

EXPERIMENTAL INVESTIGATION ON OPTIMAL TEMPERATURE LIFT OF AN INVERTER HEAT PUMP SYSTEM

by

**Fang WANG^a, Xiao-Wei FAN^{a*}, Hui-Fan ZHENG^a, Di XU^b,
and Xian-Ping ZHANG^c**

^a School of Energy and Environment, Zhongyuan University of Technology, Zhengzhou, China

^b School of Civil Engineering, Zhengzhou University, Zhengzhou, China

^c Department of Civil Engineering, Henan Institute of Engineering, Zhengzhou, China

Original scientific paper
DOI: 10.2298/TSCI1305459W

The temperature lift directly influences the efficiency of the heat pump, meanwhile, the coefficient of performance and the heat sink temperature lift of heat pump systems are mutually exclusive parameters, i.e., the higher temperature lift leads to the lower coefficient of performance while the lower temperature lift leads to the higher coefficient of performance. To deal with the dilemma, a primary theoretical analysis is performed, and a case study of an inverter water source heat pump is carried out, which is operated under the conditions of compressor frequency of 15-85 Hz and heat sink flow rate of 120/160/180/200 kg/h, respectively. The relationships among the temperature lift, coefficient of performance and compressor power consumption are analyzed, The results show that the optimal temperature lift mainly depends on the inlet temperature of heat sink, and has little to do with the compressor frequency and water flow rate, which are of significance for the optimal operation of heat pump systems.

Key words: *heat pump, optimal temperature lift, coefficient of performance, frequency, inverter compressor*

Introduction

The heat pump system is a promising technology in both residential and commercial applications due to their energy conservation, and it is also regarded as one of the key technologies that could play a significant role in achieving the CO₂ emission reduction [1]. Therefore, the R&D of high efficiency heat pump meets the development strategy of low carbon economy and energy saving and emission reductions.

Due to the fact that heat pumps have non-uniform unit load and water tank size, heat sink outlet temperature and temperature lift, the efficiency of the heat pump in the market is generally lower. In the past years, many researchers investigated optimization operation of heat pump systems. Riznić and Kovačić [2] reported heat pumps used in water temperature adjustment in spas, and found that the geothermal energy can successfully be used in spas to adjust the water temperature for balneo-and physio-therapeutical purpose. Blarke and Lund [3] pointed out that large-scale hat pump in combined with CHP plants should be given more attention. Lee *et al.* [4] discussed a novel heat exchanger with new geometries used in low temperature lift heat pump. Zhang *et al.* [5] proposed optimization measures for air source heat pump water heater to improve the coefficient of performance (COP), including refrigerant filling quantity, the length of condensation coil pipe, suitable matching of heat pump ca-

* Corresponding author; e-mail: xwfan@zut.edu.cn

capacity and water tank size. Sarkar *et al.* [6] presented energetic and exergetic analysis for optimization studies of a transcritical carbon dioxide heat pump system, and developed a computer code to obtain sub-critical and super-critical thermodynamic and transport properties. Wang *et al.* [7] studied the performance of an inverter heat pump with HFC125 operating near the refrigerant critical point. Koffi *et al.* [8] presented both theoretical and experimental analyses of the thermal performance of a solar water heater prototype with an internal exchanger using thermosiphon system. Zheng *et al.* [9] investigated solar ejector refrigeration in Zhengzhou city. All above works reveal advantages of heat pump technologies from different aspects.

For heat pump systems, *COP* and the heat sink temperature lift of heat pump systems are complementary variables, the higher temperature lift leads to the lower *COP*, conversely, the lower temperature lift leads to the higher *COP*. An ideal heat pump cycle was constructed by Zhou *et al.* [10], and an optimization formula of supply and return water temperature difference was derived, which is, however, not suitable for heat pump water heater. Furthermore, in usual applications of heat pumps, the efficiency at one condition does not predict its efficiency for a longer operation, due to the sink temperature change. *COP* and the total compressor power consumption are mutual exclusive factors.

In this paper, the relationship among the temperature lift, *COP*, and compressor power consumption is analyzed based on the ideal heat pump cycle, and an experimental study is carried out on an inverter water source heat pump device under the condition of compressor frequency 15-85 Hz, heat sink flow rate 120/160/180/200 kg/h, respectively. The results are of significance for the optimal operation of the heat pump systems.

