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Development and performance testing of a polyvalent heat pump for hot and cold water production

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ABSTRACT
This research investigates a polyvalent heat pump that simultaneously produces hot and cold water and uses natural refrigerants. The novelty of using a 48 V direct current compressor driven by solar photovoltaic (PV) energy and the staged retrofitting improvements to this heat pump are discussed. Empirical testing has indicated that using a suction line heat exchanger yields a 30% improvement in the heating Coefficient of Performance (COP). Rising ambient temperatures could positively and negatively impact its heating and cooling performance, respectively. In addition, an average COP of 3.8 was obtained after a one-hour simultaneous mode operation, with the average hot tank temperature rising from 32.7 to 58.9°C and the average cold tank temperature dropping from 18 to 14.4°C. Being capable of operating the polyvalent heat pump under renewable energy sources and utilizing all its generated heating and cooling energy contributes further to the electrification and decarbonization of residential buildings.

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KEYWORDS
Coefficient of performance; heat pump; testing; renewable energy source; residential buildings; Australia

Nomenclature

AC	Alternating current
AUD	Australian dollar
COP	Coefficient of performance
CO_2	Carbon dioxide
DHW	Domestic hot water
DC	Direct current
GHG	Greenhouse gas
PV	Photovoltaic
R290	Propane
R134a	1,1,1,2-Tetrafluoroethane
R152a	1,1-Difluoroethane
R1234yf	2,3,3,3-Tetrafluoropropene
R22	Chlorodifluoromethane
R600a	Isobutane
SLHE	Suction line heat exchanger
SVs	Solenoid valves
C	Specific heat capacity of water (4.182 kJ/kg·°C)
m	Water mass flow rate (kg/s)
P	Power required by the compressor (W)
Q	Water load of the heat pump (W)
T	Water temperature (°C)

Subscripts

c	Water-cooling only
ci	Cold water inlet to the heat exchanger
co	Cold water outlet from the heat exchanger
h	Water-heating only
hi	Hot water inlet to the heat exchanger
ho	Hot water outlet from the heat exchanger
s	Simultaneous water heating and cooling

1. Introduction

The decarbonization of buildings is becoming increasingly critical in order to reduce greenhouse gas (GHG) emissions and counteract climate change, which has always posed a significant risk to the environment and individual health. Buildings in the European Union are reported to be accountable for 40% of its total energy consumption and 36% of GHG emissions (Barrutieta et al. 2023). According to data released by International Energy Agency (2022b), over 90% of the total energy supply in Australia is represented by fossil fuels, with coal (32%), natural gas (28%), and oil (32%). Furthermore, it is estimated that Australian households account for at least 20% of Australia's GHG emissions, which translates to over 18 tons per household per year (Australian Greenhouse Calculator 2023). A significant proportion of the total energy consumption in Australian households is accounted for by thermal demand; for example, space conditioning represents 40% of total energy consumption and domestic hot water (DHW) production for 23% (Energy Consult 2023). Mitigating GHG emissions from the building sector will contribute significantly to the global goal of becoming carbon neutral by 2050 (Barrutieta et al. 2021; Omrany, Soebarto, and Ghaffarianhoseini 2022).

Heat pumps have been recognized as an environmentally friendly technology and a promising solution to achieve a zero-emission future. Air source heat pumps have the majority of installation globally due to their numerous functions, including

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space conditioning and DHW production, and their relatively low cost compared to ground source and water source heat pumps (Osterman and Stritih 2021). However, the reduced heating performance in extremely cold ambient conditions is considered an important drawback of air source heat pumps, because insufficient heat energy is absorbed from the low-temperature environment, resulting in a low coefficient of performance (COP) obtained by heat generated divided by the electrical energy consumed by the air source heat pump. This issue may be mitigated by using alternative refrigerants or adding a suction line heat exchanger (SLHE) to the refrigerant pipeline of the heat pump (Nikitin et al. 2021). On the other hand, solar photovoltaic (PV) systems are gaining widespread acceptance and continued high installation rates worldwide, for example, exceeding 30% for residential installations in Australia (Australian Renewable Energy Agency 2022). However, the limited simultaneity between peak PV generation and residential energy demand results in a low PV self-consumption rate, calculated by dividing the local PV energy consumption by its total generation. When coupling heat pumps with water storage tanks and solar PV systems, space conditioning and DHW production can be realized by consuming renewable energy generation, leading to bill savings (Wang et al. 2022) and increasing residential electrification levels, thereby contributing to the phase-out of fossil fuels. Meanwhile, the excess PV energy can be consumed during the day and transferred to thermal energy storage, resulting in an increased PV self-consumption rate.

Heat pumps are now increasingly installed in residential buildings worldwide. For example, the installation of heat pumps is estimated to reach 600 million by 2030, covering 20% of global buildings' heating needs (International Energy Agency 2022a). Numerous government incentives and associated subsidies are one of the key factors contributing to this phenomenon. The Australian government has provided considerable incentives to increase the installation of heat pumps in residential buildings. For example, Victorian homeowners can receive up to AUD 1,000 in rebates from the Hot Water Program to help with the installation of a heat pump hot water system (Solar Victoria 2023). Under the Sustainable Household Scheme introduced in the Australian Capital Territory, residents can obtain zero-interest loans of between AUD 2,000 and AUD 15,000 for the purchase of heat pump hot water systems (ACT Government 2023). Based on the global trend and government incentives, it is forecasted that the application of heat pumps will exhibit exponential growth in the next few years.

Notably, conventional heat pumps, such as split air conditioners and air–water heat pumps reviewed by (Gaur, Fitiwi, and Curtis 2021), are used to provide space heating, cooling, and DHW for residential buildings. However, when these heat pumps are in use, either only the cooling energy generated on the evaporator side of the heat pump or only the heating energy generated on the condenser side is effectively utilized, while the energy generated on the other side is not collected or utilized and is wasted. A heat pump that can achieve simultaneous heating and cooling modes, i.e. both the produced heating and cooling energy can be used simultaneously, deserves research attention and is of great importance for achieving electrification and energy transition for residential buildings. Theoretical work and empirical testing have been undertaken to investigate the performance of this type of heat pump in existing literature. A recent work by Byrne (2022) reviewed the papers on using heat pumps for simultaneous heating and cooling, and the relevant applications comprise space heating, cooling and DHW production in the residential sector as well as the saltwater desalination and refrigerant in the commercial and industrial sectors. In fact, Byrne and his team have been working on simultaneous heating and cooling heat pumps for several years. For instance, Diaby, Byrne, and Mare (2019) investigated the performance of a simultaneous heating and cooling heat pump using carbon dioxide (CO_2) as the refrigerant in Transient System Simulation programme. It was found that the heat pump compressor operated on 380 to 420 V alternating current (AC) power, and the use of CO_2 for cooling was less efficient than its use for heating, suggesting that it is unsuitable for use in regions with hot climates, such as Australia, where most buildings have substantial cooling loads. Furthermore, a very recent work on theoretical design innovations by Liu et al. (2023) discussed a novel heat pump design with dual compressors offering simultaneous heating and cooling. Also, various refrigerants on this heat pump performance were evaluated, and the authors discovered that 1,1-Difluoroethane (R152a) performed the best in both heating and cooling cycles. However, the primary flaw of this work is that it is entirely based on theoretical work without any empirical testing due to the lack of a realistic heat pump.

