Refrigerants With Low Environmental Impact For Commercial Refrigeration Systems

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REFRIGERANTS WITH LOW ENVIRONMENTAL IMPACT FOR REFRIGERATION SYSTEMS

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ABSTRACT

Refrigerants with high global warming potential (GWP), such as R404A, have been used in a wide range of refrigeration applications, but were subject to regulations and mandatory bans in several countries in the last few years. This paper presents several options to significantly reduce the environmental impact in both existing and new commercial refrigeration applications, while improving the energy efficiency.

As the leading option for retrofitting R404A in existing systems R448A is presented in a supermarket refrigeration system retrofit case study. This field evaluation showed energy savings with R448A of 9-20% depending on the ambient temperature while maintaining the operational requirements. Compressor discharge temperatures remained within manufacturer specifications and no mitigation measures were needed.

For new refrigeration systems a concept design is introduced using hermetic self-contained units to provide refrigeration at low temperature levels with R1234yf and medium temperature levels with the non-flammable blend R515A. The environmental impact of this new concept is compared with other system architectures. The R515A /R1234yf system shows up to 27% lower total emissions and up to 30% higher energy efficiency than a transcritical R744 system.

Keywords: HFO-Refrigerants, Environmental Impact, Commercial Refrigeration, Supermarkets

1. INTRODUCTION

R404A is a refrigerant blend that is used in a wide range of medium and low temperature refrigeration applications. However due to its high GWP of 3943 (IPCC, 2013) it has been the target of environmental regulations including bans and phase-downs. R404A replacements have been developed and commercialized and are under evaluation by the industry in existing equipment. One of the leading options to replace R404A is R448A. In the first section the properties of reduced GWP replacements for R404A are compared and the performance of R448A in a case study is described. In a following step a new non-flammable azeotropic reduced GWP refrigerant blend (R515A) is presented for use in new medium temperature applications. The characteristic properties and thermodynamic performance are compared to the baseline refrigerant R134a and other potential candidates like R1234yf and R1234ze(E). Finally a new system architecture for supermarket refrigeration systems using R515A is proposed and its performance compared with those of traditional systems as well as current retrofit and alternative systems. Using a holistic analysis approach, the new system architecture with R515A is shown to significantly reduce the environmental impact by addressing both direct and indirect emissions compared to other system.

2. R404A REPLACEMENST FOR REFRIGERATION SYSTEMS

R448A is a non-flammable (ASHRAE A1) hydrofluorocarbon/hydrofluoroolefin (HFC/HFO) blend with a GWP of 1273. It is designed to replace R404A in both existing and new, commercial refrigeration systems for supermarket and small self-contained freezers units. Various performance evaluations have been carried out with R448A. Abdelaziz and Fricke (2014) used a small-scale supermarket refrigeration system to show that the combined low and medium temperature energy efficiency of the system with R448A is on average about 11% higher than that with R404A. Baba and Yamagushi (2014) carried out tests with medium and low temperature condensing units under typical rating conditions and showed that R448A can yield up to 16% higher coefficient of performance (COP) and a near match in refrigeration capacity.

2.1 R448A Case Study

A field trial of R448A was carried out in an actual supermarket located in the midwestern US. The refrigeration equipment in use consisted of R404A distributed system with 14 low and medium temperature display cases and scroll compressors with a low temperature capacity of 14.4 kW and a medium temperature capacity of 37.8 kW. The system was instrumented and pressure transducers were installed in suction and discharge headers, liquid line, suction line and discharge of each compressor. The temperature of discharge air was monitored for all cases. Energy and amperage meters were installed for compressors and condenser fans. All primary measurement sensors were calibrated to ±0.2ºC for temperature and ±2.0 kPa for pressure. The power transducers had an uncertainty of ±0.5%.

