**14th IEA Heat Pump Conference**
15-18 May 2023, Chicago, Illinois

# Testing of alternative refrigerants for unitary air-conditioning and heat pump applications

Sarah Kim[a,*], Robert Elliott Low[b], Christopher Seeton[a], Ke Tang[c], Francesco Botticella[c]

[a]Koura, 950 Winter Street, Waltham, MA 02451, USA
[b]Koura, Runcorn, Cheshire WA7 4QX, UK
[c]Creative Thermal Solutions Inc, 2209 N. Willow Road, Urbana, IL 61802, USA

**Abstract**

The unitary air-conditioning and heat pump application sector is one of the largest single consumers of refrigerant today mostly with R-410A having Global Warming Potential (GWP) of 2088 or R-32 (GWP 675). Legislative phase-down of fluorinated refrigerants is driving a search for alternatives for this application with target to lower average GWP – ideally below 300. While some alternatives such as R-454B (GWP 466) or R-290 have already been identified as technically feasible, the flammability and charge size of systems may present an additional barrier to use these fluids. Use of R-744 has been considered in the past but the energy efficiency and cost of prototype systems has rendered it unattractive. A non-flammable refrigerant blend of R-744, R-1132a and R-32, working name LFR3 (submitted to standards bodies for classification), GWP 142, has been developed, which in testing has demonstrated significant energy efficiency advantage over R-744. A project is now underway to assess the feasibility of using this fluid for heat pumps. The goal is to develop baseline performance on a production system designed for R-410A then to retrofit the system with new heat exchangers and compressor suitable for use with R-744 and to assess whether comparable efficiency (EER) to the R-410A may be achieved. Performance testing with R-410A, with a near drop-in low-GWP alternative (R-468C, GWP 284)) and of the prototype high pressure system will also be presented.



*Keywords: refrigerants; low gwp, HFO, heat pumps*

## 1. Introduction

The direct impact of refrigerant emissions and their global warming effect, measured by Global Warming Potential (GWP), have been a long focus by regulators. With another HFC allowance step down scheduled in 2024 as set forth by the F-gas regulation and the Kigali Amendment to the Montreal Protocol, the HVAC&R industry worked diligently in developing lower GWP refrigerants while updating standards and procedures to safely use the increasingly common mildly flammable refrigerants in systems and buildings. In addition, the HVAC sector, heat pumps to be specific, has been identified as key in accomplishing net zero energy goals established by corporations as well as governments. The US Department of Energy (DOE) published an industry decarbonization roadmap [1] in September of 2022 that laid out pathways in reaching the net-zero GHG emissions by 2050 in the US. Amongst the four pillars that were identified by the DOE, it is clear that heat pumps will be an integral technology for the energy efficiency and industrial electrification pillars. With ever increasing demand for more efficient HVAC systems, it is critical to take a wholistic approach when selecting a new refrigerant beyond the GWP value.

Refrigerant development activities were centered around designing fluids as closely as possible to incumbent refrigerants that would allow for easy adoption for both new and retrofit applications. To that end, the first part of this paper will present a drop-in assessment of a lower GWP R-410A replacement refrigerant,

* Corresponding author. E-mail address: sarah.kim@kouraglobal.com

R-468C. The second part of the paper will focus on a very high pressure low GWP refrigerant LFR3, blend of R-1132a, R-744, and R-32 (10/69/21 in mass %), which was developed to improve the efficiency of R-744 and expand the fluid usage to warmer climate zones. It is also nonflammable as formulated, which can be a promising solution for applications with larger refrigerant charges. A R-744 based prototype unit was built within the R-410A system frame, which was then assessed for cooling and heating performance of R-744 and LFR3.

## 2. Description

### *2.1. Refrigerant properties*

As described in the previous section, four refrigerants have been experimentally evaluated in this work. They can be further categorized into two groups based on the pressure ranges: high pressure and very high pressure. Thermodynamic properties of the fluids are summarized in Table 1.