Therefore, this paper proposes a simultaneous heating and cooling heat pump, called the polyvalent heat pump, that can provide water heating and cooling modes simultaneously. Specifically, the heating energy generated on the hot water heat exchanger and cooling energy generated on the cold water heat exchanger of the heat pump are stored in two water storage tanks and are made available for space heating, cooling and DHW. Also, this heat pump can deliver water heating-only and water cooling-only mode. Notably, the main novelty of this paper compared to the above literature is that this polyvalent heat pump employs R290 (Propane) as the refrigerant and operates on 48 V direct current (DC) power, allowing it to be well coupled to residential solar PV and battery systems. This prototype of a polyvalent heat pump has also undergone a few retrofitting, including switching between refrigerants, and installing an SLHE. Empirical testing is conducted to investigate its performance under different retrofitting stages and various operating modes and ambient conditions.

The remaining sections of the paper are organized as follows: Section two explains the basic heat pump cycle, the historical development of heat pumps, and the past, present and future heating applications in Australia. Section three explains the polyvalent heat pump and its working principles in detail. Section four demonstrates the testing design, and Section five explains the results for investigating the performance of the heat pump testing under different modes and various retrofitting stages and ambient conditions. Section six provides a discussion of the paper, and section seven draws a conclusion for this paper.

2. Heat pump development

2.1. Basic heat pump cycle

Heat pumps are devices that transfer heat between the heat source and the heat sink. The source is where heat pumps collect

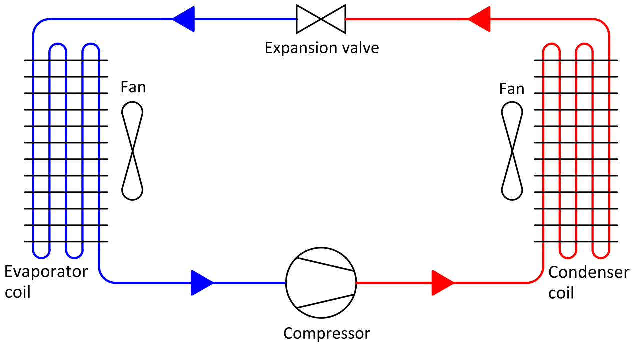


Figure 1. Schematic of a basic heat pump cycle.

Table 1. Main findings of the historical development of heat pumps.

Year	Main findings
1824	Carnot-Cycle and the second law of thermodynamics were proposed by Nicolas Leonhard Said Carnot.
1857	The first heat pump was developed for producing salt by Peter von Rittinger in Austria.
1928	Air source heat pumps were used to provide space and hot water heating by T.G.N Haldane.
1930s	A surface water heat pump was used to heat the town hall in Zurich, Switzerland.
1945	The first direct expansion-ground source heat pump was installed in Indianapolis.
1970s	Solar-assisted heat pumps were being developed and researched extensively.

the heat, while the sink is where the heat is put in, thus allowing cooling on the heat source side and heating on the heat sink side (Adamson et al. 2022). To upgrade the output heat of heat pumps, electrical or mechanical power must be applied to a compressor to raise the pressure, thus increasing the temperature of the refrigerant, which is the main working principle of heat pumps. In the residential sector, heat pumps are generally electrically driven types and are applied for space heating, cooling and DHW production. A basic heat pump cycle, also an air-to-air heat pump, is shown in Figure 1, which consists of four main components, such as a compressor, a condenser coil, an expansion valve, and an evaporator coil. Notably, by using different combinations of evaporators and condensers, the basic heat pump cycle can be modified to other types of heat pumps, including water source heat pumps, ground source heat pumps, solar-assisted heat pumps, etc. For instance, a direct expansion solar-assisted hot water heat pump can be achieved by replacing the evaporator coil in Figure 1 with a solar thermal collector and the condenser coil with a refrigerant-to-water heat exchanger connected to a water storage tank (Kong et al. 2022). Alternatively, a ground-coupled heat pump for space conditioning can be designed by switching the evaporator coil from Figure 1 to a water-to-refrigerant heat exchanger connected to a ground-loop heat exchanger (Hou et al. 2022). Undoubtedly, a four-way valve needs to be connected to the refrigerant cycle in order to switch between the heating and cooling modes.

2.2. Historical development of heat pumps

In 1824, Nicolas Leonhard Sadi Carnot published his book, Reflections on the Motive Power of Fire, leading to the 'Carnot-Cycle', and the second law of thermodynamics. In 1857, Peter von Rittinger developed and built the first heat pump system for producing salt from concentrated saltwater in Austria. Heat pumps for heating purposes were achieved by T.G.N. Haldane, who installed an air source heat pump for space and water heating from 1927 to 1928 (Holmes 1981). At the same time, he realized the possibility of using heat pumps for heating in winter and cooling in summer by reversing the refrigeration cycle (Haldane 1930). Later, the surface water heat pump was first used for room heating in the 1930s; for example, the town hall in Zurich, Switzerland, was heated by a surface water heat pump using river water as a heat source (Egli 1944).

In 1945, the first direct expansion-ground source heat pump was installed in Indianapolis. It had three underground loops of horizontal pipes measuring 152 metres in length and a compressor power of 2.2 kW (Crandall 1946). Due to the low energy price in the 1950s, high investment costs, and the corrosion to ground heat exchangers, ground source heat pumps were not economically feasible, and the research on ground source heat pumps lasted until the middle of the 1950s and stopped. From the 1970s to the early 1980s, heat pumps received renewed attention from the public due to the energy crisis as well as the capability that heat pumps to recover low-temperature waste heat. During this period, a cost-effective analysis of solar-assisted heat pumps used for space heating and cooling was conducted in the US in 1978 (Andrews, Kush, and Metz 1978), and the authors discovered that solar-assisted heat pumps could contribute to the significant cost and energy savings compared to the electric-based system. The historical development of heat pumps is summarized in Table 1.

2.3. Heating applications in Australia: the past, the present and the future

In the 1960s, electric resistance hot water systems were the most common water heating technology in the Australian residential sector. This was followed by solar hot water systems and gas heaters, which started to be used in the late 1970s and the early 1980s, respectively. The Australian government began phasing out electric water heaters in 2010 to reduce GHG emissions, and the federal government provided the Solar Hot Water Rebate in 2009. Specifically, Australian residents could apply for a maximum of AUD 1000 for a solar hot water system and a maximum of AUD 600 for a heat pump water heater (Parliament of Australia 2010).

