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Evaluation of Cycle Performance of Room Air Conditioner Using HFO1234yf as Refrigerant

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ABSTRACT

A new refrigerant, HFO1234yf, with a very low global warming potential has been proposed. We have done an improvement test, in which we modified a room air conditioner that had been using R410A to meet the properties of HFO1234yf and evaluated the cycle performance. The main modifications were doubling the number of paths of heat exchangers, triplicating the inner-diameter cross-sectional area of a gas-side connecting pipe, and installing an oil separator. The ratios of HFO1234yf/R410A COP are 97/88% at the rated/medium cooling capacity and 93/98% at the rated/medium heating capacity. Therefore, the ratio of the annual performance factor is 95%. The decrease in the COP ratio at the medium cooling capacity is because of the refrigerant accumulation in some paths under the large number of paths of the outdoor heat exchanger. The increase in the diameter of the gas-side connecting pipe involves challenges such as increasing the workload of the installation.

1. INTRODUCTION

Since hydrofluorocarbons (HFCs), which have been used as refrigerants, have high global warming potentials (GWPs), they were designated as emission control substances under the Kyoto Protocol in 1997. Moreover, in the EU the F-gas regulation was issued, and this will ban the use of refrigerants with GWPs of more than 150 for new mobile air conditioners from 2011 and for all mobile air conditioners from 2017. Therefore, R134a, which is now used for mobile air conditioners, with a GWP of 1430 will be regulated. Under these circumstances, HFO1234yf has been proposed as a substitute for R134a and mobile air conditioners using HFO1234yf are being developed. This is because HFO1234yf has a very low GWP of 4, as well as being low-toxic, low-flammable, and similar to R134a in thermodynamic properties. On the other hand, R410A, which is now used for room air conditioners, has a high GWP of 2088. Although HFO1234yf is greatly different to R410A in its thermodynamic properties, this can decrease the warming effect of the emission into the atmosphere.

Therefore, we have evaluated the performance of room air conditioners using HFO1234yf. We show the cycle performance results of an improvement test, in which a room air conditioner was modified to meet the refrigerant properties, as well as the results of a drop-in test, in which only R410A was replaced with HFO1234yf (Endoh and Matsushima, 2009).

2. THEORETICAL CYCLE PERFORMANCE

Helmholz energy equations of state presented by Akasaka *et al*. (2010) were used to estimate the thermodynamic properties needed to evaluate the performance of refrigeration cycles using HFO1234yf.

2.1 Comparison of Theoretical Cycle Performance

Table 1 shows the HFO1234yf theoretical cycle performance, compared with R410A. Cooling and heating conditions are set for a room air conditioner using R410A at the rated cooling capacity of 4 kW and the rated heating capacity of 5 kW.

The ratios of HFO1234yf operating pressures to R410A are about 40% and this shows that HFO1234yf is a low-pressure refrigerant. The discharge temperatures of HFO1234yf are about 18 °C lower than that of R410A. The ratios of HFO1234yf capacities per unit mass to R410A are about 70% and the ratios of HFO1234yf compressor suction specific volumes to R410A are about 170%. As a result, the ratios of HFO1234yf capacities per unit suction volume to 410A are about 40%; that is, a compressor suction volume of HFO1234yf needs about 2.3 times that of R410A to get the same capacity. The ratios of HFO1234yf capacities per unit mass to R410A are more than 70% and the ratios of HFO1234yf adiabatic compression work to R410A are 70% and less than 70%. As a result, the ratios of HFO1234yf COP to R410A are about 105%.

