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ABSTRACT

New refrigerants with considerable low environmental impact are currently under evaluation by the refrigeration industry. Such refrigerants could be used in place of high global warming fluids like R404A. Among these new fluids are a non-flammable option, N-40, and mildly-flammable option, HDR-110. Preliminary internal laboratory evaluations of these refrigerants in commercial refrigeration systems showed superior energy efficiency due to their good thermal properties. Larger-scale external lab evaluations confirmed these initial results. This study presents and discusses results of such evaluations. Refrigerant-oil miscibility data for N40 is also discussed.

1. INTRODUCTION

Among high pressure blends, R-404A has a relatively high GWP (3943), and is widely used in commercial refrigeration applications ranging from large centralized systems for supermarkets to small self-contained systems for freezer and refrigerators. Refrigerant charge in supermarket refrigeration applications can be significantly large which coupled with high leak rates (15% to 20% per year) produces an important environmental impact. In self-contained applications, new regulations in Europe (F-Gas) will likely limit GWP to 150. Therefore we focused this study on the experimental evaluation of low GWP options to replace R-404A in hermetically sealed and larger supermarket refrigeration systems.

In the first part, this work will focus on internal and external performance evaluations of N40, a non-flammable low-GWP replacement for R404A in retrofit and new installs. Oil-refrigerant miscibility data for commercially available lubricants will also be presented. In the second part, this paper will discuss in details the performance of a mildly-flammable option for R404A with a GWP<150 in a small self-contained application.

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. NON-FLAMMABLE REPLACEMENTS FOR R404A

2.1 Internal Lab Evaluations

In this section we discuss internal performance evaluations of newly developed N40, a non-flammable replacement for R404A. 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. Figure 1 shows a simplified schematic of the experimental facility. 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 ±2.0 kPa 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). 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 are shown in Figures 2 and 3.

