ANALYSIS ON ENERGY SAVING POTENTIAL OF WATER-SOURCE HEAT PUMP IN CHINA

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Abstract: This paper analyzed the energy efficiency of water-source heat pump in China. Statistical data shows that the average value of EER and COP for water-source heat pump is 5.61 and 4.20, the thermodynamic perfectibility of units mainly focus on 0.3-0.5. Aiming to the characteristics of water-source heat pump, the technical analysis for improving energy efficiency was carried out. The technologies include, efficient compressor, quasi two-stage compression refrigeration cycle with economizer, falling film evaporator, partitioned condenser and expander. The calculation results show that the energy efficiency can increase by about 20%~30%. The prototype base on the technologies was also designed and tested. The performance of refrigeration conditions, heating conditions of 45°C and 55°C of the prototype are 6.64, 4.79 and 3.99 respectively.

Key Words: water-source heat pump, energy efficiency, thermodynamic perfectibility, energy saving potential

1 INTRODUCTION

Water-source heat pumps is an air conditioning and heat pump technologies, which take the solar energy stored by water and ground as cold and heat source, and obtain heating/cooling air or heating/cooling water. It has merits of stable performance, energy conservation and environmental protection, and has been more used widely in China. According to statistics, by the end of 2007, the application area of water-source heat pump has reached 80 million m^2 in China (Xu 2008). Although the water-source heat pump technologies has developed faster in recent years in China, the performance level of water-source heat pump has a certain gap while being compared with the foreign similar products (ASHRAE 2007, AQSIQ 2004). This is mainly because most refrigeration equipment manufacturers lack of technological innovation, on the one hand, the design and fabrication of heat exchangers is still in the primary level, on the other hand efficient compressors are also depends on import, which makes energy consumption increases.

This paper analyzed the water-source heat pump energy efficiency level in China, discussed the technical conditions to improve the water-source heat pump energy efficiency, and designed and fabricated prototype to verification. That has great practical significance for implementing energy saving policies and building a conservation-oriented society in China.

2 INVESTIGATIONS ON WATER-SOURCE HEAT PUMP ENERGY EFFICIENCY

2.1 Energy Efficiency Analysis with EER and COP

The data on energy efficiency of more than 1000 water-source heat pumps which obtain heating or cooling water in the market in China was collected. These data main come from samples of products provided by the manufacturers. Statistics on these data were represented in Figure 1 and Figure 2. Base on investigation of the market, several conclusions can be drawn from this analysis as follows:

