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ALTERNATIVE REFRIGERANT TO R-22 IN LOW-TEMPERATURE AND AIR-CONDITIONING REFRIGERATORS

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ABSTRACT

R-32/125/134a/600 was proposed for an alternative refrigerant for replacing R-22 in large-scale refrigeration-cycle systems to reach –30 °C in our previous report. We tested actual performance in an equipment with a nominal cooling capacity of 30.2 kW refrigerator designed for a 858 m^3 refrigerated warehouse and a refrigeration- and Lorentz-cycle testing-apparatus with a 0.55 kW nominal energy consumption compressor at several temperature conditions of air-conditioning application. As a result, it is confirmed that cycle performance and pressure conditions of R-32/125/134a/600 are very similar to R-22 and actual performance of R-32/125/134a/600 is better than that of R-22.

INTRODUCTION

Finding an alternative refrigerant for replacing R-22 is getting a practical problem because general use of hydrochlorofluorocarbons (HCFCs) including R-22 is promised to be banned till 2020 in the Montreal Protocol. On the other hand, increase of refrigerated transportation, storage, and display-cases of foods requires great number of refrigeration-cycle systems chilling down to freezing temperature such as a low temperature of –30 °C. These systems are also required to work with high efficiency for eliminating CO_2 emission after the Kyoto protocol. Japan promised to eliminate global warming gas emission by 6 % from that in 1990 there. Roughly more than a half number of refrigeration systems equipped to refrigerated warehouses in Japan are using R-22 as a refrigerant. Regarding R-417A as an alternative HFC-refrigerant proposing to replace R-22, the performance was studied in the system designed for R-22 in 2000. The results were presented in a previous report [1]. The pressure drop in an evaporator was larger than that of R-22 due to higher viscosity of R-417A. We proposed to add small amount of R-32 to R-417A for low-temperature application in the previous report because R-32 has small viscosity and small specific volume ratio of saturated vapor to saturated liquid. From a different viewpoint, some hydrofluorocarbon (HFC) mixtures of two or three components among R-32, R-125, and R-134a with different compositions such as R-407C and R-410A have already been used as an alternative refrigerant for replacing R-22 in existing air-conditioning systems. By adding small amount of normal-butane R-600 to these HFC-refrigerant mixtures, existing mineral lubricants being used with R-22 can be used. The four-component mixture refrigerant enables us to use existing refrigerating machines by replacing R-22 without changing the lubricant oil.

The refrigeration performance of the four-component mixture will be studied carefully from three different approaches in this study: calculation of the theoretical-cycle performance using the thermodynamic properties derived from REFPROP [2]; actual operation in a 858 m^3 refrigerated warehouse equipped with a nominal cooling capacity of 30.2 kW refrigerator to maintain a temperature of –30 °C; and an experimental study using a refrigeration- and Lorentz-cycle testing-apparatus with a 0.55 kW nominal energy consumption compressor at several temperature conditions of air-conditioning application. The results will be summarized in the following sections.

CYCLE PERFORMANCE IN REFRIGERATED WAREHOUSE

Thermodynamic Calculations

We used REFPROP [2] for calculating thermodynamic-property values of any refrigerants including R32/125/134a/600 in this study. The refrigeration system equipped for an actual refrigerated warehouse was assumed in the refrigeration-cycle calculation. The system is shown in Fig. 1. Two-stage compressor is equipped in the system. Table 1 shows temperature conditions for the calculations. The subscript numbers correspond to the numbers in Fig. 1. We determined the conditions for the refrigerated warehouse that stores frozen food, i.e., the temperature in the warehouse is maintained at −30 °C. The 20 % of refrigerant returns at point 6 to subcooler is assumed. For zeotropic mixtures such as R-32/125/134a/600, we used average temperatures in the evaporator and the condenser for the cycle calculations.

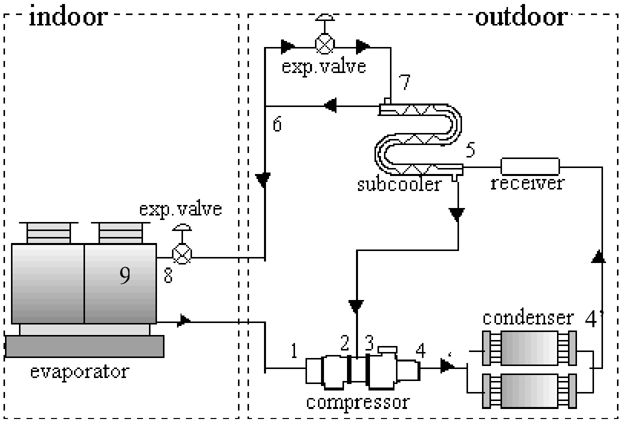


Figure 1: Layout of 30.2 kW vapor-compression refrigeration system.

