PERFORMANCE OF A HEAT PUMP WATER HEATER AT VARIABLE CONDITIONS

Ling-Yu, Chao, Researcher, Green Energy and Environment Research Laboratories, Industrial Technology Research Institute, Bldg. 64, 195, Sec. 4, Chung Hsing Rd., Chutung, Hsinchu, Taiwan 31040, R.O.C.
Hung-Wen, Lin, Researcher, Green Energy and Environment Research Laboratories, Industrial Technology Research Institute, Bldg. 64, 195, Sec. 4, Chung Hsing Rd., Chutung, Hsinchu, Taiwan 31040, R.O.C.
Shy-Her, Nian, Researcher, Green Energy and Environment Research Laboratories, Industrial Technology Research Institute, Bldg. 64, 195, Sec. 4, Chung Hsing Rd., Chutung, Hsinchu, Taiwan 31040, R.O.C.
Hsu-Cheng, Chiang, Researcher, Green Energy and Environment Research Laboratories, Industrial Technology Research Institute, Bldg. 64, 195, Sec. 4, Chung Hsing Rd., Chutung, Hsinchu, Taiwan 31040, R.O.C.

Abstract: This study investigates the performance of R410A heat pump water heater at various weather conditions. A household heat pump water heater with R410A refrigerant has been developed in ITRI. The tube-in-fin evaporator, tube-in-tube heat exchanger have been designed with in-house software based on R410A system. Meanwhile, all components have been manufactured and supplied by local companies. The assembling, optimizing tuning and performance also have been executed in a certificated laboratory in ITRI. The refrigeration system was judged according to the variable inlet temperatures of water and the weather of hot water demand. At specified condition of Taiwan domestic requirement which the water inlet and outlet temperature are fixed at 15 ℃and 55℃ respectively, the tested heat pump water heater had the heating capacity of 6.4 kW and the coefficient of performance (COP) was equal to 4.07. The operation of heat pump has shown that refrigerant subcooling was increasing with decreasing water inlet temperature. The result has also indicated that evaporator had larger pressure drop in the winter test condition because of the large volume of vaporized refrigerant which with a large specific volume resulted in a high flow resistance. It is suspected that the refrigerant subcooling at condenser outlet was limited by the high condenser water inlet temperature. The optimal operation conditions for the heat pump system, after a carefully examination of the measuring data, have concluded as following that the water inlet temperature should be kept as low as possible to obtain a larger subcooling, and the pressure ratio between the compressor inlet and outlet can be reduced such that the compressor power input is reduced as well.

Key Words: heat pump water heater, R410A, refrigeration system

1 INTRODUCTION

About 97% of energy resources used in Taiwan is imported. In consideration of high energy price and global warming effect, encouraging the use of high efficiency and environmental protection products is one of the energy-saving policies. Taiwan is located in the subtropical zone, and its climate is warm all the year round. Consequently, the expansive energy cost for providing hot water in living can be reduced when a high efficiency heat pump water heater is used.

Heat pump water heater is a machine that transfers heat from a source to others by employing a refrigeration cycle. A heat pump reverses the heat flow direction and acts as a pump to move the heat from lower to higher temperature sites. Hence, heat pump can be used both for heating in winter and for cooling in summer. In a refrigeration cycle, refrigerant is compressed to a high temperature for dissipating heat to the ambient and then expanded to reach a low temperature state for absorbing heat. Heat pump transfers heat to heat up the desired space during the winter period and, by reversing the operation, extracts heat from the same region to be cooled during the summer period.

Commercial applications of heat pump were introduced in 1950s. But Hepbasli and Kalinci (2009) pointed out that the growing utility rates inevitably made electric furnaces less competitive, and in the mean time, heat pump with its improved quality of control became more attractive. From another aspect, Harris (2005) said that the oil crisis in the early 70s had led researchers to use alternative energy sources for thermal energy production. Therefore, heat pump became very popular for heating and cooling applications and gradually developed diverse system designs including those with the ground and air heat sources.

This study aims to investigate the performance of heat pump water heater at various weather conditions. Three weather conditions and three water inlet temperatures combine a total 9 sets of experimental measurement. The results are presented as coefficient of performance (COP) and power consumption of the tested heat pump system. Sequentially, the pressure versus enthalpy diagrams showing the cycling status of system are discussed too. From the test observation, the operating characteristics of each component (*i.e.* compressor, evaporator and condenser) can be indentified by the experimental system set-up.

