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International Refrigeration and Air Conditioning Conference
School of Mechanical Engineering

2010

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ABSTRACT

Novel refrigeration working fluids with attributes of superior thermal performance and low environmental impact are in development stages approaching commercialization. These fluids known as HFO-1234yf and HFO-1234ze exhibit very low global warming potential, good refrigeration performance, improved flammability characteristics compared to hydrocarbon materials, and are in conformance with the EU F-Gas Regulation (EC 842/2006). Use of these fluids in small refrigeration machines offers the potential to improve energy performance. This article presents and analyzes results of an experimental evaluation of HFO-1234yf and HFO-1234ze in atypical vending system.

1. INTRODUCTION

Due to a growing global concern about the increasing impact of mankind on the warming of our atmosphere, the refrigerants that have been used as working fluids for small (plug-in) refrigeration applications have come under scrutiny. Regulators around the world are now focusing on the direct global warming impact of these fluids. An example of this is the European directive that will phase out the use of R-134a in automobile air conditioning systems starting in 2011 and a complete phase out scheduled for 2017. More recently the United States along with Canada and Mexico proposed adding a phase down in the use of HFCs to the Montreal Protocol calling for a 10 percent reduction by developed nations beginning in 2013, culminating in an 85 percent phase down by 2033.
As a result of the need to find suitable substitutes for higher global warming refrigerants, two new low global warming refrigerant molecules have been identified, HFO-1234yf & HFO-1234ze. These molecules are Hydro-Fluoro-Olefins (HFO) that due to their very short atmospheric life times of 11 and 18 days (as compared to 12 years for HFC-134a) have an extremely low GWP of only 4 to 6 (as compared to 1410 for R-134a). This article will discuss properties and applications of these potential refrigerant options in small refrigeration systems.

2. REFRIGERANTS PROPERTIES

2.1 Thermal, Environmental and Flammability Properties

Depicted in Table 1 are properties of both HFO-1234yf and HFO-1234ze, together with some refrigerants also proposed as replacements for R-134a. Note that boiling temperatures of proposed fluids are within a few degrees of the replaced fluid (R-134a). Additionally, both HFO refrigerants have critical temperatures consistent with R-134a. Also shown in Table 1 are Permissible Exposure Limits (PEL) and flammability limits (LFL and UFL). Both HFO fluids have very low toxicity. HFO-1234yf is already classified as "A" by ASHRAE with similar expectancy for HFO-1234ze. It is also important to note that HFO-1234ze does not exhibit flame limits under standard test conditions of ASTM E-681 or EU A11. HFO-1234ze does, however, exhibit flame limits at elevated temperatures (above 30°C).

Table 1: Refrigerant Properties

Refrigerant	GWP	Boiling Temp. (°C)	Critical Temp. (°C)	PEL (ppm)	LFL / UFL (Vol%, 23°C)
R-134a	1410	-26	101	1000	-
1234ze	6	-19	110	1000	-
1234yf	4	-30	94	500	6.2-12.3
R-600a	~5	-12	135	800	1.8-8.5
R-744	1	-78.4	31	4000	

2.2 Thermal Stability

Thermal stability evaluations were conducted using the ASHRAE standard 97 test method (ASHRAE, 2007). A typical viscosity POE appliance oil, ISO 10 was used in this evaluation. Both HFO-1234yf and HFO-1234zewere tested under extreme conditions: high moisture (1000 ppm), high temperature (200°C) and long duration (2 weeks). Visual examination of the sealed tube showed no change in the appearance (figure 1) of the refrigerant and oil. Results of the analysis of the oil show very low acidity values (TAN values ranging from 0.07 to 0.44). In addition, gas chromatography and molecular weight measurements of the refrigerant performed before and after tests show no change in the purity of the material. One can conclude from this evaluation that HFO-1234yf and HFO-1234ze are very stable with oils used in these applications.

