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Low Global Warming Refrigerants For Commercial Refrigeration Systems

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ABSTRACT

New refrigerants with the positive attributes of both high thermal performance and low environmental impact are currently in development. Initial evaluation of these refrigerants in refrigeration systems show good energy efficiency and significant lower global warming impact than current refrigerants. Some of those Low GWP refrigerants are non-azeotropic blends with moderate to high glide; therefore guidance on the use of these blends is needed to achieve the desired good performance and low environmental impact. This study discusses glide effects on the performance and operation of refrigeration systems. Issues related to servicing systems such as fractionation are also discussed. Data is presented using current refrigerants such as R407F and other refrigerant blends currently under development.

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 20% 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. We'll also present a practical study of fractionation due to leaks in real systems.
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

3.1 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.

3.2 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 figure 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. 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.

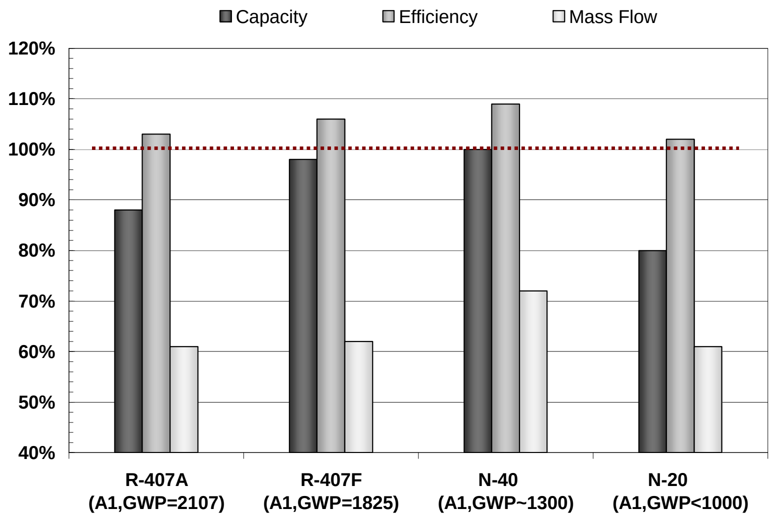

Figure 1. Low Temperature Performance (relative to R-404A).

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.

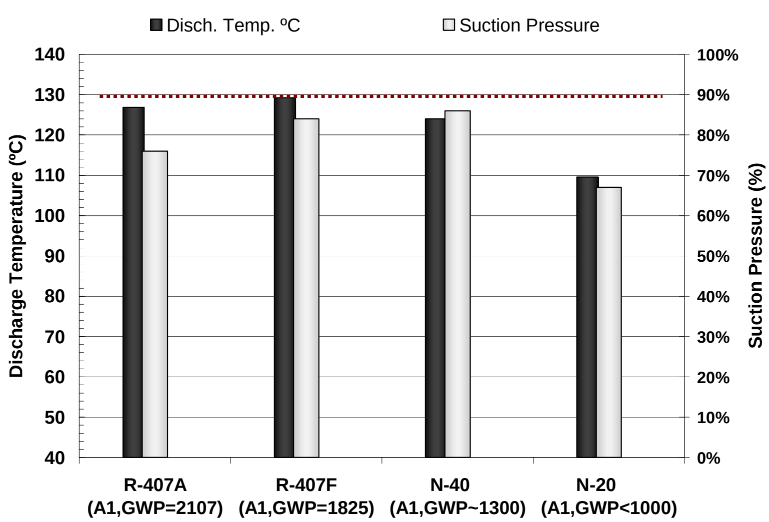

Figure 2. Discharge temperature and suction pressure in Low Temperature Tests (relative to R-404A).

