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Numerical simulation and analysis of photovoltaic-driven heat pump system integrated with energy storage

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ABSTRACT

In order to further reduce the energy consumption of heat pump system in winter, a new type of photovoltaic driven storage constant temperature storage system is proposed in this paper. The results show that the temperature in the storage room can be stably maintained at -2.0 °C to 3.7 °C. The operating efficiency of the heat pump system can be maintained between 3.0 and 4.0, the average coefficient of performance (COP) of the system can reach 1.9, and the operating power of the system is 0 kW to 0.7 kW. The cumulative heat produced by the system reached 18.0 kW·h, and the average daily accumulative consumption of electricity was only 6.8 kW·h. The system can provide a design basis for energy-saving constant temperature storage.

Keywords：Photovoltaic driven, Heat storage water tank, Simulation, Energy storage

1. INTRODUCTION

In recent decades, the energy consumption has increased significantly with rapid population growth and economic development, especially in the cold chain industry. According to statistics, the current energy consumption of the cold chain, cold storage and other refrigeration industries has reached 12 % of the total energy. It is a serious waste of energy, and the development and utilization of renewable energy sources has become an urgent task. With the advantages of easy access, safety, and cleanliness, solar energy has been widely used for heating and power generation in buildings and industries. At present, the share of solar energy in the global renewable energy market has reached 28.9 %. Studies have shown that the comprehensive of solar photovoltaic refrigeration systems can reach 69.7 %. Currently, solar photovoltaic is applied in the refrigeration industry, which is the current research direction of many scholars.

At the present time, vapor compression refrigeration system driven by photovoltaic is the most promising system and has important research implications for food and vaccine preservation. The methods of coupling between photovoltaic and vapor compression refrigeration system are mainly divided into direct coupling between photovoltaic array and compressor and indirect coupling through inverter. A photovoltaic driven vapor compression refrigeration system with a motor and phase change materials was used in a cold storage for agricultural transport by El-bahloul et al. The feasibility of the system was verified experimentally with a system COP of 1.2. Lei et al. studied a photovoltaic-driven cooling system, it was found that the average cooling output of the system under cloudy and sunny days were 416 W and 399 W, respectively, and the average performances of the system were 3.42 and 3.02, respectively. Han et al. achieved the maximum power tracking of a photovoltaic driven cooling system by an impedance matching control strategy. The experimental results showed that the average photovoltaic conversion efficiency of the system was 0.129, which was 83.7 % higher than that of the system without the control strategy.

Energy storage is required for the photovoltaic-driven cold storage to ensure a continuous cooling supply. Current technologies for auxiliary energy storage in this field include battery energy storage, phase-change material storage and ice storage. Navidbakhsh et al. theoretically analyzed phase-change material as an ice storage system for localized cold storage in building. The results showed that the electric power consumption of the system was 17.1 % lower and CO_2 emissions were 17.5 % lower compared to the conventional vapor compression refrigeration system. Liang et al. developed an operation optimization model for ice storage radiant air-conditioning. The results showed that the ice storage radiant air-conditioner has significant power saving advantages compared with conventional air-conditioner. Sanaye et al. simulated the electricity consumption of a vapor compression refrigeration system using ice storage and a conventional vapor compression refrigeration system. The results showed that the system using ice storage technology had 11.83 % and 32.65 % lower electricity consumption and cost of electricity, respectively. There are many non-negligible problems with battery storage compared to phase-change materials and ice storage and cooling, such as shorter battery life and serious environmental pollution. Comparing with battery banks and phase-change materials, the water tank energy storage is a more promising auxiliary energy storage technology. And the water tank energy storage technology can significantly reduce CO_2 emissions. In previous studies, the combination of photovoltaic and vapor compression refrigeration system is the main research direction, but for the combination of photovoltaic and heat pump system to supply heat for cold storage form is relatively little research. In this paper, a new photovoltaic-driven storage type thermostatic storage system is proposed. Based on the TRNSYS simulation system, a solar-thermal pump storage type thermal coupling model is constructed with winter conditions as the main research object. The thermostatic storage system was numerically simulated and theoretically analyzed. The feasibility and practicality of the new photovoltaic-driven storage system is investigated to provide a design basis for energy-saving thermostatic storage.

