R-404A Alternative with Low Compressor Discharge Temperature

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ABSTRACT

A primary reason R-404A has become the preferred refrigerant for commercial refrigeration over the last two decades is its low compressor discharge temperature which provides excellent protection for compressors and significantly improves their operability and durability. However, R-404A is also one of the highest GWP refrigerants in use today and has been targeted by various regulatory agencies for potential phase-down or phase-out. Several reduced GWP options have been proposed using blends of HFCs and hydrofluoroolefins (HFOs) that are around 1300 GWP. However, these blends have increased compressor discharge temperature and in some applications may require external compressor cooling. A new non-flammable refrigerant DR-34 has been developed with low compressor discharge temperature similar to R-404A and closely matches all other properties and performance. This refrigerant will be particularly suitable for transport refrigeration where compressor cooling is difficult to manage under a wide range of ambient conditions. This paper describes experimental testing in both truck and trailer transport refrigeration systems. Results demonstrate cooling capacity, energy efficiency, mass flow and compressor discharge temperature are comparable to R-404A. Miscibility of DR-34 is also measured with a polyol ester lubricant.

1. INTRODUCTION

When replacements for chlorofluorocarbon (CFC) and hydrochlorofluorcarbon (HCFC) refrigerants were needed in the early 1990s due to the ozone issue, hydrofluorocarbon (HFC) refrigerants rapidly emerged as the leading alternatives. They had no ozone depletion potential because chlorine was eliminated from their chemical structure.

They exhibited low toxicity, were non-flammable and thermally stable. And they offered a significantly lower global warming potential (GWP) reduction versus CFC refrigerants. However, they still had relatively high GWPs compared to non-fluorinated options. When climate change emerged as a leading environmental issue, HFCs came under challenge, particularly their use in more emissive applications such as automotive air conditioning and large supermarket systems where leaks are more difficult to control. Commercial refrigeration is also of concern because the leading HFC refrigerant in use is R-404A with a 100 year GWP of 3943 according to IPCC's fifth assessment report (AR5) (Myhre *et al*., 2013), among the highest of the HFC refrigerants. A new low GWP hydrofluoroolefin HFO-1234yf (CF_3CF_2=CH_2) (SAE, 2009) with a 100 year GWP of <1 (Myhre *et al*., 2013) was developed for automotive air conditioning. It was determined that even though HFO-1234yf is mildly flammable, because the charge size is small, it can be safely used in vehicles. There was therefore an opportunity to employ HFO-1234yf as a component in developing low GWP mixtures to match R-404A performance.

Two new non-flammable refrigerants have been developed to replace R-404A in commercial refrigeration based on HFO-1234yf technology. DR-33 has a GWP of 1282, but has higher discharge temperature than R-404A. In some applications, such as transport refrigeration there was a need to more closely match the discharge temperature of R-404A. Therefore, a second alternative called DR-34 was developed to closely match the discharge temperature of R-404A but still reduce the GWP by 50%. This paper will present results of performance and property evaluations of DR-34 that demonstrate it is a very close match to R-404A.

2. PROPERTY TESTING

2.1 Flammability

DR-34 has been determined to be non-flammable based on testing in accordance with ASTM E 681-04 -Standard Test Method for Concentration Limits of Flammability of Chemicals (Vapors and Gases) (ASTM, 2004). Tests were carried out at 60 ^{o}C. This is the standard industry test and temperature used to determine the flammability of refrigerants according to ASHRAE Standard 34-2010 – Designation and Safety Classification of Refrigerants (ASHRAE, 2013).

2.2 Lubricant Miscibility

The miscibility of DR-34 was tested with a mixed acid POE lubricant at a range of temperatures and refrigerant lubricant compositions. Sealed glass tubes were filled with various ratios of refrigerant and lubricant. The tubes were held at different temperatures, and then observed for phase behavior. Results are shown in Table 1 below. Complete miscibility is indicated by the letter "M" and immiscibility by the letter "N". For concentrations from 30 to 95 wt% DR-34 in POE and from -50ºC to +70ºC, DR-34 was miscible with the POE tested, except for the 70/30 wt% composition at 55 and 50ºC.