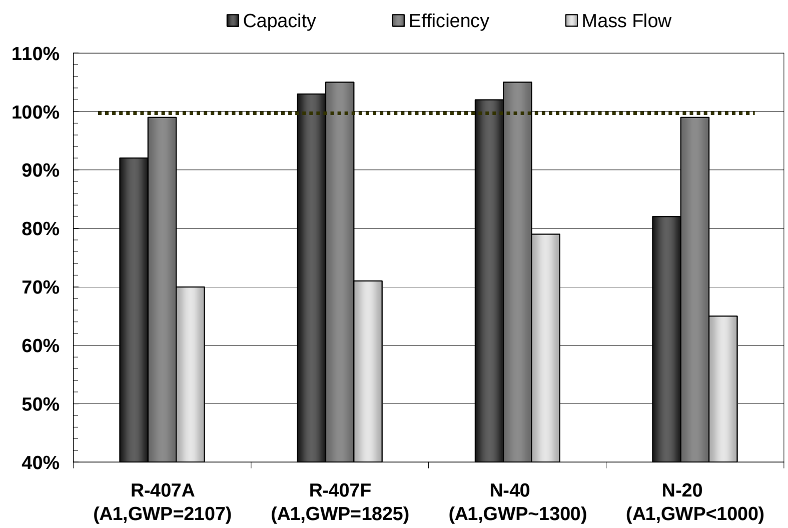

Figure 3. Medium Temperature Tests (relative to R-404A).

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 reduced GWP 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.

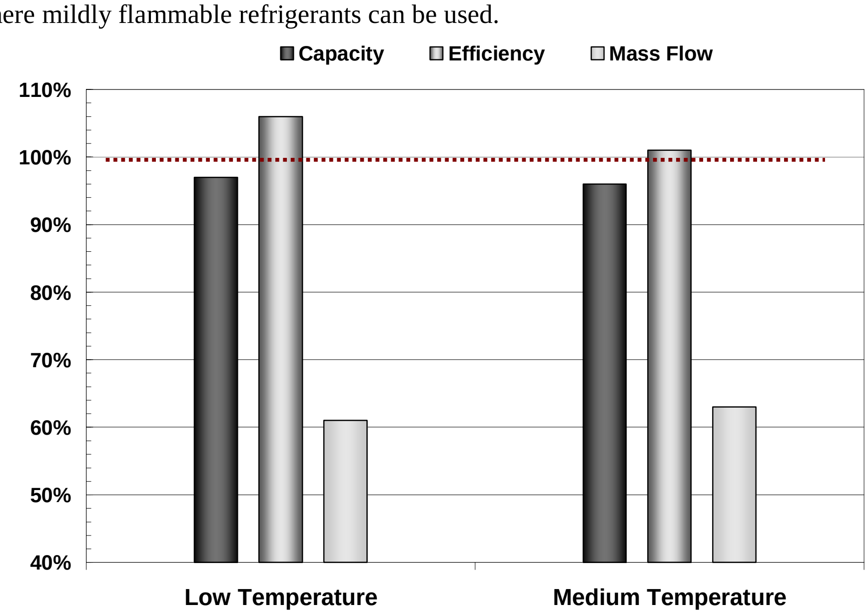

Figure 4. Lowest GWP Option L-40 (relative to R-404A).

3. EVALUATION AND HANDLING ISSUES FOR BLENDS WITH GLIDE

3.1 Compressor Data compared to Actual System Performance

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).

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 65F 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).