Table 1: HFO1234yf theoretical cycle performance; ratios and difference are relative to R410A

		Cooling	Heating
Conditions			
Condensing temperature	**(°C)**	**45**	**38**
Evaporating temperature	**(°C)**	**10**	**1**
Subcooled temperature	**(°C)**	**5**	**15**
Superheated temperature	**(°C)**	**5**	**3**
Characteristics			
Condensing pressure ratio	**(%)**	**42**	**42**
Evaporating pressure ratio	**(%)**	**40**	**40**
Discharge temperature difference	**(°C)**	**-17**	**-18**
Capacity per unit mass ratio	**(%)**	**73**	**72**
Suction specific volume ratio	**(%)**	**170**	**171**
Capacity per unit suction volume ratio	**(%)**	**43**	**42**
Adiabatic compression work ratio	**(%)**	**70**	**69**
COP ratio	**(%)**	**105**	**104**

2.2 Comparison of Theoretical Pressure Loss

The comparison of the theoretical cycle performance shows that the increase in pressure loss of HFO1234yf is expected. The specific volume of HFO1234yf is larger than that of R410A and the capacity per unit mass of HFO1234yf is smaller than that of R410A and then the mass-flow rate of HFO1234yf is larger than that of R410A. As a result, the flow velocity of HFO1234yf in a pipe becomes larger than that of R410A. Theoretical pressure losses of HFO1234yf are shown in Table 2, compared with those of R410A. The basic conditions are set for a gas-side connecting pipe for R410A at the pipe outer diameter of 9.52 mm.

At the position of compressor suction and at the rated cooling capacity, for the same pipe diameter of 9.52 mm, the flow velocity of HFO1234yf is 2.3 times that of R410A and then the pressure loss of HFO1234yf is calculated with the Nikuradse equation as 3 times that of R410A. When comparing equivalent temperatures of pressure loss, in which pressures are converted into corresponding saturated temperatures, the equivalent temperature of HFO1234yf is about 7 times that of R410A. Using the equivalent temperature can compare the pressure loss effects of different refrigerants on the cycle performances with the same index. However, since the viscosity of HFO1234yf is unknown, a correlation equation for R134a was used. On the other hand, at the position of compressor discharge and at the rated heating capacity, the equivalent temperature of HFO1234yf is 5.4 times that of R410A. Therefore, these calculations show that the pressure loss effect of HFO1234yf on the cycle performance is greatly larger than that of R410A.

Using a pipe with outer diameters of 12.7 mm (1/2 in.) and 15.88 mm (5/8 in.) enlarges the inner-diameter cross-sectional areas 2 and 3 times, respectively. At this time, at the position of compressor suction and at the rated cooling capacity, the equivalent temperatures of pressure loss of HFO1234yf are 1.3 and 0.5 times that of R410A, respectively. Moreover, at the position of compressor discharge and at the rated heating capacity, the equivalent temperatures of HFO1234yf are 1.1 and 0.4 times that of R410A, respectively.

Table 2: HFO1234yf theoretical pressure loss; ratios are relative to R410A at pipe outer diameter of 9.52mm

		Cooling			Heating		
Conditions							
Position		Suction			Discharge		
Pipe outer diameter	(mm)	9.52	12.70	15.88	9.52	12.70	15.88
Inner-diameter cross-sectional area ratio	(%)	100	196	307	100	196	307
Characteristics							
Specific volume ratio	(%)	170			147		
Viscosity ratio	(%)	95			88		
Refrigerant mass-flow rate ratio	(%)	137			140		
Flow velocity ratio	(%)	233	119	76	205	104	67
Pressure loss ratio	(%)	296	57	20	262	51	20
Pressure loss equivalent temperature ratio	(%)	694	134	47	540	106	41

3. TEST EQUIPMENT AND METHOD

Room air conditioners for the test are ones now using R410A with the rated cooling capacity of 4 kW. Figure 1 shows test equipment and Table 3 shows its specifications. In the drop-in test the same equipment was used to evaluate the performances of R410A and HFO1234yf.

To increase the compressor suction volume and decrease the pressure loss, equipment for the improvement test was modified as follows.

● Compressor displacement was increased by 1.9 times and an oil separator was installed.

● The number of paths of an indoor heat exchanger was doubled and the number of gas-side pipes was changed from one to two.

● The number of paths of an outdoor heat exchanger was doubled and diameters of pipes in the outdoor unit were enlarged by 3.18mm (1/8 in.).

● Diameter of gas-side connecting pipe was changed from 9.52 to 15.88 mm: the inner-diameter cross-sectional area of the pipe was increased by 3 times.