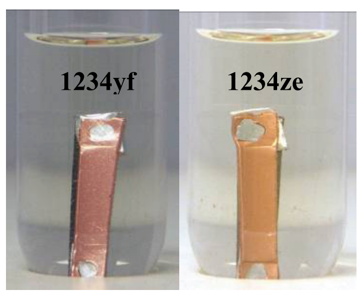

Figure 1: HFO-1234yf and HFO-1234ze with ISO 10 POE oil exposed to 200°C for 2 weeks

2.3 Refrigerant/oil properties

Measurements were made of the properties (solubility, density and viscosity) of the refrigerant and lubricant pair using an ISO 10 POE oil (ProEco 10S) with HFO-1234yf and HFO-1234ze. These pairs were found to be fully miscible for the operating range (-25 to 70ºC). Testing methodology is well explained in Seeton and Hrnjak (2009).

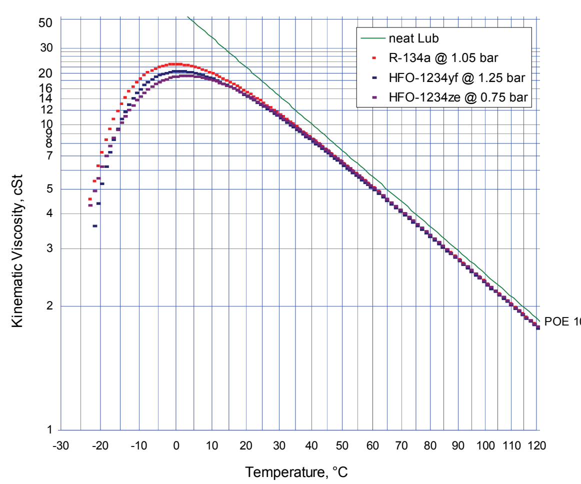

Figure 2: Refrigerant oil viscosity comparison at typical operating conditions for appliances compressors.

The results showed that HFO-1234yf and this lubricant have solubility similar to R-134a whereas HFO-1234ze is slightly more soluble than R-134a. Using this solubility information, we evaluated compressor sump viscosities at typical evaporating temperatures. As shown in figure 2, viscosities of HFO-1234yf/oil and HFO-1234ze/oil are similar to R-134a/oil. Therefore, we can conclude that lubricating properties are not likely to be impacted by use of HFO-1234yf or HFO-1234ze.

3. EXPERIMENTAL SETUP AND OPERATING CONDITIONS

An experimental study for R-134a, HFO-1234yf and HFO-1234ze was performed using a representative vending machine. The original R-134a system consisted of tube-and-fin heat exchangers, a reciprocating compressor and thermostatic expansion valve. Tests with HFO-1234yf required the use of a needle valve as expansion device to reproduce the same degrees of superheat observed with R-134a. Tests with HFO-1234ze required a needle valve as expansion device and a compressor with 75% larger displacement. The compressor used for HFO-1234ze was a commercially available larger capacity R-134a compressor.

Tests were performed operating conditions developed to evaluate efficiency and capacity. The efficiency test requires an external ambient temperature of 90ºF (32.2ºC) and 65% relative humidity while the interior space was maintained at 2ºC. The capacity test uses the same interior temperature (35.6ºF or 2ºC) but with an external ambient temperature of 105ºF (40.5ºC) and 75% relative humidity.

