature, superheating degree, and the use of IHX) on the cooling capacity, mass flow rate, compressor powerand the COP, simple theoretical study is carried out. In this theoretical study the following assumptions are made:

- Cooling Capacity - 4 KW
- Isentropic Efficiency -0.7
- Volumetric Efficiency - 0.9
- No heat transfer to the surroundings
- Pressure drops in evaporator, condenser and heat exchanger is negligible
- Possibility of using an IHX (efficiency of 50%) is considered
- Superheating degree - 10 K

The cooling capacity (Q_o) already defined as 4 KW is the product of the refrigerant mass flow rate and the refrigerating effect (enthalpy difference between evaporator outlet (h_{2K}) and inlet (h_S)):

The refrigerant mass flow rate is calculated as follows:

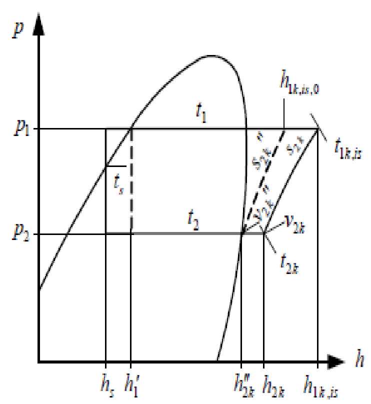

Figure 1: P-h chart.

$$m_{ref} = Q_o/(h_{2K} - h_S) \quad (1)$$

The theoretical COP only depends on thermodynamic states at the inlet and outlet of the evaporator and the compressor, and is defined as:

$$COP = (h_{2K} - h_S)/(h_{1K,is} - h_{2K})$$

Where, $h_{1K,is}$ is the specific enthalpy at compressor discharge.

These theoretical results reveals for the different parameters (Mass flow rate, COP, Pressure ratio, Compressor work)without heat exchanger as per following:

Pressure ratio (PR) is about 4-9% less in R1234yf than R134a for low condensation temperature (35°C), while it is about 7-11% less in R1234yf than R134a for high condensation temperature (55°C). Pressure ratio (PR) is about 4-7% less in R1234yf than R134a for high evaporation temperature (10°C), while it is about 9-11% less in R1234yf than R134a for low evaporation temperature (-10°C).

The mass flow rate would be 27-32% more than using R134a for low condensation temperature (35°C) and the mass flow rate would be 35-42% more than using R134a at high condensation temperature (55°C). The mass flow rate would be 32-42% more than using R134a for low evaporation temperature (-10°C) and the mass flow rate would be 27-35% more than using R134a at high evaporation temperature (10°C) (Difference in g/s which is negligible).

The refrigerating effect would be 22-25% less than using R134a for low condensation temperature (35°C) and the refrigerating effect would be 27-30% less than using R134a at high condensation temperature (55°C). The refrigerating effect would be 25-30% less than using R134a for low evaporation temperature (-10°C) and the refrigerating effect would be 22-27% less than using R134a at high evaporation temperature (10°C).

The compressor work would be 4-6% more than using R134a for low condensation temperature (35°C) and the compressor work would be 8-13% more than using R134a at high condensation temperature (55°C). The compressor work would be 6-13% more than using R134a for low evaporation temperature (-10°C) and the refrigerating effect would be 4-8% more than using R134a at high evaporation temperature (10°C).

The COP for R-1234yf is about 3-5% lower than the COP of R-134a at low condensation temperature (35°C), meanwhile the COP for R-1234yf is about 8-12% lower than the COP of R-134a at high condensation temperature (55°C). Meanwhile the COP for R-1234yf is about 3-8% lower than the COP of R-134a at high evaporation temperature (10°C), meanwhile the COP for R-1234yf is about 5-12% lower than the COP of R-134a at low evaporation temperature(-10°C).

When an Internal Heat Exchanger (IHX) (Efficiency – 50%) is used with both the refrigerants, the difference for mass flow rate, Refrigerating effect, compressor work and COP achieved as per following:

The mass flow rate would be 18-22% more than using R134a for low condensation temperature (35°C) and the mass flow rate would be 23-28% more than using R134a at high condensation temperature (55°C). The mass flow rate would be 22-28% more than using R134a for low evaporation temperature (-10°C) and the mass flow rate would be 18-23% more than using R134a at high evaporation temperature (10°C).

