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Review of Lower GWP Refrigerants For Retrofitting R-410A Applications

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ABSTRACT

R-410A is a refrigerant blend of R-32 and R-125 that is widely used in air conditioning applications. R-410A has become a target for a phase-down in line with global carbon emission reduction initiatives (Kigali amendment to the Montreal Protocol, EU F-Gas Regulation, etc.) due to its high global warming potential (GWP), lower GWP refrigerant alternatives for retrofitting into existing R-410A systems are required to be nonflammable while providing similar performance in efficiency and more importantly capacity. Development of lower GWP R-410A alternatives has been difficult and refrigerant manufacturers have developed few options that attempt to fulfill these requirements. Currently viable reduced GWP options are blends with elevated temperature glide with significantly reduced capacity that need to be considered for retrofit situations.

This paper evaluates the match between different refrigerants and the application requirements for retrofitting into R-410A air conditioning systems. A focus on temperature glide and inherent performance impact is evaluated and related to possible consideration for use. Finally material compatibility information is provided for R-466A, a nonflammable near design compatible R-410A alternative, outlining the interaction of refrigerant with materials of construction.

1. INTRODUCTION

One of the greatest challenges that mankind is facing is global climate change. The global scientific community has been investigating man-made climate change, it's impacts and consequences for the environment and potential measures to mitigate or prevent uncontrollable warming of the atmosphere for many years through the Inter-governmental Panel for Climate Change (IPCC). High GWP refrigerants are significant contributors to warming and are estimated to potentially contribute an average global temperature rise to 0.5˚C if no action was to be taken with reducing the GWP of fluorinated hydrocarbons in use today in HVACR equipment.

R-410A has been the main refrigerant used in air conditioning applications with a GWP of 2088 (Forster et al., 2007). Considering a weighted average approach of GWP of refrigerants being used today throughout the industry, the GWP will need to be less than 300 to meet the phase-down targets of the Kigali Amendment to the Montreal Protocol (Schultz et al., 2020). Multiple studies have been performed to investigate refrigerant options with a lower GWP to replace R-410A. The reduction of refrigerant GWP requires in many cases a blend design which contains lower GWP hydrofluoroolefin (HFO) refrigerant components that are often, ASHRAE Standard 34 flammability Class 2L. For example, R-410A is a blend of R-32 which is Class 2L flammable and R-125 (Class 1) is added only to render the blend non-flammable. An industry wide test program that evaluated lower GWP R-410A replacements only included R-744 as a nonflammable option along with nine lower flammable 2L options (AHRI, 2015). Lawton et al. (2018) investigated the performance of lower GWP HFC/HFO blends in a R-410A heat pump and found COP improvements when using R-1234ze(E)-based blends as well as R-32. Low (2020) compared two mildly flammable lower GWP blends based on R-1132a and described similar performance in heating and cooling while providing a GWP of around 300. Saleem et al. (2021) investigated the temperature glide impact on the performance of a R-410A water source heat pump in a numerical study. They found similar performance to reduction in efficiency depending on operating condition. High load water flow rate conditions offered performance improvement potential due to the better match between the temperature glide profiles of water and refrigerant side.

Unfortunately, nonflammable options are required for retrofitting existing R-410A equipment which significantly limits the ability to lower GWP. Schultz, (2019) reported on experimental tests of R-466A, a nonflammable design compatible refrigerant blend to replace R-410A with a 65% lower GWP. Similar performance compared to R-410A was documented in both a residential heat pump and transport refrigeration unit. Schultz and Kujak, (2019) reported on results of air-cooled water chiller tests performed with R-452B, R-32, and an experimental blend with similar composition to R-466A in comparison to the baseline refrigerant R-410A. In addition, a 3ton residential split system was compared for R-410A and the experimental blend with similar composition to R-466A. In both cases, similar performance compared to R-410A was recorded and it was determined to be potentially a candidate for replacement in existing R-410A equipment contingent upon confirmation of chemical stability and compatibility with materials of construction. Gao et al. (2021) reported on performance and compatibility information for R-466A. Similar efficiency and capacity were achieved while providing comparable lifetime to R-410A systems by using additives.

