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Indirect expansion solar assisted heat pump system for hot water production with latent heat storage and applicable control strategy

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Abstract

Integration of renewable energy with energy conversion application for hot water production is a significant technology to be studied for industrial, commercial and residential proposes. It has been further enhanced since the international energy agency (IEA) puts effort to standardize such kind of technology. In this paper, a novel study has been carried out experimentally to control an indirect solar assisted heat pump (IDX-SAHP) system integrated with a latent heat storage (PCM) tank. The PCM heat exchanger tank was designed specially and controlled automatically which allowed storing excess energy during the day and releasing it when needed. In addition, a system control strategy has been purposely designed and implemented in a Building Management System (BMS) to ensure the stable and reliable system operations. The experimental results show that the PCM heat exchanger tank installation has a significant effect on the system operation stability and can improve the COP of the IDX-SAHP system at different weather conditions and a specified hot water load profile.

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Keywords: IDX-SAHP system; PCM tank; control strategy experiment; system stability and efficiency

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Nomenclature

Cp	Specific heat capacity (J kg^{-1} K^{-1})	*Subscripts*	
H	Enthalpy (J kg^{-1})	comp	Compressor
$\dot{m}$	Mass flow rate (kg s^{-1})	*h*	Heating
Q	Heat transfer rate (W)	ref	Refrigerant
T	Temperature (^{0}C)	*sys*	System
ΔT	Temperature difference (K)	*w*	Water
Q	Heat transfer rate (W)	*wfc*	Water fan cooler
W	Work input (W)		

1. Introduction

Due to the extensive consumption of fossil fuel in heating purposes in the UK, meeting CO_2 emission reduction target remains a challenge for the country if alternative energy resources or technologies for heating cannot be applied. The heating demand can be met by green technologies and advanced systems such as a solar thermal, air-water heat pump, geothermal heat pump and their integrations. Solar domestic water heaters (SDWHs) have been increasing in popularity in the UK and other countries worldwide and can greatly save energy for water heating in the summer [1]. However, the large temperature difference between the solar collector and ambient temperatures during winter has greatly reduced system performance such that assistant heaters such as gas, wood boilers or electric heaters must be added [2, 3]. The air source heat pump water heaters are compact, simpler and economic but also work less efficiently over the cold winter period [4]. Alternative substitutes such as Solar Assisted Heat Pump (SAHP) system has been deemed the more feasible option when taking into consideration important factors such as cost, application area limitation and constant water heating production etc. [5]

The combination of solar energy and heat pump technology can be classified into two categories: direct expansion solar assisted heat pump (DX-SAHP) and indirect expansion solar assisted heat pump (IDX-SAHP) [6]. For a DX-SAHP system, the solar collector also acts as the evaporator of the heat pump unit, thereby making the system more compact but requiring greater heat pump working fluid charge [7]. In addition, when there is insufficient solar radiation, the solar collector/evaporator cannot absorb enough heat required by the heat pump and thus negatively affect system performance [8]. On the other hand, with an IDX-SAHP system, solar radiation transfers heat to water flow through the solar collector and then provides heat to the heat pump evaporator. In such circumstances, the working fluid charge in the heat pump can be greatly reduced. The IDX-SAHP can also be further classified into three design layouts based on different heat source arrangements: series, parallel and dual source. For a series IDX-SAHP system, the solar energy is collected by a solar collector and stored in a water storage tank which is used as the only heat source for the heat pump. Solar heat sources may be insufficient for meeting building heating demands in certain weather conditions and time periods. A SAHP system used for mushroom drying was experimented which was relatively similar to the series IDX-SAHP scheme for space heating [9].

