

## Thermodynamic cycle analysis of Mobile Air Conditioning system using HFO-1234yf as an alternative replacement of HFC-134a

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**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%, compressor 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% &

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.

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**Index Terms**— Thermodynamic Analysis, Drop-in, R134a, HFO-1234yf, COP, Compressor Work, Refrigerating Capacity, Heat Exchanger

### 1 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.

Today mobile air-conditioning system in passenger car contains a refrigerant, paying a major contribution to increasing the greenhouse effect & about 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 anymore with R134a. 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.

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 (Spatz and Minor, 2008).

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) &
- (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. 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.

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 (Bolaji, 2010). 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.

Refrigerant (R1234yf) does not contain chlorine, and therefore its ODP is zero (WMO, 2007), and its GWP is as low as 4 (Nielsen et al., 2007; Papadimitriou et al., 2008). About security characteristics, R1234yf has low

toxicity, similar to R134a, and mild flammability, significantly less than R152a (Koban, 2009). 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., 2012) show that future emissions would not cause significant increase in TFA rainwater concentrations.

Reasor et al. (2010) evaluated the possibility of R1234yf to be a drop-in replacement for a pre-designed system with R134a or R410A, comparing thermo physical properties and simulating operational conditions. Leck (2010) discussed R1234yf, and other new refrigerants developed by DuPont, as replacement for various high-GWP refrigerants. Endoh et al. (2010) modified a room air conditioner that had been using R410A to meet the properties of R1234yf, and also evaluated the cycle performance capacity. Okazaki et al. (2010) 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

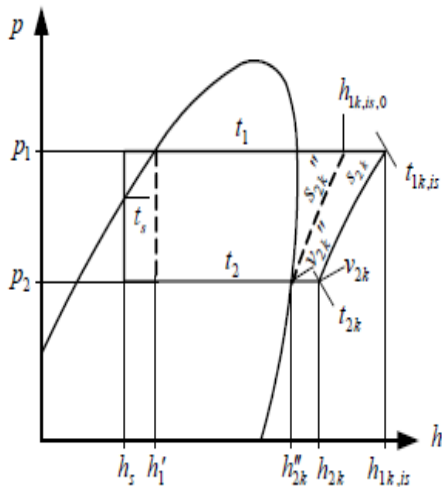
#### **Thermodynamic Analysis :**

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. 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.

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 power and 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



**Fig.1 – P-h Chart**

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:

$$\dot{m}_{ref} = Q_o / (h_{2k} - h_s) \quad (1)$$

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

The mass flow rate would be 27-32 % more than using R134a for low condensation temperature ( $35^\circ\text{C}$ ) & the mass flow rate would be 35-42 % more than using R134a at high condensation temperature ( $55^\circ\text{C}$ ). The mass flow rate would be 32-42 % more than using R134a for low evaporation temperature ( $-10^\circ\text{C}$ ) & the mass flow rate would be 27-35 % more than using R134a at high evaporation temperature ( $10^\circ\text{C}$ ) (Difference in g/s which is negligible).

The refrigerating effect would be 22-25% less than using R134a for low condensation temperature ( $35^\circ\text{C}$ ) & the refrigerating effect would be 27-30% less than using R134a at high condensation temperature ( $55^\circ\text{C}$ ). The refrigerating effect would be 25-30% less than using R134a for low evaporation temperature ( $-10^\circ\text{C}$ ) & the refrigerating effect would be 22-27% less than using R134a at high evaporation temperature ( $10^\circ\text{C}$ ).

The compressor work would be 4-6 % more than using R134a for low condensation temperature ( $35^\circ\text{C}$ ) & the compressor work would be 8-13 % more than using R134a at high condensation temperature ( $55^\circ\text{C}$ ). The compressor work would be 6-13 % more than using

R134a for low evaporation temperature ( $-10^{\circ}\text{C}$ ) & the refrigerating effect would be 4-8 % more than using R134a at high evaporation temperature ( $10^{\circ}\text{C}$ ).

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

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

The mass flow rate would be 18-22 % more than using R134a for low condensation temperature ( $35^{\circ}\text{C}$ ) & the mass flow rate would be 23-28 % more than using R134a at high condensation temperature ( $55^{\circ}\text{C}$ ). The mass flow rate would be 22-28 % more than using R134a for low evaporation temperature ( $-10^{\circ}\text{C}$ ) & the mass flow rate would be 18-23 % more than using R134a at high evaporation temperature ( $10^{\circ}\text{C}$ ).

The refrigerating effect would be 15-18 % less than using R134a for low condensation temperature ( $35^{\circ}\text{C}$ ) & the refrigerating effect would be 19-22 % less than using R134a at high condensation temperature ( $55^{\circ}\text{C}$ ). The refrigerating effect would be 18-22 % less than using R134a for low evaporation temperature ( $-10^{\circ}\text{C}$ ) & the refrigerating effect would be 15-19 % less than using R134a at high evaporation temperature ( $10^{\circ}\text{C}$ ).

The compressor work would be 2-4 % more than using R134a for low condensation temperature ( $35^{\circ}\text{C}$ ) & the compressor work would be 5-8 % more than using R134a at high condensation temperature ( $55^{\circ}\text{C}$ ). The compressor work would be 4-8 % more than using R134a for low evaporation temperature ( $-10^{\circ}\text{C}$ ) & the refrigerating effect would be 2-5 % more than using R134a at high evaporation temperature ( $10^{\circ}\text{C}$ ).

The COP for R-1234yf is about 2-3% lower than the COP of R-134a at low condensation temperature ( $35^{\circ}\text{C}$ ), meanwhile the COP for R-1234yf is about 4-7% lower than the COP of R-134a at high condensation temperature ( $55^{\circ}\text{C}$ ). Meanwhile the COP for R-1234yf is about 2-4% lower than the COP of R-134a at high evaporation temperature ( $10^{\circ}\text{C}$ ), meanwhile the COP for R-1234yf is about 3-7% lower than the COP of R-134a at low evaporation temperature ( $-10^{\circ}\text{C}$ ).

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 reduce mass 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 obtained by R1234yf in without IHX cycle..

