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Performance analysis of a multi-functional Heat pump system in heating mode

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HIGHLIGHTS

► Performance of a multi-functional heat pump system was investigated in heating mode.
► Better performance than conventional air source heat pump system.
► Parallel heat sources can provide better system performance.
► Supplying hot water has limited affection on heating capacity in space heating.
► Supplying hot water can improve the COP of the multi-functional heat pump system.

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ABSTRACT

A multi-functional heat-pump system is proposed to efficiently utilize the gray water as heat source and sink for heating and cooling of residential buildings, respectively. Heat is reclaimed from the plate heat exchanger installed at the outlet of the compressor to provide sufficient hot water for residential use. To study the performance of this innovative system, laboratory testing is performed with a prototype consisting of an outdoor heat pump, an indoor air handler, a gray water tank and a hot water tank. This system is set in two environmental chambers that they represent: the outdoor and indoor environments, respectively. In this paper, the investigation of the system is mainly focused on the heating performance. The system is designed to allow four combinations of two heat sources that they are a water-source evaporator and an air-source evaporator. The four combinations consist of air source only, water source only, air source and water source in parallel and air source and water source in series, in the refrigerant cycle. Performance of the four combinations of heat sources is experimentally investigated at a typical indoor air temperature of 21.1 °C and various outdoor air temperatures at 1.1, 8.3, and 15.6 °C. The results show that the heat source combinations influence the heating capacity and coefficient of performance (COP) of the system. Also, the system performance and the optimal heat source combination depend on the outdoor temperature. As outdoor temperature decreases, the variation of system performance among different combinations becomes small. The system performance in modes of space heating and space heating plus hot water supply are compared and analyzed. The COP of the system in the space heating plus hot water supply mode increases in all heat source combinations, compared with that in space heating only mode. The performance of the system for heating hot water from 30 °C to 48.9 °C is also studied. This proposed system can provide significant energy savings in space heating and hot water supply. The optimal source combination is critical in pursuing the maximum energy savings.

1. Introduction

To reduce energy consumption from buildings, U.S. Department of Energy (DOE) set a goal to achieve Zero-Net Energy Buildings from two perspectives: (i) to reduce the average energy use of housing by 40%–100% through improving building energy systems efficiency and conservation, and (ii) to offset the rest of the energy usage through on-site renewable energy generation [7]. Although it is a long way to achieve the goal, it is generally realized that the largest hurdle for renewable energy solutions is how to shorten the payback period and make them cost-effective. A lot of innovative technologies in this regard have resulted, and a lot of research is ongoing.

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The oil crisis in the beginning of the 1970s has led researchers to seeking alternative energy sources [17]. Later, heat pumps became popular for heating and cooling applications. Ground source, air source, combining solar energy and geothermal heat pump were proposed by many researchers [26].

Water heating accounts for an average 18% of all residential energy use in the United States, which makes it to be the second largest use of energy in residential buildings [8]. In some states (e.g., California), this percentage of energy use can reach as high as 25%. Since the 1950s, research has been performed on heat pump water heaters [11] for energy saving. The potential energy sources (for instance, air and water sources) have been considered. Ito and Miura [14] have investigated the mechanism of heat pumps for hot water supply using combined air and water sources. The system can switch to either one or both heat sources. Direct-expansion solar-assisted heat-pump system that combined solar and air heat sources was studied in generation of hot water [5,6,9,12,18,20]. Arif [3] studies on the exegetic modeling and performance evaluation of solar-assisted domestic hot water tank integrated geothermal heat pump systems for residences. However, this research work mainly focuses on saving energy in supplying hot water, and did not consider the possibility of saving energy for integrating air conditioning and hot water supply systems.

Water heating is just a part of total energy consumption. In fact, the space heating and cooling consume a significant portion of energy consumption. Heat-pump water-heaters are designed for service water heating and their hot water production rate are only 40–100% of that of the electric heating devices and 30–50% of that of the gas heating devices [15]. To provide quick recovery with this type of water heater, a household must have a large heat pump, an unusually large storage tank, and an electric backup heater. However, this electric backup heater will increase peak electrical demand and reduces energy efficiency [15].

To further improve the application area of heat pumps and energy utilization, numerous researchers are focusing on investigation of multi-functional heat pump system that not only provides hot water but also space heating and cooling. In residential buildings, the load of hot water can be satisfied by the multi-functional heat pump systems, meanwhile space cooling and heating can be provided. Ni et al. [21] investigated this type of system numerically, and showed the mean of daily hot water load in a typical residential house in New York is about 33.6 MJ. The study is based on a calculation using the methods provided by Building America Research Benchmark [27]. Considering the hourly usage profile [25,27], the mean hourly load of hot water is about 1400 kJ. Through numerical simulation, Ni et al. [21] concluded that the total source energy savings have a range of 17%–57.9% among 15 cities in different climate zones in the U.S. Hot water heating has the most significant energy savings with over 60% reduction. Ji et al. [15,16] developed a prototype system and simulation program for an integrated domestic air-conditioner and water heater. Kara et al. [17] and Kuang and Wang [19] applied the direct expansion solar-assisted heat pump for space heating, space cooling and hot water supply. Ozgener and Hepbasli [22–24] developed a multi-function heat pump system by utilizing solar energy and geothermal heat.

Waste water discharge by the residential building is also an important heat source. Baek et al. [4] have carried out a numerical study of a heat pump system using waste water. The system showed comparably high COP. However, the results were acquired from numerical simulation and this system is only for heating low-temperature hot spring water. The performance of a system supplying space heating, space cooling and hot water simultaneously using waste water was not investigated. Compared with the solar assisted heat pump system or geothermal system, air source and waste water source heat pump system are comparably economical, especially in initial cost. In addition, the geothermal heat pump has a regional limitation. However, waste water source and air source do not have the similar limitation.

This paper proposes a prototype multi-function heat pump system with utilizing air and waste-water heat sources. Ni et al. [21] have given a feasibility study of this heat pump system. The system operation strategy and energy savings has been numerically analyzed. An author of this paper has been involved in the development a gray water treating system consisted of a simple screen, a bio-filter filled with shredded tire chips and a membrane bioreactor for this application [13]. The Heat pump system has been built by a modification of conventional air source heat pump. Therefore, retrofit of existing heat pump system is possible and can reduce the initial investment and improve the energy utilization efficiency.

There are four types of combinations with air source and waste water source, consisting of “air source only”, “water source only”, “air and water sources in parallel” and “air and water in series”. The “air source only” uses the outdoor air heat exchanger alone, while the “water source only” uses the heat exchanger, located in the gray water tank. The “air and water sources in parallel” represents the heat exchangers, located in the outdoor chamber and the gray water tank, are configured in parallel. The “air and water sources in series” represents the heat exchangers, located in the outdoor chamber and in the gray water tank, are configured in series. In the present study, the system performance in different functions with different types of heat source combinations will be discussed.

2. Prototype setup

To study the performance of the multi-functional heat pump system, a prototype system is setup at a laboratory in the University of Nebraska-Lincoln, which consists of a heat pump system and a hot water supply system. The system is installed in two separate laboratory rooms that represent outdoor and indoor environments, respectively. The heat pump system consists of a compressor, an accumulator, a heat exchanger with a fan in the outdoor chamber, an indoor air handler including a heat exchanger and a fan, and a gray water tank with an immersed heat exchanger, as shown in Fig. 1(a). The immersed heat exchanger in the gray water tank is DX (Direct Expansion) coil. DX coil is easy to maintain and clean than shell and tube heat exchanger, although it has lower heat transfer efficiency. The hot water supply system consists of a water pump for circulating water in the pipe, a 30-gallon hot water tank for storage of hot water, and a plate heat exchanger for heating hot water.

