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Experimental Research on the Refrigeration Performance of PVT Solar Heat Pump in Summer Night

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Abstract. A method of refrigeration utilizing photovoltaic-thermal (PVT) solar heat pump is proposed, and long-wave radiation cooling is the key point. The PVT solar heat pump system combined cooling, heating and power (CCHP) is designed and constructed. The refrigeration performance of PVT solar heat pump during summer night is experimentally tested, including chilled water making and ice making. The refrigeration performance difference between clear sky night and cloudy sky night is compared and analyzed. The environmental condition more suitable for refrigeration is given according to the comparison result.

1. Introduction

PVT solar heat pump (SHP) is a comprehensive utilization of solar energy. Part of the solar radiation absorbed by PVT module in daytime is used for power generation by PV cell, while the other part is converted into thermal through heat pump. The temperature of PV cell will reduce through the thermoelectric synergy, which improves the photoelectric conversion efficiency at the same time [1]. However, most conventional SHP is in a shutdown state for most of the time, including nighttime, due to the less heating demand in summer, which cause a low system utilization. Considering the large cooling demand in summer, if utilizing SHP for refrigerating during the non-heating period can be realized, the comprehensive system utilization will be improved and cooling demand will be satisfied. PVT SHP has the PVT module with a large surface area, which is especially suitable for dissipating heat to low-temperature sky through long-wave radiation at night. Therefore, PVT module is an ideal heat-dissipating carrier and can be used as the condenser when utilizing heat pump for refrigerating.

The sky of night is a natural cold source and effective sky temperature of clear sky in summer nighttime can even be lower than -10℃ [2]. Therefore, scholars have done much research on the long-wave radiation cooling. The heat dissipation performance of roofs in different structures was tested, which shows that the roof temperature is significantly lower than the ambient temperature during nighttime[3]. Long-wave radiation cooling was applied in the air-conditioning system of teaching building to reduce energy consumption[4]. The heat dissipation performance of the flat radiant panel and the PVT module with water as cooling medium during summer night was tested, which can reach 90 W/㎡ and 120W/㎡ respectively[5]. According to the existing research, the long-wave radiation cooling power is relatively low compared with the cooling load of building, so the cooling demand of building can not be fully satisfied. Taking the initiative to increase the temperature of heat dissipation object can enhance the long-wave radiation cooling power from the viewpoint of heat transfer principle. By using refrigerant as working fluid, heat pump can provide a higher heat dissipation temperature (condensation temperature), while making low-temperature chilled water.

In view of the advantages of PVT module in long-wave radiation cooling and the shortcomings of conventional PVT SHP mentioned above, a method of utilizing PVT SHP for refrigerating is proposed.

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The PVT SHP runs refrigeration mode at summer night and utilizes PVT module as the condenser, while dissipating heat to sky and surroundings by long-wave radiation and convection through PVT module.

2. Experimental system design and testing principle

2.1 *Experimental system design*

The new PVT SHP needs to add refrigerating function based on the existing power generation and heating function. From the point of view in cost and integration, the components used for refrigerating and heating should be shared as much as possible. From the perspective of operational, the system should be able to switch between refrigerating and heating mode easily. From the view of energy consumption, refrigeration operates at night while mainly cooling load occurs during daytime, so cold-storage device is essential. Based on these design thoughts, the PVT SHP system combined cooling, heating and power is designed, as illustrated in figure 1. The system mainly consists of compressor, four-way reversing valve, cold-storage tank, thermal-storage tank, throttle valve, PVT module and photovoltaic inverter. Compressor, throttle valve, PVT module and the main pipeline is the shared part of refrigerating and heating. Four-way valve is used for refrigerating and heating mode switching. Cold-storage tank and thermal-storage tank are energy storage devices. PVT module can act as evaporator or condenser depends on the operation mode.

Figure 2 shows the refrigerating mode. The innovative point is that the PVT module, which absorbs solar radiation when running heating mode, acts as the condenser to release heat to sky and surroundings by long-wave radiation and convection. Ice-storage tank acts as the evaporator of the system, both contains cold-storage function.

The experimental system equips with 4 PVT module is constructed after concrete design based upon the schematic diagram. The copper coil that built-in ice-storage tank transfers heat with the water in the tank directly, which can realize chill water making and direct evaporative ice making. Figure 3, figure 4 and figure 5 show part of the physical components of the experimental system.