Other nonflammable refrigerants are available today that have a lower GWP compared to R-410A. Table 1 summarizes and compares numerous nonflammable lower GWP blends listed in ASHRAE standard 34 (ANSI/ASHRAE, 2019) in order of increasing normal boiling point temperature.

Table 1. R-410A and ASHRAE A1 classified refrigerants with GWP<1500

Refrigerant	**Composition**	**GWP_{100} AR4**	**NBP**	**NDP**	**Glide**
[-]	**[mass %]**	**[-]**	**[°C]**	**[°C]**	**[K]**
R-470A	R-744/R-32/R-125/R-134a/R-1234ze(E)/R-227ea (10/17/19/7/44/3)	979	-61.7	-35.6	26.1
R-470B	R-744/R-32/R-125/R-134a/R-1234ze(E)/R-227ea (10/11.5/11.5/3/57/7)	752	-61.0	-31.5	29.4
R-463A	R-744/R-32/R-125/R-1234yf/R-134a, (6/36/30/14/14)	1493	-59.1	-46.9	12.2
R-466A	R-32/R-125/R-13I1, (49/11.5/39.5)	733	-51.7	-51.0	0.7
R-410A	**R-32/R-125, (50/50)**	**2088**	**-51.7**	**-51.3**	**0.4**
R-464A	R-32/R-125/R-1234ze(E)/R-227ea, (27/27/40/6)	1323	-46.2	-35.6	10.7
R-460B	R-32/R-125/R-134a/R-1234ze(E), (28/25/20/27)	1352	-45.6	-36.9	8.6
R-448A	R-32/R-125/R-1234yf/R-134a/R-1234ze(E), (26/26/20/21/7)	1386	-46.1	-39.9	6.2
R-449B	R-32/R-125/R-1234yf/R-134a, (25.2/24.3/23.2/27.3)	1411	-45.8	-40.0	5.8
R-449A	R-32/R-125/R-1234yf/R-134a, (24.3/24.7/25.3/25.7)	1396	-45.7	-40.0	5.7
R-407H	R-32/R-125/R-134a, (32.5/15/52.5)	1495	-44.6	-37.6	7.0
R-449C	R-32/R-125/R-1234yf/R-134a, (20/20/31/29)	1250	-44.2	-38.2	6.1
R-448B	R-32/R-125/R-1234yf/R-134a/R-1234ze(E), (21/21/20/31/7)	1320	-44.1	-37.3	6.8
R-407I	R-32/R-125/R-134a, (19.5/8.5/72)	1459	-39.8	-32.9	6.9
R-513A	R-1234yf/R-134a, (56/44)	629	-29.6	-29.5	0.1
R-456A	R-32/R-134a/R-1234ze(E), (6/45/49)	687	-30.8	-25.4	5.4
R-407G	R-32/R-125/R-134a, (2.5/2.5/95)	1463	-29.1	-27.1	1.9
R-460C	R-32/R-125/R-134a/R-1234ze(E), (2.5/2.5/46/49)	765	-27.8	-24.5	3.3
R-475A	R-1234yf/R-134a/R-1234ze(E), (45/43/12)	616	-28.7	-28.3	0.4
R-134a	R-134a, (100)	1430	-26.1	-26.1	0.0
R-450A	R-134a/R-1234ze(E), (42/58)	604	-23.4	-22.7	0.6
R-515B	R-1234ze(E)/R-227ea, (91.1/8.9)	292	-18.9	-18.9	0.0

2. EVALUATION OF R410A RETROFIT OPTIONS

A thermodynamic model was set up using REFPROP 10 (Lemmon et al, 2018) refrigerant properties to screen the R-410A candidates to determine expected performance and ultimately their viability as a replacement candidate. Pressure drops were not accounted for in the heat exchangers and connecting lines. AHRI 210/240 A test point (AHRI, 2020) conditions were used for the study with an evaporation temperature of 10°C considering 8.3K superheat and an approach of 8.4K based on an indoor air side temperature of 26.7°C. Similarly, the condensing temperature was set at 46.1°C with 8.3K subcooling and an approach temperature difference of 2.8K based on 35°C air temperature entering the outdoor unit. The heat exchanger weighting that is applied for the evaporator and the condenser is a weighted average of the dew point and bubble point temperatures. A weighting of 0.5 represents the midpoint between bubble and dew temperatures. This weight factor is considered optimistic when evaluating refrigerant blends with elevated temperature glides. Figure 1 summarizes screening results of the relative capacity compared to R-410A for the refrigerants listed in Table 1.