Purity of HFO1234yf used for the test was 99.85 mol%. An ester oil was used as a refrigeration oil.

The test conditions are shown in Table 4. Air temperature conditions are ones of JIS B 8615-1. Indoor and outdoor fan rotational speeds were set at constant values regardless of capacities. The expansion valve was set so that superheated temperature at the evaporator outlet was 1 °C in the cooling operation and superheated temperature at the compressor suction was 3 °C in the heating operation. Compressor rotational speeds were adjusted to get the prescribed capacities. The amounts of R410A to be charged were adjusted to get the maximums of COP (capacity/total power consumption) of the rated capacities in cooling and heating operations respectively. On the other hand, the amounts of HFO1234yf to be charged were adjusted to get the same subcooled temperatures at a condenser outlet at the rated capacities as R410A and to compare the performance under the same subcooled temperature conditions.

Capacities were measured with air enthalpy measuring equipment. Power consumptions at each part were measured with power meters to calculate COP, compressor efficiency (product of total adiabatic efficiency and motor efficiency) and inverter efficiency. Mass flow rates for calculation of the compressor efficiency were measured with a mass flowmeter installed in front of the expansion valve. States at each part of the refrigeration cycle were measured with strain gauge pressure transducers and thermocouples. Moreover, oil circulation rates were measured with the weight method.

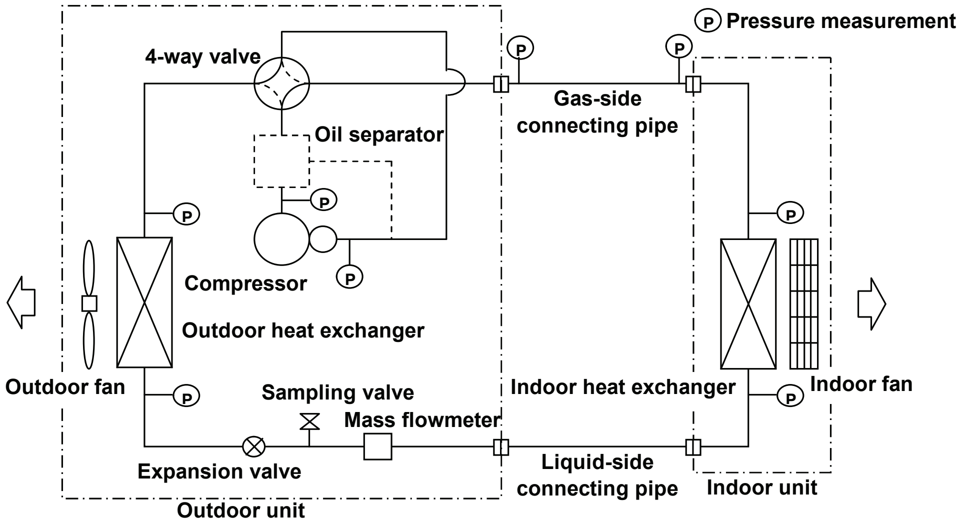

Figure 1: Test equipment

Table 3: Specifications

Test				Drop-in	Improvement
Refrigerant				R410A, HFO1234yf	HFO1234yf
Rated cooling/heating capacity			(kW)	4/5	
Indoor unit	Heat exchanger	Pipe diameter	(mm)	7	
		Rows/columns		2/19＋1/14	
		Paths		2-1	4-2
		Gas-side pipe diameter (mm) x number		9.52 x 1	9.52 x 2
Outdoor unit	Compressor	Type		Inverter-driven scroll	
		Displacement	(cm^3/rev)	14	26
		Refrigeration oil		Ester oil	
	Oil separator			without	with
	Heat exchanger	Pipe diameter	(mm)	8	
		Rows/columns		2/22	
		Paths		4-2	8-6
	Low/high-pressure side pipe diameter		(mm)	12.7/9.52	15.88/12.7
	Depression device			Electric expansion valve	
Connecting pipe	Gas/liquid-side pipe diameter		(mm)	9.52/6.35	15.88/9.52
	Length		(m)	5	