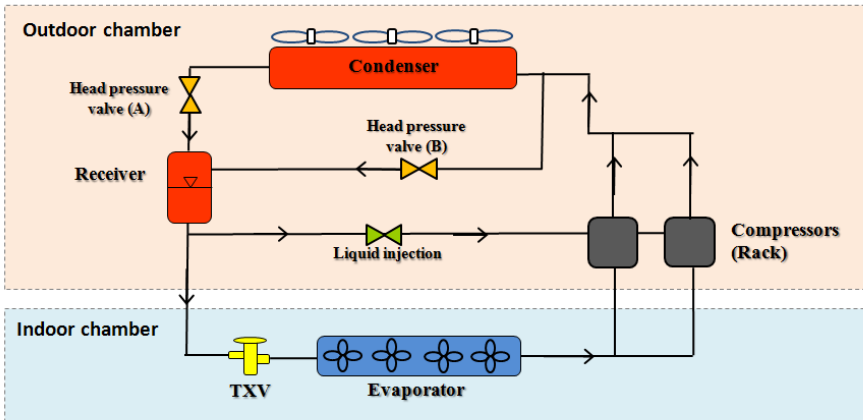

Figure 1: Schematic of the refrigeration facility

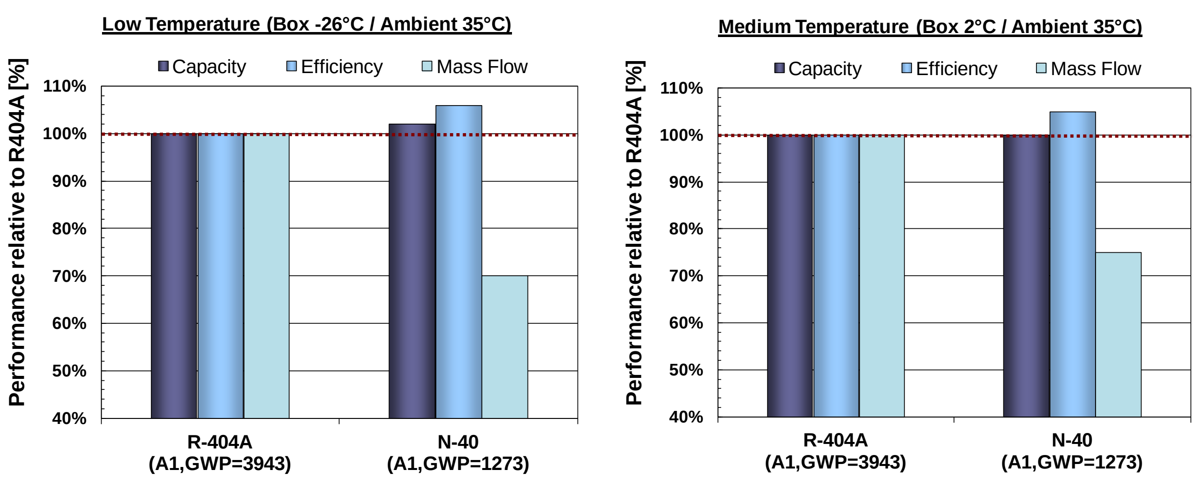

Figure 2: Internal performance evaluations of N40 and R404A

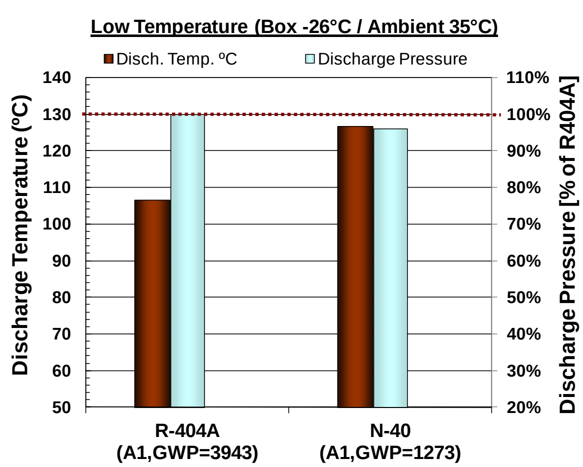

Figure 3: Discharge temperature and pressure in Low Temperature Tests

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 68% compared to R-404A with superior performance. In both medium and low temperature, N40 yielded about 6% higher system efficiency and match in capacity relative to R404A. Figure 3 shows that discharge temperatures with N40 were below the limits of the compressor (less than 130ºC) and no liquid injection was required. Moreover, discharge pressures were about 4% lower than R404A.

2.2 External Lab Evaluations

Two external performance evaluations of N40 versus R404A carried out in larger-scale systems are discussed in this section.

Evaluation at a Manufacturer's Test Facility

Rajendran (2013) presented energy consumption evaluations of R404A and N40 carried out in a supermarket mock-up facility. The test facility consists of a temperature/humidity controlled room with multiple low and medium temperature cases, a machine room for the scroll compressor racks, and a water cooled condenser. Evaporating temperatures for low and medium temperature racks were set to -30°C and -11°C, respectively. Indoor room was maintained at 24°C (dry-bulb) and 30% (relative humidity). Condensing temperature was varied (32°C, 40°C, 49°C) to simulate different ambient conditions. Figure 5 shows the results of 24h energy consumption for R404A and N40. The uncertainty for energy consumption is equal to ±1%.

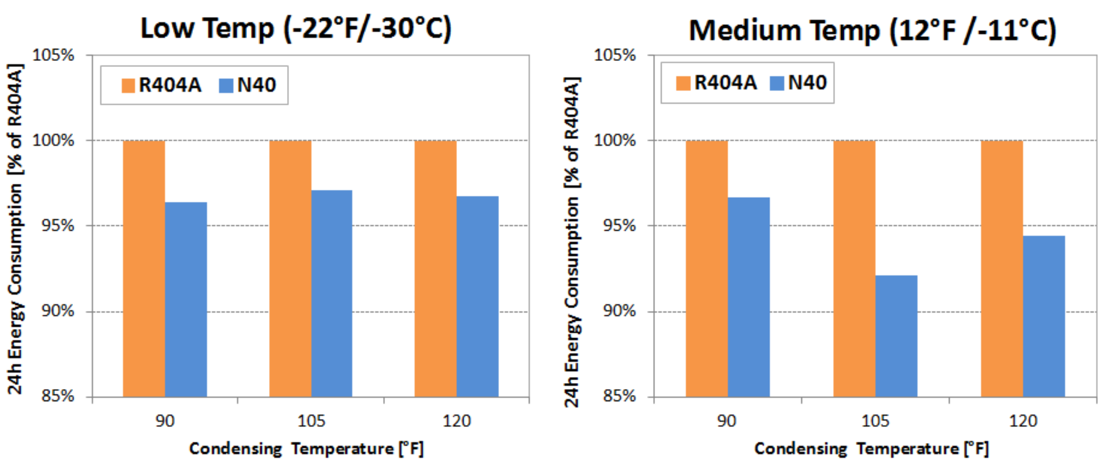

Figure 4: Performance evaluations by Rajendran (2013)