Data was collected from the system with baseline R404A over the course of four months, between August and December. Then, the system was converted to R448A. During the conversion, same POE oil was maintained and minor adjustments were made to controls. The compressor rack low pressure settings were slightly changed for R448A, so that its average saturated suction temperature matches that of R404A. The minimum condensing temperature of 21ºC and the air and refrigerant temperature difference setting for the condenser of 6ºC were kept the same. The rack controller was updated to calculate the condensing temperature of R448A based on the average of bubble and dew temperatures. After the retrofit, data was collected for R448A for about six months, from which about four consecutive months (February to June) were selected for comparison with R404A so that the resulting average ambient temperature was the same for both refrigerants. The energy consumption of both refrigerants was also compared at different bin temperatures.

Figure 1 illustrates the percentage of hours for each temperature bin for both R404A and R448A. The number of hours for different temperatures were similar resulting in average temperatures of 13.3°C for both refrigerants.

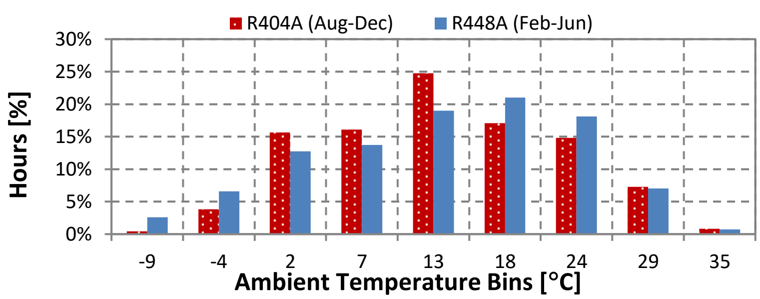

Figure 1. BIN Temperature Distribution

Figure 2 and Figure 3 show the average condensing temperature and the total condenser fan power, respectively, for different ambient temperature bins. It can be observed that the system with R404A or R448A was able to maintain an adequate condenser air-refrigerant temperature difference of about 6ºC when the ambient temperature is above about 15°C. When the ambient temperature is below around 15°C, the condensing temperature is adequately maintained at about 21°C by typical pressure control mechanisms such as variable speed fans and condenser split. Due to higher energy efficiency of R448A, the amount of heat rejected in the condenser for the given condensing temperature was lower than R404A. As a result, the total amperage drawn by the condenser fans with R448A was consistently lower than R404A.

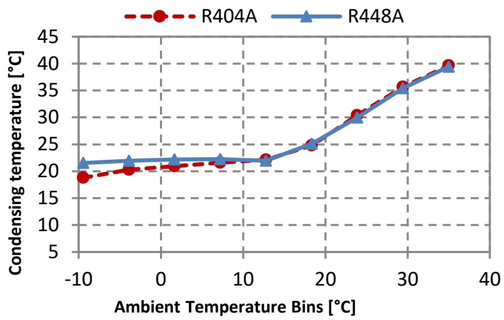

Figure 2. Condensing temperature as a function of the ambient temperature

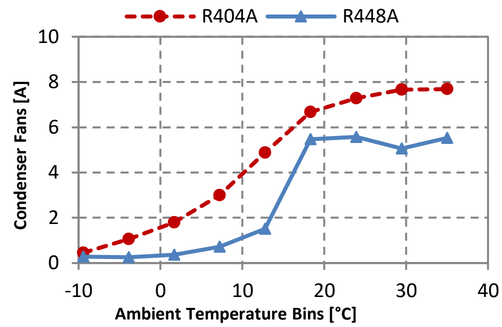

Figure 3. Condenser fan power as a function of the ambient temperature

Figure 4 shows the average compressor suction and discharge temperatures at the ambient temperature bin of 35°C. R448A yields slightly higher discharge temperatures, but remains below the limit specified by the compressor manufacturer. Even though liquid injection valves were installed, they were not triggered during the operation with R448A and R404A. A comparison of the average case temperatures for medium and low temperatures is shown in Figure 5. These values were recorded for an ambient outdoor temperature of 13.3C for both R404A and R448A. The store indoor temperature was maintained within 1°C for R404A and R448A at 21.6°C and 22.5°C respectively. At both temperature levels R448A achieved case temperature within 0.6°C of R404A indicating a close match of the set points.

