Low GWP Replacements for R404A in Commercial Refrigeration Applications

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Abstract Due to the growing global concerns around the use of refrigerants with relatively high global warming potential, new working fluids with the positive attributes of both high thermal performance and low environmental impact are currently in development. These newly developed refrigerants show high levels of energy efficiency and significantly low global warming potential, minimizing the overall environmental impact. Some of these options are non flammable, and the flammable ones exhibit significantly lower flammability characteristics than the much more flammable hydrocarbons. This work discusses in detail the performance of these new refrigerants as replacements for R-404A in commercial refrigeration applications. Thermal properties as well as experimental results in representative systems and components are presented, showing the benefits of using these new working fluids.

Keywords: Refrigerants, Global Warming, Hydro-fluoro-olefins

1 Introduction

Among high pressure blends, R-404A has a relatively high GWP (3952), and is widely used in commercial refrigeration applications. Refrigerant charge in refrigeration applications can be significantly large (e.g. supermarket) which coupled with high leak rates (15% to 25% per year) produces an important environmental impact. Therefore we focused this study on the experimental evaluation of options to replace R-404A in commercial refrigeration systems. This work will focus on both system (walk-in cooler) and component (compressor) performance evaluations.

All test data obtained in this research was analyzed using properties from Refprop NIST (Lemmon et al., 2002) which we modified to add our newly developed refrigerants. These modifications included adding properties for our newly developed refrigerants and the interaction parameters needed for the new blends. All these additions are based on experimental measurements performed in our laboratories.

2 Performance of Low GWP Refrigerants

2.1 Experimental Setup

Tests were performed using a commercially available condensing unit and an evaporator for a walk-in freezer/cooler. The system uses tube and fin heat exchangers, semi-hermetic reciprocating compressor and thermostatic expansion valve. During the installation, we employed long connecting lines as found in typical supermarket facilities. The suction line was 27.4m which included a vertical riser of 6.4m. The main purpose of using these long lines was to take into account temperature and pressure drop effects on the system performance.

Environmental chambers simulated indoor (Box) conditions for the evaporator and outdoor conditions for the condensing unit. Instrumentation was added to the system to measure refrigerant flow rate, refrigerant pressures and temperatures before and after the main component. On the air side, we measured air temperature across the evaporator and condenser. The power consumption was separately measured for indoor fan, outdoor fan and compressor. All primary measurement sensors were calibrated to ±0.15ºC for temperatures and ±0.25 psi for pressure. Overall system uncertainties (capacity and efficiency) were on average ±5%.

Experiments were performed for three outdoor ambient temperatures: 13ºC, 24.0ºC and 35.0ºC. These ambient temperatures were used to evaluate two ranges of applications: freezers (-18ºC, -26ºC) and coolers (10ºC, 2ºC**).**

2.2 Non Flammable Options

Although we did extensive testing, we will focus our analysis on one outdoor temperature (35ºC) and the two most stringent box conditions: -26ºC for low temperature and 2ºC for medium temperature.

Results in figures 1 and 3 show currently available refrigerant R-407F, which offers an important GWP reduction of over 50% relative to R-404A, and an approximately 15% reduction relative to R-407A.

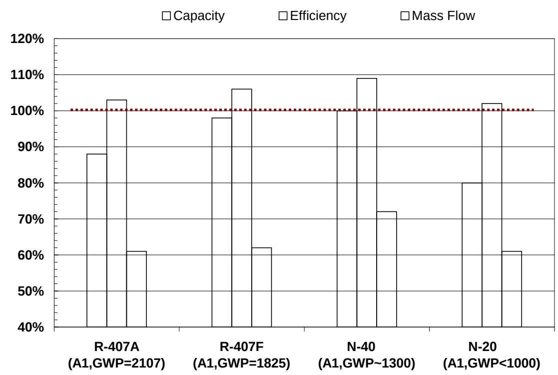

Figure 1. Low Temperature Performance (relative to R-404A).

When it comes to performance in these tests, R-407F is superior to R-404A and R-407A: it matches

R-404A's capacity and gives 6% higher efficiency for both low and medium temperature applications. All of this coupled with acceptable pressures (lower than R-404A) and compressor discharge temperature lower than 130ºC (figure 2) makes it a valuable option to reduce the overall environmental impact of current systems.