Table 2 shows a discharge temperature at compressor outlet; point 4' in Fig. 1. Pressure conditions of R-32/125/134a/600 (10/42/45/3, 15/39.5/42.5/3 mass%) are close to those of R-22. The discharge temperature is obviously lower than that of R-22. Table 3 shows the cycle performance, cooling effect Δh_c, volumetric cooling-effect Δh_v, adiabatic compression-work Δh_{ad}, and the COP, for R-22 and two different compositions of R-32/125/134a/600. Volumetric cooling-effect is very important property that means cooling capacity under the condition of using a common compressor. The cycle performances of R-32/125/134a/600 are almost equal to that of R-22. Volumetric cooling-effect R-32/125/134a/600 (15/39.5/42.5/3 mass%) is slightly better than that of R-32/125/134a/600 (10/42/45/3 mass%).

Figure 2 shows calculated volumetric cooling-capacity ratio and COP ratio of alternative refrigerants with those of R404A, R407C, R410A, and natural working fluids such as ammonia and hydrocarbons. R-32/125/134a/600 has similar characteristics to R-22. R-32/125/600 has higher volumetric capacity ratio, but its pressure is too high to be used in refrigeration systems designed for R-22.

Table 1. Temperature conditions for thermodynamic calculation

t_9	t_4	t_5	t_6	t_7	t_1
-35 °C	40 °C	30 °C	7 °C	2 °C	-25 °C

Table 2. Pressure conditions and discharge temperature at compressor

	P_1[kPa]	P_4[kPa]	t_4[°C]
R-22	132	1534	66.9
R-32/125/134a/600(10/42/45/3 mass%)	117	1527	57.3
R-32/125/134a/600(15/39.5/42.5/3 mass%)	125	1607	59.7

Table 3. Theoretical cycle performance

	Δh_C[kJ/kg]	Δh_v[kJ/m^3]	Δh_{ad}[kJ/kg]	COP[-]
R-22	188	1082	70.6	2.67
R-32/125/134a/600(10/42/45/3 mass%)	169	954	63.8	2.65
R-32/125/134a/600(15/39.5/42.5/3 mass%)	177	1016	66.8	2.64

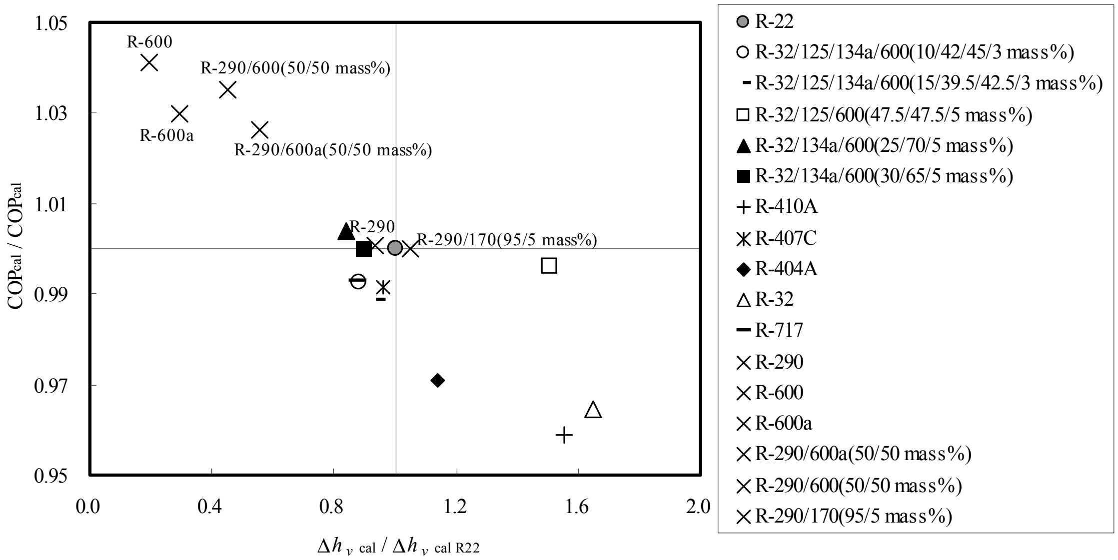


Figure 2: Calculated refrigeration cycle performance.