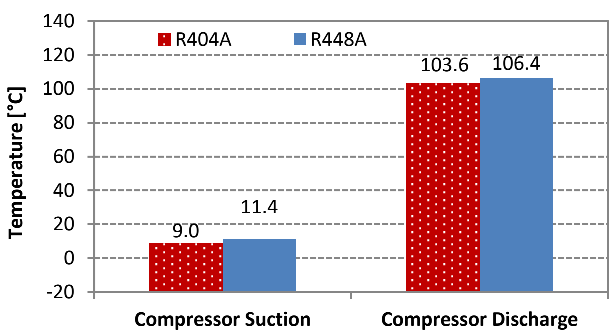

Figure 4. Compressor temperatures at 35°C ambient temperature bin

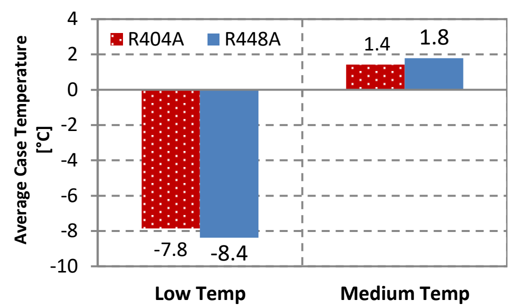

Figure 5. Average Case temperatures for LT and MT

Figure 6 shows the total system energy consumption for each temperature bin. It can be seen that R448A yields lower energy consumption than R404A at all ambient temperatures, with energy savings ranging from 9% to 20%.

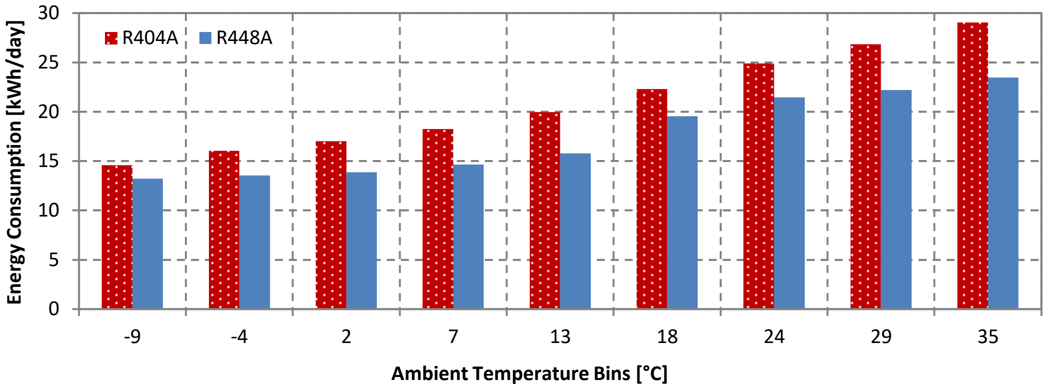

Figure 6. Total system energy consumption as a function of the ambient temperature

3. REFRIGERANTS FOR NEW SYSTEM DESIGNS

The non-flammable, azeotropic, reduced GWP refrigerant blend R515A for use in medium temperature applications for new systems has been developed. R515A is a mixture of R1234ze(E) and R227ea which is non-flammable with the ASHRAE safety classification A1. The GWP is 402.
A thermodynamic analysis using a computer model was performed to estimate the variations in capacity and COP by replacing R134a with the three low and reduced GWP replacements. This type of analysis was performed at typical medium temperature conditions using thermodynamic data from the NIST property database REFPROP 9.1 (Lemmon et al., 2013). The analysis was performed at -7°C evaporation temperature, 5.5°C evaporator superheat, 40.5°C condensing temperature, 5.5°C condenser sub cooling, 65% compressor isentropic efficiency and 100% compressor volumetric efficiency. The results of the analysis are summarized in Table 1.

