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Performance evaluation by simulation of refrigerated display cabinets using HFO refrigerant

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Abstract

For protecting the global environment, low GWP refrigerants are to be incorporated in air conditioning systems and refrigerating devices, such as refrigerated display cabinets (RDCs) commonly used in convenience stores and supermarkets. R290 (propane), as a natural refrigerant, has been receiving attention as a potential working fluid alternative but poses safety issues due to its flammable characteristic. As the demand for safe refrigeration systems with easy maintenance is increasing, this study evaluated the utilization of HFO-1234yf for RDCs, and its performance was compared to R290 and other commonly used refrigerants. Simulations were conducted based on actual ambient temperature data from a convenience store. Results showed that the COP of HFO-1234yf was slightly lower than those of R290 and R134a, but higher than those of R410A, R32, and R744. The annual power consumption and the annual performance factor of HFO-1234yf were very similar to those of R290. Hence, it is expected that RDCs using HFO-1234yf will perform as efficiently as those using R290.

Keywords: Showcase; Performance Evaluation; Refrigerants; HFO-1234yf; Simulation

1. Introduction

Recent trends in global warming prevention have been revised by the Kigali Amendment in the Montreal Protocol [1], and an obligation was established to reduce HFCs by 85% by 2036. Therefore, to achieve the reduction obligation by 2029, before the amount of HFCs becomes severe in Japan, refrigeration equipment using low GWP refrigerant and reduction of refrigerant leakage is to be developed. However, if a low GWP refrigerant is used without preliminary evaluation of the equipment performance, then it can result in (1) inefficient operation, and (2) increased energy required for manufacturing.

Apart from the proper selection of the working fluid focused on natural refrigerants to lessen direct CO2 emissions, systems that utilize these refrigerants must work efficiently to avoid over power consumption that results in indirect CO2 emissions. As of March 2019, 58,000 convenience stores operate in Japan, with annual sales exceeding 10 trillion yen [2]. Most of the energy consumption at convenience stores is due to lighting, air conditioning, and refrigeration equipment [3]. There is a high demand for refrigerated display cabinets (RDCs) as one of the commonly used refrigeration equipment to hold and preserve perishable goods while offering ease of accessibility to the customers. There are two types of RDCs: “built-in type” and “separate type.” In the former, a condensing unit, with mechanical parts such as a compressor and a condenser, is integrated with a device for displaying and cooling the product, while the latter features the separation of the evaporating and condensing units at the indoor and outdoor, respectively. Convenience stores often use built-in RDCs because they can easily accommodate changes in store layout and restrictions on the location of condensing units. Convenience store owners are also keen on the operational safety of the refrigerated display cabinets.

In this study, a simulator was built and used to evaluate alternative working fluids that can conform to the environmental standards, operational safety, and system efficiency, particularly for built-in type RDCs. The results can be used for benchmarking and preliminary assessment of the performance before manufacturing and utilization of the systems. In particular, this study evaluated the potentiality of HFO-1234yf refrigerant as a low GWP refrigerant to replace commonly used high GWP refrigerants, such as R134a, R410A, and R32. Furthermore, the performance of HFO-1234yf was compared to that of R290, as the latter has received attention for possible usage despite its high flammability that poses safety issues.

2. Methods

The annual energy performance of RDCs using various refrigerants was evaluated. Here, an annual performance evaluation simulator for RDCs was constructed based on the annual interior conditions at a store in Japan. Furthermore, the simulator evaluated the annual performance by changing the refrigerant. This feature makes it easy to assess the performance of a variety of refrigerants without incorporating them in actual equipment.

2.1. Simulator Overview

The annual performance simulator was input with specifications and conditions of the RDCs, and the store interior temperature conditions (in case of the built-in type) and the outdoor temperature conditions (in case of the separate type). The simulator provided the annual performance as output. For analyzing the applicability of low GWP refrigerants to RDCs, the annual performance of showcases was evaluated. Therefore, the annual power consumption of the RDCs, the annual average COP, and the time-series data of the operating state such as compressor discharge temperature, were obtained as output. Fig. 1 shows the input/output relationship of the annual performance simulator. The annual performance was calculated by the simulator that used the thermodynamic cycle analysis. This simulator applied pinch temperature analysis as its calculation principle [4]. For subcritical cycle refrigerants, the pinch temperature was applied at the condenser refrigerant outlet. The subcooled condition was determined by the temperature difference between the condensation temperature and ambient temperature, and the pinch temperature. In the case of R744 (CO_2), the pinch temperature was used at the gas cooler refrigerant outlet.