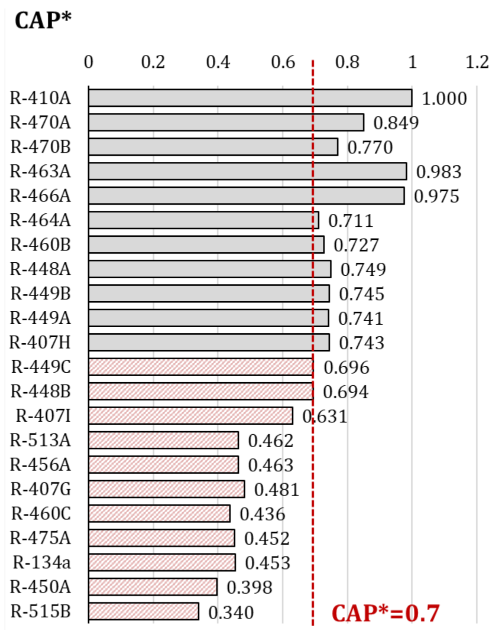

Figure 1. Relative capacity of Table 1 refrigerants compared to R-410A

The results for relative capacity show that all investigated refrigerants have lower values compared to R-410A with some being greater than 30% lower. Since it is not practical to consider refrigerants for retrofit with large capacity reductions, a capacity threshold was set at 70% relative R-410A capacity with refrigerants below this capacity highlighted in red. These lower pressure refrigerants designed for R-134a and R-404A applications are not suitable for R-410A retrofit operations as significant changes would be required to accommodate the capacity drop. These refrigerants were not considered for further analysis.

The temperature glide that can occur when blending different refrigerant components can penalize characteristic performance parameters. An overly optimistic consideration of temperature glide impact may suggest that refrigerant candidates are suitable for the target application, however in the actual experimental evaluation these expectations may become unattainable due to the reduction in heat transfer performance in the heat exchangers. Therefore, a careful consideration of glide impact needs to be investigated to determine a refrigerant's suitability. Figure 2 summarizes the temperature glide of the reduced number of investigated refrigerants across the operating ranges from –50˚C to their critical point.

The majority of the investigated zeotropic blends have an elevated temperature glide across the operating range of 5 K to 10 K with R-470A and R-470B beyond 20 K. The nonflammable blend R-466A shows the lowest temperature glide being less than 1.6 K across the range. A better treatment of glide impacts was conducted using the same thermodynamic modeling analysis approach to investigate the impact of temperature glide for these blends.