2 EXPERIMENTAL SYSTEM

The schmatic of the heat pump water heater is depicted in Fig.1. The system is composed of a scroll compressor, condenser, expansion valve, fin-tube evaporator and water tank. The refrigerant was driven by a scroll compressor with constant speed control from , and the maximum allowable pressure at the compressor discharge was 38 kgf/cm^2. The condenser, which is made of copper tube, is a coil-typed heat exchanger, with effective heat transfer length of 20 meters. The coiled tubes for water and refrigerant flow lay on top of each others and soldered at their adjacent contacts. Their outer diameters are 9.525mm (3/8") and 6.35mm (1/4"), respectively. Its detail configuration can be seen in Fig. 2. The water flow inside the smaller tube and the refrigerant flow inside the bigger tube imply a counter-flow heat transfer to obtain a smaller temperature differential. The temperature of inlet water was controlled by a thermostat to maintain at a specific test condition. The electronic expansion valve was used to regulate the refrigerant flow and heat transfer in the evaporator. The evaporator is a fin-and-tube typed heat exchanger made of aluminum fin and copper tube. The dimension of evaporator is 700 mm x 672 mm in cross-section and has tube diameter 7.93 mm , tube pitch 21 mm and fin pitch 2 mm.

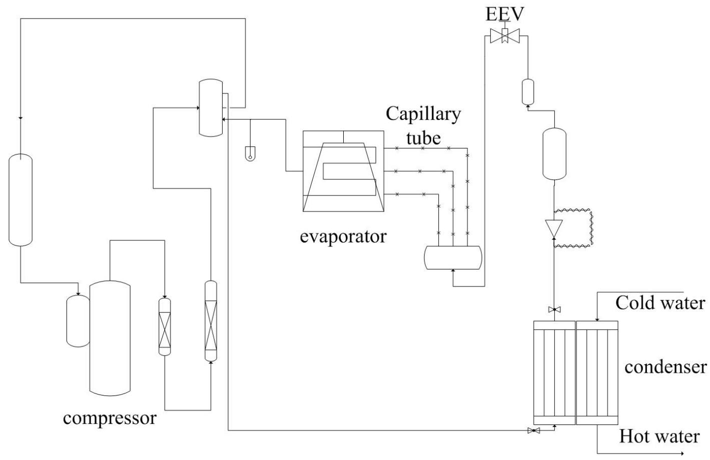

Fig. 1. Schematic of the heat pump water heater system

Fig.2. A close-up picture of the condenser

The water and refrigerant temperatures were measured by RTDs (Pt 100 Ω) with a calibrated accuracy of 0.5^{o}C, while the surface temperatures of the evaporator were measured by T-type thermocouples. Absolute pressure transducers were installed at the inlet and outlet of the compressor and the electronic expansion valve. The compressor power consumption was measured by a power meter with a maximum ranges of 10 A and 600 V. The water flowrate of the condenser was recorded by a magnetic flowmeter of accuracy 0.002 l/s. Therefore, the heat transfer can be calculated by multiplying the specific heat, flowrate and water temperature difference between inlet and outlet of the condenser. Experimental tests were conducted at three inlet water temperatures of the condenser, namely 9 ^{o}C, 17 ^{o}C and 25 ^{o}C. In addition, the weather conditions, as shown in Table 1 according to a Japanese Standard JRA-4050 entitled “water side calorimeter method”, were implied. To set up these test conditions, the high side pressure of the refrigeration system was regulated in-between 7.5 and 37 kgf/cm^2 by adjusting the electronic expansion valve. In the process, the temperature and pressure responses at the inlets and outlets of each component and power consumption of the system were recorded. When the variation of temperature measurement was less than ±0.3^{o}C and that of pressure measurement was less than ±5 kPa and continued for 30 min, the system was assumed steady and data were collected for further calculation. Table 2 lists the test condition adopted in this experimental study.

Table 1. JRA 4050 test standard

	Water side		Air side	
	Cold water inlet temperature(℃)	Hot water outlet temperature (℃)	Dry bulb temperature(℃)	Wet bulb temperature(℃)
Normal heating condition	17±1.0	65±2.0	16±1.0	12±0.5
Summer heating condition	24±1.0	65±2.0	25±1.0	21±0.5
Winter heating condition	9±1.0	65±2.0	7±1.0	6±0.5

Table 2. Experimental test conditions in this study

	Cold water inlet temperature(℃)	Hot water outlet temperature (℃)
Normal heating condition	15±1.0 25±1.0 35±1.0	55±2.0
Summer heating condition	15±1.0 25±1.0 35±1.0	55±2.0
Winter heating condition	15±1.0 25±1.0 35±1.0	55±2.0

3 EXPERIMENTAL RESULTS AND DISCUSSION

The experimental observation shows that the compressor used in this heat pump system had a refrigerant mass flow rate of 0.032 kg/s when condensing pressure was 3.35 Mpa and evaporating pressure was 1.0 MPa. The pressure conditions corresponded to the condenser outlet temperature of 20 °C, the evaporating temperature of 9°C, and the compressor outlet superheating temperature of 90 °C.

