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Performance of Alternative Refrigerants in Low Temperature Chillers

Dongsoo Jung* and Chong-Bo Kim*

Key Words : Low temperature refrigeration, Industrial chillers, R502, Alternative refrigerants

Abstract

This paper is about the performance of alternative refrigerants for low temperature and transport refrigeration chillers. A breadboard refrigeration chiller was constructed with counterflow heat exchangers. R502, its transitional alternatives of R402A and R402B, and long-term alternatives of R404A and R507 were tested in an attempt to compare the performance of each refrigerant against R502. Measurements were conducted at two condensing temperatures of 43.3℃ and 52.0℃ and the evaporating temperature was varied over a range from -25℃ to -5℃. The evaporator superheat and condenser subcooling were maintained constant at about 5℃ for all tests. Test results showed that all alternative fluids tested in this work can be used as 'drop-in fluids' to replace R502 without any major problem. It is also found that in the long run HFC alternatives are to be used due to their favorable environmental characteristics and better performance.

1. Introduction

R502 is an azeotropic CFC mixture composed of 48.8% R22 and 51.2% R115 by mass. This acts as if it were a pure refrigerant and provides larger capacity with lower discharge temperature than R22 and hence it has been preferred to R22 in low temperature refrigeration applications for the past few decades. At present, R502 is used in supermarket low temperature refrigerators, transport refrigeration units, low temperature industrial and scientific chillers, extremely low temperature chillers in multi-stage units. As the standard of living improves rapidly these days in Korea, the need for the low temperature refrigeration increases daily.

As CFC12, CFC113, CFC114, CFC115 had been identified to be responsible for the stratospheric ozone layer depletion and greenhouse warning, an international treaty called the

* Professor, Department of Mechanical Engineering, Inha University, Inchon, Korea

Montreal protocol was signed by many nation in 1987 in order to ban the trade and production of the ozone depleting substances.[1,2] Since R502 is a CFC containing CFC115, it was included in the initial CFC ban and completely phased out by the end of 1994 in Europe and by the end of 1995 in United States.[2] Korea was classified as "the Article 5 country" under the Montreal protocol and hence is allowed to have a grace period of 10 years to further use CFCs. But R502 is not produced in Korea and needs to be imported from the developed countries and its use will be restricted continually for the coming years. Therefore, it is necessary to develope or find alternative refrigerants in low temperature applications to successfully replace R502 as well as R22.

To meet this need, worldwide efforts to replace R502 in low temperature applications have been made for the past few years and US Air-conditioning and Refrigeration Institute(ARI) formed a program called "Alternative Refrigerants Evaluation Program(AREP)" in which equipment, refrigerants, and lubricant manufacturers as well as various universities and research institutions participated into a joint effort to solve the common problems encountered in applying new refrigerants. The program started in 1992 and is completed by this time.[3] The results of AREP indicated that there are no pure refrigerants as good as R502 in performance, safety, ease of use etc. and only refrigerant mixtures with proper compositions can provide similar refrigeration capacity and performance as R502.[3,4]

Based upon these findings, many refrigerant mixtures have been proposed to the refrigeration industry. At present, there are two groups of refrigerant mixtures available in the market. One group is HCFC refrigerant mixtures that can be used for the existing units and for the new units only in the transition period. The other group is HFC refrigerant mixtures developed mainly for the new units as long term alternatives.[3,4] The transitional refrigerant mixtures usually contain R22 and offer the advantage of good material and lubricant compatibility within the conventional system. R402A, R402B, R403B, and R408A belong to this group but R403B which is a mixture of 56% R22, 39% R218, and 5% R290 by mass is identified to be not acceptable since it contains R218 whose greenhouse warming potential is extremely high.[3]

In the long run, R32, R125, R134a, and R143a seem to have the potential to be the components of environmentally friendly alternative mixtures. They alone, however, have not been shown to be acceptable in low temperature applications since many performance characteristics of them are not good and hence they can be used in properly mixed refrigerants to compensate for their own deficiency. At present, R404A, R407A, R407B, and R507 are identified to be the proper mixtures for R502 and are sold in the market worldwide. Compositions and some properties of R502 alternative refrigerants available in the market are given in Table 1 and Table 2.[3,4]

In order to replace the existing refrigerants successfully, a comprehensive research and development plan needs to be set up. And in such a plan, physical properties of newly developed refrigerants are to be evaluated and refrigeration cycle characteristics with the new refrigerants as well as their behaviour in the major components of the refrigeration system are to be examined.[5,6] New refrigerants must have zero ozone depletion potential and low greenhouse warming potential. Also they should not have toxicity and flammability if possible