In this prototype system, one four-way valve is installed at the outlet of the compressor to switch between heating mode and cooling mode. As shown in Fig. 1(a), six solenoid valves are used to guide the refrigerant bypassing different heat exchangers. There are two throttling valves being used for heating mode and cooling mode, which are a thermal expansion valve and a metering device, respectively. The pressure and temperature of refrigerant flow is measured at the locations as shown in Fig. 1(a). Six pressure sensors are installed at different positions to measure the pressure distributions of the refrigerant flow. Temperatures are measured with copper–constantan thermocouples and platinum resistance thermometers. The air flow rate and temperature of the air source heat exchanger are also measured. An in-line water flow meter is used to measure the hot water flow rate. A digital power meter is used to measure the overall power consumptions of the compressor and the fans. All of the above measuring processes are monitored and controlled by a National Instruments data acquisition system. The data is recorded at each 1 s interval. The range and accuracy of the sensors installed in the system are shown in Table 1.

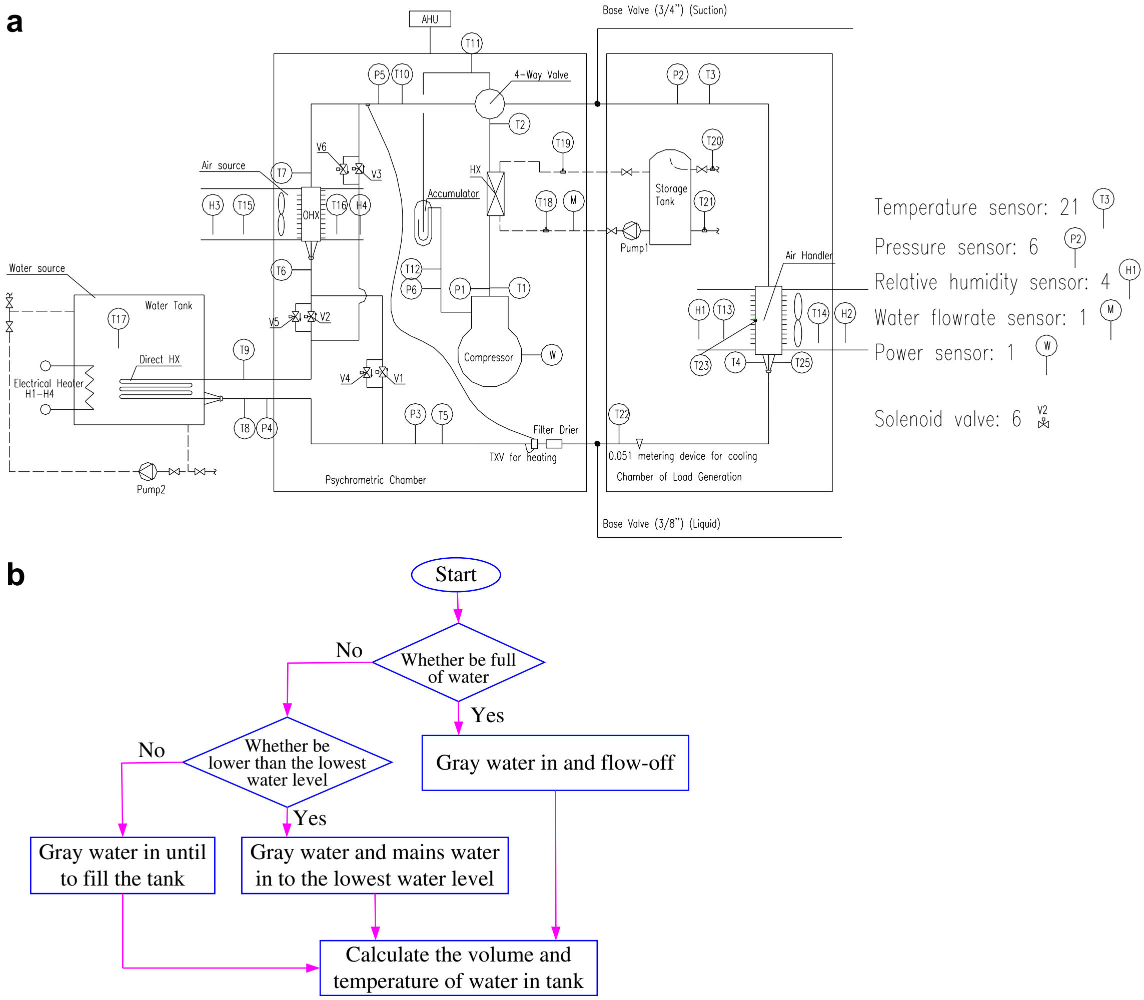

Fig. 1. (a) Schematic diagram of the prototype (multi-functional heat pump system). (b) The operation strategies of gray water tank.

This system can provide: (1) space heating only, (2) space heating plus hot water supply, (3) space cooling, (4) space cooling plus hot water supply, and (5) hot water supply only. In this paper, the study will be focused on the performance of the multi-functional system in heating mode that is the modes of (1) space heating only and (2) space heating plus hot water supply.

Table 1
Range and accuracy of sensors.

Sensors	Range	Output	Input	Accuracy
Thermocouple wire (T type)	<200 °C	N/A	N/A	0.75% Above 0 °C, 1.5% Below 0 °C
Humidity/temperature transmitters	(Humidity): 0–100% RH @ 0–50 °C (Temperature): 0–100 °C	4–20 mA	24 Vdc	±2.5% RH, ±0.3 °C
Gauge pressure transducer	0-1000 psi	4–20 mA	24 Vdc	±0.25%
	0–500 psi	4–20 mA	24 Vdc	±0.25%
	0–200 psi	4–20 mA	24 Vdc	±0.25%
In-line water flow meter	0–15 L/min, 0–121 °C	N/A	N/A	±5%
Power meter	208/240 V, 100 A	4–20 mA	9–30 Vdc	±1%

In this system, four types of heat source combinations can be implemented as showed in the following parts:

(a) Air source only

Air source is the most convenient heat source for space heating. In this mode, the air-to-refrigerant (or air-source) heat exchanger in the outdoor chamber serves as an evaporator, while the air-to-refrigerant heat exchanger in the indoor chamber works as a condenser. The refrigerant flow directly enters the outdoor heat exchanger, without passing through the immersed water-to-refrigerant heat exchanger in the gray water tank. The heat exchanger in the outdoor chamber is shown in Fig. 1(a).

(b) Water source only

In this system, the heat source is the waste heat of waste water coming from residential buildings. The water-to-refrigerant (or water-source) heat exchanger immersed in gray water tank works as an evaporator and the air-to-refrigerant heat exchanger in the indoor chamber operates as a condenser. The low temperature and low-pressure refrigerant flow pass through the water source heat exchanger without going through the air source heat exchanger discussed in part (a). Gray water usually has higher temperature than outdoor air in winter. It can improve heat pump system performance.

(c) Air and water sources in parallel

The heat exchangers of air source and water source are arranged in parallel in the refrigeration circuit. In heating mode, the heat exchangers in the outdoor chamber and gray water tank both serve as evaporators. The heat exchanger in the indoor chamber acts as a condenser. The refrigerant flow passes through two evaporators simultaneously. This arrangement will adjust the refrigerant flow passing through different heat exchangers to utilize the heat in different heat sources.

(d) Air and water sources in series

It is the same as the above (c), but the air-source and water-source heat exchangers are arranged in series in the refrigeration circuit. The refrigerant flow passes through the water-source heat exchanger and the air-source heat exchanger sequentially. Heat sources in series will make the refrigerant flow pass through each heat exchanger to absorb maximum heat. There are two arrangements in series combination. One is the refrigerant passes through the water source heat exchanger and then goes through the air source heat exchanger. The other is reversed. In this prototype, water source heat exchanger is ahead of air source heat exchanger. This arrangement puts absorbing heat from gray water at the priority position and also this way can maximize the utilization of the heat from gray water via refrigerant evaporation which normally absorbs more heat than sensible heating.

In the application of the heat pump system, the gray water tank can be used to gather the gray water from a multi-family building or only one house. Due to the variance of volume and temperature of gray water, the gray water tank in actual operation can follow the operation strategy shown in Fig. 1(b). Similar control strategies can also be found in Ref. [21]. Fig. 1(b) shows the volume of the gray water in gray water tank is maintained at a reasonable range via the use of gray water and mains water. For the experiments in the present study, the volume of water in gray water tank is maintained at the lowest water level, 220 gallon, which aims to test a worst scenario (lower bound of the performance) in a typical residential house.