Experimental Study

The tests were performed by using a vapor-compression refrigeration system equipped with a 22 kW two-stage compressor designed for R-22 as a refrigerant. This system was prepared to refrigerate an 858 m^3 warehouse constructed as an experimental facility for studying performances of commercial low-temperature refrigerated warehouse. The experimental facility has the exactly same construction as refrigerated warehouses commercially used. The test was performed to maintain inside warehouse at –30 °C by an on-off controller in Chiba, Japan, about a week for each refrigerant. Figure 1 introduced in previous section shows the layout of the refrigeration system. When the temperature in the warehouse falls to –31 °C, the refrigeration system stops, and it starts again when the temperature goes up to –29 °C. Figure 3 shows measured evaporating pressure P_1 and condensing pressure P_4 for refrigerant of R-22 or R-32/125/134a/600. P_4 was influenced by outside temperature. Figures 4 to 6 show relations among power consumption W_{comp} and outside temperature t_{outside} or temperature in the warehouse $t_{\mathrm{inside\ 1}}$. Operating period between start and stop of compressor was almost the same because three refrigerants have similar cooling capacity. The power consumption mainly depends on outside temperature as shown in Fig. 7. Power consumption of R-32/125/134a/600 (10/42/45/3 mass%) was slightly lower than that of R-22 or R-32/125/134a/600(15/39.5/42.5/3 mass%).

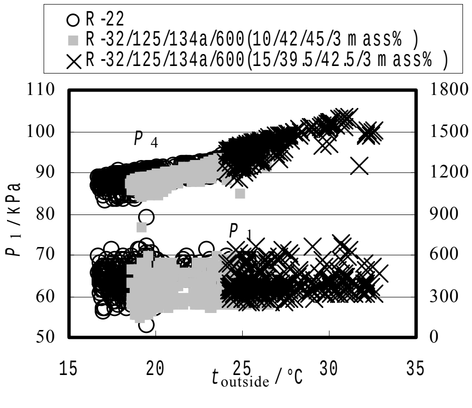


Figure 3: Pressure conditions in the case of R-22 and R-32/125/134a/600.

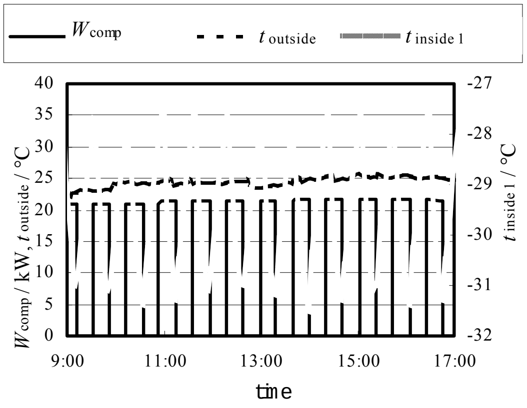


Figure 4: On-off operation with a refrigerant of R-22.

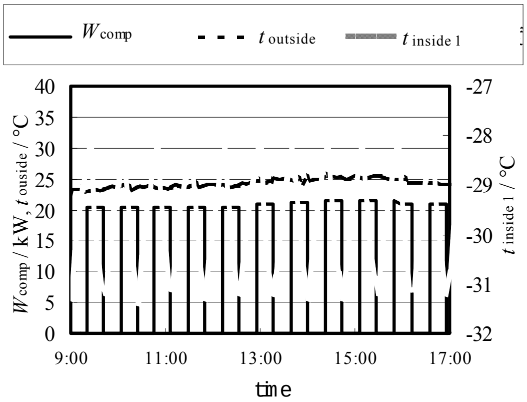


Figure 5: On-off operation with R-32/125/134a/600 (10/42/45/3 mass%).