Additionally, two new refrigerants (N-40 and N-20) have been developed. Based on our preliminary work, N-40 may be used in current R-404A equipment with little or no modifications and yet offers a GWP reduction of over 65% compared to R-404A (GWP~1300) with superior performance (9% better system efficiency). Moreover, in our tests, discharge temperatures are below the limits of the compressor (less than 130ºC).

N-20 is intended for new equipment due to its somewhat lower capacity. It provides an even further GWP reduction of over 75% (GWP lower than 1000) as compared to R-404A. It also appears in these tests to have improved efficiency (+2%) compared to R-404A.

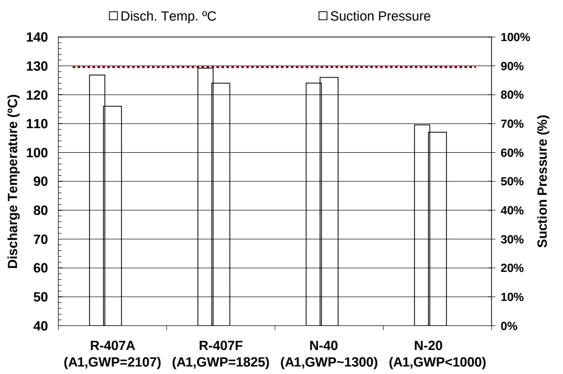

Figure 2. Discharge temperature and suction pressure in Low Temperature Tests (relative to R-404A).

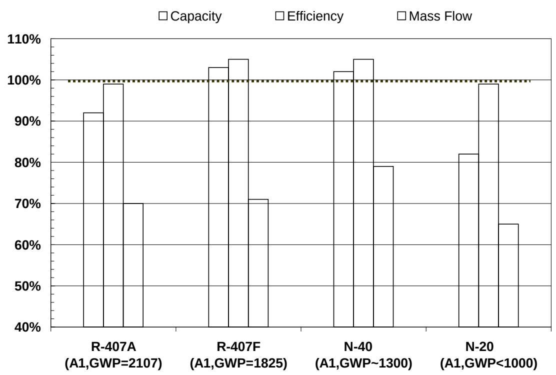

Figure 3. Medium Temperature Performance (relative to R-404A).

3.3 Mildly "A2L" Flammable Options

This section focuses on newly developed refrigerant L-40 which further reduces the direct (GWP<300) and indirect (energy consumption) emissions. However, some changes in equipment and installation are required to handle its mild flammability. Tests were performed in the same equipment used above with relatively shorter connecting lines (10m long) which simulate a typical distributed system. These results can also be extended to close coupled systems like chillers. Similarly to the analysis done for the non flammable options, we based our analysis on the two most stringent operating conditions: -26ºC for low temperature and 2ºC for medium temperature.

Figure 4 shows L-40 results for both low and medium temperature operation. As discovered through extensive research and testing, L-40 matches R-404A capacity while improving efficiency by up to 6%. Other important parameters such as working pressures and compressor discharge temperature are compatible with current R-404A systems and compressors (e.g. discharge temperature less than maximum of 130ºC). Still, this refrigerant is mildly flammable and would be classified as A2L by ASHRAE Standard 34 (ASHRAE, 2010). It is therefore intended for use in systems where mildly flammable refrigerants can be used.

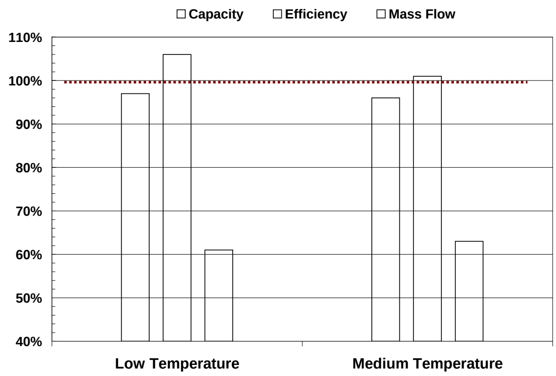

Figure 4. Lowest GWP Option L-40 Performance (relative to R-404A).

3. Compressor calorimeter Evaluation

3.1 Suction and Discharge Pressures

In a compressor calorimeter test, pressures are calculated using the dew point pressure associated with both evaporating and condensing temperatures. Pressures of a real system are the natural response to the outdoor and indoor temperatures, and they correspond to the heat transfer and pressure drop experienced by the refrigerant in the condenser and evaporator. If one needed to make thermodynamic approximation, as needed for the compressor calorimeter, an average of the bubble and dew temperature would be more appropriate for the condenser. In the case of the evaporator, this would be an average of the equilibrium temperature at the inlet and the dew temperature at the outlet. The differences between using dew pressures of average pressures are significant as they affect both compression ration and efficiencies (volumetric and isentropic).