Table 2 shows the valves schedule to switch among different heat source combinations. V1–V6 presents labels of the six solenoid valves, shown in Fig. 1, installed in the heat pump system to switch the heat source and sink combinations. The default positions of all the valves are closed. When air source is the only heat source, only solenoid valve V1 in Fig. 1 is opened. When water source is the only heat source, only solenoid valve V5 in Fig. 1 is opened. When air source and water source work in parallel, V1 and V5 valves are opened. While air source and water source work in series, only V3 valve is opened. Pump 1 presents the circulating pump in gray water tank and pump 2 presents the circulating pump in hot water supply system as shown in Fig. 1(a).

Table 2
Heat source combination in heating mode.

Heat source combinations	Opened valves	Space heating only	Space heating plus hot water supply
Air source only	V1	Pump 1 off, pump 2 off	Pump 1 on, pump 2 off
Water source only	V5	Pump 1 off, Pump 2 on	Pump 1 on, Pump 2 on
Air and water sources in parallel	V1 and V5	Pump 1 off, Pump 2 on	Pump 1 on, Pump 2 on
Air and water sources in series	V3	Pump 1 off, Pump 2 on	Pump 1 on, Pump 2 on

In heating mode, this system can realize two functions, which are (i) space heating only and (ii) space heating plus hot water supply.

(a) Space heating only mode

An air handler is a device used to dissipate heat into the room air. The circulation pump is turned off and thus there is no water circulation for hot water heating. The heat loss can therefore be neglected, when the high temperature and high pressure refrigerant vapor from the outlet of compressor passes through the heat exchanger for hot water heating. According to the standard [1,2], the room temperature is maintained at 21.1 ± 1 °C. The temperature of the outdoor chamber is controlled as required. The temperatures in the outdoor chamber and the indoor chamber are controlled by two roof top units (RTU) individually.

At the space heating mode, there is no hot water supply, and the COP of the system at any time instant (t) can be defined as:

$$\mathrm{COP}_{\mathrm{h},t} = \frac{Q_\mathrm{h}(t)}{W(t)} \tag{1}$$

where $Q_\mathrm{h}(t)$ is the heat exchange rate in the condenser. $W(t)$ is the power of the compressor and fans. Within an operating period of duration τ, the average COP is defined as

$$\mathrm{COP}_{\mathrm{h,avg}} = \frac{\int_0^\tau Q_\mathrm{h}(t)\mathrm{d}t}{\int_0^\tau W(t)\mathrm{d}t} \tag{2}$$

(b) Space heating plus hot water supply mode

In this mode, hot water heating and space heating are provided simultaneously. The high temperature and high pressure refrigerant vapor first passes through the plate heat exchanger for heating hot water and then goes into the heat exchanger in the air handler for space heating. The plate heat exchanger and heat exchanger in the air handler both work as condensers. The pump in the hot water system is turned on to maintain a constant flow rate (10 L/min) passing through the plate heat exchanger. This mode tries to improve the performance of the system and maximize utilization of the energy, especially when the system is oversized or under the partial load condition. In the present study, the hot water temperature is maintained at 48.9 ± 1 °C.

When the space heating mode and hot water supply are required simultaneously, the system COP at any time instant (t) is given as

$$\mathrm{COP}_{\mathrm{h},t} = \frac{Q_\mathrm{h}(t) + Q_\mathrm{h,w}(t)}{W(t)} \tag{3}$$

where $Q_\mathrm{h,w}(t)$ is the heat exchange rate in the plate heat exchanger for heating hot water. $W(t)$ is the power of the heat pump system includes compressor and fans. The pump used for circulation of hot water is excluded in the calculation due to its small power at 30 W. Within an operating period of duration τ, the average COP is defined as

$$\mathrm{COP}_{\mathrm{h,avg}} = \frac{\int_0^\tau \left(Q_\mathrm{h}(t) + Q_\mathrm{h,w}(t)\right)\mathrm{d}t}{\int_0^\tau W(t)\mathrm{d}t} \tag{4}$$

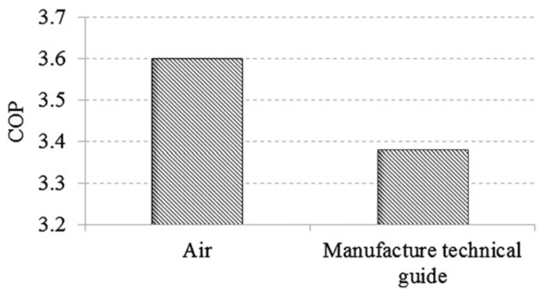

Fig. 2. COP comparison.

3. Experimental results analysis

3.1. Verification of system performance with the manufacturer's data

This multi-functional heat pump system is developed based on a market-available air-source heat pump system. To verify the modified system, the performance of the multi-functional heat pump system is compared with the rating data in a rated operation condition shown in the manufacture technical guide. The purpose is to investigate the effect of modification on the system compared with the original design. The technical guide gives the system performance rating data of the air-source heat pump on typical operating conditions in heating mode. In this comparison, the outdoor and indoor temperatures are chosen at 8.3 ± 1 °C and 21.1 ± 1 °C, respectively, referring to the rated operating condition. Other parameters are based on the standard [1,2]. The system performance is obtained from the tests of the multi-functional heat pump system with air source only.

Fig. 2 illustrates the coefficients of performance (COP) of the multi-functional heat-pump system and the original air-source heat-pump system. The multi-functional heat pump system has a slightly higher COP than the rated COP of the original system. The heating capacity and power consumption of the multi-functional heat pump system are similar to those of the air-source heat-pump system as shown in Fig. 3. The modification, therefore, maintains the system performance at a similar level.

3.2. Space heating only mode

Table 3 shows various operating conditions of the multi-functional heat pump system in space heating mode. The experiments of four heat source combinations are implemented at three different outdoor temperatures. A total of twelve experiments have been performed.

Table 3
Space heating experiment conditions.

Heater exchanger choice	Outside air temperature (°C)/average relative humidity of outdoor air (%)			Indoor air temperature (°C)	Gray water tank temperature (°C)
Air	15.6/32.06	8.3/35.81	1.1/45.92	21.1	21.1
Water	15.6/30.95	8.3/35.19	1.1/42.06	21.1	21.1
Parallel	15.6/33.52	8.3/35.90	1.1/43.62	21.1	21.1
Series	15.6/33.07	8.3/34.46	1.1/41.77	21.1	21.1

Fig. 4 shows the COP of the innovative system with the four heat source combinations at the outdoor temperature is 15.6 °C. It is observed that the best performance occurs when the heat sources are parallel. When the heat sources are in series, the performance of the system becomes the worst. Fig. 5 illustrates the heating capacity of the system with the parallel combination is the highest, and that of the system with series combination is the lowest. As the outdoor temperature drops to 8.3 °C, the COP of the system with the water source only becomes the best among the four types of operations, and that of parallel combination is second best, as shown in Fig. 6. The COP of the system with air source only combination is the lowest. However, the system with parallel combination can provide the highest heat capacity as shown in Fig. 7. The heating capacity of the system with air source only is almost the same as that of the system with the series combination. When the outdoor temperature further drops to 1.1 °C, the COP of the system with sources in parallel combination becomes the highest one as shown in Fig. 8. Moreover, the COP of the system with air source only combination is still the lowest. Although the COP of series combination is the third highest, the heating capacity is the highest among those types of operations, as shown in Fig. 9. The heating capacity of the system with the parallel combination is the second highest. The difference between the heating capacities of the parallel and series combinations is very small. Figs. 4, 6 and 8 show that the COPs of the system with all types of heat source combinations decrease as the outdoor temperature decreases. Figs. 5, 7 and 9 show that the heating capacities of the system with all types of heat source combinations decrease as the outdoor temperature decreases.

3.3. Space heating plus hot water supply mode

Table 4 shows the multi-functional heat pump system operating conditions in space heating plus hot water supply mode. The experiments of four heat source combinations are implemented at three different outdoor temperatures. A total of twelve experiments have been carried out.

