An Experimental Investigation of Thermodynamic Performance of R-22 Alternative Blends

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Key Words : R-410a, R-407c, Drop-in test, COP, Capacity, VCR, Azeotropic mixture

Abstract

R-410a and R-407c which have the best potential among R-22 alternatives were tested as drop-in refrigerants against a set of R-22 baseline tests. The performance evaluations were carried out in a psychrometric calorimeter test facility using the residential spilt type air conditioner under the ARI rating conditions. Except the lubricant and hand-operated expansion valve, the other parts of the air conditioner were the same with the commercial system. Performance characteristics were measured; compressor power, capacity, VCR, mass flow rate and COP. The tests showed that R-407c can be directly charged into the current refrigeration system because its vapor pressure and other thermophysical properties are similar to those of R-22. However, it is required to change the volume flow rate of compressor in order to achieve the volumetric capacity of R-22. This results from its relatively small VCR and capacity. Meanwhile, R-410a has vapor pressure values too high to be substituted for the current system and this resulted relatively low COP of R-410a compared to that of R-22.

Nomenclature

C_p : Specific heat capacity at constant pressure(kJ/kg · K)

C_v : Specific heat capacity at constant volume(kJ/kg · K)

COP : Coefficient of performance

H : Relative humidity(%)

Δh : Refrigerating effect(kJ/kg)

$\dot{m}$: Mass flow rate(kg/h)

ΔP : Pressure drop(kPa)

P : Pressure(bar)

Q : Volume flow rate(m^3/s)

$\dot{Q}$: Capacity

T : Temperature(℃)

VCR : Volumetric capacity of refrigerant(kJ/m^3)

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ν : Specific volume of refrigerant(m^3/kg)
W : Requird power(kW)

Superscript
comp : Compressor
cond : Condenser
ev : Evaporator
Subscript
air : Air
bub : Bubble point
dew : Dew point
i : Inlet
o : Outlet
R : Refrigerant
sat : Saturated state

1. Introduction

The developed countries, such as U.S., EC, Japan, have planed to meet the R-22 phase-out schedule.[(1)] Therefore the development of alternative refrigerant and its application technique has been a hot issue. The developed countries are actually carrying out the study for thermodynamic properties, compressor test, and performance of refrigeration system. The universities and the industries are concerned about the design of refrigerating system for alternative refrigerants.

The ozone depletion potential of alternatives must be zero, and the global warming potential must be small. They should not be flammable and toxic, and must have proper material compatibility. Also, suitable oil for alternatives must be developed. They must meet these conditions and the performances of them must not be inferior to those of the current refrigerants. Therefore, we need to estimate the thermodynamic performances of alternative refrigerants and to compare these with those of HCFCs. This is one of the main objectives of the study.

Recently, Kondepudi[(2)], Sanvordenker[(3)], Spatz and Zheng[(4)], and Murphy[(5)] carried out studies of R-22 alternatives. Kondepudi[(2)] tested R-32/R-134a and R-32/R-152a blends in a two-ton split system air conditioner. His tests showed that, compared to R-22, the R-32/R-134a blends deviate within 2% in efficiency at the similar capacity. He proposed that a proper system optimization for the new refrigerant blends is required. Sanvordenker[(3)] tested compressor calorimetry for R-32/R-134a (30%/70%) blend. Compressor calorimetric data showed that the blend is as good as or better than R-22 in efficiency at about -12℃ evaporator temperature. Spatz and Zheng[(4)] tested the performance of R-32/125(60%/40%) mixture and R-32/125/134a(30%/10%/60%) blend in a typical three-ton air-to-air heat pump. The results of their tests showed a significant increase in efficiency(9%) for the R-32/125 azeotrope and a slight decrease(2%) for the ternary blend. Murphy[(5)] tested the performance of air conditioner with R-407c and R-410a. They compared the COP and characteristic of cycle and suggested their potentiality as alternatives. But his results are based not on an old machine but on a new machine with an optimized compressor for R-410a.

This study reports the drop-in tests for R-407c and R-410a which have the best potential among R-22 alternative refrigerants. From this test, the operating characteristic of alternative refrigerant and improvement of design for the system are presented.