The refrigerating effect would be 15-18% less than using R134a for low condensation temperature (35°C) and the refrigerating effect would be 19-22% less than using R134a at high condensation temperature (55°C). The refrigerating effect would be 18-22% less than using R134a for low evaporation temperature (-10°C) and the refrigerating effect would be 15-19% less than using R134a at high evaporation temperature (10°C).

The compressor work would be 2-4% more than using R134a for low condensation temperature (35°C) and the compressor work would be 5-8% more than using R134a at high condensation temperature (55°C). The compressor work would be 4-8% more than using R134a for low evaporation temperature (-10°C) and the refrigerating effect would be 2-5% more than using R134a at high evaporation temperature (10°C).

The COP for R-1234yf is about 2-3% lower than the COP of R-134a at low condensation temperature (35°C), meanwhile the COP for R-1234yf is about 4-7% lower than the COP of R-134a at high condensation temperature (55°C). meanwhile the COP for R-1234yf is about 2-4% lower than the COP of R-134a at high evaporation temperature (10°C), meanwhile the COP for R-1234yf is about 3-7% lower than the COP of R-134a at low evaporation temperature (-10°C).

It is also observed that the difference between the theoretical refrigerating effect, mass flow rate, compressor work and COP using both refrigerants is slightly reduced when the condensing temperature is decreased. The differences in the energy performance are reduced, when an IHX is used with R1234yf compared with using R134a without IHX .

When an Internal Heat Exchanger (IHX) is used with the refrigerant R1234yf, we can reducemass flow rate up to 10-14% and can reduce compressor work up to 2-5% w.r.t. the refrigerant without Internal Heat Exchanger (R 1234yf). By providing IHX, we can increase refrigerating effect by 7-8% w.r.t. the refrigerating effect produced by R1234yf in without IHX cycle. Thus, COP obtained with R1234yf is increased, with a difference about 1-5%w.r.t. the COP obtaine by R1234yf in without IHX cycle.

Figures 3-5 show the variations of the theoretical parameters Mass flow rate, Compressor work and COP using both refrigerants varying the evaporation temperature[(-10)°C, (-5)°C, 0°C, 5°C, 10°C] at Low

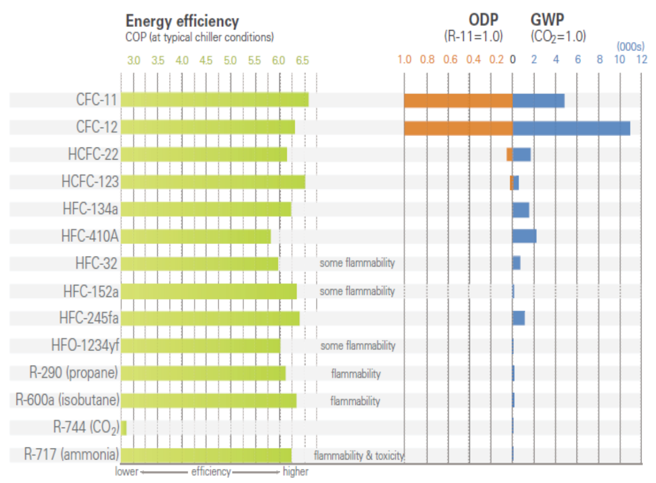

Figure 2: ODP & GWP value for various refrigerants.

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condensing temperature (35ºC), at Average condensing temperature (45ºC) and High condensing temperature (55ºC) without Internal Heat exchanger and superheating degree with Internal Heat Exchanger (IHX) for R-1234yf.

Figure 5 shows variation of COP with evaporator temperature and it can be easily inferred that as the evaporator temperature is increasing, pressure ratio decreases causing compressor work to reduce and specific refrigerating effect to increase and hence COP increases (Figures 6-8). HFO-1234yf shows lesser COP then HFC-134a. But this variation is less at low condensing temperature and high as the condensing temperature rises.

Conclusion

In this paper, thermodynamic analysis of a vapor compression system using R1234yf as a drop-in replacement for HFC-134a has been presented. In order to obtain a wide range of working conditions set of steady state results have been carried out. The results have been achieved varying the condensing temperature, evaporating temperature and use of IHX. The energetic comparison is performed on the basis of the mass flow rate, the compressor power consumption, and the COP. The main conclusions of this paper can be summarized as follows.

