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APPLIED RESEARCH

Experimental Study on Air Source Heat Pump Heating System Based on Phase Change Heat Storage

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ABSTRACT With continuous advancement of policies regarding to energy conservation, emission reduction and clean heating, the market for air source heat pumps is rapidly growing. In the current situation, the need to reduce operating costs of heat pump heating has become urgent. This study proposes a distributed air source heat pump heating system based on phase change heat storage. The system utilizes a phase change heat storage device to transfer heat load from high electricity price periods to low electricity price periods. In order to reduce operating costs, control schemes are formulated based on peak-valley electricity pricing. The system has been tested in Qinghai Province, a high-altitude area in China. Results demonstrate that the system helps to achieve the decoupling between heating and power. The proportion of low-valley electricity consumption in the system increased to an average of 57.45%, while the proportion of peak electricity consumption decreased to an average of 12.41%. The daily electricity costs were reduced by 5.28% compared to direct heat pump heating. With the same thermal storage capacity, application of suitable operation scheme increased COP by 21.76%, reduced electricity consumption and operating costs by 5.69% and 13.50% respectively. Increasing the capacity to 150 kW·h can further reduce operating costs by 10.04%.

INDEX TERMS Air source heat pump, phase change heat storage, heat load transfer, economy, operation optimization.

I. INTRODUCTION

Global CO_2 emissions have been steadily increasing each year [1].Presently, China holds the position of the world's leading emitter of carbon, contributing to 31.1% of the total global CO_2 emissions in 2021 [2]. Energy conservation and emission reduction have been imperative on a global scale. In 2020, China has outlined strategic objectives for reaching the peak of emissions and achieving carbon neutrality [3]. The promotion and utilization of renewable energy resources have emerged as crucial factors in attaining the goal of enhanced energy efficiency [3].

The energy consumed for building heating constitutes a significant portion of overall societal energy consumption. In Europe, heating and cooling of buildings contribute to 40% of the total social energy consumption [4]. In China, building energy consumption represents 21.10% of the nation's total energy consumption [5]. The substantial energy consumption in buildings presents ample opportunities for emission reduction. The United Nations' 17 Sustainable Development Goals propose the electrification of heating systems, powered by renewable energy sources [6]. The utilization of coal for winter heating not only results in carbon dioxide emissions but also contributes to environmental pollution. Chinese government has implemented a clean heating policy, wherein distributed electric heating has become the primary method of heating in rural areas.

Air source heat pump (ASHP) is an electricity-powered renewable energy device [7]. In comparison to electric heaters, ASHP has a higher ratio of electrical to thermal

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conversion [8], making it more environmentally friendly and energy efficient for heat production [9], [10]. Despite being crucial in promoting the electrification of building heating, operating costs of ASHP are still higher than those of traditional fossil-fueled heat production devices such as boilers [11]. However, by utilizing the peak and valley electricity pricing policy and leveraging the lower cost and flexible use of thermal energy storage (TES), it is possible to produce and store heat using lower-priced valley electricity. The stored heat can be released during peak hours to reduce operating costs of ASHP [12]. This approach also helps in reducing peak loads during peak hours by smoothing out energy demand fluctuations in the grid [13]. The commonly used thermal storage methods include sensible heat storage, phase change heat storage, and chemical heat storage. Phase change heat storage is widely used due to its high energy density and low temperature during phase transition [14], [15], [16].

Marini et al. [17] proposed a TRNSYS simulation of a domestic ASHP heating system with TES under different load shifts. The study examined the system's performance and operating costs based on the user's sensitivity to electricity prices. Le et al. [18] developed a dynamic stepped air-to-water heat pump heating system and validated various heating modes. Results showed that the combined heating mode, which utilizes valley electricity to store heat for meeting the heating demand during peak electricity consumption, had 4.3% lower operating costs compared to the direct heating mode and 53.2% lower operating costs compared to the indirect heating mode. Wang et al. [19] proposed a novel dual-source building energy supply system for heat pump and energy storage which utilized night-time valley electricity to store energy, and optimized the control strategy based on load forecasting and system performance. Simulation results demonstrated that annual operating cost is 55% of that of a conventional air-source heat pump system, with a dynamic payback period of 3.66 years. Lu et al. [20] proposed a latent heat thermal energy storage (LHTES) and analyzed the ASHP-LHTES combined heating system by TRANSYS. Operating costs was reduced by 32.9% while power consumption increased by 24.4%. Jin et al. [21] simulated an ASHP heating system with LHTES to shift loads to off-peak periods. Costs were saved by HKD 1071.1 /year and carbon emissions were reduced by 52.5 %.

This paper presents a novel heating system that utilizes an air source heat pump and phase change heat storage (PCHS). ASHP produces heat during off-peak electricity periods to meet the heating demands of building and PCHS. Conversely, during peak electricity periods, PCHS releases stored heat to warm building. This approach achieves thermoelectric decoupling and load transfer within the system. The control strategy is developed based on peak-valley electricity prices. Experimental evaluations are conducted to assess system performance and optimization effects of the control strategy. Results prove that the system is an economical, efficient, and stable solution for heating buildings in low-temperature environments. Additionally, it reduces operating costs by utilizing thermal storage for load transfer and diminishes the power grid's peak-time electricity load. This study presents a solution for the energy management and control of distributed thermoelectric coupling heating system.

II. HEATING SYSTEM

A. SYSTEM DESCRIPTIONS

The heating system is situated in a region of high altitude in Qinghai Province. Heating area of the building is 314 m^2. Intricate design of the system can be observed in Fig. 1.

