INFLUENCE OF WATER SUPPLY TEMPERATURE ON THE HEATING CHARACTERISTICS OF LOW TEMPERATURE AIR SOURCE HEAT PUMP WATER HEATERS

by

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One of the inherent limitations of air source heat pump water heaters is their reduced performance when the external temperature is low. In order to investigate the impact of water supply temperature on system heating in low temperature conditions, a test bench for an air source heat pump water heater with a medium pressure air supply was constructed. The findings illustrate that within the two low temperature settings of –7 °C and –15 °C, the heating capacity of the system initially increases with the rise in water supply temperature, reaching a peak at 39 °C. However, this effect is not sustained as the temperature of the water supply continues to rise. Concurrently, the system's heating capacity reaches its maximum at a water supply temperature of 39 °C. At this temperature, the heating capacity is 45.8% lower than at –7 °C, the compressor power is 42.1% lower, and the system coefficient of performance is 7.2% lower.

Key words: *heat pump water heater, supply water temperature, medium pressure supplementary air, heating characteristic*

Introduction

An air source heat pump water heater is an apparatus that efficiently converts heat energy into hot water [1]. It is a promising technology to use nanofluids to enhance the heat transfer through nanoparticles [2]. Nanofluids can be employed for the purpose of energy harvesting from waste heat sources [3]. The concentration of nanoparticles is a crucial parameter [4], as the nanoparticles themselves form a new boundary layer, which enhances the heat transfer through the boundary [5].

An air source heat pump water heater employs the use of low grade heat energy in the air, rendering it an environmentally friendly and energy-saving device. Its operation is contingent upon the utilization of thermal energy from the air. The utilization of an air source heat pump water heater not only fulfills the hot water requirements of residential, commercial, and other establishments but also reduces energy consumption and minimizes the impact on the environment. In the context of significant environmental pollution and energy scarcity, the vigorous promotion of air source heat pump water heaters aligns with the sustainable development strategy due to their high efficiency, energy-saving features, safety, and environmen-

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tal benefits when compared to traditional heat pump water heaters [6, 7]. The performance of air source heat pump water heaters is significantly influenced by the surrounding environmental temperature. This presents a challenge when the temperature drops too low, impeding normal operation. Consequently, numerous experts and scholars have devoted significant research resources to address the issues that arise from low temperatures and to expand the applicability of water heaters [8].

A number of studies have been conducted with the objective of investigating the various factors that influence the performance of heat pump water heaters. Jiang *et al.* [9] examined the influence of the opening degree of the electronic expansion valve on the heating performance of air-source heat pump water heaters. The researchers observed that a larger opening degree during system start-up resulted in greater heating capacity, while the opposite trend was observed in the later stages of system operation. Cao, *et al.* [10] examined the influence of varying air volumes on the cooling capacity of refrigeration systems. Yuan, *et al.* [11, 12] conducted separate experiments to investigate the influence of environmental temperature and initial water temperature on the heating performance of air-source heat pump water heaters. Moreover, they developed corresponding control strategies based on their findings. In a study of air-source CO_2 heat pump water heaters, Liu *et al.* [13] examined the impact of an increase in outdoor environmental temperature from –3 °C to 13 °C on system heating capacity. The findings indicated a 28% increase in system heating capacity. Zhang *et al.* [14] conducted simulations to investigate the impact of the air cooler inflow rate on heat pump water heater heating performance. The results indicated that the system heating capacity, COP, and outlet water temperature all exhibited an upward trend with increasing air cooler inflow rates. Furthermore, Wu *et al.* [15] conducted experiments to investigate the effect of supply water temperature on the heating performance of air-source heat pump water heaters. It was observed that as the supply water temperature increased, the system heating capacity initially increased before reaching a peak and then decreased.