Theoretical analysis

As an ideal cycle, reverse Carnot's cycle is usually used to evaluate the performance of heat pump systems. As well known, the Carnot efficiency describes the maximum efficiency of a working fluid cycle. It also describes the general dependence of the efficiency on the temperature lift, meaning the temperature difference between the temperature of heat gain T_{source} and temperature of heat output T_{use} . Based on the assumptions of isentropic compressor and isothermal heat transfer, the performance of a heat pump can be defined as [11]:

$$COP_{\text{ideal}} = \frac{T_{\text{use}}}{T_{\text{source}} - T_{\text{use}}} \quad (1)$$

In this study, the heat pump investigated is the electrically driven compression heat pump. Its actual efficiency can be described by the dimensionless value *COP*, which is calculated as the ratio between the heating capacity and the electrical power consumed by the compressor:

$$COP = \frac{Q_{co}}{w} \quad (2)$$

where Q_{co} is the heat withdrawn from the high temperature refrigerant by the water flowing through the condenser, *i. e.*, the heating capacity of the system:

$$Q_{co} = c_{p,w} m_w (t_{w,\text{out}} - t_{w,\text{in}}) \quad (3)$$

Based on the assumption that the following parameters are constant, such as, the thermodynamic perfect degree, the difference between condensing temperature and the outlet temperature of heat sink, the difference between evaporating temperature and the heat source

temperature, the *COP* and heating capacity varying with temperature lift was plotted in Figure 1 under the heat sink flow rate 180 kg/h and the inlet temperature 23.2 °C. Obviously, the compressor power consumption increases with the temperature difference between the refrigerant and the secondary fluid for a heat pump cycle. However, under a given condition, the variation rate of compressor power consumption and the heat capacity is not equal, in other words, the more the temperature difference, the more speed of compressor power consumption increasing, whereas, the heat capacity varies slightly with the increasing of the temperature difference. Consequently, the variation rate of compressor power input increasing is initially smaller, and then larger than that of heat capacity increasing. As the results, the *COP* initially increases and then decreases, and a peak value of it lies in the process, for a certain heat pump cycle, the temperature difference corresponding to the maximum *COP* is the optimal temperature lift.

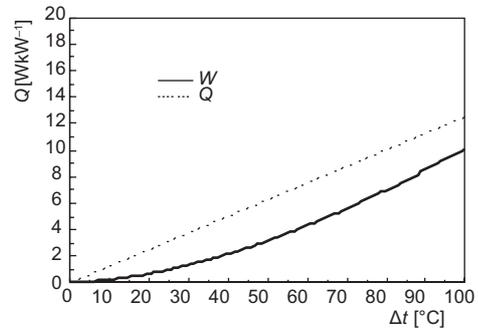


Figure 1. Relationship between compressor power input, heat capacity and heat sink temperature lift

Experimental procedure

Test rig

The heat pump works on the principle of the vapor compression cycle. The main components are the DC-inverter compressor, expansion valves, and two heat exchangers referred to as evaporator and condenser, in addition, a reservoir and an inverter in the system. The components are connected to form a closed circuit, as shown in fig. 2.

