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Experimental Performance of R-1234yf and R-1234ze as Drop-in Replacements for R-134a in Domestic Refrigerators

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ABSTRACT

Concerns about anthropogenic climate change have generated an interest in low global warming potential (GWP) refrigerants and have spawned policies and regulations that encourage the transition to low GWP refrigerants. Recent research has largely focused on hydrofluoroolefins (HFOs), including R-1234yf (GWP = 4) as a replacement for R-134a (GWP = 1430) in automotive air-conditioning applications. While R-1234yf and R-1234ze (GWP = 6) have been investigated theoretically as a replacements for R-134a in domestic refrigeration, there is a lack of experimental evidence. This paper gives experimental performance data for R-1234yf and R-1234ze as drop-in replacements for R134a in two household refrigerators – one baseline and one advanced technology.

An experiment was conducted to evaluate and compare the performance of R-134a to R-1234yf and R-1234ze, using AHAM standard HRF-1 to evaluate energy consumption. These refrigerants were tested as drop-in replacements, with no performance enhancing modifications to the refrigerators. In Refrigerator 1 and 2, R-1234yf had 2.7% and 1.3% higher energy consumption than R-134a, respectively. This indicates that R-1234yf is a suitable drop-in replacement for R-134a in domestic refrigeration applications. In Refrigerator 1 and 2, R-1234ze had 16% and 5.4% lower energy consumption than R-134a, respectively. In order to replace R-134a with R-1234ze in domestic refrigerators the lower capacity would need to be addressed, thus R-1234ze might not be suitable for drop-in replacement.

1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) (2007) states “warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level”. Carbon dioxide has a GWP of 1, while the

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hydrofluorocarbon (HFO) R-134a has a GWP of 1430 (ASHRAE, 2009). These concerns about have generated an interest in low global warming potential (GWP) refrigerants. There are policies and regulations in place which encourage the transition to low GWP refrigerants. The European Union’s F-Gas regulation bans the use of refrigerants with GWPs higher than 150 in automobile air conditioners, beginning Jan 1, 2011 for new models and Jan. 1, 2017 for all new vehicles. The Kyoto Protocol sets binding targets on greenhouse gas emissions, and hydrofluorocarbon refrigerants are one of the six target gases identified, necessitating a new generation of refrigerants (Calm, 2008).

Automotive air conditioning systems are leading the transition to low GWP refrigerants. This is due in part to the European F-Gas mandates and because R-1243yf (GWP = 4) appears to be a viable candidate for replacing R-134a in this application. The hydrofluoroolefin (HFO) R-1234yf has been selected as the preferred refrigerant by global automobile manufactures (Minor, Montoya, & Kasa, 2010).

Recent research into low GWP refrigerants has largely focused on HFOs. Brown (2009) gives a general overview of the viability of HFOs as replacement refrigerants. Much of the HFO research has focused on estimating or measuring their thermodynamic properties (Akasaka et al., 2010; Brown et al., 2010; Cang et al., 2010; Dang et al., 2010; Higashi, 2010; Leck, 2009; McLinden, 2010) including mixtures with HFCs (Akasaka, 2010; Kayukawa et al., 2010; Miyara et al., 2010). Brown et al. (2010) reviewed 21 papers for thermodynamic and transport properties of R-1234yf and gives new property correlations for vapor pressure, liquid density, and liquid dynamic viscosity. Currently, R-1234yf and R-1234ze fluids are available in REFPROP (Lemmon, Huber, & McLinden, 2010).

Leck (2010) reported on the performance of R-1234yf and other alternative refrigerants in stationary heating and air conditioning, theoretically showing R-1234yf to have 57% less capacity and 7% higher COP than R-410a. Experimental validation was performed, but not quantified in this paper. Minor et al. (2010) showed experimentally that a beverage cooler optimized for R-1234yf had energy performance very comparable to R-134a and a lower overall Life Cycle Climate Performance. Yana Motta et al. (2010) experimentally found that R-1234yf performed essentially similar to R-134a in a representative vending machine, where the thermostatic expansion valve was replaced by a needle valve. Additionally, it was found that R-1234ze had slightly more capacity and slightly less efficiency in the representative vending machine when tested with a 75% larger displacement compressor and a needle valve expansion device. (Yana Motta, Vera Becerra, & Spatz, 2010)

In domestic refrigeration applications, there has been some research into HFO replacements for R-134a. Leck (2009) estimated the thermophysical properties of R-1234yf, then used these to evaluate the theoretical performance of R-1234yf in a refrigeration cycle and a comparison was made to R-134a. R-1234yf was shown to have 2-9% less capacity and 2-7% less COP than R-134a, depending on ambient temperatures. Leck also evaluated material compatibility experimentally, showing R-1234yf to have no reaction with the metals or lubricants used in refrigeration systems. R-1234yf also performs very similar to R-134a in lubricant miscibility and polymer compatibility (Leck, 2009). Leighton et al. (2012) developed a theoretical model, which was validated using experimental R-134a data. Their model showed R-1234yf to have 9% lower COP and 6% less capacity than R-134a. The model also showed R-1234ze to have 8% higher COP and 21% lower capacity than R-134a.