Table 1. Thermodynamic properties of R134a and Low GWP replacement options

	R134a	R1234yf	R1234ze(E)	R515A
ASHRAE Safety Classification	A1	A2L	A2L	A1
Composition	R134a (100%)	R1234yf (100%)	R1234ze(E) (100%)	R1234ze(E)/ R227ea (88%/12%)
GWP (AR5)	1300	<1	<1	402
Capacity [% of R134a]	100.0%	95.9%	74.2%	73.5%
Efficiency [% of R134a]	100.0%	95.6%	100.3%	99.7%
Suction pressure [kPa]	225.5	247.4	166.0	166.1
Discharge pressure [kPa]	1016.6	1018.4	766.6	766.7
Pressure ratio [% of R134a]	100.0%	91.3%	102.5%	102.4%
Compressor discharge temperature vs. R134a [K]	0.0	-13.2	-8.8	-10.4

R1234ze(E) and R515A show a close match in efficiency to R134a. The reduction in capacity for both of these refrigerants can be compensated for new systems by an increase in compressor displacement. All of the refrigerant replacement options show reduced compressor discharge temperatures compared to R134a. An example of applying R515A in a commercial refrigeration system is investigated in the following paragraph.

4. ENVIRONMENTAL IMPACT ANALYSIS

An environmental impact analysis is a powerful tool to compare the overall equivalent carbon dioxide emissions of a refrigeration system over its lifetime. Different approaches such as Total Equivalent Warming Impact (TEWI) and Life Cycle Climate Performance (LCCP) have been developed. For both of these methods the direct and indirect emissions are evaluated. The direct emissions are hereby based on the leaking refrigerant over the lifetime of the equipment. The indirect emissions are caused by the carbon dioxide that is emitted to produce the energy that is consumed over the lifetime of the equipment. The difference between the two methods is that LCCP provides a more detailed insight by considering the emissions due to manufacturing and disposal of the system whereas the TEWI approach only considers the usage time of systems as outlined in IIR (2016). This analysis is performed to compare the baseline system using the high GWP refrigerant R404A with the leading lower GWP replacement R448A, a R744 booster system and the new concept utilizing R515A/ R1234yf.

The baseline R404A system is a centralized design that is a common architecture in supermarkets. It requires large amounts of refrigerant charge due to the long lines of refrigerant tubing throughout the store that connect the machine room that house the compressor racks with the medium and low temperature cases throughout the store. Centralized systems typically have higher refrigerant emission rates caused by a larger number of refrigerant leaks due to more connections. In addition more heat infiltration can be observed that lead to an increase in compressor suction temperature as well as pressure drop. All these factors create a penalty on the system efficiency.

Besides the existing centralized systems, distributed direct expansion concepts have been used in recent years. In these systems, the compressor racks are located closer to the medium and low temperature cases in the store which effectively reduces the necessary refrigerant tubing length and consequently the refrigerant charge. This also typically yields a reduction of refrigerant leaks due to fewer connections. In addition, lower pressure drop and less heat infiltration can be achieved leading to an improved system efficiency compared to centralized designs.

R744 booster refrigeration systems are two-stage systems that have a compressor on the low pressure side that boosts the pressure from low evaporation temperature levels to medium evaporation temperature levels. A suction line heat exchanger transfers heat from the higher temperature refrigerant after the gas cooler to the lower temperature refrigerant after the evaporators. This reduces the inlet quality of the refrigerant and by that effectively increasing the enthalpy difference in the evaporator for both medium and low temperature levels. Due to the relatively low critical point of R744 at 31°C the system can operate in a transcritical mode depending on the ambient condition. This creates a penalty on the achievable efficiency compared to subcritical operation. Different approaches to mitigate these effects were proposed in the literature. However these were not applied in this study since they could also be applied on the other investigated system concepts improving their achievable system performance.

In Figure 7, a new system architecture is proposed. The system consists of a modified cascade design that uses the refrigerant blend R515A in the medium temperature stage and R1234yf in the low temperature stage. The non-flammable blend R515A provides hereby the medium temperature cooling throughout the store as well as removing the heat from the low-temperature stage. In the low temperature stage, instead of a large system, multiple self-contained hermetic low-temperature units are used as indicated by the individual units shown in grey in Figure 7. Due to its non-flammable properties the refrigerant system charge of R515A is not limited. This makes it especially suitable for applications such as supermarket refrigeration systems with customer contact on the store floor where the system safety of larger charges needs to be considered. The low temperature design with self-contained units enables good performance with a minimum in system charge taking the mild flammability of R1234yf into account. The degree of freedom for the designer is however greatly improved compared to highly flammable A3 refrigerants such as R290 which is more restricted on the allowable charge amount.