2. SYSTEM MODEL

2.1 Principle

The photovoltaic driven steam compression thermostat proposed in this paper consists of three parts. The solar photovoltaic conversion system, the heat pump system, and the thermostatic reservoir heat exchange subsystem are the three main subsystems of the system. The refrigerant used in the heat pump system is R410A. The refrigerating medium used in the thermostatic heat accumulator heat exchange subsystem is 30 % Ethylene glycol aqueous solution.

The main operation of a solar photovoltaic system is that the solar collector collects solar energy and converts it into alternating current via inverters and frequency converters to power the heat pump.

The heat pump system's main working process is that it operates to supply heat directly to the thermostatic reservoir, while the refrigerant flow is distributed through the liquid distribution valve to meet the demand for heat storage in the water tank.

The heat exchanger subsystem of the constant temperature storage works to release the energy collected in the water tank to play the role of energy supplement for the system, supplying heat to the constant temperature storage when the energy collected by the solar panel is insufficient to keep the entire system running.

During the day, the solar panel converts the sun into direct current, which is converted into alternating current by the photoelectric conversion module to drive the compressor. If in cloudy or rainy conditions during the day, the solar radiation does not reach the conditions for the compressor to start, the heat exchange sub-system is activated by the work mass pump, and if the heat exchange sub-system still does not meet the temperature requirements of the constant temperature storage, it is driven by mains electricity, or jointly driven by photovoltaic and mains electricity. At night, the solar panel stops working and the heat exchange subsystem takes priority to work, releasing the heat stored in the water tank. When the work of the heat exchange subsystem cannot meet the temperature requirements of the constant temperature storage, the mains power is regulated and the system is supplemented by the mains power.

2.2 Mathematical models

2.2.1 Solar photovoltaic conversion model

The radiant energy received per unit area on a photovoltaic panel is made up of three main components：（Direct radiation, W/m^2; G_{dT} - scattered radiation, W/m^2; G_{gT} - reflected radiation, W/m^2; total radiation received per unit area is G_T，W/m^2.）

$$G_T = G_{bT} + G_{dT} + G_{gT} \quad (1)$$

The formula for direct radiation G_{dT} is

$$G_{bT}=G_b\frac{cos\theta}{cos\theta_Z} \quad (2)$$

Where:

ϑ- angle of incidence of the PV panel array; ϑ_z - zenith angle.

The scattered radiation G_{dT} is calculated as

$$G_{dT}=G_d\left[1-A_I\frac{1+\cos\beta}{2}+A_IR_b\right] \quad (3)$$

Where:

β-the tilt angle of the PV array.

R_b-ratio of scattered radiation from the photovoltaic array to scattered radiation from the horizontal surface.

A_L-transient anisotropy index, $A_L=G_b/G_O$.

Where:

G_O is the horizontal surface solar radiation above the atmosphere.

$$G_O=G_{SC}\left(1+0.33\cos\frac{360n}{365}\right)\cos\theta_Z \quad (4)$$

G_{SC} -solar constant.

The reflected radiation G_{gT} is calculated as

$$G_{gT}=G_d\frac{1-\cos\beta}{2}\rho_g \quad (5)$$

The photovoltaic array photovoltaic conversion efficiency is calculated as

$$\eta_{pv}=\frac{IU}{\alpha\tau GS} \quad (6)$$

Where:

η_{pv}-photovoltaic module photoelectric conversion efficiency, %.

I-operating current of the PV module, A.

U- PV module operating voltage, V.

α-solar cell absorption coefficient.

τ-surface transmittance of the photovoltaic module.

G-accumulated solar irradiance, MJ/ m^2.

S- PV panel area, m^2.

$$Q_r=Cm(T_2-T_1) \quad (7)$$

Where:

Qr heat demand of the thermal storage tank, MJ.

C-specific heat capacity of water, J/（kg·°C）.

T_2-temperature of water after the end of heat storage, °C.

T_1-the temperature of the water before the heat storage starts, °C.