2. The Experiment

2.1 The experimental apparatus

Figure 1 shows the schematic of the ex-

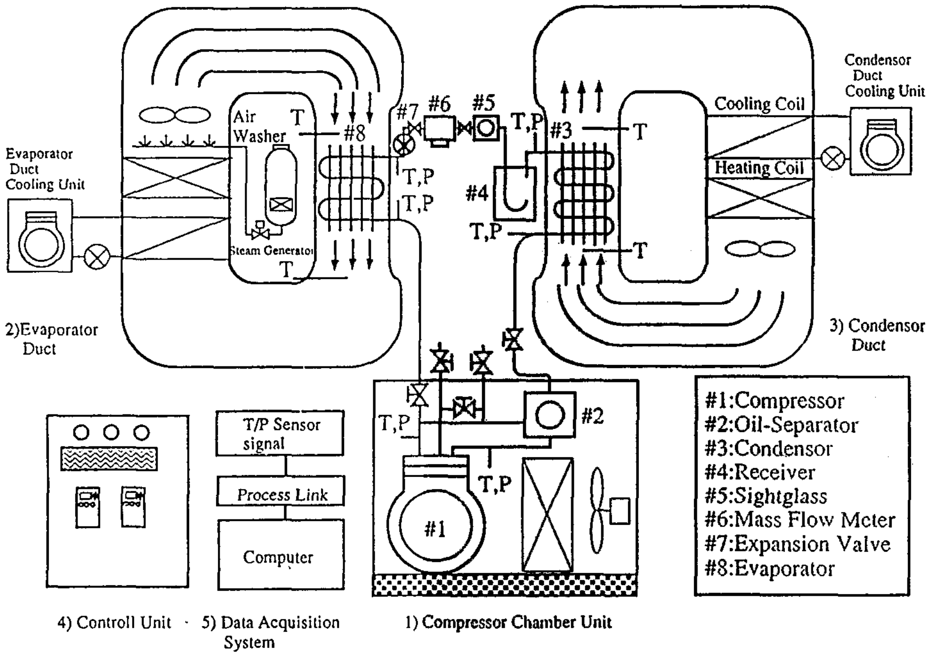


Fig.1 Schematic diagram of the experimental apparatus

perimental apparatus for the drop-in test.

The system consists of 1) compressor chamber, 2) constant temperature and velocity duct for condenser, 3) constant temperature, humidity, and velocity duct for evaporator, 4) control unit, and 5) data acquisition system. The test facility is the commercial split-type air-conditioning system for R-22. But the expansion device is not a capillary tube but a hand-operated expansion valve so that the performance of alternative refrigerant can be compared reasonablely.(2) If the same system is charged with refrigerants which have different volumetric capacities, the capacity, degree of subcooling and superheating of refrigerant, and the temperatures of condenser and evaporator are varied.

Air temperature of the compressor atmosphere can be controlled. The oil separator which is installed at compressor outlet is used to reduce the amount of the oil in the refrigerant flow. If the oil is dissolved a lot in the refrigerant, the properties of refrigerant are varied.(6) The compressor is rotary type for R-22. The duct of condenser side is at a constant temperature and velocity which are under control. A sight glass is installed between condenser outlet and mass flow meter to visualize the state at the inlet to the flow meter. The duct of evaporator side is a constant temperature, humidity, and velocity duct which control humidity as well as temperature and flow rate of air.

To measure mass flow rate, a mass flow meter(D012S-SS-200) is used. RTD and T-type thermocouples are used for temperature measurements of air and refrigerant, respectively. The pressure is measured using the pressure transducer. The temperature and pressure signals are transferred to PC through Data Acquisition System(DAS) by RS-232C communication.

2.2 Experimental conditions

The air conditions for the test are in Table 1 and Table 2. Table 1 is 'ARI Test A' condition.(3)

R-22 is a base refrigerant and R-407c and R-410a are selected for the drop-in test. The thermodynamic properties of refrigerants are calculated using REFPROP V4.01 program.(7)

Naphthenic mineral oil [54.6cSt, 40℃] currently used with R-22 are not compatible with R-134a, R-407c, and R-410a in compressors because of their poor solubility. Ester oil [65.6cSt, 40℃] is compatible with R-407c and R-410a.

