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Performance evaluation of light commercial air conditioning and heat pump system using low GWP refrigerants

Hughes Joshua[a*], Minsoo Kim[b]

[a]The Chemours Company, 1007 Market Street P.O. Box 2047, Wilmington, Delaware 19899, USA
[b]LG Electronics, LG Electronics 2nd factory Seongsan-dong Seongsan-gu, Changwon-si 51554, KOREA

Abstract

Concerns about global climate change and potential legislation that may impact the use of refrigerants with high global warming potential (GWP) have accelerated the development of new refrigerants with reduced impact on climate change. Along with the Kigali amendment to the Montreal Protocol to phase down use of HFCs, there are regulations around the world with specific GWP limits for air conditioning and heat pump applications. The most common refrigerant used globally in residential and light commercial air conditioning systems and heat pumps is R410A, with a GWP of 2088. Regulations are already in place to limit the GWP to below 750 in many regions globally, and there may be further reductions needed in the future. This paper discusses alternative fluids that have been developed to most nearly meet the most often cited requirements for environmental, physical, and performance properties for air conditioning and heat pump applications. R454B, with a GWP of 466 and both performance and properties similar to R410A, is a potential alternative to meet these requirements while maintaining compatibility with systems similar to those of existing R410A designs to enable an orderly transition to lower GWP. Performance will be evaluated in a light commercial air conditioning and heat pump system and compared with R410A at both standard air conditioning and heating operating conditions. These refrigerants are shown to provide useful options to help maintain the quality of life and health benefits from air conditioning and refrigeration, but in an energy efficient, cost-effective, and environmentally sustainable manner.

Keywords: GWP; R454B; refrigerant; air conditioning; heat pump; DR-5A; XL41; R32

Nomenclature

GWP Global warming potential
C_v Isochoric specific heat, kJ/kg-K
EEV Electric expansion valve
DB Dry bulb temperature, °C
SEER Seasonal energy efficiency ratio, Wh/Wh
COP Coefficient of performance
C_p Isobaric specific heat, kJ/kg-K
EER Energy efficiency ratio, W/W
ErP Energy-related Products Directive
WB Wet bulb temperature, °C
SCOP Seasonal coefficient of performance, Wh/Wh

1. Introduction

The current generation refrigerant for residential air conditioning and heat pumps, R410A, has a global warming potential (GWP) of 2088 [1] and is subject to regulations in many regions globally. R-410A is a

* Hughes, Joshua Tel.: +1-302-683-8275; fax: +1-302-683-8255.
E-mail address: joshua.hughes@chemours.com

non-flammable mixture of 50 wt% R32 and 50 wt% R125. R32 has been proposed for many years as an alternative refrigerant which has about 70% lower GWP than R410A and high cooling capacity. Therefore, many manufacturers have optimized some air conditioning products for the adoption of R32, with millions of air conditioning units using R32 as a refrigerant sold throughout Asia, New Zealand, Australia, US and Europe. However due to the Kigali amendment and F-gas regulation, as shown in Fig. 1, CO_2 emissions would need to be reduced significantly over time from previous baseline emissions. Therefore, R32 is likely not an ultimate solution to meet regulations for the future.

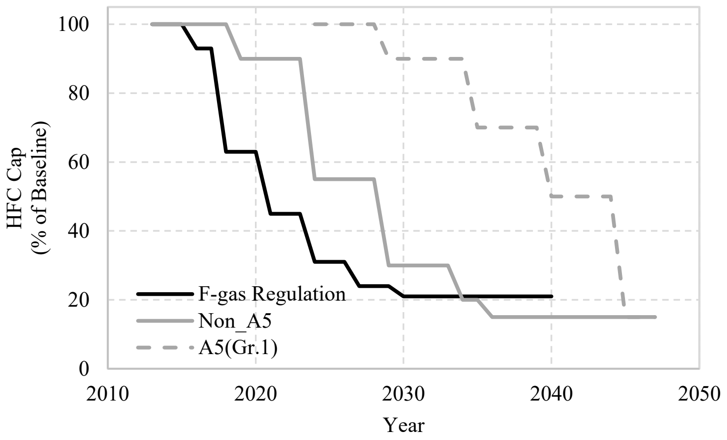


Fig. 1. HFC Phase-Down Steps of EU and Kigali Amendment (2016)