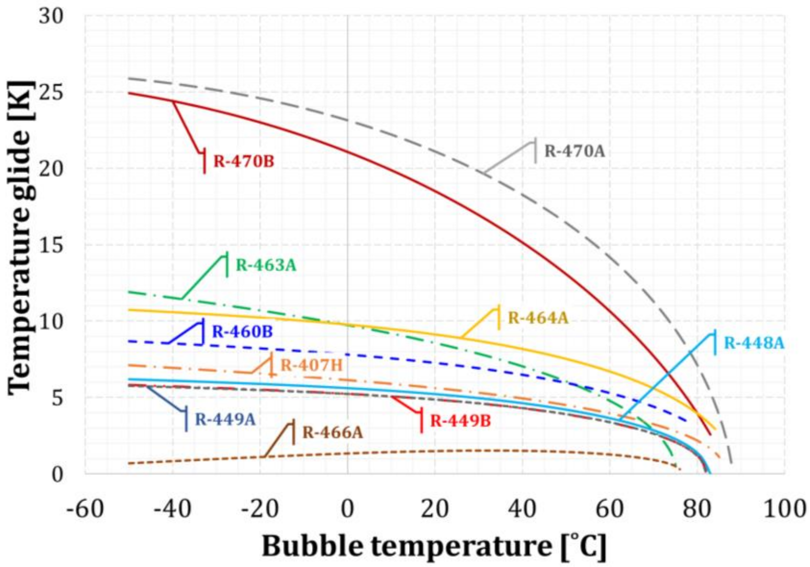

Figure 2. Temperature glide of refrigerant blends

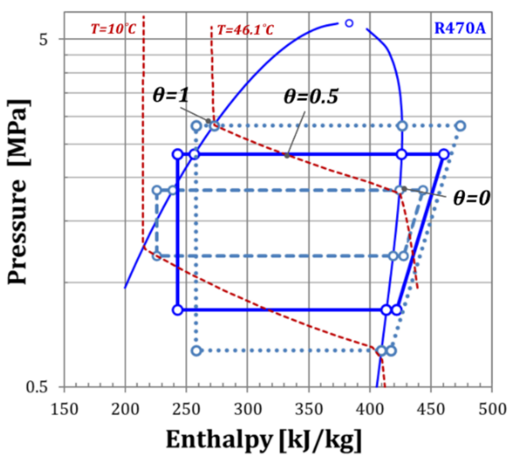

Figure 3. Pressure- Enthalpy diagram for R-470A with impact of varying heat exchanger weightings

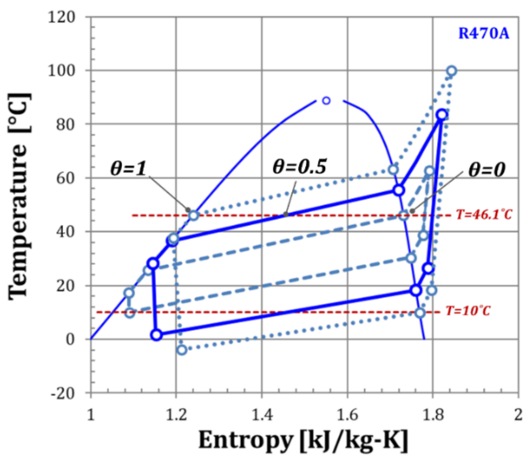

Figure 4. Temperature- Entropy diagram for R-470A with impact of varying heat exchanger weightings

R-470A with a significant temperature glide as one of the R-410A replacement candidates was chosen to visualize the approach of weighting the gliding temperature profile in the heat exchangers as shown in Figure 3 (pressure-enthalpy) and Figure 4 (pressure-entropy). Three cycles representing different heat exchanger glide weightings of $\theta = 0.0$, $\theta = 0.5$ and $\theta = 1.0$ are included using AHRI 210/240 A test point conditions. The weighting of $\theta = 0.5$ for R-470A pushes the evaporator approach toward zero, $\theta = 1.0$ certainly violates the second law with the condenser outlet matching the bubble temperature which is an overly assumption considering that on the condensing side the initial approach is smaller than on the evaporator side with $\theta = 1.0$ implying the same exit approach temperature difference for each candidate. As glide increases and/or approach decreases, θ needs to approach unity. Therefore, in addition to the midpoint weighting of $\theta = 0.5$ another more appropriate weighting for higher glide refrigerants of $\theta = 0.7$ was simulated. This considers the impact on evaporation and condensing pressure increasing the pressure ratio and by that directly affecting expectable performance. Figure 5 through Figure 12 summarize the modeling results with these new modeling assumptions and compares them to the previous modeling results using $\theta = 0.5$.

The relative efficiency (COP*) compared to R-410A is shown in Figure 5. For a heat exchanger weighting of 0.5 all evaluated refrigerants have a similar or improved COP compared to R-410A of up to approximately 5%. For the more appropriate weighting of 0.7, the refrigerant blends sensitivity towards increasing temperature glide values becomes evident. The larger temperature glide blends R-470A/B drop to a relative COP of around 0.81 and R-463A to 0.91 compared to R-410A. Other refrigerants with smaller amounts of glide remain within approximately 5% relative COP with R-466A showing the smallest variation having the smallest temperature glide.