An azeotropic refrigerant R-410a doesn't have temperature gradient during the phase change. But a non-azeotropic refrigerant R-407c has about 4~5℃ temperature gradient during the phase change. Therefore, this temperature glide of R-407c might increase the effectiveness of heat exchanger. In order to take this advantage, the heat exchanger should be counter flow type. But it is not easy to modify the current HX to counter flow type.

Table 1 Indoor and outdoor air conditions [ARI test A condition]

	Pressure (kPa)	Temperature (℃)	Relative Humidity(%)
Indoor Air	101.325	27.0	50
Outdoor Air	101.325	35.0	40

Table 2 Compressor calorimeter testing conditions[ARI standard 520-90, ASHRAE Standard 23-78]

Evaporator Temperature Range(℃)	Condenser Temperature (℃)	Ambient Temperature (℃)	Suction Superheat (℃)	Liquid Subcooling (℃)
-12 to 13	27 to 66	35	11	8.3

In this experiment, the commercial HX was used.

The condensing temperature of R-407c is defined as the average temperature of dew point and bubble point temperatures. And the evaporating temperature is defined as the average temperature of inlet temperature and dew point temperature corresponding to the pressure of evaporator. The base lines of degree of subcooling and superheating are bubble point and dew point temperature, respectively. These assumptions are the same as AREA protocol.(3)

Refrigerant is charged with superheating in the refrigeration system as high as 8.3℃. The charged amounts are given in Table 3. The superheating is to guarantee the best efficiency under ARI Test A condition. The performance of system is also varied with the charging amount of refrigerant. Therefore, the degree of superheating during the charge is kept constant, so that reasonable comparisons can be made for different refrigerants. According to Murphy(5), the charging amount of refrigerant has a small effect on COP for R-22 and R-407c. However, COP increases until the optimum charge point and decreases after the point for R-410a.

2.3 The experimental procedure

The experimental procedure is as follows.

1) The refrigeration system is cleaned using nitrogen gas and cleaner. And the system is

Table 3 Refrigerant charged

Refrigerant	Ratio (% Mass)	Charged Amount (kg)	Mass Flow Rate(kg/h)
R-22	-	1.70	61.5
R-32/R-125	50/50	1.81	77.5
R-32/R-125/R-134a	23/25/52	1.40	53.9

evacuated enough to remove any moisture and air.

2) The surrounding temperature at condenser and compressor side and the surrounding temperature and relative humidity at evaporator side is maintained at the standard condition. The refrigerant is charged at this condition. The amount of superheating is as much as 8.3℃.

3) The system is run a few hours until it is at steady state.

4) Temperature and pressure at main points and power consumption are recorded with the data acquisition system.

5) After the first experiment is finished, experiments are repeated over the condensing temperature range 40.8~49.2℃. Meanwhile, the airflow rate at evaporator side is fixed.

6) After the experiment is completed with a refrigerant, the refrigerant is replaced and the above procedures (1)~(5) are repeated. When ever the refrigerant is replaced, the system must be evacuated and cleaned.

The velocity of air is previously measured using five hole pitot tube and Hot Wire Anemometry.

Based on the above experimental results, the performance for each refrigerant is estimated as follows. Compressor power is measured using precision digital powermeter(Yokogawa 2535).

$$COP=\frac{\Delta h\times \dot{m}_R}{W^{comp}} \quad \dot{Q}(kW)=\Delta h\times \dot{m} \quad (1)$$

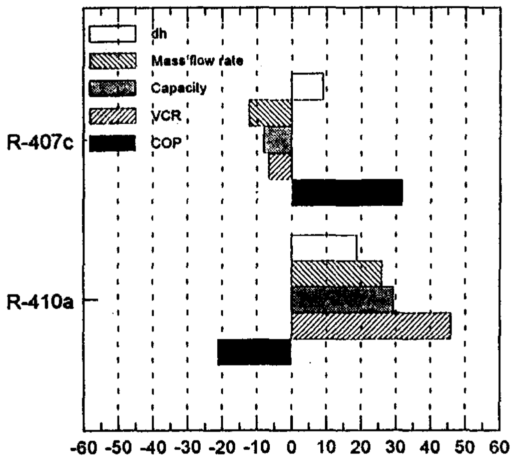
$$VCR(kJ/m^3)=\frac{\Delta h}{V_i^{comp}} \quad (2)$$

3. Results and discussion

For the comparison of performance of R-407c and R-410a, mass flow rate, compressor power, and temperature and pressure at compressor inlet and outlet are measured and COP, cooling capacity, and VCR are calculated. Pressure drop is compared at condenser and evaporator. The experimental results are given in Table 4.