Table 1: Miscibility of DR-34 with POE lubricant

	Temperature (C)																								
DR-34/POE	**-50**	**-45**	**-40**	**-35**	**-30**	**-25**	**-20**	**-15**	**-10**	**-5**	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**
95 / 5%	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
90 / 10%	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
85 / 15%	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
80 / 20 %	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
70 / 30%	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	**N**	**N**	M	M
40 / 60%	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
30 / 70%	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M

3. THERMOPHYSICAL PROPERTIES

3.1 Thermophysical Properties

A comparison of thermophysical properties of DR-34 with R-404A is shown in Table 2 below. The boiling points are very similar and the critical point of DR-34 is slightly higher than R-404A. Vapor pressures and liquid densities are also similar.

Table 2: Thermophysical properties

	R-404A	**DR-34**
100 year GWP (AR5)	3943	1945
Flammability	None	None
Boiling Point (°C)	-46	-47
Critical Point (°C)	72	75
Vapor Pressure at 25°C (kPa)	1254	1316
Liquid Density at 25°C (kg/m3)	1044	1130
Vapor Density at 25°C (kg/m3)	65.3	63.9

3.2 Thermodynamic Cycle Performance

To evaluate the thermodynamic performance under low temperature conditions, cycle modeling was performed for DR-34 versus R-404A, R-407A and R-407F. The following Conditions were evaluated Evaporator temperature = -30°C, Condenser temperature = 40°C, Subcool amount = 4K, Suction temperature = -10°C and compressor isentropic efficiency = 70%. Results are shown in Table 3.

Table 3: Thermodynamic cycle performance

	Evaporator Pressure (kPa)	Condenser Pressure (kPa)	Compressor Discharge Temperature (ºC)	Average Temperature Glide (Evap and Cond) (K)	Cooling Capacity (kJ/m3)	Cooling Capacity Relative to R-404A	COP	COP Relative to R-404A
R-404A	206	1833	87	0.4	1091	100%	1.60	100%
DR-34	192	1807	88	2.9	1050	96%	1.60	100%
R-407A	165	1717	107	4.2	1031	95%	1.69	105%
R-407F	175	1797	116	4.4	1110	102%	1.70	106%

Thermodynamic cycle modeling shows DR-34 exhibits the closest pressure match to R-404A when compared to R-407A and R-407F. It also exhibits the closest compressor discharge temperature and is only one degree higher than R-404A. The temperature glide is also the lowest of the three refrigerants.

4. SYSTEM TESTING

4.1 Test Setup

Drop-in tests on trailer and truck refrigeration units were conducted with DR-34 and compared with baseline refrigerant R-404A. The purpose of those tests was to find out if transport refrigeration systems and compressors are able to obtain similar performance parameters. Tests were performed using trailer (SLX-400) and truck (T-1200R) systems that are representative of the European transport refrigeration market. Units were tested on a calorimeter test stand designed for measuring cooling capacities of truck and trailer systems in accordance with ANSI/AHRI Standard 1110-2013 (ANSI/AHRI 2013). Figures 1 and 2 show a schematic of the test setup. Average measurement precision determined by uncertainty analysis was 2.5%.