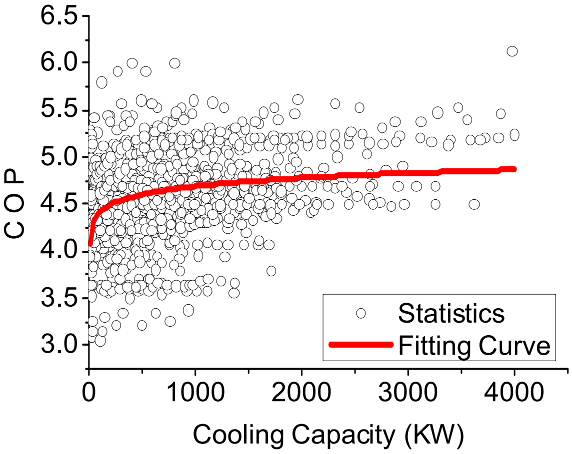

Figure 1: Heating Conditions

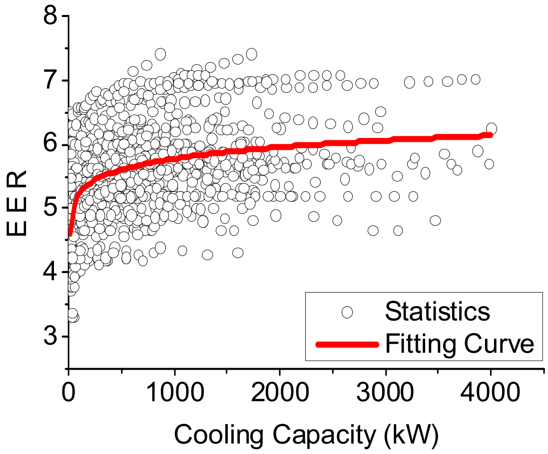

Figure 2: Refrigeration Conditions

1) Water-source heat pumps with a cooling capacity are less than 2000kW occupy most of the market.
2) When the cooling capacity is less than 2000kW, the COP (coefficient of performance under heating conditions) and EER (energy efficiency ratios under refrigeration conditions) of water-source heat pump increases as the cooling capacity increases. When it is more than 2000kW, a graph of the COP or EER forms an almost horizontal line, which means that the COP or EER will not change as the cooling capacity varies.
3) The energy efficiency of most of units is higher than the minimum allowable values in GB/T 19409-2003 shown in table 1, and it embodies the technical progress in water-source heat pump in China.

Table 1: The minimum allowable values in GB/T 19409-2003

Cooling Capacity [kW]	(0,14]	(14,28]	(28,50]	(50,80]	(80,100]	(100, ∞)
COP	3.1	3.15	3.2	3.25	3.3	3.35
EER	4	4.05	4.1	4.15	4.2	4.25

4) The enterprise technologies are uneven, with the same cooling capacity, the energy efficiency of products vary greatly.

2.2 Energy Efficiency Analysis with Thermodynamic Perfectibility

2.2.1 The concept of thermodynamic perfectibility

Thermodynamic perfectibility reflects the economy of refrigeration cycle, its significance is different from EER and COP. It reveals the practical refrigeration or heating cycle close to the reverse Carnot cycle level, its value is between 0 and 1. Thermodynamic perfectibility can exhibit a positive influence in analyzing and evaluating the energy efficiency of refrigeration and heat pump products.
The *T-S* diagram shown in figure 3 represents the vapor compression refrigeration cycle. In the diagram, the parallelogram a'-b'-c'-d'-a' is the ideal cycle, which is generally called the Lorenz cycle. It is determined by the temperature of cooling water and chilling water.

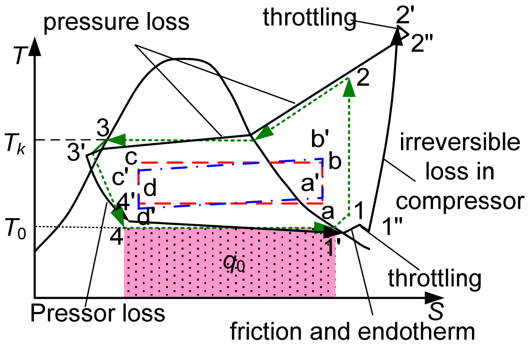

Figure 3: *T-S* diagram of Vapor Compressed Refrigeration Cycle

The rectangle a-b-c-d-a represents the inverse Carnot cycle equivalent to the Lorenz cycle mentioned above. To simplify the calculation, the temperature of the high and low temperature heat source is determined by the average temperature of the inlet and outlet temperature of cooling and chilling water. The EER_c and COP_c of the inverse Carnot cycle is calculated by the following Equations:

$$EER_c = T_{low}/(T_{high} - T_{low}) \quad (1)$$

$$COP_c = T_{high}/(T_{high} - T_{low}) \quad (2)$$

So, the COP_c of the inverse Carnot cycle for water-source heat pump is 10.45 under the standard heating conditions, the inlet and outlet temperature of the cooling water and chilling water are 40/45 ^oC and 15/7 ^oC (AQSIQ 2004) respectively. And the EER_c of the inverse Carnot cycle for water-source heat pump is 20.18 when calculate based on the standard refrigerant conditions, the inlet and outlet temperature of the cooling water and chilling water are 18/29 ^oC and 12/7 ^oC (AQSIQ 2004) respectively.

The polygon 1-2-3-4-1 represents the theoretical vapor compressed refrigeration cycle, and it is drawn based on the following assumptions: (1) the compressor efficiency is 100%; (2) the enthalpy during the throttling process is constant; (3) the evaporating and condensing process are both under the constant pressure, the evaporating and condensing temperature are related to the temperature of chilling water and cooling water. The cycle's EER_{th} or COP_{th} can be got by theoretical calculation.