Figure 2 shows COP, VCR, cooling capacity, mass flow rate, and refrigerating effect. COP of R-407c is about 21.5% higher than that of R-22. But COP of R-410a is lower about 21.4% than that of R-22. The reason is that the compressor power of R-407c is smaller than that of R-22.

On the other hand, the refrigerating effect of R-410a is better than that of R-22 while compressor power consumption is larger. To the contrary of COP, VCR of R-410a is better than that of R-407c. VCR of R-410a is about 45.9% larger than that of R-22. But VCR of R-407c is about 6.7% smaller than that of R-22. The refrigerating effect and the specific volume of R-410a is better and smaller than



$T_{air}^{cond}=35℃$, $Q_{air}^{cond}=0.7418m^3/s$, $T_{air}^{ev}=27℃$, $Q_{air}^{ev}=0.0683m^3/s$

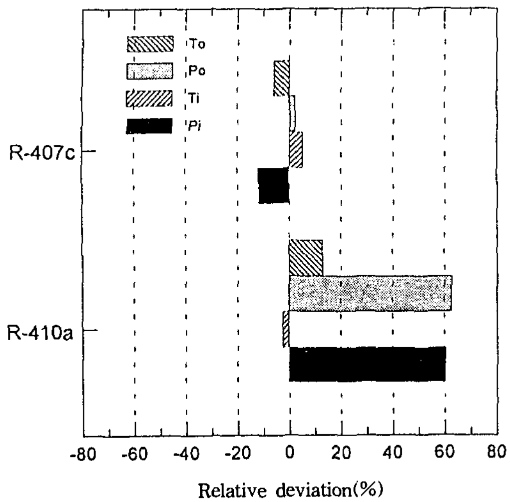
Fig.2 Relative comparison of COP, VCR, capacity, mass flow rate and evaporation enthalpy at 500kPa of R-407c and R-410a with R-22

Table 4 Summary of test results

Results \ Air Volume Flowrate (m^3/s)		Evaporator 0.0683		Condenser 0.74178
		R-22	R-407c	R-410a
COP		2.48	3.27	1.95
Capacity(kW)		2.7128	2.4929	3.5090
Mass flow rate(kg/h)		61.5	53.9	77.5
VCR(kJ/m^3)		2,548.9567	2,377.5525	3,718.9140
Compressor Power(kW)		1.0960	0.7620	1.8000
Compressor Inlet	P (kPa)	460.35	404.70	739.40
	T (℃)	35.3	37.1	34.4
Compressor Outlet	P (kPa)	1,755.83	1,794.10	2,858.99
	T (℃)	79.9	75.0	90.2
Evaporator Inlet	P (kPa)	602.09	544.40	940.2
	T (℃)	0.3	1.8	-1.1
Evaporator Outlet	P (kPa)	488.84	430.80	769.83
	T (℃)	9.0	9.2	6.6
Condenser Inlet	P (kPa)	1,705.72	1,794.10	2,831.84
	T (℃)	77.1	74.8	90.1
Condenser Outlet	P (kPa)	1,632.78	1,748.10	2,776.84
	T (℃)	41.3	37.7	42.9
Evaporator Temperature(℃)		2.9	-0.9	1.7
Condenser Temperature(℃)		43.7	43.1	46.5
Subcooling Temperature(℃)		1.1	2.4	3.1
Superheating Temperature(℃)		9.4	11.1	7.6

those of R-22, respectively. But for R-407c, although the refrigerating effect is larger than that of R-22, the specific volume is larger.

