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Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

Annex 54

Heat Pump Systems with Low-GWP Refrigerants

Country Report Korea

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Preface
This project was carried out within the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP), which is a Technology Collaboration Programme within the International Energy Agency, IEA.

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The IEA was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster cooperation among the IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development (R&D). This is achieved, in part, through a programme of energy technology and R&D collaboration, currently within the framework of nearly 40 Technology Collaboration Programmes.

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Consistent with the overall objective of the HPT TCP, the HPC seeks to accelerate the implementation of heat pump technologies and thereby optimise the use of energy resources for the benefit of the environment. This is achieved by offering a worldwide information service to support all those who can play a part in the implementation of heat pumping technology including researchers, engineers, manufacturers, installers, equipment users, and energy policy makers in utilities, government offices and other organisations. Activities of the HPC include the production of a Magazine with an additional newsletter 3 times per year, the HPT TCP webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

For further information about the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:
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Executive Summary

This report compares the performance of R32 with R410A for Window Type Air Conditioners, Wall-Mounted Type Air Conditioners, and Ceiling-Mounted Type Air Conditioners in accordance with ISO 5151 and ISO 13253 using a psychrometric calorimeter chamber.

R32 is an attractive alternative refrigerant for residential air conditioners at this time. It has a Global Warming Potential (GWP,100-year, according to AR4) of 675, and the pressure of R410A and R32 is almost the same at the same temperature. Additionally, the performance of R32 is higher than that of R410A, and the refrigerant charging quantity is lower.

For R32 window-type air conditioners, changes were made to the displacement volume of the fixed compressor, refrigerant charging, oil, and capillary tube. The compressor's displacement volume for the R32 system is 3.8% lower than that for R410A. The oil quantity of PVE type is 28.6% lower compared to R410A. The R32 charging quantity is 22.5% lower than R410A. The inner diameter and length of the capillary tube for the R32 system are smaller because the mass flow rate of R32 is about 30% lower than that of R410A.

The cooling capacity and Energy Efficiency Ratio (EER) are 2% and 6% higher for R32 compared to R410A, respectively. The combined energy efficiency ratio in cooling mode for R32 is 7% higher than that of R410A.

For R32 wall-mounted type air conditioners, slight modifications were made to the product. The oil quantity for the R32 twin rotary compressor is 12.5% lower compared to R410A. R32 charging quantity is 26.3% lower than R410A. The inner diameter of the Electronic Expansion Valve (EEV) for the R32 system is smaller because the mass flow rate of R32 is smaller than that of R410A. The compressor frequency of the R32 system is slightly lower than that of R410A in cooling mode and slightly higher for higher heating capacity at rated conditions.

The cooling EER and heating Coefficient of Performance (COP) are equal to R410A at rated conditions. The discharge temperature of R32 is 11°C higher than that of R410A in cooling and 12°C higher in heating. The Seasonal Energy Efficiency Ratio (SEER) is 3% higher for R32 than R410A at the same full load cooling value (PdesignC). The Seasonal Coefficient of Performance (SCOP) of R32 is the same as that of R410A at the heating design value (PdesignH). SCOP tends to increase by about 2% when PdesignH decreases by 20%.

According to the reinforcement of the Energy-related Products Directive (ErP) from January 1st, 2013, air conditioning units under 12kW had to meet the requirements of the ErP. The ceiling-mounted air conditioner adopting R32 was modified by increasing the size of the heat exchanger and changing operational logic to improve the energy efficiency class of the product.

For ceiling-mounted type air conditioners, the R32 system was modified by increasing the size of the heat exchanger, charging quantity, and operational logic to improve the energy efficiency class of the product (ErP). The displacement volume of the scroll compressor for R32 is 28.5% lower than that for R410A. The oil charging quantity is 23.1% lower, and the charging quantity is 11.8% lower than R410A. The compressor frequency of the R32 system is higher than that of R410A in cooling and heating mode at rated conditions.

The cooling capacity is 5% lower, but the Energy Efficiency Ratio (EER) is 2% higher for R32 at rated conditions. The heating capacity is 1% higher, and the Coefficient of Performance (COP) is 6% lower for R32 compared to R410A at rated conditions. The compressor frequency of the R32 system at rated conditions is higher than that of the R410A system due to the smaller displacement volume of the compressor, and the molar mass of R32 is also smaller than that of R410A.

Therefore, the volumetric efficiency of the compressor is lower for the R32 system compared to R410A. For these reasons, the COP of the R32 system is lower than that of R410A. The discharge temperature of R32 is 12°C higher than that of R410A in cooling mode and 8°C higher than that of R410A in heating mode at rated conditions.

The PdesignC value of cooling is 4% lower, and the Seasonal Energy Efficiency Ratio (SEER) is 25% higher for R32 compared to R410A. The PdesignH value of heating is equal, and the Seasonal Coefficient of Performance (SCOP) is 27% higher for R32 than R410A. The seasonal efficiency of the modified R32 system increases drastically compared to that of the conventional R410A system.

As the refrigerant regulations have been reinforced, R32 has been considered a prospective candidate for an alternative refrigerant to R410A. The Global Warming Potential (GWP) of R32 is about 32% compared to R410A, and the R32 refrigerant charging quantity is about 20% lower than R410A. Thus, CO_2 emissions from R32 are about 75% lower than those from R410A. Additionally, the performance of R32 is higher than that of R410A, enabling the manufacture of high-efficiency models adopting R32. Adopting R32 in new equipment with soft optimization is easy and cost-effective.

6.1 Commercialization of R-32 in a Window Type Air Conditioner for US Market and Split Air Conditioners for European Market

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6.1.1 Introduction

The current generation of refrigerant for the residential air conditioner, A1 R410A, has significant global warming potential (GWP 2088, AR4). Because of the regulations about refrigerants, HVAC&R industry has been challenged to convert to low-GWP refrigerants. To meet the regulation, the U.S. allowed to adopt A2L R32 in sealed systems in 2015. In addition, The US environmental protection agency (EPA) has enforced performance requirements of room air conditioners.

Table 6-1: EPA regulatory for room air conditioners

Capacity (Btu/hr)	Units Without Reverse Cycle	
	*$CEER_{BASE}$ (Units with Louvered Sides)	
	EPA 3.1 (2015)	EPA 4.0 (2016)
<6,000	11.0	12.1 (+10%)
6,000 to 7,999		
8,000 to 10,999	11.2	12.0 (+7%)
11,000 to 13,999		
14,000 to 19,999	11.1	11.8 (+6%)
20,000 to 27,999	9.8	10.3 (+5%)
≥ 28,000		9.9 (+1%)

*CEER= (Output cooling capacity in Btu)/(input electrical energy during use in Wh + idle input electrical energy in Wh)

Many countries adopted the Kigali amendment to phase down HFCs by more than 80 percent over the next 30 years and replace them with more environmentally friendly alternatives.

In Europe, the EU f-gas regulation controls the use of fluorinated greenhouse gases, and it significantly impacts users of HFC refrigerants. The f-gas regulation will ban refrigerants with GWP of more than 750 in single split air conditioners containing less than 3 kg in 2025.