Table 1. Thermodynamic properties of test refrigerants

| Property | Units | R-410A | R-468C | R-744 ($CO_2$) | LFR3 |
|---|---|---|---|---|---|
| GWP (AR4) | | 2088 | 286 | 1 | 143 |
| Molecular mass | g/mol | 72.6 | 73.7 | 44.0 | 47.0 |
| Critical temperature | °C | 71.4 | 77.0 | 31.0 | 41.2 |
| Critical pressure | kPa | 4900 | 4880 | 7377 | 7170 |
| Liquid density (0°C) | $kg/m^3$ | 1170 | 1084 | 927 | 935 |
| Bubble pressure (0°C) | kPa | 801 | 838 | 3485 | 2875 |

### *2.2. Test description*

A commercially available R-410A packaged heat pump with a capacity of 17.6 kW (5 Ton) was used for R-410A and R-468C drop-in testing. The thermostatic expansion valve (TXV) was set to maintain a superheat of 3 K for cooling at A condition and was not readjusted for other conditions. Capacity was measured for both air and refrigerant side, which showed good agreement throughout the testing.

Upon completion of the high pressure refrigerant testing, a prototype unit was built within the frame of the R-410A unit with a goal to maintain the same cooling capacity of 17.6 kW, Figure 1. The same baseline indoor blower (air flow rate) and outdoor fan were used while a reciprocating compressor, indoor and outdoor heat exchanger, internal heat exchanger (IHX), accumulator, and EEV designed for R-744 were implemented. The purpose of this study was to evaluate the feasibility of using very high pressure low GWP refrigerants (R-744 and LFR3) in heat pumps while maintaining the same footprint as existing equipment with lower pressure.

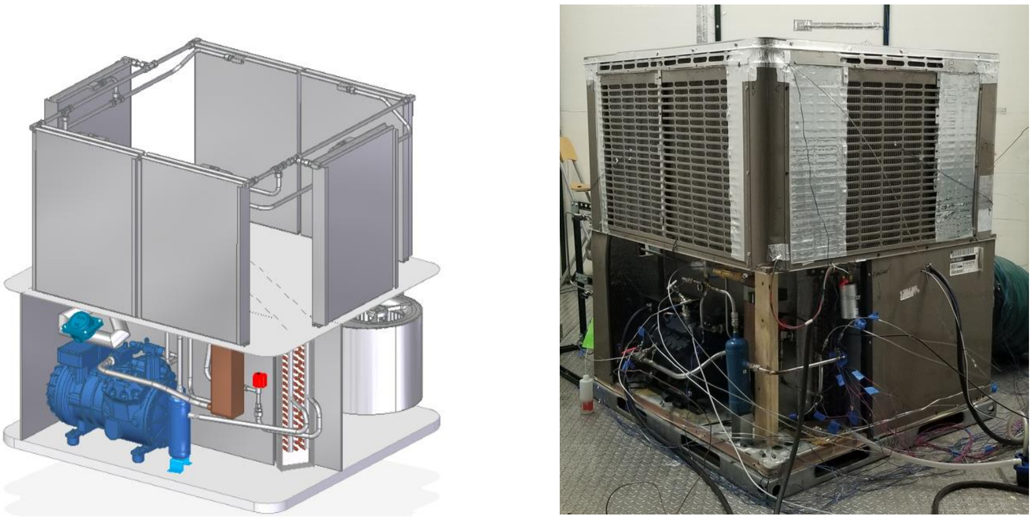

Fig. 1. R-744 system components fitted into the R-410A unit frame

## 3. Results and Discussion

### *3.1. Drop in test results for high pressure refrigerants*

Refrigerants were evaluated at two cooling (A and B) and two heating conditions (H1 and H3) as described in the AHRI 210/240 standard [2]. The optimum charge of R-468C was determined to be 5.8 kg, 9% higher than the R-410A baseline, where sufficient subcooling was observed while maximizing the cooling capacity and COP. Uncertainty values were determined as ±0.7% for COP and ±0.2% for capacity.