Figs. 10, 12 and 14 show the COPs of the system in space heating plus hot water supply mode with four types of heat source

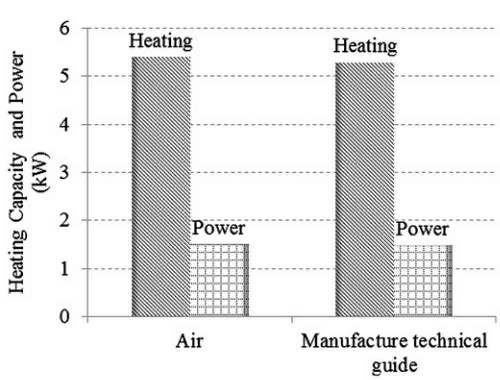

Fig. 3. Heat capacity and power comparison.

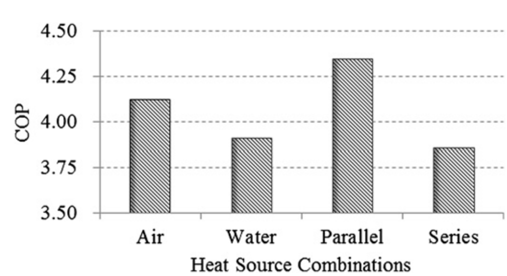

Fig. 4. COP at outdoor temperature 15.6 °C.

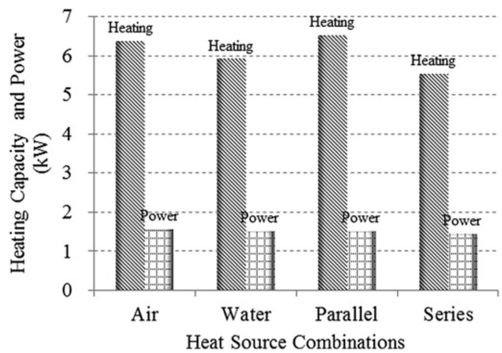

Fig. 5. Heating capacity and power at outdoor temperature 15.6 °C.

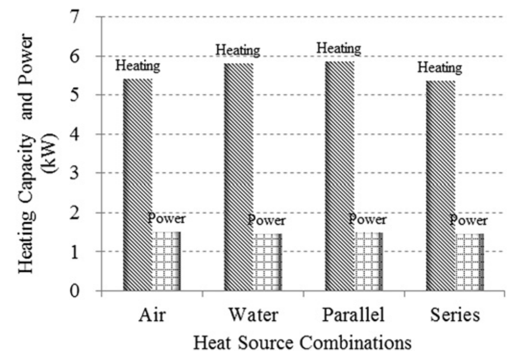

Fig. 7. Heating capacity and power at outdoor temperature 8.3 °C.

combinations at different outdoor temperatures. Figs. 11, 13 and 15 illustrate the heating capacities and power consumptions of the system under four types of heat source combinations in space heating plus hot water supply mode. According to Fig. 10, the COP of the system with the parallel combination is the highest and that of the system with the series combination is the lowest when the outdoor temperature is 15.6 °C among the four operations. Fig. 11 shows that the total heating capacity of the system with the parallel combination is the highest and that of the system with the series combination is the lowest when the outdoor temperature is 15.6 °C. When the outdoor temperature is 8.3 °C, the COP and heating capacity of the proposed system with the parallel combination are both the highest and those of the system with series combination are both the lowest according to Figs. 12 and 13, respectively. As the outdoor temperature decreases to 1.1 °C as shown in Fig. 14, the COP of the system with the parallel combination and that of the system with water source only are almost the same and are both the highest, while that of the system with air source is the lowest. However, the heating capacity of the system with the parallel combination and that of the system with the series combination is almost the same as shown Fig. 15. The COP of the system with the series combination is slightly higher than that of the system with the parallel combination at the outdoor temperature of 1.1 °C.

3.4. Compare space heating mode with space heating plus hot water supply mode

Figs. 16–21 show the comparisons between COPs and heating capacities of the system in space heating mode, and those in space heating with water heating mode under four types of heat source combinations at different outdoor temperatures. Figs. 17, 19 and 21 show the comparisons between the heating capacities of the system for space heating in space heating mode, and those in space heating with heating water mode with four types of heat source combinations. The COP of the proposed system in space heating plus hot water supply mode is always higher than that in space heating mode, except in the use of water source only at outdoor temperature 8.3 °C. The heating capacity of the system in space heating plus hot water supply mode, becomes less than that in space heating mode. But the difference between each source combination is below 12%. According to Figs. 16–21, as the outdoor temperature decreases, the decreases of COP and heating capacity for space heating are observed.

3.5. Dynamic COP and heating capacity in space heating plus hot water supply mode

In space heating plus hot water supply mode, several experiments are carried out to investigate the impact of heating water from a low temperature to a high temperature on the heat pump system performance as shown in Table 5.

Figs. 22–25 show the COPs of the system in space heating plus hot water supply mode change with the hot water temperature increase when the outdoor temperature is 8.3 °C. In Fig. 22, when the heat source is air source only, the COP decreases from around 4.5 to around 3.5 with the increase of hot water temperature. The time span is about two and half hours. In Fig. 23, when the heat source is water source only, the COP decreases from a point larger than 4.5 to around 4 and the time span is about 2 h. Fig. 24 shows the COP change over time when the air source and the water source are parallel, the COP changes above 4. The decrease rate is the slowest among all types of heat source combinations. This type of heat source combination has the shortest time span, which is about one hour and forty-five minutes. Fig. 25 presents the COP decreases from the point lower than 4.5 to around 3.5. The change curve is similar with that of air source only. The time span is about two and a half hours. Comparing Figs. 22–25, the COP decrease rate is the largest when the air heat source is involved. The COP decrease rate of parallel combination is much smaller than others as shown in Fig. 24. Fig. 26 shows the average COP while heating hot water from 30 °C to 48.9 °C. The air plus water heat source combination has a higher COP

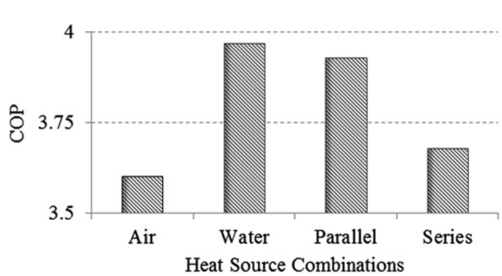

Fig. 6. COP at outdoor temperature 8.3 °C.

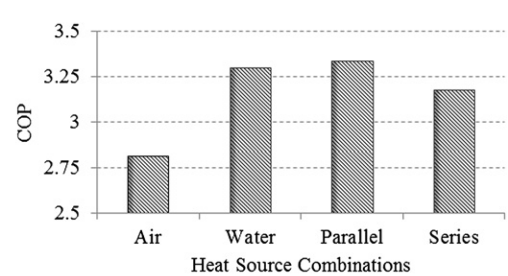

Fig. 8. COP at outdoor temperature 1.1 °C.

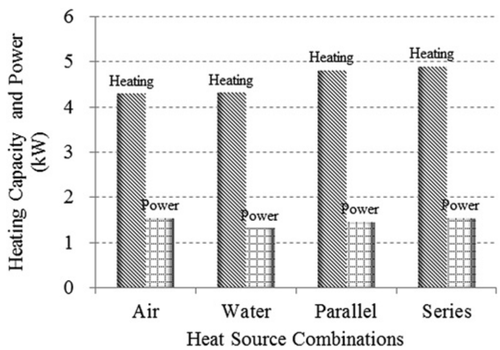

Fig. 9. Heating capacity and power at outdoor temperature 1.1 °C.

value than other heat source combination. Compare these three figures with Figs. 4, 6 and 8, it can observe that the average COP is larger than the COP at the hot water temperature maintaining 48.9 °C. So, heating hot water will not cause an extra energy consumption compared with maintaining hot water at a satisfied temperature (48.9 °C). Fig. 26 shows the average COP of the system with the four heat source combinations. The system with parallel combination has the best performance. The process of heating hot water from 30 °C to 48.9 °C usually takes 2 h.