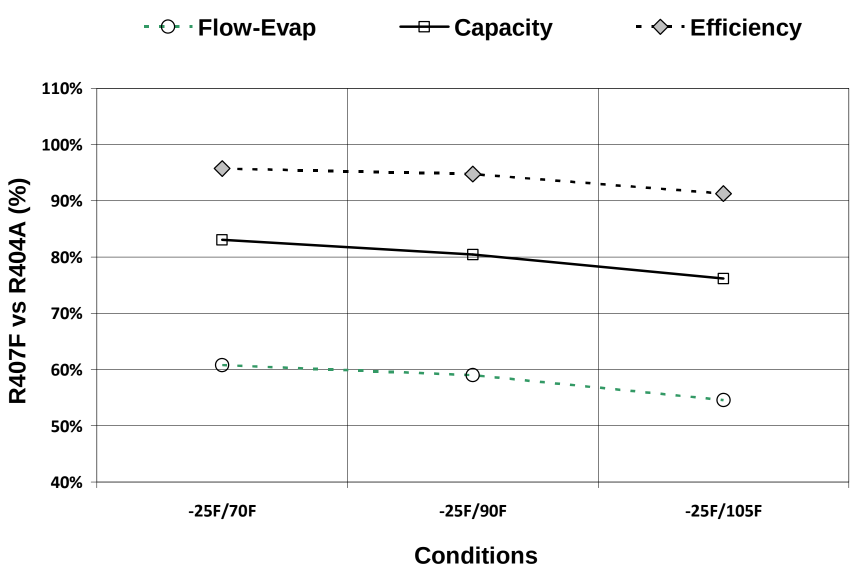

Figure 5.Standard Compressor Calorimeter tests.

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: -25F (evaporating), 105F (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.

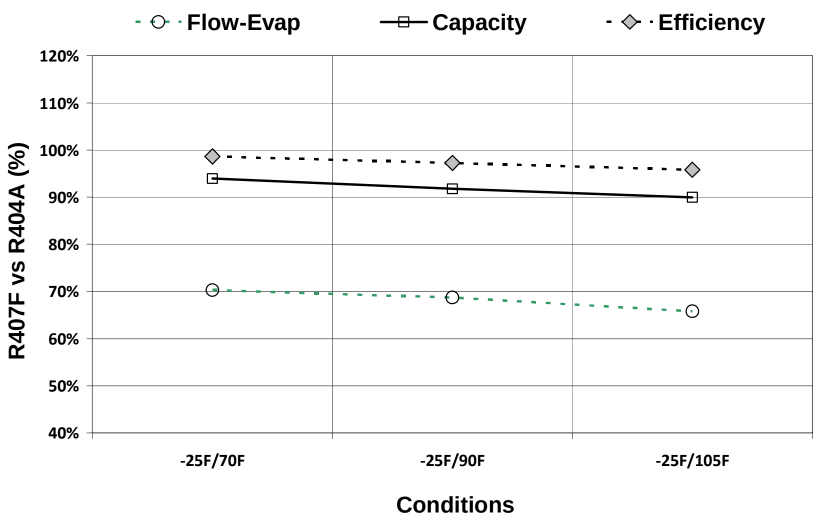

Figure 6. Modified test using average pressures for evaporating and condensing processes.

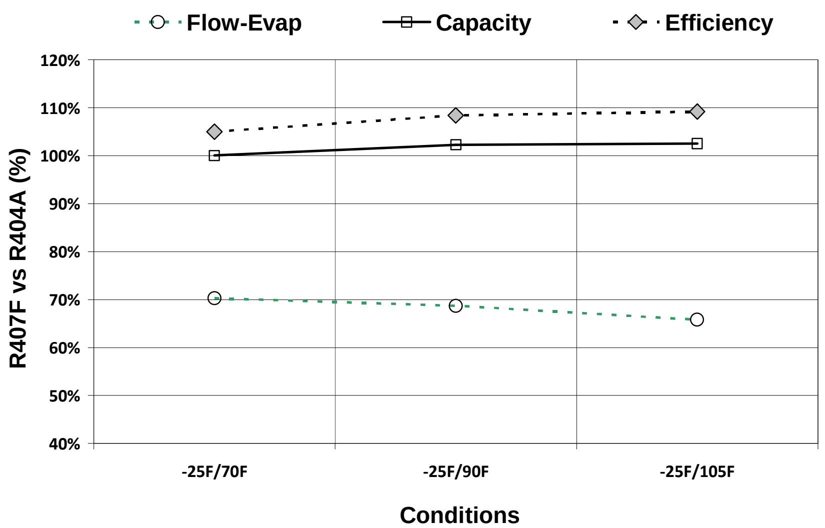

Figure 7.Combined effect of using average pressures and 10ºF superheat at evaporator outlet.