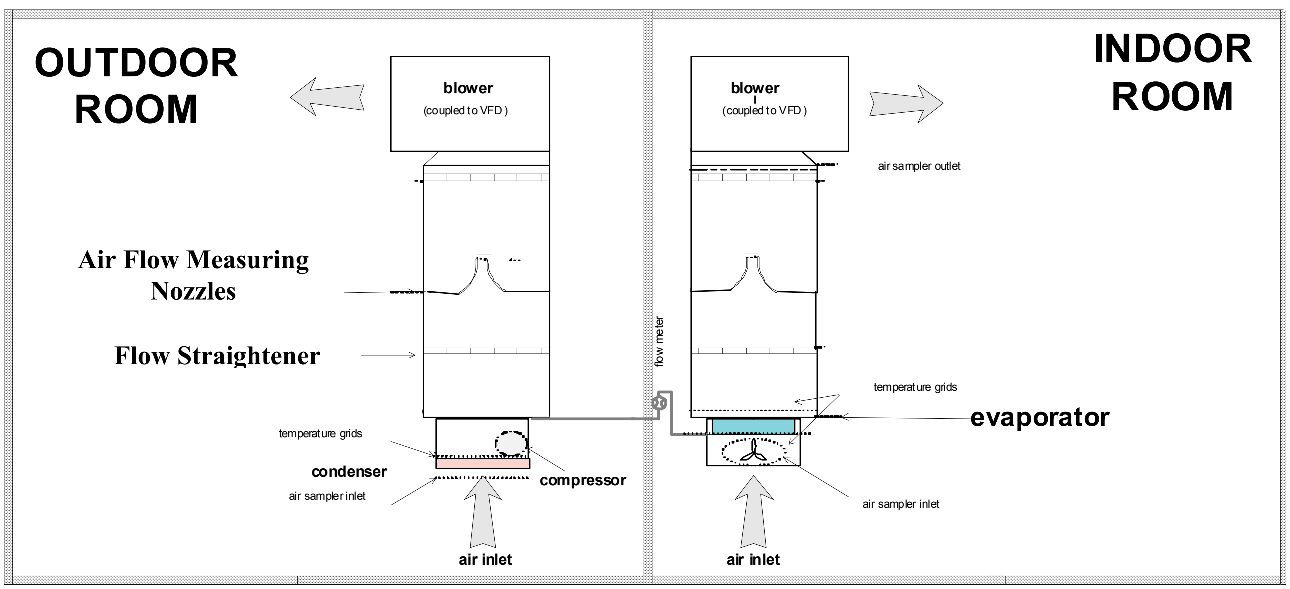

Figure 3: Experimental setup.

All tests were performed inside environmental chambers equiped with instrumentation to measure both air-side and refrigerant-side parameters (Figure 3). Refrigerant flow was measured using a coriolis flow meter while air flow and capacity was measured using an air-enthalpy tunnel designed according to industry standards (ASHRAE, 1992; AHRI, 2008). All primary measurement sensors were calibrated to ±0.27ºF (0.15ºC) for temperatures and ±0.25 psi for pressure. Overall system uncertainties (capacity and efficiency) were in average ±5%.

Although vending systems have usually closed-coupled connections, our evaluation required splitting the system in indoor (evaporator-fan) and outdoor units (condenser-fan-compressor). These units were placed at the inlet of the each tunnel which were located as close as possible to minimize connecting lines length. Pressure drop in the suction line was below the maximum recomended (1.8ºF or 1ºC). Air flow was set as expected in the actual system: free flow for the condensing unit and standard air-side pressure drop for the evaporator (0.1 inch of water).

4. RESULTS

4.1 Overall system Performance

Figure 4 and table 2 show results of the evaluation. HFO-1234yf confirms being an excellent replacement for R-134a by giving similar capacity and efficiency. Both capacity and efficiency differences are in the range of experimental uncertainty. Due to the use of a larger compressor, HFO-1234ze shows an average of 12% larger capacity and 8% lower efficiency. The higher capacity was expected due to the use of a larger displacement commercially-available compressor.