Figs. 27–30 show the heating capacity for space heating and hot water change curves. With the increase of hot water temperature, the heating capacity for heating hot water decreases and that for space heating increases. For the air heat source as shown in Fig. 27, the heating capacity for space heating increases from around 3.5 kW to below 5 kW, while that for supplying hot water decreases from around 2 kW to around 0.5 kW with the hot water temperature increases. For the water heat source as shown in Fig. 28, the heating capacity for space heating increases from around 4 kW to below 5.5 kW. The heating capacity for supplying hot water decreases from around 2 kW to around 0.5 kW. When the air source and the water source are in parallel, the heating capacity for space heating increases from around 4 kW to below 5.5 kW, as shown in Fig. 29. The heating capacity for supplying hot water decreases from around 2 kW to around 0.5 kW. Fig. 30 presents when the air source and water source are in series, the heating capacity for space heating increases from around 3.5 kW to around 4.5 kW. The heating capacity for supplying hot water decreases from around 2 kW to around 0.5 kW. According to Figs. 27–30, the heating capacity for supplying hot water stays the same in different types of heat source combinations. The total heating capacity is almost constant.

3.6. *Water temperature impaction on performance of the system*

In controlling and maintaining water volume in gray water tank, mains water plays a role of a supplement water source. In some cases, due to the irrigation need, the water volume may fall down below a minimum limit of gray water tank. The mains water will be filled in to maintain the minimum water volume in gray water tank. In some situations, the water temperature in gray water tank may be below the mains water temperature, thus the supplemental mains water temperature may be rise the temperature of the mixed water inside the tank. However, according to the control algorithm given in Ref. [21], different operation mode will be carried out to overcome the drawbacks of low water temperature. In this section, the impact of gray water temperature on the performance of the heat pump system is discussed.

The mains water temperature in a day for a typical varies significantly depending on location and the time of year. The equation below can be used to determine daily mains water temperature, which is based on Typical Meteorological Year data for the location of the prototype [10].

$$T_{mains} = \left(T_{amb,avg} + offset\right) + ratio \times \left(\Delta T_{amb,\max}/2\right) \times \sin\left[0.986\left(day\# - 15 - lag\right) - 90\right] \tag{5}$$

where: $T_{\rm mains}$ = mains (supply) temperature to domestic hot water tank, °F; $T_{\rm amb,avg}$ = annual average ambient air temperature, °F; $\Delta T_{\rm amb,max}$ = maximum difference between monthly average ambient temperatures, °F; 0.986 = degrees/day (360/365); day# = Julian day of the year, 1–365 d; offset = 6 °F; ratio = $0.4 + 0.01(T_{\rm amb,avg} - 44)$; lag = $35 - 1.0(T_{\rm amb,avg} - 44)$, °F

Attention should be paid to the unit of the term [0.986(day# − 15 − lag) − 90], which is in degree of °F.

When using this equation, a lower limit of 0 °C (32 °F) should be enforced for $T_{\rm mains}$ regardless of the local weather conditions for calculation (such lower limit will be higher in reality). The ratio and lag factors in the Eq. (5) reflect the practice of burying water pipes deeper in colder climates.

Fig. 31 shows the estimated daily mains temperature in New York, NY. The maximum temperature is 22.6 °C in July. The annual mean mains-water temperature is 15.8 °C.

In New York, the daily mains-water temperature is in a range of 9 °C–22.6 °C. Ni et al. [21] proposed an operation strategy of gray water tank in heating mode. In general, mains-water temperature is less than the waste-water temperature from indoor during most of the time in winter. Lower bound energy saving have been estimated based on an assumption of using the calculated mean mains-water temperature and the lowest mains-water temperature, respectively, as the gray water tank temperature. Heat pump system are tested at outdoor temperature 8.3 °C in space heating mode as shown in Table 6.

Fig. 32 shows the COP of the heat pump system with different heat source combinations at the gray-water tank temperature of 15.6 °C. The highest COP of the system with parallel combination has been observed, while the COP of the system with air source only is the lowest. Fig. 33 illustrates the heating capacity and power of the heat pump system with different heat source combinations at the gray-water tank temperature of 15.6 °C. Parallel-source combination has the highest heating capacity, while series–source combination has the lowest heating capacity. For a lower gray-water tank temperature at 10 °C, Figs. 34 and 35 show the COPs, the heating capacities, and the powers of the heat pump

Table 4
Space heating plus hot water supply mode experiment conditions.

Heater exchanger choice	Outside air temperature (°C)/ average relative humidity of outdoor air (%)			Indoor air temperature (°C)	Gray water tank temperature (°C)	Hot water tank temperature (°C)
Air	15.6/24.41	8.3/36.82	1.1/39.16	21.1	21.1	48.9
Water	15.6/35.95	8.3/33.41	1.1/35.99	21.1	21.1	48.9
Parallel	15.6/37.93	8.3/34.89	1.1/31.99	21.1	21.1	48.9
Series	15.6/37.52	8.3/30.23	1.1/35.62	21.1	21.1	48.9

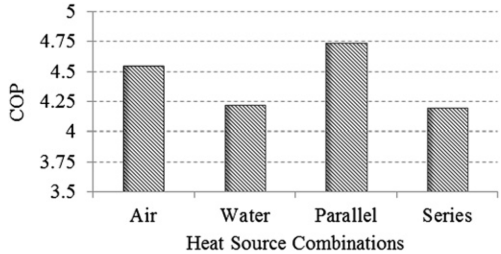

Fig. 10. COP at outdoor temperature 15.6 °C.

system with different heat source combinations. Parallel-source combination has the highest COP and heating capacity, while series–source combination has the lowest COP and heating capacity.

Compared the Figs. 12, 32 and 34, the COPs of the system using air source only and parallel–source combination are slightly changed under various gray-water tank temperatures. The change of water temperature may have a limited impact on the COP of these two combinations. As the temperature decrease, the COP of water source moderately decreases. When water temperature falls down to 10 °C, the COP reduced about 9.45%. Water temperature has a less impact on the COP of the system with series–source combination. When water temperature becomes 15.6 °C, the COP only falls about 1.16%, while water temperature drops to 10 °C, the COP becomes 5.36% reduced.

Referring to Figs. 13, 33 and 35, the heating capacities and powers of the system with air source only increase as the gray-water tank temperature decreases. As the gray-water temperature decreases, the heating capacity of the system with the parallel–source combination increases followed by a gradual decline at the range of temperatures being tested (i.e., 10–21.1 °C). At the gray-water temperature of 10 °C, the heating capacity is only 0.7% lower than that at water temperature 21.1 °C, while the power is similar to that at the higher temperature. When water temperature drops from 21.1 °C to 15.6 °C, the heating capacity of water source only decreases only 0.6%. However, when water temperature changes from 21.1 °C to 10 °C, the heating capacity decreases about 10.6%. The power of water source only increases followed by a gradual decline with decrease of water temperature.

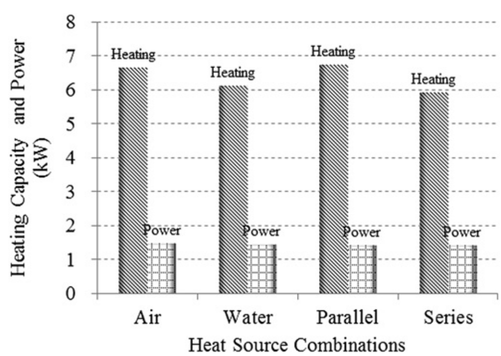

Fig. 11. Heating capacity and power at outdoor temperature 15.6 °C.

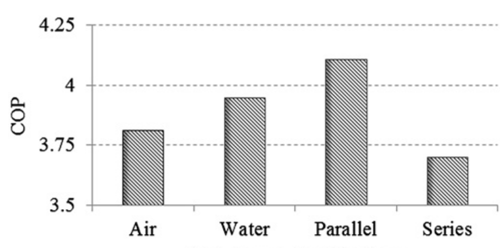

Fig. 12. COP at outdoor temperature 8.3 °C.

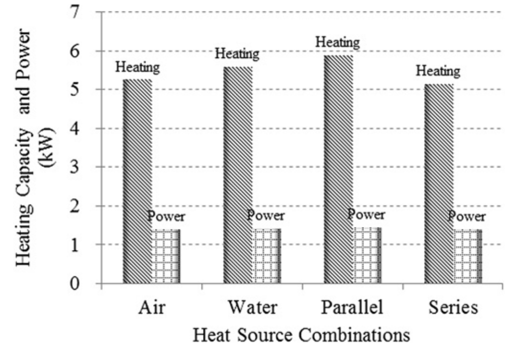

Fig. 13. Heating capacity and power at outdoor temperature 8.3 °C.