Result shows that without using an internal heat exchanger:

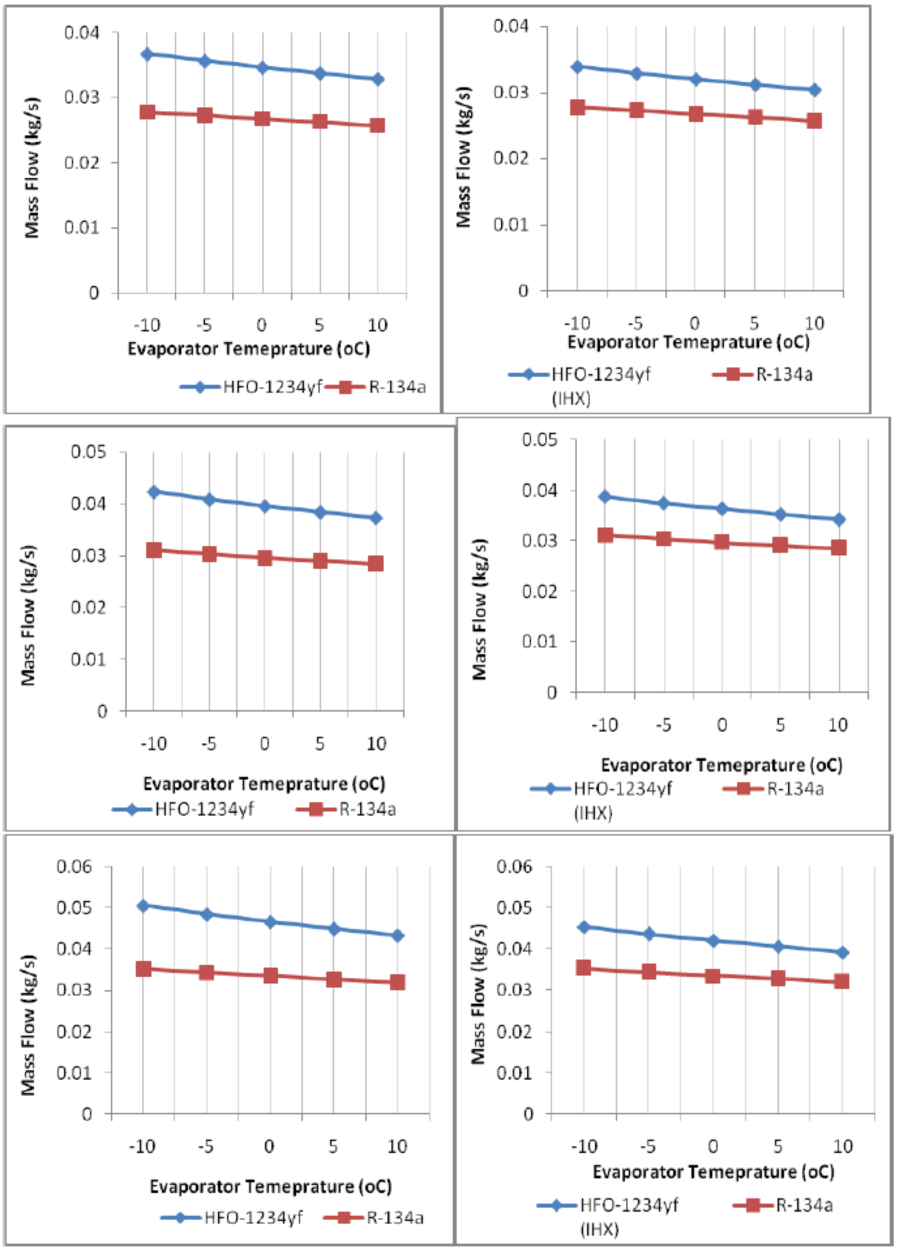

Figure 3: Mass flow rate Vs. Evaporator temperature at condensation temp 35ºC A) without IHX, B) With IHX, at condensation temp 45ºC C) Without IHX & D) With IHX and at condensation temp 55ºC E) Without IHX and F) With IHX.