Table 4: Test conditions

			Cooling	Heating
Indoor air temperature	Dry bulb	(°C)	27	20
	Wet bulb	(°C)	19	15
Outdoor air temperature	Dry bulb	(°C)	35	7
	Wet bulb	(°C)	24	6
Indoor fan rotational speed			Constant value	Constant value
Outdoor fan rotational speed			Constant value	Constant value
Superheated temperature at evaporator outlet		(°C)	1	-
Superheated temperature at compressor suction		(°C)	-	3

4. TEST RESULTS AND CONSIDERATIONS

4.1 Cycle Performance Characteristics

Cycle performance characteristics in the heating operation are shown in Figure 2. Values of HFO1234yf are represented as the ratios to those of R410A at the same capacities. In the figure designations, "DI" and "IM" specify the results of the drop-in test and the improvement test respectively. Here, COPs are converted values under the assumption that the compressor efficiencies and inverter efficiencies of HFO1234yf are the same as those of R410A and then show the cycle performance without the effect of compressor and inverter performances depending on refrigerants.

The compressor suction volume of HFO1234yf is about 2.4 times that of R410A regardless of capacities in the drop-in test and the improvement test. This value is almost the same as the ratio estimated from the theoretical cycle performance. The ratio of HFO1234yf COP to R410A in the drop-in test decreases with increasing capacity: the COP ratios are 97% at the medium capacity and 87% at the rated capacity. In the improvement test, the COP ratios are 98% at the medium capacity and 93% at the rated capacity; that is, the improvement becomes larger with increasing capacity. In the drop-in test as the capacity increases, the ratio of HFO1234yf discharge pressure to R410A increases and the ratio of suction pressure decreases as a result of the increase in the pressure loss. This is the cause of the decreasing COP ratio with increasing capacity as described above. In the improvement test, the discharge pressure ratio decreases greatly and the suction pressure ratio increases slightly, compared with those in the drop-in test.

Next, Figure 3 shows cycle performance characteristics in the cooling operation. In the drop-in test the compressor suction volume of HFO1234yf is 2.6 times that of R410A at the medium capacity and although the compressor suction volume ratio is increased, the capacity does not increase significantly. As a result, HFO1234yf can get only 65% of the rated cooling capacity at the maximum rotational speed of the compressor. On the other hand, in the improvement test the compressor suction volumes are 2.4 times at the rated capacity, 2.6 times at the medium capacity, and 2.3 times at the capacity of 4.6 kW. The compressor suction volume ratio is the product of refrigerant mass-flow rate ratio and compressor suction specific volume ratio and then the increase in the compressor suction volume ratio at the medium capacity results from the increase in the refrigerant mass-flow rate ratio. Increasing the number of paths of the outdoor heat exchanger, which functions as a condenser in cooling operation, caused an unequal distribution of refrigerant and refrigerant accumulation in some paths. This led to the shortage of amount of refrigerant circulating in the cycle and the decrease in the difference between enthalpies at evaporator inlet and outlet. As a result, the refrigerant mass-flow rate increased. Furthermore, the decrease in the compressor suction volume ratio at the capacity of 4.6 kW is because of the decrease in the compressor suction specific volume ratio and this is caused by the increase in the suction pressure ratio described below.

The ratio of HFO1234yf COP to R410A in the drop-in test is 85% at the medium capacity. The COP ratio decreases sharply with increasing capacity, and the COP ratio is then 50% at 65% of the rated capacity. However, in the improvement test the COP ratio increases significantly, compared with that in the drop-in test. The COP ratios are 97% at the rated capacity, 88% at the medium capacity, and 102% at the capacity of 4.6 kW. The reason for the decrease in the COP ratio at the medium capacity is that, as described above, the shortage of amount of refrigerant circulating in the cycle because of the refrigerant accumulation led to the decrease in the difference between enthalpies at evaporator inlet and outlet. Therefore, the theoretical COP decreased. The increase in the COP ratio at the capacity of 4.6 kW results from the increase in the suction pressure ratio as described below.

