

2008

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Li, Hongqi and Zhao, Zhigang, "Analysis of the Operating Characteristics of a Low Evaporation Temperature R404A Refrigeration System" (2008). *International Refrigeration and Air Conditioning Conference*. Paper 946.
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Analysis of the Operating Characteristics of a Low Evaporation Temperature R404A Refrigeration System

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ABSTRACT

A refrigeration system which was originally designed using R502 as refrigerant was rebuilt to adapt the special requirements of R404A. The experiments, both for R502 and R404A, on this system were done and some parameters such as evaporating temperature, condensing temperature, discharge temperature, compressor input power and so on were measured under different working conditions. Then the operating characteristics and the performances were compared between R404A and R502. The influences of R404A as refrigerant on refrigeration system were further analyzed. Some recommendations for existing R502 refrigeration systems to use R404A as refrigerants were put forward in the end of this paper.

1. INTRODUCTION

With the requirements of ozone protection and greenhouse gas emission reduction, CFCs which were widely used as refrigerants in refrigeration systems have now been substituted forcedly all over the world. Any substitute is generally asked to have specially properties such as zero ODP, as low as GWP, good thermodynamic properties, similar behaviors in refrigeration systems to original refrigerant, low price, no flammability and no toxicity to human beings etc.

Following the above principles, R404A is considered as the good refrigerant to replace R502 in the refrigeration system with low evaporating temperature. It has zero ODP, very low GWP, adjacent performances to R502 and other well characteristics.

Many researches were already done on the flow and heat transfer properties of R404A. Ferreira *et al.* (2003) studied R404A condensing processes under forced flow conditions inside smooth, microfin and cross-hatched Horizontal Tubes. The heat transfer formulae were given and the authors indicated that the pressure drop in microfin tube is 25% higher than that in smooth tube; Motta *et al.* (2000 & 2002) studied the flow characteristic of R404A and R404A/Oil mixture through adiabatic capillary tubes with different diameters, 0.6mm and 1.85, and different lengths, 1.05m, 1.30m and 1.60m. The results showed that R404A has good flow characteristic in capillary tubes; Boissieux *et al.* (2000) studied the two-phase heat transfer coefficients of three HFC refrigerants, R404A, R407C and Isceon 59, in evaporating process and in condensing process inside a horizontal smooth tube. Some formulae for heat transfer coefficients were compared; Gabriellii and Vamling (1997) did experimental researches and simulations of R407C, R404A and R410A in tube-and-shell condensers.

China has forbidden the usage of CFCs such as R502 since 2006. Thus, two challenges in this field occur, the new R404A refrigeration system designing and the rebuilding of existing R502 refrigeration systems to use R404A as refrigerants. All the researches in the past make it relatively easy to design a new R404A system. But there are many existing R502 refrigeration systems which are still in operation and could not be thrown away soon for its cost or other reasons. In this paper, a R502 refrigeration system with low evaporating temperature of -40°C, was tested first under different working conditions, then it was rebuilt to adapt the special requirements of R404A. The new system

was also tested in the same way. The operating characteristics of two systems were compared and analyzed. The major purpose of this paper is to provide some references for the engineering applications of R404A, especially in existing systems.

2. REFRIGERATION UNIT AND TEST SYSTEM

For the purpose of this paper, some rebuilding work was taken to the existing refrigeration system after the tests for R502 were completed. The compressor and the system pipe lines were cleaned with chemical solvent and dry nitrogen gas. The compressor lubricant oil was replaced with POE oil and the expansion valve was re-adjusted to adapt R404A requirements. In order to measure the refrigeration capacity of the system, a flow meter to measure the flow rate of refrigerant was added in the pipe line between the condenser and the expansion valve. Furthermore, considering that many existing R502 systems use forced-cooling evaporators, a forced-cooling evaporator was connected parallel to the original direct-cooling evaporator. Thus there are two parallel evaporators switched with some valves in this system. Some other sensors for temperature and pressure measurements were also equipped into the system. At last, the refrigerant of this system was changed to R404A.

Figure 1 shows the final refrigeration unit and the test system. A data acquisition system was used to accumulate data and transmit them to the computer.