Previous studies have focused on the relationship between the temperature of the water tank and the air source heat pump water heater system. However, there is a paucity of research on the heating performance of medium pressure air source heat pump water heater systems. In this study, R407c is employed as the refrigerant, and two low temperature operational scenarios are devised to investigate the impact of varying water supply temperatures on the heating performance of the medium pressure air-supplemented heat pump water heater. The optimal energy-saving water supply temperature is identified, providing a foundation for subsequent product development.

Design of test bench

Figure 1 depicts the flowchart of the test device for the medium pressure air-source heat pump water heater. The chart is comprised of two distinct sections: the heat pump system cycle and the user-side hot water heat exchange cycle. The heat pump circulation section comprises a compressor, plate condenser, finned evaporator, drying filter, gas-liquid separator, thermal expansion valve, capillary tube, solenoid valve, one-way valve, and four-way directional valve, among other components. The user-side hot water heat exchange cycle is composed of a water pump, flow meter, heat preservation water tank, and other components. The heat pump cycle process is as: high temperature, high pressure gaseous refrigerant is discharged from the compressor, flows through the plate heat exchanger where it heats the water on one side, and is condensed into liquid refrigerant. Subsequently, the refrigerant exits the plate heat exchanger and is divided into two channels. The auxiliary refrigerant

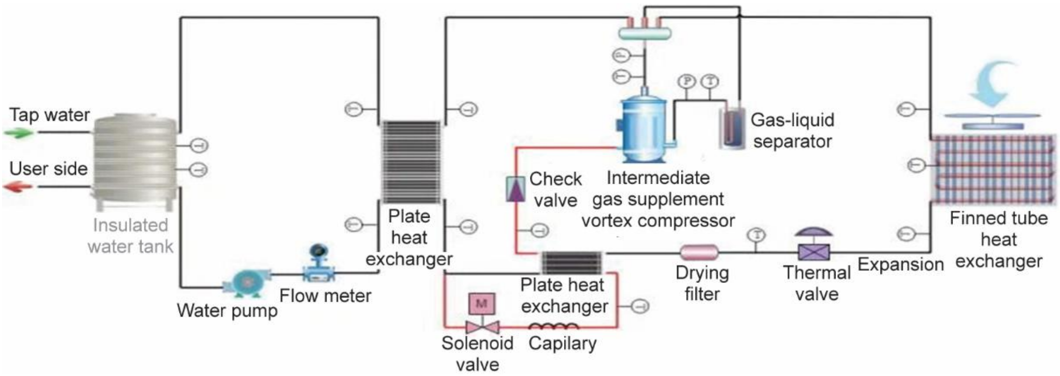

Figure 1. Test system diagram

Figure 2. Test bench

then enters the economizer after passing through the solenoid valve and capillary throttling. It absorbs the heat of the main refrigerant liquid to make it supercooled, and then enters the medium pressure air supply port. Subsequently, the main refrigerant is supercooled by the economizer, after which it travels through the drying filter and thermal expansion valve to become a low temperature, low pressure gas-liquid mixture. Subsequently, the refrigerant enters the evaporator, where it absorbs heat as a gas. Subsequently, the refrigerant enters the compressor, where it is compressed to an intermediate pressure. It is then mixed with the refrigerant gas at the intermediate air supply port and compressed into a high temperature, high pressure refrigerant gas for use in the next heat pump cycle. The process of utilizing a side hot water heat exchange cycle is as follows: the circulating water pump transports the water in the heat preservation water tank to the plate heat exchanger, where it undergoes heat exchange before returning to the heat preservation water tank. Figure 2 depicts the test bench, while tab. 1 outlines the main test device details.

The heat pump water heater test system is situated externally to the enthalpy difference laboratory, with each temperature-measuring point indicated in fig. 1. A total of eight measurement points are evenly distributed at both 1/4 and 3/4 of the liquid level of the water tank. These points are employed to ascertain the initial and final temperatures of the water heater. Furthermore, two platinum resistance thermometers (Pt 100) are positioned at both 1/4 h and 3/4 h of the liquid level.