As seen in Figure 4, for the low-temperature rack, N40 energy consumption was about 3% lower while in medium temperature, it ranged from 3% to 8% lower than R404A. These results are consistent with performance measurements shown in Figure 2.

Evaluation at a National Lab

Abdelaziz and Fricke (2014) also carried out performance tests of R404A and N40 in a supermarket refrigeration facility. The test facility consists of two separate temperature/humidity controlled rooms: one for the refrigerated cases and one for the air-cooled condenser. Commercially available reciprocating compressors, medium/low temperature cases, tube-in-fin condenser and mechanical subcooler were used. The refrigeration system was fully instrumented with thermocouples, pressures transducers, Coriolis-type mass flow meters and power transducers. Indoor room was maintained at 24°C (dry-bulb temperature) and 50% (relative humidity), while the outdoor room temperature was varied (16°C/60°F, 24°C/75°F, 35°C/95°F, 41°C/105°F). Evaporating temperatures for low and medium temperature racks were floating, with actual average values around -29°C/-20°F for the low temperature and -6.7°C/20°F for the medium temperature rack. For the condenser, the air-refrigerant temperature difference ("TD") was maintained at 10°F. Figure 5 shows the COP (coefficient of performance) results for the entire system (combined medium and low temperature) during a period of 24h for N40 and R404A. A simplified schematic of the system is also shown in Figure 5.

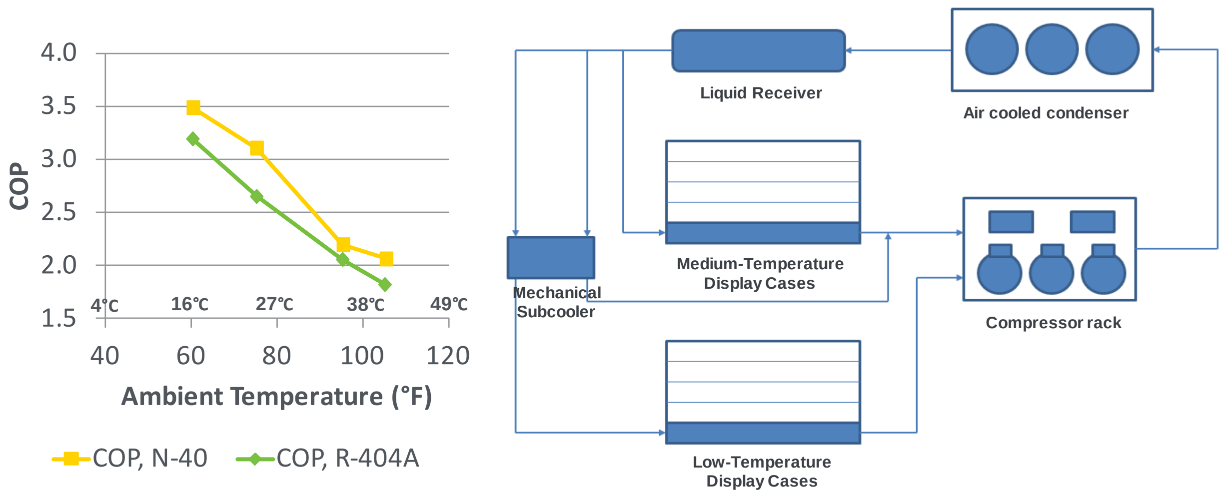

Figure 5: Performance evaluations by Abdelaziz and Fricke (2014)

As seen in Figure 5, N40 shows a higher COP in all ambient conditions, with an average improvement of 11.6%. The N40 capacity was also reported as being slightly higher than R404A. These results are consistent with our internal lab evaluations (Figure 2).