2.2.2 Systematic evaluation indicators

The COP of a heat pump is the ratio of heat production to power and is calculated as

$$COP=\frac{Q}{W} \quad (8)$$

Where:

Q - real time heat production of the PV heat pump unit, kW.

W - heat pump input power, kW.

The average system efficiency, indicating the cumulative system heat production/system energy consumption, is calculated as

$$COP_{average}=\frac{Q_H}{Q_C} \quad (9)$$

Where:

Q_H - cumulative heat production, kW·h.

Q_C- system energy consumption, kW.h.

3. NUMERICAL SIMULATION

3.1 Simulation model construction

A simulation model of the photovoltaic energy storage system was established using TRNSYS, shown in figure 1. The system first calculates the load of the constant temperature storage, after which the size of the air source heat pump model is selected and the maximum input power is determined. Based on the load, the chiller air supply volume size and coil model are calculated. The capacity and number of photovoltaic panels are determined according to the total power of the system. The corresponding modules in TRNSYS are shown in Table 1.

Table 1 Simulation module of constant temperature storage system for photovoltaic energy storage

Name	Modules	Note
Meteorological parameters	Type15	tmY2 File format
Air source heat pump	Type217	1
Water Pump	Type114	2
Heating coils	Type753	2 Import、2

		Export
Fans	Type146	2
Heat storage tank	Type1334 v2	shell and tube type
Points Calculator	Type24	Integral output results
Result Output	Type65	Output simulation results

3.2 Simulation parameters setting

3.2.1 Meteorological data

In this paper, the typical meteorological year parameters are directly exported in tmY2 file format through Meteonorm meteorological software.

3.2.2 Main parameters setting

The constant temperature storage in the simulation system effective volume is 18.75 m3 (L=3 m, W=2.5 m, H=2.5 m). the total design load of the constant temperature storage is 0.5 kW. The simulated conditions are under no-load condition and the number of ventilation and heat exchange is 2 times. The heat flow and lighting of the cargos are not considered, and the wall of the constant temperature storage uses 100 mm polyurethane heat insulation board. The heat storage tank is mainly composed of stainless steel (L=2.5 m, W=0.6 m, H=0.5 m), using polyurethane foam as insulation material, and the internal plate is double-layer heat transfer copper pipe. The maximum input power of heat pump is 2 kW, and the power of photovoltaic module is 1 kW/m^2. specific parameters are shown in Table 2. For the specificity of the location temperature and the set temperature in the storage, the simulation time was chosen to simulate continuously from 12:00 on January 12 to 12:00 on January 13, 2022. Based on the relevant data, the sunset time on the 12th is 16:57 and the sunrise time on the 13th is 7:22.

3.2.3 System control strategy

(1) Judgment on heat release of water tank: the water tank can release heat only when the following two conditions are met at the same time. The water tank temperature is greater than 10.0 °C and the room temperature is lower than 2.0 °C. When the room temperature rises to 4.0 °C or the water tank temperature is lower than 5.0 °C, the heat release of the water tank stops.

(2) Tank heat storage judgment: When the water temperature of the water tank is less than 10.0 °C and the water tank does not carry out the exothermic, the water tank starts to store heat at this time. When the water tank temperature is greater than 15.0 °C, the water tank stops heat storage.