Figs. 3, 4 and 5 show the variations of the theoretical parameters Mass flow rate, Compressor work & COP using both refrigerants varying the evaporation temperature [ $-10^{\circ}\text{C}$ ,  $-5^{\circ}\text{C}$ ,  $0^{\circ}\text{C}$ ,  $5^{\circ}\text{C}$ ,  $10^{\circ}\text{C}$ ] at Low condensing temperature ( $35^{\circ}\text{C}$ ), at Average condensing temperature ( $45^{\circ}\text{C}$ ) and High condensing temperature ( $55^{\circ}\text{C}$ ) without Internal Heat exchanger and superheating degree with Internal Heat Exchanger (IHX) for R-1234yf.

Fig.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. HFO-1234yf shows lesser COP than HFC-134a. But this variation is less at low condensing temperature and high as the condensing temperature rises.

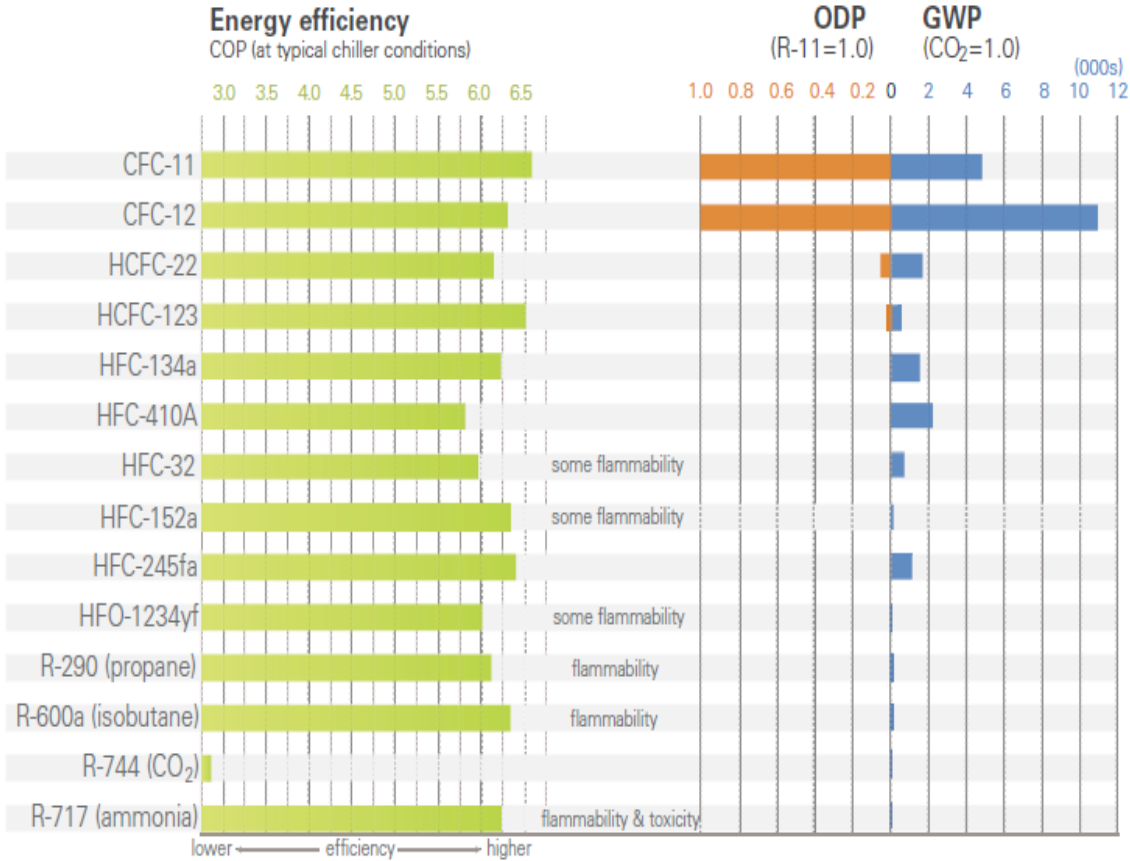


Fig.2 – ODP & GWP value for Various Refrigerants

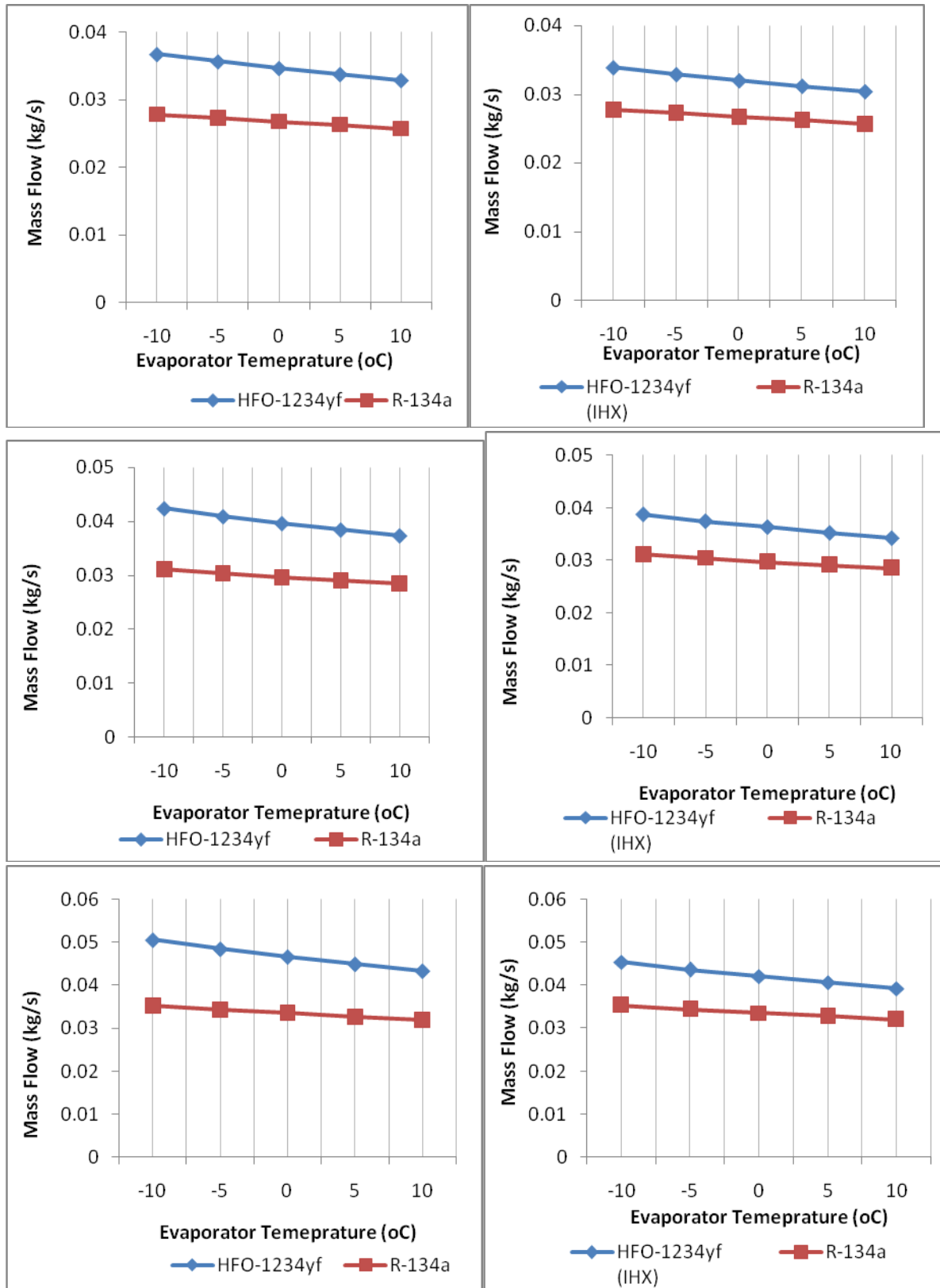


Fig.3 – Mass flow rate Vs. Evaporator Temperature at Condensation Temp 35 °C A) Without IHX , B) With IHX , at Condensation Temp 45 °C C) Without IHX & D) With IHX & at Condensation Temp 55 °C E) Without IHX & F) With IHX