The coefficients of performance at different water inlet temperatures are shown in Fig.3. COP increases as dry-bulb temperature increases. Also noting from this figure, COP is increasing with decreasing water inlet temperature significantly when holding the same weather conditions. For different climates, namely winter, normal and summer conditions, COPs have the values of 3.23, 4.07 and 4.38 respectively when the inlet water temperature is 15°C. As the water flow rate was corresponded to outlet temperature in the experiment, when detected a temperature drop of water outlet temperature, the pump operating speed was increased to maintain the demanded water outlet temperature. Hence, the water mass flow rate was increased as well. Lower water inlet temperature could lead to the foresaid condition, but in this circumstance, higher COP was obtained due to a higher refrigerant subcooling and a better compressor performance. Fig.4 depicts the profiles of power consumption versus water inlet temperature. As the condenser water temperature increase was small such as in the case of water inlet temperature of 25°C, the heat pump could heat up the water to 55°C easily without doing much work. On the contrary, the power consumption was larger at the situation of 15°C inlet water temperature. There is no doubt that heat pump water heater needed more power input to generate more heat in order to maintain the setting water outlet temperature. Fig.5 presents the variation of the condenser refrigerant inlet temperature as a function of water inlet temperature. It is evident in the figure that the condenser inlet refrigerant temperatures were the lowest in normal, medium in winter and the highest in summer condition. The variation of temperature could be attributed to the effects of both compressor work input and compressor isentropic efficiency. The highest condenser inlet refrigerant temperature (eq. more than 90°C) was found at the conditions of the summer weather condition and at the high water inlet temperature of 35 °C. At these test conditions, the combination of large refrigerant flow rate and less compressor heat loss resulted in the highest compressor refrigerant discharge temperature which could be used to improve heat exchange with water in the condenser.