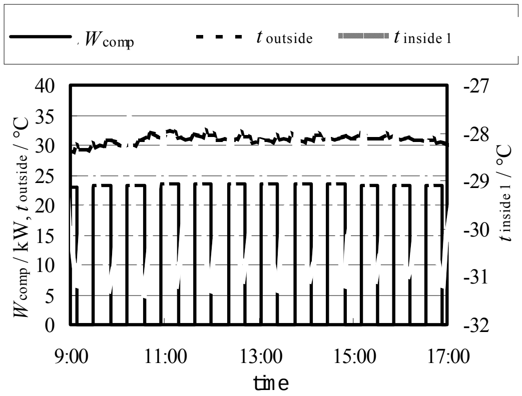


Figure 6: On-off operation with R-32/125/134a/600 (15/39.5/42.5/3 mass%).

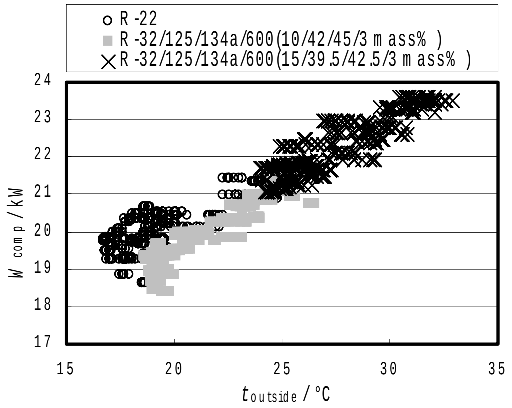


Figure 7: Measured power consumption at different ambient temperature.

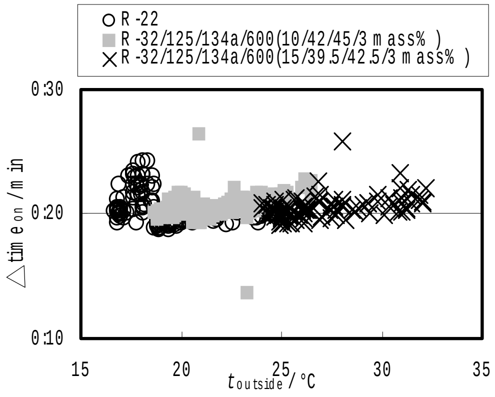


Figure 8: Operating time period in on-off operation at −30 °C.

CYCLE PERFORMANCE FOR AIR-CONDITIONING SYSTEMS

Thermodynamic Calculations

We also calculated theoretical cycle performance of R-32/125/134a/600 and R-22 at conditions of air-conditioning systems by using REFPROP[2]. Temperature conditions are listed in Table 4. We calculated theoretical cycle performances for two different conditions to get one temperature level. One condition is that evaporating and condensing temperatures (t_{eva} or t_{cond}) were defined as an average temperature in the evaporator and condenser, which is adopted in previous section. We called this condition as Case 1. This condition corresponds to a refrigeration cycle with a pure refrigerant. Another condition is called as Lorentz cycle. The input temperature of refrigerant in the evaporator or condenser was defined as t_{eva} or t_{cond}. We called this condition as Case 2.

Table 4. Temperature conditions of test for air-conditioning systems

t_{eva} : Evaporating temperature	-5, 0, 5 °C	t_{cond} : Condensing temperature	45, 50, 55 °C
Δt_{sh} : Superheating temperature difference	8 °C	Δt_{sc}: Subcooling temperature difference	5 °C