Due to their superior heating and cooling performance and energy-saving potential, heat pumps are currently gaining popularity in the residential market (Wang et al. 2021). As described in Section 1 of this paper, many researchers have focused on the development of heat pumps for simultaneous heating and cooling, which can be a great solution for residential buildings, whose thermal load accounts for a significant portion of their total energy demand, such as roughly 65% in Australia (Energy Consult 2023). The increasing installation of residential solar PV systems leads to the DC energy generation with various power range, so heat pumps capable of providing simultaneous heating and cooling and operating on 48 V DC with various speed are considered future research directions. Thus, the explanation of the polyvalent heat pump prototype will be presented in the

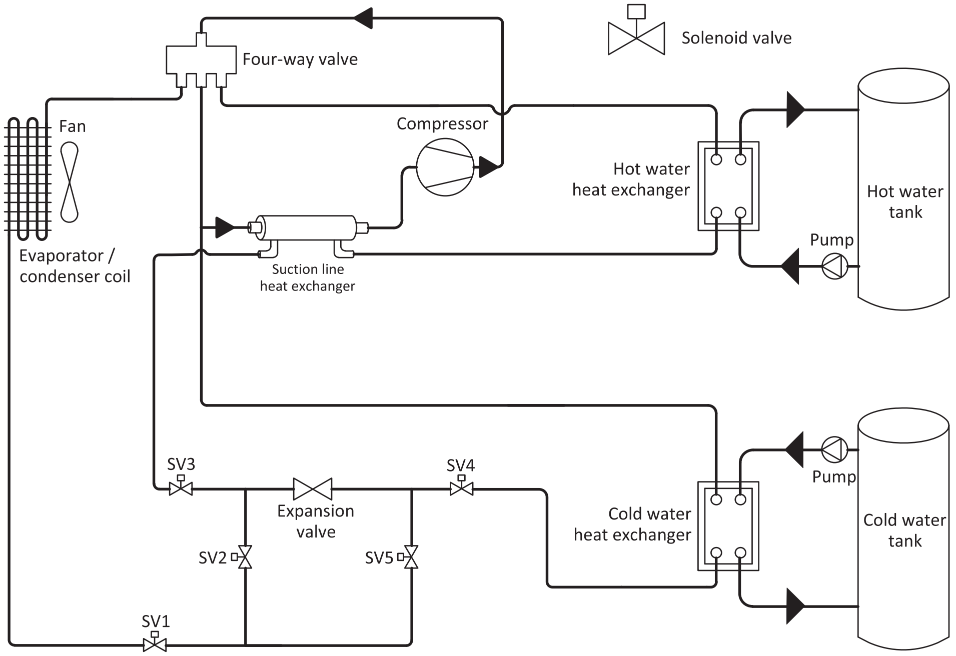


Figure 2. Schematic of a polyvalent heat pump for hot and cold water production.

Table 2. The development of heating applications in Australia.

Year	Main findings
1960s	Electrical resistance water heaters were the most common water heating technology used in Australian households.
Late 1970s	Solar hot water systems started to be used in Australia.
Early 1980s	Australian residents began to use gas water heaters.
2000s	Electrical heat pumps came to Australia.
Present	Simultaneous heating and cooling heat pumps run on AC power.
Future	Polyvalent heat pumps capable of providing simultaneous heating and cooling and operating on 48 V DC power

subsequent sections, along with its experimental results. The development of heating applications in Australia is shown in Table 2.

3. Development of a new heat pump for residential buildings

3.1. Polyvalent heat pump

In this study, a new type of heat pump, called polyvalent heat pump is proposed for residential buildings. The term 'Polyvalent' refers to having many functions or purposes. A polyvalent heat pump can operate in multiple modes, including heating-only, cooling-only, and simultaneous heating and cooling, all in one unit, which may contribute to energy savings (Wang et al. 2023) and reduced maintenance costs compared to using separate systems for each function. This also makes this type of heat pump an ideal and adaptable solution for residential buildings requiring year-round space heating, cooling and DHW. A schematic diagram of a prototype polyvalent heat pump used for hot and cold water production is shown in Figure 2.

The design of this polyvalent heat pump can assist with the heating and cooling of water stored in insulated tanks. Space conditioning can therefore be accessed via an electric pump when it is needed. The five solenoid valves (SVs) and a four-way valve used in this heat pump regulate the refrigerant flow in the refrigerant pipelines, which helps the heat pump to achieve different modes of operation. Four heat exchangers are included in this heat pump prototype. The typical or standard heat exchanger is, of course, represented by refrigerant-to-air heat exchanger in the diagram. Next, there are two plate heat exchangers, one for water heating and the other for water cooling. The last one is a SLHE, also called the internal heat exchanger, which is installed in this polyvalent heat pump prototype, and it has the following purposes in the refrigerant system: evaporating the refrigerant leaving the evaporator to prevent the liquid refrigerant from entering the compressor, subcooling the refrigerant exiting the condenser to prevent the gas refrigerant from entering the expansion valve, and moving the waste heat out of the liquid line and directly back into the suction line of the system, thus increasing the energy efficiency of the refrigeration cycle (Nasution, Idris, and Pambudi 2019). There are some examples that reported the effectiveness of using the SLHE in the refrigerant system. For instance, the effects of using R290 and a SLHE on the power consumption and COP of room air conditioners were investigated experimentally. Using a SLHE and R290 increased their energy savings and COP by approximately 28% and 38%, respectively, compared to a standard room air conditioner using Chlorodifluoromethane (R22) as the refrigerant and without a SLHE installed (Nasution, Idris, and Pambudi 2019).

Conventional heat pumps or fixed-output heat pumps can only be turned on or off. Once turned on, the compressor works continuously at full load until the heating or cooling requirements are met before shutting down. When the heat sink temperature drops or the heat source temperature rises to a certain level depending on the thermostat's temperature setting, the heat pump will turn on again and run at full speed. This often results in significant energy consumption and can easily cause the heat pump compressor to fail. To solve this problem, heat pumps with DC inverter technology are becoming a proper solution, which has been adopted in the polyvalent heat pump prototype proposed in this paper. DC inverter is an energy-saving technology that eliminates the over-running of the heat pump by effectively controlling the operating speed of the compressor. More specifically, DC inverter heat pumps use a variable speed compressor that regulates its heat output by increasing or decreasing its speed to accurately match the heating or cooling demand as well as the heat source temperature. When heating or cooling demand is relatively low, the compressor speed is reduced and maintained at a certain level that ensures continuous and necessary heat output, rather than running at full speed or stopping outright, as is the case with fixed-output heat pumps. Consequently, this may reduce the energy consumption of heat pumps and the likelihood of damage to the compressor and other components. Additionally, nowadays, using 48 V DC input heat pumps for heating, cooling and DHW production can be a great option, owing to the increasing installation of solar PV systems in houses. This integration can further reduce GHG emissions and grid energy consumption. Therefore, considering the benefits of 48 V DC voltage input to heat pump technology, the polyvalent heat pump prototype presented in this paper involves a 48 V DC compressor, which can operate directly from drawing energy from battery storage and solar PV systems.

Table 3. Specifications of components and refrigerants used in the prototype of the polyvalent heat pump.