The polygon 1'-2'-3'-4'-1' is the actual cycle, which considers the compressor's isentropic efficiency, the pressure losses during evaporating and condensing process and the irreversible losses during the throttling process. Its EER_r or COP_r can be obtained from actual testing.

According to the above analysis, thermodynamic perfectibility for refrigeration and heating conditions is respectively defined as,

$$\eta_{EER} = EER_r/EER_c \quad (3)$$

$$\eta_{COP} = COP_r/COP_c \quad (4)$$

2.2.2 Energy efficiency analysis with thermodynamic perfectibility

Using the thermodynamic perfectibility analysis, figure 4 and figure 5 show the results calculated base on figure 1 and figure 2. From the two figures, several conclusions can be drawn as follows:

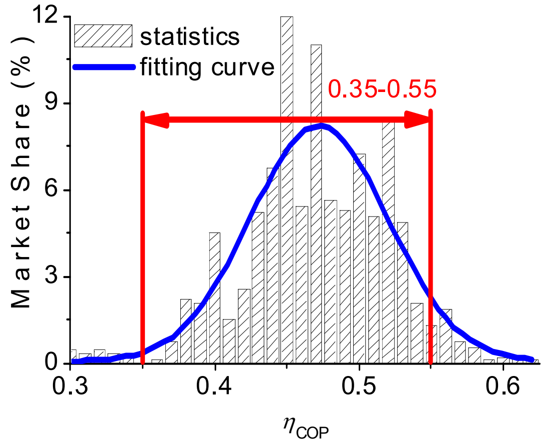

Figure 4: Market Share in the Range of Every 0.01 η_{COP}

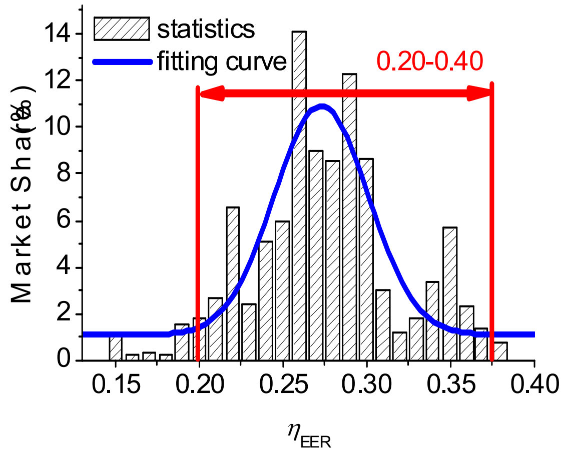

Figure 5: Market Share in the Range of Every 0.01 η_{EER}

1) The thermodynamic perfectibility of heating conditions mainly focus on 0.35-0.55, only a few efficient units can reaches up to 0.6. The thermodynamic perfectibility of refrigeration conditions mainly focus on 0.20-0.40, some inefficient units is only 0.15. Therefore, there is a great potential to improvement for most units.
2) The thermodynamic perfectibility of heating conditions is significantly higher than that of refrigeration conditions. The main reason is that current screw compressors and centrifugal compressors are difficult to reach higher energy efficiency for both heating conditions and refrigeration conditions.
Form this analysis, it is easy to show that the thermodynamic perfectibility based on the second law of thermodynamics reveals the degree of deviation of the actual cycle from the ideal cycle, it reflects the current manufacturing level of thermal machines and heat exchangers, and this implies the possibility for improvement.

3 TECHNICAL CONDITIONS ANALYSIS FOR IMPROVING WATER-SOURCE HEAT PUMP EFFICIENCY

The unit efficiency can be improved by improving the performance of refrigeration system components and/or improving the refrigeration cycle.

3.1 Improving Compressor Efficiency

Currently, the screw compressors or centrifugal compressors are adopted for large and medium-size water-source heat pump units. They are the most important part of the refrigeration or heat pump system, so the improvement of compressor efficiency plays an important role in improving the performance of the refrigeration cycle. By calculating, it can be seen that the thermodynamic perfectibility of the cycle increase 0.021 with the compressor efficiency increase 0.05. To obtain a higher efficiency compressor, we should optimize the design of the compressor first, and reduce the various irreversible loss. About this content, repeat no more in this paper.
Compressor efficiency will change as the conditions vary, this is particularly important for heat pump units. For one type of compressor there is the higher efficiency only in a certain condition. Figure 6 shown the efficiency (include motor efficiency) of three type of screw compressor changes with the conditions vary. As seen from the figure, the conditions with the total efficiency between 0.6 and 0.7 should be chosen.