2.3 Miscibility of N40 and POE

In the system heat exchangers and connecting piping, the refrigerant is transported around the system and moves into and out of the liquid phase as it absorbs and rejects heat. Under ideal conditions, the refrigerant and lubricant are completely miscible with one another, and flow together as a single liquid phase in the liquid line, and in the suction line the refrigerant returns as a vapor with a liquid oil rich lubricant. Unfortunately, under some conditions the refrigerant and lubricant are not completely miscible and the liquid refrigerant and lubricant-rich phases separate – a condition described as immiscibility. If this immiscibility occurs in the evaporator, it is possible that the lubricant rich-phase will accumulate in void regions and may not return to the compressor, or may not return until enough oil is present that a liquid slug surges back to the compressor, potentially damaging the compressor and rendering the system inoperable. Therefore, it is desirable that any low temperature immiscibility occurs only below temperatures typically encountered in the evaporator, so that the refrigerant is able to push the lubricant through the evaporator and back to the compressor.

Miscibility data was obtained for refrigerant/lubricant mixtures of R404A/POE-32 and N40/POE-32. The test facility consists of a series of cells placed inside a temperature chamber with a window in front and lights behind to allow for visual inspection of the refrigerant/lubricant mixtures in each cell. The chamber temperature was controlled over the temperature range of –40 to 100 °C and measured using a thermocouple inside an additional test cell containing lubricant. Results are shown in Figures 5 and 6.

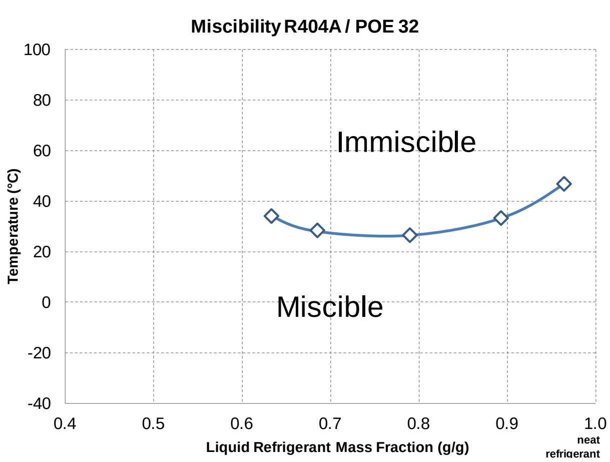

Figure 6: Miscibility of POE 32 and R404A

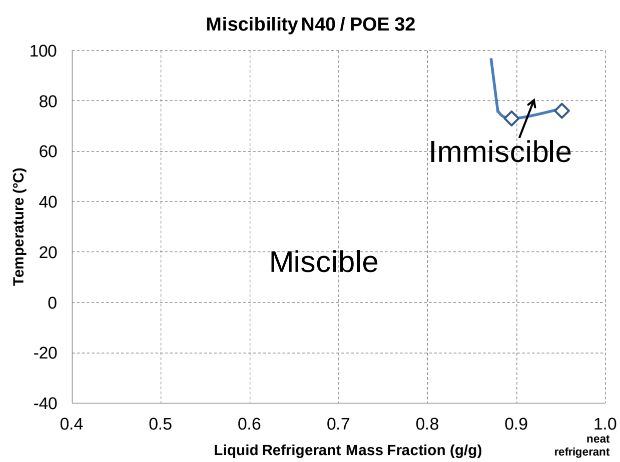

Figure 7: Miscibility of POE 32 and N40

Figures 5 and 6 indicate that N40 is miscible with the POE 32 over a wider range of temperatures than R404A. For an evaporator under typical refrigeration conditions (below 0°C), however, both N40 and R404A are miscible with POE-32 lubricant.

In the condenser, it is also generally desirable to have miscibility at concentrations greater than 95% refrigerant at the highest operation temperature (which can be up to 55°C for a refrigeration application), so as refrigerant condenses (for instance with an oil circulation ratio below 5%) the lubricant dissolves in the refrigerant and passes through the expansion valve and does not accumulate. If the oil circulation rate exceeds the lubricant miscibility concentration, accumulation of lubricant in the high pressure side of the system may take place and cause the lubricant level in the compressor to drop. This drop of oil level in the compressor may starve the bearings and permanently damage the compressor. Figures 5 and 6 indicate that, under concentrations greater than 95%, R404A would be miscible at temperatures below 50°C to 60°C while N40 would be miscible up to 70°C.