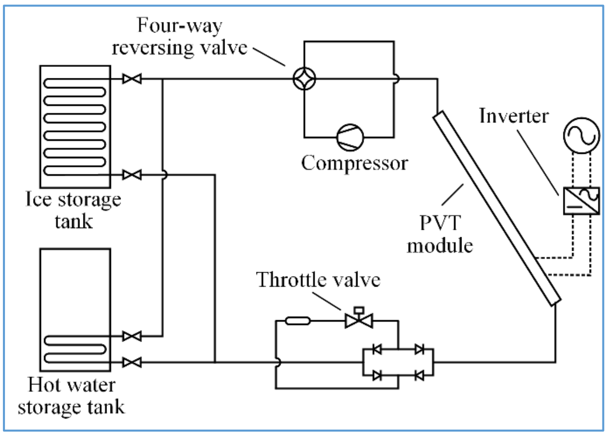


Figure 1. System schematic diagram.

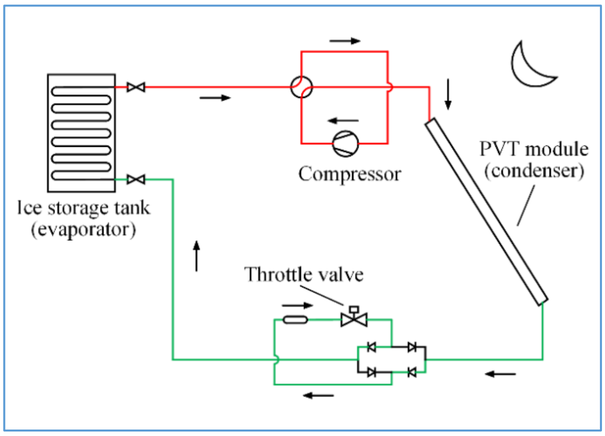


Figure 2. Refrigerating mode.

Figure 3. PVT module.

Figure 4. Ice-storage tank/hot-water tank.

Figure 5. Copper coil

2.2 *Evaluation method of refrigeration performance*

The performance index of refrigeration cycle is usually expressed as coefficient of performance (COP), representing the amount of cold energy that can be achieved upon unit's power consumption.

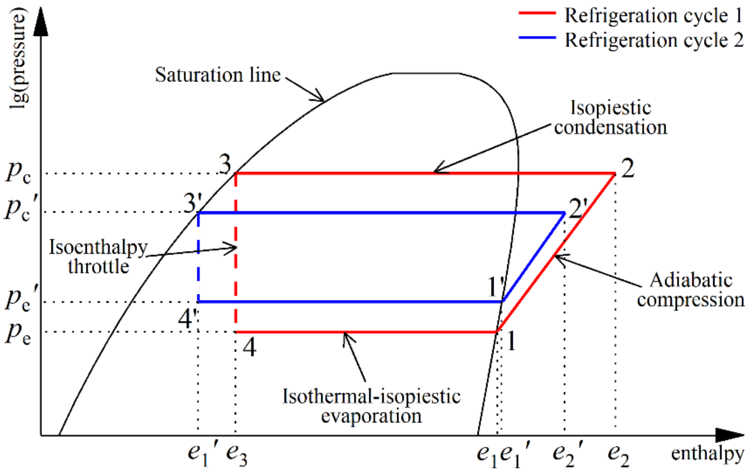


Figure 6. Refrigeration cycle.

The $1 \to 2 \to 3 \to 4 \to 1$ shown in figure 6 is a theoretical refrigeration cycle, including the following four basic processes: compression, condensation, throttling and evaporation. The theoretical COP of refrigeration cycle can be expressed as:

$$COP_{th} = \frac{Q_{th}}{P_{th}} = \frac{e_1 - e_3}{e_2 - e_1} \tag{1}$$

In practical refrigeration cycle of PVT SHP system, the Q_{th} in formula (1) refers to the actual refrigeration capacity Q_{real}, while the P_{th} refers to the actual power P_{real}. The Q_{real} can be calculated using the following formula:

$$Q_{real} = m_{ref}\left(e_{ref\text{-}out} - e_{ref\text{-}in}\right) = A\overline{K}\left(\overline{T}_{w} - \overline{T}_{ref}\right) \tag{2}$$

Where, m_{ref} is the refrigerant mass flow, $e_{ref\text{-}in}$ and $e_{ref\text{-}out}$ is the enthalpy of refrigerant at the inlet and outlet of the evaporator, A is the heat transfer surface area betweencopper coil and water in the evaporator, $\overline{K}$ is the average heat transfer coefficient between refrigerant and water, $\overline{T}_{w}$ is the average water temperature, $\overline{T}_{\mathrm{ref}}$ is the average refrigerant temperature which generally equate to evaporation temperature.