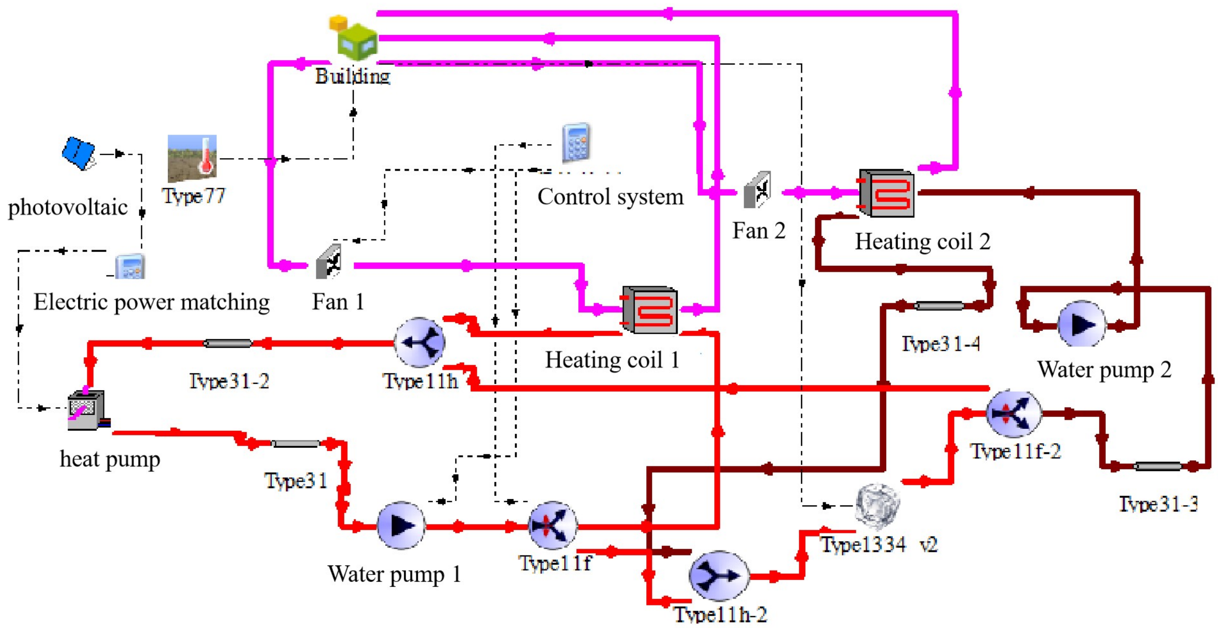


Fig 1. Simulation model of photovoltaic energy storage constant temperature storage system

(3) Utility supplement judgment: When the room temperature is lower than 2.0 °C and does not meet the exothermic condition of the water tank, the water tank exothermic control sensor will input signal to the power matching module for utility supplement.

(4) Abandoned power judgment: When the power generation of photovoltaic panels meets the power requirements of the system and the heat storage tank is no longer storing heat, at this moment, the power generation of photovoltaic panels is treated as abandoned power.

Table 2 Equipment Parameters

Name	Parameters Setting
Photovoltaic panels	Maximum power voltage: 42.05 V; open circuit voltage: 49.88 V; open circuit current: 14 A; maximum power current: 13.08 A; quantity: 2 pieces
Heat Pump	Maximum input power is 2 kW. evaporator inlet water temperature is 12 °C. Condenser inlet water temperature is 40 ℃. The inlet flow rate is 761 kg/h. The specific heat capacity of hot water is 3.56 kJ/(kg·K)
Chiller	Air delivery volume is 374m^3/h. Power is 35 W. Motor efficiency is 60 %.

4. RESULTS AND ANALYSIS

As shown in figure 2, from 12:00 on January 12 to 12:00 on January 13, the outdoor temperature ranges from -5.7 ° C to 14.9 ° C. The highest temperature occurs at 12:00 on January 13, and the lowest temperature occurs at 7:10 on the morning of January 13. Under the condition that the outdoor temperature varies greatly, the temperature inside the storehouse stays in the range of -2.0 °C to 3.7 °C in this process.