Table 1 Physical and environmental properties of R502 alternatives(transitional HCFC blends)

Refrigerant Number	Refrigerant and Molecular Weight				Average Blend Molecular Weight	Boiling Point ℃ (°F)	Critical Properties			ODP	HGWP	Temp. Glide ℃ (°F)
	R-22 86.5	R-125 120	R-143a 84	R-290 44			Temp. ℃ (°F)	Press. MPa (PSIa)	Volume m^3/kg ft^3/lb			
R-402A	38%	60%		2%	101.55	-49.0 (-56.2)	75.5 (167.9)	4.14 (599.7)	0.00185 (0.0296)	0.02	0.63	2.0 (3.6)
R-402B	60%	38%		2%	94.71	-47.4 (-53.3)	82.6 (180.7)	4.44 (644)	0.00189 (0.0302)	0.03	0.49	2.3 (4.1)
R-408A	47%	7%	46%		87	-43.5 (-46.3)	83.5 (182.3)	4.34 (629.5)		0.026	0.75	0.5 (0.9)

Table 2 Physical and environmental properties of R502 alternatives(long term HFC blends)

Refrigerant Number	Refrigerant and Molecular Weight				Average Blend Molecular Weight	Boiling Point ℃ (°F)	Critical Properties			ODP	HGWP	Temp. Glide ℃ (°F)
	R-32 50.02	R-125 120	R-134a 102	R-143a 84			Temp. ℃ (°F)	Press. MPa (PSIa)	Volume m^3/kg ft^3/lb			
R-404A		44%	4%	52%	97.6	-48.0 (-54.4)	72.6 (162.7)	3.79 (549.8)	0.00205 (0.0329)	0	0.94	0.7 (1.2)
R-507		50%		50%	98.86	-46.7 (-52.11)	70.9 (159.62)	3.79 (550.2)	0.0020 (0.0320)	0	0.96	0
R-407A	20%	40%	40%		90.11	-46.4 (-51.6)	83.0 (181.4)	4.54 (658.6)	0.0020 (0.0320)	0	0.49	6.6 (12)
R-407B	10%	70%	20%		102.9	-45.5 (-49.9)	76.0 (168.8)	4.16 (602.8)	0.00189 (0.0302)	0	0.70	4.4 (8)

and should have good material compatibility with plastics, elastomers and other materials in the refrigeration system. Besides, there should be compatible lubricants to be used with the new refrigerants. Also if they are to replace the existing refrigerants, they not only have to meet the above requirements but also should have similar performance as the existing refrigerants.[7]

In this study, among the refrigerant mixtures that are available in the market, the performance of R402A, R402B, R404A, and R507 will be measured and compared against R502 in an attempt to provide experimental data and instructions needed in the development of refrigerant mixture system for low temperature chillers.

2. Experiments

2.1 Experimental apparatus

In this study, a breadboard refrigeration system composed of a compressor, evaporator, condenser, expansion valve, and secondary fluid operation units is manufactured as shown in Fig.1. The compressor, a key com-

