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HFO-1234yf Performance in a Beverage Cooler

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ABSTRACT

HFO-1234yf is a low global warming potential refrigerant that has been selected as the preferred option to replace R-134a in automotive air conditioning systems. It was primarily chosen over carbon dioxide due to its higher energy efficiency and improved Life Cycle Climate Performance (LCCP) (SAE, 2009 and Little, 2002). It is also a close thermodynamic match to R-134a which results in fewer system modifications and potential for global implementation in auto a/c systems. The question arising given the success in automotive is whether HFO-1234yf can be used in other applications where R-134a is currently employed. In particular, vending machines and beverage coolers account for a substantial portion of R-134a use. There are over 10 million vending machines installed worldwide and a significant number of these are beverage coolers (WVA, 2010). This paper will explore the potential to use HFO-1234yf in a beverage cooler through design optimization and experimental system testing. Performance will be compared to an R-134a baseline and two systems optimized for carbon dioxide. Results will also be used in an LCCP analysis to evaluate overall environmental impact of the three options.

1. INTRODUCTION

Due to increasing concern over climate change, the European Commission has mandated a phase out for R-134a refrigerant in air conditioning in new car platforms in EU countries starting January 1, 2011. R-134a has a 100 year global warming potential value (GWP) of 1430 according to the Intergovernmental Panel on Climate Change 4th Assessment Report (Solomon *et al.,* 2007). Replacement refrigerants must have a GWP less than 150. Until recently, the leading candidate to replace R-134a had been CO_2 with a GWP of 1. However, CO_2 has several drawbacks including significantly higher pressure and lower thermodynamic cycle efficiency. The large difference in system pressure and transcritical operation requires significant design changes in order to use CO_2. This results in higher cost equipment, reliability questions, and maintenance issues.

HFO-1234yf was recently identified and selected as the preferred solution by global automotive OEMs. It has vapor pressure and other properties similar to R-134a, but a 100 year GWP of 4 which meets the EU regulation requirements and also has excellent LCCP because its energy efficiency is similar to R-134a. It has no ozone depletion potential. It is marginally flammable, but extensive risk assessments have demonstrated it can be used safely in auto a/c systems (SAE, 2009). Recent research has begun to focus on the potential to use HFO-1234yf in stationary applications with small charge sizes where the flammability properties of HFO-1234yf can be managed.

The purpose of this paper is to report on experimental cooling performance evaluation of R-134a, HFO-1234yf and CO2 in beverage coolers. A standard beverage cooler design was chosen and coolers were optimized for each specific refrigerant. Results were then used to calculate an LCCP value for each refrigerant option.

2. THERMODYNAMIC CYCLE ANALYSIS

To begin the study, a thermodynamic cycle analysis was conducted for R-134a, HFO-1234yf and CO_2. Evaporator and condenser temperatures were chosen to represent typical beverage cooler HFO-1234yf conditions. A transcritical model was used for CO_2 where pressure was adjusted to determine optimum COP. CO_2 uses a gas cooler in place of a condenser. The gas cooler exit temperature was set to be equivalent to the subcooled condenser temperature of 45°C used for R-134a and HFO-1234yf. Results are shown in Table 1. COP and volumetric cooling capacity for HFO-1234yf are within 3-4% of R-134a indicating a close match in performance. Condenser and evaporator pressures are also quite similar and the compression ratio of HFO-1234yf is slightly less than R-134a. CO_2 shows remarkably different characteristics with significantly higher system pressures, compressor discharge temperature and also higher capacity. The COP is significantly lower than the other refrigerants and only 56% of R-134a at these conditions.

Table 1: Theoretical Cycle Performance

Parameter	R-134a	HFO-1234yf	CO_2
Condenser Temp (°C)	50	50	45*
Subcool amount (K)	5	5	N/A
Evaporator Temp (°C)	-5	-5	-5
Return Gas Temp (°C)	18	18	18
Compressor Efficiency	75%	75%	75%
Condenser Pressure (kPa)	1319	1300	11403
Evaporator Pressure (kPa)	243	264	3055
Compression Ratio	5.43	4.92	3.73
Compressor Disch Temp (°C)	90.4	77.6	143.5
Volumetric Capacity (kJ/m3)	1643	1577	9914
COP	2.87	2.77	1.60
Capacity Relative to R-134a	100%	96%	603%
COP Relative to R-134a	100%	97%	56%