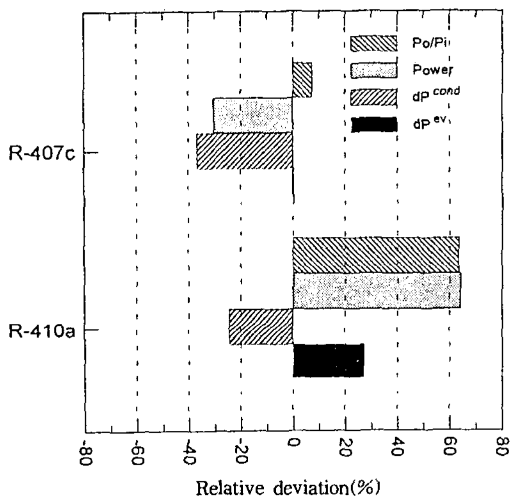
The cooling capacity of R-410a is better than that of R-407c. The cooling capacity of R-410a is 29.3% higher than that of R-22. But the cooling capacity of R-407c is about 8.1% lower than that of R-22. It is because the refrigeration effect and the mass flow rate of R-410a is better and more than those of R-22, respectively. The refrigerating effects (P_{ev}=500kPa) of R-410a and R-407c are larger than that of R-22 by 18.8% and 8.8%, respectively. Although the refrigeration effect of R-407c is better than that of R-22, the cooling capacity is lower due to the small mass flow rate. The mass flow rate of each refrigerant has a trend similar to VCR. As VCR increases, the mass flow rate increases too. The mass flow rate of R-410a is more than that of R-407c, and is about 26.0% more than that of R-22. But the mass flow rate of R-407c is 12.4% less than that of R-22. It is because the specific volume of R-410a is smaller than that of R-22. The mass flow rate of each refrigerant is roughly propotional



$T_{air}^{cond}=35℃$, $Q_{air}^{cond}=0.7418m^3/s$,

$T_{air}^{ev}=27℃$, $Q_{air}^{ev}=0.0683m^3/s$

Fig.3 Relative comparison of temperature and pressure of R-407c and R- 410a at compressor inlet and outlet with R-22



$T_{air}^{cond}=35℃$, $Q_{air}^{cond}=0.7418m^3/s$,

$T_{air}^{ev}=27℃$, $Q_{air}^{ev}=0.0683m^3/s$

Fig.4 Relative comparison of pressure ratio, compressor power consumption, and pressor drop at evaporator and con-dener of R-407c and R-410a with R-22

to the charged amount of refrigerant.

Figure 3 compares pressure and temperature at the inlet and outlet of the compressor. The inlet pressure of R-407c is similar to that of R-22, but the inlet pressure of R-410a is about 60.2% higher than that of R-22. The reason is that the vapor pressure of R-410a is higher than that of R-22. The inlet temperature is similar for all refrigerants. The outlet pressure of R-407c is similar to that of R-22, but for R-410a the outlet pressure is about 62.8% higher than that of R-22. It is the same as the inlet pressure. The outlet temperature of R-407c is similar to that of R-22, but the outlet temperature of R-410a is about 12.9% higher than that of R-22. It is because the discharge pressure of compressor and specific heat ratio of R-410a are higher than those of R-22. The measured maximum temperature is 95.3℃ in this study. If the specific heat ratio is high, the discharge pressure and temperature of compressor are increased and the volumetric efficiency is decreased. The high discharge temperature may degrade the oil.

Figure 4 compares pressure drop values at evaporator and condenser and compressor power consumption and pressure ratio. The pressure drop of R-407c at evaporator is similar to that of R-22, but the pressure drop of R-410a is about 27.3% larger than that of R-22. As the density increases at the same mass flow rate, pressure drop decreases. And as the mass flow rate and oil increase, pressure drop increases[8]. Since the mass flow rate of each refrigerant is different, it is reasonable to consider the effect of viscosity of refrigerant on pressure drop. The viscosity of R-407c at saturated vapor is smaller than that of R-22, but the viscosity of R-410a is larger than that of R-22. Therefore pressure drop of R-

410a is estimated to be higher. The pressure drop at condenser is contrary to that at evaporator. The pressure drops of R-407c and R-410a at condenser are smaller than that of R-22 by 36.9% and 24.6%, respectively.