3. MILDLY-FLAMMABLE OPTION FOR R404A IN SELF-CONTAINTED SYSTEMS

3.1 System Description Test Description

This section focuses on newly developed refrigerant HDR-110 which further reduces the direct (GWP<150) and indirect (energy consumption) emissions compared to R404A. Even though some changes in equipment would be required to handle its mild flammability, upcoming standard updates could potentially enable such refrigerants to be used in small self-contained refrigeration systems with more relaxed requirements than hydrocarbons.

Tests were performed in a commercially available 3/4 HP single-door reach-in freezer (Figure 7) with an internal volume of about 700 liters and rated capacity of roughly 560 W. The top-mount self-contained refrigeration unit (Figure 8) has a nominal charge of 354g of R404A and comprises 1/2 HP hermetic compressor, air-to-refrigerant tube-in-fin condenser and evaporator, suction-line liquid-line heat exchanger and thermostatic expansion valve. The evaporator has 3 rows with 7 tubes each and a single-circuit in parallel-flow arrangement relative to the air flow. The condenser has 4 rows with 11 tubes each and a single-circuit predominantly counter-flow relative to the air flow.

Figure 8: Reach-in Freezer

Figure 9: Top-mount refrigeration unit

3.2 Operating Conditions and Test Setup

Tests were performed according to ASHRAE 72-2005 which requires a controlled test room with a dry-bulb and wet-bulb temperatures of 24ºC and 18ºC. A total of six test simulators, two per shelf, were placed inside the freezer compartment. The simulators are 500 cm^3 temperature instrumented containers filled with sponge material and a 50%/50% mixture of glycol and water as described by the standard. The remaining of the compartment was partially filled with packages in the form of actual frozen food.

All tests were performed inside an environmental chamber capable of maintaining the conditions required by the standard. The refrigeration system was instrumented with two pressure transducers in the compressor suction and discharge lines. Thermocouples type-T were strategically placed on the refrigerant side at inlet and outlet of compressor, condenser, thermostatic expansion valve and evaporator and on the air side of both heat exchangers.

All primary measurement sensors were calibrated to ±0.15ºC for temperatures and ±2.0 kPa for pressure. Two power transducers with an uncertainty of ±0.5% were installed, one for the compressor alone and another one for the total system power. Capacity was based upon the air temperature difference across the evaporator and is always shown on a relative basis to the R404A. Capacity and efficiency uncertainty were approximately ±3%.

3.3 Results

The system was first tested with R404A (under the nominal refrigerant charge) to determine the baseline performance. Preliminary drop-in tests were then conducted with HDR-110. Results indicated capacities below 90% of R404A and slightly lower efficiency, so a couple of no-cost changes were carried out. First, the original parallel-flow evaporator was turned into counter-flow. As shown in Figure 9, the parallel-flow arrangement works fine with R404A due to two-phase pressure drop but leads to a mismatch in temperature profile for HDR-110 due to its glide (~6°C). The counter-flow arrangement, however, allows a closer temperature match between air and HDR-110 streams. The second change was related to the TXV whose spring pressure was increased to compensate for slightly lower pressure of HDR-110 and consequently to allow proper superheat at the evaporator outlet.