The HVAC&R industry has been searching for alternative refrigerants to help meet these new and anticipated future regulations. R454B, also known as DR-5A or XL41, is a low GWP replacement for R410A which provides similar capacity and energy efficiency to R410A. R454B is a mixture containing 68.9 wt% R32 and 31.1 wt% of HFO-1234yf. As shown in Table 1, R454B has a 100-year GWP (AR4) of 466 which could allow it to become a longer term solution to meet CO_2 reduction targets than other higher GWP candidates. Pressure of R454B is slightly lower than that of R410A and R32 at the same operating temperatures. Also, its lower liquid density contributes to the mass of refrigerant charge of R454B in an equivalent air conditioning or heat pump system that would be lower than that of R410A.

R454B is a mildly flammable refrigerant and has a received a safety classification of A2L under ASHRAE SSPC 34 [2]. The specific heat ratio is slightly higher for R454B compared to R410A, contributing to compressor discharge temperature of R454B that is slightly higher than that of R410A but well below the discharge temperatures of R32. Therefore, R454B is a potential alternative to meet environmental, physical and performance requirements while maintaining compatibility with systems similar to existing R410A designs.

Previous research of R454B has shown that R454B is a design-compatible replacement candidate for R410A. Schultz et al. [3] performed tests on a 4 RT (14 kW) rooftop heat pump to evaluate the performance of lower GWP refrigerants as alternatives to R410A in unitary air-conditioning and heat pump equipment. Minamida et al. [4] evaluated the system performance using R454B for VRF and mini-split air conditioner and observed R454B to have better COP than R410A. Also, previous testing by Hughes et al. [5] in a unitary ducted split air conditioning and heat pump system designed for R-410A has shown has similar cooling capacity and energy efficiency to R-410A.

Table 1. Property and performance comparison of refrigerants (ASHRAE-T condition, isentropic efficiency = 0.75)

Refrigerant	R410A	R32	R454B
GWP(AR4)	2088	675	466
Safety classification	A1	A2L	A2L
Condensing pressure [kPa]	3393	3473	3204
Evaporating pressure [kPa]	998	1018	913
Latent heat [kJ/kg]	159 (100%)	242 (152%)	194 (122%)
Volumetric capacity [kJ/m^3]	5646 (100%)	6236 (110%)	5378 (95%)
Discharge temperature [ºC]	94	115	102
Cp/Cv (specific heat ratio)	1.412	1.514	1.414
Density suction [kg/m^3]	35.5	25.7	27.7
Density condenser [kg/m^3]	870.8 (100%)	812.2 (93%)	830.5 (95%)
Displacement volume [cm^3/rev]	31.6	31.6	31.6
Mass flow rate [kg/s]	0.065 (100%)	0.047 (72%)	0.050 (78%)
Cooling capacity [kW]	10.26 (100%)	11.33 (110%)	9.77 (95%)
Work [kW]	3.09 (100%)	3.33 (108%)	2.96 (96%)
EER [W/W]	3.32 (100%)	3.40 (102%)	3.30 (100%