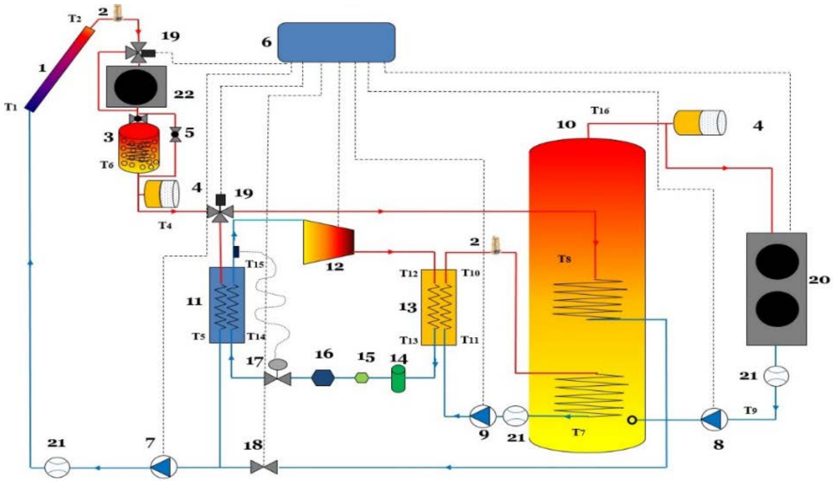
For a parallel IDX-SAHP system, a conventional solar system operates in parallel with an air source heat pump such that the heat pump operation is independent of solar energy availability. Therefore, the building heating load can be met by either the solar energy or air source heat pump. A parallel SAHP system was simulated and compared the system performances with both ground and air source heat pumps [10]. The ground source heat pump appeared promising in terms of absolute electricity saving when paralleled with solar energy.

In this paper, a new IDX-SAHP test system was designed, installed and instrumented. A PCM storage heat exchanger tank and an air-source heat exchanger were purposely built and installed in the system solar thermal loop and connected to the heat pump evaporator. Subsequently, the heat source from either solar energy or ambient air can be applied for the heat pump. In addition, a control strategy for the system was purposely designed and implemented so as to determine the optimal operation of the IDX-SAHP system. Comprehensive experimental investigations were carried out in the test rig to evaluate and compare system operation and performance in different weather conditions and structures with and without PCM tank installations. The research outcomes can lead to the optimisation of future system designs and controls [11].

2. Test facility

2.1. Test rig description

The test rig of an IDX-SAHP system is shown schematically in Figure 1. The system was designed to be installed for a standard UK dwelling to cover up to 350L per day of domestic hot water (DHW). The test system consists of a number of main components which are numbered in Figure 1 . The collector has a total surface area of 3.021 m^2 and 52° tilt angle. The insulated water storage tank (WST) has a capacity of 300L with two coils immersed inside: one for direct solar thermal operation and the other for the IDX-SAHP system. The phase change material (PCM) heat exchanger tank was installed to store excessive solar energy during day-time operation. The PCM has a melting point of 17°C with a mass of 30 kg charged in the heat exchanger tank. The energy stored in the tank is designated to be used as heat source for the heat pump during the night or when the solar irradiance during the day is poor. The heat pump consists of typical components of traditional heat pump.



1- Evacuated tube collector
2- Deaerator
3- PCM heat exchanger tank
4- Expansion tank
5- Bypass- ball valve
6- BMS controller
7- Solar / heat source pump
8- Load simulation pump
9- Heat sink pump
10- Water storage tank
11- Evaporator
12- Compressor
13- Condenser
14- Receiver
15- Filter
16- Sight glass
17- TXV
18- 2-way valve
19- 3-ways valve
20- Fan cooler
21- Flowmeter
22- Water fan cooler

Fig. 1. Test rig schematic diagram

The solar collector operates periodically between two loops. The first one is a direct solar thermal loop which is applied to produce hot water completely from solar energy through the solar collector and transport the hot water to the WST, similar to any traditional solar thermal system. This loop will work independently if the solar irradiance is sufficient to heat up the WST. In the second loop, the solar collector operates as a heat source for the IDX-SAHP. This applies when the solar irradiance is not sufficient to heat up the WST directly but it is enough to act as a heat source to the heat pump through the liquid-cooling evaporator and/or to charge the PCM tank when the heat pump is not switched on. In the case of insufficient solar irradiance or deficient energy stored in the PCM tank, heat source from ambient air through an air-water heat exchanger (AWHX) will be applied for the heat pump.