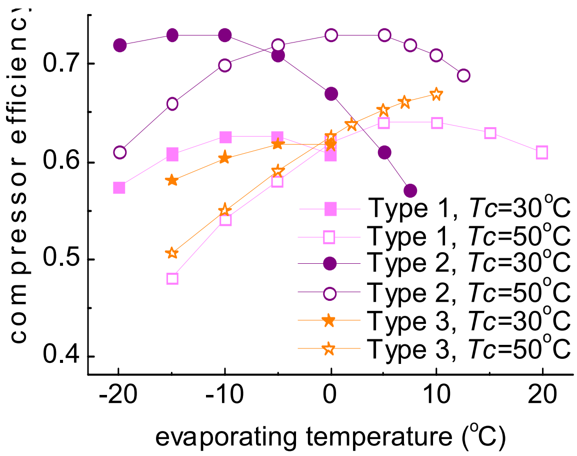

Figure 6: The Change of Compressor Efficiency under the Different Conditions

Normally, heat pump units are designed according to heating conditions, the heating temperature under heating conditions is higher than the cooling water temperature under refrigeration conditions, the compression ratio is also much higher than that of refrigeration conditions. This has resulted in the thermodynamic perfectibility of heating conditions being higher than that of refrigeration conditions. So the compressors require special design. For centrifugal compressors, in order to reduce compression ration when refrigeration conditions, the throttling method such as intake throttling is adopted, but that will increase irreversible loss and decrease the EER. Therefore, the method of variable-frequency regulating or changing stages of compressor can be used to improve the energy efficiency. For screw compressors, the changes of compression ratio will probable cause over-compressing or under-compressing, this can also lead to the unit performance decline. Currently, the advanced design scheme of changing compression ratio is changing the screw effective length with slide valve, namely adjusting the interior volume ratio.

3.2 Adopting Quasi Two-stage Compression Refrigeration Cycle

The quasi two-stage compression refrigeration cycle with economizer can increase more heating capacity but less power consumption for heat pump system, so the system performance can be improved obviously (Zhao et al. 2006), and it has the remarkable energy saving effect.

The flow diagram and lg*p*-*h* diagram of quasi two-stage compression cycle with throttling forward economizer were shown figure 7. The higher temperature and higher pressure refrigerant discharged by compressor enters condenser and releases heat. Then the refrigerant enters economizer and flashes via the first throttling, of which the medium pressure refrigerant vapor enters the air compensating hole of screw compressor, and the liquid refrigerant enters evaporator after depressurizing by the second throttling. The refrigerant after heat absorbing and gasifying in evaporator was inhaled by the inlet of compressor, and was compressed a certain pressure. Then mixing with the medium pressure refrigerant vapor inhaled through the air compensating hole, and was discharged by compressor after further compression. This completes the cycle.

Hypothesizing the air compensating process of screw compressor is a process that the refrigerant pressurizes under thermal insulation and mixes under constant volume. So the equation 5 can be got according to the energy balance in air compensating process,

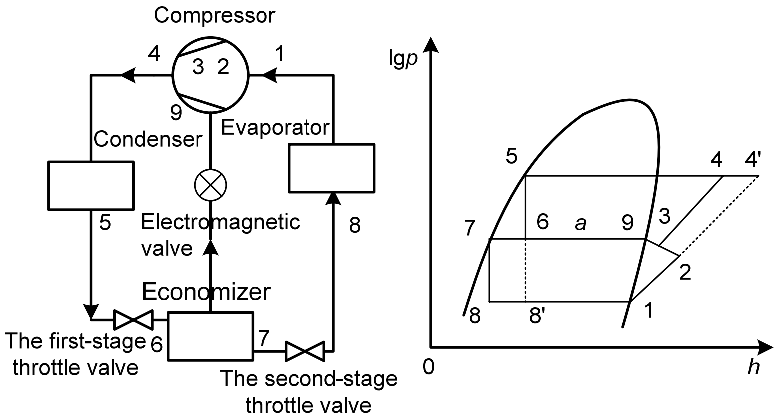

Figure 7: The Flow Diagram and lg*p*-*h* Diagram of Water-source Heat Pump with Economizer