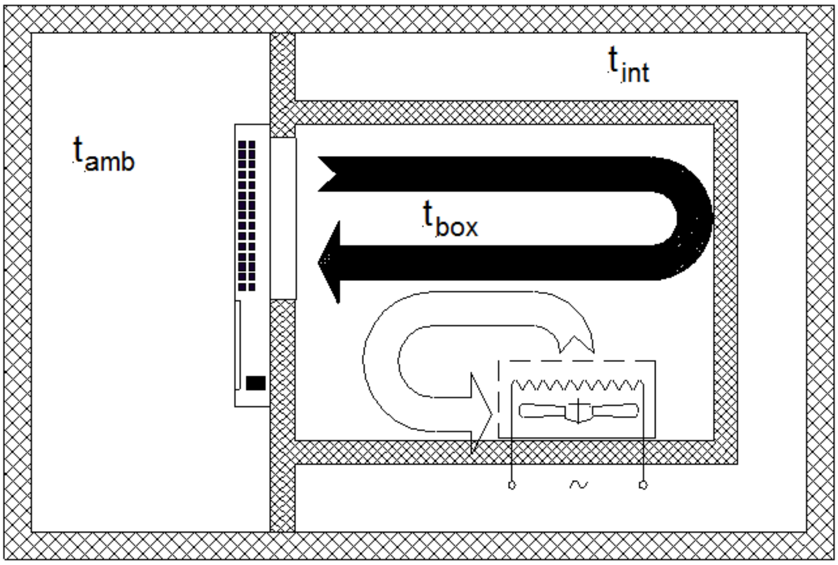

Figure 1: Units calorimeter testing

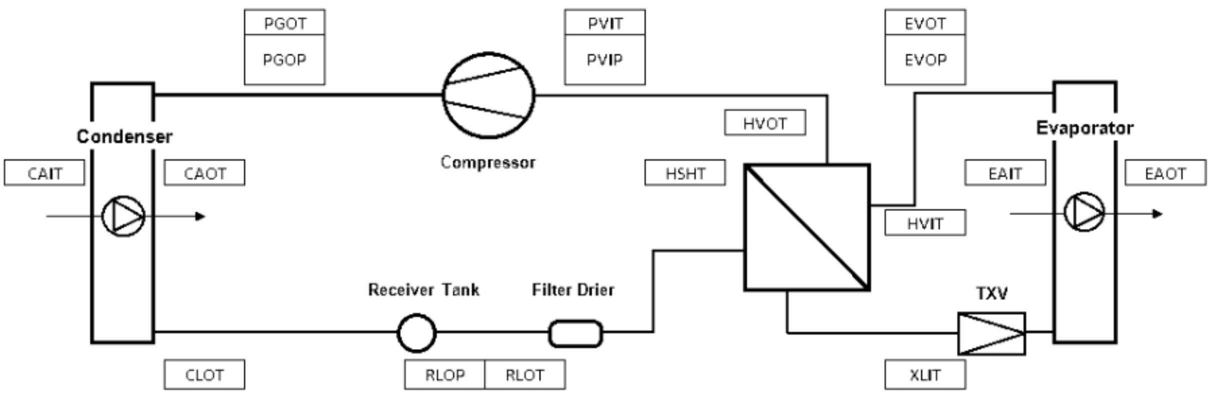

Figure 2: Refrigeration cycle diagram and probe placement

4.2 Test Conditions and Results

The products tested were a SLX-400 trailer unit and a T-1200R truck unit, each using R-404A as the refrigerant. The trailer unit's rated net cooling capacities at high speed engine operation under the following ATP (ECE/TRANS/219, 2010) conditions are: 17.5 kW at 30 ºC ambient/0 ºC evaporator return air temperatures and 9.3 kW at 30 °C ambient/-20 °C evaporator return air temperatures. The truck unit's rated net cooling capacities at high speed engine operation under the following ATP conditions are: 12.5 kW at 30 ºC ambient/0 ºC evaporator return air temperatures and 6.7 kW at 30 °C ambient/-20 °C evaporator return air temperatures. DR-34 is considered a drop-in replacement for R404A. Thus the same compressor lubricant was used and only the thermostatic expansion valve was adjusted to set proper evaporator superheat. Tests were performed under standard ATP ambient temperature and box temperature conditions. Two compressor drive speeds were set based on the type of the drive - high speed for the diesel engine drive mode and electric standby speed for the electric motor (EL) drive mode. During initial set of tests the refrigerant charge of DR-34 and the evaporator superheating (ESH) were optimized. Results are shown in Figure 3 and 4.