The relative capacity (CAP*) in Figure 6 confirms the results seen in the previous screening of candidates in that the capacity penalty limits the number of viable replacement candidates for R-410A. R-463A and R-466A show the closest match to R-410A within 3% for a weighting of 0.5. For a weighting of 0.7, this drops to a relative capacity of within about 7% for R-463A while R-466A remains within 4% relative capacity. CAP* for R-470A and R-470B decreases from around 85% and 77% relative capacity respectively at 0.5 to around 72% and 64% respectively for a weighting of 0.7 driven by the larger glide impact. All remaining candidates have around 66% to 75% relative capacity which is too low to be considered as a replacement refrigerant in existing R-410A equipment. Additional system changes would be needed to compensate for the drop in capacity.

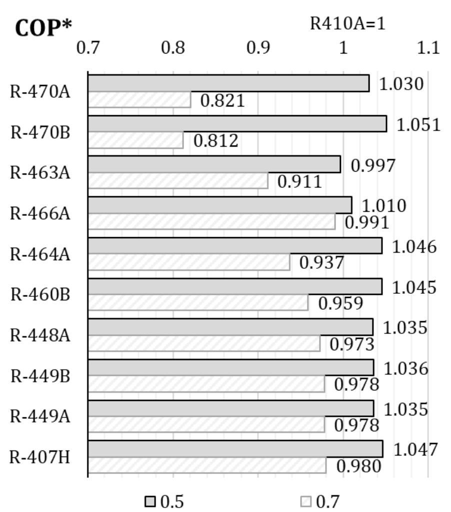

Figure 5. Relative COP compared to R-410A

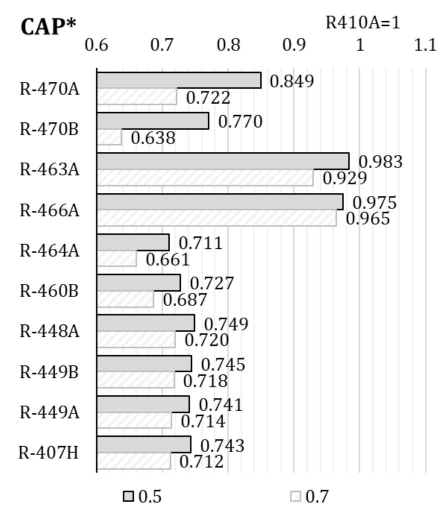

Figure 6. Relative capacity compared to R-410A

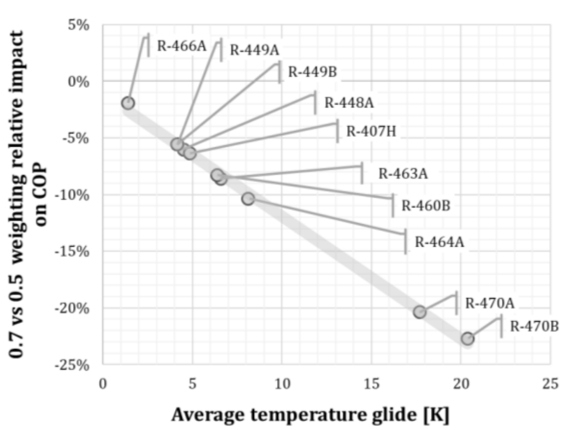

Figure 7. Relative COP penalty of 0.7 vs 0.5 heat exchanger weighting

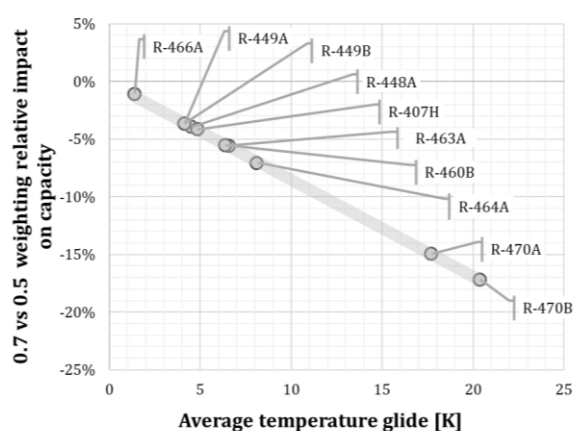

Figure 8. Relative capacity penalty of 0.7 vs 0.5 heat exchanger weighting

Figure 7 and Figure 8 summarize the relative difference between an optimistic glide weighting of 0.5 to a more appropriate weighting of 0.7 to simulate the impact of larger temperature glide on COP and capacity respectively. R-466A experiences both smallest COP and capacity penalty at 70% weighting compared to 50% having the smallest temperature glide of the investigated blends. With increasing temperature glide the relative penalty becomes more significant with around 20% COP penalty and around 15% capacity penalty for the higher glide R470 blends, confirming the importance during the selection process. Other characteristic parameters that are relevant for the operation of the system with compressor discharge temperature (Figure 9) and pressure ratio (Figure 10) determined by the ratio of condensing (Figure 11) and evaporation (Figure 12) pressure are shown in the following figures.