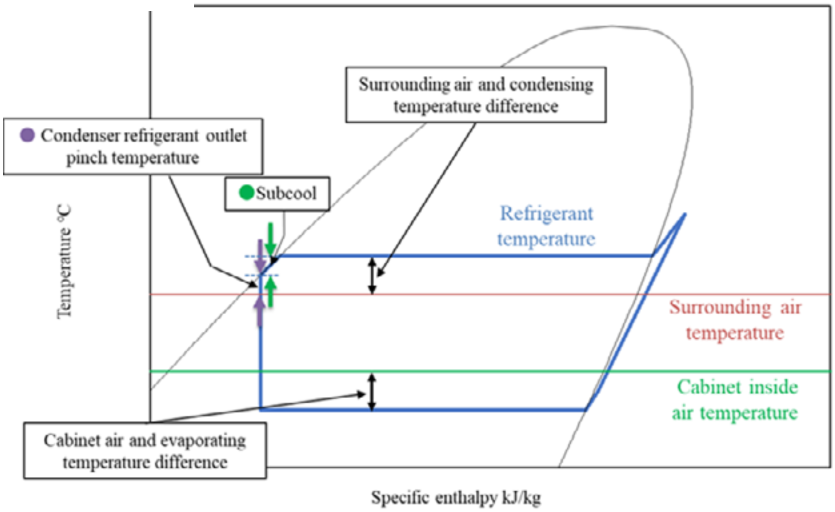


Fig. 1. Temperature-enthalpy diagram

2.2. Calculation prerequisites

The performance of RDC systems using various refrigerants can be compared in the thermodynamic cycle. Table 1 shows the computational elements used for the performance calculation.

Table 1 Computational elements

Computational elements
Difference between the evaporating temperature and the surrounding air temperature
Evaporator outlet superheat
Difference between the condensing temperature and the surrounding air temperature
Compressor adiabatic efficiency
Isenthalpic process at the expansion valve

The procedure to determine the cycle is as follows:

1. Determine the evaporation temperature from the cabinet air temperature.
2. Determine the condenser temperature from the surrounding air temperature and the refrigerant outlet pinch temperature.
3. Determine the refrigerant properties of the compressor suction considering the evaporator superheat.
4. Determine the refrigerant properties at the compressor outlet considering compressor adiabatic efficiency.

A fixed temperature difference between the heat exchanger and the ambient temperature was employed, where the difference in heat transfer performance and pressure loss due to the physical properties of the refrigerant was not considered. This is because the thermal resistance on the air side is dominant and there is no significant difference in the temperature difference between refrigerants.

3. Results and Discussion

3.1. Annual exterior and interior temperatures at an actual store

Various measurement data obtained at an actual convenience store were examined to conduct the simulation under conditions that represent those in an actual store. Fig. 2 shows the exterior and interior store temperatures measured for one year in an actual store. This data was measured at one-hour intervals between June 1, 2017, and May 31, 2018. However, there are some missing data.

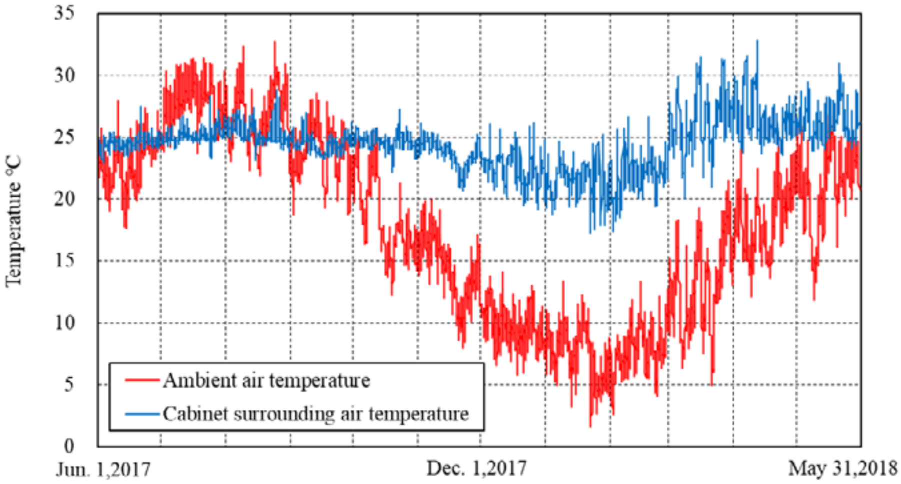


Fig. 2. Indoor and outdoor air temperature of an actual store

The simulator used the physical properties of the refrigerants based on the data from the NIST REFPROP [5]. Tables 2 and 3 list the physical properties, GWP, and the safety classifications of the refrigerants considered in the study.