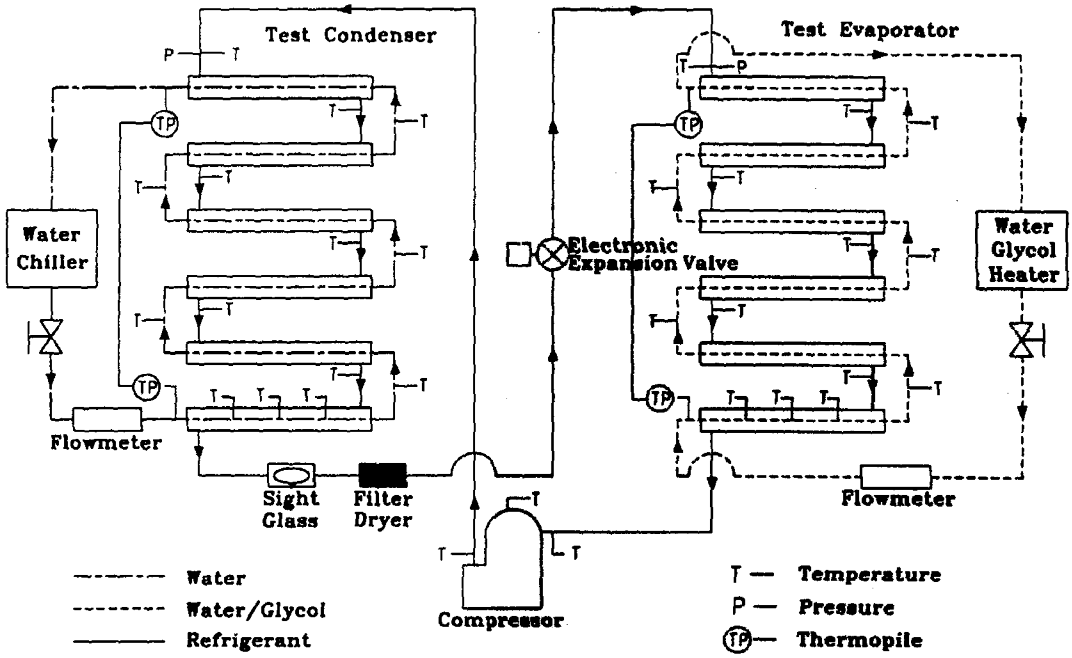

Fig.1 Schematic diagram of the low temperature chiller test facility

ponent in the refrigeration system, was of the hermetic type designed originally for R502. Double pipe heat exchanger sticks with inner fins to improve the heat transfer were connected to be the system evaporator and condenser. The length of each stick is 610mm and inner and outer diameters are 12.8mm and 22.8mm respectively and the thickness of the pipe was 1.0mm. For both condenser and evaporator, the secondary fluids passed through the inner tube while the refrigerant passed through the annular space and also the secondary heat transfer fluid and refrigerants flowed in a counter-current manner. As the secondary heat transfer fluids, water was used for the condenser side while water and ethylene glycol mixture of 75%/25% by mass was used in the evaporator side since the secondary fluid temperature went down below 0℃ in the evaporator side.

Thermocouples and pressure transducers were installed at many locations to examine the system state parameters. At the inlet and outlet of the secondary fluid passage, thermopiles were installed to determine the temperature difference, ΔT, across the heat exchanger accurately. From this temperature difference, the capacity of the heat exchanger was determined. 3-way valves were installed, coupled with pressure transducers in the evaporator and condenser, to measure the pressure drop across the heat exchangers. Digital watt meter was used to measure the compressor power. Refrigerant mass flow rate and evaporator pressure were controlled by a needle valve with an electronic stepping motor. To see the refrigerant state and figure out if the system is properly charged, a sight glass was installed at the condenser exit and also a filter/drier was installed before the expansion valve to prevent moisture and dirts from circulating inside the system. Finally, HP3852 data acquisition and control unit with Instrument Basic program was used to acquire such data as temperature, pressure, mas flow rate, power from the test apparatus.

2.2 Experimental procedure

The simplest way to test the performance of alternative refrigerants without altering the system greatly is to test them in a "drop-in" manner.[3] This method requires a minimal change in the system and hence existing system is maintained as before and only lubricant is changed and an expansion valve is adjusted with various refrigerants.[7] Many researchers have adopted the "drop-in method" since efforts and cost to evaluate various refrigerants would be reduced significantly using this method. Hence in this study, the refrigeration system was not changed except for the lubricant change and expansion valve adjustment.

For this purpose, R502 was charged to the system first and its baseline performance was measured in the following manner. Before charging the system, the system was evacuated for more than 1 hour. And then refrigerant was charged to the system while system variables were monitored. And at the same time, refrigerant state was observed through the sight glass as well. The temperatures and mass flow rates of the secondary fluids were adjusted in the external heating bath and chiller. It took usually 3~4 hours until the system reached steady state at desired conditions. And then data were taken every 30 seconds for 1 hour and stored in the computer.

After R502 experiments were completed, R402B, R402A, R404A, and R507 were in turn tested under the same condition as the baseline tests with R502. Since "drop-in replacement" tests were carried out, only the filter /drier was changed in the system with the change in refrigerant. For R502, R402A, and R402B, mineral oil of the viscosity grade of $32mm^2/s$(150 SUS) was used while for R404A and R507 polyol esther oil of the same viscosity grade(Mobil, EAL Arctic 32) was used since they are HFC refrigerants.[4,9]

2.3 Test conditions

To make a fair comparison for the performance of various refrigerants, evaporating and condensing temperatures and subcooling and superheat were to be maintained constant for all tests. In heat exchangers, evaporation and condensation temperatures change during the phase change for nonazeotropic refrigerant mixtures while they are constant for pure fluids if no pressure drop was assumed across the heat exchanger. Therefore, evaporating and condensing temperatures are to be set properly to make a fair comparison for all fluids tested.