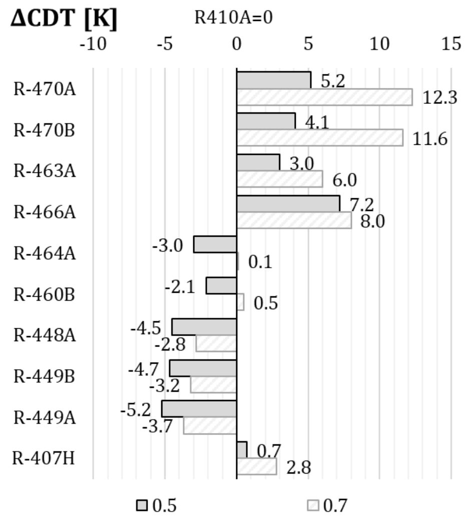

Figure 9. Compressor discharge temperature difference relative to R-410A

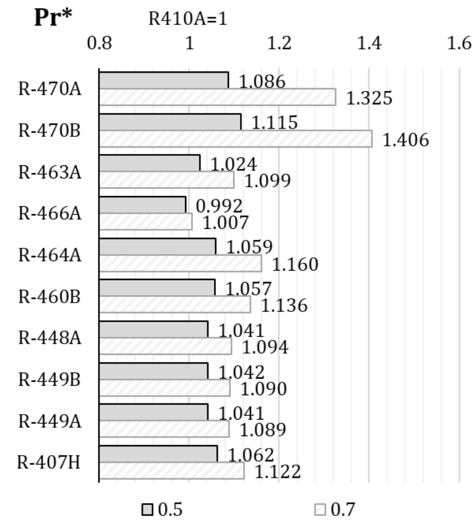

Figure 10. Pressure ratio relative to R-410A

Compressor discharge temperature is an important parameter that can potentially affect the reliability of the system. Excessive compressor discharge temperature beyond component limitations can lead to lubricant breakdown, reduced tolerance because of the expansion of components and ultimately increased wear potentially causing reduced component and system lifetime. The results for the compressor discharge temperature difference shown in Figure 9 show increasing values with a weighting of 0.7 for all candidates. Ultimately the specific application and operating range would need to be reviewed to determine potential limitations under demanding conditions.

The pressure ratio (Figure 10) is an indicator for the lift the compressor must provide based on the evaporation and condensing pressure levels. Increased compressor lift can reduce compressor efficiency and reliability. Similar to slightly increased values are seen for alternative candidates with moderate glide whereas higher glide options have higher increased values especially for the evaluation at a 0.7 heat exchanger weighting impact with approximately 10% (R-463A) to 40% (R-470B). The simultaneous increase of the condensing pressure and reduction of the evaporation pressure led to the most severe impacts on pressure ratio for higher glide refrigerants.