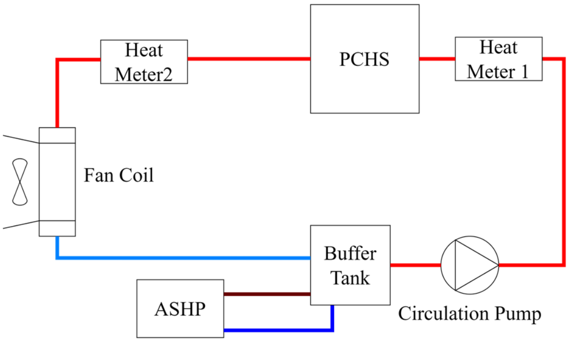


FIGURE 1. Intricate design of the heating system.

The heating system comprises of an air source heat pump, a phase change heat storage device, and heating pipes. PCHS is composed of four tanks with the same heat storage medium and capacity (theoretical capacity of 37.5 kW·h). Each tank has individual inlet and outlet valves that can be controlled. Operation of the system is divided into two processes: charging process and discharging process. They can be alternated multiple times a day.

During the charging process, ASHP heats water from buffer tank, which is then returned to buffer tank. Circulation pump transports hot water from buffer tank to heating pipes. Hot water first passes through PCHS, where it is at a higher temperature than phase change material (PCM). PCM absorbs heat and stores energy, while fan coils utilize remaining hot water from PCHS for heating. Hot water then cools down and flows back into buffer tank.

During the discharging process, ASHP stops working, but circulation pump continues to circulate water in heating pipes. Lower temperature water flows through PCHS first, where it is at a lower temperature than PCM. This causes PCM to release heat. The water is then warmed up and dissipated through fan coils to provide heat for building. Additionally, ASHP can supply heat directly.

B. EQUIPMENT

The low-temperature air source heat pump is designed to extract heat from surrounding air. As stated in manufacturer's product manual, the nominal heating coefficient of performance (COP, W/W) for this air source heat pump is 2.41.

PCM absorbs or releases a significant amount of latent heat during phase change process, thereby facilitating efficient

TABLE 1. Peak and valley tariff periods.

Classification	Period	Price (CNY/kW·h)
Valley electricity	0:00-8:00	0.28
Flat electricity	12:00-18:00	0.48
Peak electricity	8:00-12:00, 18:00-24:00	0.58

heat storage and release. Specifically, PCM used in this study is a hydrated salt with a phase change temperature of 48±2°C and a theoretical latent heat of phase change equal to or greater than 180kJ/kg.

The data collection interval was set at 1 minute, with room and ambient temperatures being recorded at 30 minutes intervals.

III. CONTROL SCHEMES, MODELS, AND EVALUATION INDICATORS

A. CONTROL SCHEMES

The peak and valley tariff periods specific to this region can be observed and referred to in Table 1.

Operation of the heating system is optimized by planning the operating time of ASHP and capacity of PCHS based on peak and valley tariffs. The goal is to reduce working time of ASHP during peak hours and minimize operating costs. By discharging stored heat for heating during peak hours, operating costs decrease obviously. Performance and operating costs of the system using seven different control schemes are evaluated. The heating system maintains indoor temperature in each house above 18°C. Investigation of the system's response to varying durations of thermal storage and heat discharge is carried out through the implementation of schemes 1-4, while ensuring that the PCHS capacity remains constant. Evaluation of the system's performance with varying PCHS capacities is conducted using schemes 4-7. The theoretical capacity of a single storage tank in PCHS is 37.5 kW·h. In the subsequent text, the theoretical capacity of a heat storage box is denoted as 1T. Depending on control schemes, one or more tanks were utilized. For schemes 1-7, ASHP outlet water temperature was set to 53°C, whereas direct heating mode of ASHP operated with an outlet temperature of 45°C. Further details and descriptions of schemes 1-7 can be found in Table 2.

TABLE 2. Schemes 1-7.

Scheme	Heat storage time (h)	Heat discharge time (h)	PCHS capacity
1	19	5	2T
2	17	7	2T
3	16	8	2T
4	15	9	2T
5	15	9	1T
6	10	14	3T
7	7.5	16.5	4T

B. MODELS

During operation, a temperature difference exists between PCM and water flowing through pipes. It leads to a continuous process of heat exchange, either through heat absorption or heat discharge. Air circulation is facilitated by fan coils, which allowed air to absorb heat from hot water in coils. Heated air is then discharged to maintain room temperature at the desired set value. Calculation of heat storage capacity of PCHS as well as heat discharge capacity of both PCHS and fan coils, is based on changes in inlet and outlet water temperatures, as well as water flow rates. Data regarding inlet and outlet water temperatures, as well as water flow rates, are recorded every 60 seconds. It is assumed that the heat storage and release process achieved a state of stability within this time interval.

The heat storage capacity and heat discharge capacity of PCHS are calculated by (1):

$$\begin{cases} Q_c = \int_{\tau=\text{start}}^{\tau=\text{end}} P_c \mathrm{d}\tau = \sum_{i=0}^{m} P_{c,i} t/3600 \\ Q_d = \int_{\tau=\text{start}}^{\tau=\text{end}} P_d \mathrm{d}\tau = \sum_{j=0}^{n} P_{d,j} t/3600 \end{cases} \tag{1}$$

where Q_c is heat storage capacity, kW·h;Q_d is heat discharge capacity, kW·h;P_c is PCHS's thermal power of charging, kW;P_d is PCHS's thermal discharge power, kW;t is sample time, s.