This conference paper gives experimental performance data for R-1234yf and R-1234ze as drop-in replacements for R-134a in domestic refrigeration applications. An experiment was conducted to evaluate and compare the performance of R-134a, R-1234yf, and R-1234ze using AHAM standard HRF-1 (2008) to evaluate energy consumption. These refrigerants were tested as drop-in replacements, with no performance enhancing modifications to the refrigerators. Two different refrigerators were used: one representing baseline technology and the other representing advanced technology. This was to determine if a refrigerator with advanced technology was better able to adapt to a change in refrigerant.

### 2. LOW GWP REFRIGERANTS

There are many viable low GWP candidates to replace the current HFC refrigerants. These candidates can be generally classified into hydrofluoroolefins, hydrocarbons, and refrigerant mixtures. These categories of refrigerants are discussed below and an overview of the selection criteria is presented.
2.1 Hydrofluoroolefins
HFOs are fluorinated propene isomers, which include R-1225 isomers, R-1234 isomers, and R-1243 isomers. R-1234yf appears to be the leading candidate for replacing R-134a in automotive applications (Minor, Montoya, & Kasa, 2010). R-1243 isomers have largely been ruled out due to their flammability and R-1225 isomers are no longer being developed because of toxicity concerns (Calm, 2008).

R-1234yf has a GWP of 4. It is mildly flammable, classified as A2L by ASHRAE Standard 34 (2011) due to its low burning velocity and high minimum ignition energy. R-1234yf shows low toxicity, performing as well or better than R-134a in toxicity tests (Minor & Spatz, 2008). Leck (2009) performed an ASHRAE/ANSI Standard 97 evaluation of R-1234yf with copper, steel, aluminum, and POE refrigeration oils shows no evidence of breakdown or reaction. Additional testing with polymers and lubricants shows R-1234yf to have material compatibilities similar to R-134a.

R-1234ze has a GWP of 6 and is A2L classified by ASHRAE Standard 34 (2011). It has two stereoisomers, R-1234ze(E) and R-1234ze(Z), which exhibit different properties. R-1234ze(E) was used for this test and will be referred to as R-1234ze throughout this paper. An ASHRAE/ANSI Standard 97 evaluation of R-1234ze showed it to be thermally stable and compatible with POE oils (Yana Motta, Vera Becerra, & Spatz, 2010).

2.2 Hydrocarbons
Hydrocarbons are already prevalent in domestic refrigeration, with propane and isobutane being the most common (Goetzler, Burgos, & Sutherland, 2010). Isobutane (R-600a) is found in the majority of Chinese refrigerators and all European and Japanese units (EPA, 2010). Despite the widespread usage of hydrocarbons, the ASHRAE Standard 34 Class 3 flammability and perceived risk inhibit their use in the United States. The Environmental Protection Agency Significant New Alternatives Policy (2011) approved the use of R-600a in domestic refrigerators and R-290 (propane) in stand-alone retail refrigerators.

The hydrocarbons that would likely serve as refrigerants have a GWP less than 5 (Goetzler, Burgos, & Sutherland, 2010). These hydrocarbons show superior transport properties and experimental efficiency improvements of 2-10%. Due to the small charge quantity in household refrigerators, they are unlikely to create an ignitable atmosphere (Radermacher & Kim, 1996).

2.4 Mixtures
If no single component refrigerant performs acceptably in domestic refrigerator/freezers, a combination of refrigerants can be used to achieve the desired properties. Some mixtures have been shown to improve efficiency in optimized systems, while others have shown a slight increase in energy consumption. The temperature glide exhibited by a zeotropic refrigerant mixture can be used to a thermodynamic advantage in the modified Lorenz-Meutzner cycle, which has shown a 16.5 to 17.3% energy savings (Radermacher & Kim, 1996).