Table 2 Physical properties, GWP, and safety class of various refrigerants (1/2)

Refrigerant	GWP [6]	Critical temperature °C	Critical pressure MPa	Safety class
R134a	1430	101.06	4.059	A1
R1234yf	< 1	94.70	3.382	A2L
R290	3.3	96.74	4.251	A3
R410A	2088	71.34	4.901	A1
R32	675	78.11	5.783	A2L
R744	1	30.98	7.377	A1

Table 3 Physical properties of various refrigerants (2/2)

Refrigerant	Condensing pressure MPa	Evaporating pressure MPa	COP	Volume capacity kJ/m³	Suction density kg/m³	Capacity kJ/kg Refrigerant
R134a	0.887	0.243	4.01	1865	11.780	158.30
R1234yf	0.895	0.266	3.89	1806	14.556	124.05
R290	1.218	0.406	3.96	2597	8.686	298.99
R410A	2.144	0.678	3.78	4440	25.111	176.80
R32	2.190	0.691	3.84	4815	18.176	264.93
R744	8.019	3.046	2.66	12446	79.064	157.42

Table 4 lists the preconditions of the RDC set for the calculation. These input conditions do not necessarily reflect actual machine data, but by maintaining these uniform conditions, a calculation can be performed to an approximate refrigeration system in accordance with the physical properties of various refrigerants. As the condensation temperature of R744 cannot be defined under the calculation conditions shown in Table 4, the pinch temperature of the gas cooler outlet temperature sets the pressure at which the COP is maximum as the high operating pressure [7].

Fig. 3 shows COP calculation results of various refrigerants. In terms of the COP, the results confirm that R1234yf is slightly inferior to R134a and R290, equivalent to R32, and superior to R410A and R744.

Table 4 Specifications of the calculation

Condition	Value
Difference between condensing temperature and the surrounding air temperature °C	10
Cabinet temperature °C	25
Surrounding air temperature °C	5
Difference between evaporating temperature and the surrounding air temperature °C	10
Evaporating temperature °C	-5
Evaporator outlet superheat °C	5
Compressor adiabatic efficiency	0.7

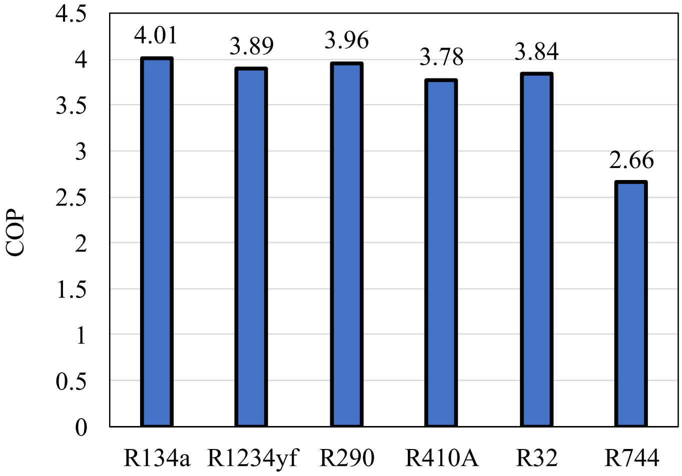


Fig. 3. COP calculation results of various refrigerants

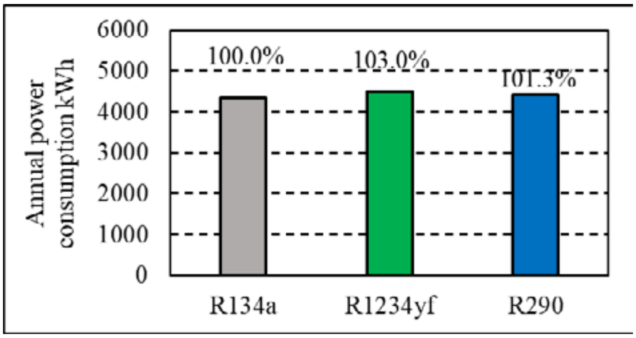
3.2. Annual performance evaluation with fixed heat load