3.2 Suction temperature effect on cooling capacity, discharge temperature and efficiency.

Compressor data assumes suction and evaporator temperatures as being the same (e.g. 65ºF) while the evaporator inlet temperature is defined using saturated liquid (e.g. 90ºF). This defines a refrigerating effect that includes a large portion of superheated vapor, which in real systems does not provide any useful refrigerating effect. Most Systems will have about 10ºF of superheat at the evaporator outlet. This type of calculation would typically mask capacity shortcoming of refrigerants with low latent heat (e.g. R404A, R407A).

In addition to the above mentioned issues, fixing the suction temperature as 65ºF affects both volumetric and isentropic efficiencies. It will also exacerbate the penalties associated with high discharge temperature beyond what will happen in an actual system. Actual refrigerating systems rarely work under these conditions (large degree of superheat).

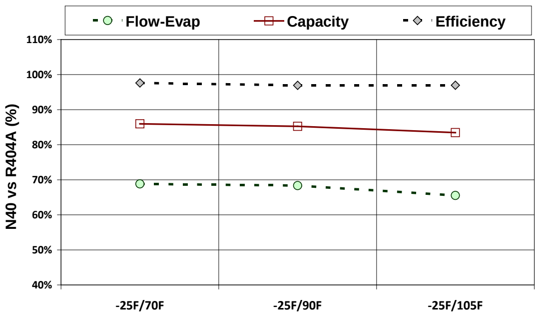

Figure 5. Standard Compressor Calorimeter tests.

Compressor calorimeter tests were performed using a 3.2 Ton semi-hermetic reciprocating compressor, which is equipped with a liquid injection system to mitigate high discharge temperatures. Although this compressor was designed for R22, it can also be used with R404A and other HFC blends. A secondary-fluid compressor calorimeter was employed for these experiments. All the refrigerant circuit is fully instrumented to measure pressure, temperature and flow rate (evaporator and liquid injection line). Compressor and heaters power consumption are also measured separately. Using this setup, we performed three types of tests:

1) At first, tests were performed using standard compressor calorimeter conditions as detailed in AHRI standard 540. These tests require the use dew pressures corresponding to evaporation and condensing temperatures, 65ºF suction temperature, and 90ºF saturated liquid.

2) Next, we varied the suction temperature at one condition: -25 ºF (evaporating), 105ºF (condensing).

3) Finally, we performed similar tests but using average pressures for both condensing and evaporating processes while suction temperature was still kept at 65ºF.

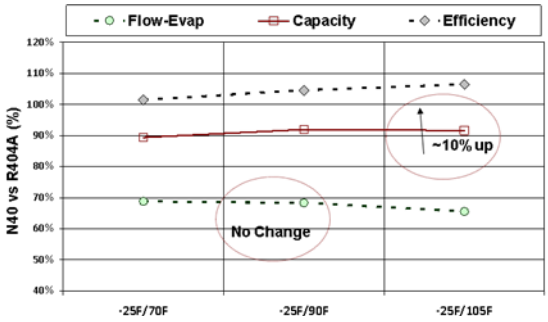

Figure 6. Modified test using 10ºF superheat at evaporator outlet.

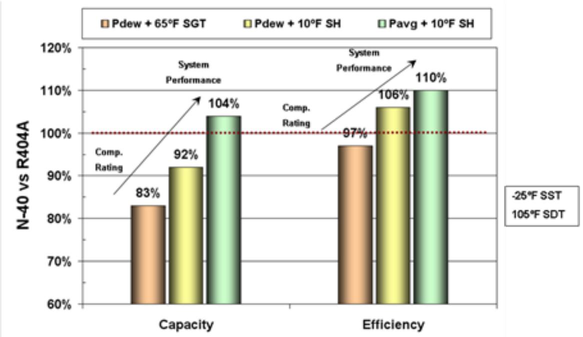

Figure 7.Combined effect of using average pressures and 10ºF superheat at evaporator outlet.