The heat transfer liquid used in either evaporator, condenser or the solar thermal loop is a mixture of 30% Ethylene Glycol and 70% water with a freezing temperature of -15^{0}C.

There is also an addition loop called load simulation loop which includes an expansion tank, a water fan cooler (WFC) and a water pump connected to WST. Since it is hard to implement the experiment in an actual dwelling, the load simulation loop has been purposely constructed in order to simulate and establish a standard UK dwelling hot water consumption profile during a long typical day [12]. Based on the designed load profile, the circulation pump speed is controlled accordingly by an inverter in order to modulate the required feed water flow rate to the storage tank. This can be implemented by controlling the pump motor frequency as it is directly proportional to the water flow rate. In the meantime, as shown in Figure 1, the feed water temperature at the WFC outlet is controlled by the water cooler's fan speed and is maintained as low as ambient air temperature. One of novelties of this study is that a fully automated control strategy by building management system (BMS) was deployed in order to maintain the outlet WST temperature at 55°C by controlling consequently with each operational mode. This can contribute significantly to facilitate further development and actual system application.

2.2. System control strategy

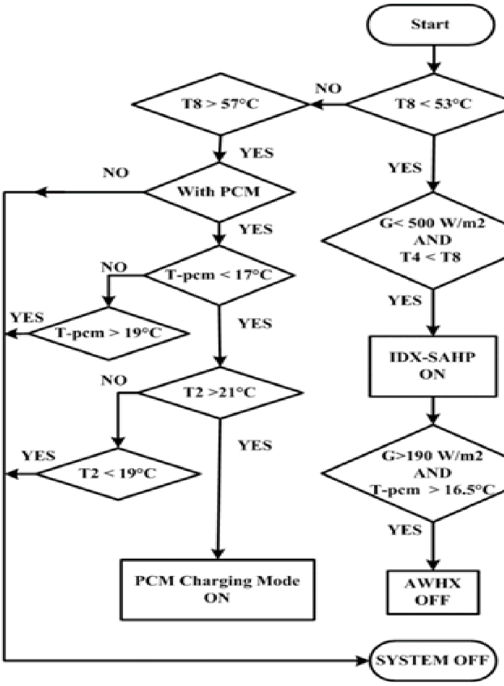


Fig. 2. System Control Strategy

As shown in Figure 2 the system control strategy has been purposely designed to maintain the water temperature at the middle of the WST (T8) at 55^0C with ±2 K dead band during a 24-hour operational day. If the T8 is less than its permitted lower value (53^0C), the control will check the instant solar irradiance G and the supply water temperature (T4) to the WST. If there is no enough solar irradiance (G<500 W/m^2) and the T4 is less than T8, the IDX-SAHP should be switched on. The control will then check the applicable heat source for the IDX-SAHP. If G is greater than 190 W/m^2 or PCM tank temperature T-pcm is larger than 16.5^0C, either the solar irradiance or heat stored in the PCM tank can be used as the heat source such that the AWHX should be turned off. Otherwise, the AWHX needs to be switched on considering of a specific dead band for each parameter so that the ambient air can be utilised as the heat source. On the other hand, if the solar irradiance is sufficient (G>550 W/m^2) or T4 is greater than T8 plus 2 K dead band, the IDX-SAHP should be off and the solar mode will be on. When the T8 is controlled within the setting point band (55 ± 2^0C), the system maintains its operating state. If T8 is above its higher band, the control will switch off the whole system if the PCM tank is not applied. Otherwise, it needs to determine if the PCM tank needs to be charged by assessing the PCM tank temperature (T-pcm) and water temperature at the solar collector outlet (T2). If the T-pcm is less than 17^0C, the PCM charging mode needs to be turned on when T2 is greater than 21^0C, otherwise, the whole system will be off (2 K dead band for T2). Alternatively, if the T-pcm is greater than 17^0C and less than 19^0C, nothing will be changed. However, if the T-pcm is higher than 19^0C, the whole system will be off.