The performance of RDC systems were evaluated from two sets of simulations: with fixed heat load and with heat load variation when the type of refrigerant was changed based on the indoor temperature and the inside of cabinet temperature data measured at an actual store. The result for one year was calculated at hourly intervals. For the cabinet temperature of the refrigerated showcase, the actual average value of one-minute interval data per day for each season was considered, because there were no hourly data throughout the year.

At first, we simulated the performance of RDC systems with fixed heat load. The heat load was fixed at 2 kW. Linear interpolation was applied to account for some missing time-series data. The comparisons were focused mainly on R1234yf and R290 with R134a as the baseline, as these refrigerants have shown better COP values compared to the other working fluids presented in the previous section. Additionally, these three refrigerants exhibit similar critical temperatures and properties. Fig. 4 shows the ratio of the annual power consumption of R1234yf and R290 with respect to R134a, and Fig. 5 shows the annual average COP obtained by dividing the annual total refrigeration load by the power consumption. Table 5 shows the assumed specifications of the RDC set.

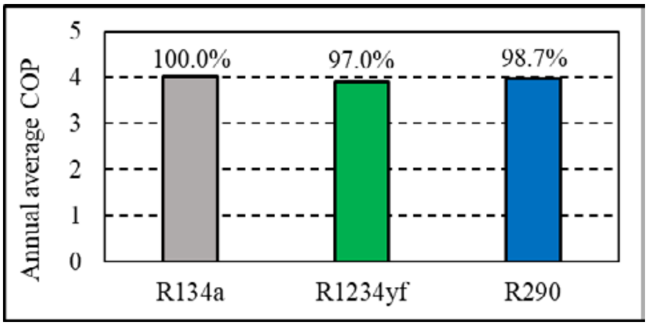
Table 5. Specifications of the RDC set

Specifications	
Rated refrigeration load	2 kW
Type	Built-in type
Physical size	Standard size (specific size is not considered)



Refrigerant	Annual power consumption (kWh)
R134a	4343
R1234yf	4475
R290	4400

Fig. 4. Annual power consumption calculation results for three refrigerants at 2kW heat load



Refrigerant	Annual average COP
R134a	4.03
R1234yf	3.92
R290	3.98

Fig. 5. Annual average COP calculation results for three refrigerants at 2kW heat load

Fig. 6 shows the results of calculating the hourly change in the COP of three refrigerants for one year. From Fig. 4–6, it is evident that the performance of R1234yf is similar to that of R290.

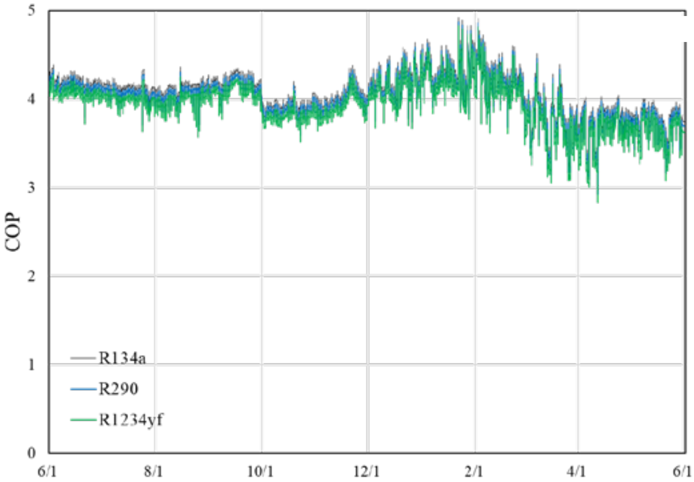


Fig. 6. Hourly COP for one year for three refrigerants at 2kW heat load

3.3. Annual performance evaluation with varying heat load

Next, we simulated the performance of RDC systems with varying heat load. This is because the surrounding air temperature at RDC changes in the case of an open refrigerated display cabinet. The heat load is assumed to change due to cold air leaks from the RDC while an outside air infiltrates [8]. Varying the heat load was obtained from the correlation between the difference of the inside and surrounding air temperature of RDC, and the heat load calculated from the experimental values. The experimental measurements were taken using the actual machine during three periods with varying temperatures at the surrounding environment of the RDC: summer, mid-term, and winter, and the heat load was calculated from the evaporator inlet/outlet temperature and airflow rate.