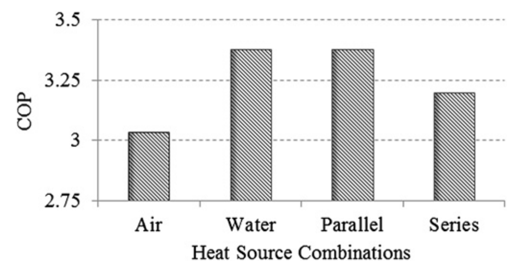

Fig. 14. COP at outdoor temperature 1.1 °C.

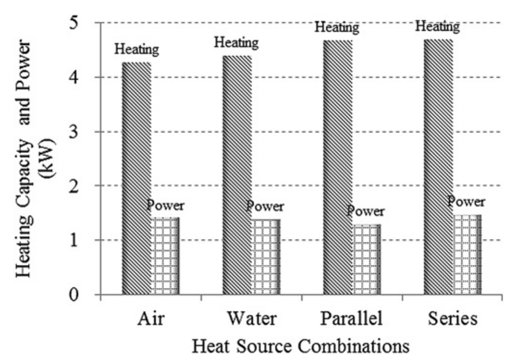

Fig. 15. Heating capacity and power at outdoor temperature 1.1 °C.

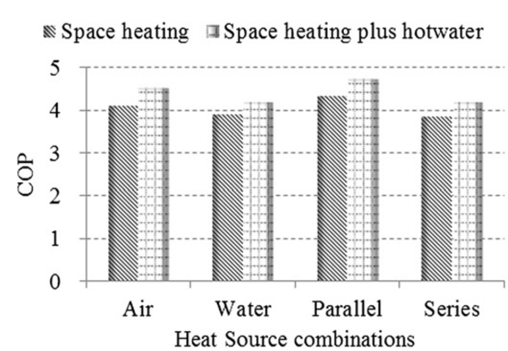

Fig. 16. COP at outdoor temperature 15.6 °C.

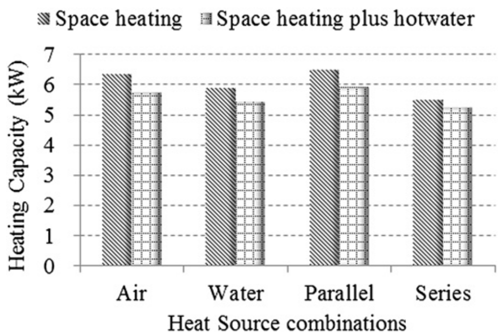

Fig. 17. Heating capacity at outdoor temperature 15.6 °C.

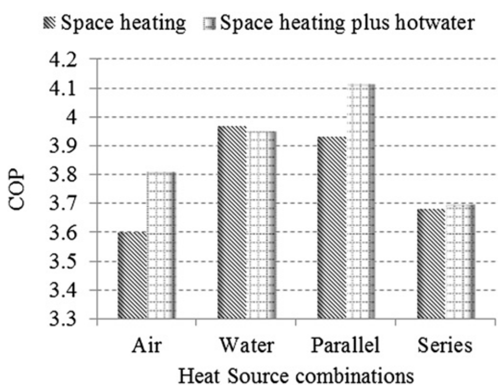

Fig. 18. COP at outdoor temperature 8.3 °C.

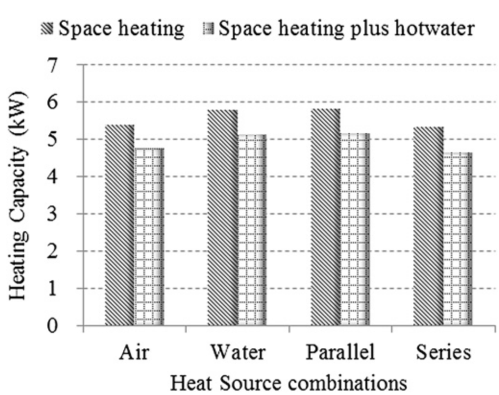

Fig. 19. Heating capacity at outdoor temperature 8.3 °C.

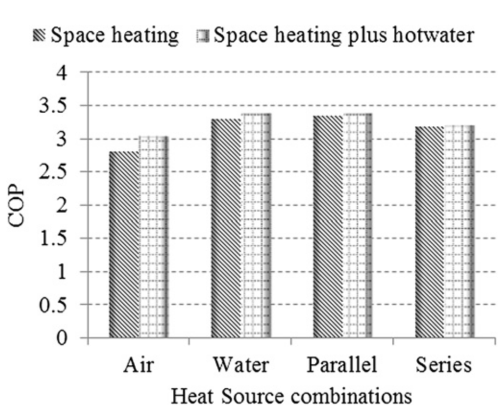

Fig. 20. COP at outdoor temperature 1.1 °C.

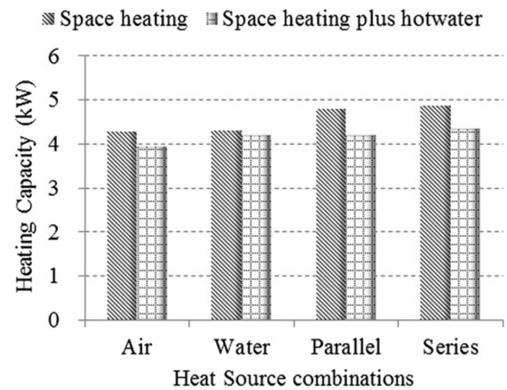

Fig. 21. Heating capacity at outdoor temperature 1.1 °C.

Table 5
Dynamic COP experiment conditions.

Heater exchanger choice	Outside air temperature (°C)	Indoor air temperature (°C)	Gray water tank temperature (°C)	Hot water tank temperature (°C)
Air	8.3	21.1	21.1	30–48.9
Water	8.3	21.1	21.1	30–48.9
Parallel	8.3	21.1	21.1	30–48.9
Series	8.3	21.1	21.1	30–48.9

Remark: Relative humidity is referred to Tables. 3 and 4.

Water temperature change has significant impact on the heating capacity of series–source combination. When water temperature becomes 15.6 °C and 10 °C, the heating capacity falls about 4.1% and 10%, respectively (c.f., the heating capacity at gray-water temperature of 21.1 °C). Compared with manufacture data provided in Figs. 2 and 3, the series–source combination has poor performance for space heating at low gray-water temperature. Even water temperature in gray water tank becomes 10 °C, the performances of the system with other three heating source combinations are still better than the manufacture data shown in Figs. 2 and 3.

4. Discussion

4.1. The impact of outdoor temperature on the performance of the multi-functional heat pump system with water source only

In space heating mode and space heating plus hot water supply mode, the COP and the heating capacity of the heat pump system decrease with the outdoor temperature referring to Figs. 4–9 as discussed in Section 3.2 and Figs. 10–15, as discussed in Section 3.3.

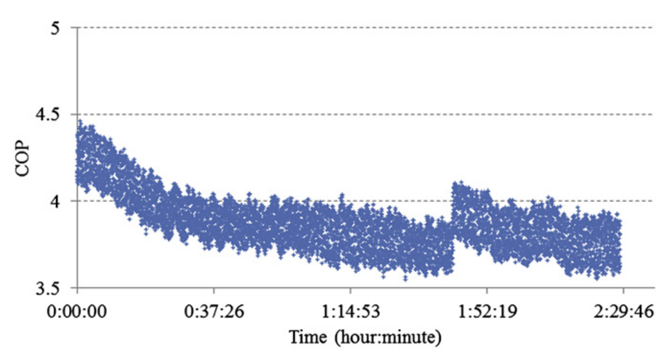

Fig. 22. COP for air source at outdoor temperature 8.3 °C.