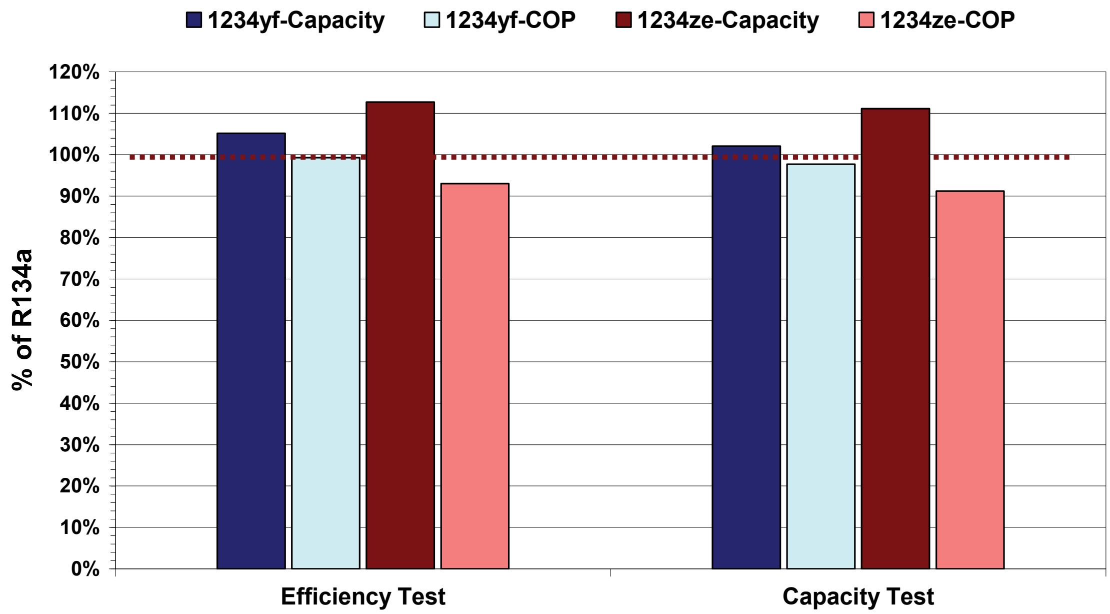

Figure 4: Overall system performance results.

Table 2: Summary of evaluations.

Fluids / Tests		Overall System			Heat Exchangers					Compressor		
		Cap.	COP	Mass Flow	Cond. Temp	Evap. Temp	Disch. Temp.	ΔT-sat Evap	ΔT-sat Cond	Pd/Ps	Isent. Eff.	Vol. Eff.
		% of R134a	% of R134a	% of R134a	% of R134a	% of R134a	ºF	ºF	ºF	% of R134a	% of R134a	% of R134a
R134a	Eff. Test	100%	100%	100%	100%	100%	179	2.0	0.4	100%	100%	100%
	Cap. Test	100%	100%	100%	100%	100%	196	1.9	0.3	100%	100%	100%
1234yf	Eff. Test	105%	99%	127%	105%	112%	166	2.6	0.5	95%	84%	98%
	Cap. Test	102%	98%	119%	104%	106%	183	2.6	0.3	95%	84%	95%
1234ze	Eff. Test	113%	93%	125%	104%	112%	189	4.8	0.6	109%	82%	92%
	Cap. Test	111%	91%	123%	103%	109%	206	4.6	0.5	110%	82%	91%

4.2 Heat Exchangers Analysis

Figure 6 shows condensing and evaporating temperatures of both HFO refrigerants compared to R-134a. HFOs show slightly higher condensing and evaporating temperatures. The higher condensing temperature indicates that some improvements in the design are possible. On the other hand, the higher evaporating temperature is explained by the larger mass flow improving the in-tube heat transfer.

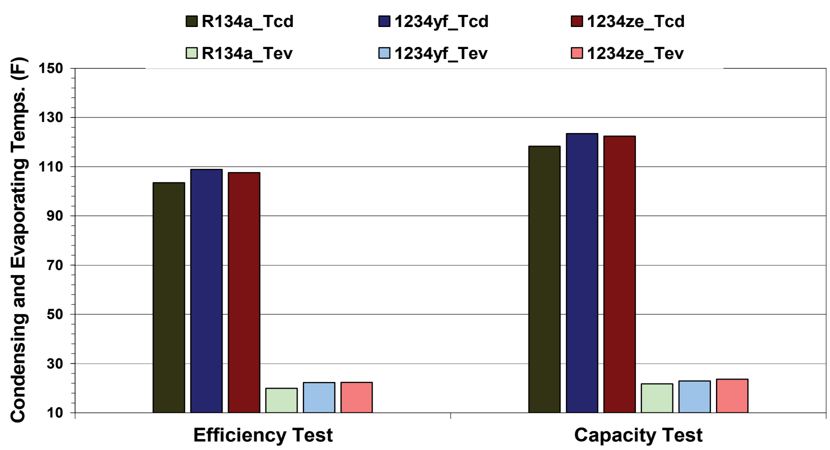

Figure 5: Condensing and Evaporating Temperatures

Figure 6 reinforces the above by showing significant differences in saturated pressure drop penalties between R-134a and the new HFOs. Since evaporator impact on performance is usually more significant, some minor modifications to the evaporator design can furher improve the performance, especialy for HFO-1234ze.