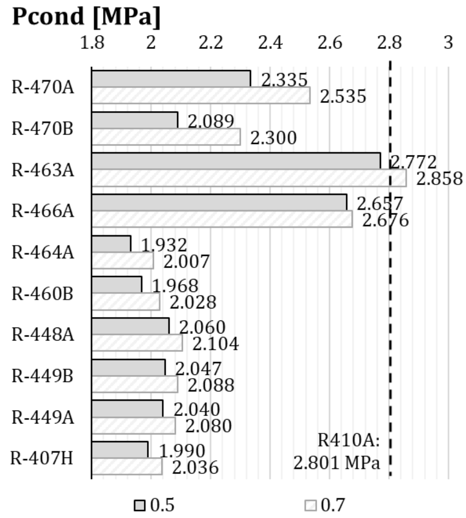

Figure 11. Condensing pressure

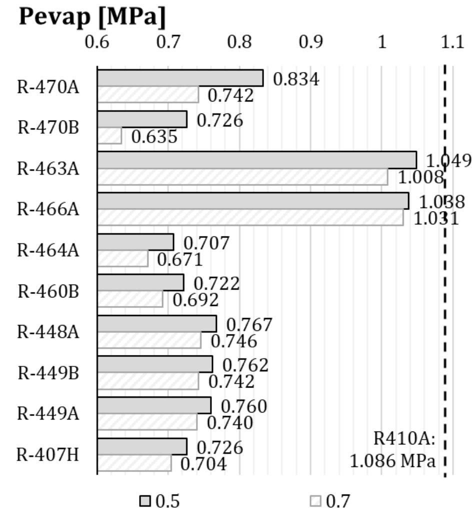

Figure 12. Evaporation pressure

The contributing pressures at the condenser and evaporator are shown in Figure 11 and Figure 12 respectively. Most of the candidates experience modest pressure rises on the condenser side and small reductions in evaporation pressure. This impact becomes more pronounced with increasing blend temperature glide for a weighting of 0.7. R-470A and R-470B with the largest relative changes for the condenser and evaporator of about 0.2 MPa and 0.09 MPa respectively. It should be noted that R-463A exceeds the condenser pressure of R-410A which could exceed the limits of the R-410A pressure vessel designs.

3. R-466A MATERIALS COMPATIBILITY RETROFIT CONSIDERATIONS

Chemical and material compatibility of refrigerants are important parameters given the expectation that HVACR products will have design lives of 15 to 20+ years. While most of the refrigerants considered here are blends of existing HFCs with HFOs or R-744 which have generally similar chemical stability and materials compatibility, R-466A is a Class A1 blend of R-13I1 (39.5%) with R-32 (49%) and R-125 (11.5%). R-13I1, trifluoroiodomethane, was considered in the CFC/HCFC to HFC transition period but was abandoned because of chemical stability concerns driven by the iodine atom in the molecule. Halogenated refrigerant chemical stability generally follows the rule that fluorine substitutions are most stable, followed by chlorine, bromine, and finally iodine. The chemical stability of R-13I1 (CF3I) was first studied in the 1990's because of a need to replace R-13B1 as a flame suppressor for aircraft applications.

Kujak and Sorenson (2021) reported results of sealed glass tube evaluations of both R-13I1 and R-466A as well as chemical stability studies in accelerated equipment operation with and without optimized materials. Sealed glass tube studies were performed with and without lubricants at varying times and temperatures to develop an understanding of reaction kinetics and Arrhenius behavior. Table 2 provides a summary of the chemical stability evaluations with and without additives with various HVACR materials. The targeted breakdown product, R-23 (CF_3H), was used as the indicator of breakdown of the R-13I1 in the R-466A. R-466A was shown to be more reactive with various materials with a POE lubricant present. They found that a more chemically stable standardly available POE with a proprietary additive package allowed for better chemical stability in laboratory highly accelerated life tests (HALT) sealed glass tube evaluations. They next performed equipment accelerated life tests (ALT) with the optimization of materials and additives to verify the results of the sealed tube HALT results. The optimized units experienced acceptable R-466A stability that remained stable over the course of the ALT testing based on R-23 generated over time.

Optimization of materials in these units was very straightforward and did not result in equipment redesign for performance. Since highly alloyed zinc materials showed high reactivity with R-13I1, it was determined the best course of action would be to minimize their use regardless of additive performance. The zinc counterweight in the compressor was replaced with a cast iron counterweight and a few zinc galvanized steel parts were replaced with nongalvanized versions. The compressor lubricant was stabilized with the addition of commonly used HVACR system additives. The additives used were triaryl-phosphate (TAP–antiwear), alkylated naphthalene (radical scavenger), and 2-ethylhexyl glycidyl ether (acid catcher) and were simply added to the same POE used by the compressor OEM.