In this study, instructions suggested by US Air-conditioning and Refrigeration Institute were followed.[3] According to their instructions, the evaporating temperature is defined to be the arithmetic average of the saturation temperatures corresponding to the measured pressures at the inlet and outlet of the evaporator. In fact, thus determined evaporator temperature was very close to the temperatures measured by the thermocouples attached to the second and third heat exchanger sticks, showing roughly a difference of 0.5℃. Condensing temperature was defined in a similar manner.

The superheat in the evaporator was defined as the difference between the measured temperature at the evaporator outlet and calculated saturation temperature corresponding to the measured pressure at the evaporator outlet. The subcooling in the condenser was defined as the temperature difference between the calculated saturated liquid temperature corresponding to the measured pressure at the condenser outlet and measured temperature at the condenser outlet. For all tests, the superheat and subcooling were maintained at 5℃ with a deviation of 0.5℃. The superheat was adjusted by controlling the temperature and mass flow rate of the secondary fluid while the subcooling was adjusted by the amount of refrigerant charge. As indicated by many researchers, the performance of HFC refrigerants was sensitive to the amount of charge, and hence much care was exercised in charging the right amount of refrigerant for fair drop-in replacement comparison.[8] Under the same condition, in general alternative refrigerants required almost the same or little bit less charge than R502.

2.4 Test data

There are two types of condenser: air-cooled and water-cooled. It is customary to take data at temperatures corresponding to the two types of condensers and compare them when the performance of R502 alternatives is evaluated.[3,4] Therefore, all tests were carried out in this study with the condensing temperature, T_c, fixed at 52.0℃(126°F) and 43.3℃(110°F) that represent the condensing temperatures of the air-cooled and water-cooled units. Once the condensing temperature was fixed, tests were carried out at the evaporating temperature, T_e, of -25℃ and then the evaporating temperature was increased up to -5℃ with an interval of 3~4℃. Therefore, for a give condensing temperature, 5~6 data were taken for each refrigerant.

In order to compare the performance of a refrigeration system with various fluids, compressor power and refrigeration capacity were to be measured. The compressor power was measured by a digital watt meter and the capacity was determined by measuring the mass flow rate and temperature difference across the evaporator of the secondary heat transfer fluid by the following equation.

$$\dot{Q}_e = \dot{m} C_p \Delta T \tag{1}$$

where $\dot{Q}_e$, $\dot{m}$, C_p, ΔT are the amount of transferred in kW, mass flow rate in kg/sec, specific heat in kJ/kgK, and the temperature difference of the secondary fluid across the heat exchanger in ℃ respectively

In this study, a turbine meter was used to measure the mass flow rate of the secondary fluid. Since the turbine meter needs to be calibrated once in a while to maintain the reliability, an accurate mass flow meter of 0.2% accuracy based upon a Coriolis force principle was used for the calibration of the turbine meter. Since the specific heat of the secondary fluid in equation (1) was dependent upon the fluid temperature, it had to be determined quite accurately for accurate heat transfer measurement and for this purpose, ASHRAE data were used in the temperature range studied.[10]

3. Results and discussion

3.1 Performance comparison of alternative refirgerants

Refrigeration capacity is the most important variable in the comparison of the performance of the refrigeration system. Figure 2 and Figure 3 show the capacity for all refrigerants tested. The capacity curves for both condensing temperatures show the si-

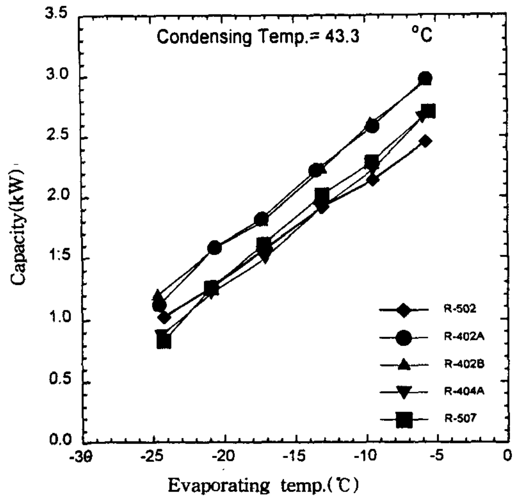

Fig.2 Refrigeration capacity of R502 and its alternatives(T_c=43.3℃)

