THERMODYNAMIC ANALYSIS OF MODERATE/HIGH TEMPERATURE HEAT PUMP SYSTEM USING WATER AS WORKING FLUID

Haixia LIU, Graduation student, College of Environmental and Energy Engineering
Beijing University of Technology, Beijing, China
Guoyuan MA, Professor, College of Environmental and Energy Engineering*
Beijing University of Technology, Beijing, China
Xin LI, Graduation student, College of Environmental and Energy Engineering
Beijing University of Technology, Beijing, China
Shuxue XU, Research fellow, College of Environmental and Energy Engineering
Beijing University of Technology, Beijing, China

Abstract: Water is an environment-friendly, low-cost and harmless natural working fluid, of which ozone depletion potential (ODP) is zero and global warming potential (GWP) less than 1, and it is a better alternative fluid for moderate/high temperature heat pump. The thermodynamic performances of moderate/high temperature heat pump system using water as working fluid are analyzed when the condensation temperature varies from 50 °C to 140 °C. The results demonstrate that the working fluid of water owns lower operation pressure and heat capacity per displacement than the others, but higher pressure ratio and discharge temperature. The coefficient of performance (COP) of the system using water as working fluid changes almost linearly with the condensation temperature, and is higher than the other fluids when it keeps more than 95 °C and comparative to others when it is between 70 °C and 95 °C, lower when it keeps less than 70 °C. Generally, water is a prospective working fluid for moderate and high temperature heat pump system.

Key Words: heat pump, water vapour, natural working fluid

1. INTRODUCTION

The heat pump technology with heat output at temperature of 60 °C and below is well-researched, and has been widely used in heating and hot water supply for buildings, such as air-source heat pump, ground-coupled heat pump and water-source heat pump etc. Meanwhile, the demand for the moderately/high temperature heat pumps with heat output between 60°C and 140°C, or higher temperature, goes up rapidly, which is mainly used in efficient utilization of low-grade thermal energy such as geothermal energy, solar energy and industrial waste heat. As the chlorofluorocarbons (CFCs) used as the refrigerant of moderately/high temperature heat pump has been banned, the hydrochlorofluorocarbons (HCFCs) with lower ODP, such as HCFC123 and HCFC142b, and the hydrofluorocarbon (HFCs) with zero ODP, such as HFC152a HFC245fa, performs very well in moderately/high temperature heat pumps under different range of temperature. The basic thermo-physical properties, ODP and GWP values of the refrigerants suitable to use in moderately/high temperature heat pump are listed in Table 1. However, HCFC refrigerants with non-zero ODP have already been accelerated to phase out in the world, and HFC refrigerants with high GWP have been scheduled to phase down although its ODP is zero. The hydrocarbons (HCs) refrigerant own a better thermodynamic performance in moderately/high temperature heat pump, but high flammability, so its application is always restricted in industrial plant.

Table 1 : Basic properties, ODP and GWP of Refrigerants suitable to use in moderately/high temperature heat pump

Refrigerant	HFC152a	HCFC123	HCFC142b	HFC245fa	H_2O
Molecular weight	66.05	152.93	100.50	134.05	18
Boiling point(K)	-24.0	27.8	-9.1	15.1	0
Critical temperature(K)	113.3	183.8	137.1	154	374
Critical pressure(MPa)	4.52	3.66	4.06	3.65	22.064
ODP	0	0.02	0.07	0	0
GWP	124	77	2310	1030	<1