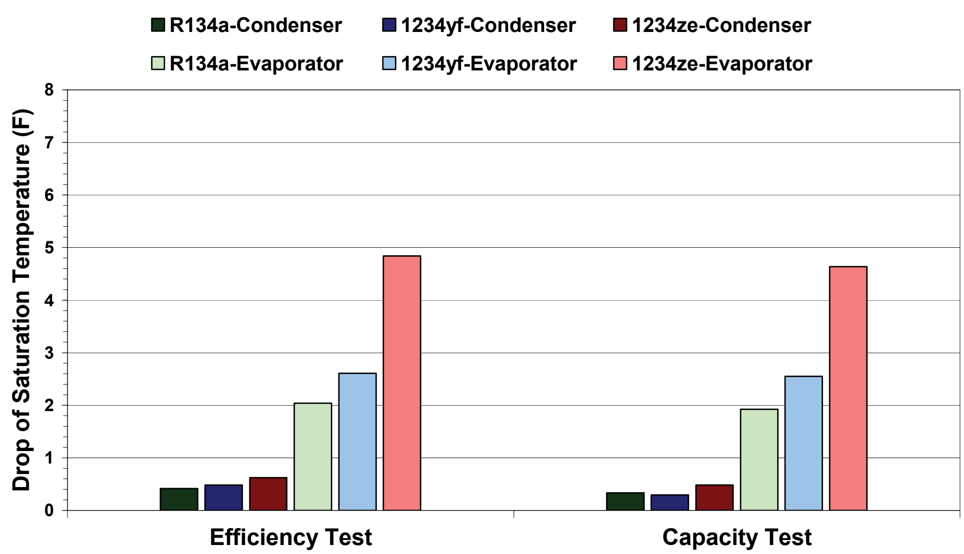

Figure 6: Drop of saturated temperature in heat exchangers

4.3 Compressor Analysis

Figure 7 shows HFO-1234yf as having volumetric eficiencies comparable to R134a while its isentropic efficiencies were about 16% lower. These results coupled with the lower discharge temperature and compression ratio (5% lower), shown in figure 8, indicate potential for further improvement in the compressor design.
In the case of HFO-1234ze, both volumetric and isentropic efficiencies were significant lower (9% and 18% respectively). In addition, compression ratio and discharge temperature were higher than R-134a's. These last reults were largerly affected by the larger pressure drops in the system and the use of an oversized compressor. This loss of efficiency can be recovered using a compressor designed for HFO-1234ze and an electric motor properly sized.