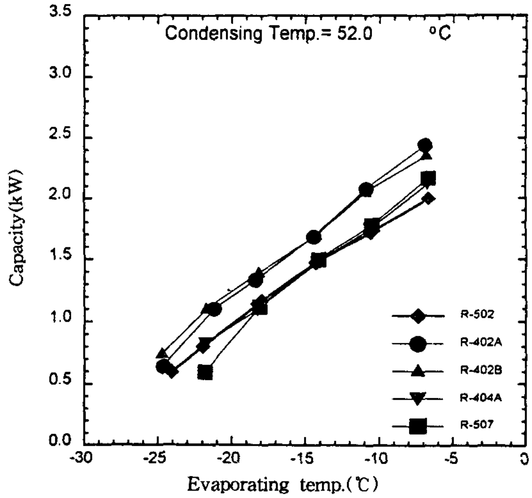

Fig.3 Refrigeration capacity R502 and its alternatives(T_c=52.0℃)

milar trend for all refrigerants. HCFC refrigerant mixtures of R402A and R402B show somewhat higher capacities than R502 in the entire evaporating temperature range and HFC refrigerant mixtures of R404A and R507 show the similar capacities as R502. To be more specific, the average capacity of R402A is 18.5% higher than that of R502, showing an increase of 6.8%~36.8%. On the other hand, the average capacity of R402B is 20.3% higher than that of R502, showing an increase of 13.8%~36.7%. Also for both fluids, the increase in capacity becomes larger as the evaporating temperature increases.

On the other hand, R404A and R507 show lower capacities than R502. In the low temperature range, the capacities of these fluids are lower than those of R502 but as the temperature increases, capacities increase and in the temperature range of -18℃~-13℃ they are similar to those of R502 and finally in the high temperatures, they become even higher than those of R502. In the entire evaporating temperature range, the average capacity of R404A is similar to that of R502, showing a maximum decrease of 14.4% and a maximum increase of 7.9% as compared to R502. And the average capacity of R507 is also similar to that of R502, showing a maximum decrease of 25.6% and a maximum increase of 10.1% as compared to R502.

Figure 4 and Figure 5 show the compressor power as a function of evaporating temperature for all refrigerants tested. As shown in these figures, the refrigerants tested in this study all require more compressor power than R502. Especially, the transitional fluids constraining R22 such as R402A and R402B require more compressor power than the long term alternatives, R404A and R507. To be more specific, the average compressor powers of R402A and R402B are roughly 15% higher than those of R502 while those of R404A and R507 are 4.0% and 1.4% higher than those of R502. And for R402A and R402B, the slope of the compressor power curve is similar to that of R502 but for R404A and R507, the compressor power is similar to that of R502 in the low temperature range and as the evaporator temperature increases further, the power

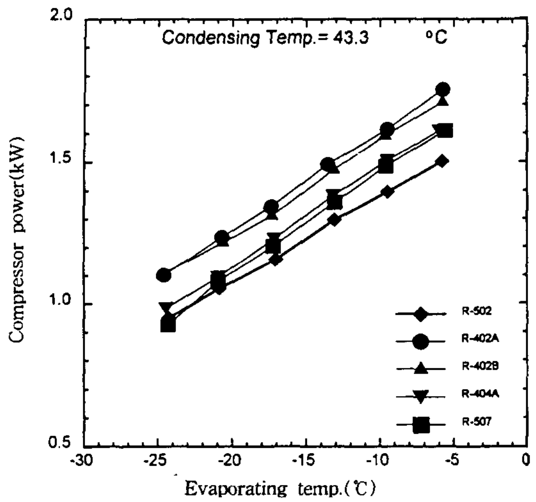

Fig.4 Compressor power of R502 and its alternatives(T_c=43.3℃)

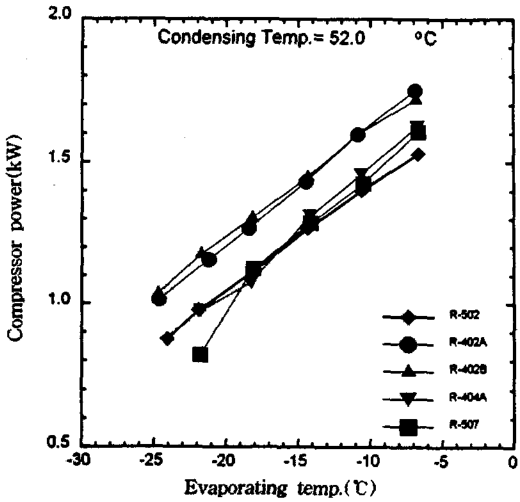

Fig.5 Compressor power of R502 and its alternatives(T_c=52.0℃)

increases rapidly resulting in an increase of 7.0~7.9% as compared to R502. The increase in compressor power inevitably would result in a decrease in system efficiency and hence based upon the above findings, it can be said that the long term alternatives, R404 and R507, are better than transitional fluids of R402A and R402B in R502 replacement.