Figure 5 shows a comparison between R407F (blend with glide) and R404A (blend with negligible glide). When compared at standard conditions and using as the -25F/90F as a reference, R407F shows 80% capacity and 95% efficiency compared to R404A. When tested at average pressures (figure 6), R407F experiences substantial capacity and efficiency recoveries (92% capacity, 98% efficiency). If using the same data, we recalculate the cooling capacity using 10ºF of superheat at the evaporator outlet; further performance recovery is seen (figure 7). This time, the capacity is 102% while efficiency is 108%. These latest values are similar closer to system evaluations shown in figures 1 (low temperature) where R407F matches R404A's capacity and has superior efficiency (106%).

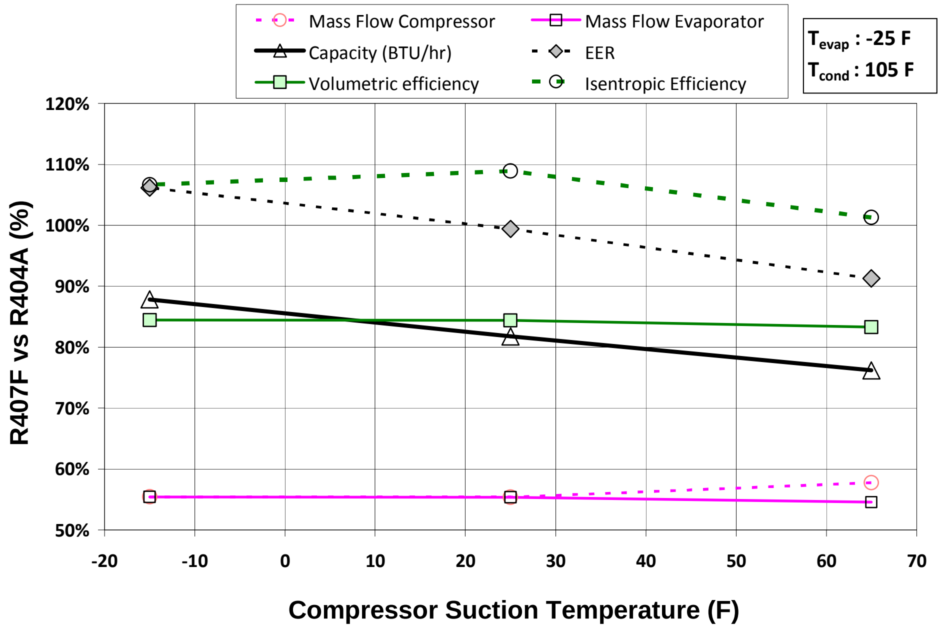

Figure 8. Effect of suction temperature on compressor efficiency.

Figure 8 shows tests performed using standard calorimeters conditions (dew pressures) but varying the suction temperature. Results for the most typical condition indicate significant loss of capacity and efficiency (larger than experimental uncertainty of 5%); especially at 65ºF suction temperature. This is in part due to liquid injection happening at that condition.

3.2 Fractionation due to leaks in an actual system.

The fractionation of refrigerant blends have been previously studied (e.g. Biancardi et al 1996). These studies were mainly focused on potential shifts of composition due to charging procedures. They also studied the usual change of composition experienced after a blend reaches equilibrium in a given system.

No one of these studies addresses fractionation due to leaks while the system is in use, which is a question often asked by system users and owners. The present study employed a standard 1.0 Ton walk-in cooler/freezer system equipped with a semi-hermetic reciprocating compressor, a liquid receiver, tube-and-fin heat exchangers, and charged with R407F. The refrigerant charge was 19 lb (8636g) and the compressor used 2200 ml of POE oil (ISO 32). This system was tested during a real operation while serving a low temperature box (-15ºF). Ambient temperatures varied between 50ºF to 60ºF. As for the type of leaks, we focused on slow leaks (worst case), which we characterized using a small orifice (0.1mm ID). The events simulated were divided in two groups:

1) Refrigerant leaks from the vapor side (compressor discharge line), while the system is working.
2) Refrigerants leaks from the two-phase side (middle of the condenser coil), while the systems is working.
3) Refrigerant leaks from the vapor side (top of indoor coil) while the system is down for long periods of time (i.e. unused).