As an environment-friendly, low-price, safe and harmless refrigerant, water (R718) owns zero ODP and very low GWP(Calm J M. 1998), and its basic properties are listed in Table 1. With development of steam-jet, absorption and adsorption refrigeration and heat pump technology, water becomes a popular refrigerant, but is seldom used in vapour compression refrigeration and heat pump system. Water vapour compression refrigeration system was studied early by many scholars. Comparative study on thermodynamic properties of several natural refrigerants, such as air, carbon dioxide, propane and ammonia etc., are conducted by Paul (1994). Very low evaporation pressure and steep vapour pressure curve of water vapour result in some special requirements for water vapour compressor such as large volumetric flow rate and high pressure ratio. A scoping study of water vapour compressor was completed by Sharon E Wight et al in order to determine which compressor configuration might be “best” suited for water vapour compressor applications. The primary focus of this work was to determine the attainable efficiency and power levels, as well as approximate geometries of single and multistage axial and centrifugal compressors for the selected refrigeration cycle (Wight 2000). Through the thermodynamic calculation, it is found out that water as the working fluids of vapour compression cycle owns a higher coefficient of performance (COP) than many other refrigerants, and its value is higher than 9 (Yuan 2003). The principle and analytical model of water refrigeration system consisting of evaporator, vacuum pump and diffuser was described and a prototype water refrigeration system designed. The calculating results demonstrated that the system with working fluid of water can obtain relative high coefficient of performance (COP) comparing to R22 and ammonia (Shen and Cao 1999); The recent research work on high speed centrifugal refrigeration compressor was presented, and application prospect of such kind compressor for water vapour compression system was also discussed (Yu and Yuan 2005). The theory and merits & demerits of water compression refrigerating machine was discussed, and its application in chiller, heat pump, ice-making and ice storage system was also presented (Ren 2008).

In this paper, the performance characteristics of the water vapour compression heat pump cycle will be discussed in detail when the condensing temperature varies from 50°C to 140°C, and is compared with that of the heat pump system using the four organic fluids listed in Table 1 under the same basic operating conditions. Also, the feasibility of water as the working fluid for moderate/high temperature heat pump will be explored.

2. THERMODYNAMIC ANALYSIS OF HEAT PUMP CYCLE

The theoretical cycle for vapour compression heat pump is shown in Figure 1. In the P-h diagram, process 1-2 is isentropic compression process, process 2-3 is isobaric condensation process, process 3-4 is adiabatic throttling process, and process 4-1 is isobaric evaporation process. By thermodynamic calculation, the performance parameters of the heat pump are as follows.

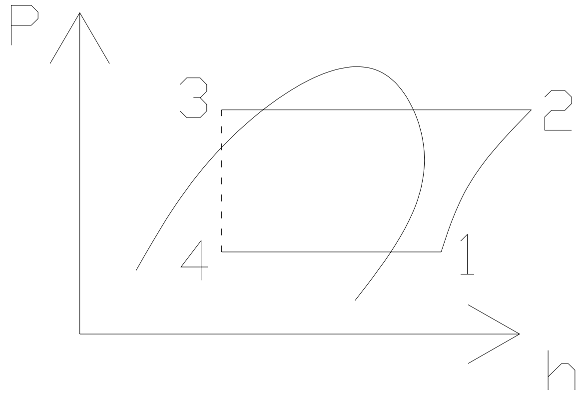

Figure 1 P–h diagram of the moderate and high temperature heat pump cycle

Referring to Fig.1, the heating capacity per mass flow rate of the working fluid is equal to the enthalpy difference between the inlet and outlet of the condenser, and can be written as:

$$q_c=h_3-h_2 \tag{1}$$

Where, h_2 is specific enthalpy at the condenser inlet and h_3 is specific enthalpy at the outlet.

And the specific volumetric capacity, viz. the heating capacity per volumetric flow rate of the working fluid can be written as:

$$q_v=q_c/v_1 \tag{2}$$

Where, v_1 is specific volume at the compressor inlet.

The compression work per mass flow rate of the working fluid can be written as:

$$w_p=h_2-h_1 \tag{3}$$

Where, h_1 is the specific enthalpy at the compressor inlet, and h_2 is the specific enthalpy of discharge gas at the compressor outlet.