*Gas Cooler Exit Temp (°C)

3. EXPERIMENTAL TESTING

Experimental system cooling performance was measured using standard 19 cubic foot (0.54 m^3) beverage coolers. One cooler with unchanged design was used as the R-134a baseline. Another cooler was optimized for HFO-1234yf and a third and fourth cooler were optimized for CO_2 using two different compressor types. Design details are shown in Table 2. The main changes involved optimization of the capillary tube length and condenser coil design. HFO-1234yf used a slightly longer capillary tube than R-134a (144" versus 120", 3.66 m versus 3.05 m). For CO_2, one system used a presostatic expansion valve and the other a capillary tube 150" (3.81 m) in length and also with a smaller inner diameter. The fully instrumented coolers were placed in an environmental chamber to allow control of temperature and humidity. Ambient test conditions were 40.6°C and 75% relative humidity.

Table 2: Beverage Cooler Description

Description	R-134a	HFO-1234yf	CO_2-A	CO_2-B
Refrigerant Charge Size	0.49 kg	0.51 kg	0.480 kg	0.49 kg
Cooler Type	G3-19 D BMAD	G3-19 D BMAD	G3-19 Danfoss	G3-19 Sanyo
Compressor	NF8.4FX.2 Danfoss recip	NF8.4FX.2 Danfoss recip	TN1416 Danfoss recip	C-C30 Sanyo two stage
Condenser coil	72 tubes, 4 rows, 5/16"Φ Cu tubes w/o Al fins	72 tubes, 4 rows, 5/16"Φ Cu tubes w/o Al fins	40 tubes, 4 rows, 5/16"Φ Cu tubes, 3.5 FPI Al fins	40 tubes, 4 rows, 5/16"Φ Cu tubes, 3.5 FPI Al fins
Condenser Fan Motor	9W, ECM	9W, ECM	9W, ECM	9W, ECM
Condenser Fan Blade	8.75"Φ - 28° - 5P	8.75" Φ - 28° - 5P	8" Φ - 28° - 5P	8" Φ - 28° - 5P
Evaporator Coil	20 tubes, 4 rows, 3/8"Φ Cu tubes, 5 FPI Al fins	20 tubes, 4 rows, 3/8" Φ Cu tubes, 5 FPI Al fins	20 tubes, 4 rows, 3/8" Φ Cu tubes, 5 FPI Al fins	20 tubes, 4 rows, 3/8" Φ Cu tubes, 5 FPI Al fins
Evaporator Fan Motor	9W, ECM	9W, ECM	9W, ECM	9W, ECM
Evaporator Fan Blade	8" Φ - 28° - 5P	8" Φ - 28° - 5P	8" Φ - 28° - 5P	8" Φ - 28° - 5P
Capillary Tube	0.049" Φ X 120" long	0.049" Φ X 144" long	Presostatic valve	0.031" Φ X 150" long

Cooling performance was evaluated several different ways. First, the time was determined to cool an empty beverage cooler to 0°C. Then the cooler was loaded full with a prescribed number of beverage cans at room temperature. The cooler was started and time measured of initial pull down (IPDT – Initial Pull Down Time) to condition as well as energy consumed during the pull down. Next, one half of the cans were removed and reloaded with cans at room temperature. Then the pull down time (HRT – Half Reload Time) and energy consumption were again measured. Finally steady state energy consumption over a 24 hour period (ECT – Energy Consumption Time) with a fully loaded system was measured. Test results are shown in Table 3 below.

Table 3: Experimental Beverage Cooler Test Results

Description	R-134a	HFO-1234yf	CO_2-A	CO_2-B
No. Cans Loaded	630	630	630	630
Time to Reach 0°C Empty	37 min	37 min	33 min	34 min
Initial Pull Down Time - IPDT	23 hr, 45 min	23 hr, 40 min	19 hr, 47 min	19 hr, 58 min
Energy Consumed – IPDT (kW/hr)	10.816	10.875	12.520	12.950
Half Reload Time – HRT (kW/hr)	16 hr, 55 min	16 hr, 41 min	11 hr, 24 min	12 hr, 10 min
Energy Consumed – HRT (kW/hr)	7.254	7.279	8.229	8.739
Steady State Energy Consumption – ECT (kW/hr)	5.784	5.798	7.996	8.290
ECT Rel to R-134a (%)	100%	100.2%	138.2%	143.3%
Energy per can - Watts	9.18	9.20	12.69	13.16

Results show that HFO-1234yf energy performance is very comparable to R-134a for IPDT, HRT and ECT performance. Though CO_2 demonstrates good initial pulldown times, the steady state energy consumption of CO_2 is from 38-43% higher than R-134a.