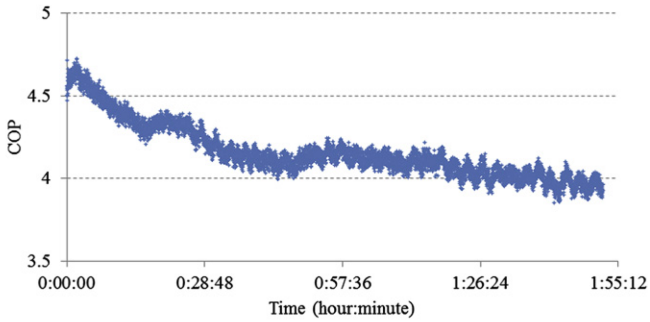

Fig. 23. COP for water source at outdoor temperature 8.3 °C.

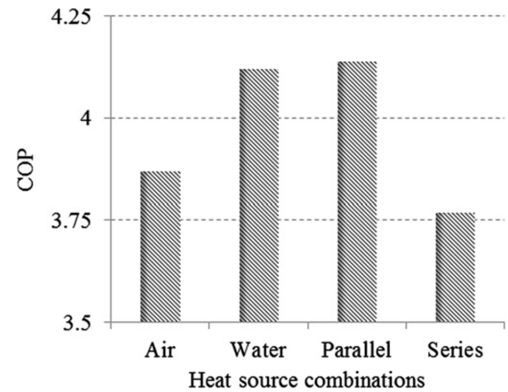

Fig. 26. COP at outdoor temperature 8.3 °C.

When outdoor temperature decreases, the ability of absorbing heating from outdoor air of air-source heat exchanger will be declined. In addition, the power of the compressor increases and thus the performance of the system decreases, as the evaporator and condenser pressures decrease.

In heating mode, air-source and water-source heat exchangers work as evaporators. They make four heat source combinations as mentioned above. According to Figs. 4–9 and Figs. 10–15, the system performance varies with different heat source combinations. There is only one thermal expansion valve for throttling and controlling the total refrigerant flowing through the evaporators. Therefore, unlike each evaporator has a corresponding thermal expansion valve, the amount refrigerant passing each evaporator will be decided by the evaporation pressure. The experiments at the outdoor temperature 8.3 °C in space heating mode are taken as an example, which the system performance is shown in Figs. 6 and 7. Parallel source has the highest COP and heating capacity, while air source only has the lowest COP and heating capacity. Table 7 shows the evaporation and condense pressure, as well as their ratio (Pc/Pe). Air source only has the lowest average evaporation pressure and the highest average ratio of evaporation and condense pressures. Series–source combination has the second lowest average evaporation pressure, and the second highest average ratio of evaporation and condense pressures. Parallel–source combination has the highest average evaporation pressure, and the average ratio of evaporation pressure and condense pressure is slightly higher than that of water source only. The superheat of each heating source combinations maintains at normal range (<10 °C) by thermal expansion valve. It results in lower evaporation and thus the lower refrigerant passing through the evaporators. Therefore, the performance of the heat pump system decreases. Also, the heat transfer rate of each evaporator is different. According to Figs. 4 and 5, the COP and the heating capacity of water source only is lower than those of air source only. This is because the heat exchanger in gray water tank is DX coil. The water circulated by a pump goes through heat exchanger. The heat transfer efficiency is not as good as that of air source heat exchanger. It causes the variation of the

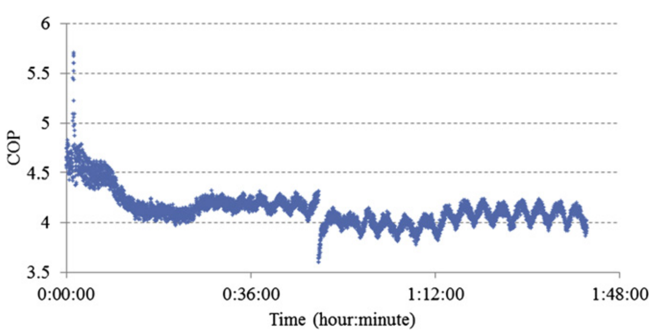

Fig. 24. COP for parallel at outdoor temperature 8.3 °C.

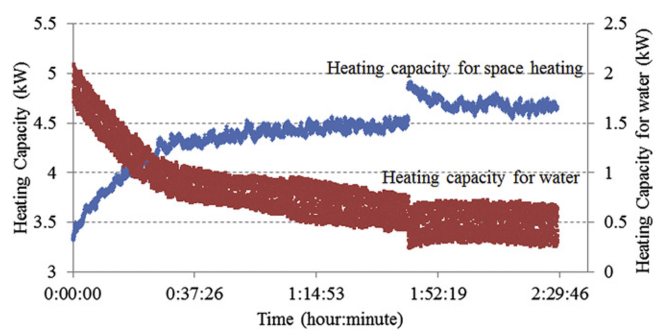

Fig. 27. Heating capacity for air source. Outdoor temperature 8.3 °C.

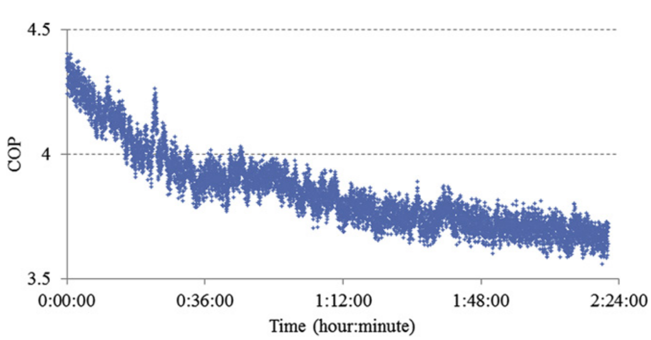

Fig. 25. COP for series at outdoor temperature 8.3 °C.

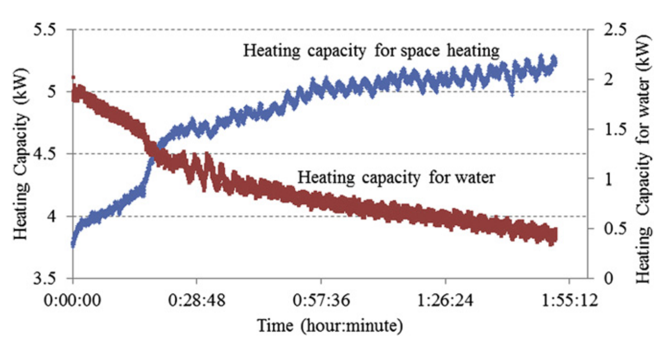

Fig. 28. Heating capacity for water source. Outdoor temperature 8.3 °C.

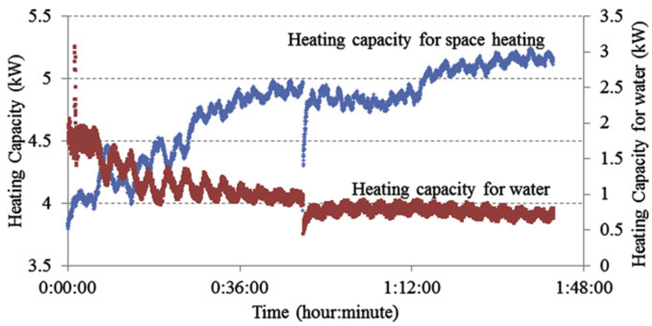

Fig. 29. Heating capacity for parallel. Outdoor temperature 8.3 °C.

performance of the heat pump system with the different heating source combinations.

The COP and the heating capacity of water source only should not be theoretically affected by the outdoor temperature, because no heat will be absorbed from the outdoor environment. However, in the existing prototype design, the system performance is affected by several factors. Firstly, the heat loss of refrigerant pipes exists. Secondly, in heating mode, the outlet of air source evaporator is connected with the outlet of the water source evaporator as shown in Fig. 36. The temperature sensor of the thermal expansion valve is installed after the merge point of the outlets of the air and water source evaporators. When the low pressure and low temperature refrigerant vapor leave the water source evaporator, some of the refrigerant vapor may enter to the air source evaporator and evaporates again due to the low outdoor temperature and the downstream pipe resistance. It results in the outdoor temperature affects the temperature measured by the sensor and affects the refrigerant flow rate in the present study.