In comparing the performance of a refrigeration system or a refrigerant, besides the capacity, the coefficient of performance(COP) is one of the most important parameters to be considered. In fact, COP is obtained by dividing the refrigeration capacity by the compressor power and hence it contains an economic indicator within. In order to decrease the greenhouse warming, the energy efficiency of a refrigeration system must be improved and hence selecting the proper refrigerants that do not deplete the ozone and at the same time energy efficient is very important. Therefore, the system or refrigerants whose COP is higher than that of the existing units or refrigerants are to be preferred from the view point of environmental protection as well as economics.

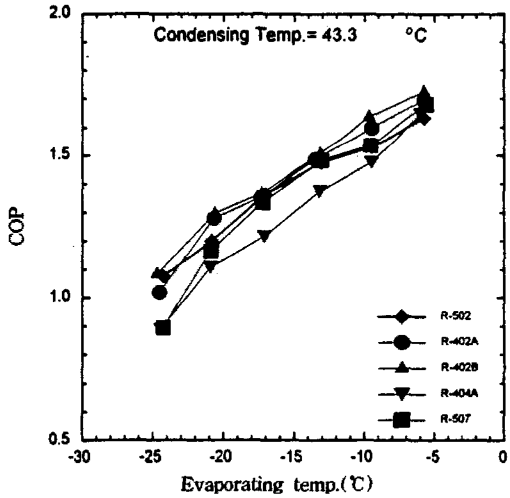

Fig.6 COP of R502 and its alternatives (T_c=43.3℃)

Figure 6 and Figure 7 show the COP of four refrigerants tested in this study. The COP of R402A, a HCFC refrigerant mixture, is very similar to that of R502 in the low temperature range for both condensing temperatures of 43.3℃ and 52.0℃. As the evaporator temperature becomes higher than -15℃, how-

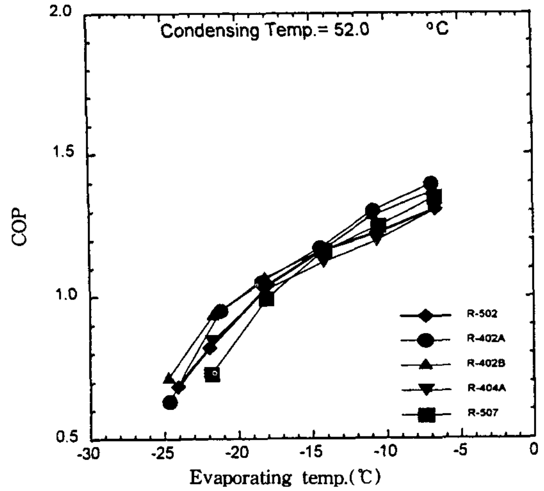

Fig.7 COP of R502 and its alternatives (T_c=52.0℃)

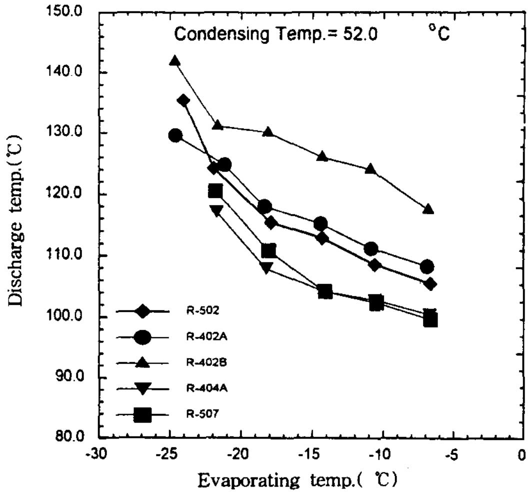

Fig.9 Discharge temperature of R502 and its alternatives(T_c=52.0℃)

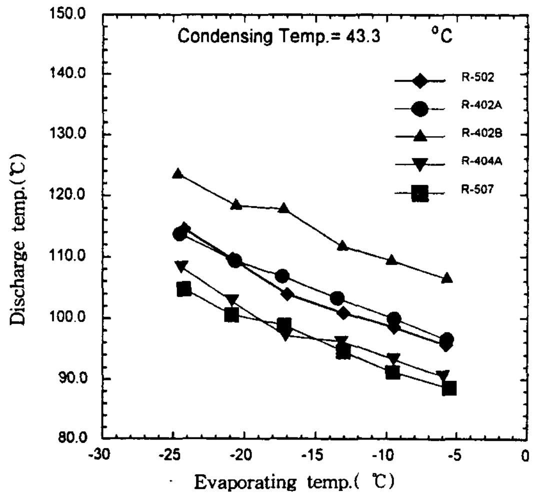

Fig.8 Discharge temperature of R502 and its alternatives(T_c=43.3℃)

ever, the COP becomes larger than that of R502. In the entire temperature range, the average COP of R402A is 2.7% higher than that of R502 and for the higher condensing temperature, the increase in COP becomes larger as the evaporating temperature increases. R402B, a similar transitional alternative as R402A, shows the similar trend as R402A and in the entire temperature range, the average COP is 4.4% higher than that of R502. But unlike R402A, in the low temperature range the increase in COP becomes larger as the evaporator temperature increases.