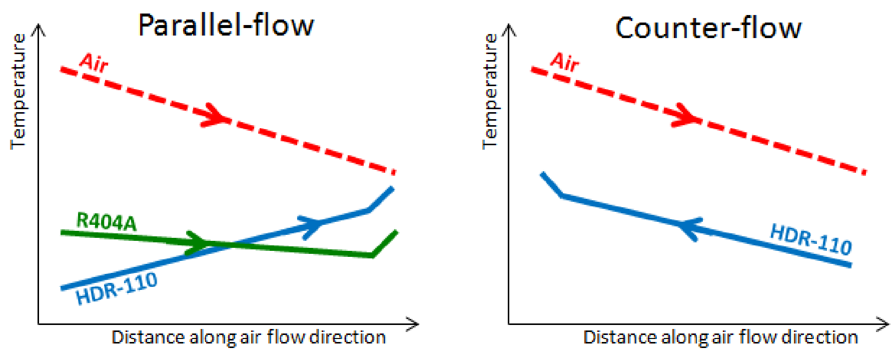

Figure 10: Parallel versus Counter-flow evaporator

Since self-contained systems are usually critically charged (without a liquid receiver), a refrigerant charge optimization (Figure 11) was carried out to determine the efficiency-maximizing charge. Prior to that, the system had been left in steady operation (no change in product temperature) over 24h. All properties, in addition to capacity and efficiency, were averaged over the 8th compressor cycle after a defrost period. Results in Figure 10 show a continuous increase in condensing temperature and subcooling as charge is added to the system due to accumulation of liquid refrigerant on the high-side (condenser and liquid-line). The maximum efficiency observed is mostly a result of a trade-off between the drop in liquid temperature at the TXV inlet (increases efficiency) and the increase in condensing temperature (reduces efficiency).

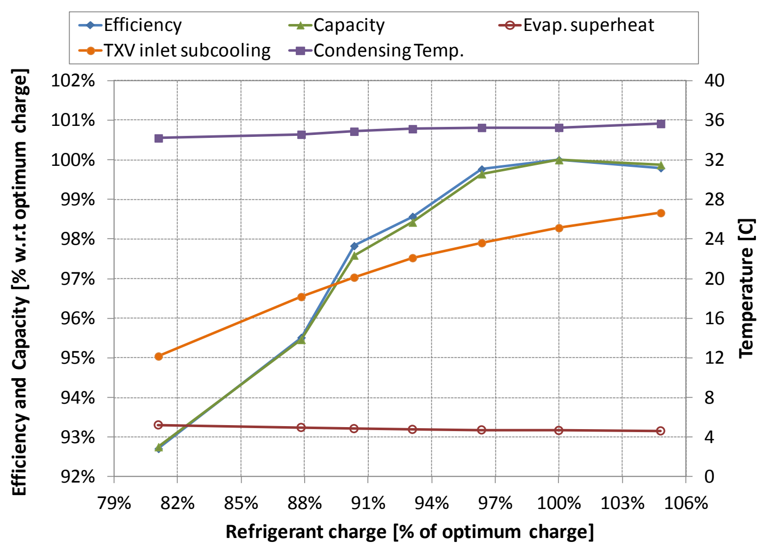

Figure11: Charge determination for HDR-110

Figure 12 illustrates total power and product temperature during typical system on/off cycling, including an initial defrost period, for both R404A and HDR-110. Both refrigerants show steady product temperature with HDR-110 showing about 0.3°C lower average value. In addition, it can be seen that compressor and defrost cycling of HDR-110 are very similar to R404A.