The heating coefficient of performance of the heat pump is:

$$COPh=q_c/w_p \tag{4}$$

Using the above formula, the performance characteristics of the heat pump cycle for the 5 working fluids listed in Table 1 were calculated when the condensation temperature in the range from 50°C to 140°C. In the calculations, the temperature rise of the heat pump, viz. the temperature difference between evaporator and condenser, was considered to be 45°C. The superheating degree at the outlet of the evaporator was considered to be 5°C, and the subcooling degree at the outlet of the condenser was 5°C. It was assumed that the compression process is isentropic.

From Table 1, it is seen that the critical temperature of HFC152a and HCFC142b is relatively lower and their values are 113.3°C and 122.3°C, respectively. In practical application, the upper limit of their condenser temperature is fitted to be lower than 100°C, so the condensation temperature range of these two fluids in calculating the cycle parameters of the heat pump was taken to be from 50°C to 100°C. Other fluids listed in Table 1 own higher critical temperature and the value is more than 160°C. So, their condensation temperature range is taken to be from 50°C to 140°C.

3. RESULTS AND DISCUSSION

The thermodynamic properties of the working fluids for the cycle calculations were based on the equations, tables and diagrams in reference in the book (Cao and Shi 2003).

To compare the cyclic performance with various refrigerants, the operation conditions for the calculation should be decided at first. In the performance calculation for each refrigerant, the difference between the evaporation and condensation temperature was fixed at 45℃ while the condensation temperature varied from 50℃ to 140℃ without subcooling. For each refrigerant, the condensation pressure, coefficient of performance, compression ratio, specific volumetric capacity and discharge temperature were calculated under the various conditions, and the results were illustrated in the curves in the following sections.

The condensation pressure of the five fluids varying with condensation temperature is shown in Fig.2. It can be seen that the condensation pressure increase with condensation temperature, and the pressure of water rises very slowly and its pressure the lowest in the calculating range of condensation temperature, comparing to other fluids. When the condensation temperature is lower than 100°C, the condensation pressure of water is less than 1 atm, and the heat pump system using water runs in vacuum condition. Although it needs special design for its construction, the system is not restricted by the codes related to pressure vessel. The condensation pressure of water is only 0.3612 MPa when the condensation temperature is 140°C, so the heat pump using water is suitable for operating in conditions of high temperature exceeding 100°C. The condensation pressure of HFC152a is 2.342MPa when the condensation temperature is 80°C, and the condensation pressure of HFC142b is 2.13MPa when the condensation temperature is 100°C. Therefore, HCFC142b could be used in the heat pump operating in the conditions of condensation temperature below 100°C, and HFC152a the conditions of condensation temperature below 80°C based the pressure level borne by the existing vapour compression heat pump system.

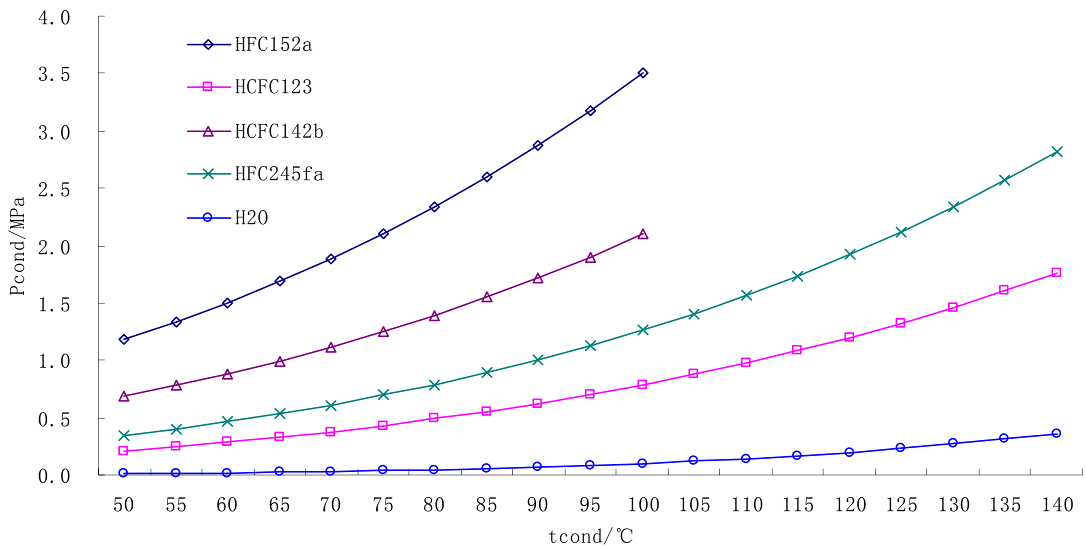

Figure 2 Condensation pressure of the 5 fluids varying with condensation temperature