Components	Specification
Twin-rotary compressor	Company: Panasonic Model number: 6KDZ20ZAA2 Power supply: 48 V DC Nominal cooling capacity: 3465 W
Plate heat exchangers	Company: Sanhua holding group Number of plates per heat exchanger: 60 Area: 2.09 m^2
Refrigerant-to-air heat exchanger	Type: finned coil heat exchanger Coils: 31 rows of copper coils; each row is 900 mm in length and 8.1 mm in outer diameter
SLHE	Company: Packless industries Model number: HXR − 50 Capacity: 735.5 W Maximum working pressure: 3.10 Mpa
Solenoid valves	Company: Sanhua holding group Model number: SQ-D31048-000001 Power supply: DC48V Power input: 7.5W
Four-way valve	Company: Sanhua holding group Model number: SHF(L)—4H-23U-P Maximum working pressure: 4.2 Mpa Flow coefficient: 1.6 m^3/h
Electronic expansion valve	Company: Sanhua holding group Model number: DPF-09003 Flow coefficient: 1.6 m^3/h Maximum operating pressure: 4.2 Mpa
Refrigerant – R134a	Critical temperature: 101 °C Critical pressure: 4.059 Mpa Latent heat at a dewpoint temperature of 0 °C: 198.6 kJ/kg
Refrigerant – R290	Critical temperature: 96.70 °C Critical pressure: 4.247 Mpa Latent heat at a dewpoint temperature of 0 °C: 374.7 kJ/kg
Control strategy	Type: Modbus protocol Communication interface: RS485

In the very early stages, the refrigerant used in the heat pump prototype was 1,1,1,2-Tetrafluoroethane (R134a). However, since heat pumps use conventional refrigerants with very high global warming potential (GWP) and ozone depletion potential (ODP), refrigerant leaks and improper disposal at the end of life can produce large GHG emissions. For this reason, heat pumps should be designed and moved towards the use of natural refrigerants with no ODP and low GWP (Moradkhani et al. 2022). There are numerous natural refrigerants, such as water, CO_2 and hydrocarbons. They have the characteristics of non-corrosiveness, non-toxicity (Sisti et al. 2023), environmental friendliness (Tsimpoukis et al. 2021) and low freezing and boiling point, high latent heat of vaporization. Hydrocarbon refrigerants are composed of high concentrations of hydrogen and carbon in crude oil. They are environmentally friendly and can be great alternatives to conventional refrigerants that are toxic and have high GWP and ODP (Du, Wu, and Wang 2020). R290, butane, and ethane are some hydrocarbon refrigerants. They are excellent refrigerants in terms of their energy efficiency, thermodynamic properties and critical point.

The system performance of a split air conditioner with R22 and R290 under different conditions was compared experimentally (Zhou and Zhang 2010). It was observed that the refrigerant mass flow rate for R290 was only 47% of that for R22, and the energy efficiency ratio of R290 is around 8.5% higher than that of R22, which effectively exhibits the benefits of using R290 as a refrigerant in a split air conditioner. By researching R134a, R290, isobutane (R600a), and 2,3,3,3-Tetrafluoropropene (R1234yf), a mathematical model of a small cooling vapour compression refrigeration system was created in order to construct an energy-efficient system with low costs and minimal environmental effect (de Paula et al. 2020). The authors found that among all the studied refrigerants, R290 has outstanding energy, environmental and economic performance and is the most suitable refrigerant to replace R134a. Therefore, considering the positive impact of natural refrigerants on the environment and system efficiency, we changed the refrigerant used in this polyvalent heat pump prototype from the previous R134a to R290. Table 3 summarizes the specifications of components used in the prototype of the polyvalent heat pump.

3.2. *Polyvalent heat pump functions*

As explained previously, the polyvalent heat pump can operate in three modes: water heating-only, water cooling-only, and simultaneous water heating and cooling, and their operating diagram is shown in Figure 3.

Depending on the operating mode of the heat pump, the ON and OFF of its various components, such as the expansion valve, SVs, four-way valve, and fan, are controlled automatically by the heat pump control system. When the heat pump operates in the water heating-only mode, it works as an air-to-water heat pump. The principle is that high-temperature and high-pressure gas refrigerant from the compressor flows to the hot water heat exchanger via the four-way valve for producing hot water. Due to releasing heat to the water from the hot water tank, the

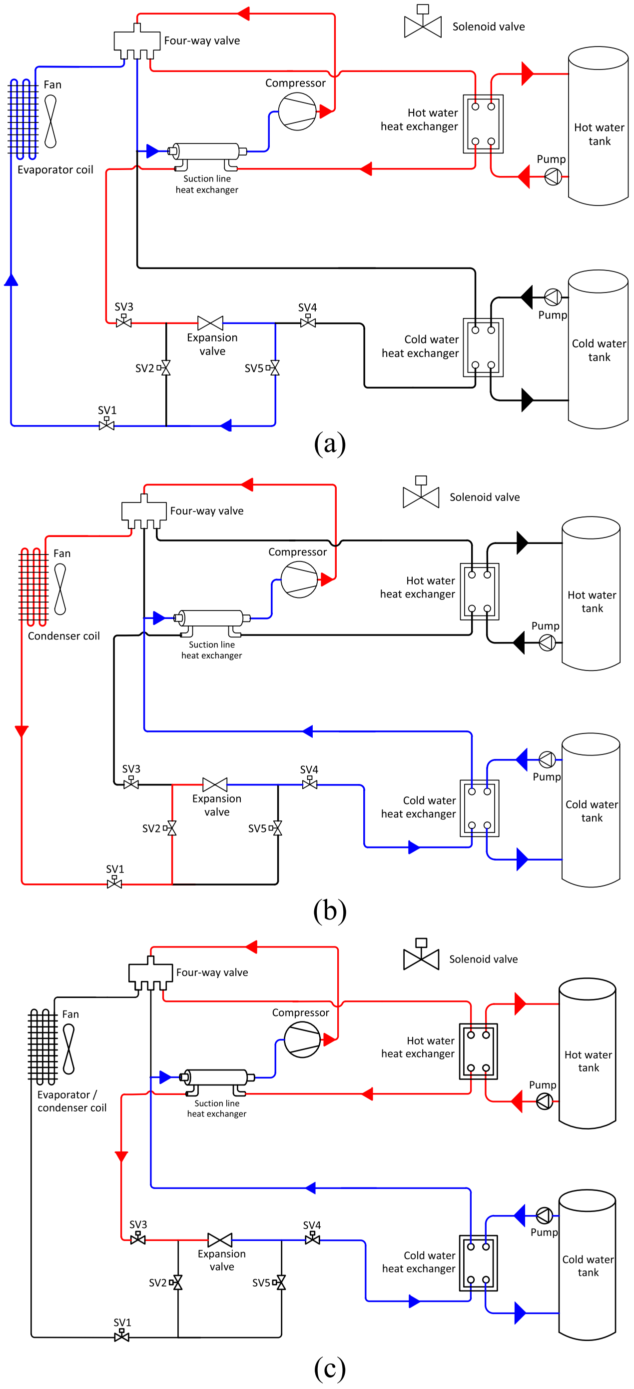


Figure 3. Operational diagram of the polyvalent heat pump in three modes. (a) Water heating-only mode; (b) Water cooling-only mode; (c) Simultaneous water heating and cooling mode.

gas refrigerant is condensed into liquid refrigerant, which then passes through the SLHE, SV3, the expansion valve, SV5 and SV1, before entering the evaporator coil. Due to absorbing heat from the ambient air, the mixture of gas and liquid refrigerant created by flowing through the expansion valve is evaporated into the gas refrigerant. The evaporated gas refrigerant is sent back to the SLHE for further evaporation before flowing to the compressor for the next cycle.