The main monitored and compared parameters were cooling capacity, fuel consumption, compressor discharge temperature, evaporating and condensing pressure and heating capacity. Tests were also performed on electric standby in which case electrical power input was measured. As mentioned above, the intention was to obtain the same or better cooling capacity or energy efficiency and to find optimal combination for drop-in charge replacement.

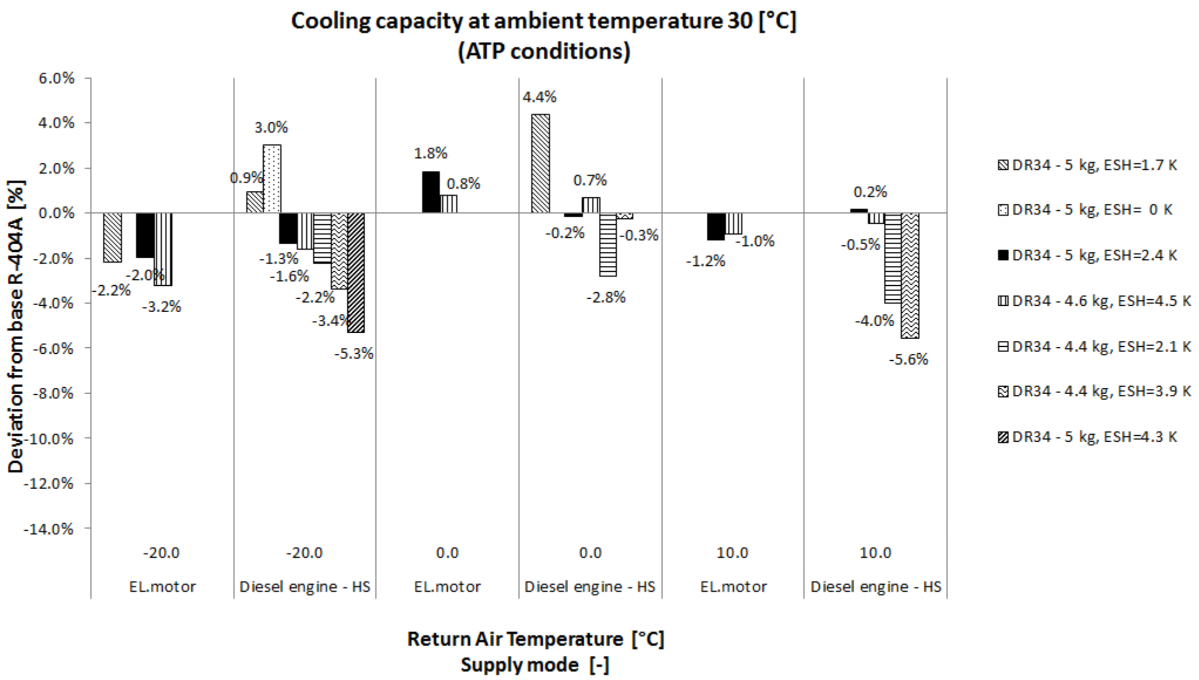

Figure 3: SLX-400 cooling capacity comparison

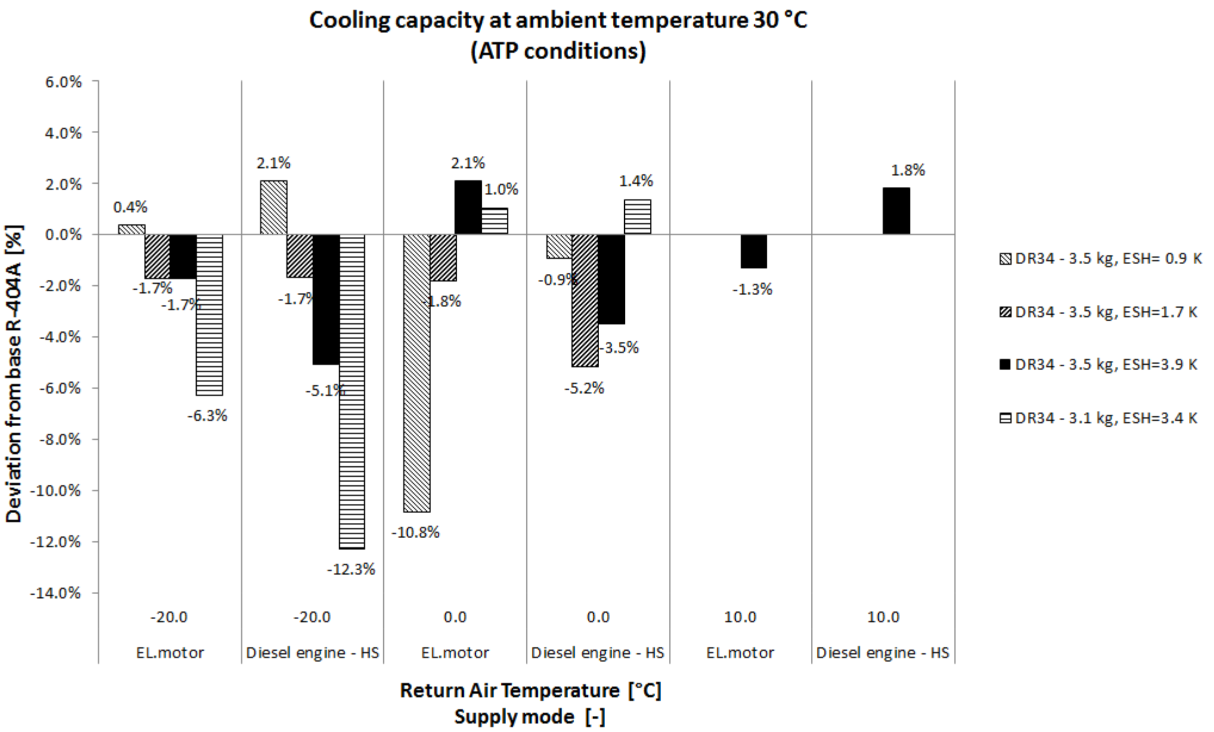

Figure 4: T-1200 cooling capacity comparison

The figures show different values of the cooling capacities based on conditions, power supply, the refrigerant charge and the evaporator superheat setting. Considering the inevitable measurement error from the point of view of the same cooling capacity the charge of 5 kg and the superheat of 2.4 K seem to be the optimal combination for SLX-400 and the charge of 3.5 kg and the superheat of 3.9 K seem to be the optimal combination for T-1200R.

Energy efficiency was calculated as a ratio of the cooling capacity divided by the drive input power which was either measured directly in case of the electric motor or calculated from the fuel consumption. Results are shown in Figures 5 and 6 below. For the SLX-400 trailer unit, energy efficiency ranged from -2.8% to +1.8% relative to R-404A. For the T-1200R truck unit, there was more variability in the results, with energy efficiency ranging from -7.1% to +9.7% compared to R-404A.