Table 6 shows the results of the heat load during the three periods. The calculated heat load from the experimental values was linearly approximated.

Fig.7 presents the results of the correlation for the difference between the surrounding air and inside temperature of the RDC, against the heat load.

As observed from Fig. 7, the heat load of the target RDCs was less than 1kW.

Table 6. Calculated heat load during the three periods

	Summer	**Mid-term**	**Winter**
RDC surrounding air temperature ℃	27	25	19.3
RDC inside temperature ℃	5	4.6	4.6
Heat Load kW	0.953	0.831	0.464

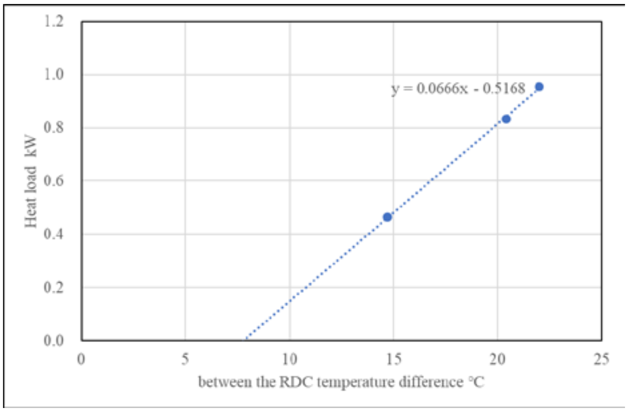
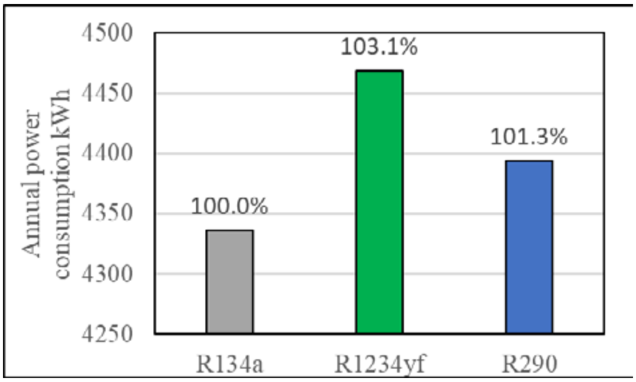


Fig. 7. Correlation between the RDC temperature difference and heat load

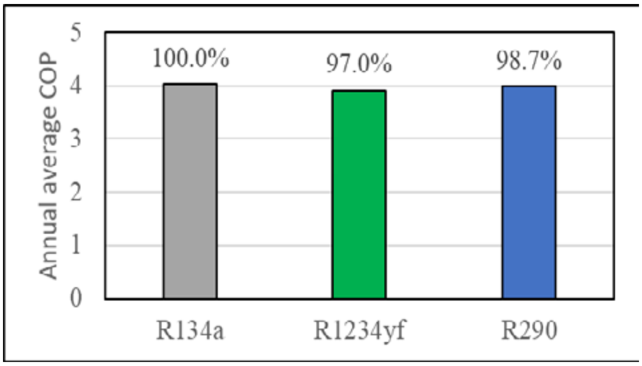
To compare the annual power consumption and annual average COP for fixed and variable loads, the correlation equation shown in Fig. 7 was scaled up so that the average heat load conforms to 2 kW. The results are shown in Fig. 8 and Fig. 9. Furthermore, the correlation equation between the heat load and heat exchange temperature difference does not apply because it varies with the geometry of each equipment and refrigerant, hence the set of preconditions of the RDC from Table 4 was used for the calculation.

Fig. 8 shows the ratio of the annual power consumption of R1234yf and R290 with respect to R134a, while Fig. 9 shows the annual average COP.



Refrigerant	Annual power consumption (kWh)
R134a	4336
R1234yf	4468
R290	4394

Fig. 8. Annual power consumption calculation results for three refrigerants with varying heat load



Refrigerant	Annual average COP
R134a	4.04
R1234yf	3.92
R290	3.98

Fig. 9. Annual average COP calculation results for three refrigerants with varying heat load

Table 7 shows the calculated values for the annual power consumption and the average annual COP for fixed and variable heat load. The results show that the error in the average annual power consumption figure is about 0.15%, and the average annual COP changed insignificantly.