On the other hand, the COP of R404A, a long term HFC alternative, is lower than that of R502 in the entire temperature range and especially in the low temperature range, the decrease in COP is large showing a maximum decrease of 17.3% for the condensing temperature of 43.3℃. But as the evaporator temperature increases, the deviation from R502 becomes smaller and finally the COP of R404A exceeds that of R502 by 2.8%. R507C, a long term HFC alternative, shows the similar COP to that of R502 but in the temperature range of below -20℃, the COP deteriorates significantly(See Fig.6 and Fig.7)

One of the factors greatly affecting the system performance greatly is the compressor discharge temperature. Figure 8 and Figure 9 show the compressor discharge temperatures of various fluids for both condensing temperatures. As shown in the figures, the discharge temperatures of the transitional fluids are higher than those of R502 while those of long term fluids are lower than those of R502. To be more specific, the discharge temperatures of R402A are similar to those of R502 in the entire temperature range and those of R402B are 11.0℃ higher than those of R502 showing a decrease of 6.4℃ and an increase of 15.4℃ as compared to R502. On the other hand, the long term alternatives show consistently lower discharge temperatures in the entire temperature range. For example, the average discharge temperatures of R404A are 6.3℃ lower than those of R502, showing a decrease of 4.8℃~8.7℃ as compared to R502. The average discharge temperatures of R507 are 6.7℃ lower than those of R502, showing a decrease of 3.8℃~9.9℃ as compared to R502.

The compressor discharge temperature is closely related to the lifetime of a compressor. If the discnarge temperature is too high, the lubricant or the refrigerant may be decomposed and hence that results in an increase in acid content in the system and in turn a lubricating problem as well. Furthermore, corrosion or copper plating may be caused by the excessive discharge temperatures and hence the lifetime of compressor might be significantly shortened.[11] Therefore, it is better to select an alternative refrigerant having a lower discharge temperature as long as the capacity and efficiency are similar to those of the existing refrigerants. From this view point, long term HFC alternatives offer advantages over the HCFC alternatives.

Finally, Figure 10 and Figure 11 show the pressure ratio across the compressor in the entire evaporator temperature range. As shown in the figures, the pressure ratio of all refrigerants tested is larger than that of R502 except for one case. For all four refrigerants, the pressure ratio is 5.0~6.3% higher than that of R502. Especially, the pressure ratio becomes larger with an increase in condenser temperature as well as with a decrease in evaporator temperature. It might be due to the fact that the difference between the com-

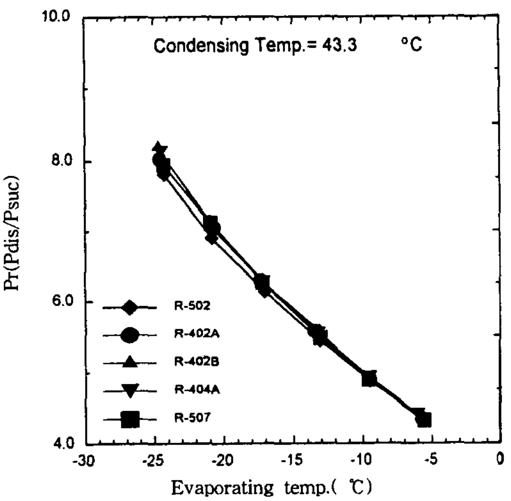

Fig.10 Pressure ratio of R502 and its alternatives(T_c=43.3℃)