Currently, mixtures of HFOs and HFC-32 are being researched. Koyama et al. (2010) found that adding R-32 to R-1234ze improves the COP and capacity in a heat pump, and they state that this type of mixture is a strong candidate for replacing R-410a in domestic heat pumps. Fujitaka et al. (2010) found that a mixture of R-1234yf/R-32 (50/50 wt%) has 95% of the cooling COP and 94% of the heating COP compared to R-410a in a room air conditioner as a drop in. The Environmental Protection Agency Significant New Alternatives Policy (2011) approved the use of hydrocarbon mixture R-441a in domestic refrigerators.

2.5 Selection Criteria
When selecting a refrigerant for a given application there are a wide variety of parameters that need to be evaluated. While GWP is the parameter that drives this research, other factors must be considered. This includes flammability, toxicity, material compatibility, development costs and production costs. One must also assess the overall environmental impact, not just the GWP, by using a method such as the Life Cycle Climate Performance (LCCP) (Papasavva, Hill, & and Brown, 2008). The LCCP takes into account the direct and indirect climate effects of the refrigerant. The direct effects are attributed to the release of the refrigerant itself into the atmosphere during production, service, and end of life disposal. The indirect effects are attributed to power plant emissions that are a result of the energy needed to run the refrigeration system over its lifetime.
Due to the hermetically sealed system in domestic refrigerators, refrigerant leakage during the useful life of the refrigerator is a non-issue. Additionally, they have a small charge of refrigerant and it is assumed that losses during production and end of life disposal are minimal. Therefore, the direct effects of domestic refrigerators are relatively small compared to the indirect effects of lifetime energy consumption. Since the majority of the warming effect is due to indirect effects, climate performance is mainly a function of the refrigerator’s energy efficiency. As such, energy performance should be the driving factor when comparing alternative refrigerants in domestic refrigerators, provided they meet the necessary safety, reliability, and compatibility requirements.

3. TEST SETUP

In order to evaluate the performance of alternative refrigerants R-1234yf and R-1234ze, they were tested and compared to a baseline established with R-134a. These refrigerants were tested in two different refrigerators. Refrigerator 1 (Ref1) represented those with basic technologies, while Refrigerator 2 (Ref2) represented those with more advanced technologies. This was to determine if a refrigerator with more advanced technology was better able to adapt to a change in refrigerant.

3.1 Refrigerators

Ref1 is an energy star rated 17.3 ft³ top freezer model. It has traditional technologies, such as a single evaporator, a suction line heat exchanger, and a single knob temperature control. Ref2 is an energy star rated 26.0 ft³ bottom freezer French door model. It has more advanced technologies, such as a single compressor dual evaporator cycle, a variable speed compressor, and an electronic control system.

3.2 Test Procedure

The test procedure is based on AHAM standard HRF-1-2008, the DOE standard for evaluating the energy consumption of refrigerator/freezers. The tests were carried out at an ambient temperature of 90 ± 1°F (32.2 ± 0.6°C) and relative humidity of 50 ± 1% in an environmental chamber. A watt transducer with ± 0.4 W accuracy measured the power consumption of each refrigerator. The resulting wattages were integrated over time to obtain energy consumption. The AHAM standard prescribes the location of thermocouples both outside and inside the cabinet. Temperature measurements were obtained with T-type thermocouples accurate to ± 1°C. Copper cylinders one inch in diameter and height were used as thermal masses for the thermocouples within the cooled compartments.

Energy consumption is evaluated at a target temperature of 39°F (3.9°C) for the fresh food compartment and 0°F (−17.8°C) for the freezer compartment. Rather than adjusting the temperature control of the refrigerators to achieve these temperatures, HRF-1 has a two part test. For the 1st test, the temperature control was set to the median position and was allowed to run until steady state conditions were reached in each of the cooled compartments. After steady state was reached energy consumption was recorded. For the 2nd test, the thermostat was set at the highest position if both compartment temperatures were below the target temperatures or the lowest position if either of the compartment temperatures were above the target temperatures. Energy consumption for each of these tests was assessed for no less than 3 hours and included an integer number of complete compressor cycles. A complete compressor cycle is one full “on” period and one full “off” period. Five complete compressor cycles were sampled where possible.