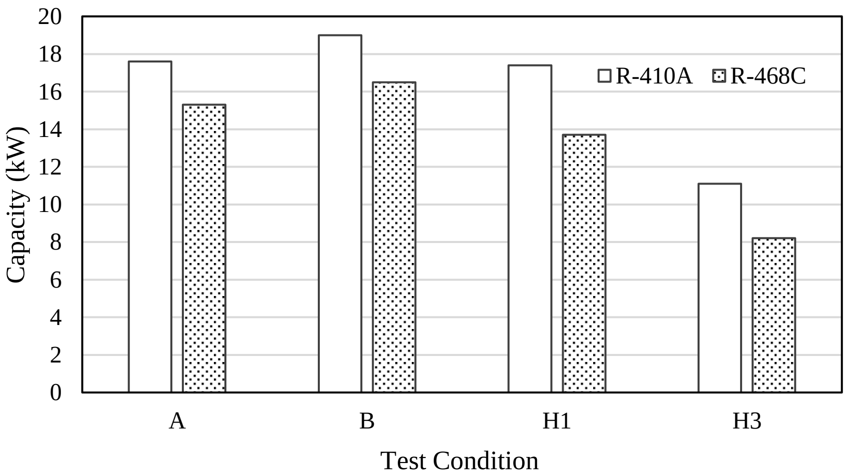


Fig. 2. Capacity of R-410A and R-468C at cooling and heating modes

R-468C showed slightly lower capacity values than R-410A especially during heating mode, Fig. 2. COP also showed a similar trend where R-468C exhibited comparable results to R-410A at cooling mode and lower efficiencies at heating mode, Fig. 3. These results are similar, but somewhat lower compared to previous drop in test results conducted in a R-410A split system where R-468C was reported as LFR1C [3]. Low reported similar or higher COP of R-468C than R-410A especially in heating mode. One potential reason for this discrepancy could be due to the testing in this work being carried out and optimized around cooling mode, which may have inadvertently hurt the heating performance. Also, it was noted that the performance was sensitive to the TXV opening and thus the superheat values, however, the TXV setting was not adjusted once it was set for A condition. A use of an electronic expansion valve (EEV) may help better modulate between the two modes. R-468C also has a higher glide of 4 to 5 K compared to R-410A's glide of 0.1 K, therefore the direction of flow in the heat exchangers can favor one mode over the other and provides an opportunity to optimize the system based on primary operations.

*3.2. Test results for very high pressure refrigerants in the prototype unit*

Three parameters can be changed to adjust the capacity and high side pressure of the R-744 based system:

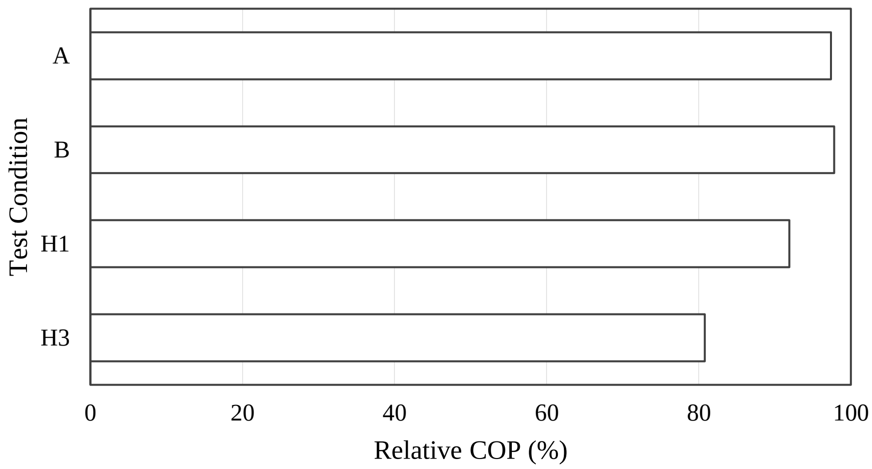


Fig. 3. COP of R-468C relative to R-410A at cooling and heating modes

1. Refrigerant charge,
2. Compressor speed, and
3. EEV opening.

*3.2.1. Cooling mode*

At each refrigerant charge, the EEV opening and thus the gas cooler inlet pressure was adjusted to maximize the COP. Then the corresponding compressor speed was set accordingly in order to match the cooling capacity of 17.6 kW. Summary of the test results at optimum refrigerant charge are shown in Table 2. Uncertainty was determined as ±1.0% for COP and ±0.3% for capacity. LFR3 operated at a higher compressor speed compared to R-744, but showed higher COP and compressor volumetric efficiency ($\eta_{vol}$) while exhibiting 20% lower optimal gas cooler pressure.

Table 2. Test summary of R-744 and LFR3 at A condition

| Fluid | COP | Optimal gas cooler pressure (MPa) | Refrigerant charge (kg) | Compressor frequency (Hz) | $\eta_{vol}$ |
|---|---|---|---|---|---|
| R-744 | 2.51 | 9 | 4.1 | 40.9 | 0.69 |
| LFR3 | 2.64 | 7.3 | 4 | 47.1 | 0.75 |

Compressor speed and refrigerant charge found in A condition were kept constant for B condition tests. The result trends for B condition were consistent to those observed in A condition, Table 3. The consistently higher cooling efficiency of LFR3 over R-744 was also reported when tested in a heat pump system for bus applications [4].