Experimental process

In accordance with the specifications outlined in GB/T21362-2008, *Heat Pump Water Heaters for Commercial or Industrial Use and Similar Purposes*, and GB/T23137-2008, *Heat Pump Water Heaters for Household and Similar Use*, the water tank volume is set at 450 L, the water pump circulation flow rate is 2.69 m^3/h, and the refrigerant R407c charge volume is 3.0 kg. The side inlet air temperatures of the evaporator are set at –7 °C and –15 °C, respectively, and the initial water temperature on the hot water side is set at 9 °C. Once the

Table 1. Specifications and parameters of the main components and measuring devices

Device name	Specification and model
Expansion valve of main path	Main valve: Danfoss thermal expansion valve TGEX 4TR 067N2152, 1 unit Rated refrigeration capacity: 14 kW Superheat controllable range: 0-8 K
Auxiliary capillary	Inner diameter: 1.6 mm, length: 600 mm
Gas-liquid separator	Sanrong, 1 unit
Dry filter	EMERSON EK-084S, 1 unit, Capacity at 1 psi pressure drop (Tr): 7.1
Intermediate heat exchanger	Danfoss B3-020-10-H, design capacity: 3.03 kW, reference temperature: main side: 21.44 ℃, auxiliary side: 40.0 ℃, maximum pressure drop: main side: 200.0 kPa, auxiliary side: 50.0 kPa
Compressor	Panasonic C-SBS120H38Q, 1 set, refrigerant R407c, cooling capacity: 10.1 kW, exhaust volume: 55.7 cm^3/rev, fixed speed: 2900 rpm, voltage range: 342-456 V
Evaporator	L-shaped finned tube evaporator, 1 set, dimensions: 608×45×718 mm, 480×45×718 mm, fin spacing: 2 mm, fin thickness: 0.2 mm, vertical hole spacing: 25 mm, copper tube: TP2Mø9.52, horizontal spacing: 23 mm, tube pass: 12, fin surface area 32 m^2×2
Condenser	Danfoss plate heat exchanger B3-052-50-H, 1 set, design capacity: 12.12 kW, reference temperature: 56.50 ℃ on refrigerant side, 52.50 ℃ on water side, maximum pressure drop: main side 50.0 kPa, auxiliary side 50.0 kPa
Standard water tank	More than 450 L, 1 set
Thermocouple	Type T thermocouples, 10 units
Water pump	Boyu horizontal centrifugal pump BYWP60/0.37, 1 set, flow 3.5 m^3/h
Water flow meter	Xiangyun Rotameter LZB-50, 1 set, measuring range (0.4~4) m^3/h
Platinum resistance thermometer	Shen Zhen BD RTD Sensors Technology Co., Ltd., PT100, accuracy ±0.3 ºC/ TIPC, CAS PT100, accuracy ±0.3 ºC, 2 units

system has been initiated, the changes in the compressor exhaust temperature, heating capacity, compressor power, and COP are recorded at the following supply water temperatures: 19 ℃, 29 ℃, 39 ℃, 49 ℃, and 55 ℃, respectively. The recorded data can be utilized to analyze the system heat supply performance in accordance with alterations in the supply water temperature.

Calculation formula

The term *heating capacity* is employed to describe the efficiency and effectiveness of a system or equipment with regard to the transfer of heat under specified conditions. The heating capacity, Q_h, can be expressed by:

$$Q_{\mathrm{h}} = \frac{CG(t_2 - t_1)}{3600H1000} + Q_x + Q_{\mathrm{l}} \tag{1}$$

where C is the heat capacity at the average water temperature, G – the mass of hot water, t_1 – the initial water temperature, t_2 – the final water temperature, H – the heating time, and Q_{l} – the heat leakage of the water tank and pipes.

Heat storage of the pipes and water tank, Q_x, can be expressed by:

$$Q_x = \frac{\sum C_i G_i (t_2 - t_1)}{1000} \tag{2}$$

where C_i is the specific heat capacity of the pipes and various parts of the water tank at average temperature and G_i – the mass of the pipes and various parts of the water tank.