The pressure ratio, viz. the ratio of the discharge pressure the suction pressure, affects directly the efficiency and discharge temperature of the compressor. The pressure ratio of the 5 fluids varying with condensation temperature is shown in Figure 3. It can be easily seen that the pressure ratio of the fluids decreases with increase of the condensation temperature, tcond, ranging from 50°C to 140°C. Among the five fluids, the pressure ratio when using water is highest and its varying trend is sharpest. For example, when the condensation temperature is 50°C, the pressure ratio using water is 14.3 and 3 to 4 times higher than that using other fluids, and it is 4.6 and 1.3 to 1.4 times higher than that using others when the condensation temperature is 140°C. This demonstrates that steam compressor owns much higher efficiency and more remarkable superiority when running under high temperature conditions than that under low temperature conditions.

The discharge temperature is directly related to the running reliability of the compressor, its variation with the condensation temperature is shown in Figure 4. It can be seen that the discharge temperature of the compressor using water in the calculating range of the condensation temperature is very particular. The discharge temperature will fall with increase of the condensing temperature when the condensing temperature is below 100°C. On the contrary, the exhaust temperature will increase when the condensing temperature is above 100°C. On the whole, the discharge temperature of the compressor using H_2O is the highest compared with other fluids, and its minimum value exceeds yet 250°C. Therefore, the discharge temperature will be quite high when H_2O is compressed as a working fluid. To solve this problem, in the actual products, the liquid injection to the compression chamber is usually used to make the discharge temperature dropping to about 150°C in the compressed process. It will prevent the compressor motor from operating abnormally as the high temperature protection device starts frequently.