2. Details of test setup

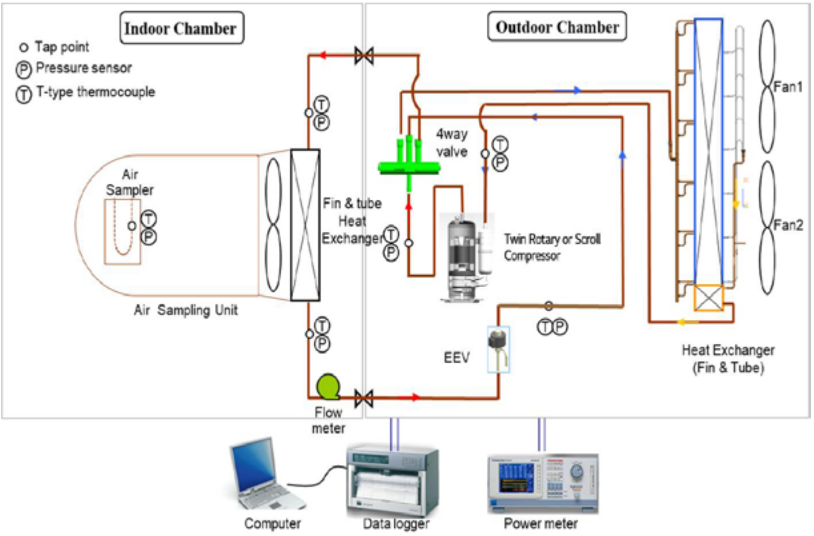


Fig. 2. Calorimeter layout for ceiling-mounted system (arrows show direction of refrigerant flow in space heating operation)

The wall-mounted type and ceiling-mounted type air conditioners commonly used in non-ducted air conditioning and heat pump systems were used to compare the performance of R410A replacement candidates. The specifications of each of the products are detailed in Table 2. The wall-mounted type air conditioner consists of an inverter rotary compressor for a conventional system and inverter twin rotary compressor for the modified system. Both the conventional and modified systems have two fin-tube type heat exchangers, one indoor fan, one outdoor fan, a 4-way reversing valve and EEV. The ceiling-mounted type air conditioner consists of inverter twin rotary compressor for the conventional system and an inverter scroll compressor for the modified system. Both systems have two fin-tube type heat exchangers, one indoor fan, two outdoor fans, a 4-way reversing valve and EEV.

Table 2. Specification of products

Product	Wall-mounted type	Ceiling-mounted type
Capacity	12kBtu/hr	48kBtu/hr
Compressor	Inverter Twin Rotary 10.6cm³/rev	Inverter Scroll 31.6cm³/rev
Indoor heat exchanger	Φ7 2R 15C 21FPI S-Fin(Half) L616.8mm	Φ7 2R 12C 21FPI Louver L2084mm + Φ7 1R 10C 21FPI Louver L1930mm
Outdoor heat exchanger	Φ7 2R 22C 18FPI Louver fin L667mm	Φ7 2R 64C 14FPI Wide Louver L950mm
EEV orifice inner diameter [mm]	Φ1.65	Φ2.0

The baseline R410A test, R32 test and R454B tests have been completed as per ISO 13253 in a psychrometric calorimeter chamber at the conditions shown in Table 3 with the layout of the test apparatus detailed in Fig. 2 (ceiling-mounted schematic shown; wall-mounted system layout was similar). Each experimental parameter was recorded using a data acquisition system after the system reached a quasi-steady state. It was determined that the system is in the quasi-steady state when the measured parameters of the cycle do not change for 15 minutes after the change of the experimental conditions, such as the change of the compressor frequency. Then experimental data were recorded for 35 minutes at intervals of 5 seconds. The temperatures of the indoor chamber and the outdoor chamber were controlled in the range of -35-60°C and 0-50°C, respectively. Dry and wet bulb temperatures of the two chambers were controlled within the range of ±0.1°C. All temperatures in the system are monitored using T-type thermocouples. The accuracy of the temperature measurements is estimated to be ± 0.2°C.

Table 3. ErP test conditions and extra test conditions (EN14511 – Rated conditions, EN14825 – Part load conditions)

Conditions		Indoor		Outdoor	
		DB[°C]	WB[°C]	DB[°C]	WB[°C]
Cooling mode at rated condition		27	19	35	24
Heating mode at rated condition		20	15	7	6
SEER	Cooling A	27	19	35	24
	Cooling B			30	20
	Cooling C			25	16
	Cooling D			20	12
SCOP	Heating A	20	15	-7	-8
	Heating B			2	1
	Heating C			7	6
	Heating D			12	11
	Heating E			-10	-11
	Heating F			-8	-9
Cooling overload		32	23	48	29
		32	19	54	32
Heating low temperature		20	15	-5~-25	-

SEER is seasonal efficiency of a unit calculated for the reference annual cooling demand, which is determined from mandatory conditions given in this European Standard and used for marking, comparison and certification purposes. SCOP is seasonal efficiency of a unit calculated for the reference annual heating demand(s), which is determined from mandatory conditions given in this European Standard and used for marking, comparison and certification purposes.