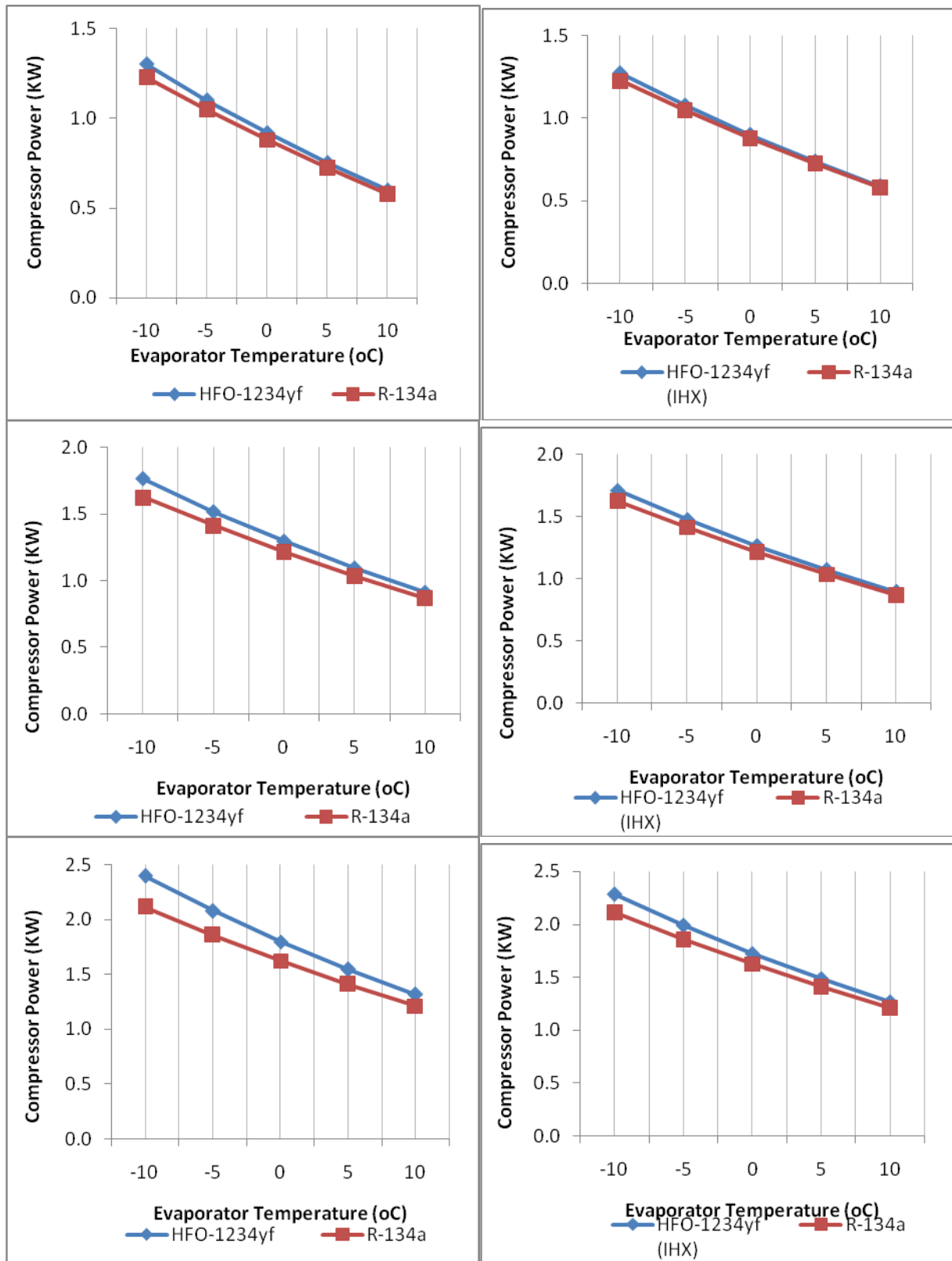
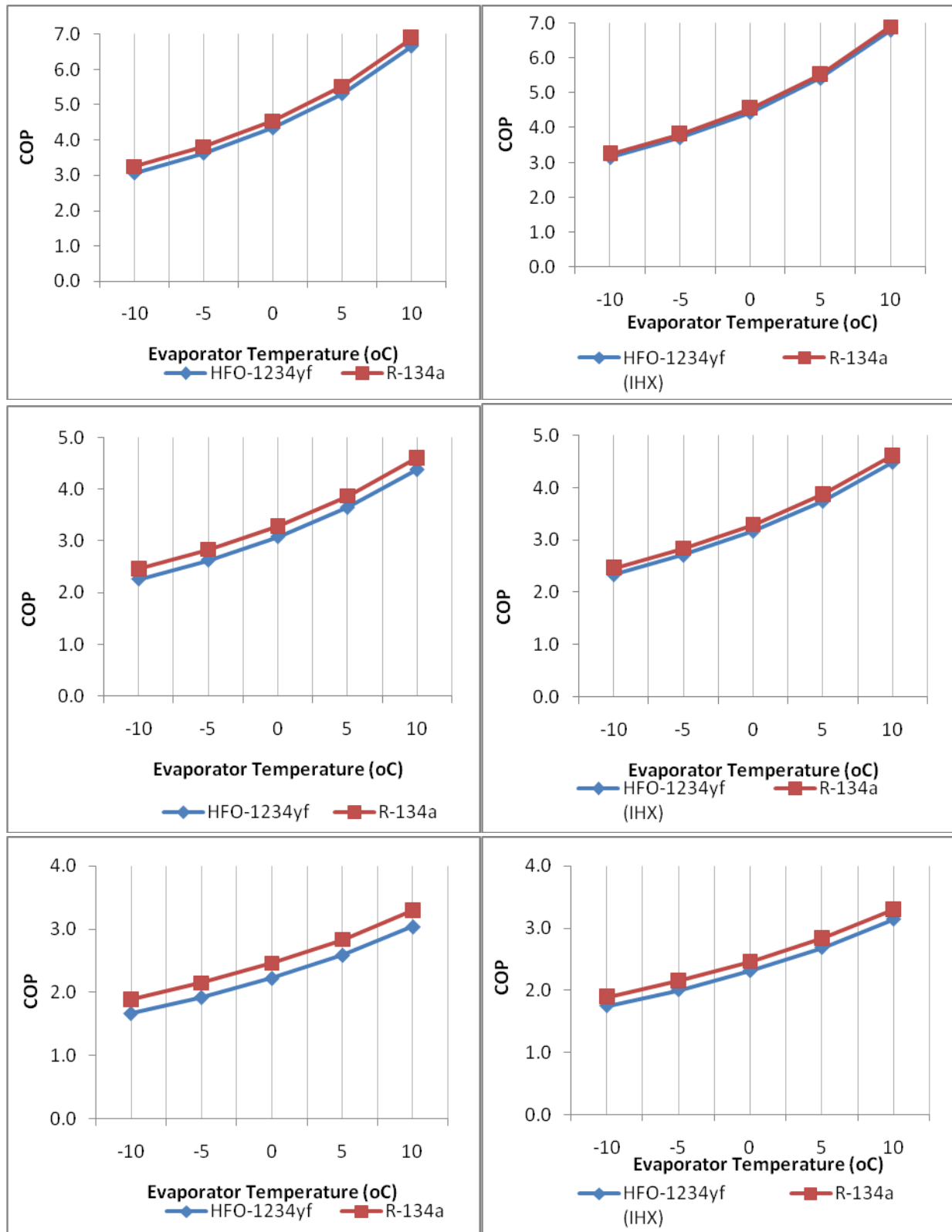