Based on similar principles, the polyvalent heat pump works as a water-to-air heat pump in the water cooling-only mode and as a water-to-water heat pump in the simultaneous water heating and cooling mode. During the simultaneous operation mode, it is essential to note that the heat pump generates hot and cold water in two plate heat exchangers where are stored in two separate storage tanks. When the water temperature in one of the tanks reaches its preset point, the heat pump will automatically switch to water heating-only or water cooling-only mode to produce more hot or cold water. The heat pump will then stop running until the temperature of the second tank reaches its preset point. It is also worth noting that the SLHE only functions in the water heating-only and simultaneous water heating and cooling modes, while in the water cooling-only mode, it does not function because the refrigerant flows through only one of the two tubes in the SLHE. Table 4 summarizes the operating status of each component of the polyvalent heat pump in the three modes.

4. Performance testing of the polyvalent heat pump

The polyvalent heat pump performance may have been affected due to the installation of SLHE in the refrigeration pipelines. In order to study the performance of this heat pump before and after the use of SLHE and its performance in the three operation modes and under different ambient conditions, some tests were performed for the heat pump prototype, and data were recorded. This section will detail the test design of the polyvalent heat pump, the calculation of the heat pump COP in the three modes, and the testing results.

4.1. Testing design

The COP is a key indicator to evaluate the performance of the heat pump, and it is calculated by dividing the thermal output of the heat pump by the electrical input. Heat pumps operate differently under various ambient conditions and in their varying stages of input and output temperatures. In order to study the COP of this polyvalent heat pump prototype before and after the use of the SLHE and in different operating modes, some equipment was set up for experiments and data collection. The specifications of the relevant equipment used to perform the experiments are listed in Table 5.

This polyvalent heat pump is designed to produce hot and cold water that can be used for heating, cooling and DHW in residential buildings. Using a 48V DC input compressor ensures that the heat pump can be operated from battery storage or by consuming instantaneous solar PV power. This, therefore, led to the decision to test the water heating-only performance of the heat pump at a higher ambient temperature which we selected around 20°C in this paper. This is because using water storage tanks allows the heat pump to operate at higher ambient temperatures during the day and store hot water for use during peak periods. Also, a large amount of PV power may be generated during the day to provide sufficient electricity supply for the heat pump operation, and the higher temperatures during the day enable the heat pump to efficiently produce hot water. Meanwhile, in order to understand the impact of different ambient temperatures on the heating performance of the polyvalent heat pump, we run the heat pump under the water heating-only mode at 30 °C and collect temperature and energy consumption

Table 4. Operating status of various components of the polyvalent heat pump with a SLHE under the three modes.

Modes	SV1	SV2	SV3	SV4	SV5	Fan	SLHE	Evaporator/ condenser coil
Water heating-only	Open	Close	Open	Close	Open	Open	Functioning	Evaporator coil
Water cooling-only	Open	Open	Close	Open	Close	Open	Not functioning	Condenser coil
Simultaneous water heating and cooling	Close	Close	Open	Open	Close	Close	Functioning	Not functioning

Table 5. The specifications of relevant equipment used for polyvalent heat pump COP testing.

Equipment	Specifications
Polyvalent heat pump	Input voltage: 48 V DC, maximum current: 43A
Two water pumps	Input power: 100 W, input voltage: 24 V DC, lifting range: 12 m, Flow rate: 10 L/min
Two insulated water tanks	Rated capacity: 120 L each
Thermocouples	Name: Type T thermocouple (Copper/Constantan), temperature range: −270 to 370 °C, accuracy: +/− 1.0 °C
Power source	Brand: Pylontech US2000 Lithium battery, nominal voltage: 48 V DC, battery capacity: 7.2 kWh = 3×2.4 kWh each
Power metre	Voltage measurement range: 6.5–100 V DC, current measurement range: 0-100A, power measurement range: 0–10kW

Figure 4. Photograph of the experimental setup.

data for comparison. Furthermore, separate experiments at an ambient temperature of about 12°C are conducted to explore the change in performance of the polyvalent heat pump before and after using the SLHE.

On the other hand, ambient temperatures below 30°C were chosen to evaluate the cooling performance of the polyvalent heat pump in water cooling-only mode, as the heat pump is probably more effective at these lower temperatures, and the use of a cold water tank enables the cooling energy to be stored and used during peak cooling periods. Furthermore, an experiment was conducted to test the relationship between the temperature of the two water tanks and the polyvalent heat pump COP over time in the simultaneous water heating and cooling modes. Figure 4 shows the photograph of the experimental setup.

4.2. Key parameters

Australian/New Zealand Standard 5125.1:2014 (Standards Australia 2014) defines the calculation of COP for heat pump water heaters, and they consider the heat loss of the tank and its pipes connected to the heat pump. However, this paper assumes that there is no heat loss from the two water tanks and their water pipes since they are well insulated. Also, as the operation of the polyvalent heat pump in water cooling-only mode is very similar to the water heating-only principle, the COP calculation for the polyvalent heat pump in both modes is defined based on the Australian/New Zealand Standard 5125.1:2014.

When the polyvalent heat pump operates in water heating-only mode, the hot water heating load of the heat pump, Q_h, can be calculated as follows:

$$Q_h = Cm_{hi}(T_{ho} - T_{hi}) \tag{1}$$

where:

$C =$ specific heat capacity of water (4.182 kJ/kg·°C);

$m_{hi} =$ hot water inlet mass flow rate

$T_{ho} =$ hot water outlet temperature from the heat exchanger;

$T_{hi} =$ hot water inlet temperature to the heat exchanger.

Then, the COP of the polyvalent heat pump under the water heating-only mode at any instant time, COP_h, is given by:

$$COP_h = \frac{Q_h}{P} \tag{2}$$

where:

$P =$ the power required by the compressor

When the polyvalent heat pump operates in water cooling-only mode, the cold water cooling load of the heat pump, Q_c, can be calculated as follows:

$$Q_c = Cm_{ci}(T_{ci} - T_{co}) \tag{3}$$

where: $m_{ci} =$ cold water inlet mass flow rate

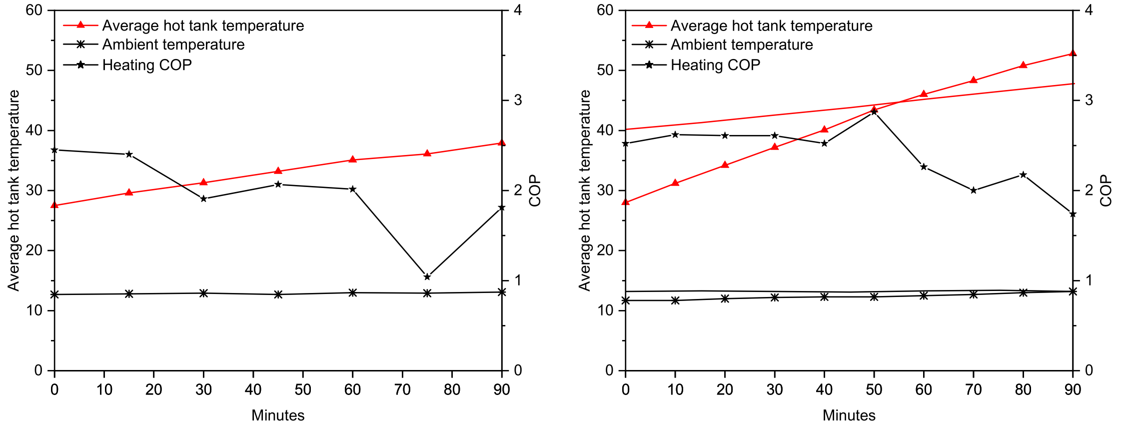
$T_{ci} =$ cold water inlet temperature to the heat exchanger;

$T_{co} =$ cold water outlet temperature from the heat exchanger.