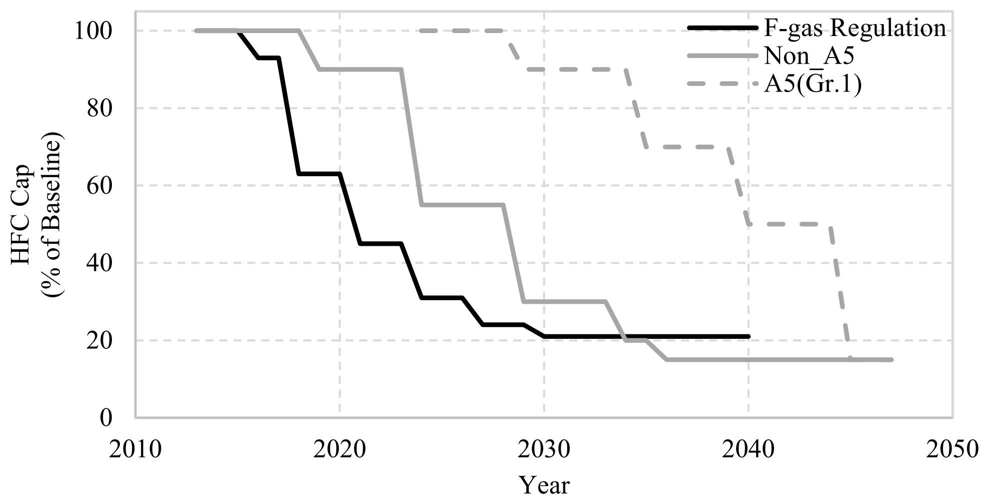

Figure 6-1: HFC Phase-Down Steps of EU and Kigali Amendment (2016)

For these reasons, R32 is currently an attractive alternative refrigerant for the residential air conditioner. R32 has a 100-year GWP of 675, and the pressure of R410A and R32 is almost the same in the same temperature conditions. In addition, the performance of R32 is higher than R410A. The capacity of R32 is 10% higher than that of R410A in the same compressor volume because of the high latent heat. Also, the refrigerant charging quantity of R32 is lower than that of R410A.

However, R32 is a mildly flammable refrigerant (A2L), and the specific heat ratio is higher for R32 compared to R410A, so the discharge temperature of R32 is higher than that of R410A. The simulated results for R410A and R32 in the ASHRAE-T condition are as below. At the given displacement volume of the compressor, the cooling capacity of R32 is 10% higher than that of R410A, and efficiency is 2% higher for R32 compared to R410A. When the isentropic efficiency is 0.75, the discharge temperature of R32 is 21^{o}C higher than that of R410A.

Table 6-2: Property and Performance Comparison of R410A and R32

ASHRAE-T: Cond Temp 54.4℃, Evap Temp 7.2℃, Suction Temp 18.3℃, Sub-cooling Temp 46.1℃		
Refrigerant	R410A	R32
GWP (AR4)	2088	675
Safety Classification	A1	A2L
Condensing Pressure [kPa]	3393	3473
Evaporating Pressure [kPa]	998	1018
Delta Enthalpy [kJ/kg]	159 (100%)	242 (152%)
Volumetric Capacity [kJ/m^3]	5647 (100%)	6236 (110%)
Isentropic Efficiency	0.75	0.75
Discharge Temperature [°C]	94	115
Cp/Cv (Specific heat ratio)	1.412	1.514
Density Suction [kg/m^3]	35.5	25.7
Density Condenser [kg/m^3]	870.8 (100%)	812.2 (93%)
Displacement Volume [cm^3/rev]	31.6	31.6
Mass Flow Rate [kg/s]	0.065 (100%)	0.047 (72%)
Cooling Capacity [kW]	10.26 (100%)	11.33 (110%)
Work [kW]	3.09 (100%)	3.33 (108%)
EER [W/W]	3.32 (100%)	3.40 (102%)

Despite these concerns, many manufacturers have optimized the products to adopt R32. Millions of air conditioning units using R32 as a refrigerant have already been sold throughout Asia, New Zealand, Australia, the US, and Europe. The sales volume of the split and packaged systems under 6 HP for residential and light commercial applications adopting R32 was about 20 million in 2017 and 35 million in 2018. However, R32 is not a long-term answer. To achieve the ultimate goal of the Kigali amendment, we have to find alternatives that have a GWP value near 300.

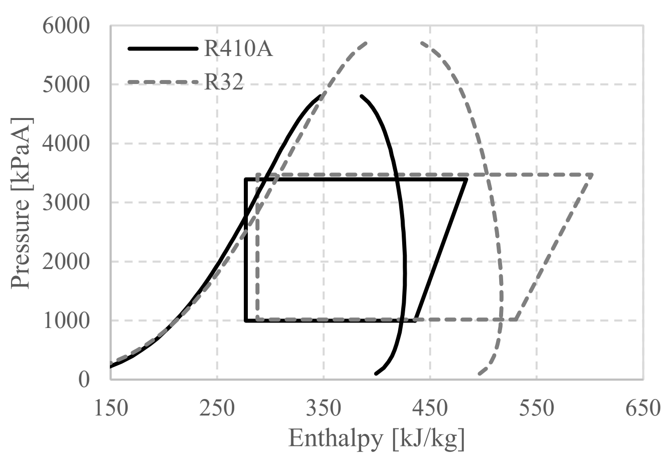

Figure 6-2: P-h Diagram of R410A and R32 (ASHRAE-T Condition)

6.1.2 Details of test setup

The window type, wall-mounted type and ceiling-mounted type air conditioners are used as experimental apparatus to compare the performances of the conventional systems adopting R410A with those of modified systems adopting R32. The window type air conditioner consists of a fixed speed rotary compressor, two fin-tube type heat exchangers, one fan and capillary tube.

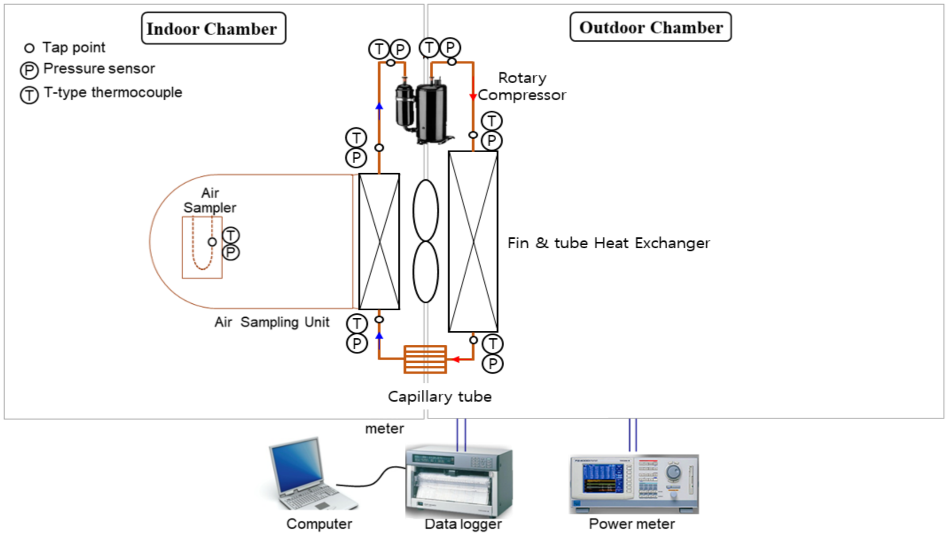

Figure 6-3: Calorimeter Layout (Window Type Air Conditioner)

The wall-mounted type air conditioner consists of an inverter rotary compressor for conventional system and inverter twin rotary compressor for modified system. Both systems have two fin-tube type heat exchangers, one indoor fan, one outdoor fan, 4way reverse valve and electronic expansion valve. The ceiling-mounted type air conditioner consists of inverter twin rotary compressors for conventional systems and inverter scroll compressor for modified system. Both systems have two fin-tube type heat exchangers, one indoor fan, two outdoor fan, 4way reverse valve and electronic expansion valve. The baseline R410A test and R32 test have been accomplished as per ISO 5151 standard for window type air conditioner and ISO 13253 for split type air conditioners in psychrometric calorimeter chamber. 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 even after the change of the experimental conditions such as the change of the compressor frequency. Then, the experimental data was recorded for 35 minutes at intervals of 5 seconds.