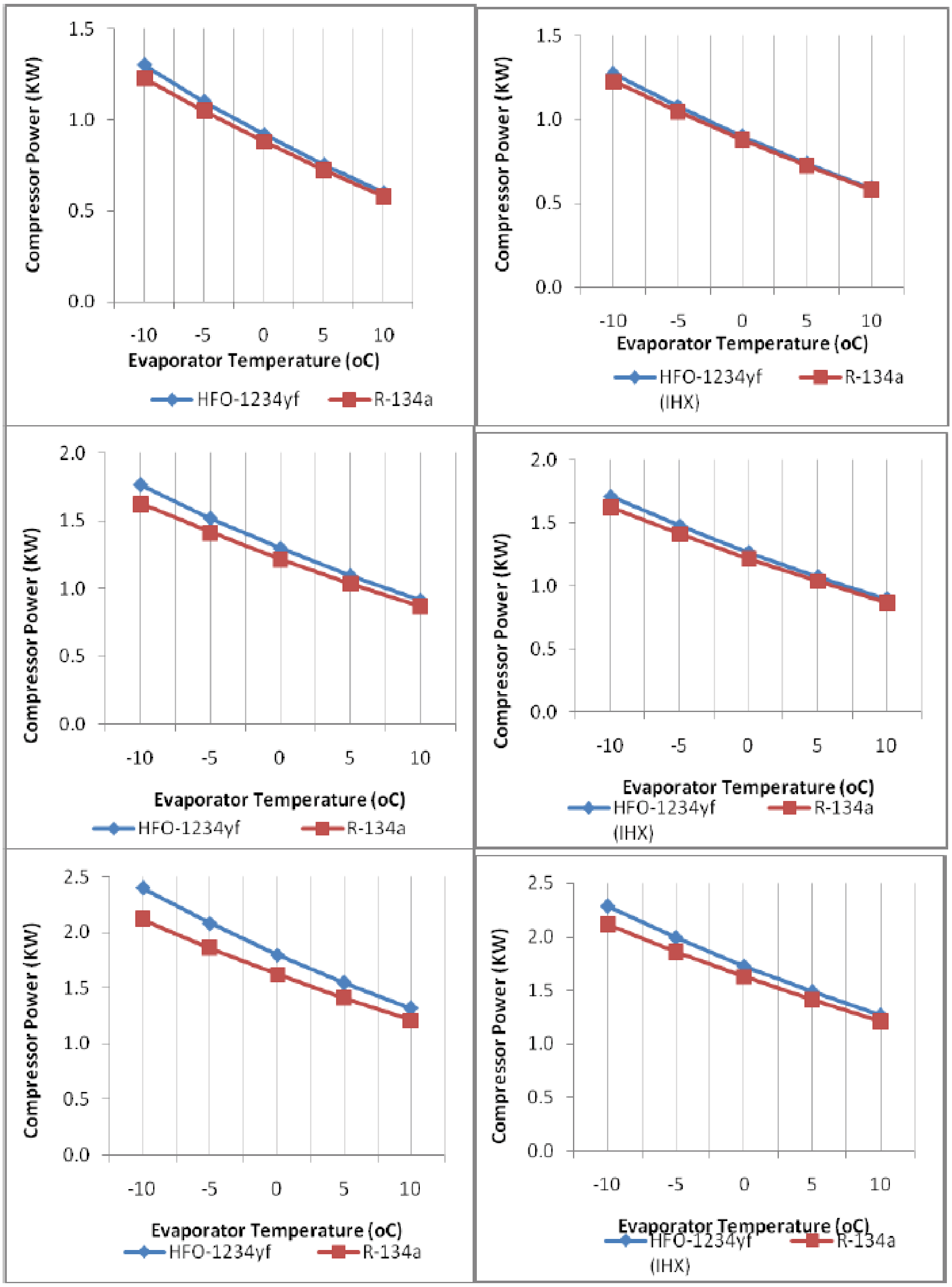

Figure 4: Compressor Work Vs. Evaporator Temperature at condensation temp 35°C A) Without IHX, B) With IHX, at condensation temp 45°C, C) Without IHX and D) With IHX and at condensation temp 55°C E) Without IHX and F) With IHX