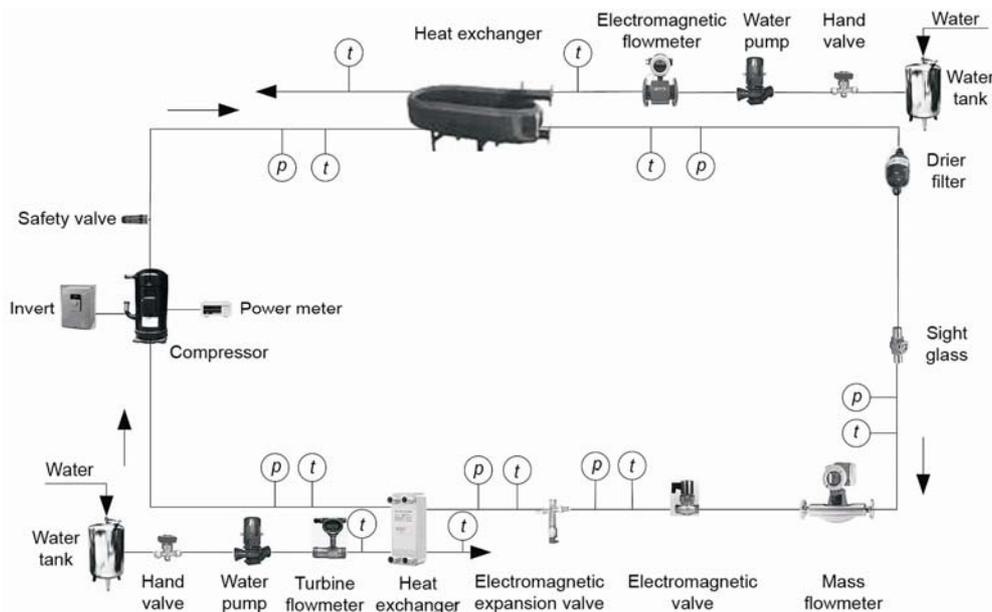


Figure 2. Schematic diagram of heat pump experimental system

When the system works, after an endothermic process from water and evaporating in evaporator, the refrigerant is compressed into high pressure and temperature vapour in compressor, and then flows into condenser, where refrigerant vapour turns into liquid by cooling water. By the expansion valves, the liquid refrigerant become low temperature and pressure liquid-gas mixture, and then, re-enters into the evaporator. Between the two expansion valves, a 5 L high pressure reservoir is installed to guarantee system's operating under different conditions. In this study, the compressor is a hermetic pendulum DC-invert compressor for R410A and the condenser is tube in tube counter-flow heat exchanger with four coaxial nested copper tubes and two groups cascade while the evaporator is plate heat exchanger. Refrigerant flows inside the inner tube and cooling water flows through the annular space in a counter current. The inner tube is the smooth copper tube with ID 4.35 mm and OD 6.35 mm, and the heat transfer length of single tube is 6000 mm.

The experimental system is designed for multi-function heat pump unit. An electric heating water tank is used to simulate bath water for heat consumer, which is connected with an electromagnetic flow-meter, a pump and valves. Another water tank is applied to simulate chilled water for air conditioning, piping with a turbine flow-meter, a pump and valves. This study is just restricted to heat exchange in condenser without considering of the heat exchange in evaporator.

To evaluate the performance of the system, the following parameters need to measure, such as refrigerant temperature and pressure, water temperature, compressor frequency and power input. According to the above requirements, seven test points are set for pressure measurement along the refrigerant flow at inlet (outlet compressor), midst and outlet of condenser, inlet and outlet of evaporator, before and after two expansion valves. At the same time, nine test points are arranged for temperature along the refrigerant flowing direction at outlet of compressor, inlet, midst and outlet of condenser, outlet of drier filter, outlet of evaporator and after two expansion valves. Along water flowing direction, three testing points for temperature are arranged at inlet, midst and outlet of condenser respectively. At the inlet of evaporator in water side, a testing point for water flow rate is laid at inlet of evaporator and two measuring points for temperature are arranged at inlet and outlet of evaporator. The determination of water flow rate is calibrated by electronic scale. All testing data are collected by Angilent data acquisition system. The measurement instruments are given in tab. 1.

Table 1. Transducers specifications

Transducer	Measurement value	Measurement range	Accuracy
SETRA pressure sensor	Pressure	0-60 Bar	0.25%
Resistance temperature sensor	Temperature	-100-200 °C	0.1 °C
Electromagnetic flowmeter	Water flow rate	0.0636-9.54 m ³ /h	0.01 m ³ /h
Turbine flowmeter	Water flow rate	0.6-4 m ³ /h	0.5%
Electronic scale	Water flow rate	0-100 kg	10 g
Frequency converter	Frequency	0.1-440 Hz	0.1 Hz
Active power transducer	Power	0-5 kW	0.5%

Experimental methods and procedures

First, under the condition of good seal, the refrigerant was filled into the system after vacuum pumping. Then, the water level of water tank was examined, under the condition of

suitable water capacity, the water pump was started and the valve opening was adjusted to make the water flow in the condenser and evaporator at the setting position. In order to simulate the actual application of heat pump water heater, the water in evaporator was kept stable, and the one in condenser was set to the proper value. It is difficult to control the high side pressure by using thermostatic expansion valve. To ensure the safe operation of system, the heat pump cycle can be realized by adjusting compressor frequency and water flow rate. Before the system runs, a certain frequency of the compressor is set and the water flow rate into condenser is set too. When the system runs at the steady-state, the parameter was continually tested for 30 minutes, and the rate of data acquisition is 6 times/min. When a set of experimental results were obtained, another test at different frequency would be carried out by changing the compressor frequency (15-85 Hz). When 15 sets of different frequency test were completed, a new test would be carried out by adjusting the water flow into the condenser, at the same time, the water flow in evaporator side kept constant. Then, the experiments have been done according to the above experimental procedure. The experimental set-up and procedures were reported in reference [7].