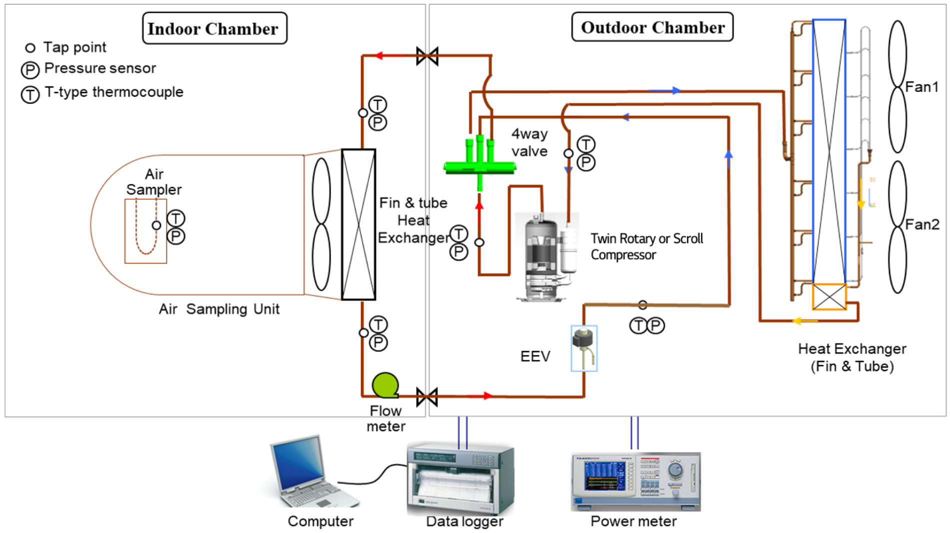

Figure 6-4: Calorimeter Layout (Split Type Air Conditioner)

Table 6-3: Window Type Air Conditioner Test Condition (ANSI/ASHRAE Standard 37)

Conditions	Indoor		Outdoor	
	DB[°C]	WB[°C]	DB[°C]	WB[°C]
Cooling mode at rated Condition	26.7	19.4	35.0	23.9
Cooling mode at partial load condition 1	26.7	19.4	26.7	19.4
Cooling mode at partial load condition 2	26.7	19.4	28.3	19.7

CEER = the combined energy efficiency ratio in cooling mode, in Btu/Wh

$$\mathrm{CEER} = \left[\frac{ACC}{\left(\frac{AEC}{k \times t}\right)}\right] \quad (1)$$

where ACC = adjusted cooling capacity in Btu/hr

AEC = annual energy consumption in cooling mode, in kWh/year

k = 0.001kWh/Wh conversion factor for watt-hours to kilowatt-hours

t = number of cooling mode hours per year

Table 6-4: Test Conditions for Split Type Air Conditioners

(EN14511 - Rated Conditions, EN14825 – Partial Load Conditions)

Conditions		Indoor		Outdoor	
		DB[^oC]	WB[^oC]	DB[^oC]	WB[^oC]
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

SEER = 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 = 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 hertz of compressor should be very low. It can miss the operational range of compressor so that efficiency of product may decrease despite of low power consumption.

6.1.3 Results

6.1.3.1 Window type air conditioner with constant speed rotary compressor

6.1.3.1.1 <u>Modification of cycle specification</u>

For R32, the displacement volume of compressor, refrigerant charging, oil and capillary tube were changed in window type air-conditioner. The displacement volume of compressor for R32 system is 3.8% lower than that for R410A. Compressor oil for R32 is PVE oil and oil charge quantity is 28.6% lower for R32 compared to R410A. R32 charge quantity is 22.5% lower than R410A charge quantity. The inner diameter and length of capillary tube for R32 system are lower than those for R410A system because mass flow rate of R32 system is about 30% lower than that of R410A system.

Table 6-5: Specification of Modified System (Window Type, 12kBtu/hr)

		Base	Modified
Compressor	Type	Rotary (Fixed Speed)	Rotary (Fixed Speed)
	Displacement Volume [cm^3/rev]	10.6	10.2
	Oil	*POE 350 cc (100%)	*PVE 250 cc (71.4%)
Refrigerant [g]		R410A 585 (100%)	R32 395 (77.5%)
Indoor Heat Exchanger		Φ7 3R 12C 20FPI S-Fin(Half) L490mm	Φ7 3R 12C 20FPI S-Fin(Half) L490mm
Outdoor Heat Exchanger		Φ5 3R 18C 20FPI S-Fin(Half) L500mm	Φ5 3R 18C 20FPI S-Fin(Half) L500mm
Capillary tube [inner diameter, mm]		Φ1.2, L1350	Φ1.0, L950

*POE – Polyol Ester, PVE – Polyvinyl Ether

6.1.3.1.2 Performance comparison of R410A and R32

The cooling capacity and EER are 2% and 6% higher for R32 compared to R410A, respectively. The combined energy efficiency ratio in the cooling mode of R32 is 7% higher than that of R410A. To meet the performance requirement, the modification of the system was slight to increase the efficiency of the product.

Table 6-6: Comparison of Performance (Window Type, 12kBtu/hr)

	Base	Modified
Cooling Capacity at Rated Condition [kW]	3.45	3.52
EER [W/W]	2.97	3.15
CEER [Btu/Wh]	11.2	12.0

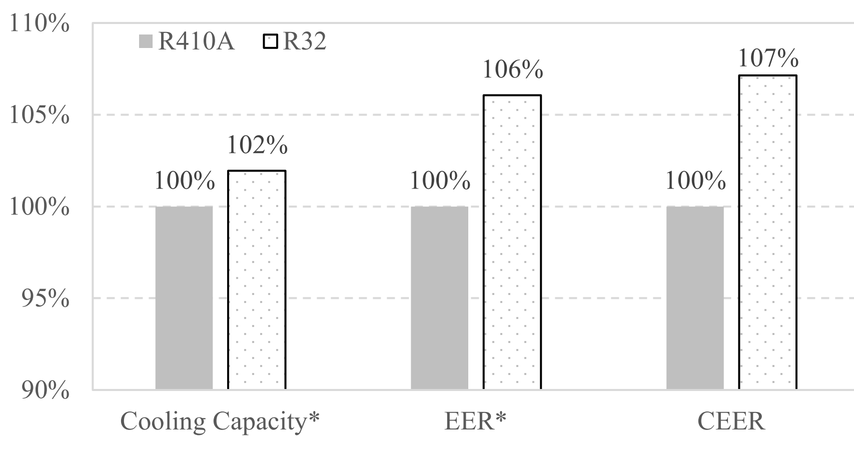

Figure 6-5: Performance Test Result (Window Type, *at Rated Condition)

6.1.3.2 Wall-mounted type air conditioner with inverter compressor

6.1.3.2.1 Modification of cycle specification

There's no major modification of the product when R32 is adopted in the wall-mounted air conditioners. The parts of the products have slightly changed and the performance has increased slightly. For R32, the type and frequency of compressor, refrigerant charging, oil, and EEV are changed in the wall-mounted type air-conditioner. The compressor for R32 is a twin rotary compressor. The oil charge quantity is 12.5% lower for R32 compared to R410A. The R32 charging quantity is 26.3% lower than the R410A charging quantity. The inner diameter of the EEV for the R32 system is smaller than that for the R410A system because the mass flow rate of the R32 system is lower than that of R410A. The compressor frequency of the R32 system is slightly lower than that of R410A in cooling mode and slightly higher than that of R410A in heating mode at rated conditions.