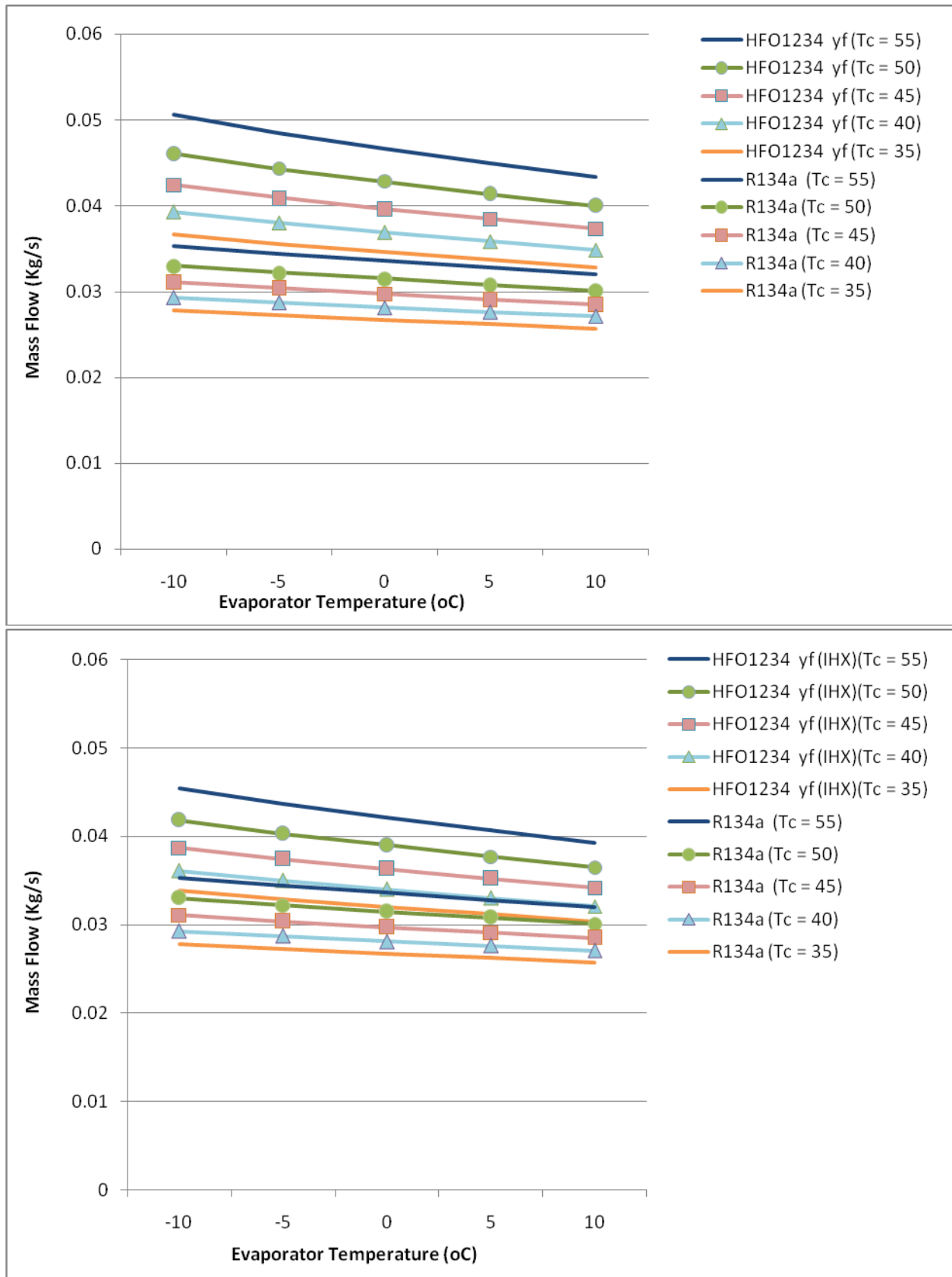