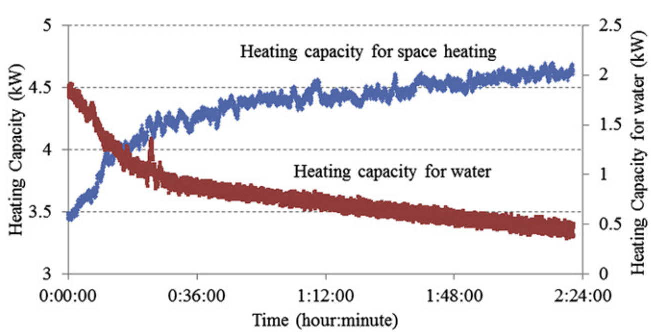

Fig. 30. Heating capacity for series. Outdoor temperature 8.3 °C.

Table 6
Experiment conditions at water temperature change.

Heater exchanger choice	Outside air temperature (°C)	Indoor air temperature (°C)	Gray water tank temperature (°C)	
Air	8.3	21.1	15.6	10
Water	8.3	21.1	15.6	10
Parallel	8.3	21.1	15.6	10
Series	8.3	21.1	15.6	10

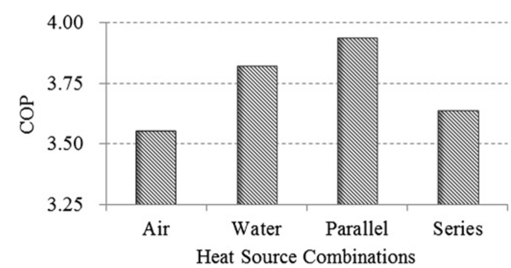

Fig. 32. COP at water temperature 15.6 °C.

4.2. The comparison of heating capacity in space heating

In space heating plus hot water supply mode, the heat exchanger for heating hot water and the heat exchanger in the indoor air-handler work as condensers. Parts of the total heating capacity of the system are used for heating hot water. In Figs. 17, 19 and 21, the system still have enough heating capacity for space heating, compared with the sample data provided by the manufacture against selecting the proper heat source combination.

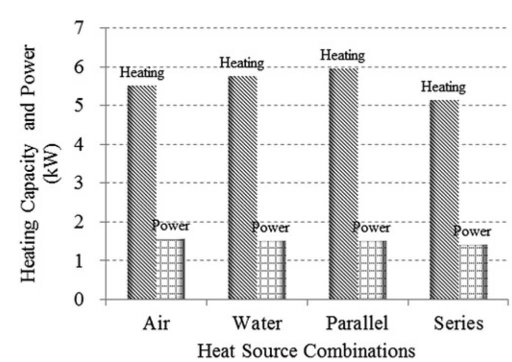

Fig. 33. Heating capacity and power at water temperature 15.6 °C.

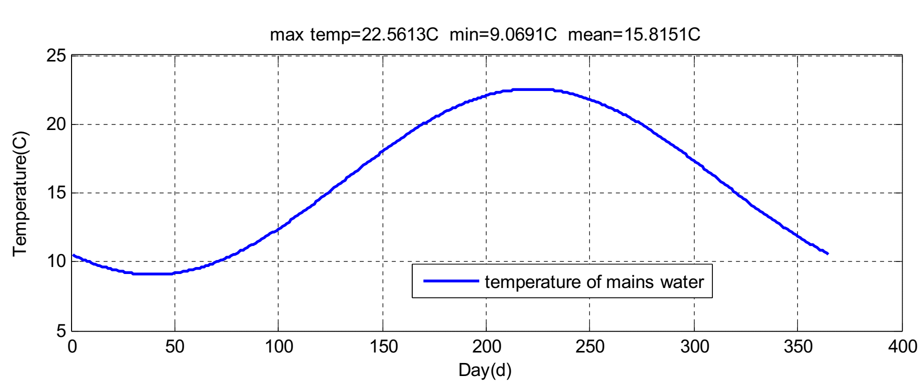

Fig. 31. Daily mains-water temperature in New York, NY.

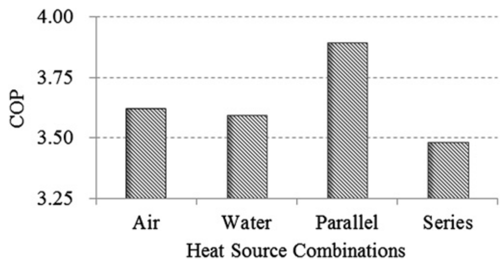

Fig. 34. COP at water temperature 10 °C.

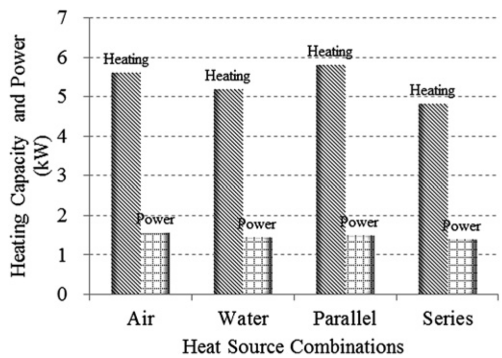

Fig. 35. Heating capacity and power at water temperature 10 °C.

Table 7
Evaporation pressure and condense pressure (gauge pressure).

	Air	Water	Parallel	Series
Evaporation pressure (Bar)	7.68	8.41	8.46	7.99
Condense pressure (Bar)	25.11	24.66	25.27	24.36
Pc/Pe	3.27	2.93	2.99	3.05
Superheat (°C)	3.52	4.23	2.16	2.02

4.3. The change curve of heating capacity for heating hot water and that for space heating in space heating plus hot water supply mode

Figs. 27–30 show the heating capacity for space heating and the hot water change curves. The heating capacity for space heating increases and that for the hot water supply decreases as the hot water temperature increases. It is because when the hot water temperature is about 30 °C, the temperature difference between the refrigerant and the hot water is large. As the hot water temperature increases, the temperature difference becomes smaller, as well as the heating capacity for heating hot water. The heating capacity for space heating correspondingly increases.

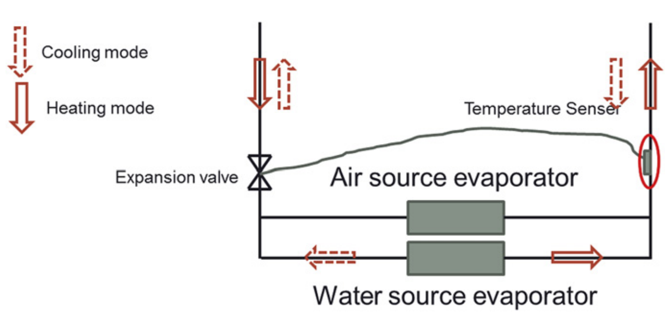

Fig. 36. Schematic of evaporator configuration.

5. Conclusion

In this study, the multi-functional heat pump system shows superior performance in heating mode compared with the conventional air source heat pump system. The system with air and water heat sources in parallel has the best performance in both space-heating mode and space-heating plus hot water supply mode, compared with the system with other heat source combinations. The performance of the innovative system with all types of heat source combinations decreases as the outdoor temperature decreases in both space-heating mode and space-heating plus hot water supply mode. The heating capacity for space heating of the multi-functional heat pump system in space heating plus hot water supply mode is smaller than that in space heating mode. However, the COP of the system in space heating plus hot water supply mode is higher than that in space heating mode. The difference of the heating capacities in two modes is less than 12%, while that of the COP in two modes is less than 6%. The space heating plus hot water supply mode is suitable for many operation conditions, such as an oversized system, and a partial heating load, which can prevent the frequent on-off situation and also can provide enough hot water. In space heating plus hot water supply mode, the system COP decreases as the hot water temperature increases. The heating capacity for heating hot water decreases, and the heating capacity for space heating increases as the hot water temperature increases. The process of heating hot water from 30 °C to 48.9 °C usually takes 2 h. The average COP of the innovative system in heating hot water from 30 °C to 48.9 °C is almost the same as that in maintaining a hot water temperature at 48.9 °C. Gray-water temperature has less impact on air source only and parallel–source combinations and has significant impact on series–source combination and water source only. The lower-bound estimated performance of the heat pump system is better than the conventional system.

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