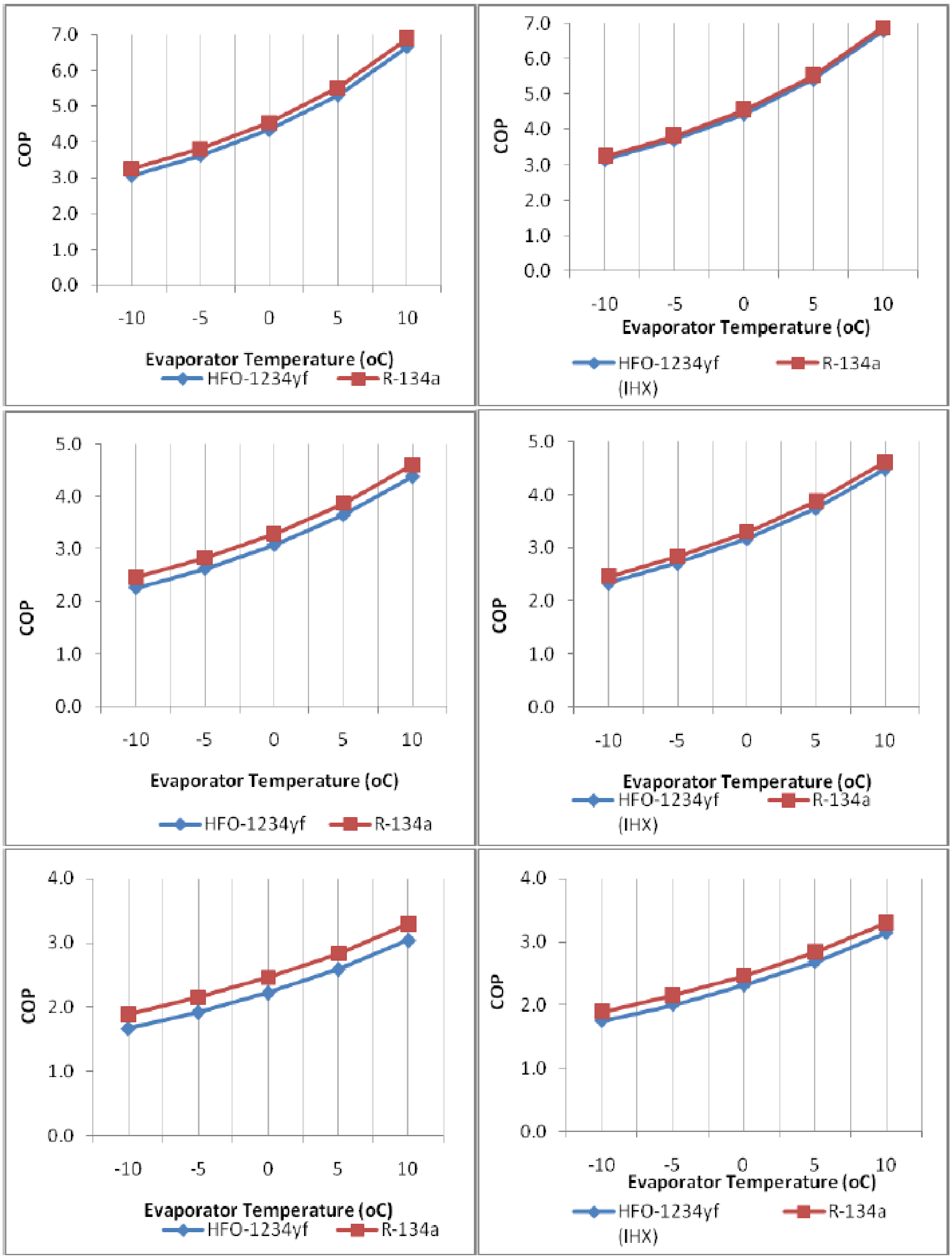

Figure 5: COP Vs. Evaporator Temperature at condensation temp 35°C A) Without IHX, B) With IHX, at condensation temp 45°C C) Without IHX & D) With IHX and at condensation temp 55°C E) Without IHX and F) With IHX.