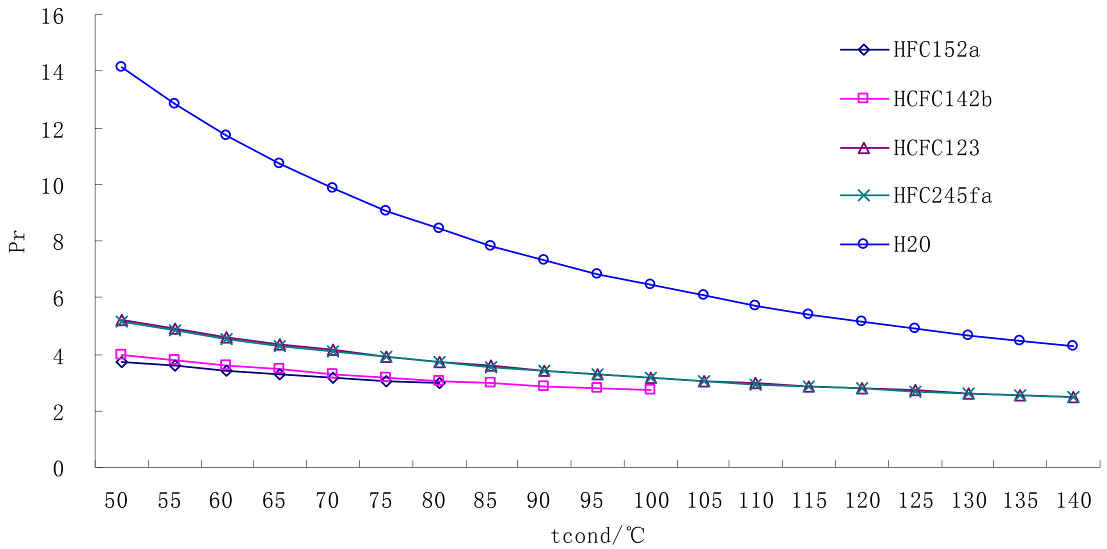

Figure 3 Pressure ratio of the 5 fluids varying with condensation temperature

Except the fluid of H_2O, the discharge temperature of the compressor using anyone of other fluids will increase as the condensing temperature increases. The discharge temperatures using HCFC123 is very close to that using HCFC245fa. When the condensing temperature reaches to about 140°C, the discharge temperatures using HCFC123 and HFC245fa, respectively, are both close to 140°C。 This will lead to compressor security risk if the compressor is running long time at such high discharge temperature. However, It is believed that the problem caused by high discharge temperature can be solved with the development of compressor technology, update of compressor material, and improvement of compressor manufacturing process.

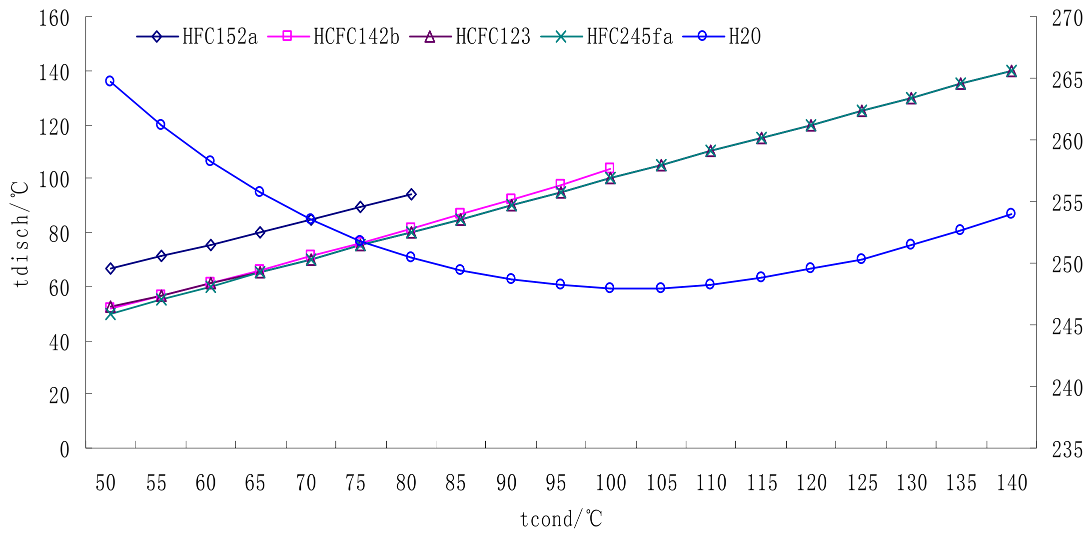

Figure 4 Discharge temperature of the 5 fluids varying with condensation temperature

The specific volumetric capacity varying the condensation temperature is shown in Figure 5. It is seen that the specific volumetric capacity for heating using anyone of the fluids will increase as the condensing temperature increases. In the whole condensing temperature range, the specific volumetric capacity using H_2O is clearly smaller than that using other fluid, and its curve changes much smoothly. For example, the specific volumetric capacity using H2O is 50kJ/m3 and about 0.25 percent of the capacity using HFC152a, whereas it is 1050kJ/m3 and about one fourth of the capacity using HFC152a. So the volume of compressor that uses H2O as refrigerant is quite large. Therefore, the size of the compressor using H2O is much large but becomes small with increase of the condensation temperature. The higher the temperature is, the more compact the compressor.