$$(1+a)h_3=ah_9+h_2 \tag{5}$$

$$a=\Delta m/m \tag{6}$$

Wherein, a is the relatively air compensating of compressor, kg/kg. m is the refrigerant flow rate of evaporator, kg/s. Δm is the medium pressure refrigerant vapor flow rate enters compressor through the air compensating hole, kg/s. h is the enthalpy, kJ/kg. Subscript represents the state point, the same below.

Moreover, the other formula of a can also be obtained by the energy balance of economizer,

$$a=(h_9-h_6)/(h_6-h_7) \tag{7}$$

The power consumption of air compensating before and after are determined by equation 8 and 9 respectively.

$$W_{2\text{-}1}=m(h_2-h_1) \tag{8}$$

$$W_{4\text{-}3}=m(_1+a)(h_4-h_3) \tag{9}$$

Then, the heating capacity and COP are defined as respectively,

$$Q_c=m(1+a)(h_4-h_5) \tag{10}$$

$$\text{COP}=Q_c/W= m(1+a)(h_4-h_5)/(W_{2\text{-}1}+W_{4\text{-}3}) \tag{11}$$

If the single-stage vapor compression refrigeration cycle is adopted, the coefficient of performance is determined by the following formula,

$$\text{COP}'=Q_c'/W'=(h_4'-h_5)/(h_4'-h_1) \tag{12}$$

Compared with the single-stage vapor compression refrigeration cycle, the COP of quasi two-stage compression refrigeration cycle increase degree is defined as,

$$\lambda_{\text{COP}}=(\text{COP}-\text{COP}')/\text{COP}' \tag{13}$$

This paper takes a water-source heat pump with cooling capacity of 250kW for example, refrigerant is R22. The energy efficiency of quasi two-stage compression refrigeration cycle and single-stage vapor compression refrigeration cycle are calculated respectively under different conditions (obtain different heating water temperature between 40 and 60^{o}C, and different chilling water temperature between 4 and 11^{o}C). The results were shown in figure 8.

As can be seen from the figure, the performance of heating conditions and refrigeration conditions were both increase when adopting quasi two-stage compression refrigeration cycle. The increase degree of heating conditions is higher than that of refrigeration conditions under the calculation conditions. The increase degree increases as the heating water temperature increases under heating conditions, but the increase degree decreases as the chilling water temperature increases under refrigeration conditions. Under the standard heating and refrigeration conditions (heating water temperature of 45^{o}C and chilling water temperature of 7^{o}C), the performance increase 7.3% and 4.5% respectively.

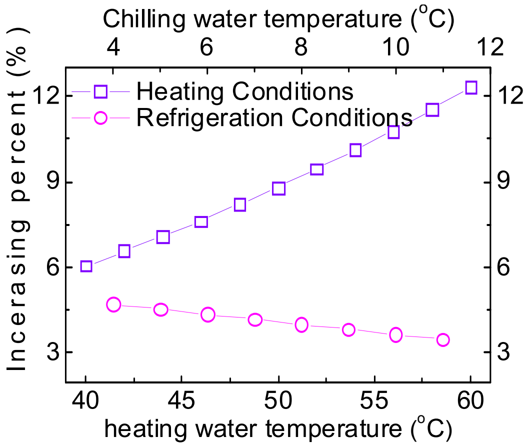

Figure 8: COP Calculation Results of the Two Refrigeration Cycles

3.3 Reducing Heat Transfer Temperature Difference

The heat transfer temperature difference is an important factor for the departure of practical heat pump cycle from the ideal reverse Carnot cycle. From equation 14 (Zeng et al. 2002), it can be seen that the larger the heat transfer temperature difference, the higher the irreversible loss and the deviation extent from ideal cycle.

