2014

Long Term Viability of HFO-1234yf in Stationary Refrigeration Systems – Multi-Year Evaluation of Refrigerant, Lubricant, and Compressor Performance in a Domestic Freezer

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ABSTRACT

In recent years, HFO-1234yf has been introduced as a low global warming potential (GWP) replacement for HFC-134a in a variety of refrigeration and air conditioning applications both as a pure fluid (mildly flammable) and in refrigerant blends (both mildly flammable and non-flammable). A large and growing body of work on HFO-1234yf exists for mobile air conditioning, however recently interest in the use of R-1234yf in stationary refrigeration applications is growing.

This paper will report the results of the longest continuous test to date (> 4 years) of a commercial stationary system operating on R-1234yf refrigerant. The test was initiated in 2009 in a 4ft reach in chest freezer by recovering the R-134a and replacing with R-1234yf. Since that time the system has operated normally and energy usage and operating data has been continuously collected. Recently, the freezer was shut down, refrigerant and oil samples collected for chemical and physical analyses and the compressor removed for a tear down inspection.

Operational and energy performance data for the system over the duration of the extended test period will be presented and compared to baseline operation on R-134a. Results of the system performance data as well as the chemical stability measurements of R-1234yf and POE oil, along with the compressor tear down metrology will be used to validate the long term viability of this new class of low GWP refrigerants (HFO's) and R-1234yf in particular.

1. INTRODUCTION

In recent years, HFO-1234yf has been introduced as a low global warming potential (GWP) replacement for HFC-134a in a variety of refrigeration and air conditioning applications both as a pure fluid (A2L-mildly flammable) and in refrigerant blends (both mildly flammable and non-flammable). A large and growing body of work on HFO-1234yf exists for mobile air conditioning, however recently interest in the use of R-1234yf in stationary refrigeration applications is growing.

This paper reports the results of the longest continuous test to date (> 4 years) of a commercial stationary system operating on R-1234yf refrigerant. The test was initiated in 2009 in a reach in chest freezer by recovering the R-134a refrigerant and replacing with R-1234yf. Since that time the system has operated normally and energy usage and operating data has been continuously collected. Recently, the freezer was shut down, refrigerant and oil samples collected for chemical and physical analyses and the compressor removed for a tear down inspection.

2. SYSTEM CONVERSION AND DECOMMISSIONING

2.1 System Conversion

In the fall of 2009 a Frigidaire Model # FFN15M5HHWA chest freezer (48"x 27.5"x 30") was installed in a semi-sheltered out-door loading dock area at the DuPont Refrigerants Testing Center in Wilmington, DE where it was allowed to operate year round and subjected to local ambient weather conditions. After initial start-up and base line data monitoring for several months, the freezer was converted from operation on R-134a refrigerant to R-1234yf (2, 3, 3, 3 tetrafluoro prop-1-ene

Table 1: Basic Properties of R-134a and R-1234yf

	R-134a	**R-1234yf**
Name	1,1,1,2 Terafluoro ethane	2,3,3,3 Tetrafluoro prop-1-ene
Chemical Formula	CF3CFH2	CH2=CFCF3
Molecular Weight	102	114
Normal Boiling Pt, C	-26.1	-29.4
Sat Vap Pres (kPA) @20C	774.3	794.3
Sat Vap Pres(kPA) @60C	1884	1844
Critical Temperature, C	101.1	94.7
GWP (AR5) CO2 = 1.0	1300	< 1

The basic physical and chemical properties of R-1234yf are listed in Table 1 along with those of R-134a. (1)

The retrofit procedure followed standard industry protocols including recovery of refrigerant, evacuation of the system, and charging with the new refrigerant. No changes were made to the lubricant. The only other modifications to the system were the installation of data monitoring devices to collect operating pressures, temperatures, and energy consumption.

2.2 System Decommissioning and Refrigerant, Lubricant, and Compressor Analysis

Just prior to 2014 the freezer was shut down and decommissioned from service by recovering the refrigerant and lubricant. Samples of each were sent to the laboratory for chemical analyses. The compressor was purged with nitrogen, sealed and submitted to an engineering company for tear down inspection and wear analysis.

3. RESULTS AND DISCUSSION

3.1 System Performance

Throughout the four plus year evaluation period using R-1234yf the freezer was operated continuously while located in an out-door loading dock area in Wilmington, Delaware where it was subjected to seasonal variation in ambient temperature and humidity. In the coldest winter months the compressors would operate less frequently, depending on weather conditions. The unit operated normally over this extended time period. Manual defrosts of the chest freezer were performed 1-2 times per year in the summer months.