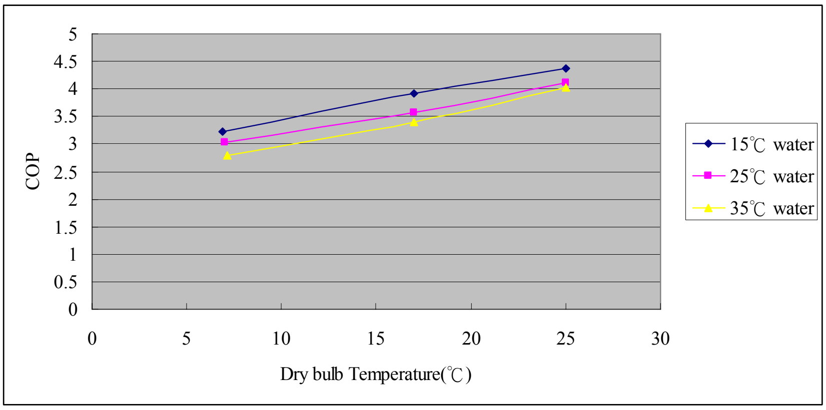

Fig.3. COP versus various water inlet temperature

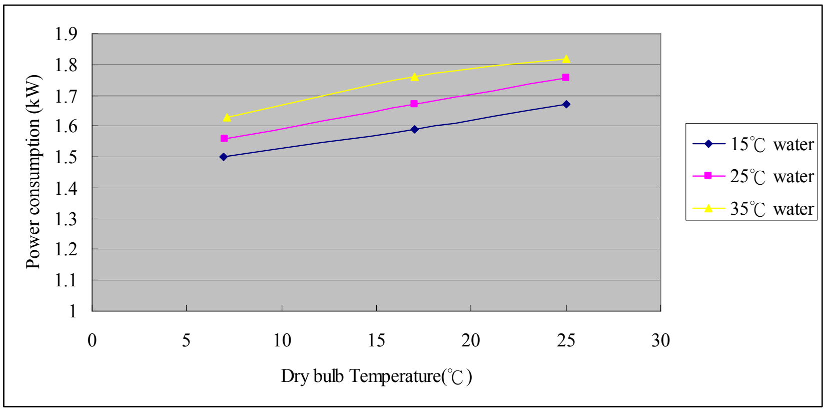

Fig.4. Power consumption versus various water inlet temperature

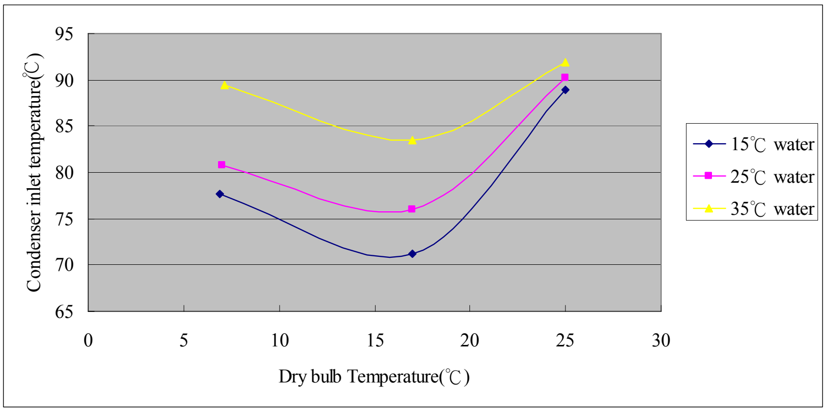

Fig.5. Condenser refrigerant inlet temperature versus inlet water temperature

Fig.6 to Fig.8 present the pressure versus enthalpy diagrams of heat pump water heater in different weather conditions and with various water inlet temperatures. Fig.6 illustrates the relationship at different water inlet temperatures in the winter condition. Black, blue and red color lines stand for the refrigeration cycles at the water inlet temperature of 15°C, 25°C and 35°C, respectively. Similarly, the cycles are drawn in Fig.7 for the normal weather condition and in Fig.8 for the summer condition. In the summer condition, the system had the largest refrigerant subcooling when the inlet water temperature was 15°C. In the winter condition, due to the low ambient temperature, the condensing temperature decreased slightly. In addition, when the evaporator could not absorb enough heat from the surrounding environment, the compressor must operate at a higher speed to create a low evaporating pressure and temperature condition to maintain the demanded water outlet temperature. Moreover, due to the large specific volume of vaporized refrigerant, there was a very large pressure drop in the evaporator compared to other weather conditions. In contrast, the evaporating pressure was the highest in the summer condition because of the high ambient temperature and the easy heat gain from the ambient. Consequently, the inlet pressure of the compressor in the summer condition was higher than that of the winter condition. Thus, the compressor needed less work input in the summer condition.

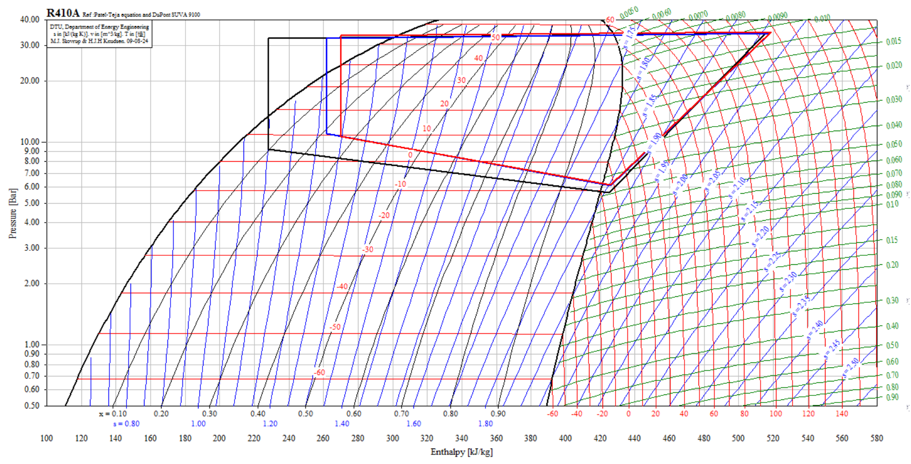

Fig.6 System PH diagrams for three water inlet temperatures in the winter weather condition.