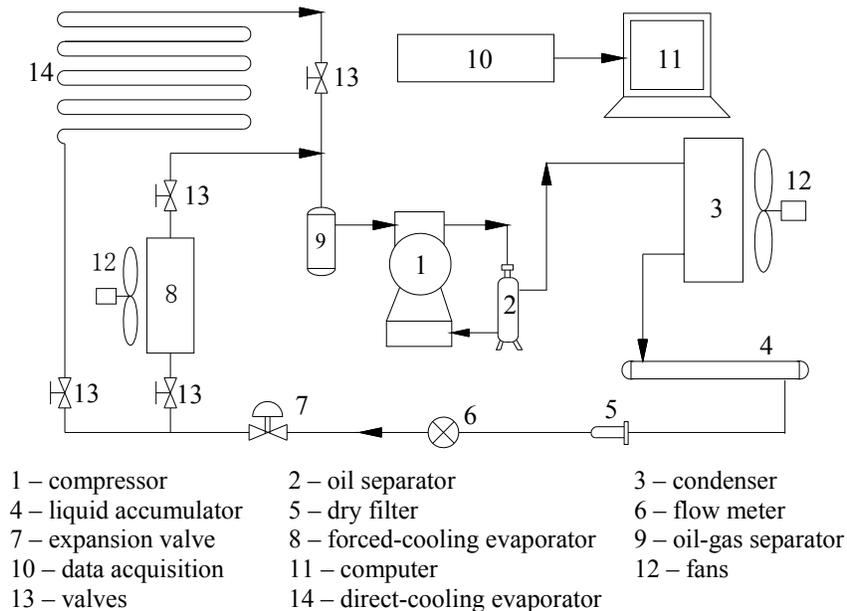


Figure 1: Refrigeration unit and test system

Table 1 below shows the technical characteristic of the main parts of this refrigeration unit.

Table 1: Technical characteristic of the main parts

Compressor	Type: 755FSV2-F semi-hermetic reciprocating compressor Refrigeration capacity: 5500W
Condenser	Capacity: 15000 W Air rate: $2 \times 3000 \text{ m}^3/\text{h}$ Heat transfer area: 49 m^2
Forced-cooling evaporator	Capacity: 2350 W Heat transfer area: 5 m^2 Air rate: $950 \text{ m}^3/\text{h}$
Direct-cooling evaporator	Heat transfer area: 12 m^2
Expansion valve	Type: AA-1/2H-2.50

An electric heating device whose heating power could be adjusted was equipped inside the cold room to control the room temperature, and the out-door temperature was also controllable. In this way, the following parameters were measured under different working conditions:

Discharge temperature and pressure of the compressor	Input power of the compressor, the fans
Suction temperature and pressure of the compressor	Air flow rate through the condenser
Refrigerant inlet temperature and pressure of the condenser	Air flow rate through the evaporator
Refrigerant outlet temperature and pressure of the condenser	Sub-cooling temperature
Refrigerant inlet temperature and pressure of the evaporator	Air outlet temperature of the evaporator
Refrigerant outlet temperature and pressure of the evaporator	Air temperature in the cold room
Air inlet and outlet temperatures of the condenser	Refrigerant flow rate

The performance of this refrigeration unit was therefore calculated with these parameters.

3. CALCULATIONS OF REFRIGERATION CAPACITY AND EER

3.1 Refrigeration Capacity

The refrigeration capacities under different working conditions of this unit can be easily calculated with equation (1) as below:

$$Q = G \times \Delta h \quad (1)$$

Where, Q – the refrigeration capacity of the unit, kW ;

G – the mass flow rate of refrigerant, kg/s ;

Δh – enthalpy difference of refrigerant between outlet and inlet of the evaporator, kJ/kg .

Because the two parallel evaporators operate independently, the refrigeration capacity in each operating mode can be calculated with this equation.

Especially, for the forced-cooling evaporator, the refrigeration capacity was also calculated in another way as showed below to make a validation:

$$Q = Q_1 + Q_2 \quad (2)$$

$$Q_1 = \frac{w_a (h_{a1} - h_{a2})}{v_a (1 + d_a)} \quad (3)$$

$$Q_2 = \frac{w_a \times c_{pw} \times t_2' \times (d_1 - d_2)}{v_a \times (1 + d_a)} \quad (4)$$

Where, w_a – air flow rate through the evaporator, m^3/s ;

h_{a1} – air enthalpy inlet the evaporator, kJ/kg ;

h_{a2} – air enthalpy outlet the evaporator, kJ/kg ;

v_a – air specific volume in the cold room, m^3/kg ;

d_a – moisture content of air in the cold room, kg/kg ;

c_{pw} – specific heat of water, $kJ/(kg K)$;

t_2' – wet-bulb temperature of air outlet the evaporator, K ;

d_1 – moisture content of air inlet the evaporator, kg/kg ;

d_2 – moisture content of air outlet the evaporator, kg/kg .