Results and discussion

All the data are obtained by testing and calculating under the same inlet water temperature of heat source water (23.2 °C) and a similar ambient temperature (the temperature difference is less than 1 °C).

Figure 3 shows the relationship between heat sink temperature lift and compressor frequency at a given water flow rate. The heat sink temperature lift increases linearly with compressor frequency increasing, and this trend is more evident with water flow rate reducing which is the result of heat sink temperature lift increasing, when the compressor frequency increasing, the flow rate of refrigerant, transfer heating to water, increases, consequently, the heat exchange between refrigerant and water is bigger.

Figure 4 shows the *COP* variation with heat sink temperature lift, heat output and compressor power consumption at the water flow rate 120 kg/h. it can be observed the compressor consumption increases gradually with heat sink temperature lift increasing, the heating capacity is also linearly increasing, the system *COP* increases at first then decreasing, which is corresponding with the theoretical analysis. The reason may be that at a constant flow rate when temperature lift decreases with the reduced compressor input frequency, the

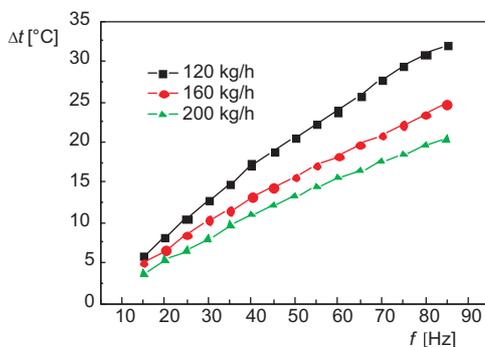


Figure 3. Variation of heat sink temperature lift with compressor frequency under different water flow rate

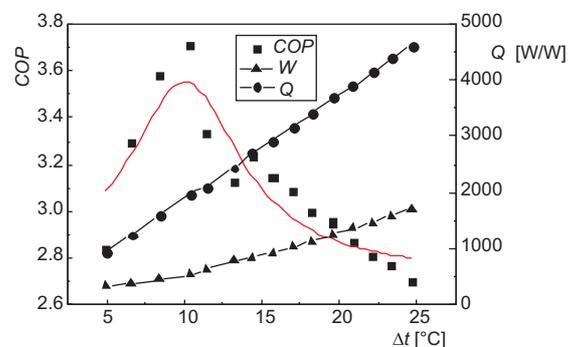


Figure 4. Variation of *COP*, heating capacity and compressor power consumption with heat sink temperature lift ($G = 120$ kg/h)

working fluid flow velocity decreases, and with the decreased condensation temperature and increased evaporation temperature, COP increases gradually with the reduced temperature lift. When the compressor frequency continuously decreased leading to a further reduce in temperature lift, heat transfer temperature difference between working fluid and water decreases, of which a certain value is reached, the equivalent heat transfer area between working fluid and water begins to decrease. As a result, decrease in heating capacity is greater than that in power, which contributes to a reduced COP with the decreased temperature rise. Therefore, the system COP increases at first and then decreases, there is a maximum COP during the process, as shown in fig. 4, the peak value is near 10 °C, which is the optimal heat sink temperature lift at that water flow rate.

Figures 5 (a) and (b) show variation of heat sink temperature lift with the COP , heating capacity and compressor power consumption at the water flow rate of 160 kg/h and 200 kg/h, respectively, which verified the analysis discussed again. From figs. 5-6, it can be observed that the optimal temperature lift does not change significantly when water flow rate changes. The optimal heating capacity and power consumption, corresponding to the maximum COP , increases with the water flow rate increasing, therefore, the COP at large water flow rate is higher than that at small water flow rate under the same compressor frequency.