The power consumption of the unit E can be expressed by:

$$E = \frac{N_0}{H} \tag{3}$$

where N_0 is the total power consumption of the heat pump water heater in one cycle.

The COP can be expressed by:

$$COP = \frac{Q_\mathrm{h}}{E} \tag{4}$$

Analysis of test results

As illustrated in fig. 3, when the water supply temperature remains constant, a decrease in the environmental temperature results in a reduction in both the evaporation temperature and evaporation pressure. Consequently, there is a reduction in the compressor pressure ratio and the suction specific volume of the compressor. Consequently, there is an increase in the mass-flow rate of the refrigerant flowing through the entire system loop, accompanied by an increase in the discharge temperature of the compressor. Conversely, for a given environmental temperature, the discharge temperature of the compressor increases in a progressive manner with the rise in water temperature. At an environmental temperature of –15 °C, the exhaust temperature is higher than at –7 °C when the water supply temperature is held constant. This discrepancy can be attributed to the phenomenon of evaporation pressure remaining stable at a given environmental temperature. Consequently, the condensing temperature rises, resulting in an increase in the system compressor pressure ratio and compressor suction specific volume. This alteration results in a reduction in the mass-flow of refrigerant throughout the system circuit, thereby increasing the exhaust temperature of the compressor.

Figure 4 illustrates the variation in the system heating capacity as a function of the supply water temperature. Initially, as the water temperature increased, the system's heating capacity exhibited a gradual increase until reaching a peak at 39 °C. Subsequently, the heating capacity exhibited a decline with further temperature increments. It is notable that the heating capacity at an ambient temperature of –15 °C is inferior to that at –7 °C. In particular, the maximum heating capacity diminishes from 7.31 kW to 3.95 kW, reflecting a significant 45.8% reduction, when transitioning from –7 °C to –15 °C at a supply water temperature of 39 °C. As the temperature rises in the initial phase, the pressure ratio of the system compressor increases, accompanied by an analogous rise in the mass-flow rate of the system condenser refrigerant. This leads to an enhancement in the heating capacity. However, if the water supply temperature is excessively elevated, it will result in a compressor pressure ratio that exceeds the normal range, thereby reducing the compressor volumetric efficiency, the heat exchange effect of the condenser, and ultimately, the system's heating capacity. Furthermore, at a constant supply water temperature, a reduction in environmental temperature from –7 °C to –15 °C results in a decline in evaporator temperature. Consequently, the compressor pressure ratio increases, thereby reducing the heating effect of the system.

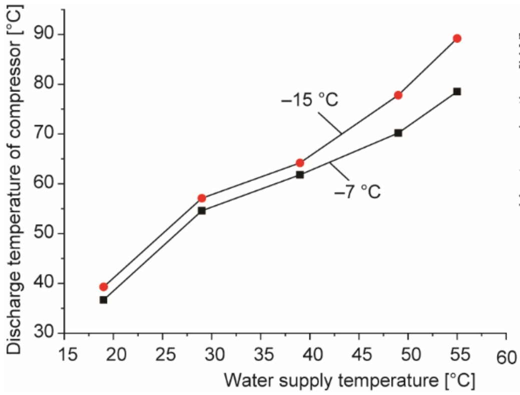

Figure 3. The relationship between exhaust temperature and water supply temperature