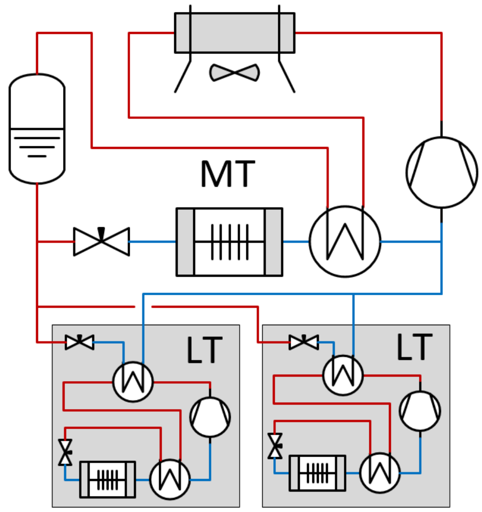

Figure 7. R515A/ R1234yf Cascade Refrigeration System

The system cooling efficiency for the four system types was simulated for a store size of 4180 m^2. The assumptions that were made for the determination of the system performance are summarized in Table 2. A higher evaporation temperature was used for R744 in comparison to R404A and R448A, to account for its heat transfer properties. The modified cascade system with R515A/R1234yf is also assumed with a slightly higher evaporation temperature due to the benefits of the self-contained design with short lines creating only very low suction line pressure drop and fewer heat infiltration losses.

Table 2. Refrigeration system assumptions

Description	**Unit**	**R404A**	**R448A**	**R744**	**R515A/ R1234yf**
Global Warming Potential (AR5)	[-]	3943	1273	1	402/<1
Refrigerant charge	[kg]	1450	750	1000	750
Leak rate	[%]	15%	10%	15%	10%
MT Evaporation temperature	[°C]	-6.7	-6.7	-6.1	-6.7
LT Evaporation temperature	[°C]	-28.9	-28.9	-28.3	-27.8
Superheat MT and LT	[°C]	5.5			
Isentropic efficiency MT	**[-]**	0.7			
Isentropic efficiency LT	**[-]**	0.67			
Volumetric efficiency	**[-]**	0.95			
Approach temperature Evaporator	[°C]	5.5			
Approach temperature Condenser	[°C]	5.5	5.5	5.5 SC, 2.8 TC	5.5

Based on the assumptions for a typical store, the system efficiency of the four system designs was determined for varying ambient temperatures as shown in Figure 8. The influence of different minimum condensing temperatures is hereby highlighted by the dashed lines for the systems employing R404A, R448A and R515A/ R1234yf. Significant improvement potential can be realized with using electronic expansion valves that allow the variation of the minimum condensing temperature. For the R744 system, the benefit of electronic expansion valves and lower minimum condensing temperatures is already taken into account. The highest performance of the investigated systems can be seen by the cascade design using R515A/ R1234yf. It can be observed that R744 shows improved performance only at low ambient conditions when it operates in subcritical mode. At higher ambient conditions the transcritical operation leads to increased losses penalizing the system performance.