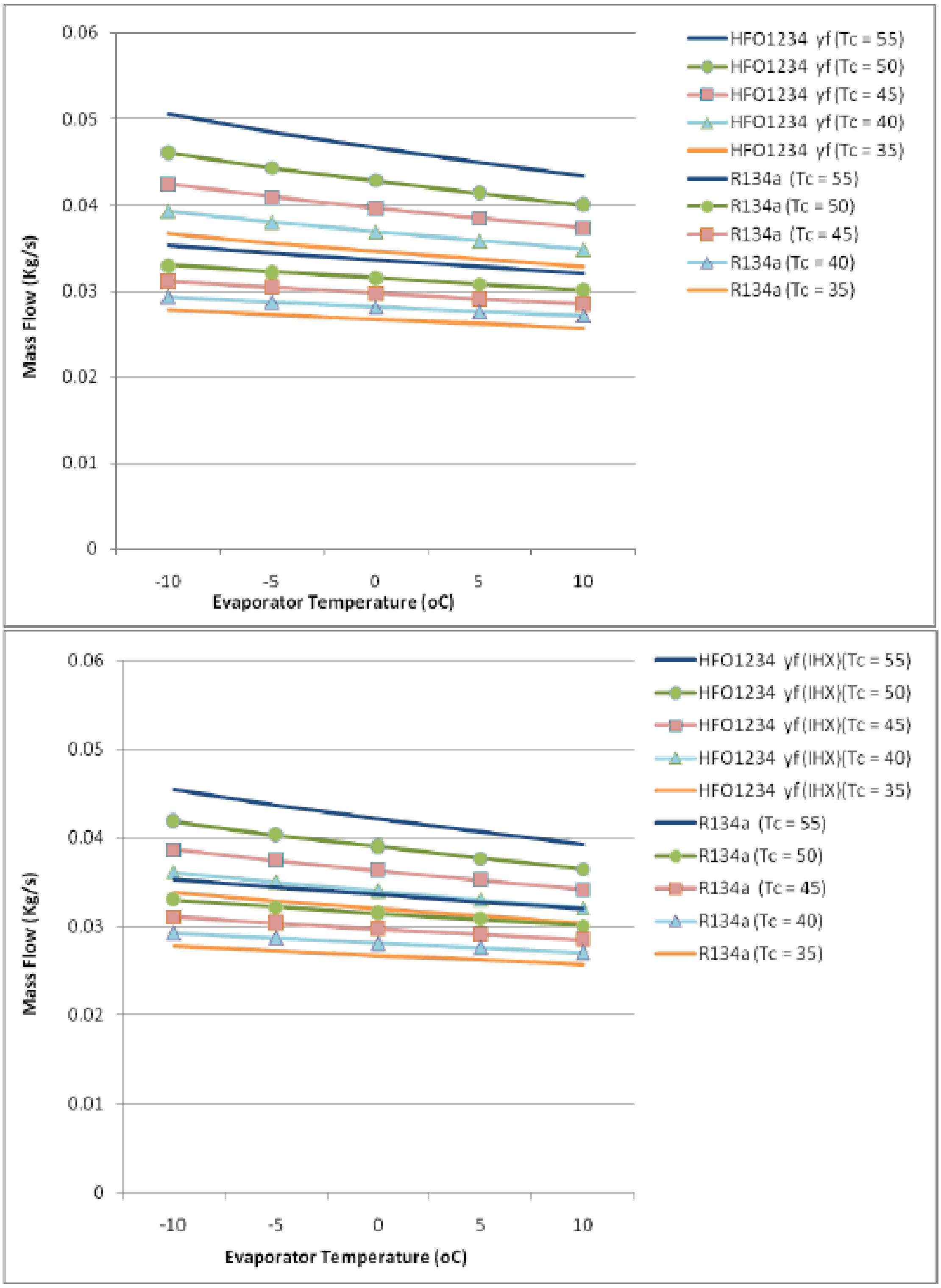

Figure 6: Theoretical Mass flow rate Vs. Evaporator Temperature (At varying condenser temp) (with and without heat exchanger).