Fig.4 – Compressor Work Vs. Evaporator Temperature at Condensation Temp 35 °C A) Without IHX , B) With IHX , at Condensation Temp 45 °C C) Without IHX & D) With IHX & at Condensation Temp 55 °C E) Without IHX & F) With IHX



**Fig. 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 & at Condensation Temp 55 °C E) Without IHX & F) With IHX**





**Fig. 6– Theoretical Mass flow rate Vs. Evaporator Temperature (At varying Condenser Temp) (With & without Heat Exchanger)**

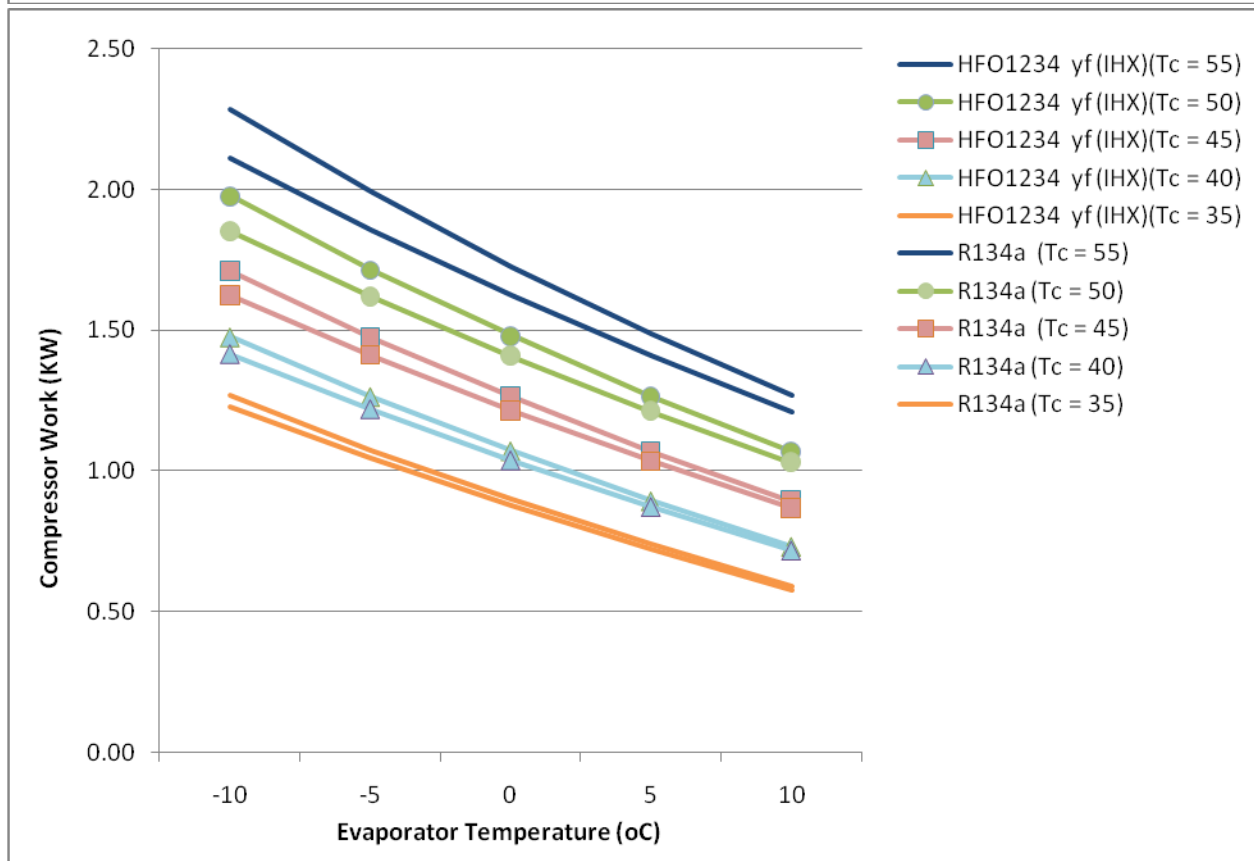
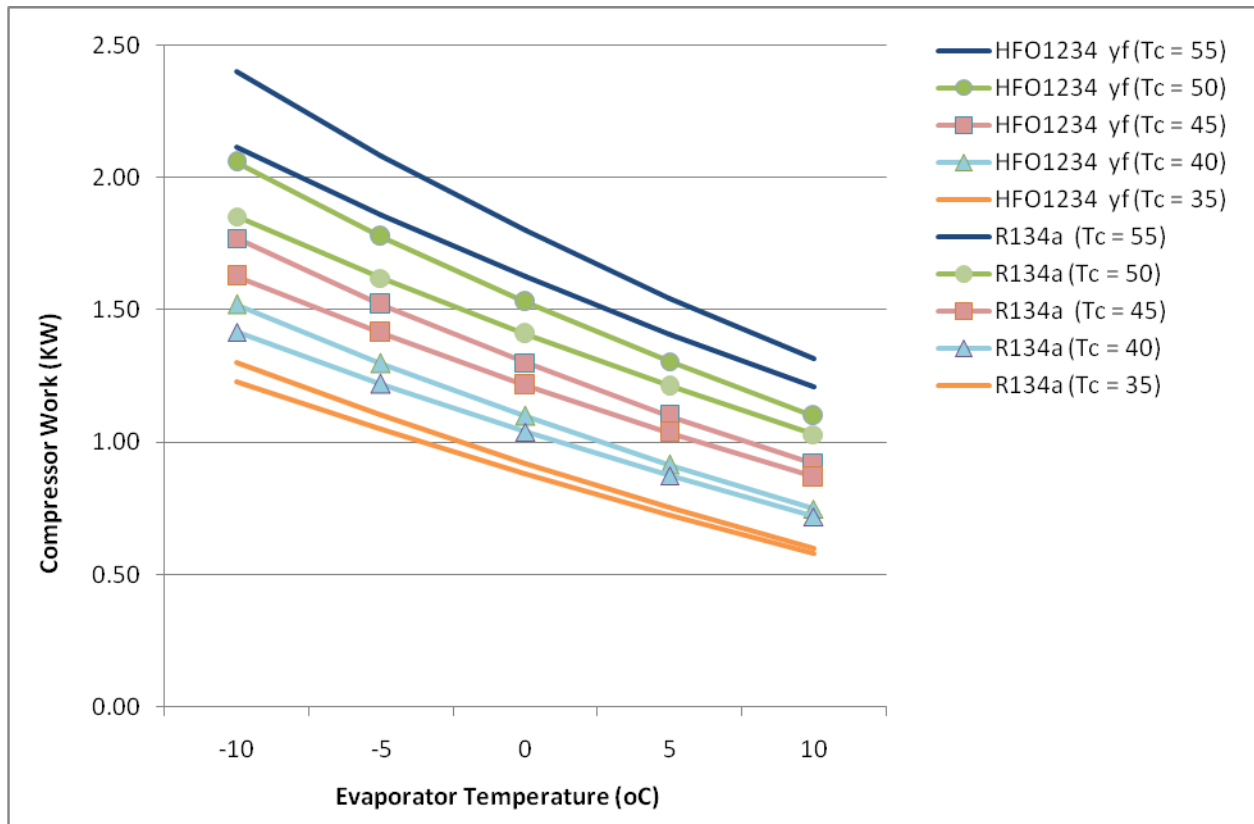