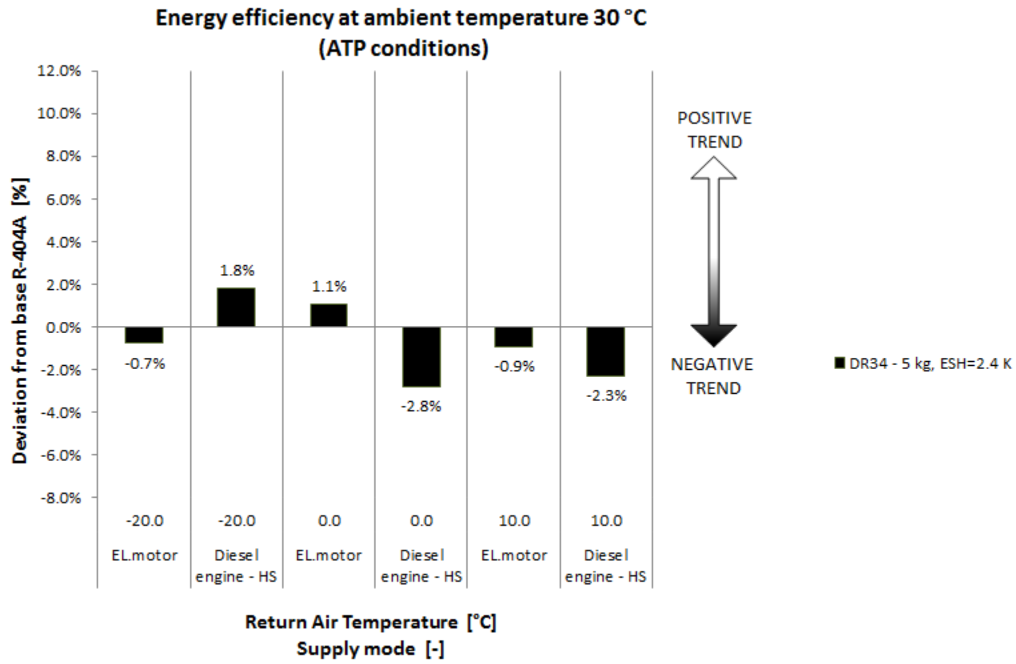

Figure 5: SLX-400 energy efficiency comparison

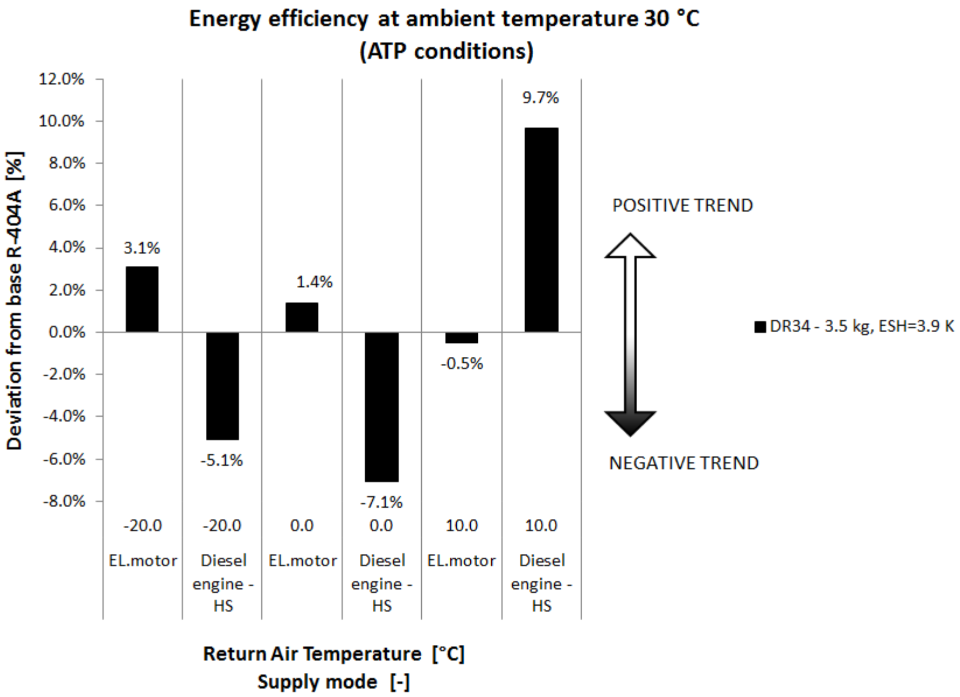

Figure 6: T-1200R energy efficiency comparison

A mass flow meter was installed on the liquid line of the system and mass flow rates for DR-34 were measured and compared relative to R-404A. Results are shown in Figures 7 and 8 below. Mass flow rates ranged from -1% to +5% relative to R-404A.