Table 2 shows the average values for various operating parameters such as suction and discharge pressures and temperatures, as well as compressor cut-in, run times, etc. during selected periods when the compressor was operating over the duration of the evaluation.

Table 2: Selected System Data during Compressor Operation

Year	Date	Dry Bulb Temp (C)	Suction Pressure (kPA)	Discharge Pressure (kPA)	Suction Temperature (C)	Discharge Temperature (C)	Number of cut-ins	Compressor Run time (mins)	Daily Fraction Run time	Daily Average Box Temp (C)
2009	9-Sep	18.3	98.0	875.4	26.2	57.2	19	494	0.34	-17.5
2010	9-May	11.4	88.7	719.5	16.5	43.9	17	386	0.27	-16.9
2010	11-Jul	27.7	107.5	1075.0	37.5	72.6	18	644	0.45	-17.7
2011	2-May	18.3	101.2	906.0	28.0	58.9	15	494	0.34	-17.1
2011	19-Jul	30.6	109.2	1133.6	39.6	76.6	15	686	0.48	-17.5
2011	22-Oct	11.8	90.1	761.1	19.2	46.8	13	364	0.25	-17.4
2012	19-Apr	17.7	94.5	901.4	26.5	57.8	12	478	0.33	-16.1
2012	5-Aug	29.5	105.8	1088.3	37.9	74.0	13	674	0.47	-16.2
2012	13-Oct	11.8	89.8	793.9	21.2	49.8	10	384	0.27	-15.5
2013	4-Jun	21.8	101.6	961.2	30.3	63.2	12	550	0.38	-16.2
2013	16-Jul	32.6	108.2	1192.5	41.9	80.2	13	742	0.52	-16.7
2013	31-Oct	16.1	93.9	815.2	23.7	52.6	19	512	0.36	-17.0

Figure 1 is a plot of daily energy consumption for the chest freezer over the duration of the test period shown for the R-134a baseline period, R-1234yf operation for years 2009-12 combined, and finally R-1234yf for the year 2013.