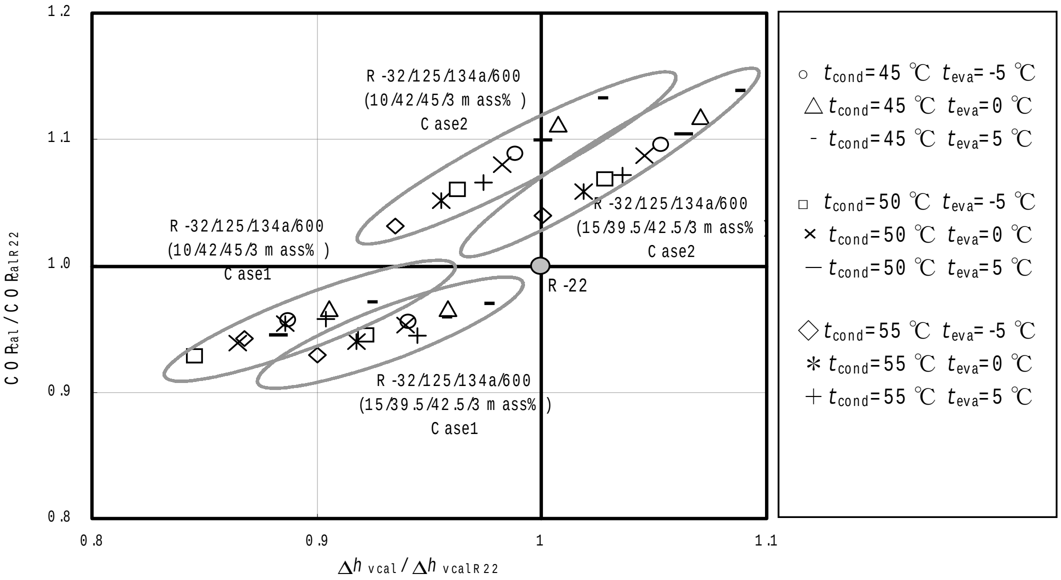


Figure 9: Calculated cooling capacity and COP of R-32/125/134a/600 in comparison with those of R22.

Experimental Apparatus

Figure 10 shows the layout of experimental apparatus for testing refrigeration cycle at conditions of air-conditioning system. This apparatus consists of evaporator, condenser, expansion valve, and compressor. Superheater is installed at the compressor inlet, and subcooler is installed at the inlet of expansion valve. Nominal cooling capacity of compressor is 0.55 kW. Counter-flow type heat exchangers are prepared as evaporator and condenser. Secondary working fluid is brine for the evaporator and water for the condenser.

Seven parameters (two pressures of refrigerant at compressor inlet and outlet, three temperatures of refrigerant at inlet of expansion valve, evaporator, and compressor, as well as two temperatures of brine and water at the inlet of evaporator and condenser) were accurately controlled in this apparatus.

Power consumption, W_{exp}, is calculated by using equation (1).

$$W_{\mathrm{exp}} = \dot{m}_{\mathrm{R}} \Delta h_{\mathrm{ad}} / \eta_{\mathrm{ad}} \tag{1}$$

where W_{exp}: Power consumption of compressor; $\dot{m}_{\mathrm{R}}$: Mass flow rate of refrigerant; Δh_{ad}: Theoretical work of adiabatic compression; and η_{ad}: Compressor efficiency of adiabatic compression. η_{ad} can be known by equation (2) as well as W_{exp} is measured by an electric power meter.

$$\eta_{ad} = \frac{\dot{m}_{\mathrm{R}} \Delta \eta_{\mathrm{ad}}}{W_{\mathrm{exp}}} \tag{2}$$

On the other hand, mass flow rate is expressed by equation (3).

$$\dot{m}_{\mathrm{R}} = \eta_v \rho_v \dot{V} \tag{3}$$

where η_v: Volumetric compressor efficiency; ρ_v: Density at compressor inlet; and $\dot{V}$: Compressor discharge volume. The volumetric compressor efficiency is

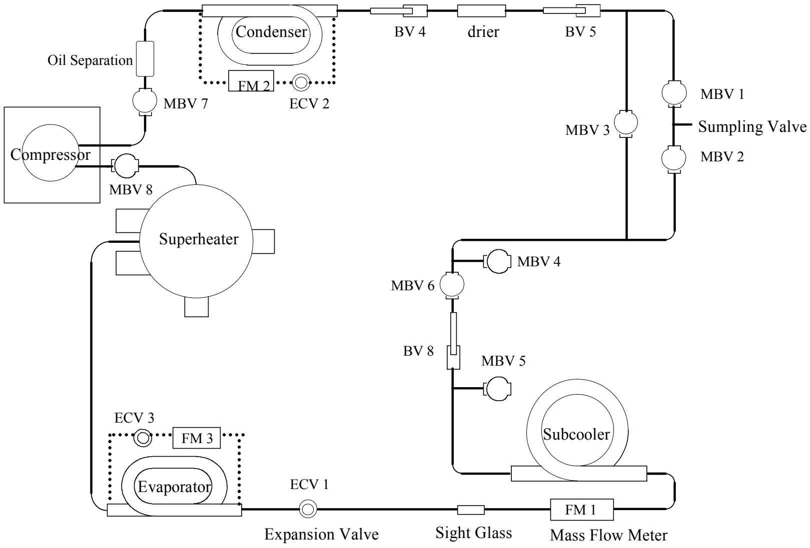
$$\eta_v = \frac{\dot{m}_{\mathrm{R}}}{\rho_v \dot{V}} \tag{4}$$