Fig.7 – Theoretical Compressor work Vs. Evaporator Temperature (At varying Condenser Temp) (With & without Heat Exchanger)

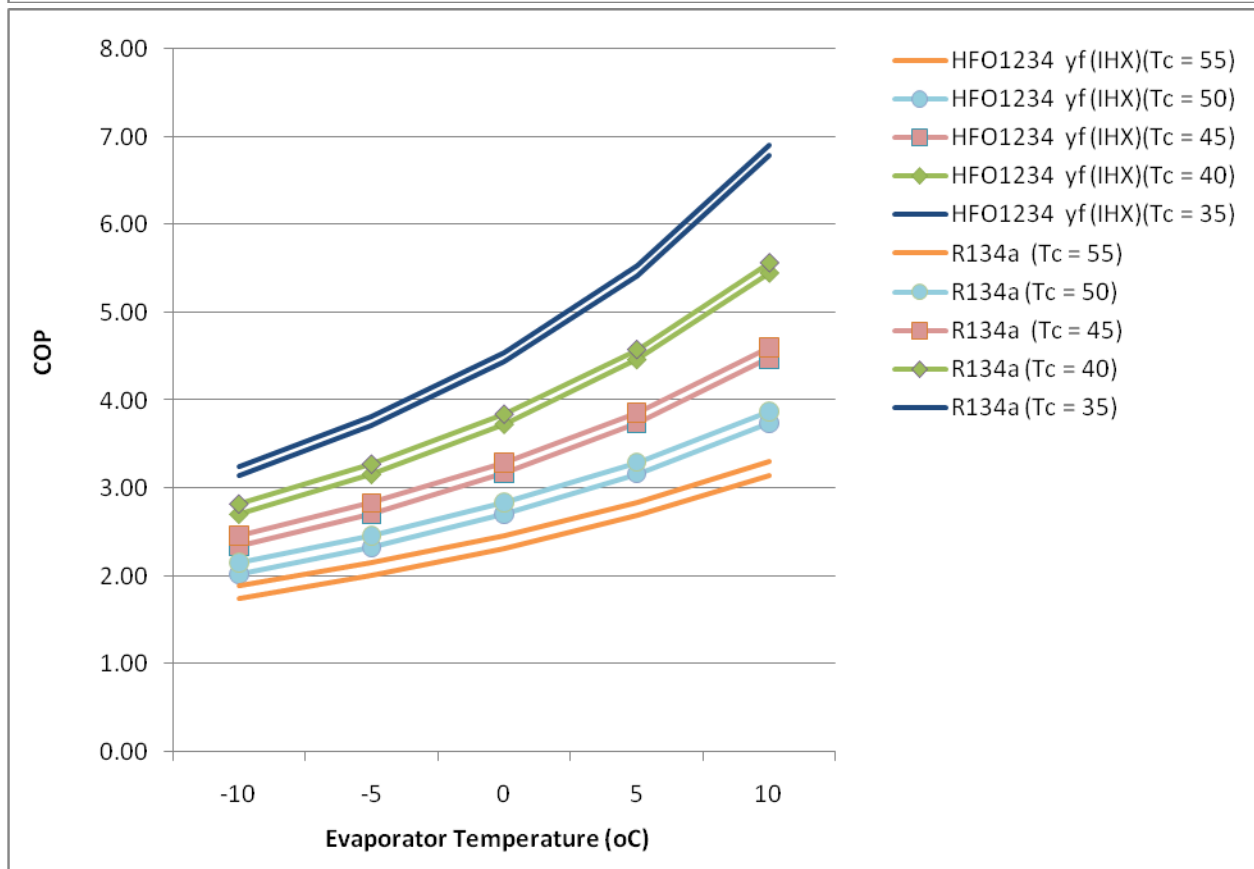
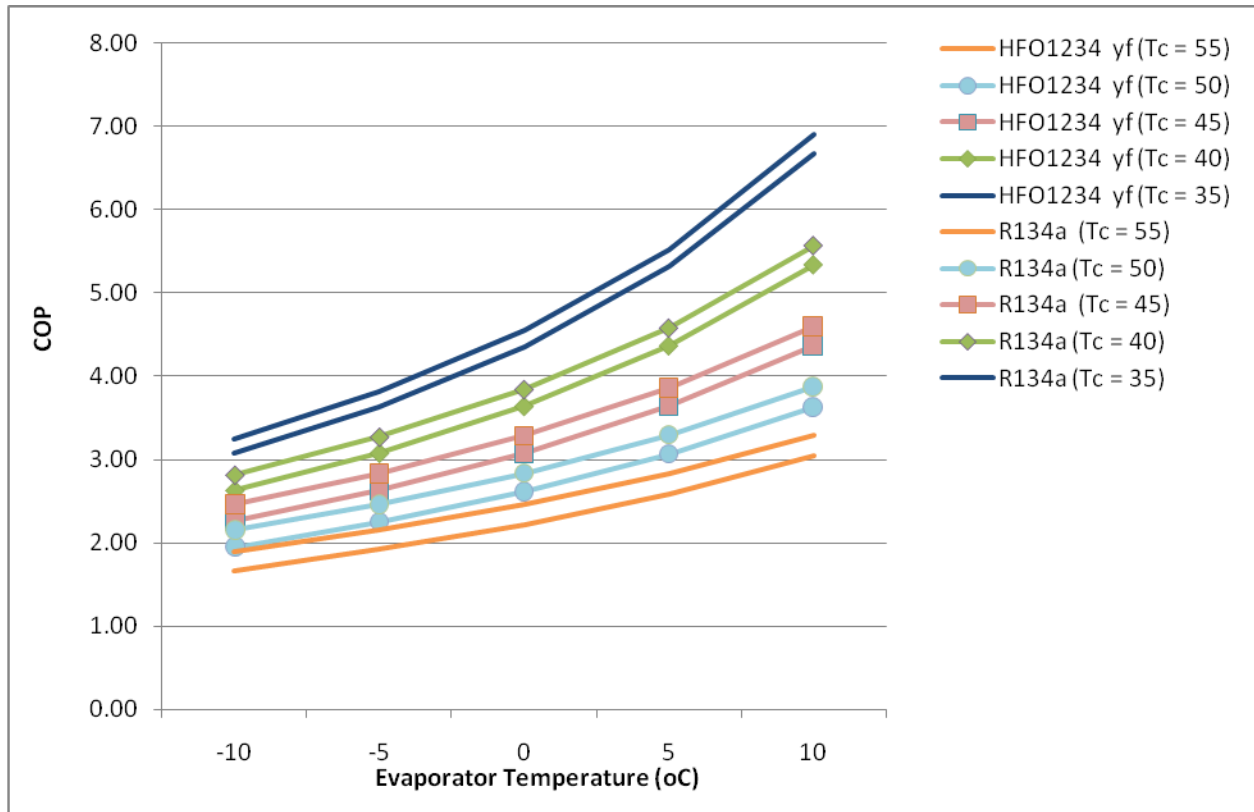