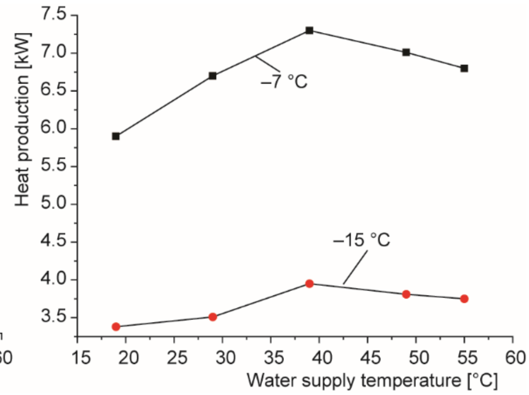

Figure 4. The relationship between heating capacity and water supply temperature

Figure 5 illustrates the variation in the power of the system compressor as a function of the temperature of the supplied water. In the same environmental temperature, the supply water temperature also increases, resulting in an increase in the system compressor power. Furthermore, when comparing the compressor power at a specific supply water temperature, it is observed that the power is lower at an environmental temperature of –15 °C compared to –7 °C. Specifically, at a supply water temperature of 39 °C, the compressor power decreases from 2.52 kW to 1.46 kW, representing a decrease of 42.1%, as the environmental temperature drops from –7 °C to –15 °C. This phenomenon can be attributed to the fact that the evaporation pressure remains constant when the environmental temperature stabilizes. Concurrently, the temperature and pressure of the condensed water also increase, resulting in an elevated system compressor pressure ratio and, subsequently, higher power consumption. Conversely, when the environmental temperature declines from –7 °C to –15 °C, the reduction in the system evaporator temperature increases the compressor pressure ratio. The rise in the pressure ratio results in an expansion of the compressor suction volume, which in turn reduces the flow rate of the refrigerant mass and consequently the compressor power.

Figure 6 depicts the alteration in the system COP in correlation with the supply water temperature. The figure illustrates that as the supply water temperature increases, the system COP also increases, while maintaining a constant environmental temperature. In addition, the system COP decreases from 2.91 to 2.7 when the water supply temperature rises to 39 °C. Moreover, the compressor power is lower at an environmental temperature of –15 °C compared to –7 °C, representing a 7.2% decrease as the environmental temperature drops from –7 °C to –15 °C. This change in the COP is attributed to the combined effect of the system compressor power and the heating capacity.

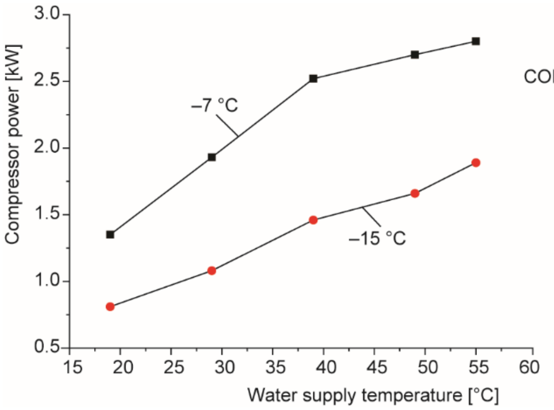

Figure 5. The relationship between power consumption and water supply temperature

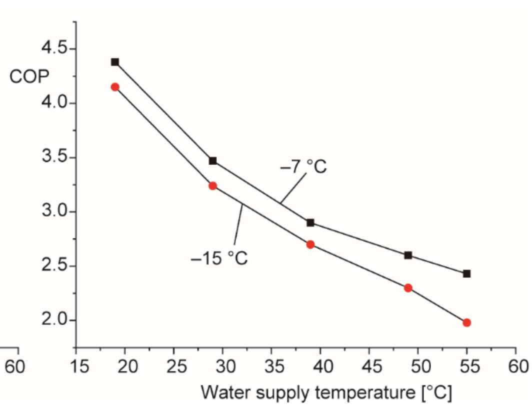

Figure 6. The relationship between COP and water supply temperature

Conclusions

The objective of this experimental investigation was to examine the impact of supply water temperature on the heat characteristics of medium pressure supplementary air source heat pump water heaters in low temperature conditions. The following conclusions were drawn from the study.