The ratio of HFO1234yf suction pressure to R410A in the drop-in test decreases sharply with increasing capacity because of the increase in the pressure loss of the low-pressure side pipe including the gas-side connecting one. This means that although the compressor suction volume ratio is increased, the capacity does not increase much, as described above. In the improvement test, the suction pressure ratio increases greatly, compared with that in the drop-in test. The suction pressure ratio decreases with increasing capacity to 3.5 kW. Meanwhile, the ratio increases with increasing capacity from 3.5 kW. This is because installing the oil separator in the improvement equipment reduced the oil circulation rate and the decrease in the oil circulation rate had a large effect on the decrease in the pressure loss in the range of a large capacity.

In the improvement test the ratio of HFO1234yf annual performance factor to R410A was calculated to be 95% from the COP ratios described above. The calculating method was based on JIS C 9612.

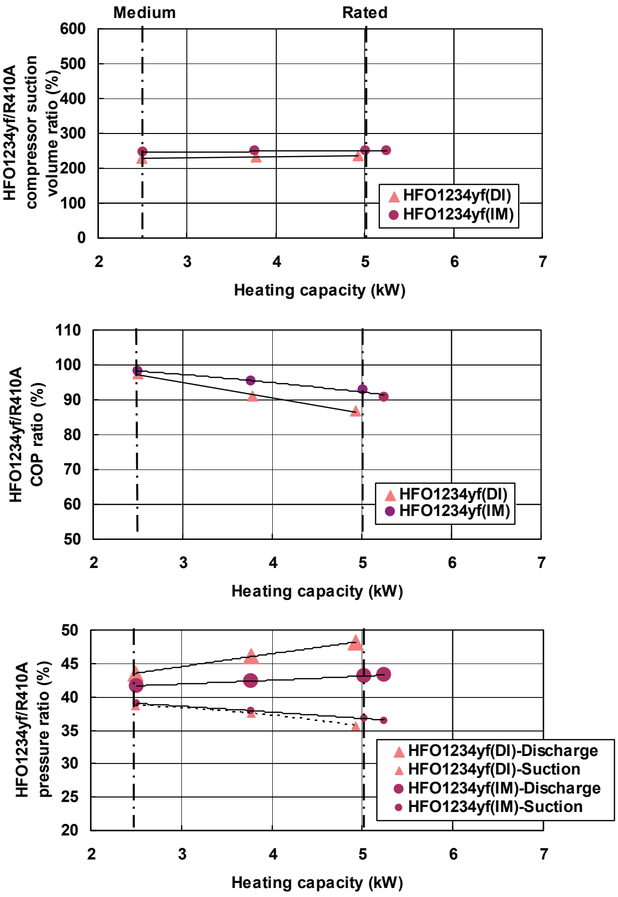

Figure 2: Cycle performance characteristics in heating operation

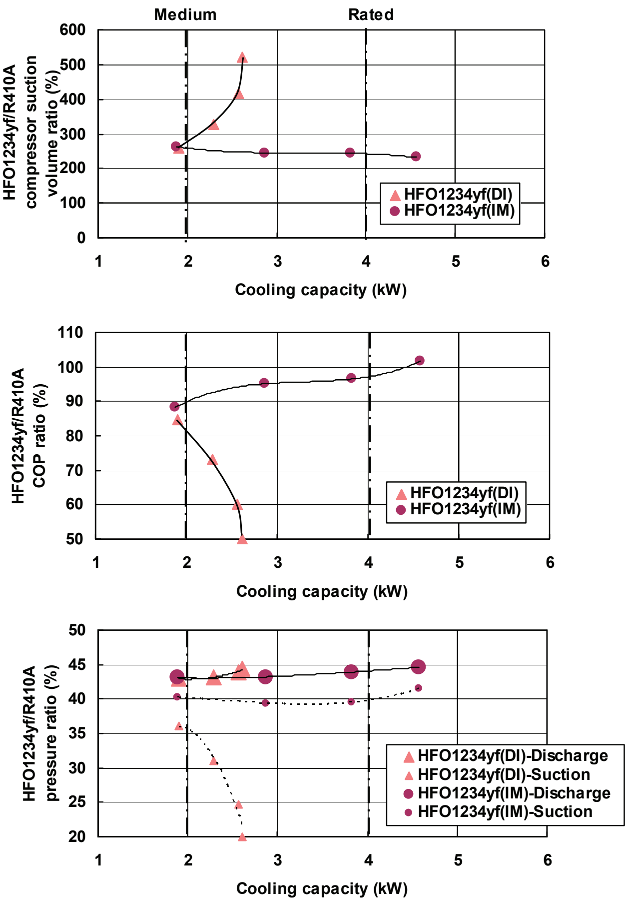

Figure 3: Cycle performance characteristics in cooling operation

4.2 Pressure Loss Characteristics

The pressure loss characteristics of R410A, HFO1234yf drop-in test and HFO1234yf improvement test equipment at the rated heating capacity is shown in Figure 4. The equivalent temperatures explained in sub-section 2.2 are used to compare the pressure losses.

The pressure loss equivalent temperatures of the condenser and the evaporator in the HFO1234yf drop-in test equipment are about 5 times those in the R410A equipment, meanwhile, the equivalent temperature of the part between the compressor outlet and the condenser inlet, which includes the gas-side connecting pipe, is about 9 times. This actual ratio is lager than that of 5.4 estimated in sub-section 2.2. Measuring the oil circulation rates showed that the oil circulation rate of HFO1234yf was larger than that of R410A and this increase caused the increase in the ratio of the equivalent temperature between the compressor outlet and the condenser inlet.