Then, the COP of the polyvalent heat pump under the water cooling-only mode at any instant time, COP_c, is expressed by:

$$COP_c = \frac{Q_c}{P} \tag{4}$$

Although AS/NZS: 5125.1:2014 does not explain how the COP of the polyvalent heat pump should be calculated under both water heating and cooling mode, it is believed that the COP of the polyvalent heat pump under this mode should be calculated by considering both the hot water heating load and the cold water cooling load, as both the hot and cold energy generated on the two heat exchanger sides, respectively, are useful and stored in two separate tanks. Therefore, the COP of the polyvalent heat pump under the simultaneous water heating and



(a) (b)

Figure 5. Heating performance of the polyvalent heat pump under the water heating-only mode before and after the installation of a SLHE. (a) Polyvalent heat pump without a SLHE; (b) Polyvalent heat pump with a SLHE.

cooling mode at any instant time, COP_s, will be calculated by using Equation 5.

$$COP_s = \frac{Q_h + Q_c}{P} \tag{5}$$

5. Testing results

As described in Section 3.2, the SLHE operates in water heating-only mode and simultaneous water heating and cooling mode. Due to the limited experiments on this polyvalent heat pump before using the SLHE, only the impact of SLHE on the heating performance of the heat pump is explained here. This section will also introduce the performance of the heat pump under different ambient temperatures in water heating-only and water cooling-only modes. Moreover, the performance of the polyvalent heat pump in simultaneous water heating and cooling modes is demonstrated and explained.

5.1. *Effect of SLHE on heating performance*

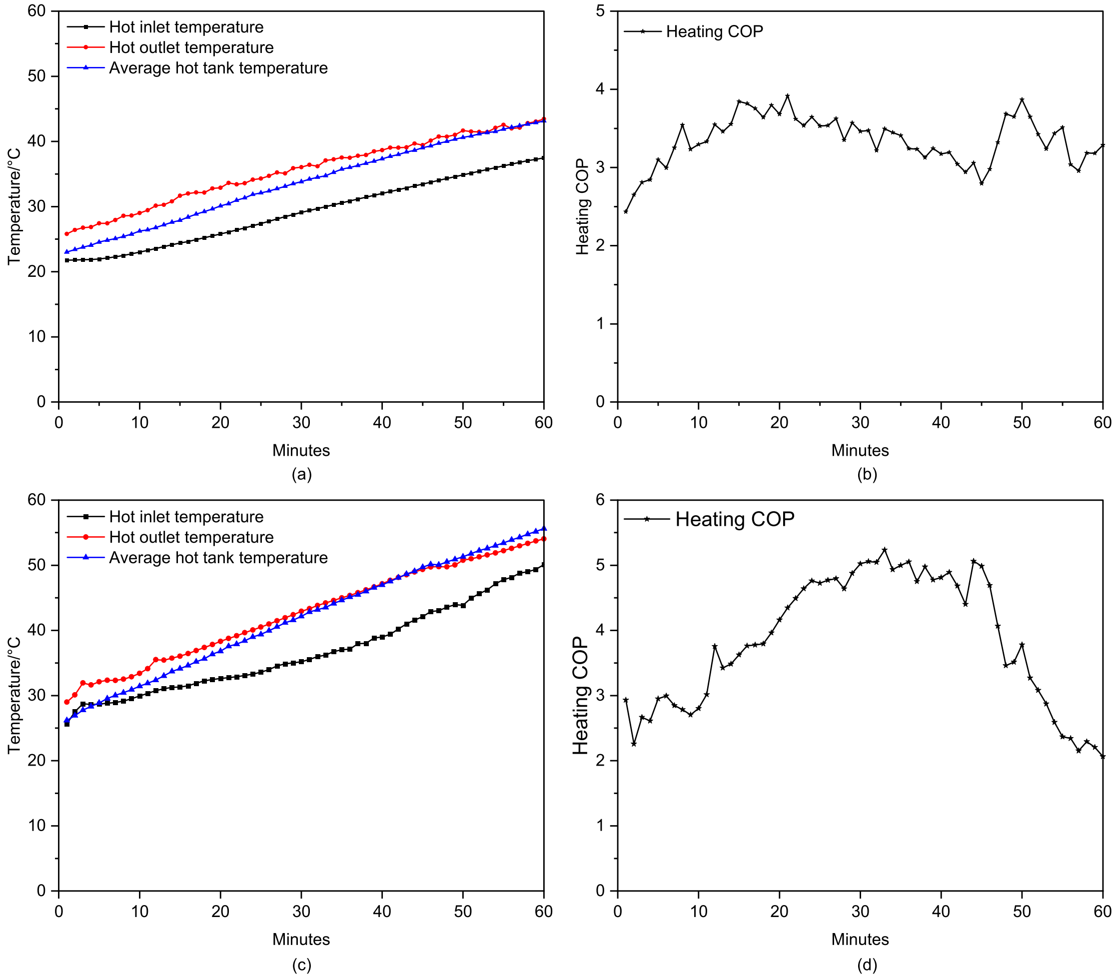
To investigate the effect of using SLHE on the performance of the polyvalent heat pump system, we ran the heat pump in water heating-only mode before and after the installation of SLHE. Since only the average temperature of the hot water tank and the power consumption of the compressor were recorded, the COP for both operations were calculated by dividing the thermal energy accumulated in the hot water tank during 10 and 15 min by the energy consumption during the corresponding periods, and the results are plotted in Figure 5. It can be seen that the heating COP of the polyvalent heat pump tends to decrease gradually in both cases as the average temperature of the hot water tank increases, which is due to the increased difficulty in transferring heat from the refrigerant to the hot water as the hot water temperature rises. Importantly, at a similar ambient temperature of about 12°C, the use of the SLHE increased the average heating COP of the polyvalent heat pump by 30%, from 2.0 to 2.6. In the absence of the SLHE, the average temperature of the hot water tank increased from 27.5°C to 37.9°C after one and a half hours of operation of the heat pump, while this temperature increased from 28°C to 52.8°C after the installation of the SLHE. Therefore, it can be argued that using a SLHE can effectively increase the performance of the polyvalent heat pump under the water heating-only mode.

5.2. *Effect of ambient temperature on heating performance*

To figure out the heating performance of the polyvalent heat pump, we ran the heat pump in water heating-only mode at an average ambient temperature of 22°C. Noteworthy, under the water-heating mode, the ambient air acts as the heat source from which the refrigerant absorbs heat as it flows into the evaporator coil, while the hot water tank acts as the heat sink to which heat will be released to produce hot water. The hot water inlet and outlet, average hot tank and ambient temperatures, and heating COP over one hour were collected, and the results are illustrated in Figure 6-(a) and (b). It is interesting to find that the average hot tank temperature is higher than the hot inlet water temperature at the beginning of the experiment. This is due to the stratification of the water temperature in the tank, i.e. the hotter water stays at the top of the tank, and the colder water stays at the bottom of the tank. Therefore, in this experimental design, the bottom outlet of the tank was connected to the inlet of the hot water heat exchanger to achieve maximum heat exchange efficiency.