- At environmental temperatures of –7 °C and –15 °C, an increase in the water supply temperature initially results in an increase in the system heating capacity, which then decreases. The system reaches its maximum heating capacity when the water supply temperature is 39 °C. Moreover, as the water supply temperature continues to increase, the system compressor discharge temperature and power gradually rise, resulting in a reduction in the system COP.
- When the water supply temperature remains constant, the system exhaust temperature, heating capacity, compressor power, and COP exhibit variations in different environmental temperatures. Specifically, as the environmental temperature decreases from –7 °C to –15 °C, all these parameters exhibit a downward trend.
- At the optimal water supply temperature of 39 °C, the maximum heating capacity decreases from 7.31 kW to 3.95 kW, representing a 45.8% reduction. Concomitantly, the compressor power declines from 2.52 kW to 1.46 kW, signifying a 42.1% reduction. Furthermore, the system COP decreases from 2.91 to 2.7, representing a 7.2% reduction.

References

[1] Qiu, F. Q., *et al.*, Experimental Research on Dynamic Performance of an Air/Water Source Heat Pump Water Heater, *Thermal Science*, *28* (2024), 3A, pp. 2067-2074
[2] Chandran, S. S. R., *et al.*, Empirical Correlation to Analyze Performance of Shell And Tube Heat Exchanger Using TiO_2 Nanofluid-DI Water in Solar Water Heater, *Case Studies in Thermal Engineering*, *60* (2024), 104652
[3] He, J.-H., Abd-Elazem, N. Y., The Carbon Nanotube-Embedded Boundary Layer Theory for Energy Harvesting, *Facta Univ.-Ser. Mech.*, *20* (2022), 2, pp. 211-235
[4] He, J.-H., *et al.* Efficacy of a Modulated Viscosity-Dependent Temperature/Nanoparticles Concentration Parameter on a Nonlinear Radiative Electromagneto-Nanofluid Flow along an Elongated Stretching Sheet, *J. Appl. Computat. Mech.*, *9* (2023), 3, pp. 848-860
[5] Kou, S. J., *et al.*, Fractal Boundary Layer and Its Basic Properties, *Fractals, 30* (2022), 9, 22501729

[6] Yang, Y., A Brief Analysis of the Current Status and Development Trend of Heat Pump Water Heaters, *Technology and Economic Guide*, *27* (2019), 20, 66
[7] Du, J., *et al.*, Application Status and Analysis of Household Heat Pump Water Heaters, *Refrigeration & Air Conditioning*, *22* (2008), 5, pp. 71-74
[8] Wang, F. H., *et al.*, Research Progress and Prospect of Air Source Heat Pump in Low Temperature Environment, *Journal of Refrigeration*, *34* (2013), 5, pp. 47-54
[9] Jiang, M. L., *et al.*, Research on the Control Laws of the Electronic Expansion Valve for an Air Source Heat Pump Water Heater, *Building and Environment*, *46* (2011), 10, pp. 1954-1961
[10] Cao, K., *et al.*, Effects of the Air Volume on Cooling Performance of a Refrigeration System, *Thermal Science*, *27* (2023), 3A, pp. 1865-1871
[11] Yuan, C. Y., *et al.*, The Influence of Environmental Temperature on the Performance of Air Source Heat Pump Water Heater System, *Fluid Machinery*, *45* (2017), 8, pp. 48-52
[12] Yuan, C. Y., *et al.*, Effect of Initial Water Temperature on the Performance of Air-source Heat Pump Water Heater System, *Journal of Refrigeration*, *39* (2018), 6, pp. 73-79
[13] Liu, Z. Q., *et al.*, Experimental Study on the System Characteristics of Household Air Source CO_2 Heat Pump Water Heater, *Fluid Machinery*, *47* (2019), 2, pp. 70-74
[14] Zhang, C., *et al.*, Research on the System Characteristics of Low temperature Air Source CO_2 Heat Pump Water Heater, *Fluid Machinery*, *45* (2017), 11, pp. 66-71
[15] Wu, X. H., *et al.*, The Influence of Supply Water Temperature on the Heating Performance of Low Temperature Air Source Heat Pump, *Journal of Refrigeration*, *40* (2019), 3, pp. 66-71

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