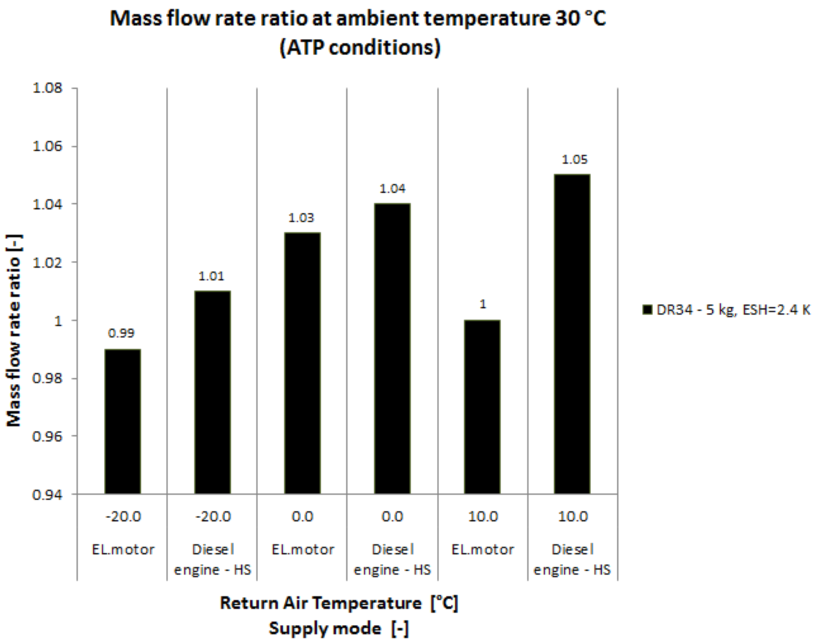

Figure 7: SLX-400 mass flow comparison

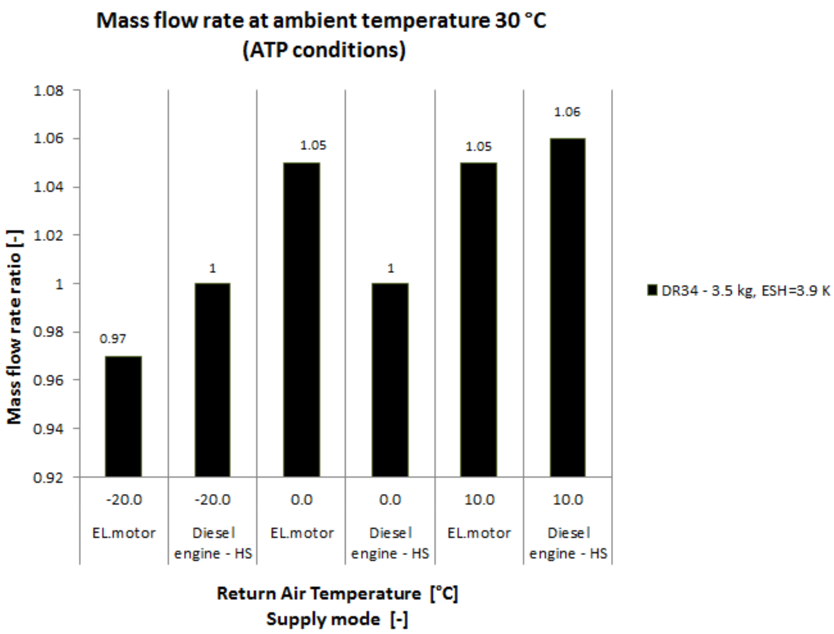

Figure 8: T-1200R mass flow comparison

Compressor discharge temperature results are shown in Figures 9 and 10. The compressor discharge temperature is 2-3K higher for DR-34 in the SLX-400 trailer system and 0.2-1 K higher in the T-1200R truck system which is consistent with the thermodynamic modelling.