Also, it can be found that the average tank temperature gradually increases from 23°C to 43°C in one hour, and the heating COP starts from 2.5 and peaks at a hot water temperature of 30°C, then starts to decrease and stays at an average COP of 3.2. Therefore, it can be said that the heating COP of the polyvalent heat pump is related to the water tank temperature. Specifically, when the hot water temperature in the tank rises, it becomes more challenging to absorb heat from the refrigerant in the hot water heat exchanger, which leads to a decrease in the heating performance of the polyvalent heat pump, i.e. a reduction in the heating COP.

To investigate the effect of ambient temperature on the heating performance of the polyvalent heat pump, we operated the heat pump in water heating-only mode again, but with an average ambient temperature of 30°C. The relevant temperature of this heat pump operation and its heating COP are plotted and



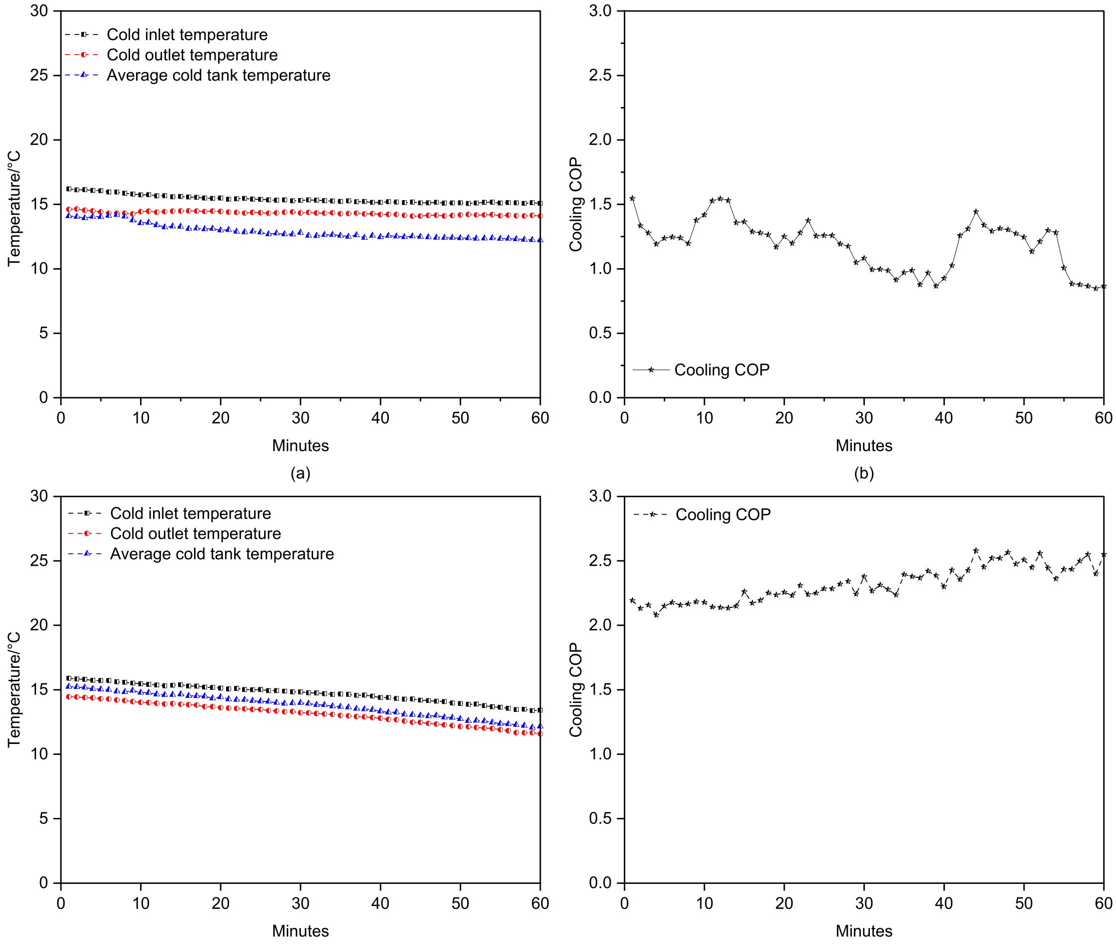
(a) (b) (c) (d)

Figure 6. Heating performance of the polyvalent heat pump under the water heating-only mode at an average ambient temperature of 22°C and 30°C. (a) Water temperatures at an average ambient temperature of 22°C; (b) Heating COP at an average ambient temperature of 22°C; (c) Water temperatures at an average ambient temperature of 30°C; (d) Heating COP at an average ambient temperature of 30°C.

displayed in Figure 6-(c) and (d). It can be found that the average hot tank temperature rises from 26°C to 56°C in one hour, which is more than 10°C higher than the average tank temperature rise (from 23 to 43°C) at the average ambient temperature of 22°C. Also, as can be seen in Figure 6-(d), the heating COP of the polyvalent heat pump starts at 2.9, peaks at 5.2 at an average hot tank temperature of 43°C, and then gradually decreases, with the average heating COP for this hour calculated to be 3.8, which is about 19% higher than the average heating COP of the heat pump at an average ambient temperature of 22°C. Again, as explained earlier, it is more difficult for the refrigerant to release heat to the hot water when the tank temperature increases. Given that the average hot water tank temperature and the average heating COP achieved by running the polyvalent heat pump at an average ambient temperature of 30°C are higher than the values achieved by running the heat pump at an average ambient temperature of 22°C, it can be concluded that the ambient temperature has a positive effect on the heating performance of the polyvalent heat pump, i.e. the higher the ambient temperature, the higher the heating COP.

5.3. Effect of ambient temperature on cooing performance

The polyvalent heat pump was operated in water cooling-only mode to test its cooling performance, and the average ambient temperature at that time was 28°C. When the polyvalent heat pump is operated in water cooling-only mode, it works as a water-to-air heat pump, meaning that the cold water tank is the heat source and the ambient air is the heat sink. The experimental results of this operation, including the average cold tank temperature, inlet and outlet water temperatures, and cooling COP versus time, are shown in Figure 7-(a) and (b). It can be observed that after one-hour operation of the heat pump, the average tank temperature dropped from 14.1°C to 12.2°C. The cooling COP has been fluctuating drastically, and the average value remains roughly at 1.2. Furthermore, the fact that the cold water inlet temperature is higher than the average tank temperature can be attributed to the temperature stratification in the cold water tank. Therefore, the top outlet of the cold water tank is connected to the inlet of the cold water heat exchanger in order to obtain the best heat exchange efficiency. In summary,



(a) (b)

(c) (d)

Figure 7. Cooling performance of the polyvalent heat pump under the water cooling-only mode and at an average ambient temperature of 28°C and 22°C. (a) Water temperatures at an average ambient temperature of 28°C; (b) Cooling COP at an average ambient temperature of 28°C; (c) Water temperatures at an average ambient temperature of 22°C; (d) Cooling COP at an average ambient temperature of 22°C.

the cooling performance of the heat pump in the water cooling-only mode does not seem to be very impressive, even with the special design of the plumbing connections.