Fig.8 – Theoretical COP Vs. Evaporator Temperature (At varying Condenser Temp) (With & without Heat Exchanger)

#### 4. 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 & 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:

- 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% &
- 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. 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 of an 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 be a good alternative to HFC-134a because of its environmental friendly properties with introducing IHX also.

#### REFERENCES

- [1] Akasaka, R., Tanaka, K., Higashi, Y., 2010, "Thermodynamic property modeling for 2,3,3,3-tetrafluoropropene (HFO-1234yf)", International Journal of Refrigeration 33, 52-60.
- [2] Bryson, M., Dixon, C., St Hill, S., 2011, "Testing of HFO-1234yf and R152a as mobile air conditioning refrigerant replacements" Ecolibrium, 30-38.
- [3] BSI, 2004, "Determination of Explosion Limits of Gases and Vapors". BS EN 1839:2003. The British Standards Institution (BSI), London, UK.
- [4] Bolaji, B.O., 2010, "Experimental study of R152a and R32 to replace R134a in a domestic refrigerator", Energy 35, 3793-3798.
- [5] Directive 2006/40/EC of The European Parliament and of the Council of 17 May 2006 relating to emissions from air conditioning systems in motor vehicles and amending
- [6] Council Directive 70/156/EC. Official Journal of the European Union, 2006.
- [7] Endoh, K., Matsushima, H., Takaku, S., 2010. "Evaluation of cycle performance of room air conditioner using HFO-1234yf as refrigerant. In: International Refrigeration and Air Conditioning Conference at Purdue, West Lafayette, IN, USA. Paper No. 1050.
- [8] Global Environmental Change Report GCRP, 1997. "A Brief Analysis Kyoto Protocol", vol. IX, p. 24.
- [9] Henne, S., Shallcross, D.E., Reimann, S., Xiao, P., Brunner, D., O'Doherty, S., Buchmann, B., 2012. "Future emissions and atmospheric fate of HFC-1234yf from mobile air conditioners in Europe", Environment Scientific Technology 46, 1650-1658.
- [10] Koban, M., 2009. "HFO-1234yf low GWP refrigerant LCCP analysis", SAE Technical Paper 2009-01-0179, <http://dx.doi.org/10.4271/2009-01-0179>.
- [11] Leck, T.J., 2010. New high performance, low GWP refrigerants for stationary AC and refrigeration. In: International Refrigeration and Air Conditioning Conference at Purdue, West Lafayette, IN, USA. Paper No. 1032.
- [12] Lee, Y., Jung, D., 2012. "A brief performance comparison of R1234yf and R134a in a bench tester for automobile applications", Applied Thermal Engineering 35, 240-242.
- [13] Lemmon, E.W., Huber, M.L., McLinden, M.O., 2007. Reference Fluid Thermodynamic and Transport Properties (REFPROP), Version 8.0, in NIST Standard Reference