Equation (2) means that the total refrigeration capacity can be divided into two parts: the part to cool the air in the

cold room and the part to condense the moisture water in the air.

The refrigeration capacity was calculated in these two different ways. The results showed that the calculating error was within 3%.

3.2 EER

The performance, EER, of the refrigeration unit can be easily calculated with equation (5):

$$EER = \frac{Q}{P} \quad (5)$$

Where, P is the input power, including those of compressor, fans and controller, etc.

4. RESULTS AND ANALYSIS

The operating characteristics of the refrigeration unit were tested under different evaporating temperatures, condensing temperatures, sub-cooling degrees, over-heating degrees, etc. The performances of this unit are hence calculated with these test data. Some of the test results and the calculated results are shown in the following figures. The reference parameters in these figures are the condensing temperatures of this unit.

Figure 2 is the comparison of discharge temperatures of the compressor between R404A and R502. It is clear that both the discharge temperatures of R404A and R502 increase with the drop of the evaporating temperature and the increase of the condensing temperature. But, at the same condensing temperature and the same evaporating temperature, the discharge temperature of R404A is obviously lower than that of R502. The difference is about 3-12°C. The lower the evaporating temperature is and the higher the condensing temperature is, the greater the difference will be. It means that R404A contributes the better working conditions to the refrigeration system, such as lower oil temperature, better lubrication, lower motor temperature and higher life, etc. It also means that lower viscosity oil might be used in R404A system and thus higher energy efficiency could be expected.

Figure 3 shows the variety of the pressure ratio of the compressor with the condensing temperature and the evaporating temperature both for R404A and R502. The pressure ratio obviously increases with the decrease of the evaporating temperature and the increase of the condensing temperature. With the evaporating temperature getting higher, the influence of the condensing temperature on the pressure ratio is getting less. Different from the situation of discharge temperature, the pressure ratios both of R404A and R502 are almost the same though the pressure ratio of R404A is slightly higher than that of R502. Therefore, there will be not structure strength and material problems for a R502 system to use R404A as refrigerant.

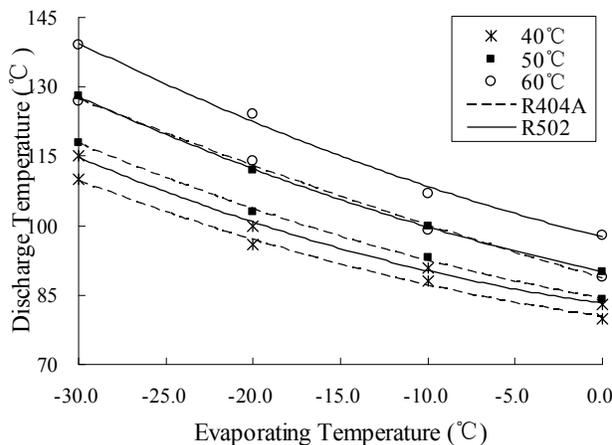


Figure 2: Test results of discharge temperatures

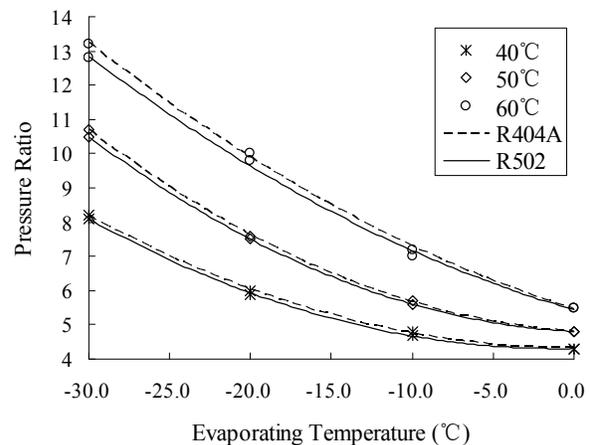


Figure 3: Pressure ratio of the compressor

Figure 4 compares the EER between R404A and R502 at different condensing temperatures and different evaporating temperatures. It is the basic principle of refrigeration, as shown in figure 4, that the EER increases with the increase of evaporating temperature and the decrease of condensing temperature. But the test results present a negative influence of R404A on EER. It is clear that, at all condensing and evaporating temperatures, the EER of