The heating D condition is the lowest part load ratio condition. Therefore, to meet the part load of heating D condition, the frequency (Hz) of the compressor should be very low. It can miss the operational range of the compressor so the efficiency of the product may decrease despite having lower power consumption.

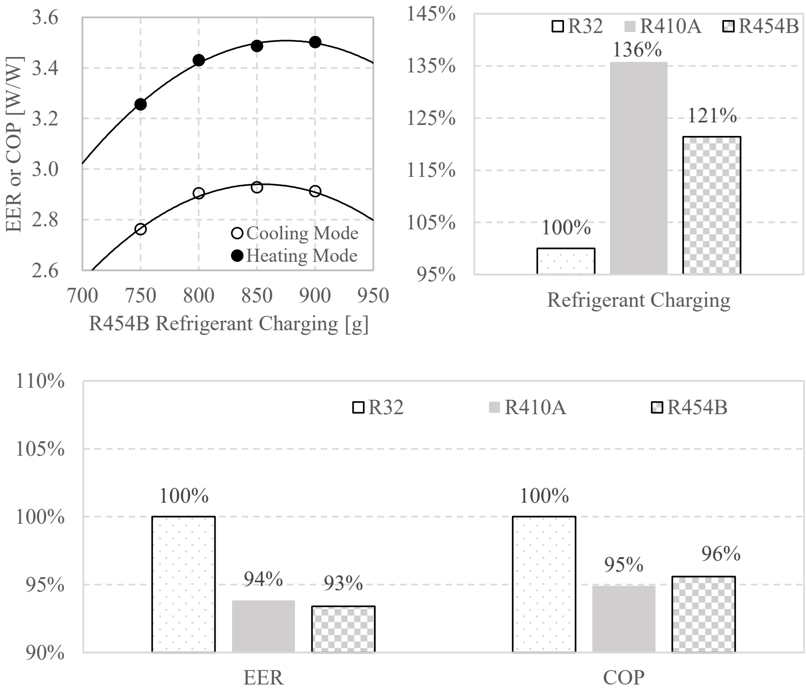
3. Results and discussions

3.1. Wall-mounted type air conditioner with inverter rotary compressor

As shown in Table 4 and Fig.3, R454B refrigerant charge size is 11% lower than the R410A charge. The R32 refrigerant charge size is 26% lower than R410A charge. The EER and COP of R454B are almost same with those of R410A. The EER and COP is 7% and 5% higher respectively for R32 compared to R410A. The discharge temperature of R454B is 5°C higher than that of R410A in cooling standard condition and 4°C higher than that of R410A in heating standard condition. The discharge temperature of R32 is 12°C higher than that of R410A in cooling standard condition and 11°C higher than that of R410A in heating standard condition.

Table 4. Comparison of performance (wall-mounted type)

Refrigerant	Refrigerant Charging [g]	Cooling mode (3.5kW at rated condition)		Heating mode (4.0kW at rated condition)	
		EER [W/W]	Discharge Temperature [°C]	COP [W/W]	Discharge Temperature [°C]
R410A	950	2.94	73	3.46	76
R32	700	3.14	85	3.65	87
R454B	850	2.93	78	3.49	80