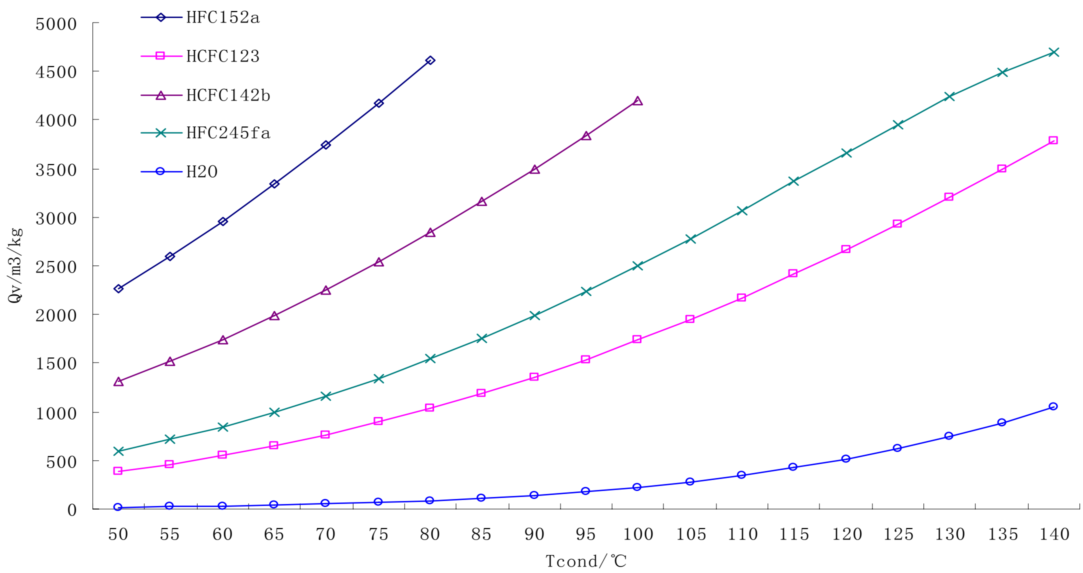

Figure 5 Specific volumetric capacity of the 5 fluids varying with condensation temperature

The COPh varying with the condensing temperature is show in Figure 6. It can be seen that the varying trends of the COPh using other fluids, viz. the curves will increase firstly and then descend as the condensing temperature increase, are almost consistent except the one using H_2O. Among the organic working fluids, the COPh using HCFC123 is the highest in the whole temperature range, and the COPh using HCFC142b is close to that using HFC245fa but is lower than that using HCFC123. And the COPh using HFC152a is the lowest. The COPh using H_2O rises significantly and linearly with increase of the condensing temperature. Its COPh is 50% higher with the condensing temperature of 50°C than that with the condensing temperature of 140°C. When the condensing temperature is below 70°C, the COPh using H_2O is lower than that using other organic fluids. The COPh using H_2O is higher than that using HFC152a but less than HCFC123 when the condensation temperature keeps between 70°C and 90°C. The COPh using H_2O is higher than that using HCFC142b and HFC245fa when the condensing temperature exceeds 75℃. When the condensing temperature is higher than 95°C, the COPh using H_2O is much higher than that using any of other fluids. This demonstrates that the heat pump system using H_2O as the working fluid will have better performance in the case of higher supply temperature.