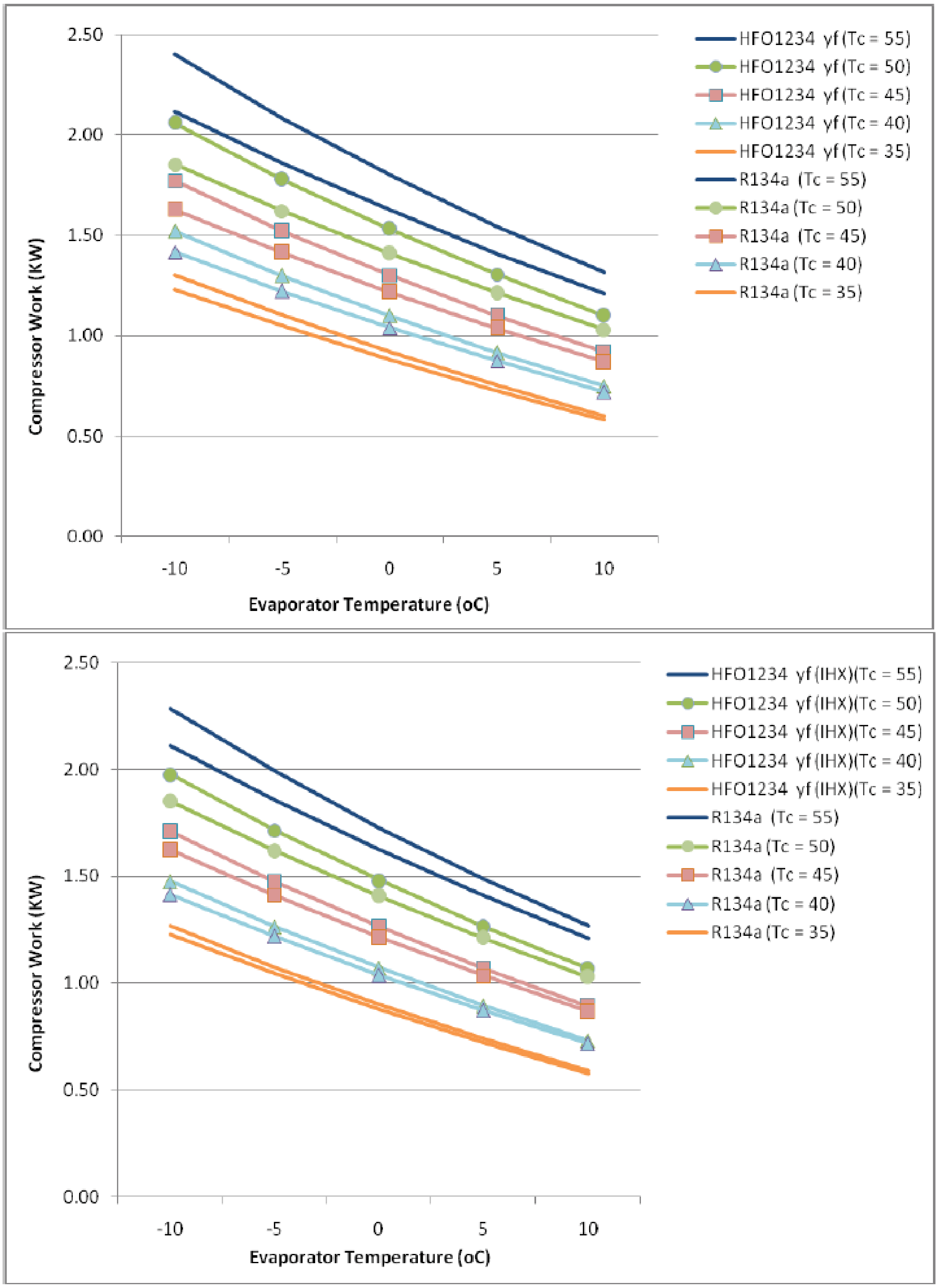

Figure 7: Theoretical Compressor work Vs. Evaporator Temperature (At varying condenser temp) (with and without heat exchanger)