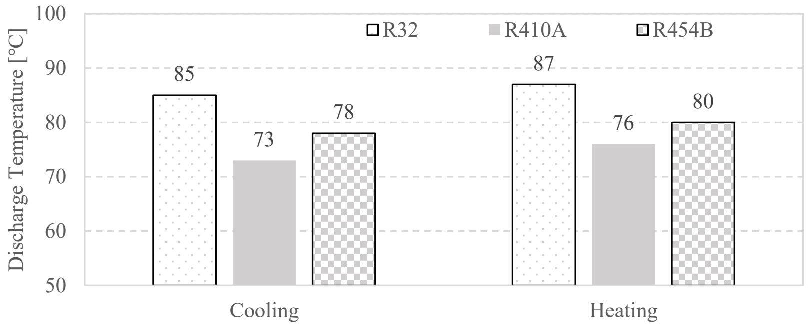


Fig. 3. Performance test results at rated conditions (wall-mounted type)

As shown in Fig. 4, as the ambient temperature increases in cooling condition and decreases in heating condition, R454B shows higher reduction of cooling capacity than R410A because of the higher discharge temperature. At high ambient temperature in cooling mode and cold climate condition in heating mode, buildings require high cooling and heating demand. So, in those conditions, it may be desired for the air conditioning system to increase the compressor frequency of an inverter compressor. When the inverter system is used in those conditions, the compressor frequency is limited by discharge temperature. The discharge temperature of compressor is affected by specific heat ratio (C_p/C_v) and the specific heat ratio of R454B is higher than that of R410A. Also, the molar mass of R454B is smaller than that of R410A, so the effect of refrigerant leakage in the compressor is larger for a R454B system compared to a R410A system. This could cause the reduction of volumetric efficiency of the compressor and higher discharge temperature. Thus, the capacity of R454B system decreases more abruptly than that of R410A in those conditions because of the higher discharge temperature.

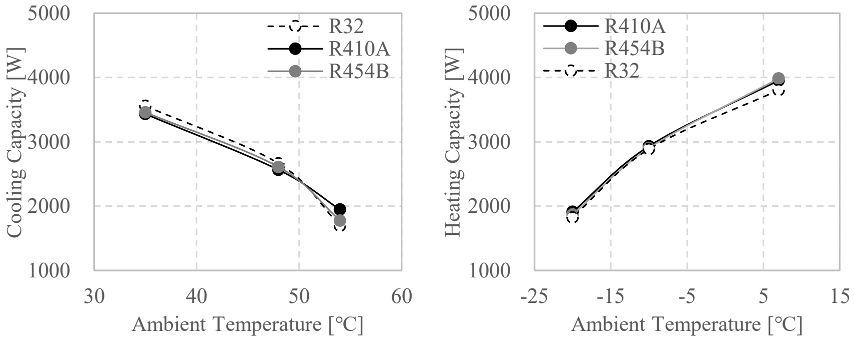


Fig. 4. The capacity comparison at high ambient temperature in cooling mode and cold climate condition in heating mode (wall-mounted type)

As shown in Fig. 5, The SEER is 2% higher and SCOP is almost equal for R454B compared to R410A. The SEER is 6% higher and SCOP is almost equal for R32 compared to R410A.