When the condensation temperature decreases orevaporator temperature increases, the refrigeration cycle becomes $1' \rightarrow 2' \rightarrow 3' \rightarrow 4' \rightarrow 1'$, as shown in figure 6, and theoretical COP becomes that shown in equation (3):

$$COP_{\mathrm{th}}' = \frac{e_1' - e_3'}{e_2' - e_1'} > \frac{e_1 - e_3}{e_2 - e_1} = COP_{\mathrm{th}} \quad (3)$$

Equation (3) points out lower condensation temperature and higher evaporation can achieve higher COP, which is also applicableinpractical refrigeration cycle. For PVT SHP system, lower condensation temperature means lower surface temperatures of PVT module and better heat dissipation performance. Evaporation temperature related to the state of heat-exchange medium in the evaporator.

3. Experimental results analysis

A large number of PVTSHP refrigeration experiments were carried out during the summer nighttime from August to September 2017 in Dalian City. The refrigeration mode contains chilled water making and ice making, and environmental condition includes clear sky night and cloudy sky night.

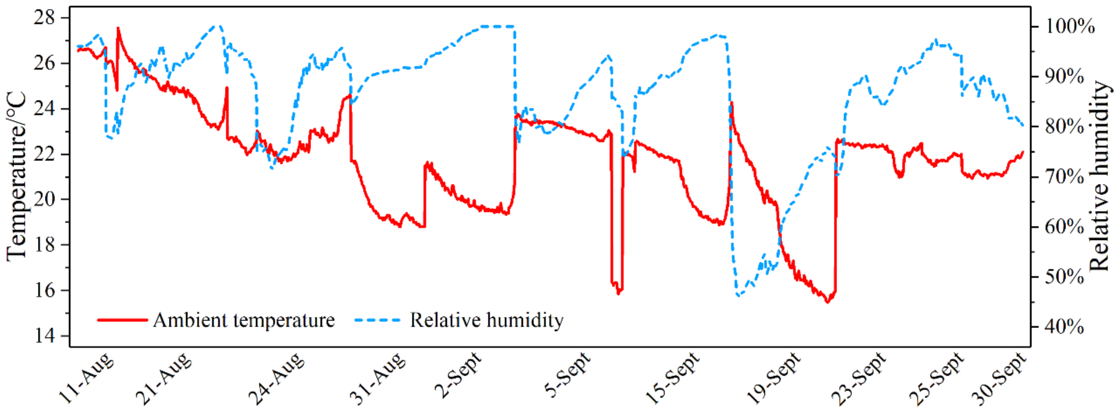


Figure 7. Outdoor meteorological parameters.

The meteorological parameters of the environment during these experiments is shown in figure 7. The ambient temperature range from 16℃ and 28℃ and the relative humidity from 45% to 100%, which is consistent with the summer night meteorological features in Dalian City.

According to the chilled water temperature requirement (<12℃) in air conditioning system, the experimental data of ice making and 5℃~12℃chilled water making were chosen to process and analyze, and these stages also called as effective refrigeration stage.