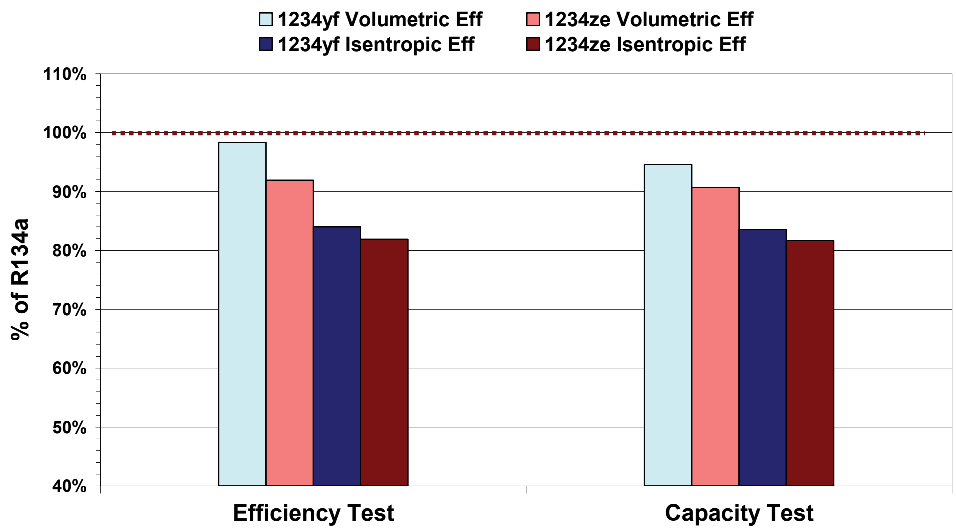

Figure 7: Isentropic and Volumetric Efficiencies

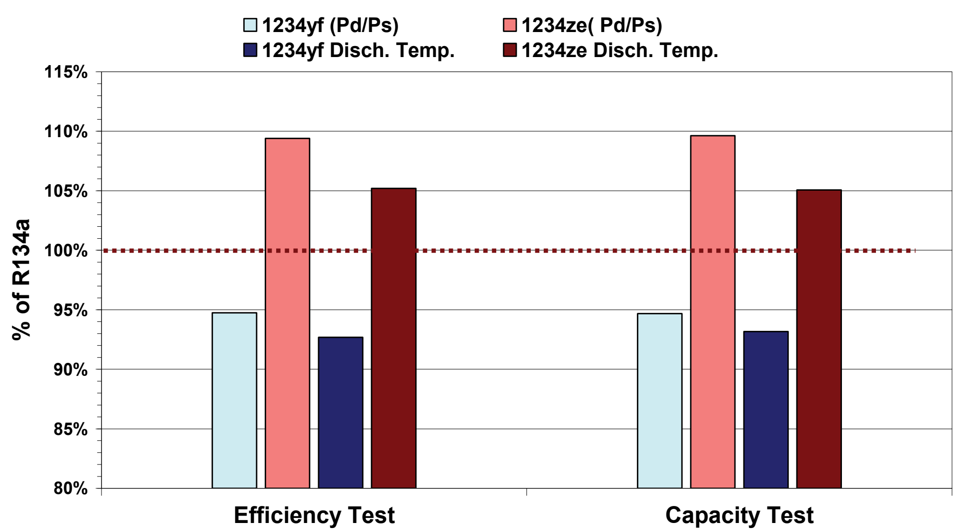

Figure 8: Compression ratio and Discharge temperature

5. CONCLUSIONS

HFO-1234yf and HFO-1234ze have potential in applications such as small commercial and residential refrigeration systems and other areas where a medium pressure refrigerant can be efficiently employed and where low global warming refrigerants are needed or desired.

This study reported detailed performance evaluation of these HFO refrigerants in an actual vending system. Overall results show that comparable performance to R-134a can be achieved without significant hardware modification. The thermal stability and good interaction with POE oils used in this applications has also been demonstrated.

HFO-1234ze efficiencies were lower than R-134a and HFO-1234yf . This was mainly due to pressure drop losses in the evaporator and compressor penalties (suction passages and electric motor sized for R-134a). Neverthless HFO-1234ze had an COP of 1.11 (efficiency), which is above the minimum level (1.0) mentioned by previous studies (DeAngelis and Hrnjak, 2005). We believe that this loss of efficiency can be recovered using a compressor properly sized and designed for HFO-1234ze as well as some minor modifications to the evaporator.

HFO-1234yf performance is comparable to R-134a using current vending systems designs. Better efficiencies are possible with minor design changes in the compressor and by the use of Suction-Line/Liquid-Line (SL-LL) heat exchangers. This is to exploit HFO-1234yf's low discharge temperature and compression ratio. The use of capillary tubes as expansion device and SL-LL heat exchanger, similarly to domestic refrigerators, is suggested.

This study showed that using HFO fluids can enable the design of vending systems with low environmental impact. This is achievable by reducing direct (low GWP) and indirect emissions (good efficiency). Further investigations for these applications should include additional performance evaluations as well as flammability risk assessments where appropriate.

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