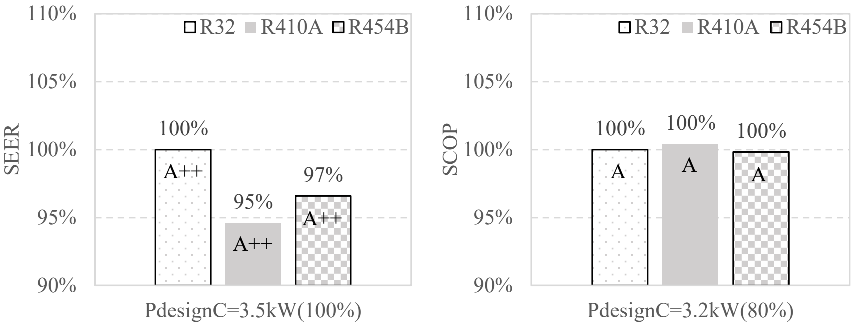


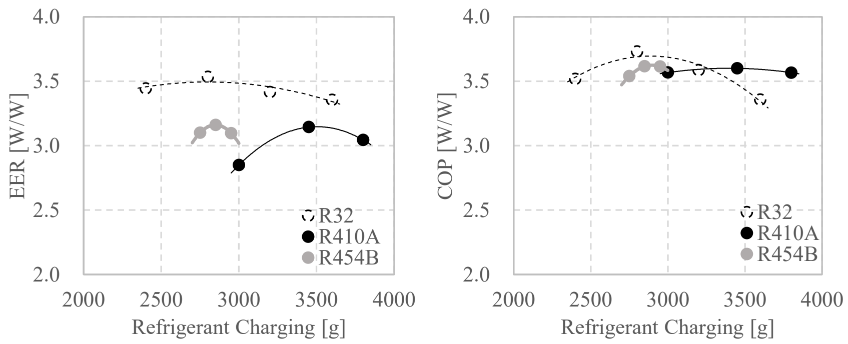
Fig. 5. Cooling and heating seasonal performance (wall-mounted type)

3.2. Ceiling-mounted type air conditioner with inverter scroll compressor

As shown in Table 5 and Fig. 6, R454B refrigerant charge size is 14% lower than the R410A charge and R32 refrigerant charge size is 19% lower than R410A charge. The EER and COP is 1% and 4% higher respectively for R454B compared to R410A. The EER and COP is 12% and 7% higher respectively for R32 compared to R410A. The discharge temperature of R454B is 6°C higher than that of R410A in cooling standard condition and 7°C higher than that of R410A in heating standard condition. The discharge temperature of R32 is 10°C higher than that of R410A in cooling standard condition and 20°C higher than that of R410A in heating standard condition.

Table 5. Comparison of performance (ceiling-mounted type)

Refrigerant	Refrigerant Charging [g]	Cooling mode (14.0kW at rated condition) EER [W/W]	Discharge Temperature [°C]	Heating mode (16.0kW at rated condition) COP [W/W]	Discharge Temperature [°C]
R410A	3450	3.14	66	3.50	73
R32	2800	3.53	86	3.73	83
R454B	3950	3.19	81	3.62	79



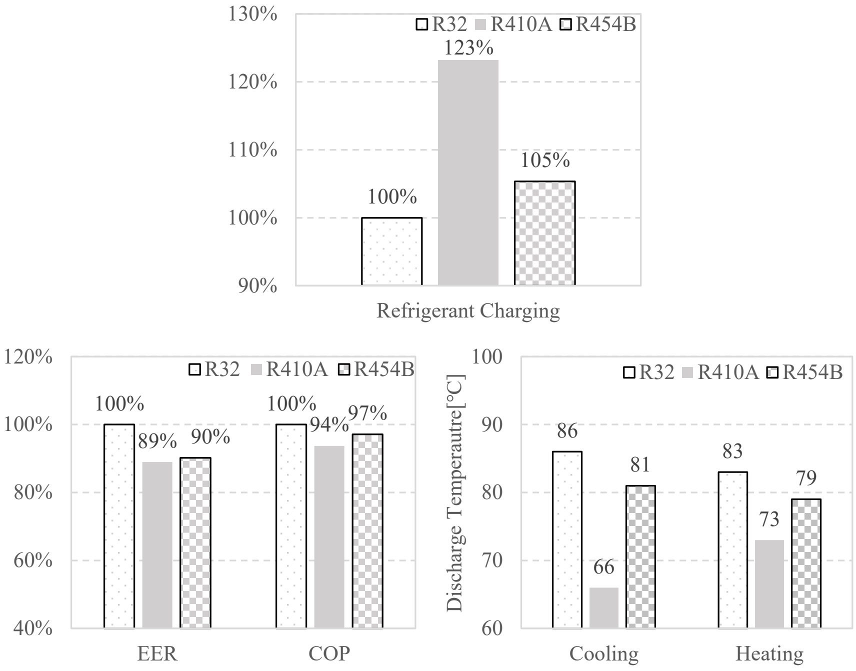


Fig. 6. Performance test results at rated conditions (ceiling-mounted type)

As shown in Fig. 7, as the ambient temperature increases in cooling condition and decreases in heating condition, R454B again shows higher reduction of cooling capacity than R410A because of the higher discharge temperature. Because of compressor current limitations, the maximum heating capacity of R32 is lower than that of R410A and R454B at the ambient temperature of 7ºC.