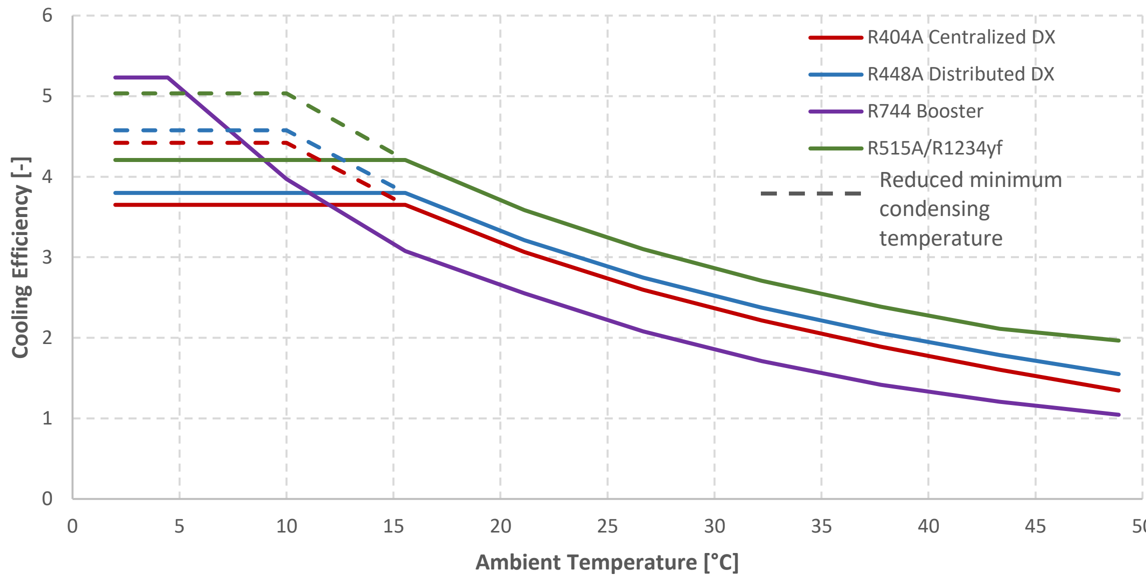

Figure 8. Cooling efficiency of supermarket refrigeration systems at different ambient temperatures

Based on the system efficiency curves, the environmental impact of the three systems for a 15-year lifetime was determined for global locations in Sao Paulo, Brazil, Atlanta, US and Shanghai, China. For the local temperatures an hourly BIN approach was used to obtain a good representation of seasonal fluctuations. The overall system capacity was assumed at 300 kW with a third of the load for low temperature and the remaining for medium temperature assigned. The local electricity emission factors for Sao Paulo, Atlanta and Shanghai are 0.136 $kgCO_2/kWh$ (MCT, 2014), 0.497 $kgCO_2/kWh$ (eGRID, 2016) and 0.831 $kgCO_2/kWh$ (IEA, 2017) respectively. The results for direct and indirect emissions as well as average COPs are shown in Figure 9. The average COP is determined based on the BIN temperatures for the locations over the course of one year.