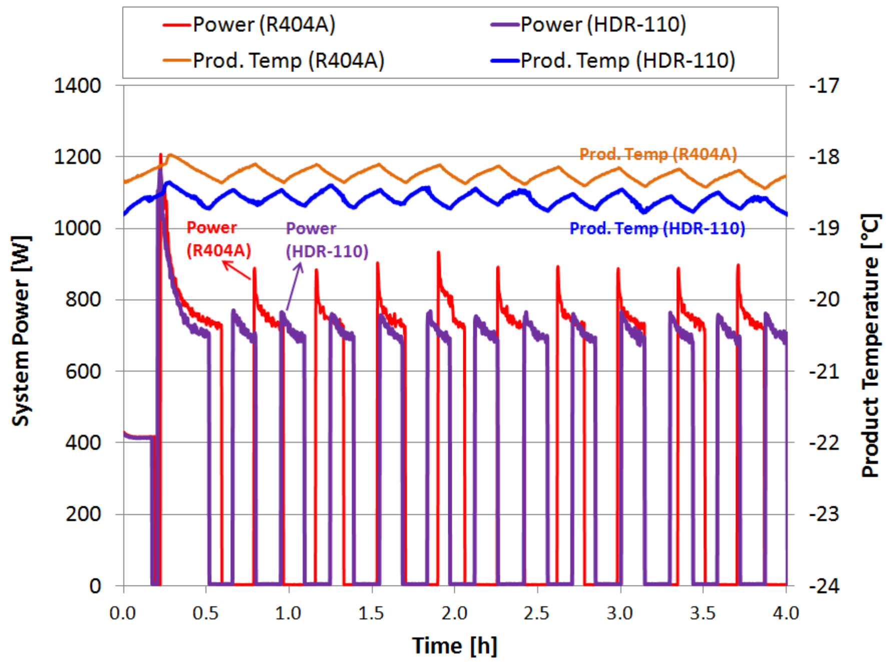

Figure12: R404A and HDR-110 power and product temperature

Table 1 shows several performance parameters for both R404A and HDR-110 over a 24 h period. The box temperature is equal to the average of three thermocouples placed in the refrigerated compartment. The product temperature is equal to the average of the six test simulators. HDR-110 was capable of maintaining the same box temperature and slightly lower product temperature. Run-time ratio of HDR-110 was about 4% higher due to slightly lower capacity. Maximum discharge temperature was about 8°C higher than R404A, but well within compressor limits (about 135°C). HDR-110 also led to a 6% reduction of compressor energy consumption mostly due to superior thermodynamic properties. When the total power was taken into account, energy savings with HDR-110 reached about 3%.

Table 1. Summary of 24h Performance

	Run Time Ratio	Box Temp.	Product Temp.	Maximum Discharge Temp.	24h Energy Consumption (compressor only)	24h Energy Consumption (system)
	[% of R404A]	[°C]	[°C]	[°C]	[% of R404A]	[% of R404A]
R404A	100%	-19.1	-18.3	100	100%	100%
HDR-110	104%	-19.1	-18.6	108	94%	97%

Table 2 shows the detailed performance of the refrigeration system during the “ON” period of a compressor cycle for both R404A and HDR-110. Evaporating temperature remained nearly the same, with HDR-110 about 0.5°C lower due to slightly lower capacity. As previously mentioned, the TXV had been slightly closed so that the evaporator superheat would approach the R404A value as demonstrated in Table 2. Compressor suction temperature was about 4°C lower with HDR-110, mostly due to slightly lower temperatures at the condenser exit. Condensing temperatures were about 2°C higher due to a small drop in heat transfer performance. However, during the design of a new system for HDR-110, changes in the circuitry and tube sizing could address some of those shortcomings and improve the condenser performance. The capacity was about 4% lower, a value that is consistent with a higher run time ratio shown in Table 1. Finally, compressor-only efficiency (capacity divided by compressor power) and overall system efficiency (capacity over total system power) were, respectively, 6% and 3% higher R404A both values in line with lower energy consumption measured during the 24 h period (Table 1).

Table 2. Detailed performance during a compressor "ON" cycle

	Evaporating Temp.	**Evaporator Superheat**	**Suction Temp.**	**Discharge Temp.**	**Condensing Temp.**	**Condenser Subcooling**	**Inlet TXV Subcooling**	**Capacity**	**Efficiency (compressor only)**	**Efficiency (system)**
	[°C]	**[°C]**	**[°C]**	**[°C]**	**[°C]**	**[°C]**	**[°C]**	**[% of R404A]**	**[% of R404A]**	**[% of R404A]**
R404A	-34.9	5.9	-3.9	100	33.5	4.2	20	100%	100%	100%
HDR-110	-34.4*	5.1*	0.1	108	36.1	2.9	21	96%	106%	103%

*Based on average of bubble and dew point temperatures

4. CONCLUSIONS

Low global warming refrigerants with potential to replace R-404A were developed through extensive experimental testing. One of these refrigerants, the N40, is non-flammable and may be used in current refrigeration systems based on the preliminary findings discussed here, providing a great reduction of environmental impact. This is mainly due to reduction of GWP and significant higher efficiencies. Both internal and external larger-scale lab evaluations were consistent in showing that N40 has a superior energy efficiency compared to R404A, with improvements between 3% and 11%.

Other options such as HDR-110 provide further reduction of GWP, and may be used in future self-contained systems capable of working with mildly flammable refrigerants. Experimental evaluations of HDR-110 conducted in R404A reach-in freezer showed lower energy consumption and near match in capacity. However, more work is needed to fully explore potential application of this refrigerant in such systems.

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