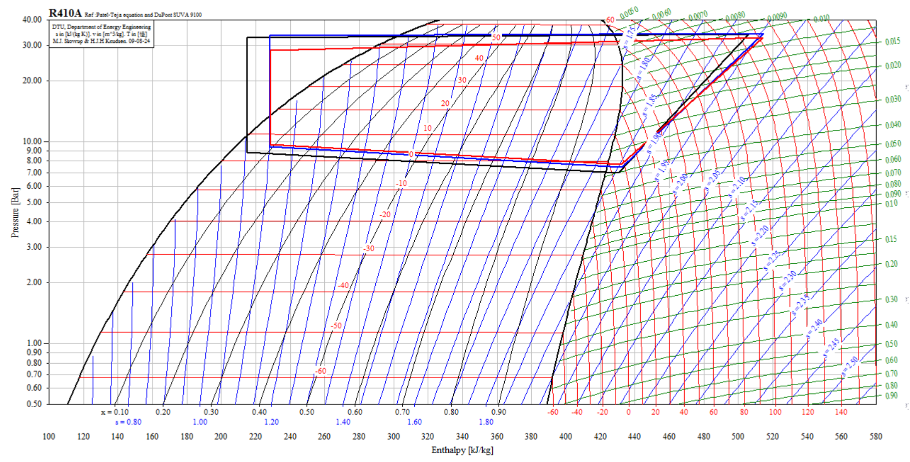

Fig.7 System PH diagrams for three water inlet temperatures in the normal weather condition.

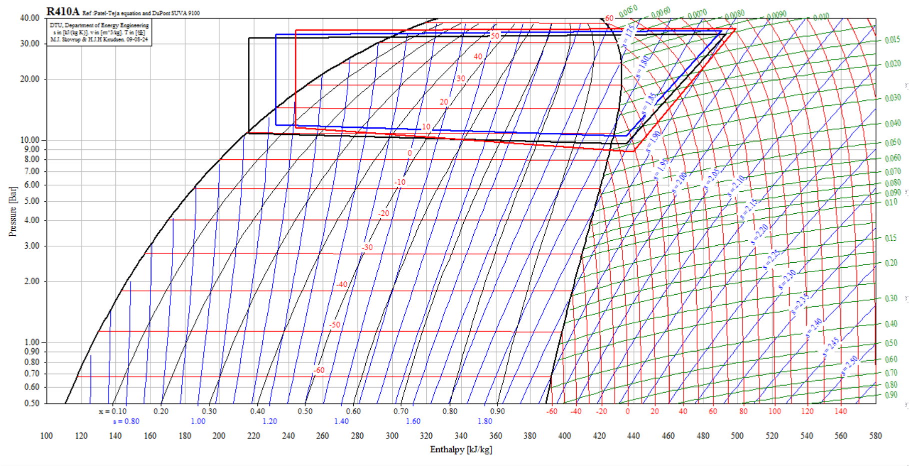

Fig.8 System PH diagrams for three water inlet temperatures in the summer weather condition.

4 CONCLUSIONS

This paper reveals some system characteristics found in the experimental study of a novel heat pump water heater. The influences of ambient temperature and inlet water temperature on the performance of the heat pump water heater were examined. As the ambient temperature was kept at 25°C, the COP of the heat pump could reach a high value of 4.0. Evidentially, the high performance could be attributed to the increasing refrigerant subcooling in the low water inlet temperature condition. However, the risk of liquid compression increases if the refrigerant flow control valve is inappropriately functioning. Some optimal system design ideas were found in the prototype test. For examples, the temperature of water extracted from the tank should be kept as low as possible in order to obtain a maximum refrigerant subcooling and, as a result, an improved COP of system. The capacity of evaporator was strongly dependent on the ambient temperature. The evaporator easily absorbed more heat as the ambient temperature was high, and consequently, the evaporating pressure was high. Furthermore, the compressor loading was reduced because of a smaller compression ratio.

Refrigerant superheating was affected by the refrigerant temperature at evaporator inlet and the compressor overall performance. Under such circumstances, the best choice of the condensing temperature should be adjusted in the range of 55 to 60 °C if the demanded water outlet temperature was kept at 55°C. To avoid the compressor overloading, the condensing temperature should not exceed to 60°C and moreover, water inlet temperature should not exceed to 45°C. These experimental results have summarized the best operating conditions which should be useful in constructing an optimal control strategy for an energy-saving heat pump water heater.

5 ACKNOWLEDGEMENTS

The authors would like to express gratitude for Energy R&D funding from Bureau of Energy, Ministry of Economic Affairs, R,O.C. (Taiwan) to support this research work.

6 REFERENCES

1. Arif Hepbasli, Yildiz Kalinci 2009, A review of heat pump water heating systems, *Renewable and sustainable energy reviews* 13:1211-1229

2. Harris J, Neme C, Calwell C. 2005, Residential heat pump water heaters: energy efficiency potential and industry status. *Energy Efficiency Potential and Industry Statu*
3. Christopher L. Goodman, 2008, Modeling, validation and design of integrated carbon dioxide heat pump and water heaters, thesis, *Georgia Institute of Technology*, 33-38p.
4. C. Kuo, S. Nian, L. Chao, 2009, An experimental study of performance of heat pump system using carbon dioxide, *International Conference on Compressors and Coolants*, Slovak Republic.