Heat discharge capacity of fan coils is calculated by (2):

$$Q_{FC} = \int_{\tau=\text{start}}^{\tau=\text{end}} P_{FC} \mathrm{d}\tau = \sum_{k=0}^{m+n} P_{FC,k} \cdot t/3600 \tag{2}$$

where Q_{FC} is heat discharge capacity, kW·h; P_{FC} is fan coils' thermal discharge power, kW; t is sample time, s. P_c, P_d and P_{FC} are determined using following equations:

$$\begin{cases} P_c = c\rho v(T_{in,PCHS} - T_{out,PCHS}) \\ = 4200v(T_{in,PCHS} - T_{out,PCHS})/3600, \\ T_{in,PCHS} > T_{out,PCHS} \\ P_d = c\rho v(T_{out,PCHS} - T_{in,PCHS}) \\ = 4200v(T_{out,PCHS} - T_{in,PCHS})/3600, \\ T_{in,PCHS} < T_{out,PCHS} \end{cases} \tag{3}$$

$$P_{FC} = c\rho v \Delta T_{FC} = 4200f(T_{in,FC} - T_{out,FC})/3600 \tag{4}$$

where c is specific heat capacity of water, 4.2×10^3J/ kg·°C); ρ is density of water, 10^3kg/m^3; v is water flow rate of heating pipes, m^3/h; $T_{in,PCHS}$ and $T_{out,PCHS}$ are inlet and outlet temperature of PCHS, °C; $T_{in,FC}$ and $T_{out,FC}$ are inlet and outlet temperature of fan coils, °C.

C. EVALUATION INDICATORS

In order to assess performance of the heating system, energy efficiency indicators and economic indicators are taken into account. COP, known as the coefficient of ASHP performance, is calculated using the equation represented as (5):

$$COP = \frac{Q_{ASHP}}{W_{ASHP}} = \frac{Q_c - Q_d + Q_{FC}}{W_{ASHP}} \tag{5}$$

where Q_{ASHP} is heat capacity of ASHP, kW·h; Q_c is stored heat of PCHS, kW·h; Q_d is released heat of PCHS, kW·h; Q_{FC} is stored heat of fan coils, kW·h; W_{ASHP} is power consumption of ASHP, kW·h.

Economic indicators are operating costs C and valley electricity utilization rate γ. They are determined by following equations:

$$C = W_V \cdot C_V + W_F \cdot C_F + W_P \cdot C_P \tag{6}$$

$$\gamma = W_v / W_T \tag{7}$$

where W_V is power consumption during valley period, kW·h; W_F is power consumption during flat period, kW·h;W_P is power consumption during peak period, kW·h; C_V is price of valley electricity; C_F is price of flat electricity;C_P is price of peak electricity; W_T is power consumption of the system, kW·h.

IV. RESULTS AND ANALYSIS

A. ENVIRONMENTAL IMPACTS ON THE SYSTEM

1) PERFORMANCE OF ASHP

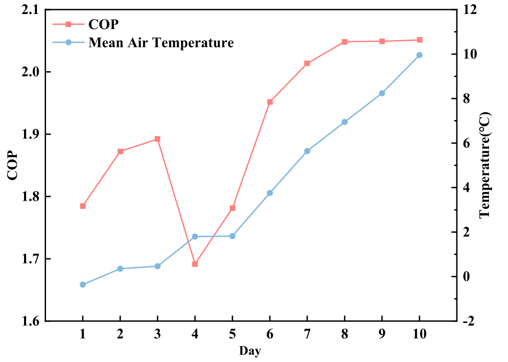
In the system, ASHP has the largest power consumption and its COP is susceptible to environmental changes. Changes in heating performance of ASHP have a significant influence on energy consumption. Fig. 2 shows ASHP's COP of the system containing PCHS using scheme 4.

The heating efficiency of ASHP is mainly influenced by air temperature and frost. In the absence of frost, COP shows a positive correlation with the average temperature throughout the day. When the maximum temperature difference between the average temperatures of the entire day is 10.32°C, COP on day 1 is 12.87% lower than that on day 10.

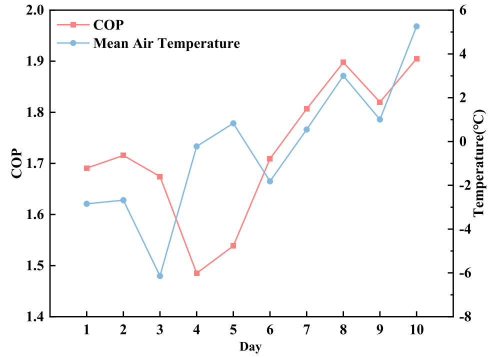
During rainy or snowy days with high air humidity, the low-temperature environment causes water vapor to frost on the surface of ASHP's heat exchanger. This leads to a significant decrease in the heat exchange capacity of heat exchanger, resulting in a notable reduction in COP. As a consequence, power consumption increases, negatively impacting energy efficiency of the system. The heating capacity of days 4, 5 and 6 are comparable. However, frost appears on the morning of days 4 and 5, causing a sharp decline in COP. Although the average temperature in the morning on days 4 and 5 is 1.59°C and 2.65°C higher than that on day 6, respectively, COP during that time decreases by 13.11% and 8.74%, respectively. Furthermore, COP for the entire day on days 4 and 5 decreases by 13.33% and 9.57%, respectively, compared to day 6.

2) POWER CONSUMPTION

Hot water produced by ASHP passes through heating side pipes and buffer water tank, but no sensor is installed in the pipes, thus the heat loss in this section is not accounted for. The heat measured represents the total heat obtained from the heating circulating water loop, which is less than the actual heating capacity of ASHP. The time for thermal storage and discharge are 15 hours and 9 hours, respectively. Table 3 presents test data for the PCHS heating system.



(a) All-day.



(b) In the morning.