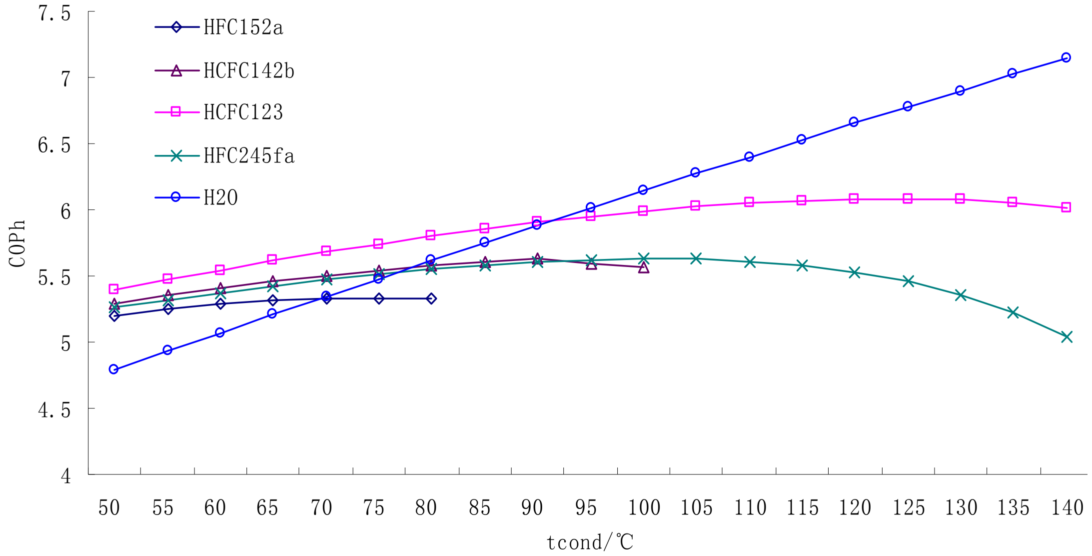

Figure 6 Coefficient of performance of the 5 fluids varying with condensation temperature

4. CONCLUSION

The performance characteristics of the water vapour compression heat pump cycle were analyzed in detail when the condensing temperature varies from 50°C to 140°C, and is compared with that of the heat pump system using the four organic fluids under the same basic operating conditions. The results show that water as the working fluid of heat pump has its unique characteristics, such as lower condensing pressure, higher pressure ratio and discharge temperature, and lower specific volumetric heating capacity. Therefore, the steam compressor own large size, and performs better under the conditions of high pressure ratio and great flow rate. In the calculating range, the coefficient of performance of the heat pump using H2O changes almost linearly with the condensing temperature, and higher than that using any of other organic fluids when the condensing temperature is above 95℃, and comparative when it is between 70℃than 95℃, and lower when it is below 70℃. So, the heat pump using water as working fluid has a perspective application particular in high temperature heat supply.

ACKNOWLEDGEMENTS

The study has been financially supported by the 8th Science Fund Project of Beijing University of Technology, No. ykj-2010-4529.

REFERENCES

Limin Ma, Huaixin Wang, Chenming Zheng and Fang Liu 2005.” Performances of Refrigerants and a Refrigerant Mixture for Moderate and High Temperature Heat Pumps”, Journal of Tianjin University, vol 38, No.8, pp 689-694.

Zhiyong Cao 2007.” Cycle Performance of Working Fluids for Moderate/High Temperature Heat Pump”, Tianjin: Tianjin University.

Tao Guo 2008. “Theoretical and Experimental Cycle Performance of Working Fluids for Moderate/High Temperature Heat Pumps”,Tianjin: Tianjin University.

Calm J M. 1998.” Preperty, Safety, andd Environmental Data for Alternative Refrigerants In:”, Earth Technologies Forum, Washington DC,pp 201-205

S. E. Wight, T. Yoshinaka and E. A. Brenda A. Le Drew 2000.” The Efficiency Limits of Water Vapor Compressor “, AIR-CONDITIONING AND REFRIGERATION TECHNOLOGY INSTITUDE,Virginia.

Weixing Yuan, Xiugan Yuan, Zhiqiang Yu 2003. “Theoretical Analysis On Vapor-Compression Refrigeration Cycle Using Water as Refrigerant”, Journal of Refrigeration, Vol. 24, No.3, pp. 16–19.

Guangyu Shen, Qi Cao 1999.” Technological Research in a Refrigeration System Using Water as Refrigerant”, Design and research,No.03, pp43-45.

Zhiqiang Yu, Weixing Yuan 2005.” Current State of High Rotation Speed Centrifugal Compressor”, Refrigeration and Air-conditioning,Vol.5,No.3, pp 1-3.

Jinlu Ren 2008. “Water Compression Refrigerating Machine “, Refrigeration and Air-conditioning ,vol 8,No B06, pp 53-59.

Desheng Cao, Lin Shi 2003. The application handbook for refrigerants (in Chinese), Metallurgical Industry Press of China.