Experimental cooling capacity, Q_{exp}, and experimental cycle performance, $\mathrm{COP}_{\mathrm{exp}}$, are calculated as follows.

$$Q_{\mathrm{exp}} = \dot{m}_{\mathrm{bra}} C_{\mathrm{bra}} \Delta t_{\mathrm{bra}} \tag{5}$$

where $\dot{m}_{\mathrm{bra}}$: mass flow rate of brine at evaporator; C_{bra} : heat capacity of brine; and Δt_{bra} : temperature difference of brine between inlet and outlet of evaporator.

$$\mathrm{COP}_{\mathrm{exp}} = \frac{Q_{\mathrm{exp}}}{W_{\mathrm{exp}}} \tag{6}$$



BV: Ball Valve
ECV: Electric Controlled Valve
FM: Flow Meter
MBV: Electric Ball Valve

Figure. 10: Layout of experimental apparatus.

Test Results

Tables 5 to 7 show evaporating pressure p_1 , condensing pressure p_2, and discharge temperature t_2 at compressor for R-22 and R-32/125/134a/600. Pressure conditions of R-32/125/134a/600 are almost equal to that of R-22 and discharge temperature of R-32/125/134a/600 is lower than that of R-22. Table 8 shows efficiency of adiabatic compression. The efficiency of adiabatic compression for R-32/125/134a/600 is also similar to that of R-22 while there are several results being a little lower than R-22 in Case 1 due to a slightly larger compression ratio. Figure 11 shows measured cooling capacity ratio and the COP ratio to those of R-22. In Case 1, cooling capacity of R-32/125/134a/600 (10/42/45/3 mass%) is smaller than that of R-22 by 2 - 9% and the COP is smaller than that of R-22 by 4 - 9 %. The cooling capacity of R-32/125/134a/600 (15/39.5/42.5/3 mass%) is smaller than that of R-22 by 6 - 0 %, and the COP by 9 – 4 %. In Case 2, both cooling capacity and COP of R-32/125/134a/600 (10/42/45/3, 15/39.5/42.5/3 mass%) are greater than those of R-22 at almost all conditions. By experimental results in Case 1, it is shown that R-32/125/134a/600 can be used as a drop-in refrigerant in air-conditioning systems. If R-32/125/134a/600 is used in evaporator and condenser having counter-flow heat exchanger, energy consumption can be saved than that of R-22.

Table 5. Pressure and temperature conditions for testing performance of R-22

t_{cond} [°C]	t_{eva} [°C]	p_1 [kPa]	p_2 [kPa]	t_2 [°C]
45	-5	419	1740	73.7
	0	494	1738	71.7
	5	580	1740	69.3
50	-5	419	1945	78.7
	0	498	1946	76.6
	5	584	1949	73.0
55	-5	419	2180	84.8
	0	492	2192	80.0
	5	582	2191	81.8

Table 6. Pressure and temperature conditions for testing performance of R-32/125/134/600 (10/42/45/3 mass%)

		Case 1			Case 2		
t_{cond} [°C]	t_{eva} [°C]	p_1 [kPa]	p_2 [kPa]	t_2 [°C]	p_1 [kPa]	p_2 [kPa]	t_2 [°C]
45	-5	403	1849	67.7	440	1723	63.6
	0	481	1850	66.3	521	1724	62.0
	5	563	1830	64.3	614	1723	59.9
50	-5	400	2063	72.7	435	1922	68.1
	0	477	2065	71.41	519	1934	67.3
	5	562	2064	66.9	607	1934	64.3
55	-5	404	2252	76.7	430	2126	71.9
	0	475	2264	75.3	510	2147	71.2
	5	568	2250	75.0	602	2147	69.7

Table 7. Pressure and temperature conditions for testing performance of R-32/125/134a/600 (15/39.5/42.5/3 mass%)