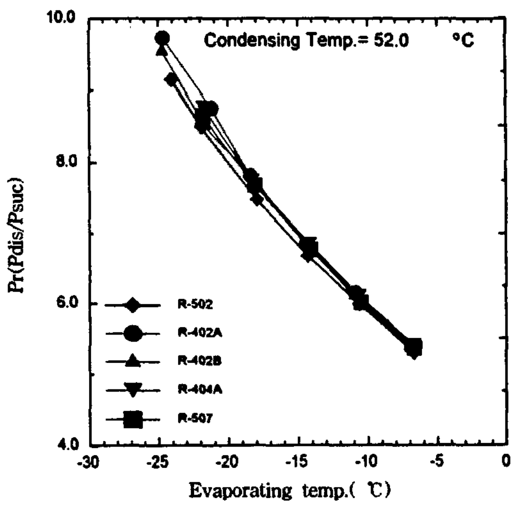

Fig.11 Pressure ratio of R502 and its alternatives(T_c=52.0℃)

pressor suction and discharge pressures becomes larger as the mass flow rate of the refrigerant decreases. But an increase of 5~6% in pressure ratio would not cause any problem even in the refrigeration system designed for R502. Therefore, from the viewpoint of pressure ratio, all the proposed refrigerants seem to be acceptable without requiring any significant change in the system.

Based on the performance characteristics of various refrigerants, it can be readily shown that refrigerant mixtures composed of similar family of pure fluids(for example, HFC family or HCFC family) have the similar characteristics and hence their behavior in the system is also similar. Also the overall performance of the transitional alternative fluids as well as the long term alternative fluids are poorer than that of R502 and hence more research work needs to be carried out to improve the system performance with alternative fluids.

3.2 Comparison with other data

Shiflett and Yokozeki[12] carried out a computer simulation study for R402A, R402B, and R404A and evaluated the thermodynamic performance of these fluids for three different condenser temperatures(54.4℃, 43.3℃, 32.2℃) in the evaporator temperature range of -40℃ ~-17.8℃. Their simulation results show that the discharge temperature of R402A is similar to that of R502 and the capacity and COP are 6%~11% higher and a little bit lower than those of R502 respectively. On the other hand, the discharge temperature of R402B is 5℃~15℃ higher and the capacity and COP are 4%~7% higher and up to 2% higher than those of R502 respectively. And the discharge temperature of R404A is 5℃~8℃ lower and the capacity and COP are 4%~5% higher and roughly 2% higher than those of R502 respectively.

Park[13] also carried out a computer modeling of the similar experimental apparatus as the present one for two condenser temperatures of 30℃ and 40℃ and for three evaporator temperatures of -10℃, -20℃, and -30℃. Even though the simulation condition of Park is somewhat different from that of Shiflett and Yokozeki, and hence absolute comparison can not be made, the relative performance of the alternative refrigerants compared to the baseline data of R502 of Park's study was very similar that of Shiflett and Yokozeki.

Besides these theoretical data, the experimental results of Snelson et al.[14], Barreau et al.[15], Weng and Wu[16], and Kwon[4,17] also showed the similar trend as the present data. Since they all evaluated the performance of alternative refrigerants from the view point of "drop-in replacement", the comparison with their data would bear quite a significance. Snelson et al.[14] carried out a series of tests for various alternative refrigerants and their results show that the compressor discharge temperature of R404A is 4.8℃~6.3℃ lower and the capacity is a little bit lower in the low temperature range but higher up to 5.5% as the evaporator temperature increases. The COP of R404A is a little bit lower than that of R502 in the entire temperature range.

In the recent conference for the Ozone Protection Technologies, Barreau et al.[15], Weng and Wu[16], and Kwon[17] reported that R404A is being currently used in Europe as the optimum alternative fluid to replace R502 and expected that R404A will be used worldwide in a few years. Among them, the results of Weng and Wu[15] agree very well with the present data and their graphs of the capacity and COP for R404A and R502 lie on top of those in Fig.2 through Fig.7. Also the results of Kwon[17] show the similar trend as the present data. From this comparison, the present experimental data are proven to agree with the previous theoretical and experimental data of other researchers and hence the reliability of the present experimental apparatus and data is verified indirectly.

4. Conclusions

In this study, the performance of alternative refrigerants for CFC502 used in low temperature applications is measured experimentally and the following conclusions are drawn.

1) Four refrigerants tested in the study provided acceptable performance in "drop-in replacement" of R502.

2) Long term alternatives, R404A and R507, have good performance in compressor power consumption.

3) Transitional alternatives R402A and R402B have excellent performance in refrigeration capacity.

4) The COP of the alternative fluids tested is very similar to that of R502.

5) Except for R402B, other alternative refrigerants' compressor discharge temperatures are lower than those of R502. In order to use R402B in low temperature applications, some measures are to be taken to compensate for the increase in discharge temperature.

6) In consideration of all the aspects studied, HFC refrigerant mixtures seem to be better than HCFC refrigerants. Especially, R507 is very good since it provides almost the same capacity and efficiency as R502.

Acknowledgement

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