Figure 5 shows a comparison between N-40 (blend with glide) and R404A (blend with negligible glide). When compared at standard conditions and using as the -25F/90F as a reference, N-40 shows 83% capacity and 97% efficiency compared to R404A.
If we recalculate the cooling capacity using 10ºF of superheat at the evaporator outlet, N-40 experiences substantial capacity and efficiency recoveries (92% capacity, 106% efficiency, as shown in figure 6).

When tested at average pressures (figure 7) and the 10F degree of superheat is used, further performance recovery is seen (figure 7). This time, the capacity is 104% while efficiency is 110%. These latest values are similar to system evaluations shown in figures 1 (low temperature) where N-40 matches R404A's capacity and has superior efficiency (109%).

4. LCCP Analysis

Using the performance data developed above, we performed an LCCP analysis of technologies used in supermarket refrigeration. The baseline was a typical 45,000 ft2 supermarket store located in Atlanta (Georgia, USA). This system had both medium temperature (64%) and low temperature (36%) loads. As described by Kazachki (2007), the baseline direct expansion (DX) had a charge of 3200 lb (1455 kg) of R404A an annual leak rate of 15%. Refrigerants considered include commercially available blends (R407A, R407F) and our newly developed N-40.

Other technologies considered include distributed systems, which reduce the charge to 800 lb (364 kg) and an annual leak rate of 10%. The secondary system considered the use of glycol for the medium temperature system only, so the charge is reduced to 1600 lb (727 kg) and an annual leak rate of 10%.

As for the more recent technologies, we included the pumped CO2 systems with a charge of 800 lb (364 kg) and an annual leak rate of 5%. The cascade CO2 syetm has a charge of 320 lb (145 kg) and an annual leak rate of 2%. The refrigerants options are commercially available blends (R407A, R407F) and our mildly flammable refrigerant L-40, assuming that safety can be easily accomodated for this blend.

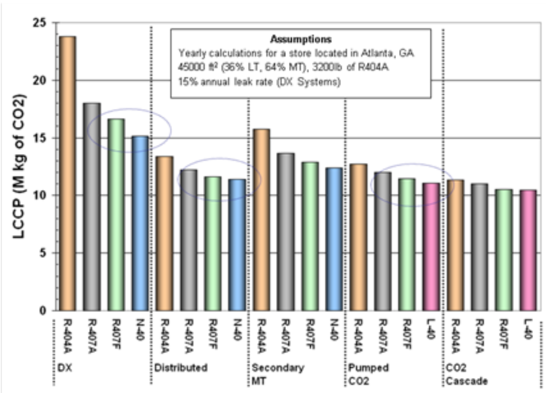

Figure 8. LCCP analysis for most common technologies used in supermarkets.

Results shown in table 8 clearly demonstrate that the use of N-40 (and even R407F) allows considerable reduction of environmental impact when retrofitting existing systems (~50%). It also shows that current DX technologies, such as distributed systems using N-40 produce environmental impact similar to more sophisticated technologies (cascade and pumped CO2). Overall, N-40 and L-40 enable considerable reduction of the environmental impact without major changes in system designs.

5. Conclusions

Low global warming refrigerants with potential to replace R-404A were developed through extensive experimental testing. Some of these refrigerants may be used in current refrigeration systems (R407F, N-40, N-20) providing a great reduction of environmental impact. This is mainly due to reduction of GWP and significantly higher efficiencies.

Other options such as L-40 provide further reduction of GWP, and may be useful in future systems capable of using mildly flammable refrigerants. Such applications could include high side of secondary fluid systems (chillers), Cascade systems (combined with CO2), small close-coupled systems, and even distributed systems.

Differences between compressor calorimeter and actual system evaluations were clearly established through experimental evaluations. Results show that typical compressor calorimeter tests impose unrealistic penalties on blends with glide. These penalties can artificially degrade capacity (-20%) and efficiency (-13%) with respect to what is seen in system evaluations. Compressor calorimeter data should be used with caution when sizing systems for blends.

This study has shown promise for new Low GWP refrigerants (N-40, N-20) that offer great reduction of environmental impact in current and future refrigeration systems. LCCP analysis demonstrates that superior Energy-Efficiency and lower GWP (~1300) reduce the carbon footprint of current and future systems. Further studies in larger refrigeration systems (e.g. supermarkets) are needed to validate these laboratory scale results.

As for the mildly flammable blends (L-40), they allow further reduction of the environmental impact. More work is needed to fully explore potential application in secondary fluid, cascade and pumped CO2 systems. This would include, among other work, additional performance evaluations as well as conducting flammability risk assessments where appropriate.

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