Table 6-7: Specification of Modified System (Wall-Mounted Type, 12kBtu/hr)

		Base	Modified
Compressor	Type	Rotary (Inverter)	Twin Rotary (Inverter)
	Displacement Volume [cm^3/rev]	10.2	10.2
	Oil [cc]	POE or PVE 320 (100%)	PVE 280 (87.5%)
Refrigerant[g]		R410A 950 (100%)	R32 700 (73.7%)
Indoor Heat Exchanger		Φ7 2R 15C 21FPI S-Fin(Half) L616.8mm	Φ7 2R 15C 21FPI S-Fin(Half) L616.8mm
Outdoor Heat Exchanger		Φ7 2R 22C 17FPI S-Fin(Half) L667mm	Φ7 2R 22C 18FPI Louver fin L667mm
EEV Orifice Diameter [mm]		Φ1.65	Φ1.32
Compressor Operating Frequency Range [Hz]		15~120	10~130
Compressor Frequency at Rated Condition [Hz]		65 (cooling) 69 (heating)	61 (cooling) 71 (heating)
Connection Pipe Length [m]		7.5	7.5

6.1.3.2.2 Performance comparison of R410A and R32

The heating capacity is 5% higher, and the cooling capacity, EER, and COP are equal to R32 compared to R410A at rated conditions. The discharge temperature of R32 is 11°C higher than that of R410A in cooling mode and 12°C higher than that of R410A in heating mode at rated conditions.

Table 6-8: Comparison of Performance (Wall-Mounted Type, 12kBtu/hr)

	Base	Modified
Cooling Capacity at Rated Condition [kW]	3.50	3.50
EER [W/W]	3.24	3.24
Discharge Temperature at Rated Cooling Condition [°C]	66	77
SEER [kWh/kWh] ($P_{designC}$ = 3.50 kW)	6.4	6.6
Heating Capacity at Rated Condition [kW]	3.80	4.00
COP [W/W]	3.8	3.81
Discharge Temperature at Rated Heating Condition [°C]	69	81
SCOP [kWh/kWh] ($P_{designH}$ = 2.5 kW)	4.0	4.0

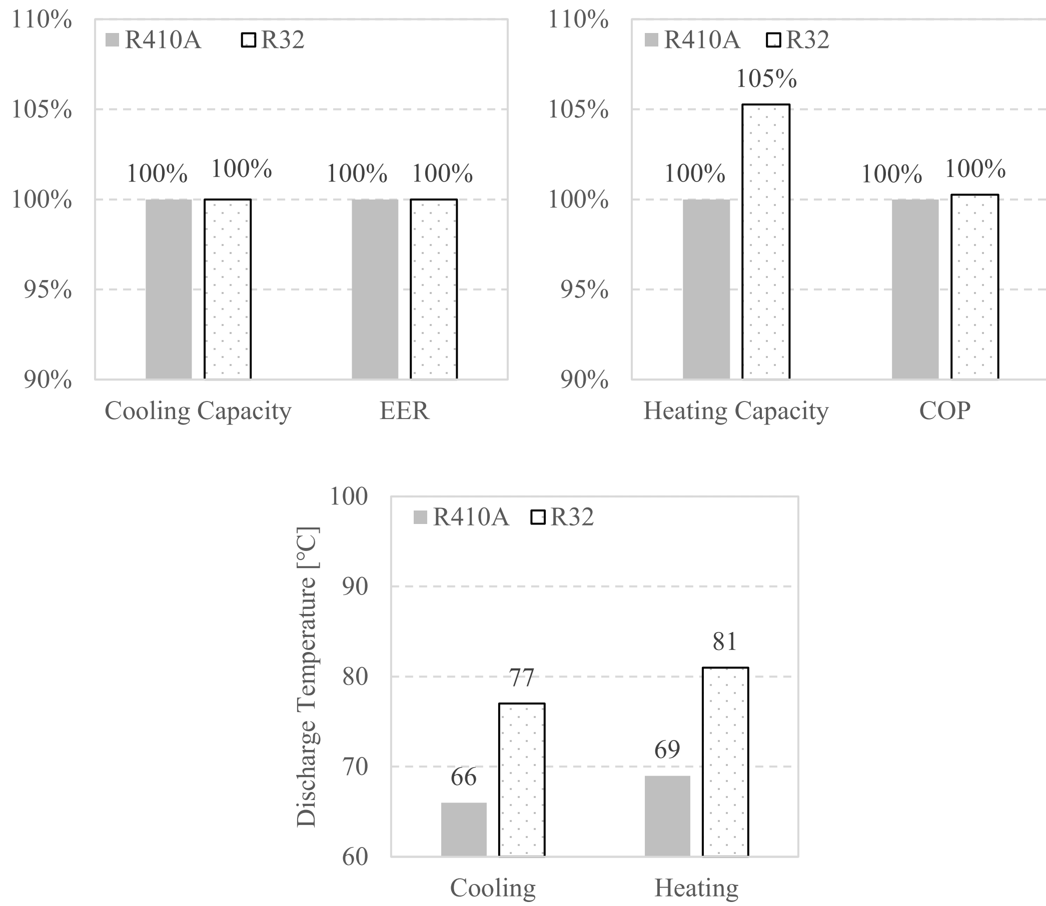

Figure 6-6: Performance Test Results at Rated Conditions (Wall-Mounted Type)

The P_{design} (full load) value of cooling is equal, and SEER is 3% higher for R32 compared to R410A. The P_{design} (full load) value of heating and SCOP of R32 is same with those of R410A. When the SCOP value is calculated, P_{design} (full load) value of heating is lower than heating capacity at rated condition. Manufacturers reduce the value of full heating load ($P_{designH}$) lower than heating capacity at rated condition to improve the energy efficiency class of product. SCOP tends to increase about 2% when the $P_{designH}$ decreases by 20%.

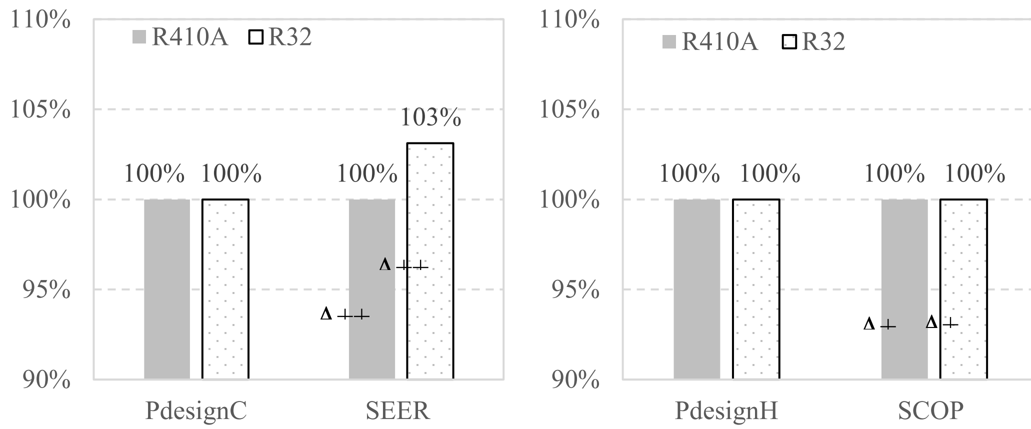

Figure 6-7: Cooling and Heating Seasonal Performance (Wall-Mounted Type)

6.1.3.3 Ceiling-mounted type air conditioner with inverter compressor

6.1.3.3.1 Modification of cycle specification

For R32, the type and frequency of compressor, refrigerant charging, oil, Indoor Heat Exchanger were changed in Ceiling-mounted type air-conditioner.