The pressure loss equivalent temperatures of the condenser and the evaporator in the HFO1234yf improvement test equipment are almost the same as those in the R410A equipment. On the other hand, although the pressure loss equivalent temperature of the gas-side connecting pipe in the HFO1234yf improvement test equipment is estimated to be 0.4 times that in the R410A equipment in sub-section 2.2, the actual equivalent temperature of the part between the compressor outlet and the condenser inlet, which includes the gas-side connecting pipe, is 1.3 times. Moreover, the equivalent temperature of the part between the evaporator outlet and the compressor inlet in the HFO1234yf improvement test equipment is much larger than that in the R410A equipment, which is nearly zero. These increases are caused by the increase in length and the number of bends of the pipe caused by the modification of the outdoor unit.

A comparison of the performance of the heat exchangers in the R410A equipment and the HFO1234yf improvement test equipment is shown in Figure 5, in which the differences between the pressure equivalent temperatures of HFO1234yf and R410A at the condenser inlet and the evaporator outlet are seen. Lower temperature at the condenser inlet or higher temperature at the evaporator outlet shows higher performance of the heat exchanger. The temperature of HFO1234yf is higher than that of R410A at the condenser inlet and the temperature of HFO1234yf is lower than that of R410A at the evaporator outlet. These show that the heat exchange performance of HFO1234yf is lower than that of R410A.

Next, Figure 6 shows the pressure loss characteristics and Figure 7 shows the heat exchanger characteristics at the rated cooling capacity. Although the pressure loss equivalent temperature of the condenser and the evaporator in the HFO1234yf improvement test equipment are almost the same as those in the R410A equipment, the heat exchange performance of the HFO1234yf equipment is lower than that of the R410A one, as well as that at the rated heating capacity. The equivalent temperature of the part between the evaporator outlet and the compressor inlet in the HFO1234yf improvement test equipment is 1.5 times that in the R410A equipment, and Figure 8 shows these breakdowns. The connecting pipe had an actual equivalent temperature of 0.4 times, although the equivalent temperature of HFO1234yf was estimated to be 0.5 times that of R410A in sub-section 2.2. This decrease is because of the decrease in the oil circulation rate with the oil separator. The change in the number of pipes used indoors from 1 to 2 results in the decrease in the pressure loss. On the other hand, the outdoor pipe had an equivalent temperature of HFO1234yf that is much larger than that of R410A because of the increase in length and the number of bends of the pipe caused by the modification of the outdoor unit.