FIGURE 2. COP and mean air temperature.

TABLE 3. Test data for the PCHS heating system.

Day	Power consumption (kW·h)	Heating capacity (kW·h)	Mean air temperature (°C)
1	136.83	211.46	-0.36
2	130.13	209.30	0.35
3	133.50	217.86	0.47
4	131.74	191.82	1.80
5	130.44	199.66	1.82
6	119.71	198.24	3.76
7	112.55	189.68	5.64
8	101.51	170.16	6.95
9	102.73	173.24	8.24
10	95.92	157.76	9.96

As shown in Table 3, average temperatures from day 1 to day 10 exhibit a steady upward trend. Heating capacity and electricity consumption are generally negatively correlated with mean temperature. As the temperature decreases, building's heat load increases. The decrease in temperature also lead to a decline in COP. The two factors contribute to an increase in electricity consumption. Electricity consumption is directly proportional to heating capacity, and they exhibit a similar growth trend. The temperature difference between day 1 and day 10 is the largest at 10.32°C. On day 1, heating capacity increases by 46.13% and electricity consumption increases by 42.65% compared to day 10. Using data from day 10 as a reference, the ratio of electricity consumption and heating capacity for the remaining da days is calculated. The ratio results are shown in Fig. 3. And Fig. 4 presents indoor and outdoor temperatures.

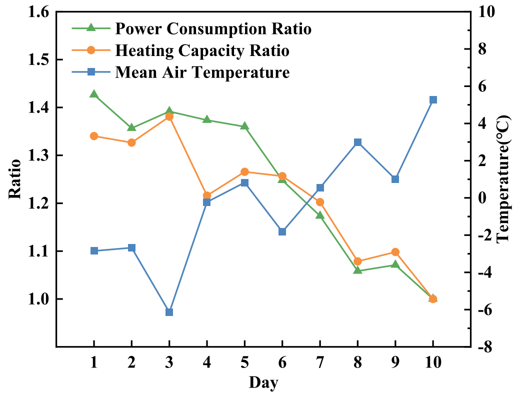


FIGURE 3. Ratio of power consumption and heating capacity.

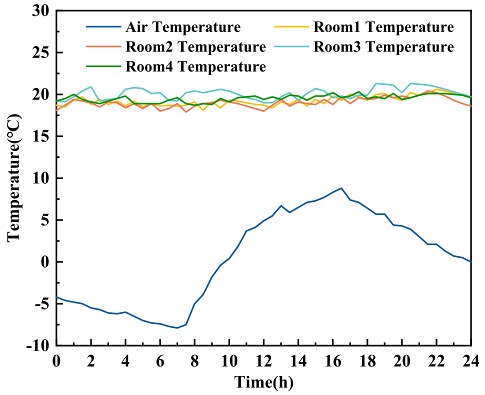


FIGURE 4. Indoor and outdoor temperatures.

The mean temperature on days 2 and 3 differ by only 0.12°C, yet there is a significant difference in heating capacity and electricity consumption. Average temperatures in the morning on day 2 and day 3 are −2.67°C and −6.14°C, respectively. The decrease in temperature lead to an increase in heating load. Compared to day 2, power consumption and heat discharged by PCHS in the morning on day 3 increase by 7.78% and 10.35%, respectively. In the afternoon, the temperature on day 3 is higher than that of day 2, resulting in a decrease in heating load. To meet the nighttime heating demand, heat storage load of PCHS has been higher on day 3 than that of day 2. The heating capacity in the afternoon on both days are only different by 0.15 kW·h. However, power consumption during that time on day 3 decreases by 6.19% compared to day 2. During the lower-temperature period, PCHS discharges more heat to meet heating demand. While during the higher-temperature period, COP increases, resulting in a reduction in power consumption. Due to application of PCHS, electricity consumption on day 3 increases by 4.09% compared to day 2, which is lower than the 7.78% increase in electricity consumption.

TABLE 4. Daily operation costs.

Mean air temperature (°C)	Costs (CNY)
-0.36	52.52
0.35	49.80
0.47	50.33
1.80	50.49
1.82	50.36
3.76	44.91
5.64	42.68
6.95	39.17
8.24	38.88
9.96	36.70

COP is significantly affected by frost. COP decreases and power consumption increases substantially when frost occurs. Heating capacity from day 4 to day 6 is similar. The average temperature in the morning on days 4 and 5 is 1.59°C and 2.65°C higher than that of day 6, respectively. However, appearance of frost in the early morning of days 4 and 5 result in increased energy consumption. Heating capacity on day 4 is 6.42 kW·h lower than that of day 6, but power consumption increases by 10.05%. Compared to day 6, heating capacity on day 5 only increases by 1.42 kW·h, while power consumption increases by 8.96%.

3) ECONOMY

Under the same control scheme, operating time of ASHP remains consistent. As the temperature increases, heat load decreases, resulting in a decrease in daily operating costs and power consumption. Daily operating costs are illustrated in Table 4. The maximum temperature difference throughout 10 days is 10.32°C, and the daily electricity costs at the highest temperature is 30.12% lower than that at the lowest temperature. On days 4 and 5, frost appears, causing an increase in power consumption. On day 4, heating capacity is 3.24% lower than day 6, but daily operation costs increase by 12.42% compared to day 6. On day 5, heating capacity is only 0.72% higher than day 6, but daily electricity costs increase by 12.14% compared to day 6. Low temperature and frost affect heating load and COP, and environmental factors have a significant impact on costs.