$$E_{n,heatex} = \int_1^2 dQ \frac{T_1 - T_2}{T_1 T_2} T_a \qquad (14)$$

Usually, in the refrigeration system design, the condensing temperature is 3~5°C higher than the outlet temperature of cooling water, and the evaporation temperature is 2~4°C lower than the outlet temperature of chilling water. But, for water-source heat pump, the temperature difference reaches 11°C between inlet and outlet of cooling water under refrigeration conditions, and that is also 8°C between inlet and outlet of chilling water under heating conditions. So if the water-source heat pump is designed according to the traditional methods, the heat transfer temperature difference is larger and the EER or COP certainly will decrease. And this time, the methods, (1) increasing the heat transfer area appropriately, (2) designing the heat exchangers in partition and forming step heat transfer, (3) using the materials with heat transfer of surface strengthening treatment, can be adopted to reduce the heat transfer temperature difference.
Currently, the flooded evaporator is used for the large and medium-size water-source heat pump, and in recent years the falling film evaporators have also got application (Gherhardt and Anthony 2005, Roques et al. 2002, Mohamed 2007). Figure 9 shows the structure of falling film evaporator. The main characters are as follows, (1) having a higher heat transfer coefficient; (2) simplifying return oil system and reducing cost; (3) neglecting the refrigerant pressure drop of pipe and therefore the temperature difference loss can be decreased; (4) reducing refrigerant charge, According to the statistical analysis of the large quantity data, it can be seen that the refrigerant charge of units with falling film evaporator is about 30% less than that of units with flooded evaporator under the same cooling capacity (Ma and Wang 2010).

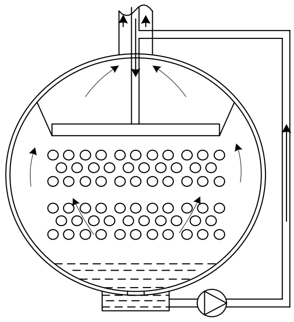

Figure 9: Falling Film Evaporator

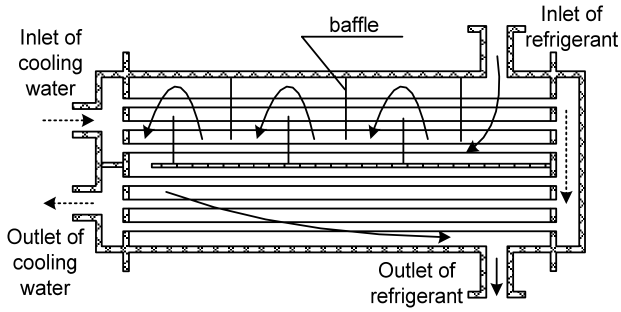

Figure 10: Partitioned Condenser

The condensation process of high temperature and high pressure refrigerant in condenser can be divided into superheated vapor region, two phase region and supercooled liquid region. So the condenser can be design in partition to strengthen condensation heat transfer and reduce heat transfer temperature difference, seen in figure 10. The upper portion of horizontal shell and tube condenser is the superheated vapor region, and in which the multiple baffles are set to increase the refrigerant vapor speed and strengthen heat transfer. The under part is the two phase region and supercooled liquid region, to obtain the reasonable temperature match the reasonable heat transfer are and enhanced heat transfer surface is designed.

3.4 Recovering Expansion Work

The throttling process is irreversible process, the expansion work loss changes into heat and is absorbed by refrigerant, so the effective cooling capacity is decrease and the refrigeration cycle performance also decreases. Especially under the heating conditions, the higher the heating water temperature, the larger the irreversible loss.

The expansion work can be recovered by using expander instead of throttle valve. And some research achievements about expander have got on CO_2 refrigeration or heat pump system (Nickl et al. 2005, Li et al. 2008). But for the other refrigerants, the expander is not easy to technically attain because of the larger expansion ratio and the design difficulty of gas-liquid two-phase flow expander.