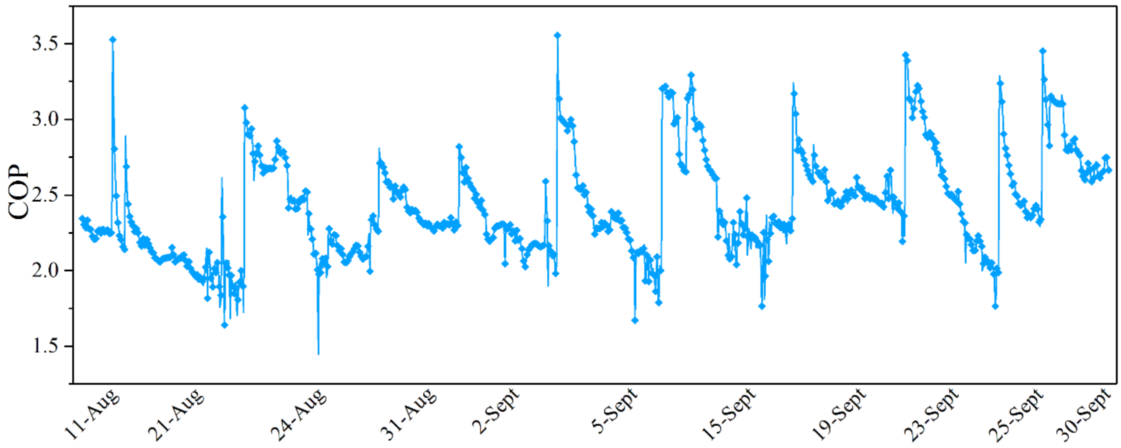


Figure 8. COP in effective refrigeration stage.

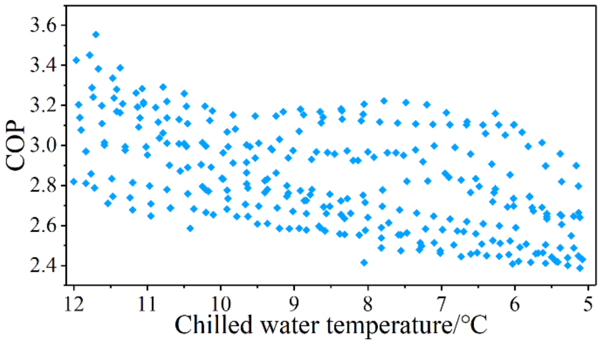


Figure 9. Chilled-water-making COP.

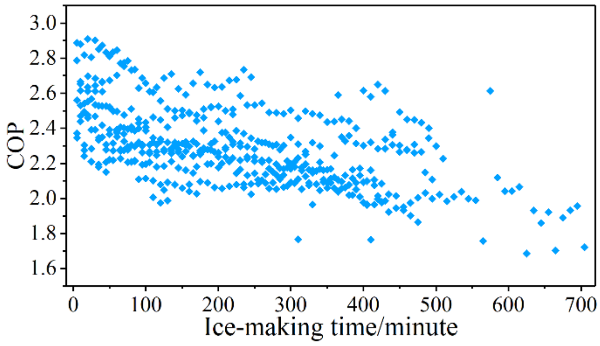


Figure 10. Ice-making COP.

The COP of effective refrigeration stage is shown in figure 8. As can be seen that the COP ranges from 1.7 to 3.5, and the average level is 2.4. Figure 9 and figure 10 illustrate a huge number of experimental results in chilled water making and ice making. The COP of chilled water making varies from 2.4 to 3.5 with an average level of 2.8, and presents overall downtrend with the chilled water temperature declining, as is shown in figure 9. Figure 10 shows the average COP of ice making is 2.3, with a range of 1.8 ~ 3.5,and the COP also shows a descending trend as the ice making time increases.

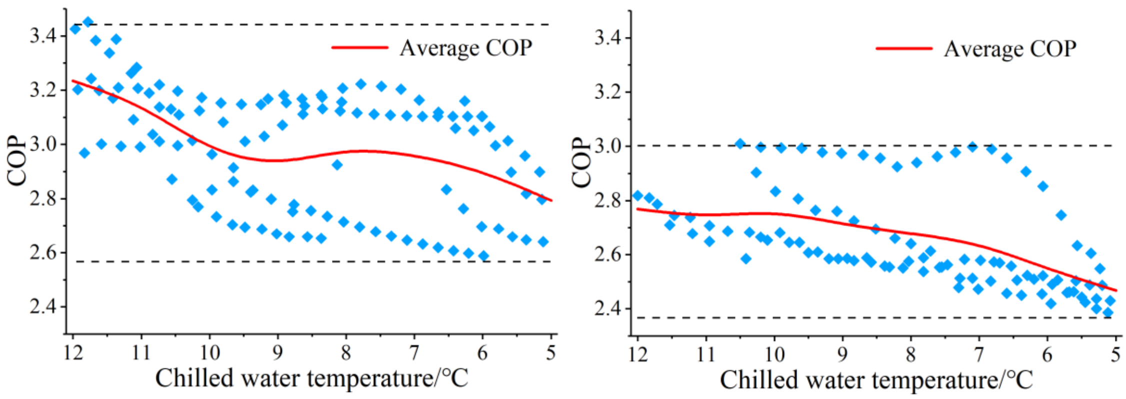
From the formula (2), it can be found that for the chilled water making, when water temperature decreases, the temperature difference between water and refrigerant will reduce accordingly, causing refrigeration capacitydecline. For ice making, the ice thickness increases with ice making time, so heat transfer coefficient will decrease accordingly, also causing refrigeration capacity decline. In both cases, the control system will increasethe temperature difference of heat transfer by reducing evaporation temperature to ensure sufficientrefrigeration capacity. From equation (3), it can be seen that reducingevaporation temperature will cause COP dropping, which is the reason why COP presents overall downtrend both in chilled water making and ice making. Due to the ice layer on the surface of the coil, as shown in figure 5, the thermal resistance of ice making is higher than chilled water making, causing a lower evaporator temperature to ensure refrigeration capacity, so the average COP of ice making is 19.4% lower than chilled water making. However, the volume of cold storage equipment for ice storage is smaller than that for chilled water storage in the case of same cold storage capacity, and ice can also providea lower cooling temperature, which means ice storage is better than chilled water storage in terms of cooling quality and system miniaturization.