B. EFFECTS OF ADJUSTING DURATION OF HEAT STORAGE AND DISCHARGE

In addition to environmental factors, both system control schemes and capacity of PCHS can affect COP and energy consumption. To make full use of off-peak electricity, the PCHS heating system should enter the heat storage state as much as possible during valley electricity period. Suitable control schemes are developed to appropriately shorten working time of ASHP during peak electricity periods in order to reduce power consumption and costs.

1) IMPROVING PERFORMANCE OF ASHP

PCHS's capacity for schemes 1, 2, 3 and 4 are consistent. Heat storage times of schemes 1, 2, 3 and 4 are19 hours, 17 hours, 16 hours, and 15 hours, respectively. When PCHS stores heat, working time of ASHP during the period of lower temperatures is gradually shortened.

ASHP stops working when backwater temperature reaches the set water temperature. The number of starts and stops for schemes 1, 2, 3 and 4 are 26, 17, 16, and 14, respectively. As the heat storage time is reduced, the number of starts and stops decreases and COP increases. By shortening operating time of ASHP during the low-temperature period, the improvement in COP for schemes 2, 3 and 4 is recorded at 8.17%, 21.17%, and 21.76%, respectively, compared to scheme 1. Frequency of starts and stops for ASHP can be reduced by moderately shortening heat storagetime of PCHS during the low-temperature period in the morning, thereby improving the stability of ASHP. COP for schemes 1, 2, 3 and 4 are shown in Fig. 5.

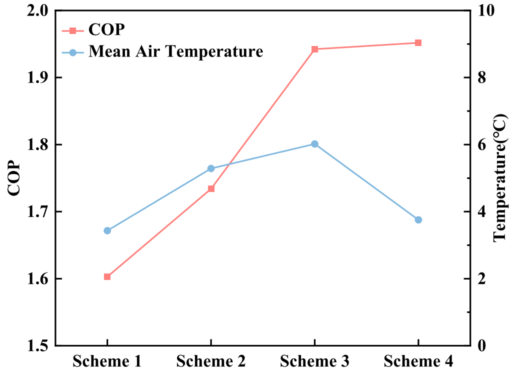


FIGURE 5. COP for schemes 1, 2, 3 and 4.

2) REDUCING POWER CONSUMPTION

Fig. 6 presents the data for schemes 1, 2, 3 and 4. As heating load of building is higher during the early morning hours, PCHS needs to store heat. During valley electricity period, demand for heating capacity reaches its peak. Application of PCHS during the low-temperature period in the early morning leads to an increase in heating capacity, resulting in a sharp rise in power consumption. Although average daily temperatures increase, the average temperature in the morning decreases, causing an increase in heating capacity, which aligned with the trend of average temperature.

Improvement in COP leads to a decrease in daily power consumption. Heating capacity of scheme 4 is 24.16 kW·h higher than that of scheme 1, representing a 13.88% increase. However, daily power consumption of scheme 4 is 7.22 kW·h lower than that of scheme 1, indicating a 5.69% decrease. By adjusting the duration of heat storage and heat pump operation, as well as increasing the transferable heat load during periods of higher temperatures, power consumption of scheme 4 significantly decreases compared to scheme 1.

For scheme 1, ASHP and heat storage work together for a duration of 19 hours. And once heat storage of PCHS reaches its peak, it cannot continue to store heat. ASHP operates during periods of low temperature while its COP is low. Although temperature rises in the afternoon, the heating load during this period is lower, which result in ASHP operating at a lower load and increasing the number of start-stop cycles. It weakens effects of the improved COP due to temperature increase. Duration of heat discharge for scheme 1 is only 5 hours and ASHP operates for a longer period during the low-temperature period, leading to the highest energy consumption. Duration of heat storage for scheme 4 is reduced by 4 hours compared to scheme 1. Application of scheme 4 improves COP and achieves more energy-saving effects.

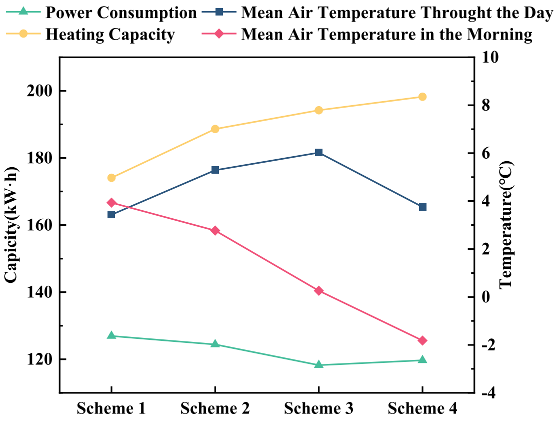


FIGURE 6. Operating data for schemes 1, 2, 3 and 4.

The storage duration of PCHS in scheme 4 is 8 hours. During the off-peak electricity period, heat storage is completed and heat stored in PCHS is discharged for 4 hours in the morning, reducing working time of ASHP during the low-temperature period. As temperature rose, COP also improves. Due to the heat discharged in the morning, heat storage of PCHS decreases, and heating capacity during the second storage period in the afternoon is 63.93% higher than in scheme 1. While the power consumption only increases by 14.81%. By implementing a two-cycle heat storage and discharge process within 24 hours, PCHS is utilized multiple times. In comparison, heat load of scheme 1 is transferred only for 5 hours during the night, while duration for transferred heat load of scheme 4 increases to 10 hours. The operating load of ASHP during higher temperature periods increases which can make better use of the improved COP due to the rising temperature. By extending heat discharge duration and shortening storage duration to reduce working time of ASHP during the low-temperature period, application of suitable strategy can improve COP and reduce power consumption.