Figure 11 shows the variation of recovery ratio (defines as percentage of expansion work recovered account for the compressor power consumption) with the change of expander efficiency under the different conditions, and the refrigerant is R22. As you can see from figure 11, expansion work recovered increases with expander efficiency is increase, and the increase amplitude is also increase with expander efficiency increases. The expansion work recovered of heating conditions is higher than that of refrigeration conditions under the same efficiency. The higher the water temperature, the larger the expansion work recovered, this is because compression ratio increase makes the inlet pressure and temperature of expander increasing, and the work capability of expansion also increases accordingly.

An experimental study on the centrifugal chiller with expander is presented by Carrier. The refrigerant is R134a, and the total cooling capacity is 8720kW. The results show that the actual expansion work recovered is 54kW, it accounts for 64% and 2.5% of the ideal expansion work recovered and the compression power consumption respectively (Ma et al. 2003). Although the expansion work recovered is not much for each unit, it foots up to a respectable sum aiming at the application of air conditioning and heat pump in China. That offers a possible way to increase energy efficiency and decrease energy consumption for water-source heat pump.

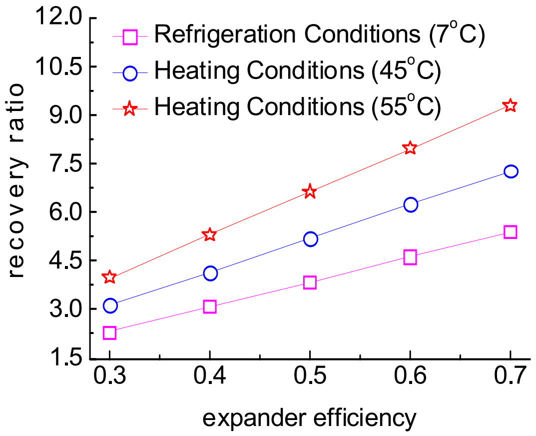

Figure 11: Recovery Ratio under the Different Conditions

Figure 12: The Water-source Heat Pump Prototype

4 ANALYSIS ON ENERGY SAVING POTENTIAL OF WATER-SOURCE HEAT PUMP

Base on the technologies above, the energy efficiency of new water-source heat pump was calculated. The prototype shown in figure 12 (not include expander) was also designed and tested to verify the energy saving potential. The calculation results and test results were shown in table 2.

Table 2: Improvement Potency

Data Source	Refrigeration conditions		Heating conditions of 45°C		Heating conditions of 55°C	
	EER	η	COP	η	COP	η
Traditional Design	5.34	0.264	4.11	0.410	3.34	0.426
Statistical Data	5.61	0.270	4.20	0.423		
New Unit Calculation Results	7.03	0.348	5.22	0.521	4.32	0.550
Compare with Traditional Design	32%	32%	27%	27%	29%	29%
Compare with Statistical Data	25%	29%	24%	23%		
Test Data	6.64	0.329	4.79	0.470	3.99	0.508

The results indicate that the performance of new unit has greatly improved compare with the traditional units, it increases by about 20%~30%. Therefore, the technologies mentioned previously both have a good energy saving effect.

5 CONCLUSION

The energy efficiency of water-source heat pump in China was analyzed in this paper. Although, the technologies of water-source heat pump in China have a progress, the performance level is still quite low because of short of technological innovation. Aiming to the characteristics of water-source heat pump, the analysis of some technologies for improving energy efficiency was carried out, and the prototype base on the technologies was also designed and tested to verify the energy saving potential. From this study, some overall conclusions can be made, as follows:

(1) The average value of EER and COP for water-source heat pump is 5.61 and 4.20, and the corresponding thermodynamic perfectibility is 0.270 and 0.423. In the market, the thermodynamic perfectibility of units mainly focus on 0.3-0.5, only a few efficient units can reaches up to 0.6, some inefficient units is only 0.15. Therefore, there is a great potential to improvement for most units.

(2) Some methods include, efficient compressor, quasi two-stage compression refrigeration cycle with economizer, falling film evaporator, partitioned condenser and expander can reduce

the irreversible loss and increase the thermodynamic perfectibility. The energy efficiency can increase by about 20%~30% compared with the traditional units.
(3) The performance of refrigeration conditions, heating conditions of 45°C and 55°C for the prototype are 6.64, 4.79 and 3.99 respectively. This verifies the energy saving potential.

6 ACKNOWLEDGEMENTS

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