From the experimental results above, it can be concluded that it is feasible to utilize PVT SHP for refrigerating in summer nighttime. The average COP of chilled water making is 2.8, and ice makingis 2.3. The energy efficiency of chilled water making can reach the level 4 (2.8~2.99) in Chinese air conditioning energy efficiency rating standards.

4. Refrigeration performance in different environmental conditions

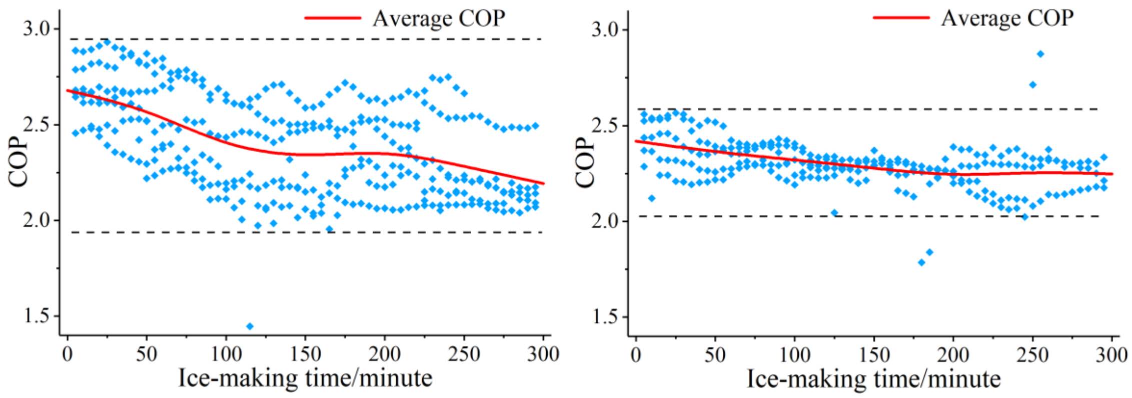
Any changes of the outdoor environmental conditions will affect the refrigeration performance of the system since PVT module radiate heat to the surroundings and sky directly. Therefore, figuring out the impact of environmental condition on the refrigerating performance is significant for improving the system performance and optimizing the operation strategy. The summer nighttime can be classified into clear sky and cloudy sky according to meteorological characteristics, and less cloudiness is the main feature of clear sky compared with cloudy sky. In the following comparison, clear sky refers to the average cloudiness less than 0.1, while cloudy sky refers to more than 0.3.

Figure 11 presents the COP of chilled water making in clear sky and cloudy sky. The COP in clear sky ranges from 2.6 to 3.4 with an average level of 3.0, while that in cloudy sky varies from 2.4 to 3.0 with an average level of 2.7. The average COP in clear sky is 12.4% higher than that in cloudy sky. Figure 12 shows the COP of ice making with a same ice-making time of 300 minutes, which can be seen that the COP in clear sky varies from 1.9 to 2.9 with an average level of 2.4, while that in cloudy sky ranges from 2.0 to 2.6 with an average level of 2.3. The average COP in clear sky is 4.8% higher than that in cloudy sky.