Table 6-9: Specification of Modified System (Ceiling-Mounted Type, 48kBtu/hr)

		Base	Modified
Compressor	Type	Twin Rotary	Scroll (R1=Brand Name)
	Displacement Volume [cm^3/rev]	44.2 (100%)	31.6 (71.5%)
	Oil [cc]	PVE 1300 (100%)	PVE 1000 (76.9%)
Refrigerant [g]		R410A 3400 (100%)	R32 3000 (88.2%)
Compressor Operating Frequency Range [Hz]		15~100	10~135
Compressor Frequency at Rated Condition [Hz]		66 (cooling) 72 (heating)	75 (cooling) 85 (heating)
Indoor Heat Exchanger		Φ7 2R 12C 21FPI Louver L2052mm	Φ7 2R 12C 21FPI Louver L2084mm + Φ7 1R 10C 21FPI Louver L1930mm
Outdoor Heat Exchanger		Φ7 2R 64C 14FPI Wide Louver L950mm	Φ7 2R 64C 14FPI Wide Louver L950mm
EEV Orifice Diameter [mm]		Φ3.0	Φ3.0
Connection Pipe Length [m]		5	5

The compressor of the R32 system is a scroll-type compressor. The displacement volume of the compressor for R32 is 28.5% lower than that for R410A. The oil charging quantity is 23.1% lower for R32 compared to R410A. The R32 charging quantity is 11.8% lower than the R410A charging quantity. The compressor frequency of the R32 system is higher than that of the R410A system in cooling and heating mode at rated conditions.

6.1.3.3.2 Performance comparison of R410A and R32

The cooling capacity is 5% lower, and EER is 2% higher for R32 compared to R410A at rated condition (Table 6-10 and Figure 6-8). The heating capacity is 1% higher, and COP is 6% lower for R32 compared to R410A at rated conditions. Because of the small displacement volume of the compressor, the compressor frequency of the R32 system is higher than that of the R410A system. Also, the molar mass of R32 is smaller than that of R410A, so the volumetric efficiency of the compressor is lower for the R32 system compared to R410A. For these reasons, the COP of the R32 system is lower than that of R410A. The discharge temperature of R32 is 12°C higher than that of R410A in cooling mode and 8°C higher than that of R410A in heating mode at rated conditions. The P_{design} (full load) value of cooling is 4% lower, and SEER is 25% higher for R32 compared to R410A. The P_{design} (full load) value of heating is equal, and SCOP is 27% higher for R32 than R410A. The seasonal efficiency of a modified system increases drastically compared to that of a conventional system. Manufacturers must follow the Energy-related Products Directive (ErP) in the European market. This European Standard provides part load conditions and calculation methods for calculating the Seasonal Energy Efficiency Ratio (SEER) and Seasonal Coefficient of Performance (SCOP) of such units when they are used to fulfill the cooling and heating demands. From 1st January 2013, air conditioning units under 12 kW had to meet the requirements of the ErP. However, the product adopting R410A didn't have to meet requirements because the rated capacity of it exceeded 12 kW. However, as the requirements of ErP were reinforced, manufacturers had to meet requirements even if the capacity of the product exceeded 12 kW. Therefore, the ceiling-mounted air conditioner adopting R32 was modified by increasing the heat exchanger size and changing operational logic to improve the energy efficiency class of the product.

Table 6-10: Comparison of Performance (Ceiling-Mounted Type, 48kBtu/hr)

	Base	Modified
Cooling Capacity at Rated Condition [kW]	13.9	13.4
EER [W/W]	3.01	3.08
Discharge Temperature at Rated Cooling Condition [°C]	79	91
$P_{designC}$ [kW]	13.9	13.4
SEER [kWh/kWh]	5.2	6.52
Heating Capacity at Rated Condition [kW]	15.4	15.5
COP [W/W]	3.41	3.22
Discharge Temperature at Rated Heating Condition [°C]	67	75
SCOP [kWh/kWh], $P_{designH}$ = 9.3 kW	3.2	4.05

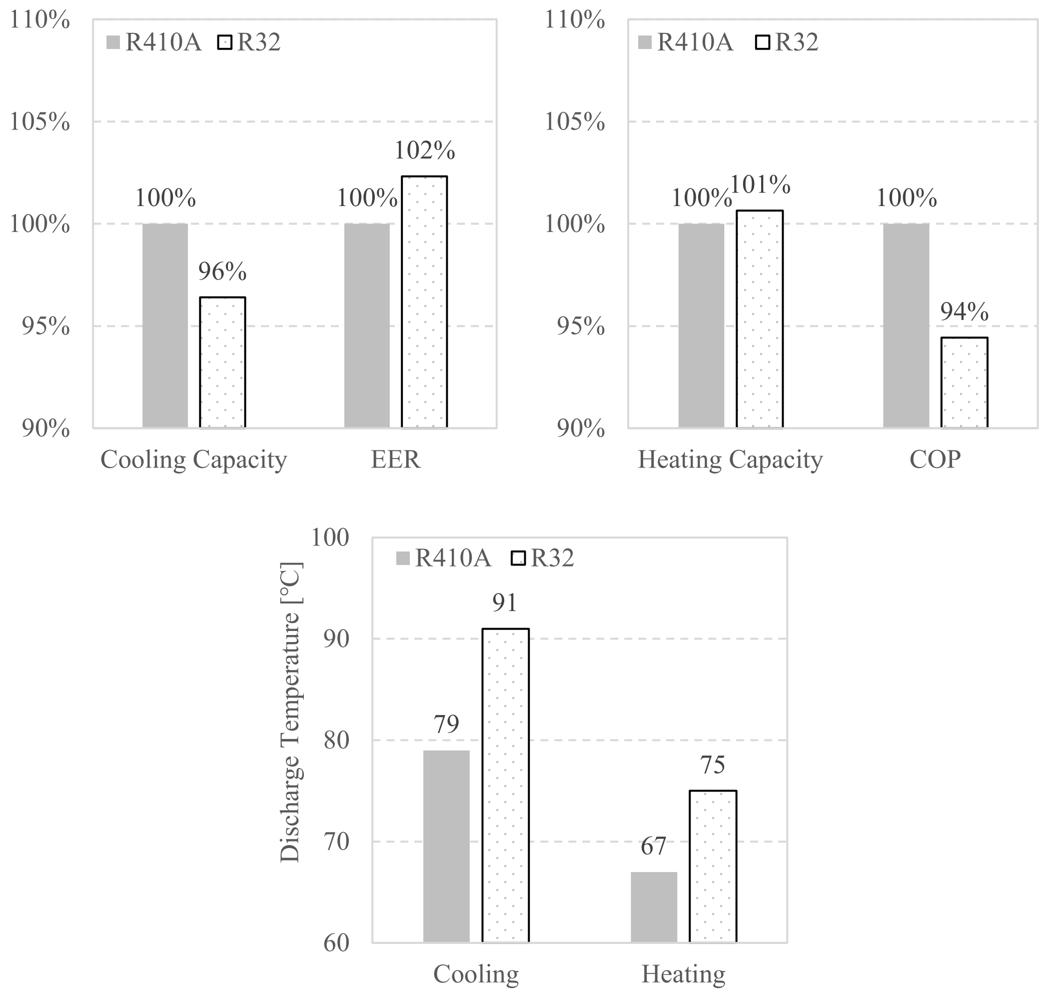

Figure 6-8: Performance Test Result at Rated Condition (Ceiling-Mounted Type)