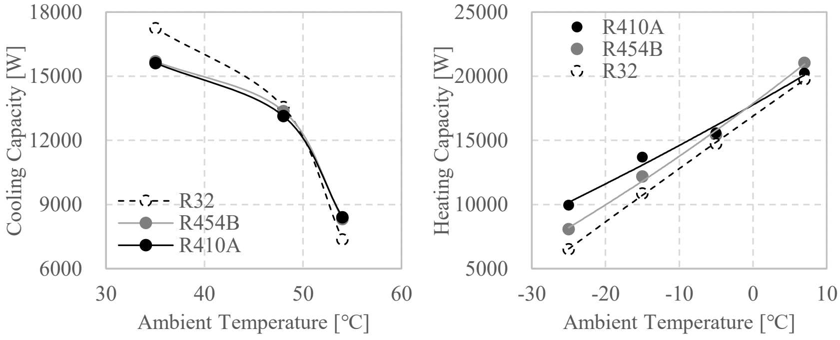


Fig. 7. The capacity comparison at high ambient temperature in cooling mode and cold climate condition in heating mode (ceiling-mounted type)

As shown in Fig. 8, the SEER and SCOP are 1% higher for R454B compared to R410A. The SEER and SCOP is 7% and 2% higher respectively for R32 compared to R410A.

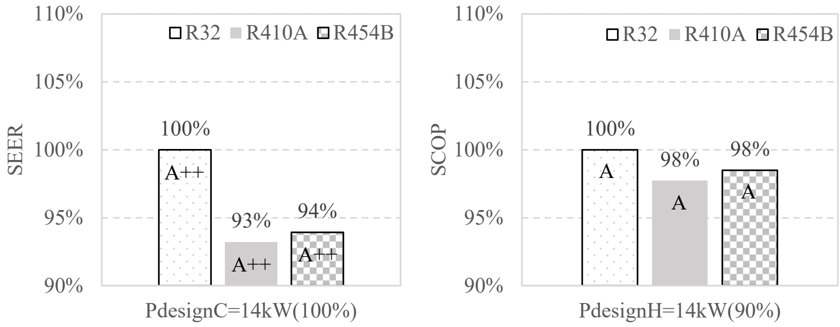


Fig. 8. Cooling and heating seasonal performance (ceiling-mounted type)

4. Conclusions

The performance of low GWP refrigerant alternatives for R410A was evaluated in light commercial air conditioning and heat pump systems and compared with R410A. Performance was tested in both wall-mounted and ceiling-mounted air conditioning and heat pump equipment. The energy efficiency and discharge temperature of R454B are slightly higher than R410A. The capacity of R32 was also higher in conjunction with higher discharge temperature, primarily because of the high value of specific heat ratio and small molar mass. As the ambient temperature increases in cooling condition and decreases in heating condition, the capacity of R32 system abruptly decreases because of the high discharge temperature.

The performance of R32 and R454B suggest they could be lower GWP alternatives to R410A in air conditioning and heat pump systems. Because of its similar properties and performance characteristics to R410A, R454B could be compatible in new system designs that are similar to R410A equipment. As research to develop replacement refrigerants for R410A has been on-going for several years, many small air conditioning and heat pump systems in Asia and Europe using R410A are being transitioned to R32. However the GWP of R32 may be too high to meet phasedowns being proposed around the world to reduce global warming over the long term. R454B is well-positioned to replace R410A with both good energy performance and with a lower GWP that could enable it to be a viable option further into the future. The lower GWP of R454B could enable it to be a promising long-term solution to help meet global CO_2 emissions goals and reduce the potential impact on the environment.

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