The refrigerant composition was sampled and analyzed before charging the system and at different times while the leak was occurring. Samples size were small (4g each) so they would not affect the outcome of the experiment. The test lasted until bubbles were seen in the liquid sight glass, which clearly indicate low charge level affecting the system operation.

	Description	Start	Sample 1	Sample 2	Sample 3
	Time (hours)	0	8.2	23.7	26.7
	Charge (%)	100%	94%	84%	82%
Composition	R32	30.8%	31.3%	31.9%	31.8%
	R125	29.3%	29.5%	29.8%	30.0%
	R134a	39.9%	39.2%	38.3%	38.2%
Performance	Capacity (%)	100%	101%	102%	102%
	COP (%)	100%	100%	100%	100%

Table 1. Results for slow vapor leaks while system is working.

Table 1 depicts results for the first type of leak event. As shown changes of composition happen but they are lower than the typical tolerances (±2%). Also performance estimates for the different compositions show variations inside the range of experimental uncertainty (±5%).

	Description	Start	Sample 1	Sample 2	Sample 3
	Time (hours)	0	5.5	22.1	28.2
	Charge (%)	100%	94%	78%	72%
Composition	R32	30.8%	29.5%	28.3%	27.7%
	R125	29.5%	28.7%	28.0%	27.7%
	R134a	39.8%	41.8%	43.7%	44.6%
Performance	Capacity	100%	98%	96%	95%
	COP	100%	100%	100%	100%

Table 2. Results for slow two-phase leaks while system is working.

Next we simulated leaks from the two-phase region. This type of leak produced slightly larger changes of composition than the first tests (table 2). Still based on the performance data, it is believed that this type of leak would not affect significantly the performance of the system. The performance data doesn't show variations larger than the typical experimental error (±5%).

We also simulated slow leaks that happen when the system is unused for long periods of time. This time the changes of composition were slightly larger should not affect system performance beyond typical experimental uncertainty.

	Description	Start	Final
	Time (hours)	0	52.5
	Charge (%)	100%	66%
Composition	R32	29.9%	27.0%
	R125	28.6%	27.0%
	R134a	41.5%	46.0%
Performance	Capacity	100%	95%
	COP	100%	100%

Table 3. Results for slow vapor leaks while system is OFF.

Overall, our results confirm field reports that leaks occurring while the system is operating do not produce significant shift of composition. This is probably due to the inherent mixing caused by the flow of refrigerant which is very often turbulent. As for the slow leaks while the system is down, although variations are larger, we believe the change of composition was not as dramatic as predicted by known theoretical models (Domanski, 2011). This shows the actual system as being a complex one where the oil presence and the dynamic movement of refrigerant affect the results. Further study is being performed to understand the reasons for this modest change of composition.

4. 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 significant 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.

Fractionation events due to leaks in real systems were also studied. Results showed that leaks while the system is running do not cause any major shift of composition. In most cases, the performance variation was inside the range of experimental uncertainty (±5%). The small shift of composition was attributed to the turbulent flow inside the refrigeration system which causes good mixing of the blend components.

The worst case scenario of a slow leak in a system not in use (down or OFF) was also studied. Initial results showed some changes in composition (larger that typical tolerance of ±2%), still performance degradation was in the range of experimental uncertainty. This last case is still under study as the effect of refrigerant solubility in oil and the dynamics of the leak phenomena need to be better understood.

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. Further studies in larger refrigeration systems (e.g. supermarkets) are needed to validate these laboratory scale results.

As for the mild 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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