We also ran the polyvalent heat pump in water cooling-only mode at an average ambient temperature of 22°C to investigate the impact of ambient temperature on the cooling performance of the device. Figure 7-(c) and (d) display the testing results. The average cold tank temperature dropped from 15.2°C to 12.0°C in an hour, over one degree higher than the average tank temperature drop at an average ambient temperature of 28°C. Figure 7-(d) demonstrates that the cooling COP remained at an average value of 2.3, which is around 44% greater than the average cooling COP at the average ambient temperature of 28°C. Therefore, it can be concluded that the ambient temperature also affects the cooling performance of the polyvalent heat pump. The lower the ambient temperature, the higher the cooling COP, which can be explained by the fact that heat can be released more easily into a cooler environment, leading to better cooling performance.

5.4. Simultaneous water heating and cooling performance

The polyvalent heat pump was also operated in simultaneous heating and cooling mode to investigate its performance. Figure 8 depicts the results obtained. The average temperature of the hot water tank increased from 32.7°C to 58.9°C after one hour of operation, whereas the average temperature of the cold water tank decreased from 18°C to 14.4°C. As a result, the simultaneous COP of the polyvalent heat pump varied between 2.5 and 5 during this operation, reaching an average value of 3.8. Notably, the energy produced at the heating and cooling sides of the heat pump is stored, resulting in zero energy loss. Consequently, it can be asserted that a heat pump capable of supplying simultaneous heating and cooling and operating under solar PV energy is worth studying, despite the fact that it is still in the prototype stage and its performance is moderate.

6. Discussion

Space conditioning and DHW, which account for more than half of home energy use, are receiving a lot of attention as the residential sector moves towards the goal of low carbon emissions. The polyvalent heat pump proposed in this paper is essential for decarbonizing residential buildings. The use of a 48 V DC compressor enables direct connection to residential PV and battery system. Additionally, the use of hot and cold water tanks enables the heat pump to operate and store the generated energy during the day when PV energy is abundant, decreasing the need for grid power. Moreover, despite the fact that the performance

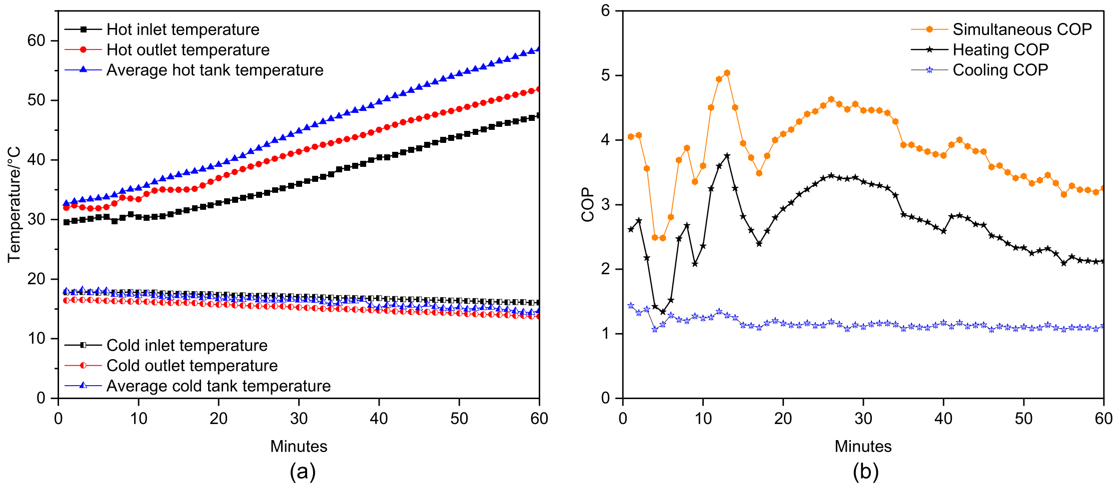


Figure 8. Heating and cooling performance of the polyvalent heat pump under the simultaneous water heating and cooling mode. (a) Hot and cold water temperatures; (b) Heating, cooling and simultaneous COP.

of polyvalent heat pumps is relatively modest in terms of COP and needs to be enhanced, it is significant that in the mode of simultaneous water heating and cooling, no energy is wasted by dissipating into the environment. Consequently, polyvalent heat pumps can operate continuously, producing and storing more heating and cooling energy by consuming PV power, also known as ‘free energy’.

According to the experimental results in Sections 5.2 and 5.3, the polyvalent heat pump prototype yielded better performance under the water heating-only mode than the water cooling-only mode at the same ambient temperatures of 22 °C. One of the reasons could be that using a SLHE allows the refrigerant to recover the heat from itself in the SLHE, thus improving the heating performance of the polyvalent heat pump. Comparably, under the water cooling-only mode, the high-temperature refrigerant travels into the condenser coil to dissipate heat into the surroundings, then through the expansion valve into the cold water heat exchanger to produce cold water, ultimately flowing to the compressor to start the subsequent cycle. As a result, the refrigerant only passes through the SLHE once every cycle, meaning that the SLHE is not functioning. Another method of enhancing heat pump performance is to use different types of heat exchangers, such as shell-in-tube and tube-in-tube heat exchangers. The polyvalent heat pump proposed in this paper is intended to generate hot and cold water that can be utilized in residential buildings for space conditioning, and DHW. A heat exchanger that provides more heat exchange surface area resulting in better heat transfer efficiency, may be helpful and will be the future research direction of this paper.

7. Conclusion

The heat pump has been recognized as a promising approach to reducing energy use and GHG emissions, achieving a decarbonized energy future. When coupled with thermal storage systems, heat pumps can consume locally generated electricity and produce hot and cold water for storage, increasing the PV self-consumption and achieving a zero-emission future. This paper introduces a polyvalent heat pump that can deliver water heating-only, water cooling-only and simultaneous water heating and cooling mode all in one single unit as well as running on 48 V DC power and using R290 as the refrigerant, making it more attractive to occupants and the market due to the increasing installation of solar PV systems and the realization of future decarbonization of heating and cooling.

The results of the experimental tests showed that using a SLHE increased the average heating COP of the heat pump by 30% from 2.0 to 2.6. Furthermore, the polyvalent heat pump performed better in water heating-only mode than in water cooling-only mode at similar ambient temperatures, possibly due to the use of SLHE, which allows heat recovery from the refrigerant itself in the refrigeration piping. One-hour simultaneous water heating and cooling operations of the polyvalent heat pump yielded an average simultaneous COP of 3.8.

Despite the moderate performance of this heat pump prototype, it is important to note that its energy consumption is significantly lower than that of a conventional heating system that has been operating for decades. Furthermore, it has the ability to meet the cooling, heating, and DHW needs of residential buildings without emitting any GHG due to the use of natural refrigerants and renewable power supply. As a result, polyvalent heat pumps are of great interest for further research. In doing so, the sizing of heat pumps will also need to be considered, because as PV systems continue to be installed in residential buildings, ensuring that heat pumps operate even in the mornings and evenings when PV generation is minimal will make an important contribution to increasing the self-consumption of PV systems, reducing grid power consumption and meeting the thermal energy needs of homes.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

Data will be made available on request.

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