2.3. Experimental procedure

In order to examine experimentally the effect of the PCM tank on system stability and performance, four test days have been conducted in 24 hours each at four combined climate conditions and PCM integrations. These included sunny with and without PCM tank and cloudy with and without PCM tank. As shown in Figure 3 the solar irradiances during two sunny test days with and without PCM tank were almost steady with maximum values of 621 W/m^2 and 625 W/m^2 respectively while the irradiances during those two cloudy test days had too many fluctuations. It is also noticed that the solar energy was only available during day time when the solar irradiance was greater than zero. Figure 4 shows the feed water flow rate or load profile supplied to the WST for each operational day. Each flow rate was controlled by a variable circulation pump speed which was regulated by BMS according to the specified load profile [12]. It is seen that the load profile for each test day was controlled almost the same with each other which of course should be independent on weather conditions and system designs.

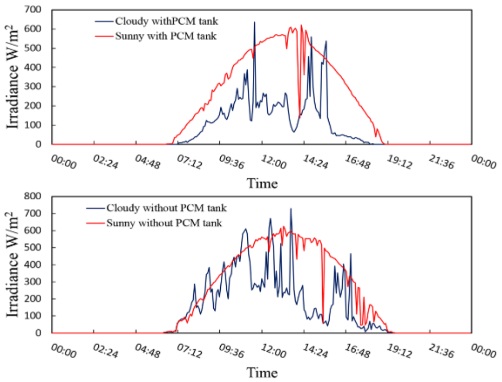


Fig. 3. Variations of solar irradiance during four test days

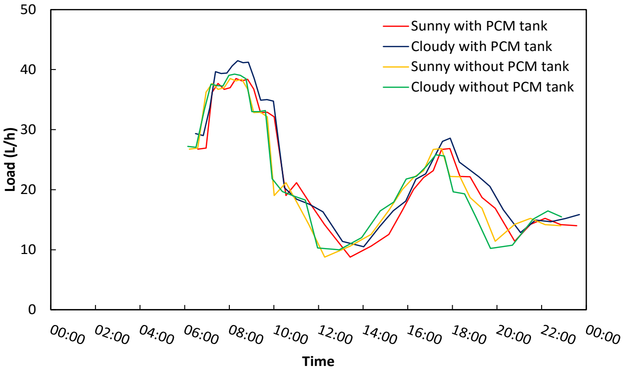


Fig. 4. Variations of load profiles during four test days

2.4. Thermodynamic analysis

The mass flow rate of refrigerant is calculated by the energy balance of water and refrigerant sides across the condenser assuming there is no heat loss to ambient:

$$\dot{m}_{ref}(\Delta h)_{ref} = \dot{m}_w C_{p.w}(\Delta T)_w \quad (1)$$

The thermo-physical properties of R134a used for thermodynamic analysis are calculated using Engineering Equation Solver (EES®) (Klein, 2014). The heating capacity of the system in IDX-SAHP mode is calculated based on water side inlet and outlet parameters of the condenser:

$$Q_h = \dot{m}_w C_{p.w}(\Delta T)_w \quad (2)$$

The heating COP of the system is calculated with the ratio of the total heating capacity to the total power consumption of the system:

$$COP_{sys} = \frac{Q_h}{W_{comp} + W_{wfc} + W_{pumps}} \quad (3)$$

3. Experiment findings and discussion

Based on the proposed system control strategy described previously, experimental investigations were carried out on the IDX-SAHP system during those four test days and some of the test results are demonstrated and evaluated in this section. As illustrated in Figure 5 and Figure 6 for the temperature development inside the WST, the system could meet the DHW demand by supplying hot water flow from the WST top with temperatures between 52°C and 57°C during all these four test days. To understand clearly the system controls, the variation of water temperature from the PCM tank outlet (T4) is also presented in each plot.