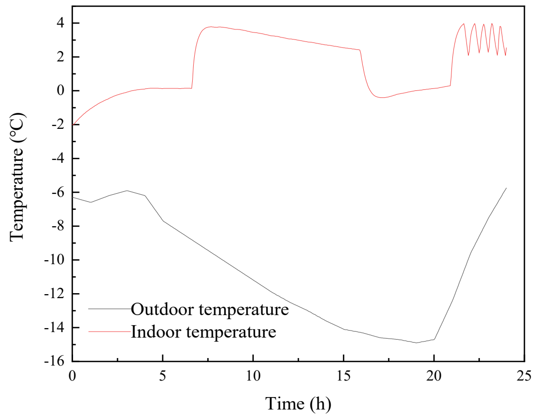
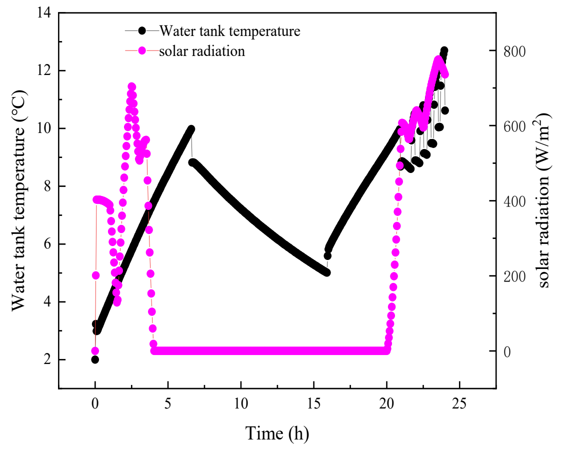
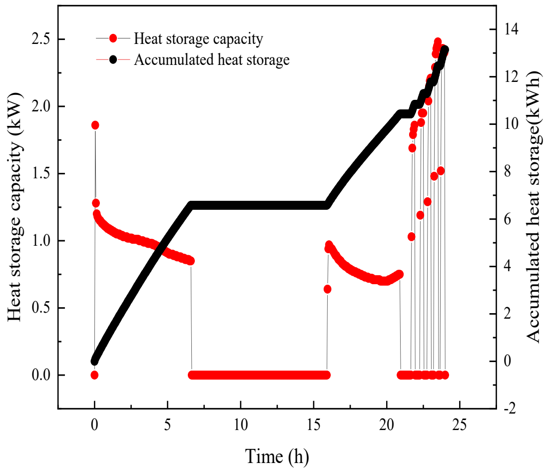


Fig. 2 Temperature change inside and outside the constant temperature storage

As shown in figure 3, the temperature range of the water tank is between 2.0 °C and 12.0 °C. The rising part is the heat storage process of the water tank, and the falling part is the heat release process of the water tank. From figure 3 and figure 3 (a) (b) in combination, on the 12th at better due to higher outdoor temperature and light conditions, so the water tank has been in a heat storage phase. At about 18:00 on the 12th, the temperature of the water tank dropped suddenly, which may be because the ambient temperature was greatly reduced and the sunlight was weak. At this time, the photovoltaic power generation efficiency was low. As shown in figure 3 (a) and (b), the water tank is always in the heat release state from 18:00 pm on 12th to 3:00 am on 13th, and the water tank cannot carry out heat storage. At this time, the system is always operated by the heat exchange subsystem. From 3:00 am to 7:00 am on the 13th, the temperature of the water tank rose, indicating that all the heat stored in the water tank was released, the mains electricity was added to replenish it, and the heat storage process of the water tank was carried out at the same time. From 7:00 to 12:00, the temperature range of the tank changes greatly, which is caused by the great changes in outdoor temperature and lighting conditions. As can be seen from figure 2, the temperature in the reservoir changes frequently at this stage.



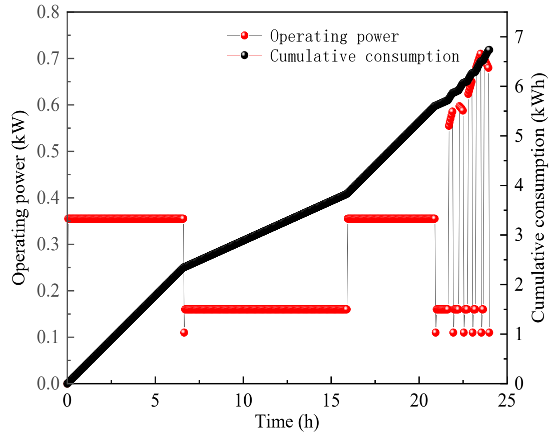
(a) Temperature and solar radiation of heat storage tank