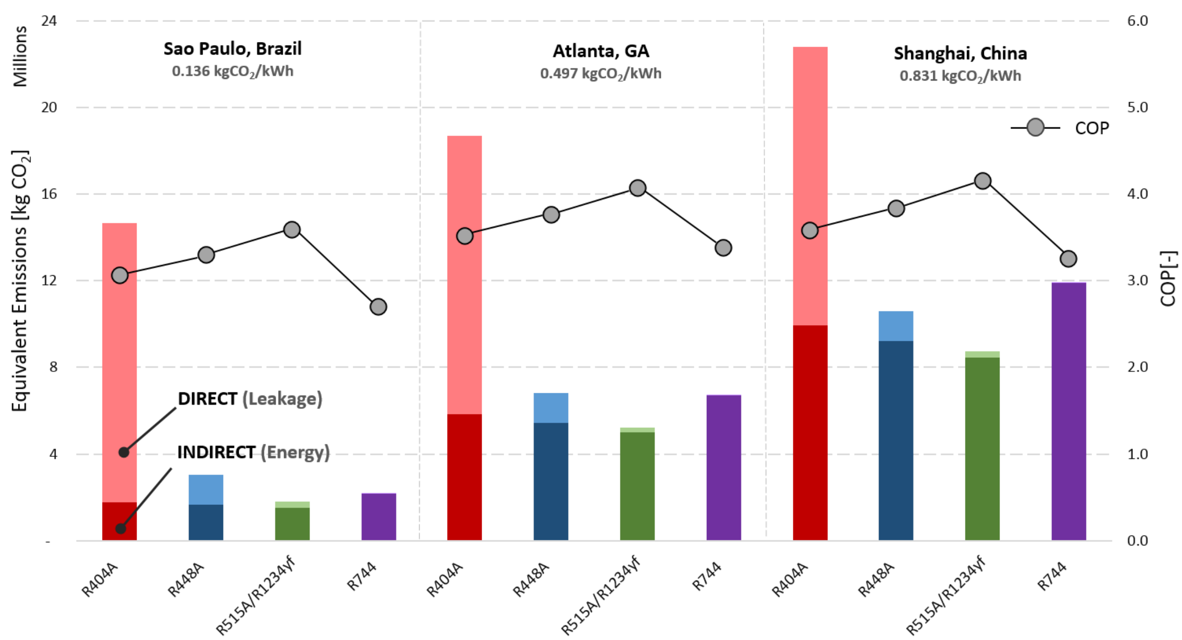

Figure 9. Direct and Indirect Carbon Dioxide Equivalent Emissions

It can be seen that the R404A baseline system has the largest overall emissions due to the high GWP and leak rate. The switch to R448A reduces the direct emissions due to the 68% lower refrigerant GWP as well as the reduced system charge amount and leakage rates to significantly decrease the overall direct impact in distributed systems. In addition, an improvement of energy efficiency due to refrigerant and system effects effectively reduces the indirect emissions. Overall emission reduction from R404A can be achieved for R448A between 79% and 53% for Sao Paulo and Shanghai respectively. R448A even achieves similar emissions compared to R744 in all three locations. Besides the emissions the energy efficiency is especially interesting for the user of the equipment since it is a significant contributor to the determination of the operating cost due to system energy consumption. R448A shows hereby better performance than R404A and R744 effectively reducing the operating cost.
The R744 booster system has the lowest GWP of the four investigated solutions. However the penalty it experiences due to transcritical operation leading to the lowest efficiency of the investigated systems limits the emission reduction.
The overall best results for all locations can be seen for the R515A/ R1234yf self-contained cascade system which benefits from the best efficiency and reduced GWP. The emissions are reduced compared to R404A by 87% for Sao Paulo 72% for Atlanta and 62% for Shanghai. In comparison to R744, the R515A/ R1234yf system reduces the environmental emissions between 17% for Sao Paulo and 27% for Shanghai. A 22% emission reduction can be seen for average temperatures in Atlanta. The energy efficiency is 25% to 30% higher than R744 for Atlanta and Sao Paulo respectively.

5. CONCLUSIONS

This paper evaluated options to replace high GWP refrigerants such as R404A in existing installations and new system designs. The close capacity match and beneficial efficiency characteristics of R448A were presented in a field case study in which energy savings between 9 and 20% depending on ambient conditions were achieved. Compressor discharge temperatures were only slightly above R404A levels which were below temperature limitations specified by the compressor manufacturers. Installed mitigation techniques such as liquid injection were not triggered during the trial period even at elevated ambient temperatures.

In the second part of the paper an option for new system designs was presented with the refrigerant blend R515A for medium temperature refrigeration applications. R515A shows a close match in efficiency to R134a with lower capacity that can be taken into account for new designs by an adjusted compressor displacement volume. The environmental impact was investigated for four system designs including R404A centralized DX, R448A distributed DX, R744 booster and a new concept using R515A for medium temperature and R1234yf for low temperature in a self-contained systems. For all four architectures the overall CO_2 equivalent emissions over their lifetime and the average COP were determined. It was demonstrated that for three global locations representing low, average and elevated emission factors the new system approach using R515A and R1234yf has the lowest environmental impact and highest system efficiency. The comparison of the four architectures also revealed that the lowest GWP does not automatically lead to the lowest environmental impact. The overall system and refrigerant efficiency affecting the indirect emissions is the main parameter for end users to consider in order to minimize the equivalent carbon dioxide emissions and operating cost. The new proposed R515A/ R1234yf cascade system also shows 25-30% higher energy efficiency than R744 transcritical system.

Therefore, R515A is a promising option for commercial refrigeration systems and can lead to significant reduction in direct and indirect emissions compared to R404A as well as other currently proposed options to become a vital part in the process to reduce the environmental impact of commercial refrigeration systems.

NOMENCLATURE

DX	Direct Expansion	MT	Medium Temperature
EPA	Environmental Protection Agency	SC	Subcritical
GWP	Global Warming Potential	TC	Transcritical
LCCP	Life Cycle Climate Performance	TEWI	Total Equivalent Warming Impact
LT	Low Temperature		

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