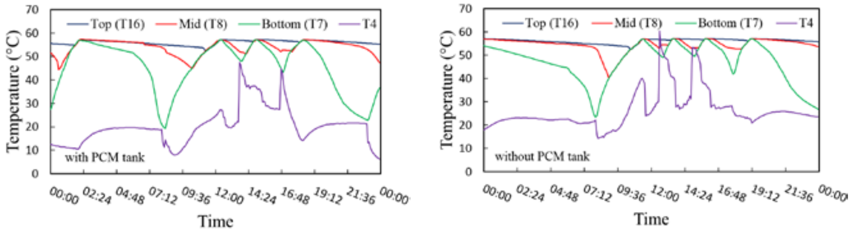


Fig. 5. Variations of WST water temperatures and temperature T4 during two sunny test days

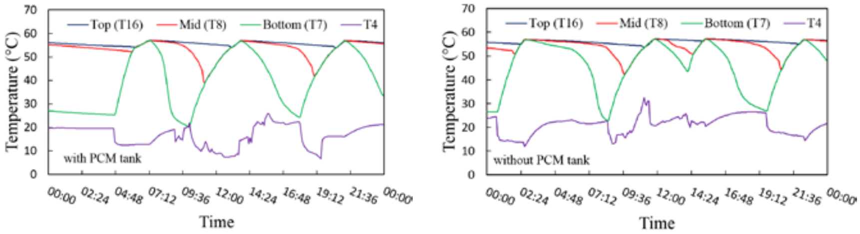


Fig. 6. Variations of WST water temperatures and temperature T4 during two cloudy test days

Meanwhile, the feed water temperature for each operational day was different due to various ambient air temperatures. Consequently, there were different lowest bottom tank water temperatures for these four test days. To fully understand the system performance, the test results of these four operating days are explained separately in the following parts.

For the sunny test day with PCM tank, the compressor started at midnight with no heat stored in the PCM tank as the PCM temperature (T-pcm) inside the PCM tank was 14.5°C which was below its melting point. That resulted in switching the AWHX on during that period to utilise the heating source from the ambient air, as shown later on in Figure 10. The heat pump compressor operated until 2:05 pm when T8 was higher than 57.0 ^{0}C and the system then started in PCM charging mode. During this period the maximum value for the total power consumption, condenser capacity and COP were 2.2 kW, 9.632 kW and 4.7 respectively as shown in Figure 7, Figure 8 and Figure 9 each.