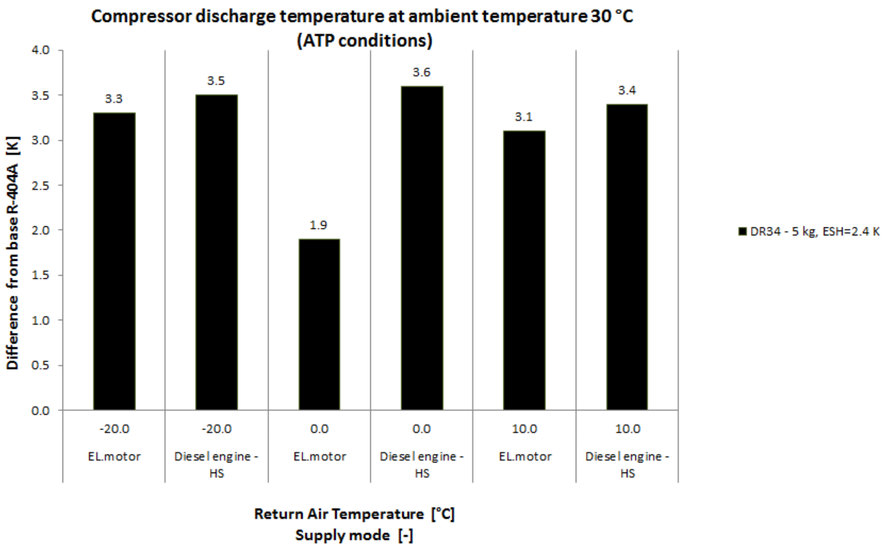

Figure 9: SLX-400 compressor discharge temperature comparison (ATP condition)

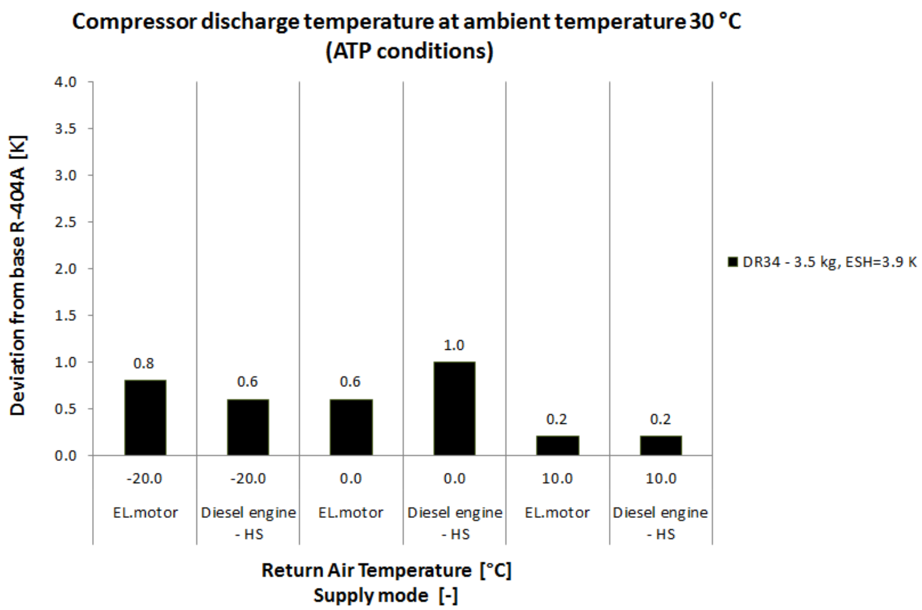

Figure 10: T-1200R compressor discharge temperature comparison (ATP condition)

5. CONCLUSION

Property and performance testing demonstrate DR-34 is a suitable alternative for R-404A in transport refrigeration. DR-34 has a GWP 50% lower than R-404A. DR-34 is non-flammable, has good miscibility with POE lubricant and comparable thermophysical properties. System tests show DR-34 can be used as a drop-in replacement of R404A in the transport refrigeration systems. Test results show no significant loss of the cooling capacity or increase of the input power and compressor discharge temperatures only slightly higher then R-404A. The next step should be expanding the investigation of refrigeration systems using DR-34 from the thermodynamics and heat transfer point of view. This includes mapping of different types and models of compressors and also the further refrigeration testing to fully understand the performance in different systems.

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