Table 3. Test summary of R-744 and LFR3 at B condition

| Fluid | COP | Optimal gas cooler pressure (MPa) | Refrigerant charge (kg) | Compressor frequency (Hz) | $\eta_{vol}$ |
|---|---|---|---|---|---|
| R-744 | 3.3 | 7.0 | 4.1 | 40.9 | 0.72 |
| LFR3 | 3.49 | 6.4 | 4 | 47.1 | 0.77 |

*3.2.2. Heat pump mode*

As the prototype unit was not assembled as a reversable system, the unit needed to be modified and re-piped prior to heat pump testing. It was also noted that the IHX was probably oversized and the combination of IHX and the accumulator contributed to additional pressure drop. Therefore, the accumulator was removed during the conversion. For cooling mode, the evaporator was mounted in parallel flow in order to have the same heat exchanger performing in counter flow in heat pump mode. As LFR3 is a zeotropic refrigerant, it was expected that the performance would further improve from the flow direction. The EEV opening was adjusted to maximize the COP while refrigerant charge and compressor frequency were kept at the previously determined values. The uncertainty was found to be ±0.6% for COP and ±0.3% for capacity.

Table 4. Test summary of R-744 and LFR3 at H1 condition

| Fluid | COP | Capacity (kW) | Optimal gas cooler pressure (MPa) | $\eta_{vol}$ |
|---|---|---|---|---|
| R-744 | 3.27 | 21.9 | 8.2 | 0.72 |
| LFR3 | 3.26 | 21.5 | 7.0 | 0.70 |

LFR3 and R-744 showed similar efficiencies, which is contrary to previous testing of LFR3 in an air-source heat pump water heater designed for R-744 where 15% higher heating capacity and 35% higher COP of LFR3 relative to R-744 were reported [5]. These very high pressure refrigerants, however, showed approximately 25% improvement in heating capacities at the H1 condition compared to R-410A. The noticeable frost formation during the LFR3 runs may have led to lower than expected COP value, which is due to the combination of glide as well as parallel flow in the evaporator that brought down the evaporator inlet temperature to below 0°C.

Further testing on H3 condition is on-going and will be presented at the conference.

## 4. Conclusion

R-468C and LFR3 were evaluated as low GWP solutions in a packaged heat pump system. R-468C showed comparable performance as a R-410A alternative while providing more than 85% reduction in GWP. It should be noted that R-468C is an A2L safety class per ASHRAE 34 and should only be used in systems designed for mildly flammable refrigerants.

It was also demonstrated that it is feasible to use very high pressure refrigerant LFR3 while providing matching capacity and footprint as existing commercially available equipment. The heating results were particularly promising considering that a reciprocating compressor was used in lieu of a higher efficiency scroll compressor. While LFR3's COP was measured to be approximately 20% lower than R-410A in average, the results are encouraging given that they were obtained from a first-generation prototype unit. Proper sizing and selection of components with optimized heat exchanger designs will allow for further performance improvement.

## Disclaimer

Although all statements and information contained herein by Koura Global are believed to be of sound scientific judgement, they are presented without guarantee or warranty of any kind, expressed or implied. Information provided herein does not relieve the user from the responsibility of carrying out its own tests and experiments, and the user assumes all risks and liability for use of the information and results obtained. Statements or suggestions concerning the use of materials and processes are made without representation or warranty that any such use is free of patent infringement and are not recommendations to infringe on any patents.

## Nomenclature

$\eta_{vol}$ Compressor volumetric efficiency

## References

[1] United States Department of Energy. Industrial Decarbonization Roadmap. *DOE/EE*-2635; 2022.
[2] AHRI Standard 210/240-2023(2020), Performance Rating of Unitary Air-conditioning & Air-source Heat Pump Equipment, 2023, Air-Conditioning, Heating, and Refrigeration Institute, 2311 Wilson Boulevard, Suite 400, Arlington, VA 22201, U.S.A.
[3] Low R., 2021. "High-Performance Air-Conditioning Refrigerants With Low GWP," 2nd IIR Conference on HFOs and Low GWP blends. Japan.
[4] Petersen, M., Kujak, S., Galanský, M., Houdek, P., Kolda, M., Nayak, G., 2022. "Comparison of R744 and R744-based HFC/HFO blend in mass transit mobile AC and HP applications," 15th IIR-Gustav Lorentzen conference on Natural Refrigerants. Trondheim, Norway.
[5] Low R., 2020. "Pushing The Envelope: Extending The Range And Performance Of R-744," IIR International Rankine 2020 Conference – Heating, Cooling and Power Generation. Glasgow, UK.