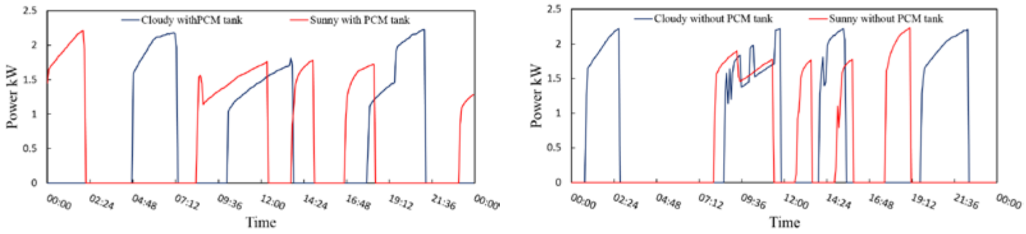


Fig. 7. Variations of system power consumptions during four test days

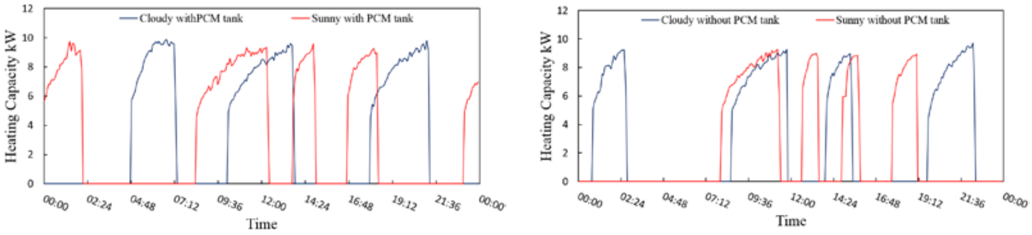


Fig. 8. Variations of system heating capacities during four test days

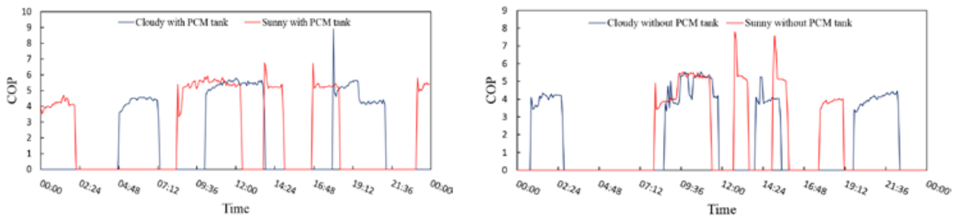


Fig. 9. Variations of system COPs during four test days

The PCM charging mode operated until 8:20 am when T8 started to drop below 53^0C and the heat pump compressor was switched on again. Up to that point, the PCM inside the tank was still not charged significantly since its temperature was only at 12.8^0C such that the AWHX needed to operate. The AWHX operated until at 8:35 am when the solar irradiance G reached above 190 W/m^2 and could be utilised as the heat source for the IDX-SAHP. Correspondingly, at that instant, the system power consumption thus dropped abruptly and the COP increased sharply, as shown in Figure 7 and Figure 9 respectively. The heat pump compressor kept running until at 12:20 when T8 started to be higher than 57^0C again. During this period, the PCM temperature T-pcm started to drop to its minimum temperature at 8.3 ^{0}C at 9:10 am since the AWHX was on at the beginning. The T-pcm was then picked up at different rates when the AWHX was off and more solar irradiances were available. These included significant 8.7^0C increase from 9:10 am to 10:50 am due to sensible PCM heating process and only 1 ^{0}C increase from 17^0C to 18^0C at the time period between 10:55 am to 12:05 because of latent PCM heating process involved.

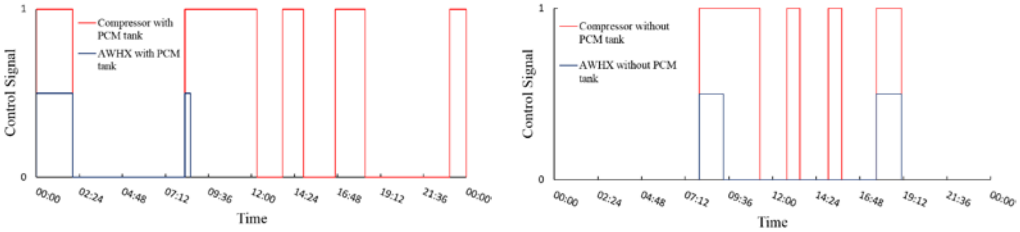


Fig. 10. Variations of compressor and AWHX fan control signals during two sunny test days

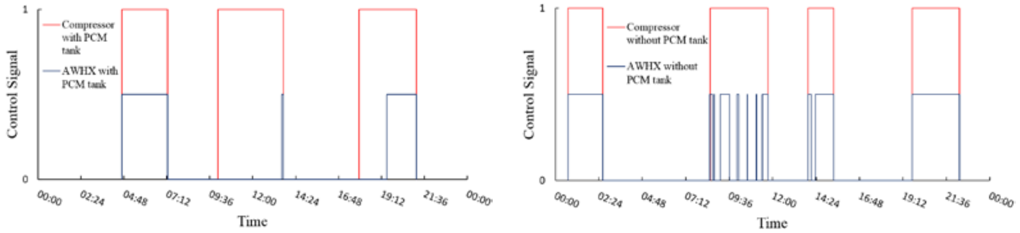


Fig. 11. Variations of compressor and AWHX fan control signals during two cloudy test days