4. FLAMMABILITY CONSIDERATIONS

Since HFO-1234yf is marginally flammable, it is subject to industry standards such as European EN 378-1 which have limitations on refrigerant charge size based on room volume (EN 378-1, 2007). Currently, HFO-1234yf would be considered an A2 refrigerant under EN-378-1, though a new classification of 2L for marginal flammability, based on burning velocity <10 cm/s is under consideration. According to EN 378-1, Table C.1, the maximum refrigerant charge for A2 refrigerants is given in Equation (1).

$$\text{maximum refrigerant charge (kg)} = \text{practical limit (kg/m}^3\text{)} * \text{room volume (m}^3\text{)} \qquad (1)$$

For most flammable refrigerants, the practical limit is defined by EN 378-1 as is 20% of the lower flammability limit (LFL). The LFL for HFO-1234yf is 6.2 vol% in air per ASTM E681-04, 2004 (Minor and Spatz, 2008) which is 0.289 kg/m3. Therefore, the practical limit is 0.0578 kg/m3. The beverage cooler tested contained an HFO-1234yf charge of 0.51 kg. Therefore, the minimum size room this cooler can be placed in according to EN 378-1 is 0.51/0.0578 = 8.8 m^3. Given an average room height of 2.4 m (8 ft), the room floor area would need to be at least 3.7 m^2 (40 ft^2) which is about 2 X 2 m. This represents a very small room which indicates this HFO-1234yf beverage cooler is suitable for use in most rooms per EN 378-1.

In the United States, UL Standard 471 (UL 471, 2006), for Commercial Refrigerators and Freezers has a maximum charge limit for A2 refrigerants of 0.225 kg maximum which is more restrictive then EN 378. ASHRAE Std 34 – Designation and Safety Classification of Refrigerants (ANSI/ASHRAE Std 34, 2007) was recently revised to incorporate the 2L marginal flammability classification. Therefore, ASHRAE Std 15- Safety Standard for Refrigeration Systems (ANSI/ASHRAE/Std 15, 2007) is currently under review to determine revisions required to employ 2L refrigerants. This could eventually lead to modification of UL 471 and other standards as well.

5. LIFE CYCLE CLIMATE PERFORMANCE

Life Cycle Climate Performance, (LCCP) is a widely recognized tool to understand total product environmental impact beyond the direct global warming potential (GWP) of the refrigerant (Hill and Papasavva, 2005 and Little, 2002). This is a cradle-to-grave analysis of the environmental impact at all points in the life cycle chain, including (1) manufacture of refrigerant, (2) energy used during system operation, (3) refrigerant emissions and (4) refrigerant losses at end-of-life disposal. An LCCP analysis was conducted using the steady state energy data from the beverage cooler tests. The results for the two CO_2 beverage cooler systems were averaged in the analysis. The following assumptions were made:

- beverage cooler equipment life – 10 years
- average refrigerant leak rate – 15% over 10 years or 1.5% per year
- refrigerant loss at end of life – 85% of charge

LCCP results from the steady state beverage cooler energy test are shown in Figure 1 and 2 below. Figure 1 assumes a CO_2 energy factor for the US of 0.5436 kg CO_2/kWhr (WRI, 2010). Figure 2 uses the average value for 27 EU countries is Europe at 0.354 kg CO_2/kWhr (WRI, 2010). Results in Figure 1 and 2 show that contribution from refrigerant manufacture has a negligible impact on LCCP, less than 1% of the total. Refrigerant leakage also has a relatively low impact due to the low leak rate from this type of equipment. The primary contributor to overall climate impact is the energy use or energy efficiency of equipment operation over its lifetime. For both the US and the EU, results show HFO-1234yf has the lowest LCCP and is therefore the lowest environmental impact over the lifetime of the system. Overall, the EU values are lower than the US values because less CO_2 is formed during energy production in the EU on average.