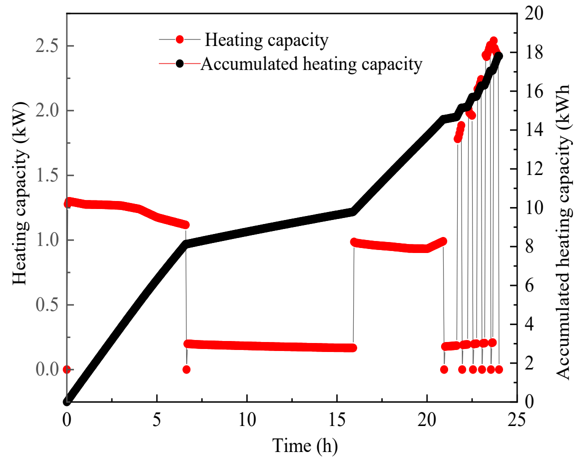
(b) Heat storage capacity of heat storage tank

Fig. 3 Temperature of heat storage tank Solar irradiation and heat storage

As shown in figure 4, are the real-time heat production and operating power of the heat pump and their cumulative values in the statistical simulation process. The cumulative value refers to the data obtained by the accumulation of hourly heat produced by the heat pump over time. As shown in figure 4 (a), the operation power of the heat pump is in the range of 0 to 0.7 kW, and the daily average cumulative mains power consumption is only 6.8 kW·h. It can be seen from figure 4 (b) that the cumulative heat production of the heat pump can reach 18.0 kW·h. The power and heat production of the heat pump suddenly decreased at 18:00 on December 12, as shown in the solar radiation curve in figure 3 (a). At this stage, the photovoltaic panel stopped working due to no illumination after sunset, and the heat exchange system of the heat storage tank began to start. From 7:00 to 12:00 on 13th, the operating power and heat production of the heat pump changed greatly and the power reached the maximum value, which may be because the outdoor temperature and solar radiation changed dramatically, in addition, the heat storage tank continued to store heat and release heat, and the constant temperature storage load was large.



(a) Heat pump operating power and accumulated power consumption



(b) Heat pump heating capacity and cumulative heat pump heating capacity

Fig. 4 Heat Pump Operation Characteristics

The average COP of the system refers to the cumulative heat supply to the repository divided by the cumulative energy consumption. As shown in figure 5, the COP of the real-time heat pump can reach up to 4.3, and can basically be maintained at 3.0 to 4.0 during the normal operation of the heat pump. The average COP of the system can reach 1.9, and the overall performance curve is also consistent with figure 5.

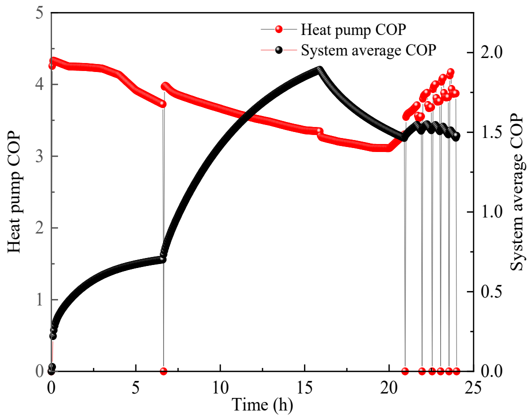


Fig. 5 Hourly performance indicators under system operation

5. CONCLUSION

In this paper, a new photovoltaic-driven energy storage thermostat system was established. The system was simulated by TRNSYS software to obtain relevant data and performance evaluation indexes. The feasibility and system performance of the system were verified. And the following conclusions are reached:

(1) The temperature of the constant temperature storage can be maintained between -2.0 °C and 3.7 °C for 24 hours during the operation of the new photovoltaic-driven energy storage thermostatic storage system. The water temperature curve in the constant temperature storage is consistent with the temperature curve and the performance curve of the heat pump operation process, which indicates that the system can operate stably and continuously.

(2) The COP of the heat pump system can reach 3.0 to 4.0 during stable operation, and the average COP of the system can reach 1.9. The COP variation is mainly affected by the heat absorption and exothermic process of the heat storage tank.

(3) The operating power of the heat pump system is 0 to 0.7 kW, and the average daily power consumption is only 6.8 kW·h. The accumulated heat production of the heat pump system reaches 18.0 kW·h, which achieves the purpose of energy saving and emission reduction.

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