At 12:05, the PCM was totalled melted and from there only sensible PCM heating existed such that the T-pcm increased abruptly from 12:05 to 12:20. From there, the whole system was shut down since the T-pcm was higher than 19.0^0C. The tank water temperature at T8 thus started and continued to drop to below 53.0 ^{0}C at 13:40 when either IDX-SAHP or solar mode needs to be controlled. From that time as shown in Figure 5, although the solar irradiance G was higher than 500 W/m^2, the water temperature T4 was still lower than T8 such that the IDX-SAHP mode was on and the AWHX was off due to the higher G values. Meanwhile, the PCM temperature T-pcm had a big jump due to the high temperature from the solar collector outlet and the PCM sensible heating process. The T-pcm then followed the changes of the solar collector outlet water temperature and the PCM absorbed and released heat respectively to the water flow depending on the temperature differences between these two temperatures. Correspondingly, from 19:15 the water received heat from the heat stored in the PCM tank. The system was switched off at 14:55 when T8 was above 57^0C and the T-pcm was higher than 19^0C. After that, the IDX-SAHP had two on periods staring at 16:45 and 23:10 respectively when T8 were both lower than 53.0 ^{0}C and one off period starting at 18:25 when T8 was above 57^0C. It is noted that the AWHX was always off during this period since the T-pcm was continuously higher than 16.5^0C.

For the cloudy test day with PCM tank, the same control strategy shown in Figure 2 would be follow. As shown in Figure 6, from midnight the system was continued off until at 4:45 am when the water temperature T8 dropped below 53.0^{0}C. After that, the heat pump compressor had three times running periods and three times off periods due to the variations of T8, as shown in Figure 11. Meanwhile, there were still two longer and one shorter on periods for the AWHX considering of the corresponding lower solar irradiances and lower T-pcm then. Subsequently, the variations of system power consumption, heating capacity and COP could be found from Figure 7, Figure 8 and Figure 9 respectively.

For the sunny test day without PCM tank, the system operation on or off was dependent only on the water temperature T8 and any changes of T-pcm shown in Figure 2 would be ignored. As shown in Figure 5, from midnight the system was continued off until at 8:00 am when the water temperature T8 dropped below 53.0^{0}C. After that, the heat pump compressor had four times running periods and four times off periods due to the variations of T8.

In summary, the total system power consumption, heating capacity and COP are calculated based on measurements for each of these test days. Despite the total power consumptions and heating capacities varied with different test days, the sunny day with PCM had the maximum COP of 4.99, the COP on cloudy day with PCM the second at 4.80, the COP on sunny day without PCM the third at 4.70 while the COP on cloudy day without PCM the least at 4.21.

4. Conclusions

A new IDX-SAHP test system has been designed, built and instrumented. There are three operational loops in the system including solar thermal, IDX-SAHP and load profile. A control strategy was intentionally designed and implemented with building management system so as to maintain constant temperature of hot water production and ensure high efficient system operations. Comprehensive measurements were carried out for four test days with different weather conditions (sunny and cloudy) and system structures (with and without PCM tank). The experimental results show that the designed IDX-SAHP system can meet the daily hot water load demand with constant hot water supply irrespective of weather conditions and system structures. In addition, the IDX-SAHP system could have various performance improvements at different weather conditions when PCM tank was integrated. Quantitatively, the average COP of the IDX-SHAP system with PCM tank could increase 6.1% and 14.0% on sunny and cloudy days respectively comparing to those systems without PCM tank integrations.

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