		Case 1			Case 2		
t_{cond} [°C]	t_{eva} [°C]	p_1 [kPa]	p_2 [kPa]	t_2 [°C]	p_1 [kPa]	p_2 [kPa]	t_2 [°C]
45	-5	422	1911	72.3	458	1797	67.9
	0	503	1909	69.3	542	1795	66.2
	5	593	1895	67.3	638	1790	64.1
50	-5	419	2117	76.8	454	2019	73.9
	0	501	2130	74.8	537	2027	71.6
	5	592	2121	73.1	634	2010	69.3
55	-5	417	2368	81.0	449	2259	79.7
	0	498	2370	81.8	534	2169	77.2
	5	589	2376	74.4	628	2256	74.4

Table 8. Experimental results on efficiency of adiabatic compression

t_{eva}	t_{cond}	R-22	R-32/125/134a/600 (10/42/45/3 mass%)		R-32/125/134a/600 (15/39.5/42.5/3 mass%)	
℃	℃		Case1	Case2	Case1	Case2
45	-5	0.57	0.53	0.57	0.56	0.57
	0	0.60	0.56	0.59	0.58	0.59
	5	0.62	0.58	0.61	0.60	0.60
50	-5	0.57	0.53	0.57	0.55	0.57
	0	0.60	0.55	0.59	0.58	0.59
	5	0.62	0.57	0.61	0.60	0.61
55	-5	0.55	0.52	0.56	0.54	0.56
	0	0.58	0.56	0.59	0.56	0.58
	5	0.60	0.57	0.61	0.59	0.61

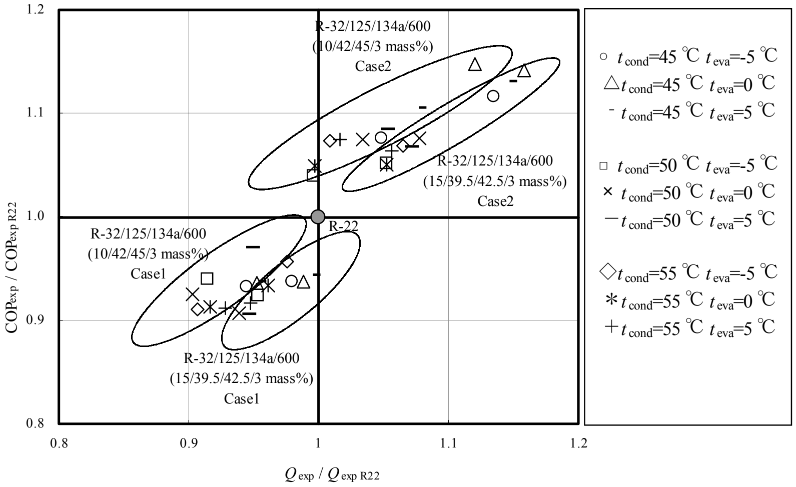


Figure 11: Measured cooling capacity and COP of R-32/125/134a/600 in comparison with those of R-22.

CONCLUSIONS

We propose R-32/134a/125/600 (10/42/45/3 or 15/39.5/42.5/3 mass%) as a drop-in refrigerant to low-temperature refrigeration systems such as refrigerated warehouse and air-conditioning systems designed for R-22.

The following results are obtained in the case for refrigeration systems of refrigerated warehouses.

- There is no problem to use R-32/125/134a/600 as a drop-in refrigerant regarding not only pressure and temperature conditions of the system designed for R-22 but also discharge temperature and using mineral lubricant oil.
- Although difference of cooling capacity between R-32/125/134a/600 (10/42/45/3 or 15/39.5/42.5/3 mass%) and R-22 was calculated as being –12 or –6 %, respectively, and the COP of R-32/125/134a/600 was similar to that of R-22, refrigeration cycle performance of R-32/125/134a/600 was experimentally confirmed as being very similar to that of R-22 from actual operation of 30.2 kW cooling capacity refrigerating system having two-stage compressor installed at 858 m^3 refrigerated warehouse.

The following results are obtained in the case for air-conditioning systems.

- It was theoretically and experimentally confirmed that pressure conditions of R-32/125/134a/600 are quite similar to that of R-22 and the cycle performance was a little inferior to that of R-22 by 9-0 %.
- It was suggested if R-32/125/134a/600 is used in counter-flow type heat-exchangers, the cycle performance can be better than that of R-22.

As a conclusion, R-32/125/134a/600 would be one of the most appropriate drop-in refrigerants for replacing R-22 in refrigerated warehouse or air-conditioning systems.

ACKNOWLEDGEMENTS

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