Further improving the performance requires equalizing the refrigerant distribution under the large number of paths of the outdoor heat exchanger and decreasing the pressure loss of the outdoor pipe. Furthermore, the equipment used in the test, in which the diameter of the connecting pipe was enlarged, involves challenges such that when the air conditioner is installed, the workload of pipe bending and layout increases.

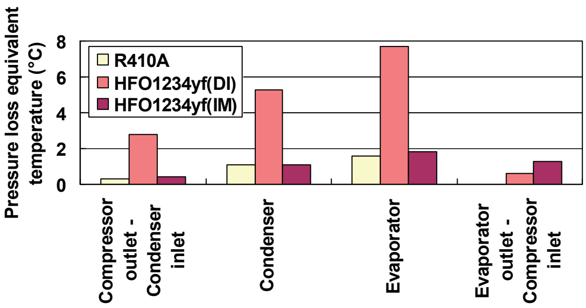

Figure 4: Pressure loss characteristics at rated heating capacity

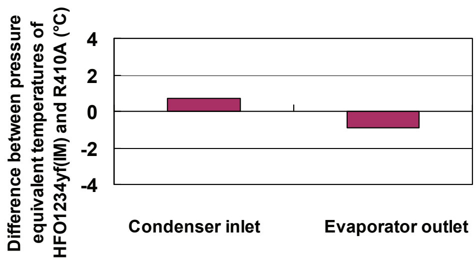

Figure 5: Heat exchanger characteristics at rated heating capacity

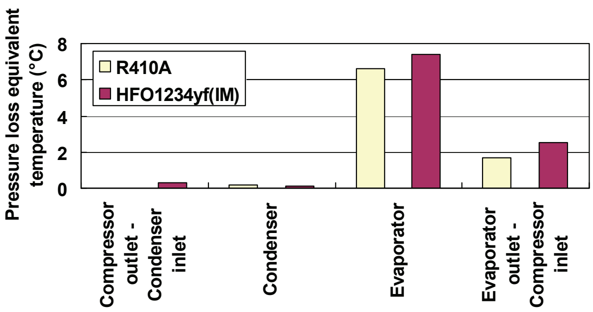

Figure 6: Pressure loss characteristics at rated cooling capacity

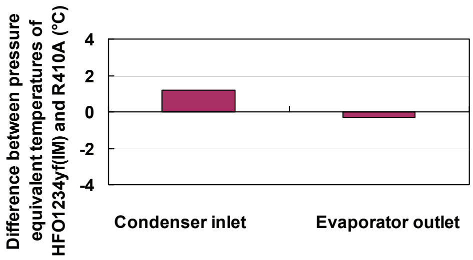

Figure 7: Heat exchanger characteristics at rated cooling capacity

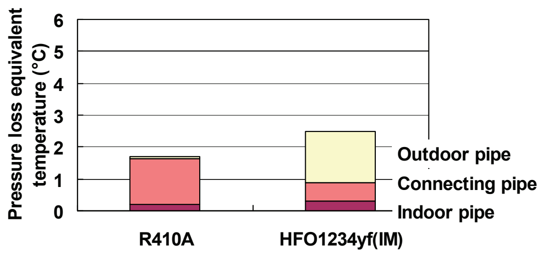

Figure 8: Pressure loss breakdowns between evaporator outlet and compressor inlet

5. CONCLUSION

We have evaluated the performance of room air conditioners using HFO1234yf. To meet the properties of HFO1234yf, we modified a room air conditioner that had been using R410A. The main modifications were doubling the number of paths of the heat exchangers, triplicating the inner-diameter cross-sectional area of the gas-side connecting pipe, and installing the oil separator. The ratios of HFO1234yf/R410A COP are 97/88% at the rated/medium cooling capacity and 93/98% at the rated/medium heating capacity. Therefore, the ratio of the annual performance factor is 95%. The decrease in the COP ratio at the medium cooling capacity is because of the refrigerant accumulation in some paths under the large number of paths of the outdoor heat exchanger. Equalizing the refrigerant distribution of paths is then required. The increase in the diameter of the gas-side connecting pipe involves challenges such as increasing the workload of the installation.

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