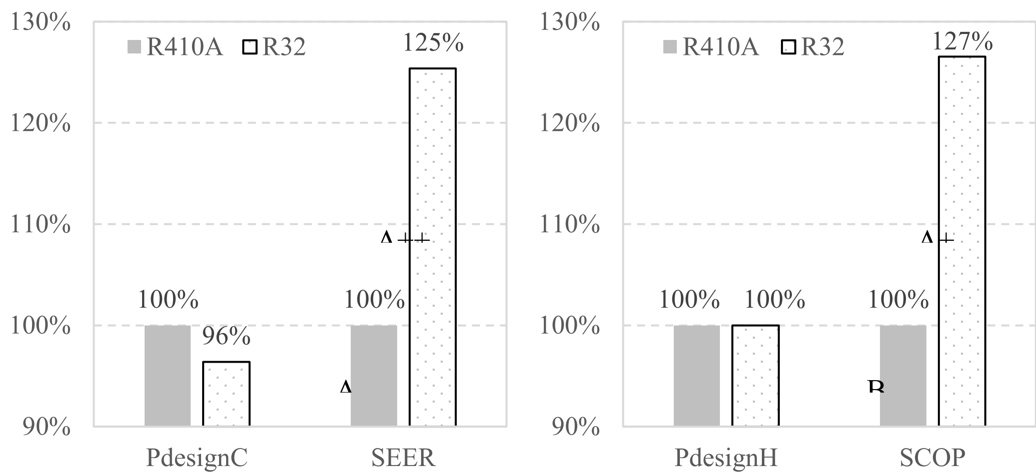

Figure 6-9: Cooling and Heating Seasonal Performance (Ceiling-Mounted Type)

6.1.4 Conclusions

As the refrigerant regulations have been reinforced, R32 has been considered as a prospective candidate for R410A alternative refrigerant. The GWP of R32 is about 32% compared to R410A, and the R32 refrigerant charging quantity is about 20% lower than R410A refrigerant charging quantity. Thus, the CO2 emission of R32 is about 75% lower than that of R410A. Also, the performance of R32 is higher than that of R410A, which enables us to manufacture a high-efficiency model by adopting R32. Adopting R32 in new equipment with minor modifications is easy and cost-effective.

The product has no major modifications when R32 is adopted for window type and wall-mounted air conditioners. The parts of the products have slightly changed, and the performance has increased.

For window-type air conditioners, the cooling capacity and EER are 2% and 6% higher for R32 compared to R410A, respectively. The combined energy efficiency ratio in the cooling mode of R32 is 7% higher than that of R410A.

For wall-mounted type air conditioners, the heating capacity is 5% higher, and the cooling capacity, EER, and COP are equal for R32 as compared to R410A at rated conditions. The discharge temperature of R32 is 11^{o}C higher than that of R410A in cooling mode and 12^{o}C higher than that of R410A in heating mode at rated conditions.

To follow ErP, the ceiling-mounted air conditioner adopting R32 was modified by increasing the size of the heat exchanger and changing the operational logic to improve the energy efficiency class of the product.

For ceiling-mounted air conditioners, the cooling capacity is 5% lower and EER is 2% higher for R32 compared to R410A at rated condition. The heating capacity is 1% higher, and COP is 6% lower for R32 compared to R410A at rated condition. The discharge temperature of R32 is 12^{o}C higher than that of R410A in cooling mode and 8^{o}C higher than that of R410A in heating mode at rated conditions.

6.1.5 Discussions

The buildings require high cooling and heating demand at high ambient temperatures in cooling mode and cold climate conditions in heating mode. So, in those conditions, the air conditioning system should increase the compressor volume of the fixed-speed compressor or compressor frequency of the inverter compressor. When the inverter system is used in those conditions, the compressor frequency is limited by discharge temperature. The discharge temperature of the compressor is affected by the specific heat ratio (Cp/Cv), and the specific heat ratio of R32 is higher than that of R410A. Also, the molar mass of R32 is smaller than that of R410A, so the effect of refrigerant leakage in the compressor is larger for the R32 system compared to the R410A system. It causes the reduction of the volumetric efficiency of the compressor and high discharge temperature. Thus, the capacity of the R32 system abruptly decreases in those conditions because of the high discharge temperature.

6.2 Applications of Low-GWP Refrigerants: High Temperature Heat Pump and Showcase

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6.2.1 Abstract

In this report, a literature review is conducted regarding low-GWP refrigerants for high-temperature heat pumps and showcases. Through the literature review, the present report provides trends of the recent study and research direction on investigating refrigerants with low-GWP. In the application of high-temperature heat pumps, R1233zd(E), R1234ze(Z), and R1336mzz(Z) are the most promising alternative refrigerants with very low GWP. In the case of the showcase, R448A and R449A are the possible alternatives to the conventional refrigerant. However, the two refrigerants still have moderate GWP, which must be replaced.

6.2.2 Introduction

A high-temperature heat pump (HTHP) is an energy-efficient device that can recover waste heat to produce high-temperature thermal energy such as hot water or steam (Yang et al., 2014). Since a large amount of heat is wasted in the air in various industries, using HTHP is beneficial from the perspective of energy saving and environmental issues. However, the conventional refrigerant used for the HTHP, mostly R245fa, has a high GWP of 858. Accordingly, a large number of research has investigated alternative refrigerants of R245fa. In addition, a showcase is a commercial refrigerator widely used in supermarkets and convenience stores to keep food temperature low. R404A is one of the most used refrigerants for the typical showcase owing to the low evaporating temperature of the system with R404A. However, R404A has a very high GWP of 3260. Therefore, numerous studies have been carried out to replace R404A. This report overviews the recent research trend on low-GWP refrigerants applied to high-temperature heat pumps and showcases. For each application, summaries are tabled, and candidates for the conventional refrigerants are listed.

6.2.3 High-temperature heat pumps

The HTHP is frequently used in connection with industrial heat pumps, mainly for waste heat recovery in process heat supply with heat sink temperatures generally above 100 °C. This section summarizes the current research on the applications of low-GWP refrigerants in high-temperature heat pumps.

Chamoun et al. (2014) carried out experimentations under industrial operating conditions (130−140 °C) to estimate the potential of a high-temperature heat pump using water as the working fluid. A new dynamic model of the heat pump was developed to consider the presence of non-condensable gases and purging mechanisms, especially during the start-up procedure. Xiaohui et al. (2014) developed a near-azeotropic refrigerant mixture named BY-4 for a high-temperature heat pump. This study tested the performance of a single-stage high-temperature heat pump with BY-4 as a working fluid. At the inlet water temperature of 50–70 °C in the evaporator, the outlet water temperature of the condenser could reach 80–110 °C.

Table 6-11: Summary of literatures for high-temperature heat pumps

Author	Refrigerant	Condensing temp.	Note
Chamoun et al. (2014)	Water	130–140 °C	New dynamic model
Yu et al. (2014)	BY-4	80–110 °C (water T)	Feasibility of BY-4
Yang et al. (2017)	CO_2 & R152a	92, 97, 102 °C	Combined cycle
Cao et al. (2014)	R152a	95 °C (water T)	Two-stage heat pump
Zhao et al. (2016)	Ammonia	65–85 °C	New semi-empirical model for twin screw compressors
Lim et al. (2018)	R245fa	90–120 °C	Heat transfer performance
He et al. (2015)	R124	88 °C (water T)	Economizer vapor injection
Mateu-Royo et al. (2018)	n-Pentane, Butane, R1233zd(E), R1336mzz(Z)	110, 130, 150 °C	Energy performance evaluation for the alternatives of R245fa
Li et al. (2002)	R22 & R141b	70, 80 °C (water T)	Effect of composition ratio
Zhang et al. (2017)	BY-5	110–130 °C	Feasibility of BY-5
Longo et al. (2014)	R1234ze(Z)	29.9–40.1 °C	Heat transfer performance
Fukuda et al. (2014)	R1234ze(E) R1234ze(Z)	105, 125 °C	Thermodynamic assessment
Bamigbetan et al. (2019)	R600	115 °C (water T)	Prototype compressor
Arpagaus et al. (2018)	R1336mzz(Z), R718, R245fa, R1234ze(Z), R600, R601	90–160 °C (water T)	Review for current research
Kim et al. (2010)	R134a	90 °C	Hybrid of compression & absorption cycle
Yang et al. (2014)	N/A	120–150°C (waterT)	Travelling-wave thermoacoustic heat pump

BY-4 was recommended as the working fluid for the high-temperature heat pump with a single-stage cycle due to its good properties and excellent cycle performance.