The energy consumption is then calculated from the aforementioned tests with equations outlined in AHAM HRF-1. After computing the daily energy consumption in kWh/day for the 1st and 2nd tests from the 3+ hour test periods, equations (1) and (2) are used. Equation (1) uses fresh food compartment temperatures (TR1 and TR2) and daily energy consumption (ET1 and ET2) from the 1st and 2nd tests to get the energy consumption at the target fresh food temperature. Equation 2 uses freezer compartment temperatures (TF1 and TF2) and daily energy consumption (ET1 and ET2) from the 1st and 2nd tests to get the energy consumption at the target freezer temperature. The higher of the two values is taken as the daily energy consumption of the refrigerator.

\[
E = ET1 + (ET2 − ET1) × (39.0 − TR1) / (TR2 − TR1)
\]

\[
E = ET1 + (ET2 − ET1) × (0 − TF1) / (TF2 − TF1)
\]

The third AHAM HRF-1 test accounts for the defrost heater in the overall energy consumption. This test was not performed, as this information is not necessary for comparing the refrigerants.
3.3 Refrigerator Retrofit
In order to test the alternative refrigerants a charging port was added. In order to monitor superheat and subcooling two pressure transducers and thermocouples were added to each refrigerator, as seen in Figure 1.

![Figure 1: Refrigerator system layout, pressure transducer (PT) and thermocouple (TC) placement](image)

The refrigerators were recharged with R-134a and retested according to the AHAM standard to ensure performance was not diminished by the addition of the pressure transducers and charging ports. For each of the refrigerants tested, the refrigerators were recharged with the factory charge amount plus an additional 5g to account for the extra refrigerant left in the charging hose.

4. RESULTS

4.1 Refrigerator 1
Figure 2 shows a single compressor cycle for each refrigerant in Ref1. The peak height of the wattage curve is indicative of the compressor work. R-1234yf requires slightly more compressor work than R-134a, while R-1234ze requires significantly less. The overall run time is indicative of the capacity. R-1234yf has a shorter run time to complete a compressor cycle, while R-1234ze has a significantly longer run time. During the 1st tests at the median setting the fresh food compartment was higher than the target temperature for each refrigerant, so Ref1 was set to the coldest temperature setting for the 2nd tests. When the refrigerator was set to the coldest setting with R-1234ze, it was not able to complete 5 compressor cycles at steady state compartment temperatures between defrost cycles. The mean time between defrost cycles was significantly reduced with R-1234ze, which would increase the daily energy consumption.

Subcooling was 9°F (–12.8°C) with R-134a, 2°F (–16.7°C) with R-1234yf, and 2°F (–16.7°C) with R-1234ze at the end of the compressor runtime. Subcooling of 2 to 4°F (–16.7 to –15.6°C) at the end of compressor run time is said to be optimum for single evaporator refrigerators (Liu, Haider, Liu, & Radermacher, 1994). The higher subcooling experienced with R-134a may indicate overcharge. All tests used the same amount of refrigerant, the factory charge plus 5g, which was not adjusted based on subcooling for these tests.

Figure 3 shows the AHAM calculated results for the three refrigerants. R-134a and R-1234yf have comparable energy consumption, while R-1234ze has significantly lower energy consumption. Equation 1 gives an energy consumption of 1.48 kWh/day for R-134a, 1.52 kWh/day for R-1234yf, and 1.25 kWh/day for R-1234ze. Equation 2, for the same tests, shows an energy consumption of 1.07 kWh/day for R-134a, 1.01 kWh/day for R-1234yf, and 1.08 kWh/day for R-1234ze. The values from the freezer equation are higher than those from the fresh food equation, so they are taken to be the actual energy consumption values.
There is a large difference in the result of the energy consumption calculation based on Equation 1 and Equation 2 for R-134a and R-1234yf. This is due to high fresh food temperatures and low freezer temperatures during both testing conditions for both refrigerants. Fresh food temperatures ranged from 43.1°F (6.2°C) to 40.2°F (4.6°C) and freezer temperatures ranged from −4.0°F (−20°C) to −8.4°F (−22.4°C). The result of the fresh food calculation is 38% and 51% higher than the result of the freezer calculation for R-134a and R-1234yf, respectively. By comparison, R-1234ze yields a value from the fresh food calculation that is 15% higher than the value from the freezer calculation. Similarly, the energy consumption for Ref2 based on the fresh food temperature is within 4% of the value based on the freezer temperature for all refrigerants tested. Since AHAM HRF-1 prescribes taking the higher of the two calculated values, the results for R-134a and R-1234yf may be unrealistically high.

4.2 Refrigerator 2

Figure 4 shows a single compressor cycle for each refrigerant in Ref2. The peak height of the wattage curve is indicative of the compressor work. R-1234yf requires slightly more compressor work than R-134a, while R-1234ze requires significantly less. The overall run time is indicative of the capacity. R-1234yf has a shorter run time to complete a compressor cycle than R-134a, while R-1234ze has a significantly longer run time. During the 1st tests at
the median setting both compartments were lower than the target temperature for each refrigerant, so Ref1 was set to the warmest temperature setting for the 2nd tests.