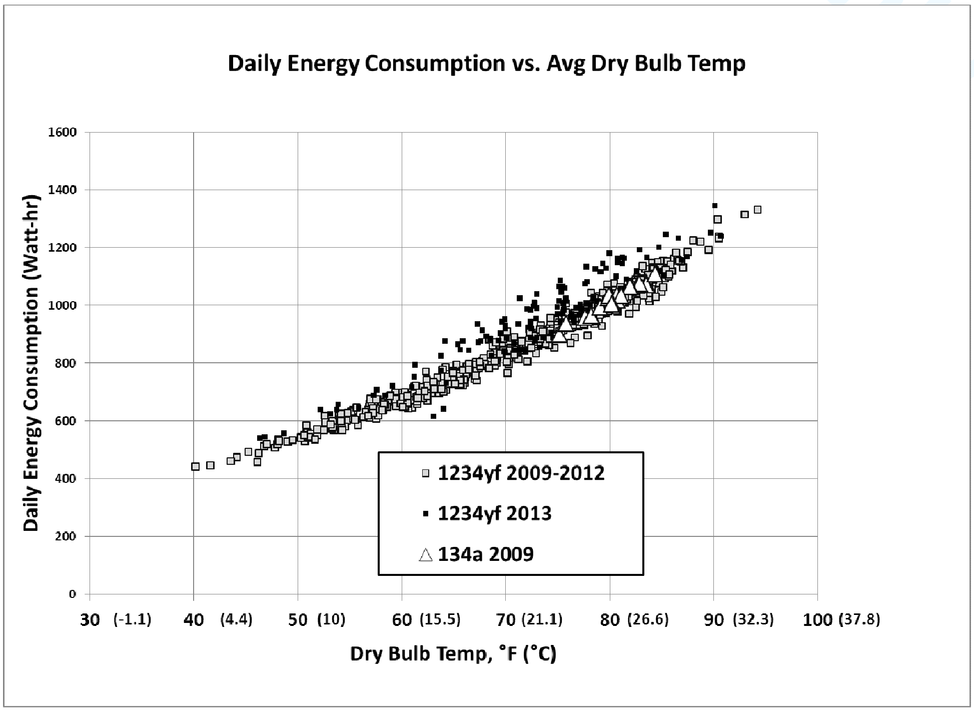

Figure 1: Chest Freezer Energy Performance Over 4+ Years

The energy consumption of the freezer operating on R-1234yf correlated very well with ambient dry bulb temperature and closely matched the baseline energy data obtained with the original R-134a refrigerant. The energy consumption year over year continued to reproduce very well until just a few months prior to the conclusion of the test. In the fall of 2013 it was noticed the energy consumption appeared to have increased. Further data analysis and investigation lead to the discovery of a large amount of ice inside the bottom of the freezer compartment which had insulated and dislodged the thermostat sensing bulb. This layer lead to large swings in box temperatures, increased run time and power consumption. Data analysis allowed pin-pointing of this problem to an electrical storm and extended power outage which evidently was the root cause of the poor performance. After a full defrost and drying of the unit, the system was restarted and the energy consumption returned to baseline levels which were maintained until termination of the test.

3.2 Recovered Refrigerant and Lubricant Analysis

The result of the laboratory gas chromatography/mass spectrometry (GC/MS) organic purity analysis of the recovered R-1234yf refrigerant is reported in Table 3 below.

Table 3: Organic Purity of Used R1234yf by GC/MS

Impurity in Recovered R-1234yf	ppm, wt
HFC-134a	8707
Mostly HFC-134	15
HFC-1243zf	11
HCFC-22	111
HFC-245eb	3
Isobutane	1
n-Butane	2
Tetrahydrofuran	10
1,4-Dioxane	4
Possible Butenoic acid ester	1
Small others	6
HFO-1234yf Organic Purity	99.11%

The GC/MS analysis showed the overall purity of the R1234yf to be quite good, with no indication of change, instability or breakdown of the refrigerant during service and consistent with results from sealed glass tube stability tests with R-1234yf, an industry standard for evaluating thermal stability of refrigerants. The amount of R-134a and to a lesser extent R-22 reported in this analysis are likely carry over residual contamination from the system oil (which was not changed out), or from the charging/recovery equipment.

Table 4 contains the laboratory analysis of the refrigerant and oil for acidity and fluoride and chloride content which again, would be an indication of refrigerant and/or lubricant decomposition.

Table 4: Laboratory Results for Recovered Oil and R-1234yf Refrigerant

Chemical Analysis of Used R1234yf Refrigerant and Oil				
Acidity as HCl equiv. = 1.6 ppm				
TAN = 0.01 mg				
	Measured Anions		Actual Anions	
Sample ID	F^-	Cl^-	F^-	Cl^-
	ppm	ppm	ppm	ppm
Oil sample	0.12	0.66	<MDL	<MDL
1234yf Refrigerant sample	0.01	0.43	<MDL	<MDL
Min Detection Limit (MDL) : F-= 3.00 ppm Cl-= 4.50 ppm				

The lubricant was clear with no signs of breakdown. The lab reported a subtle yellow hue, but as the photo in Figure 2 shows, it is very subtle indeed. No significant acid or halides were detected, with results very close to a virgin sample of appliance grade POE. Again, the results of these analyses are typical of what is to be expected in a system of this type, operating under these conditions, over this time period.

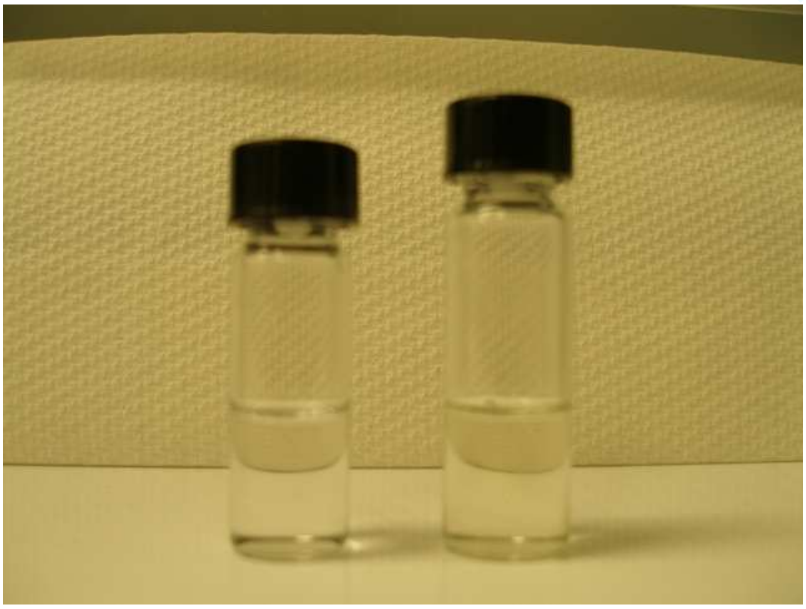

Figure 2: Virgin and Recovered Compressor Oil

Finally, the lubricant was submitted for trace metals analysis, a good indicator of compressor wear in a hermetic refrigeration system. The wear metals analysis by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) result is presented in Table 5.