Wang et al. (2017) proposed a high-temperature heat pump system composed of a CO_2 transcritical cycle and R152a subcritical cycle for heat and cooling cogeneration. Under the same operating conditions, the system COP and exergy efficiency of the combined system increased by about 54.7% and 175%, respectively, as compared to those of the single R152a heat pump and single CO_2 transcritical cycle working alone.

Cao et al. (2014) used different heat pump systems to recover the heat from wastewater with a mean temperature of 45 °C and produce hot water with a temperature of up to 95 °C. The COP and exergy efficiency for both two-stage heat pumps with flash tanks and two-stage heat pumps with flash tanks and intercoolers were quite similar and much higher than those of other systems. Besides, the payback period of both systems pump with flash tank and intercooler was also shorter as compared to other systems. Zhao et al. (2016) introduced a novel system employing higher temperature ammonia twin screw compressors and analyzed for recovering heat and supplying hot water. A new semi-empirical model was specially developed for high-pressure twin screw compressors.

He et al. (2015) applied a vapor injection technique in a high temperature heat pump (HTHP) to provide hot water at temperatures up to 88 °C. A prototype HTHP system with economizer vapor injection was developed, and its performance was experimentally investigated under various operating conditions. Mateu-Royo et al. (2018) evaluated the energy performance and the volumetric heating capacity of five vapor compression systems using n-Pentane, Butane, R1233zd(E), and R1336mzz(Z) as alternative fluids of R245fa for heating production at the temperatures of 110, 130, and 150 °C.

Li et al. (2002) studied high-temperature hot water heat pumps experimentally. The performance of the system was characterized by refrigerant compositions, compressor RPM, and water temperature change. At the inlet water temperature of 40 °C in the evaporator and the inlet and outlet water temperatures of 70 and 80 °C in the condenser, respectively, the experiments showed that the COP is maximum when the molar component of R22 was about 75%. Zhang et al. (2017) proposed a new binary near-azeotropic mixture named BY-5 as the refrigerant of a high-temperature heat pump. An experimental investigation of a heat pump using BY-5 was carried out at high-temperature levels of 70–80 °C in the evaporation unit and 110–130 °C in the condensing unit. The results demonstrated the feasibility and reliability of BY-5 as a new high-temperature refrigerant.

Lim et al. (2018) measured the condensation heat transfer characteristics of R245fa in a shell and plate heat exchanger (SPHE) by varying the mean vapor quality from 0.16 to 0.86, mass flux from 16.0 to 45.0 kg m^{-2} s^{-1}, heat flux from 1.3 to 9.0 kW m^{-2}, and saturation temperature from 90 to 120 °C for high-temperature heat pumps (HTHPs). Longo et al. (2014) presented the experimental heat transfer coefficients and pressure drop of R1234ze(Z) measured during condensation inside a commercial brazed plate heat exchanger (BPHE). They compared the data with similar measurements previously obtained for R236fa, R134a, R600a, and R1234ze(E) to experimentally assess R1234ze(Z) for high-temperature heat pumps. R1234ze(Z) exhibited a heat transfer coefficient much higher than those of all refrigerants now used in heat pumps, and the frictional pressure drop was similar to R600a at the same mass flux.

Fukuda et al. (2014) studied low global warming potential refrigerants R1234ze(E) and R1234ze(Z) as the refrigerants for high-temperature heat pumps in industrial applications. Their thermodynamic attributes were thermodynamically, experimentally, and numerically assessed.

The theoretical COPs were maximized at a condensation temperature of approximately 20 K below the critical temperatures for each refrigerant. Bamigbetan et al. (2019) investigated a prototype compressor in a high-temperature heat pump for industrial waste heat recovery from 50 °C to heat delivery at 115 °C. It was found to have a total compressor efficiency of 74% and a volumetric efficiency of 83%. The results showed good operating parameters (temperature, pressure) and the potential for even higher temperature heat delivery. Arpagaus et al. (2018) reviewed the current research activities of high-temperature heat pumps (HTHPs) with heat sink temperatures in the range of 90 to 160 °C. The refrigerants investigated were mainly R1336mzz(Z), R718, R245fa, R1234ze(Z), R600, and R601. R1336mzz(Z) to achieve exceptionally high heat sink temperatures up to 160 °C.

Table 6-12: Main refrigerants for high-temperature heat pumps

Refrigerant	T_C [°C]	P_C [bar]	ODP [-]	GWP [-]	Safety class
R245ca	174.4	39.3	0	716	N.A.
R245fa	154.0	36.5	0	858	B1
R365mfc	186.9	32.7	0	804	A2
SES36	177.6	28.5	0	3126	A2
R1233zd(E)	166.5	36.2	0.00034	1	A1
R1234ze(Z)	150.1	35.3	0	<1	A2L
R1224yd(Z)	155.5	33.3	0.00012	<1	A1
R1336mzz(E)	137.7	31.5	0	18	A1
R1336mzz(Z)	171.3	29.0	0	2	A1
R600	152.0	38.0	0	4	A3
R600a	134.7	36.3	0	3	A3
R601	196.6	33.7	0	5	A3
R717	132.3	113.3	0	0	B2L
R718	373.9	220.6	0	0	A1
R744	30.98	73.77	0	1	A1

Kim et al. (2010) investigated an innovative heat pump system based on the hybrid concept combining a compression cycle and an absorption cycle. The simulation was designed a compression/absorption hybrid heat pump system which can make high temperature above the level of 90 °C and low temperature of 20 °C as well at the same using 50 °C geothermal heat water. Yang et al. (2014) presented a novel TWTAHP (travelling-wave thermoacoustic heat pump) to meet the requirement, which can potentially solve the problems occurring in conventional vapor-compression heat pumps such as high discharge temperature, high pressure ratio, and low efficiency. TWTAHP has a high relative Carnot efficiency of about 50–60%. Using a reliable linear compressor and a thermoacoustic heat pump with no-moving parts, the technology has an inherent potential for high reliability.

6.2.4 Showcase

The R404A is one of the refrigerants most extended in commercial refrigeration systems for freezing and showcasing. Due to European F-gas regulation (EU Regulation No 517/2014), high GWP refrigerants like R404A will be phased out in most commercial refrigeration to reduce the global warming effect. Many alternative refrigerants to replace R404A have been studied. Refrigerants with a GWP of more than 2500 used in refrigerators and freezers for commercial (hermetically sealed equipment) will be prohibited by 2020. After 2022, refrigerants with a GWP of more than 150 will be prohibited. This section summarizes the current research on the applications of low-GWP refrigerants in the showcase.