3) REDUCING OPERATING COSTS

Fig. 7 presents power consumption and operating costs for schemes 1, 2, 3 and 4. It is demonstrated that heat capacity increase while power consumption decrease. Specifically, power consumption for schemes 1, 2, 3 and 4 is measured at

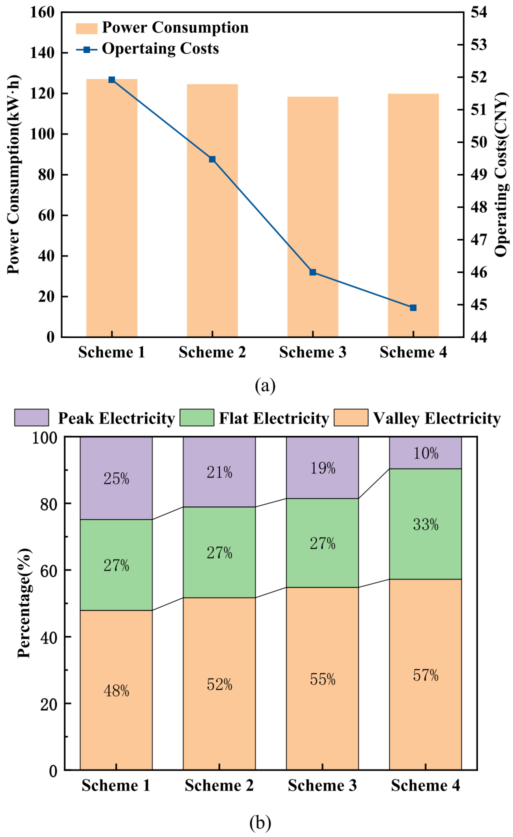


FIGURE 7. Power consumption and operating costs for schemes 1-4.

126.93 kW·h, 124.42 kW·h, 118.25 kW·h, and 119.71 kW·h, respectively. Daily operating costs for the four schemes are ￥51.92, ￥49.48, ￥45.99, and ￥44.91, respectively. In comparison to scheme 1, operating time of ASHP for scheme 2, 3 and 4 is reduced by 1 hour, 2 hours, and 4 hours, respectively. Compared to schemes 1 and 2, energy consumption of scheme 4 decreases by 5.69% and 3.79%, respectively, and daily electricity costs of scheme 4 are cut by 13.5% and 9.24%, respectively.

ASHP's operating time gradually decreases for all four schemes. Compared to scheme 1, schemes 2, 3, and 4 exhibit a reduction in the proportion of energy consumption during peak periods by 3.80%, 6.31%, and 15.24%, respectively. And the proportion of energy consumption during valley increased by 3.80%, 6.90%, and 9.32%, respectively.

Given high electrical load of electric heating equipment, and the weaker power supply capacity in rural areas, the existing capacity of distribution transformer for power lines is insufficient to meet increasing electricity demand for heating after electrification. Application of PCHS can shift the load during peak electricity periods, significantly increasing the proportion of energy consumption during valley periods, thus facilitating peak shaving, valley filling. By a rational planning of heat storage and discharge, energy consumption and system operating costs can decrease, valley electricity is fully utilized. It also mitigates the impact of heating loads during peak electricity periods on the power grid.

C. EFFECTS OF REGULATING PCHS CAPACITIES

In order to fully utilize the stored heat, it is necessary to correspondingly extend the duration of heat release after increasing capacities. When the PCHS capacity is 1T, 2T, 3T and 4T, the duration of heat storage is 15 hours, 15 hours, 10 hours, and 7.5 hours.

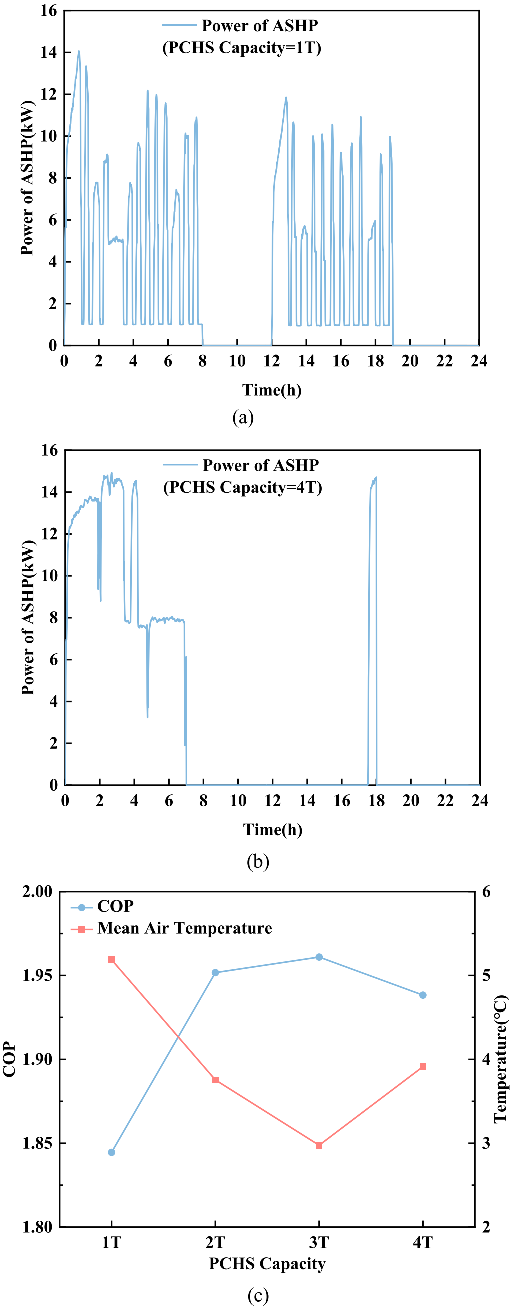


FIGURE 8. Power of ASHP and COP.