Table 5: Analysis of Recovered Oil for Wear Metals Using ICP/MS

ICP Analysis for Trace Metals		
	RL10H Virgin Oil	Chest Freezer Oil Sample
Al	2 ug/g	3 ug/g
B	1	2
Ca	7	3
Cr	<1	<1
Cu	<1	<1
Fe	<1	2
Mg	<1	<1
Mn	<1	<1
Na	2	1
Ni	<1	<1
Si	26	11
Si	1	2
Zn	2	1

All values were low and consistent with standard operation of the compressor and other system components. Trace metal content from the lubricant used in the system for 4 years was comparable to that found in virgin oil of similar type and gave no indication of significant compressor wear, metallurgic, or lubrication issues.

3.3 Compressor Tear down Analysis Results

3.3.1 Engineering Firm's Overall Conclusion:

> ***"…From what we know about the compressor's life history running with HFO-1234yf, the amount of wear observed would be comparable to, and appropriate for, a compressor with a similar life history that had been charged with R-134a. In our opinion, the use of HFO-1234yf refrigerant did not have a detrimental effect on compressor wear compared to R-134a."***

3.3.2 Tear down Analysis – Running Conditions and Procedural Details

A summary of the running conditions experienced by the compressor over the duration of this test is presented in Table 6.

Table 6: Compressor Running History

Running Field Service Conditions	
Discharge Pressure	619.8 to 1488 kPA
Discharge Temperature	20.9 to 97.8 C
Suction Pressure	72.4 to 193.7 kPA
Suction Temperature	1.7 to 62.5 C
Superheat	7.7 to 68.2 C
Freezer Box Temperature	-23.1 to -9.4C
Service Time	4+ years

Note: The Embraco model EM2Z60HLT compressor features a directed suction gas inlet that makes it more efficient, but also more vulnerable to damage from refrigerant floodback. Due to limitations in the run condition data it was not possible to determine whether floodback occurred during the compressors life, however given the condition of the compressor, it is not believed that excessive floodback played a major role in the wear observed.

The compressor was removed from the freezer, purged with nitrogen, sealed and shipped to the engineering lab for analysis. The compressor shell was cut-apart and the pump disassembled for analysis of all appropriate wear surfaces. Photographs were taken at each stage of disassembly. Visual analysis of the wear surfaces were conducted with the aid of 10X and 20X microscopes and photographs were also taken of each wear surface. Surface metrology data was then obtained with a profilometer for all wear surfaces.

3.4 Summary of Visual and Metrology Analysis

- Wrist pin and wrist pin bearing showed only light polish on the loaded quadrant

- Eccentric journal bearing had light polish w/ light wear and moderate circumferential scratch likely caused by a small foreign piece of dirt, sand or metal that migrated with oil

- Thrust bearing components all showed an expected amount of burnish

- The shaft's top lower journal surface showed very light wear with a couple of light scratches on the loaded quadrant. The flange's top lower bearing also had a moderate scratch with two 1mm wide regions of light to moderate wear. Though not severe, the wear in the 1mm regions was the heaviest observed that could not be attributed to foreign particles. However, the moderate scratch was likely due to foreign particles that migrated with the oil and did not originate from either surface.

- The most visible wear was the moderate to heavy polish and light wear on the loaded half of the shaft's bottom lower journal Much of the phosphorus coating was worn away from the journal and underlying shaft surface was exposed and moderately polished

- Overall, the compressor motor and pump assembly appeared in good shape. All of the gaskets and seals were found intact. The stator coil winding and Mylar® electrical insulation showed no signs of heat damage

4. Conclusions

The results of the refrigerant/lubricant chemical analysis as well as the compressor tear down reported here confirm the stability of R-1234yf in stationary refrigeration applications and its compatibility with typical system lubricant types and compressor materials of construction. Additionally, the operating performance metrics as well as the energy consumption further validate R-1234yf as an excellent low GWP replacement option for R-134a in stationary equipment.

The viability of R-1234yf specifically, as well as other HFO's, both neat and in blends is an important development as the HVACR industry transitions to a new generation of low GWP refrigerants. The HFO's like R-1234yf, and blends thereof, provide a very attractive balance of performance, safety, and environmental sustainability as working fluids in the systems of the future.

5. References

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