The compressor power of R-407c is less than that of R-22 by 30.5%, but the compressor power consumption of R-410a is more than that of R-22 by 64.2%. Because the vapor pressure of R-410a is higher than that of R-22 and the pressure difference between condenser and evaporator is large, the more compressor power of R-410a is required.

As a result, if R-410a is charged into the current system which is for R-22, the discharge pressure and temperature increase. This may degrade the oil. The volumetric efficiency of compressor decreases. And also this may result in compressor power loss and all components and tubes must be strengthened.

The pressure ratios of R-407c and R-410a are higher than that of R-22 by 7.3% and 63.6%, respectively. Therefore the compressor power of R-410a is larger than that of R-22.

4. Conclusion

The drop-in tests are carried out for R-410a and R-407c as R-22 alternatives. The main components of system are residential split type air conditioning system except that a hand-operated expansion valve is used instead of capillary tube. And each refrigerant is charged with superheating of as much as 8.3℃. Test is carried out under the ARI Test A. The conclusions are as follow:

1) COP of R-407c is about 31.9% higher than that of R-22. Nevertheless VCR, refrigerating capacity, and refrigerating effect of R-410a are better than those of R-22 and COP of R-410a is 21.4% less than that of R-22. The reason is that the compressor power of R-410a is larger than R-22 due to the high vapor pressure and pressure ratio.

2) The refrigerating effect of the two alternative refrigerants is large than that of R-22. The mass flow rate of R-410a is higher than that of R-22, therefore the refrigerating capacity of R-410a is also about 29.3% larger than that of R-22. But the mass flow rate of R-407c is smaller than that of R-22, therefore the cooling capacity of R- 407c is about 8.1% smaller than that of R-22.

3) Since pressure drop and heat of vaporization of both R-407c and R-410a at condenser are smaller and larger than those of R-22, respectively, it is an advantage for the design of heat exchanger.

According to these results, since the pressure and thermodynamic properties of R-407c are similar to those of R-22, R-407c may be charged into the current system as it is. But since VCR and refrigerating capacity of R-407c is relatively small, the volume flow rate must be varied to obtain the same capacity as with R-22. The volume flow rate can be varied by displacement or speed of compressor.

On the other hand, R-410a for all aspects is better than R-22 with the exception of COP. But since the pressure of R-410a is very high, R-410a must not be charged into the current system as it is. But if the compressor is modified, R-410a may be an excellent R-22 alternative. The modification is to reduce the displacement of compressor. It may result in the decrease of the discharge pressure and the power consumption.

Reference

(1) Global climate change from CO_2 and CFCs,

ASHRAE Journal, May, 1995, p. 10.
(2) Kondepudi, S. D., 1993, "Drop-in testing of R-32 blends as R-22 alternatives in a split system air conditioner", ASHRAE Trans., Vol. 99, Part 2, pp. 406~413.
(3) Sanvordenker, K. S., 1993, "Experimental evaluation of an R-32/R-134a blend as a near drop-in substitute for R-22", ASHRAE Trans., Vol. 99, Part 2, pp. 773~778.
(4) Spatz, M. W., and J., Zheng, 1993, "R-22 alternative refrigerants : Performance in unitary equipment", ASHRAE Trans., Vol. 99, Part 2, pp. 779~785.
(5) F. T. Murphy, 1995, "Comparison of R-407c and R-410a with R-22 in a 10.5kW (3.0TR)", Residential Center Air-Conditioner, Int. CFC and Halon Conference, pp. 31~40.
(6) J. J. Grebner and R. R. Crawford, "The effects of Oil on the thermodynamic properties of dichlorodifluoromethan(R-12) and tetrafluoroethane(R-134a)", ACRC TR-13.
(7) NIST, REFPROP version 4.01, 1993, Gaithers-burg, MD : National Institute of Standards and Technology.
(8) Torikoshi K., Ebisu T., 1993, "Heat transfer and pressure drop characteristic of R-134a, R-32, and a mixture of R-32/R-134a inside a horizontal tube", ASHRAE Trans., Vol. 99, Part 2, pp. 90~96.