Subcooling was 5°F (-15°C) with R-134a, 3°F (-16.11°C) with R-1234yf, and 4°F (-15.56°C) with R-1234ze at the end of the compressor runtime. Subcooling of 3 to 5 °F at the end of compressor run time is said to be optimum for dual evaporator systems (Liu, Haider, Liu, & Radermacher, 1994). All tests used the same amount of refrigerant, which was not adjusted based on subcooling.

Figure 5 shows the AHAM calculated results for the three refrigerants. R-134a and R-1234yf have comparable energy consumption, while R-1234ze has slightly lower energy consumption than R-134a and R-1234yf. The fresh food equation (eq. 1) gives an energy consumption of 1.44 kWh/day for R-134a, 1.45 kWh/day for R-1234yf, and 1.41 kWh/day for R-1234ze. The freezer equation (eq. 2) for the same tests shows an energy consumption of 1.49 kWh/day for R-134a, 1.51 kWh/day for R-1234yf, and 1.37 kWh/day for R-1234ze. For R-134a and R-1234yf, the values from the freezer equation are higher than those from the fresh food equation, so the freezer values are taken to be the actual energy consumption. For 1234ze, the value from the fresh food equation is higher than the value from the freezer equation, so the fresh food value is taken to be the actual energy consumption.
4.2 Performance Comparison

Table 1 summarizes the energy consumption and run time for the refrigerants in both refrigerators relative to R-134a. Ref1 has higher relative energy consumption and a shorter run time with R-1234yf compared to Ref2. Ref1 has lower relative energy consumption and a longer run time with R-1234ze compared to Ref2. Compressor run time, and thus capacity, is less affected by a change in refrigerant in Ref2. The more advanced technology of Ref2 enabled it to better adapt to a change in refrigerant capacity. Additionally, Ref2 had more accurate temperature control, which gave similar results from AHAM equations (1) and (2). The more advanced technology of Ref2 also gave significantly better energy consumption per ft³ at 0.057 kWh/day/ ft³, compared to 0.086 kWh/day/ ft³ in Ref1, with R-134a.

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>Energy Consumption</th>
<th>Run Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-134a</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>R-1234yf</td>
<td>102.7%</td>
<td>84.3%</td>
</tr>
<tr>
<td>R-1234ze</td>
<td>84.5%</td>
<td>150.8%</td>
</tr>
<tr>
<td>R-134a</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>R-1234yf</td>
<td>101.3%</td>
<td>89.0%</td>
</tr>
<tr>
<td>R-1234ze</td>
<td>94.6%</td>
<td>140.0%</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

This paper has examined the relative performance of R-134a, R-1234yf, and R-1234ze. It is shown that R-134a and R-1234yf have similar energy consumptions and capacities in both refrigerators tested, thus R-1234yf would make a good drop-in replacement for R-134a in domestic refrigeration applications. R-1234ze performed favorably in terms of energy consumption in Ref1 and Ref2. However, the lower capacity of R-1234ze resulted in increased compressor run time and shorter time between defrost cycles. While the defrost energy is not accounted for in the daily energy consumption in this paper, the increased frequency of defrost cycles would be detrimental to the real world energy efficiency. As such, system modifications would need to be made to account for the lower capacity of R-1234ze, making it unsuitable for drop-in replacement of R-134a.

Ref1 had compartment temperatures with a large deviation from the targets with R-134a and R-1234yf. This resulted in daily energy consumption values for R-134a and R-1234yf calculated from the fresh food equation (eq. 1) 38% and 51% higher than the value from the freezer equation (eq. 2), respectively. Since AHAM HRF-1 prescribes taking the higher of the two values outright, this may have given artificially high daily energy consumption values for these refrigerants. In Ref2 the energy consumption based on the fresh food temperature is within 4% of the value based on the freezer temperature for all refrigerants tested. Additionally, the subcooling of R-134a was too high in Ref1 despite being charged with the manufacturers charge plus 5g to account for the volume of refrigerant left in the hose used for charging. R-1234yf and R-1234ze exhibited desirable subcooling in Ref1, as did every refrigerant used in Ref2.

The more advanced technology of Ref2 enabled it to better adapt to a change in capacity of a refrigerant. Additionally, the more accurate temperature control of Ref1 gave similar results from AHAM equations (1) and (2). The more advanced technology of Ref2 also gave significantly better energy consumption per ft³ compared to Ref1.

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