R404A system is obviously lower than that of R502 system. The difference is about 0.1 to 0.2 or 7% to 26%. The reason for this phenomenon might be the natural characteristic of R404A or that the refrigeration system originally designed for R502 is needed to be redesigned and optimized for R404A to obtain perfect performance. The further confirmation work will be necessary.

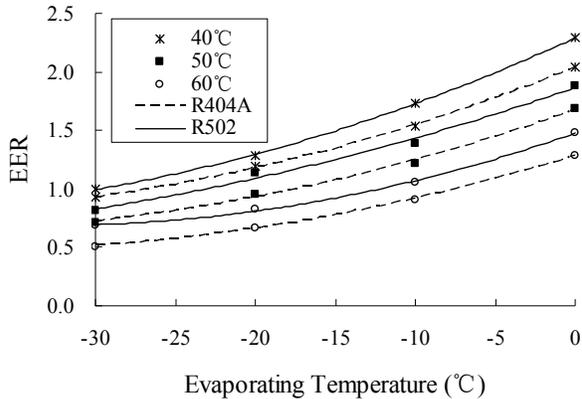


Figure 4: Variety of EER with evaporating temperature

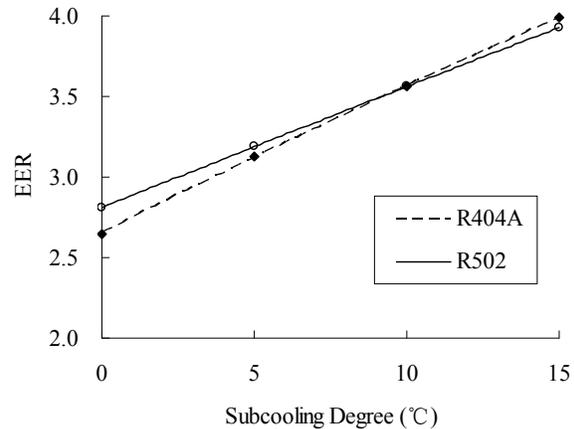


Figure 5: Variety of EER with sub-cooling degree

Figure 5 shows the EER variety with the sub-cooling degrees both for R404A and R502 at certain condensing and evaporating temperature. It is certain that, from the basic refrigeration principles, the EER quickly increases with the increase of sub-cooling degree. The important information obtained from this figure is that there is almost no difference of EER between R404A and R502 when sub-cooling degree varies. The EER of R404A is slightly higher than that of R502 at higher sub-cooling degree but the situation is contrary at lower sub-cooling degree.

5. CONCLUSIONS

The test results and the comparisons of operation parameters and performance between R404A and R502 show that R404A has very close behaviors to R502 in the applications of low evaporating temperature refrigeration systems. It is a good substitute for R502. Some common factors which influence the operating characteristic and performance were analyzed in this paper. The further work on this issue is still undertaken.

It can be concluded from mentioned above that, besides the necessary changes in non-metal materials and oil, R404A can almost directly used in a existing R502 refrigeration system. Some improvements during this process might bring certain benefits in performance and life.

- The discharge temperature of R404A is lower than that of R502. This will improve the reliability and life of the compressor. It also makes it possible to use lower viscosity oil and then to improve the performance.
- Though the pressure ratio of R404A is slightly higher than that of R502, no technical response is necessary due to the very small difference.
- To properly increase the sub-cooling degree of R404A is helpful for the performance improvement. But the achievement might be small.

The lesson from this paper shows that, the performance will grow worse when R404A is directly charged into an existing R502 refrigeration system. Some necessary optimizations in operating parameters such as expansion valve control are recommended to obtain satisfactory performance.

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ACKNOWLEDGEMENT

The research was supported by the Natural Science Foundation of Beijing, No: 3071001