Table 6-13: Summary of literatures for showcase

Author	Refrigerant	Evaporating temp.	Note
Mota-Babiloni et al. (2015a)	ARM-32a, DR-33, N40, ARM-30a, DR-7, ARM-31a, L40, D2Y65	−15, −35, −10 °C	Energy evaluation for alternatives to R404A
Mota-Babiloni et al. (2017)	R448A, R454A, R407F, R410A, R448A, R449A	−40 to −30 °C	Review for alternatives to R404A
Bortolini et al. (2015)	R404A, R410A, R407F	−25, −15, −5, 10 °C	Comparison of thermodynamic performance
Hu et al. (2018)	R404A, R407A, R407F	−7 °C	Optimization of refrigerant change amount
Oruç et al. (2018)	R442A, R453A	−6, −3, 0 °C	Cycle performance evaluation
Mota-Babiloni et al. (2018)	R454C, R455A	−30, −21.5, −13 °C	Cycle performance evaluation
Mota-Babiloni et al. (2014)	R407A, R407F, L40, DR-7, N40, DR-33	−40, −10 °C	Performance comparison among basic cycle, subcooler cycle, direct injection cycle, basic cycle with IHX
Mota-Babiloni et al. (2015b)	R404A, R448A	−33, −20, −8 °C	Cycle performance evaluation
Sethi et al. (2016)	R448A, R455A	−8.4, −7.6 °C	Cycle performance evaluation
Makhnatch et al. (2017)	R404A, R449A	−8.3, −5.7 °C	TEWI (total equivalent warming impact) evaluation

Mota-Babiloni et al. (2015a) analyzed alternative refrigerants (ARM-32a, DR-33, N40, ARM-30a, ARM-31a, D2Y65, DR-7, L40) to replace R404A, theoretically. The alternative refrigerants showed lower cooling capacity than R404A. However, they consumed less power than R404A, so the COPs of the alternatives were higher than those of R404A. In this case, the suggested best options were ARM-30a, ARM-31a, D2Y65, and DR-7. Mota-Babiloni et al. (2017) reviewed the alternative refrigerants used in various applications. Alternative refrigerants to replace R404A were R448A and R454A for refrigerators and freezers for commercial, and R407F, R410A, R448A, and R449A for stationary refrigeration equipment. Bortolini et al. (2015) experimentally compared the thermodynamic performances of R404A, R410A, and R407F refrigerants for medium (−5, 10 °C) and low (−25, −15 °C) temperatures. The COP and cooling capacity of R407F and R410A were higher at the medium temperature range, and R407F yielded the best cooling capacity. However, the COP of R410A was higher. R410A was not usable at the lower temperature because of the compressor overheating and cooling capacity.

Table 6-14: Main refrigerants for showcase

Refrigerant	T_C [°C]	P_C [bar]	ODP [-]	GWP [-]	Safety class
DR-7	89.17	45.5	0	250	A2L
L40	89.89	48.4	0	300	A2L
R1234yf	94.7	33.82	0	4	A2L
R1234ze(E)	109.36	36.36	0	7	A2L
R125	66.015	36.29	0	3500	A1
R134a	100.95	40.6	0	1430	A1
R152a	114	47.6	0	124	A2
R290	96.68	42.47	0	5	A3
R32	78.4	53.8	0	675	A2
R404A	72.0	37.3	0	3260	A1
R407A	82.3	45.5	0	2107	A1
R407C	86.2	46.32	0	1774	A1
R407F	82.6	47.55	0	1825	A1
R410A	71.35	47.539	0	2088	A1
R448A	83.7	46.6	0	1390	A1
R449A	81.5	44.5	0	1397	A1
R455A	85.6	46.6	0	145	A2L
R717	132.3	113.3	0	<1	B2L
R744	30.98	73.77	0	1	A1

Hu et al. (2018) experimentally investigated the optimization of the refrigerant charge range of R404A, R407A, and R407F based on year-round performance evaluation (CC, PI, EER, sub-cooling degree, superheating degree, and DT of a medium temperature cold storage unit). Oruç et al. (2018) experimentally compared the performances of R442A and R453A in three different evaporation temperatures (−6, −3, and 0 °C) and three condenser temperatures (35, 40, and 45 °C). The cooling capacities of R442A and R453A were greater by 1−8% than that of R404A. The power consumption of the compressor was lower for R442A and R453A than R404A at three condenser temperatures. Compared with R404A, the COP was better by 5–12% using R442A and 10−14% using R453A.

Mota-Babiloni et al. (2018) carried out experiments using a vapor compression refrigeration test bench with R454C and R455A at condensing temperatures of 32.0, 39.5, and 47.0 °C, and evaporation temperatures of −30.0, −21.5, and −13.0 °C. Compared with R404A, the COP was 15% and 10% higher for R454C and R455A, respectively. Although the performance results using

IHX were positive with R404A, the increase in the maximum COP was only 4% for the alternative mixtures, and their discharge temperatures were near the operating limit. Mota-Babiloni et al. (2014) also carried out a performance comparison of 4 types of vapor compression cycles: basic cycle, subcooler cycle, direct injection cycle, and basic cycle with internal heat exchanger using R407A, R407F, L40, DR-7, N40, and DR-33. The most efficient refrigerants were very low-GWP long-term alternatives of L40 and DR-7. However, those have low flammability. In the applications where mildly flammable refrigerants were not allowed, the best options in terms of energy performance were DR-33 and N40. Furthermore, Mota-Babiloni et al. (2015b) experimentally compared the performances of R404A and R448A. R448A presented slightly less volumetric efficiency but much lower mass flow rate, cooling capacity, and power consumption than R404A. The discharge temperature of R448A was higher than R404A, however, it was below the limit temperature. In terms of the cooling capacity, R448A can be considered a good replacement for medium temperature being possibly not enough for low temperature. R448A was more benefited than R404A from higher condensation temperatures, which can be considered as a good alternative in warm countries.

Sethi et al. (2016) evaluated the performance of R448A and R455A in a low-temperature self-contained freezer and a commercial walk-in freezer. In the self-contained freezer, R448A showed a capacity similar to R404A with 9% lower compressor energy consumption. R455A also showed a capacity similar to R404A with about 6% lower compressor energy consumption. In a walk-in freezer, R448A showed 4% to 8% higher efficiency than R404A. Makhnatch et al. (2017) carried out a performance comparison in an indirect supermarket refrigeration system using R404A and R449A. It was indicated that the charge amount of R449A was higher than that of R404A by about 4%. They found that the cooling capacity of R449A was lower by nearly 13%. It was demonstrated by TEWI calculation that R449A could reduce the total CO_2 equivalent emission in the system originally designed for R404A.

6.2.5 Conclusions

A literature review regarding refrigerants used in high-temperature heat pumps and showcases has been carried out. A number of research have been conducted on high-temperature heat pumps, and some of the possible alternative refrigerants are R1233zd(E), R1234ze(Z), and R1336mzz(Z), owing to their very low GWP. Since R404A has a very high GWP, many studies have been conducted to suggest alternatives to R404A for the showcases. As a result of the recent studies, R448A and R449A are suggested as possible replacements for R404A. However, the two refrigerants still have moderate GWP around 1300. Therefore, the two refrigerants can be used as transitional alternative refrigerants toward low-GWP refrigerants, which ultimately are to be replaced.

6.2.6 Reference

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6.3 Overall Conclusions

R32 has been considered a prospective candidate for an alternative refrigerant to R410A. The GWP of R32 is about 32% of R410A, and the R32 refrigerant charging quantity is about 20% lower than R410A. Thus, CO_2 emissions from R32 are about 75% lower than those from R410A. Additionally, the performance of R32 is higher than that of R410A, enabling the manufacturing of high-efficiency models adopting R32. Adopting R32 in new equipment with soft optimization is easy and cost-effective.

A literature review has been conducted on refrigerants used in high-temperature heat pumps and showcases. Some research has been conducted on high-temperature heat pumps, and some of the possible alternative refrigerants are R1233zd(E), R1234ze(Z), and R1336mzz(Z), owing to their very low GWP. Since R404A has a very high GWP, many studies have been conducted to suggest alternatives to R404A for the showcases. As a result of recent studies, R448A and R449A are suggested as possible replacements for R404A. However, the two refrigerants still have moderate GWP around 1300. Therefore, the two refrigerants can be used as transitional alternative refrigerants toward low-GWP refrigerants, which ultimately are to be replaced.

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