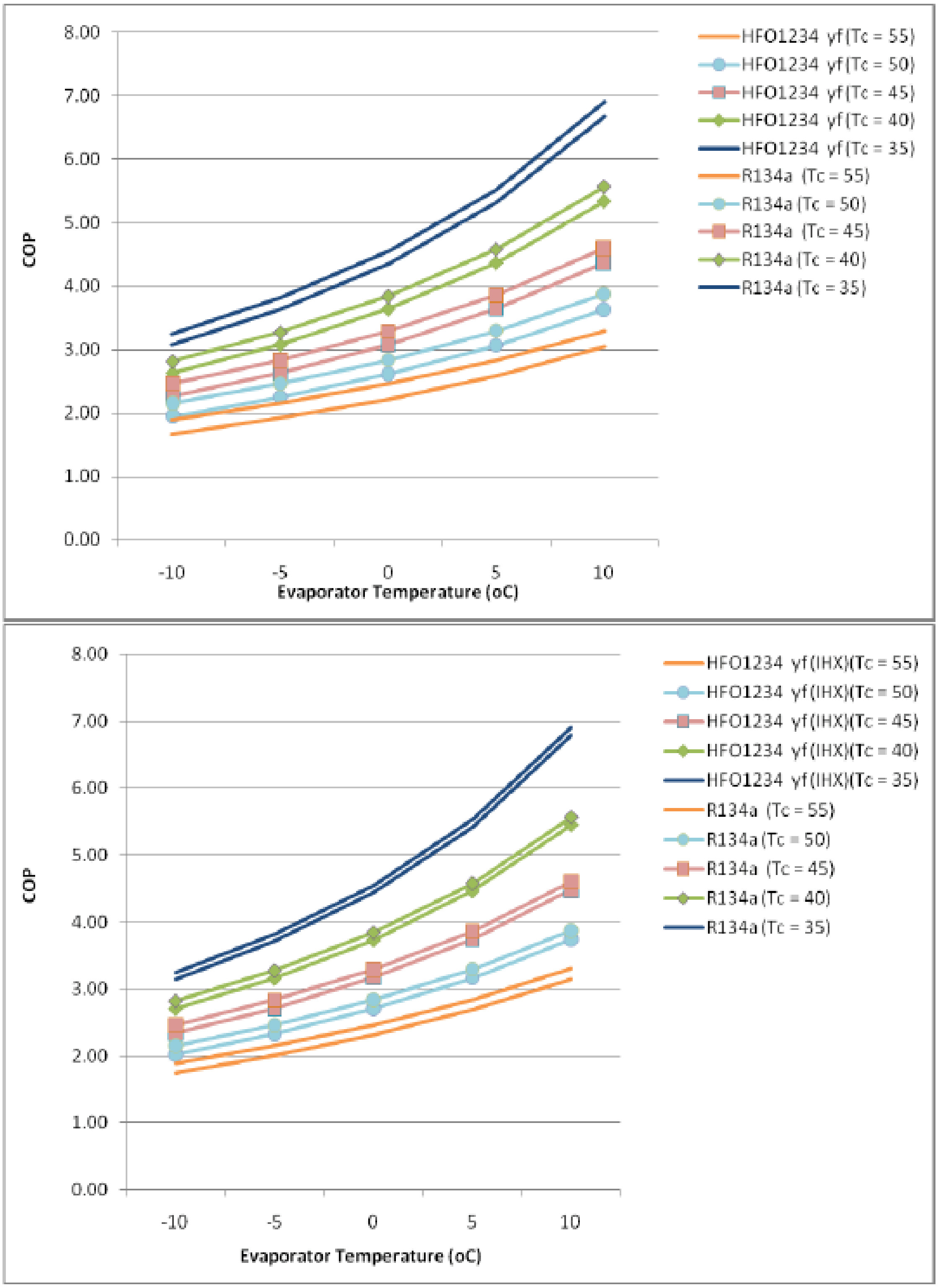

Figure 8: Theoretical COP Vs. Evaporator Temperature (At varying condenser temp) (with and without heat exchanger).

1) At lower condensing temperature (35°C), Mass flow rate increases about 27-32%, refrigerating effect decreases 22-25%, compressor work increases 4-6% and COP decreases about 3-5%.

2) While at higher condensing temperature (55°C), mass flow rate increases about 35-42%, refrigerating capacity decreases 27-30%, and compressor work increases 8-13% and COP decreases 7-10%.

Using an internal heat exchanger (IHX), these differences in the energy performance are significantly reduced.

1) At lower condensing temperature (35°C), mass flow rate decreases about 18-22%, refrigerating capacity decreases 15-18%, compressor work increases 1-3% and COP decreases about 2-3% and

2) At higher condensing temperature (55°C), mass flow rate decreases 23-28%, refrigerating capacity decreases 18-22%, compressor work increases 5-8% and COP decreases about 4-7%.

We can obtain remarkable difference in various parameters at high condensing temperature and using with IHX.

The cooling capacity of R1234yf used as a drop-in replacement in a HFC-134a refrigerant facility is about 3-12% lower than that presented by HFC-134a in the different range of operating condition [44-46]. This difference in the values of cooling capacity obtained with both refrigerants decreases when the condensing temperature decreases and when an IHX is used.

Finally, it can be concluded, from the above results, that the energy performance parameters of R1234yf in a drop-in replacement are close to those obtained with HFC-134a at Low condensing temperatures and making use ofan IHX.

Hence, even though the values of performance parameters for HFO-1234yf are smaller than that of HFC-134a, but the difference is small, so it can a good alternative to HFC-134a because of its environmental friendly properties with introducing IHX also.

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