Table 2. Chemical Stability Screening of R-466A with Individual Metals

Condition	Catalyst	% Purity	R-23 (ppm)
100% R-466A	Copper UNS C12200	99.9	58
	Iron UNS G10100	99.9	162
	Aluminum UNS A03800	99.9	126
	Brass C360	99.8	309
	Zinc-Al Alloy	99.9	211
50% R-466A 50% Unadditized POE	Copper UNS C12200	99.8	1749
	Iron UNS G10100	99.9	933
	Aluminum UNS A03800	99.9	569
	Brass C360	99.7	2357
	Zinc-Al Alloy	78.6	208,100
50% R-466A 50% Additized POE	Cu/Fe/Al Together	99.9	118
	Brass C360	99.7	120
	Zinc-Al Alloy	99.9	54

In most cases, retrofitting of existing R-410A units with R-466A would not be as simple as changing of the refrigerant and addition of the additives to the lubricant. Most compressor OEMs use zinc as compressor counterweights, and many have galvanized steel parts in compressors. Essentially an assessment of the unit design would need to be reviewed and zinc parts and components would need to be replaced with zinc free parts, e.g. essentially replacement of the compressor with zinc free compressor along with possibly other components depending on the OEMs design. In several ALT units tests conducted by Kujak, some OEMs have zinc free compressor designs and retrofitting only required the changing of refrigerants and addition of the lubricant additives.

4. CONCLUSIONS

A number of potential R-410A alternatives as listed in ASHRAE standard 34 were evaluated based on their viability as a retrofit solution for aftermarket R-410A applications. R-410A is a ASHRAE Class A1 refrigerant (lower toxicity with no flame propagation, i.e. nonflammable, refrigerant blend which requires a retrofit solutions to have the same ASHRAE A1 safety classification. A list of 23 refrigerants was initially screened for relative capacity to R-410A but reduced to candidates with a relative capacity of greater than 70% of R-410A. The remaining blends were more closely evaluated regarding their performance sensitivity due to temperature glide. For this, the impact of temperature glide was evaluated as an optimistic assumption with a 50% heat exchanger weighting and a more appropriate weighting of 70%.

It was found that R-466A showed the closest match to R-410A in the investigated performance criteria in part due to having the smallest temperature glide. Both relative capacity and efficiency were within 5% compared to R-410A while providing the lowest GWP. The next closest candidate R-463A with a GWP of about 1500 showed a relative drop in capacity of about 7% compared to R-410A for a heat exchanger weighting of 0.7. R-470A and R-470B with even larger temperature glides showed larger penalties which makes them unsuitable as retrofit candidates for R-410A. This screening process can help in evaluating expectable performance of potential refrigerant candidates but a more detailed analysis applying heat exchanger and other component models is needed to make a final decision on refrigerant selection and design of system components for the specific application.

While R-466A was shown to be a near design compatible retrofit solution for R-410A systems, the sensitivity of R-466A related to chemical stability and material compatibility requires closer evaluation to determine if a retrofit is an option with existing components. It has been demonstrated that POE lubricant additives commonly used today in HVACR applications have been shown to improve the chemical stability of R-466A to acceptable levels. Materials of construction need to be reviewed and removal of highly zinc alloyed or zinc coated parts from the compressor and other system components needs to occur to ensure good materials compatibility.

ACKNOWLEDGEMENT

The discussions and insightful comments from Ken Schultz of Trane Technologies are greatly appreciated.

NOMENCLATURE

ALT	Accelerated Life Tests	HFO	Hydrofluoroolefin
AR4	IPCC AR4 report	HVACR	Heating, Ventilation, Air-Conditioning and Refrigeration
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers	IPCC	Intergovernmental Panel for Climate Change
CAP*	Relative Capacity compared to R-410A	NBP	Normal boiling point
CFC	Chlorofluorocarbon	NDP	Normal dew point
COP*	Relative Coefficient of performance compared to R-410A	Pcond	Condenser pressure
ΔCDT	Compressor discharge temperature difference	Pevap	Evaporator pressure
GWP	Global Warming Potential	POE	Polyolester
HALT	Highly Accelerated Life Tests	Pr*	Relative compression ration compared to R-410A
HCFC	Hydrochlorofluorocarbon	TAP	Triaryl-phosphate
HFC	Hydrofluorocarbon	θ	Heat exchanger weighting

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