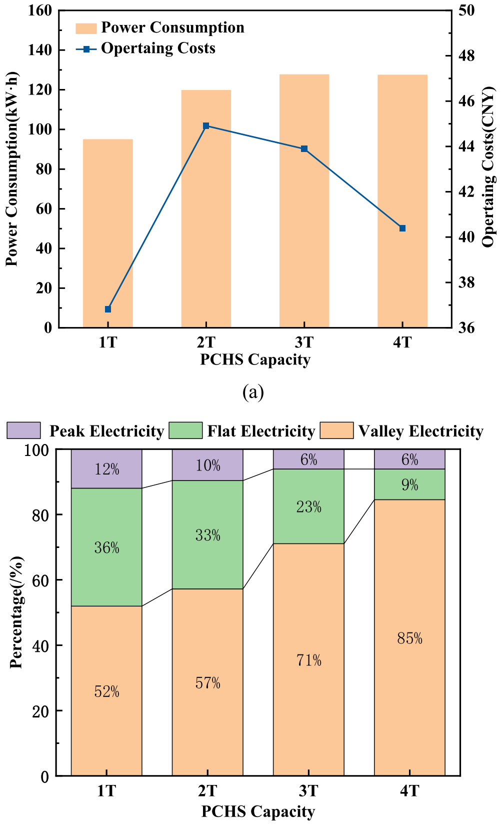
1) INFLUENCE ON PERFORMANCE OF ASHP

Increasing capacities of PCHS can enhance the load of ASHP, thereby improving COP. Fig. 8 illustrates power of ASHP. When PCHS capacity is 1T, ASHP experiences frequent start-stop cycles due to lower backwater temperature differential.

The total number of start-stop cycles in a day reaches as high as 43. When PCHS capacities are 2T, 3T, and 4T, the total number of start-stop cycles reduce to 19, 8, and 5.

When PCHS capacity is 1T, average temperature reaches its peak while the heating load is at its lowest. This leads to a higher frequency of start-stop cycles for ASHP and a decrease in COP. Decrease in COP was found to be 5.49%, 5.94%, and 4.84% for PCHS capacities of 2T, 3T, and 4T, respectively.

For system with PCHS capacity of 4T, due to the majority of ASHP's operating time being during low-temperature period in the early morning, its COP decreases by 1.16% compared to a PCHS capacity of 3T. Increasing PCHS capacity can enhance COP. When the operating duration of PCHS capacity and heat pump is higher during low temperature periods, it will result in a decrease in COP.



(a)

(b)

FIGURE 9. Operating data for the system with different PCHS capacities.

2) ECONOMY

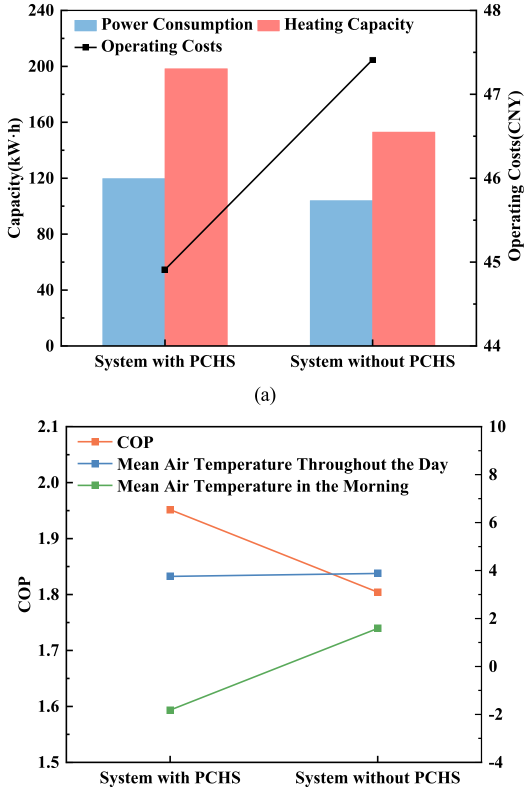
Fig. 9 presents operating costs, proportion of peak and valley electricity consumption. When PCHS capacity is 1T, heating load is minimal. For PCHS capacities of 2T, 3T and 4T, heating loads are similar, power consumption is 119.71 kW·h, 127.61 kW·h, and 127.42 kW·h, respectively, with daily electricity costs of ￥44.91, ￥43.89 and ￥40.40, respectively.

When increasing capacity of PCHS, it is imperative to effectively prolong the duration of heat discharge. This will allow for optimal utilization of stored heat and minimize operational time of ASHP, particularly during periods of high electricity demand. When PCHS capacity is 2T, 3T, and 4T, valley electricity consumption accounts for 57.23%, 71.08%, and 84.52%, respectively, while peak electricity consumption accounts for 9.62%, 6.09%, and 6.09%, respectively. Compared to the system for PCHS capacity of 2T, electricity consumption of the system for PCHS capacities of 3T and 4T increases of 6.60% and 6.44%, respectively, and daily costs of them decrease by ￥1.02 and ￥4.51, respectively.

When PCHS capacity increases from 2T to 3T, operating time of ASHP decreases by 4 hours and 1 hour, respectively, resulting in a 2.27% reduction in costs. When PCHS capacity increases to 4T, ASHP does not operate during peak periods and only operates for 0.5 hours during flat periods. It results in a 10.04% decrease in daily electricity costs compared to a PCHS capacity of 2T. Therefore, when PCHS capacity increases, it is possible to further reduce operating time during flat periods, thus reducing operating costs. Increasing PCHS capacity and extending heat discharge duration can effectively reduce operating costs of the system with PCHS.