Table 7 Comparison of annual energy consumption and annual average COP at fixed and variable heat loads

Refrigerant	Heat load fixed		Heat Load Variation	
	Annual energy consumption	Annual average COP	Annual energy consumption	Annual average COP
R134a	4343	4.03	4336	4.04
R1234yf	4475	3.92	4468	3.92
R290	4400	3.98	4394	3.98

Fig. 10 shows the results of calculating the hourly change in the COP of three refrigerants for one year. As in the case of fixed heat load, the performance of R1234yf is similar to that of R290.

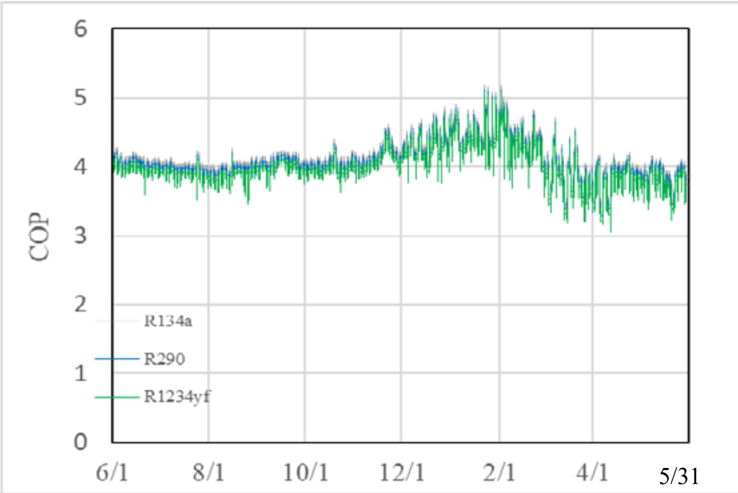


Fig. 10. Hourly COP for one year for three refrigerants with varying heat load

These results show that the annual power consumption and the average annual COP for fixed and variable heat loads are almost the same. One of the reasons for this is that the surrounding air temperature at RDC does not change much because the target is built-in RDCs, and the heat load does not consequently change much throughout the year.

3.4. Parameter study

A simulation calculation was performed to examine the effect of varying the cabinet temperature of the RDC on the annual power consumption and annual average COP. This simulation was performed with a fixed heat load of 2kW. Table 7 and Table 8 list the calculation results of annual power consumption and annual average COP, respectively.

Table 7 Annual power consumption (kwh)

Refrigerant	**Cabinet temperature**		
	4 °C	5 °C	6 °C
R134a	4388	4271	4151
R1234yf	4522	4398	4271
R290	4445	4328	4207

Table 8. Annual average COP

Refrigerant	**Cabinet temperature**		
	4 °C	5 °C	6 °C
R134a	3.99	4.10	4.22
R1234yf	3.87	3.98	4.10
R290	3.94	4.05	4.16

It is evident from Table 7 that when the cabinet temperature is lowered by 1 °C, the annual power consumption increases, and annual average COP decreases by approximately 3%. Table 7 and Table 8 indicate that the power consumption of R1234yf increases by approximately 1–2% compared to that of R290, and annual average COP decreases by 1–2%. Thus, it can be concluded that the performance of R1234yf is closely equivalent to that of

R290.

4. Conclusion

Simulations were performed to compare the performance of HFO-1234yf refrigerant to those of various refrigerants when used for refrigerated display cabinets. The COP of HFO-1234yf refrigerant was slightly lower than R134a and R290, but higher than conventionally used high GWP refrigerants such as R410A, and even R32. HFO-1234yf also outperformed R744 (CO_2). Based on the annual power consumption and annual average COP results, and it was confirmed that HFO-1234yf performed as efficiently as R290. Therefore, RDCs using HFO-1234yf are expected to exhibit a system performance that is as efficient as those using R290. Owing to the safety desired from integrated RDCs installed in stores and supermarkets, the low GWP refrigerant, R1234yf, is considered to be more suitable than R290.

In the future, as the built-in type refrigerated display cabinet was considered in this study, the separated type will be considered. Furthermore, to verify the accuracy of the simulation results, we plan to conduct more experiments to evaluate the performance with actual machines.

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