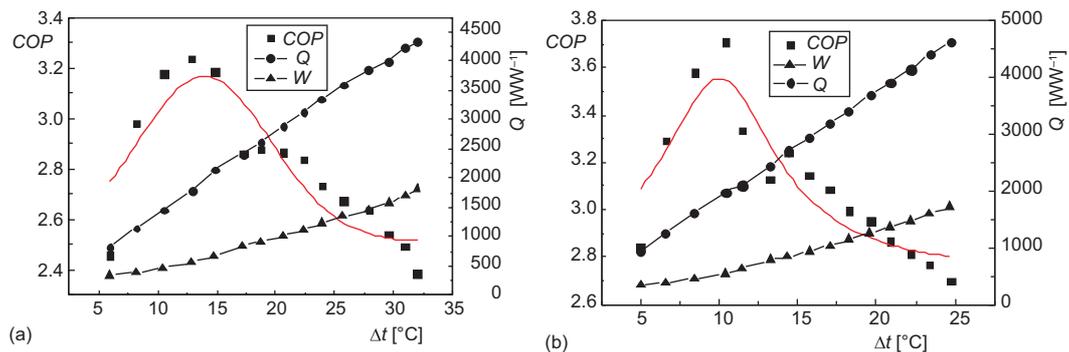


Figure 5. Variation of COP , heating capacity and compressor power consumption with heat sink temperature lift; (a) ($G = 160$ kg/h), (b) ($G = 200$ kg/h)

Conclusions

In this study, the relationship among heat sink temperature lift and COP of the heat pump, compressor power consumption were analyzed based on the ideal heat pump cycle, and a case study on a water source inverter heat pump, under the compressor frequency 15-85 Hz and heat sink flow rate 120, 160, 180, and 200 kg/h, respectively, was carried out. The main conclusions derived from the present study may be summarized.

- The optimal heat sink temperature lift related to inlet water temperature of the condenser, COP and temperature difference between refrigerant and water. However, when the heat pump runs at steady state, COP and temperature difference between refrigerant and water are variable slightly, the optimal heat sink temperature lift mainly depends on inlet water temperature of the condenser.
- The results of the experimental study indicate that the COP of the heat pump increases at first and then decreases with heat sink temperature lift decreases, and there is a maximum COP in the process, the corresponding temperature lift to it is the optimal heat

sink temperature lift. For this study, the optimal temperature rise is 10-13 °C, which mainly depends on inlet water temperature of the condenser, and is little affected by the heat sink flow rate and compressor frequency.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (No. 51176207), and key science and technology project of Henan Province (No. 122102210557, No. 122102310617, No. 132102210176).

References

- [1] Greening, B., Azapagic, A., Domestic Heat Pumps: Life Cycle Environmental Impacts and Potential Implications for the UK, *Energy*, 39 (2012), 1, pp. 205-217
- [2] Riznić, D., Kovačić, B., Water Temperature Adjustment in Spas by the Aid of Heat Pumps, *Thermal Science*, 16 (2012), 4, pp. 1127-1136
- [3] Blarke, M. B., Lund, H., Large-Scale Heat Pumps in Sustainable Energy Systems System and Project Perspectives, *Thermal Science*, 11 (2007), 3, pp. 143-152
- [4] Lee, H., *et al.*, Optimization of Novel Heat Exchanger Design for the Application to Low Temperature Lift Heat Pump, *Energy*, 42 (2012), 1, pp. 204-212
- [5] Zhang, J., *et al.*, System Optimization and Experimental Research on Air Source Heat Pump Water Heater, *Applied Thermal Engineering*, 27 (2007), 5-6, pp. 1029-1035
- [6] Sarkar, J., *et al.*, Optimization of a Transcritical CO₂ Heat Pump Cycle for Simultaneous Heat Source and Heating Applications, *International Journal of Refrigeration*, 27 (2004), 8, pp. 830-838
- [7] Wang, F., *et al.*, Experimental Study on an Inverter Heat Pump with HFC125 Operating near the Refrigerant Critical Point, *Applied Thermal Engineering*, 39 (2012), pp. 1-7
- [8] Koffi, P., *et al.*, Theoretical and Experimental Analysis of the Thermal Performance of a Solar Water Heater with Internal Exchanger Using Thermosiphon System, *Energy Conversion and Management*, 49 (2008), 8, pp. 2279-2290
- [9] Zheng H. F., *et al.*, Experimental Research about Solar Ejector Refrigerant Based on the Climate Condition in the Zhengzhou Region (in Chinese), *Acta Energetica Sinica*, 32 (2011), pp. 1169-1173
- [10] Zhou, X. J., *et al.*, The Optimal Temperature Difference of the High Temperature Heat Pump System (in Chinese), *Acta Energetica Sinica*, 25 (2004), pp. 394-398
- [11] Huchtemann, K., Muller, D., Simulation Study on Supply Temperature Optimization in Domestic Heat Pump Systems, *Building and Environment*, 59 (2013), January, pp. 327-335