D. DIRECT HEATING SYSTEM WITHOUT PCHS

In order to ascertain the cost-effectiveness of the ASHP heating system based on PCHS, a direct heating system using ASHP is tested. Power consumption, operating costs, and COP of the PCHS heating system and the direct heating system are shown in Fig. 10.



(a)

(b)

FIGURE 10. Power consumption, operating costs and COP.

Due to heat loss of PCHS, thermal efficiency of PCM is 85%∼90%. Heat demand of the PCHS heating system is higher than that of the direct heating system. The average temperature in the morning of the PCHS heating system are 3.41°C lower than that of the direct heating system. Heat demand of the PCHS heating system is increased by 45.32 kW·h compared to the direct heating system, while power consumption increases by 15.73 kW·h. Although PCHS stores heat in the early morning, resulting in a significant increase in power consumption, the PCHS heating system reduces working time of ASHP by 9hours. The PCHS heating system transfers nighttime heat load to the afternoon, resulting in an increase in heat load during flat electricity period. In the afternoon, higher temperature improves COP, leading to a reduction in power consumption required to produce the same amount of thermal energy.

When ASHP is directly used for heating, the temperature difference between backwater and supply water is increased to 5°C, frequent start-stop phenomena still occur, with 24 start-stop cycles throughout the day, resulting in a decrease in COP. Power of ASHP during direct heating is shown in Fig. 11.

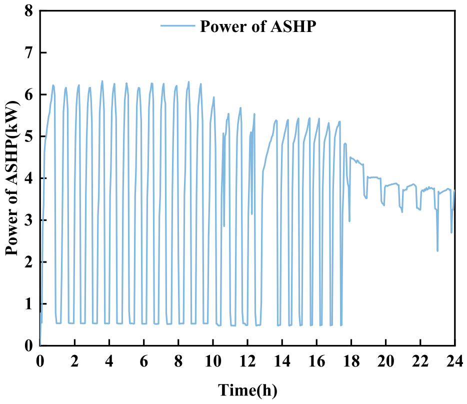


FIGURE 11. **Power of ASHP during direst heating.**

Compared to the direct heating system, COP of the PCHS heating system is improved by 8.18%. It can reduce working time and start-stop cycles of ASHP during low-temperature period, thereby improving heating efficiency of ASHP.

The PCHS heating system transfers peak electricity period loads through the phase change heat storage device. Although its power consumption is increased by 15.13% compared to the direct heating system, the system operating cost is reduced by 5.28%. Direct heat pump heating accounts for 31.79% and 39.56% of the total electricity consumption during valley and peak periods, respectively. Due to the high proportion of peak electricity consumption, daily electricity cost of the direct heating system is higher than that of the PCHS heating system. The PCHS heating system consumes 57.23% and 9.62% of total power consumption during valley and peak periods, respectively. Due to the increase in heat load caused by low temperatures, power consumption of the PCHS heating system is higher than that of the direct heating system.

By utilizing PCHS for thermal-electric decoupling, the proportion of valley electricity consumption is increased and the proportion during peak periods is decreased, thereby reducing operating costs.

V. CONCLUSION

This article presents a distributed ASHP heating system for buildings based on phase change heat storage. The main conclusions are as follows:

(1) The ambient temperature is a major factor affecting performance of the PCHS heating system. Low temperatures result in increased heat load and decreased COP of ASHP, leading to an increase in power consumption. When the average temperature difference is 10.32°C, COP decreases by 12.87%, power consumption and operating costs increase by 42.65% and 43.10% respectively. COP can significantly decrease in frosty weather conditions. During frosty weather compared to sunny weather, COP decreases by 13.33% and power consumption and operating costs increase by 10.05% and 12.42% respectively.

(2) When PCHS capacity is the same, COP is improved while energy consumption and operational costs are reduced by strategically planning the duration of heat storage. For a PCHS system with a capacity of 2T (theoretical capacity of 75 kW·h), shortening working hours of ASHP during low temperature and high electricity price period in the morning by 4 hours can increase COP by 21.76% and reduce power consumption by 5.69% and daily electricity cost by 13.50%.

(3) When heat storage capacity is increased, extending the duration of heat discharge during high electricity price periods can significantly reduce operating costs. When PCHS capacity is 4T, daily electricity costs decrease by 10.04% compared to the system with a PCHS capacity of 2T.

(4) In order to achieve decoupling of heat and electricity and reduce operating costs, heat is stored during low electricity price periods and discharged during high electricity price periods. The proportion of valley electricity consumption with PCHS increased to 57.45%, while the proportion of peak electricity consumption decreased to 12.41%. The system exhibits a notable disparity in electricity consumption patterns when compared to a direct heating system. Specifically, there is a significant increase of 25.66% in valley electricity consumption, while the proportion of peak electricity consumption experiences a substantial decrease of 27.15%. Furthermore, power consumption of the system increased by 15.73 kW·h and heating capacity wad enhanced by 45.32 kW·h. This led to an improvement of 8.18% in COP, as well as a 5.28% reduction in daily electricity expenses.

(5) Application of phase change heat storage enables the transfer of peak electricity loads in heating systems to valley periods, thereby achieving peak load shifting. This approach effectively mitigates the impact of the electrification of heating systems on the power grid during high-demand periods, ultimately enhancing the stability of grid.

Application of PCHS is flexible, and by optimizing control strategies, it can be matched with the characteristics of renewable energy sources such as photovoltaic and wind power. PCHS stores energy during periods of abundant photovoltaic and wind power generation, and releases heat during intermittent periods of renewable energy, the consumption of renewable energy and the improvement of the economic viability of heating systems can be achieved.

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