(a) Chilled-water-making COP in clear sky (b) Chilled-water-making COP in cloudy sky

Figure 11. Chilled-water-making COP in clear sky and cloudy sky.



(a) Ice-making COP in clear sky (b) Ice-making COP in cloudy sky

Figure 12. Ice-making COP in clear sky and cloudy sky.

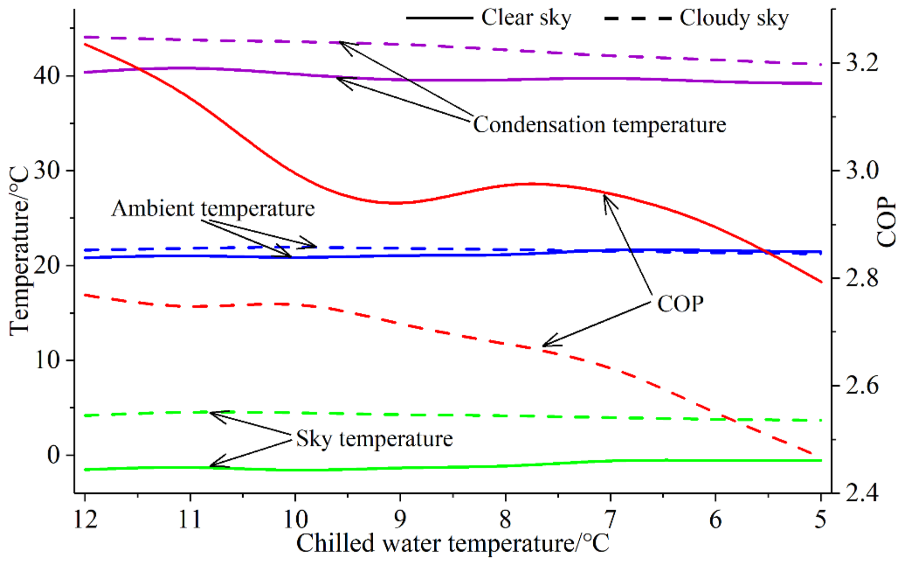


Figure 13. Influencing factor of chilled-water-making COP in clear sky and cloudy sky.

From the experimental result, the COP in clear sky is higher than cloudy sky, either in chilled water making or ice making. From the perspective of radiation heat transfer, less cloudiness in atmosphere causes less long-wave radiation absorbed from the ground, resulting in a lower effective sky temperature, which is conducive to radiative heat dissipation for PVT module. Therefore, the condensation temperature will decrease and the COP will be promoted according to equation (3).Experimental data also supports this conclusion. Take the testing data in chilled water making as an example, as shown in figure 13 (the data in figure13 is the average level of all these experiments). As can be seen from figure 13, the average ambient temperature between clear sky night and cloudy sky night shows little difference, while the effective sky temperature in clear sky is about 5 ℃ lower than that in cloudy sky, causing a lower condensation temperature of 2℃ ~ 4℃. Therefore, the heat dissipation performance of the PVT module is better, anda better COP can be achieved in clear sky. From the comparison result of different environmental conditions, it can be concluded that the average

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COP in clear sky is higher than cloudy sky due to the lower sky temperature, so the PVT SHP system is recommended to run refrigerating mode in clear sky.

5. Conclusion

By analyzing the characteristics and the existing problems of PVT SHP and combining with the cooling demand in summer, a method of utilizing PVT SHP for refrigerating during summer nightis proposed. The main innovation is using PVT module as the condenser of heat pump to dissipate heat through long-wave radiation. The PVT SHP combined with cooling, heating and power was designed and a concrete experimental system was set up.

The experimental result shows that utilizing PVT SHP for refrigerating is feasible. The average COP of chilled water making is 2.8 andice making is 2.3. The refrigeration performance of chilled water making is higher than that of ice making, while ice making have advantages in cooling quality and system miniaturization.

From the comparison result of the performance in different environmental conditions, it can be concluded the refrigeration performance in clear sky is better than that in cloudy sky due to the lower effective sky temperature. The averageCOPof chilled water making in clear sky is 3.0, which is 12.4% higher than that in cloudy sky night. The comparison conclusionalso provides a reference for the optimization of the PVT SHP operation strategy, that is utilizing PVT SHP for refrigeratingis recommended tooperatein clear skynight.

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