- Database 23. National Institute of Standards and Technology, Gaithersburg, MD.
- [14] Nielsen, O.J., Javadi, M.S., Sulbak, A., Hurley, M.D., Wallington, T.J., Singh, R., 2007. Atmospheric chemistry of  $\text{CF}_3\text{CF}_2\text{CH}_2$ : kinetics and mechanisms of gas-phase reactions with Cl atoms, OH radicals, and  $\text{O}_3$ . *Chem. Phys. Lett.* 439, 18-22.
- [15] Okazaki, T., Maeyama, H., Saito, M., Yamamoto, T., 2010. Performance and Reliability Evaluation of a Room Air Conditioner with Low GWP Refrigerant. In: *Int. Symp. On Next-generation Air Cond. and Refrig. Technol.* Tokyo, Japan.
- [16] Reasor, P., Aute, V., Radermacher, R., 2010. Refrigerant R1234yf performance comparison investigation. In: *Int. Refrig. and AirCond. Conf. at Purdue*, West Lafayette, IN, USA. Paper No. 1085.
- [17] Spatz, M., Minor, B., 2008. HFO-1234yf: A low GWP refrigerant for MAC. VDA Alternative refrigerant. Winter Meeting. Saalfelden, Australia.
- [18] UNEP, 1987. Montreal Protocol on Substances that Deplete the Ozone Layer. Final Act. United Nations, New York.
- [19] Wongwises, S., Kamboon, A., Orachon, B., 2006. Experimental investigation of hydrocarbon mixtures to replace HFC-134a in an automotive air conditioning system. *Energy Convers. Manage.* 47, 1644-1659.
- [20] World Meteorological Organization (WMO), 2007. Scientific Assessment of Ozone Depletion: 2006, Global Ozone, Research and Monitoring Project Report 50. Switzerland, Geneva.
- [21] Zilio, C., Brown, J.S., Schiochet, G., Cavallini, A., 2011. The refrigerant R1234yf in air conditioning systems. *Energy* 36, 6110-6120.
- [22] J. Navarro-Esbrí, J.M. Mendoza-Miranda, A. Mota-Babiloni, A. Barragán-Cervera, J.M. Belman-Flores. Experimental analysis of R1234yf as a drop-in replacement for R134a in a vapor compression system, "International Journal of Refrigeration 36 (2013) 870-880
- [23] M. Mohanraj, S. Jayaraj and C. Muraleedharan, "Environment friendly alternatives to halogenated refrigerants - a review," *Int. J. Greenhouse Gas Control*, 3, 108-119, 2009.
- [24] United Nations Environmental Programme, "Montreal Protocol on Substances that Deplete the Ozone Layer, Final act," New York, United Nations, 1987.
- [25] Global Environmental Change Report, "A Brief Analysis of the Kyoto Protocol, IX," P.24, 1997.
- [26] "Official Journal of the European Union," Directive 2006/40/EC of the European Parliament and of the Council, 14.6.2006.
- [27] B. Minor and M. Spatz, "HFO-1234yf low GWP refrigerant update," In: *International Refrigeration and Air Conditioning Conference at Purdue*, West Lafayette, IN, USA, Paper No. 2349, 2008.
- [28] C. Zilio, S.S. Brown and A. Cavallini, "Simulation of R-1234yf performance in a typical automotive system," *Proceedings of the 3rd Conference on Thermo physical Properties and Transfer Processes of Refrigeration*, Boulder, CO, USA, Paper No. 128, 2009.
- [29] J.S. Brown, "HFOs - New, Low Global Warming Potential Refrigerants," *ASHRAE Journal*, 22-29, 2009.
- [30] R. Akasaka, Y. Kayukawa, Y. Kano and K. Fujii, "Fundamental Equation of State for 2,3,3,3-Tetrafluoropropene (HFO-1234yf)," *International Symposium on Next-generation Air Conditioning and Refrigeration Technology Tokyo: New Energy and Industrial Technology Development Organization*, 2010.
- [31] J.S. Brown, C. Zilio and A. Cavallini, "Critical Review of the Latest Thermodynamic and Transport Property Data and Models, and Equations of State for R-1234yf," *13th International Refrigeration and Air Conditioning Conference at Purdue*, West Lafayette, 2450, 1-9, 2010.
- [32] C. Cang, S. Saitoh, Y. Nakamura, M. Li and E. Hihara, "Boiling Heat Transfer of HFO-1234yf Flowing in Smooth Small-Diameter Horizontal Tube." *International Symposium on Next-generation Air Conditioning and Refrigeration Technology*, Tokyo: New Energy and Industrial Technology Development Organization, 2010.
- [35] Y. Higashi, "Thermophysical Properties of HFO-1234yf and HFO-1234ze(E)," *International Symposium on Next-generation Air Conditioning and Refrigeration Technology*, Tokyo: New Energy and Industrial Technology Development Organization, 2010.
- [33] E.W. Lemmon, M. L. Huber and M. O. McLinden, "NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties," REFPROP, Version 9.0. National Institute of Standards and Technology, Standard Reference Data Program. Gaithersburg, 2010.
- [34] T.J. Leck, "Evaluation of HFO-1234yf as a Potential Replacement for R-134a in Refrigeration Applications," *3rd IIR Conference on Thermophysical Properties and Transfer Processes of Refrigerants*, Boulder, 155, 1-9, 2009.
- [35]. T.J. Leck, "New High Performance, LOW GWP Refrigerants for Stationary AC and Refrigeration," *13th International Refrigeration and Air Conditioning Conference at Purdue*, West Lafayette, 2160, 1-8, 2010.
- [36] S.F. Yana Motta, E.D. Vera Becerra and M.W. Spatz, "Analysis of LGWP Alternatives for Small Refrigeration (Plugin) Applications," *13th International Refrigeration and Air Conditioning Conference at Purdue*, West Lafayette, 2499, 1-7, 2010.
- [37] B. Minor, C. Montoya, and F.S. Kasa, "HFO-1234yf Performance in a Beverage Cooler," *13th International Refrigeration and Air Conditioning Conference at Purdue*, West Lafayette, 2422, 1-6, 2010.

- [38] P. Reaser, V. Aute and R. Radermacher, "Refrigerant R1234yf Performance Comparison Investigation," International Refrigeration and Air Conditioning Conference 1085, 2010.
- [39] S. J. Zhang, H. X. Wang and T. Guo, "Evaluation of non-azeotropic mixtures containing HFOs as potential refrigerants in refrigeration and high-temperature heat pump systems," *Sci China Tech Sci*, 53, 1855-1861, 2010.
- [40] D. Leighton, Y. Hwang and R. Radermacher, "Modeling of Household Refrigerator Performance with LGARs," ASHRAE Winter Conference, Chicago, 2012.
- [41] O. Abdelaziz, K.M. Karber and E.A. Vineyard, "Experimental Performance of R-1234yf and R-1234ze as Drop-in Replacements for R-134a in Domestic Refrigerators," 14th International Refrigeration and Air Conditioning Conference at Purdue, West Lafayette, 2241, 1-10, 2012.
- [42] J. N. Esbri, J.M.M. Miranda, A.M. Babiloni, A.B. Cervera and J.M.B. Flores, "Experimental analysis of R1234yf as a drop-in replacement for R134a in a vapor compression system," *International Journal of Refrigeration* 36, 870-880, 2012.
- [43] D. Jung, Y. Lee and D. Kang, "Performance of virtually non-flammable azeotropic HFO1234yf/HFC134a mixture for HFC134a applications," *International Journal of Refrigeration* 36, 1203-1207, 2013.
- [44] M. Richter, M.O. McLinden, and E.W. Lemmon, "Thermodynamic Properties of 2,3,3,3-Tetrafluoroprop-1-ene (R1234yf): Vapor Pressure and p-rho-T Measurements and an Equation of State," *Journal of Chemical and Engineering Data*, 56, 3254-3264, 2011.
- [45] R. Akasaka, "New Fundamental Equations of State with a Common Functional Form for 2,3,3,3-Tetrafluoropropene (R-1234yf) and trans-1,3,3,3-Tetrafluoropropene (R-1234ze(E)),", *International Journal of Thermophysics*, 32, 1125-1147, 2011.
- [46] S.A. Klein and F. Alvarado, engineering Equation Solver, F Chart software, Middleton, WI, Version 9.223, 2012.