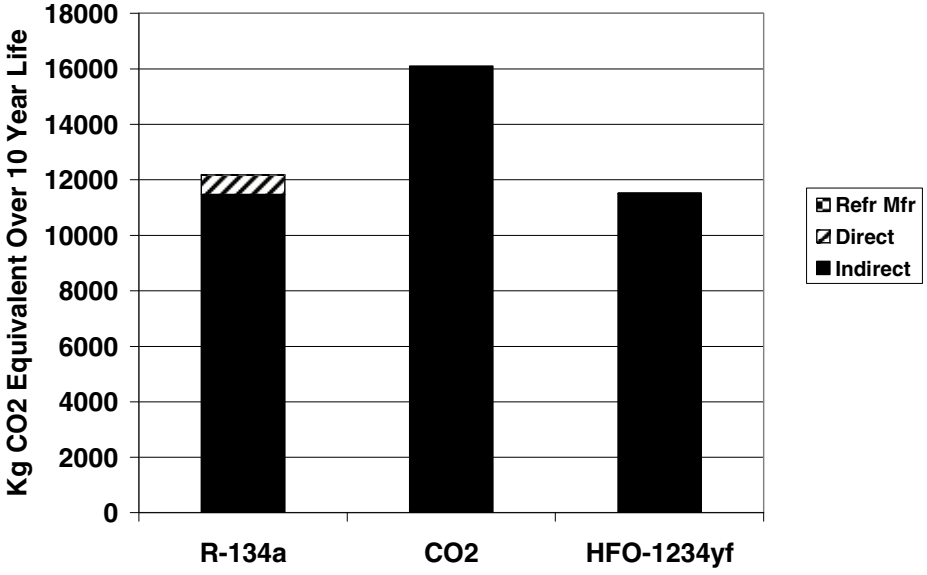

Figure 1: Beverage Cooler LCCP in the United States

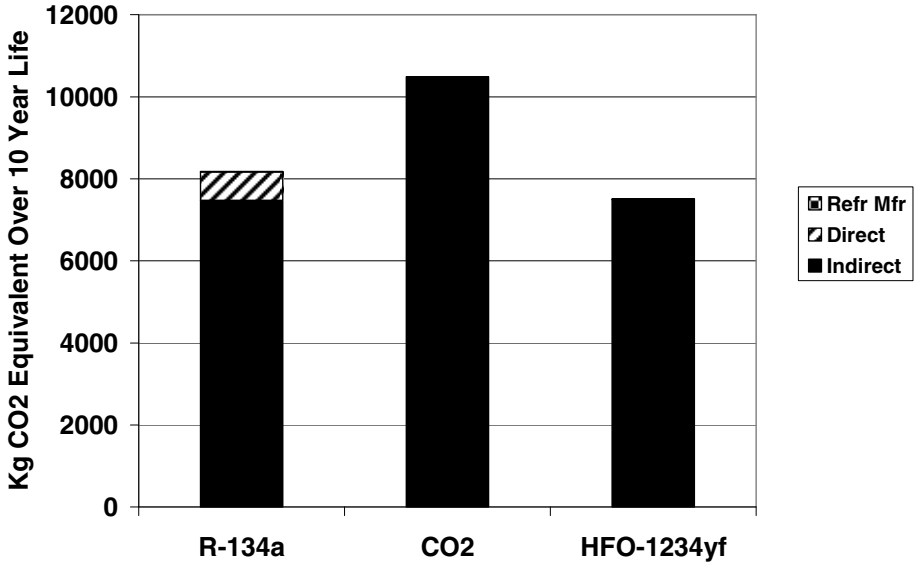

Figure 2: Beverage Cooler LCCP in the EU

6. CONCLUSIONS

HFO-1234yf has significant potential as a new low global warming refrigerant for small stationary applications such as vending machines and beverage coolers. It has excellent environmental properties which can have a long term favorable impact on climate change and meet current and future climate regulations. Test results from beverage coolers optimized for R-134a, HFO-1234yf and CO_2 demonstrate that coolers can be designed for HFO-1234yf that demonstrate similar energy efficiency and cooling capacity compared to R-134a. Only minor modifications were required to achieve equivalent performance. HFO-1234yf also has the lowest LCCP giving it the most favorable environmental profile due to its energy efficiency and low direct GWP. Though HFO-1234yf is marginally flammable, risk assessments have demonstrated it can be used safely in automotive air conditioning systems. Standards development for commercial stationary refrigeration systems is in progress which will help define use requirements for 2L refrigerants.

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