ISSN 2004-2965 Energy Proceedings, Vol. 18, 2021

International Conference on Applied Energy 2021
Nov. 29 - Dec. 5, 2021, Thailand/Virtual
Paper ID: 900

STUDY ON THE PERFORMANCE OF SOLAR COUPLED HEAT PUMP COGENERATION ZERO CARBON ENERGY SYSTEM FOR VILLA

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ABSTRACT

In this paper, a cogeneration system coupled with low concentrating photovoltaic/thermal (LCPV/T) technology and heat pump is proposed to meet the energy consumption of villa. The system is mainly composed of low concentrating photovoltaic/thermal module (LCPV/T), water source heat pump and capillary network radiation ceiling. LCPV/T generates clean electric energy and thermal energy by absorbing solar radiation, the system can achieve self-sufficiency in electricity / heat and achieve the goal of zero carbon building with appropriate operation mode. Taking the real weather data of Tianjin as the input parameters, the system performance is simulated by using the simulation software TRNSYS. The results show that the electric energy and heat energy produced by the system can fully meet the annual power consumption and the heat load in the heating season of the villa. LCPV/T system can also improve the cop of heat pump and save energy. Overall, the comprehensive utilization efficiency of solar energy of the system can reach 75%, including electric efficiency of 12% and thermal efficiency of 65%.

Keywords: low concentrating, photovoltaic/thermal (PVT), heat pump, cogeneration

1. INTRODUCTION

In order to implement the temperature control goal of the Paris Agreement and achieve carbon neutrality, countries all over the world are expanding the proportion of renewable energy in energy consumption. Among all kinds of renewable energy, solar energy has become a reliable form to improve the energy structure because of its huge quantity and easy utilization [1]. As one of the forms of solar energy utilization, solar photovoltaic photothermal (PV/T) recovers waste heat by exchanging heat between the heat conducting fluid flowing in the flow channel and the solar panel, so as to improve the power generation efficiency of solar cells and realize cogeneration [2]. Combined with heat pump technology, it can not only provide electric energy, but also further improve the efficiency of heat pump.

Vallati et al. [3] studied the photovoltaic photothermal heat pump system with heat storage tank and believed that it can meet the energy demand of small houses to a certain extent, and the application of underground heat storage technology and concentrating technology will make the system more robust and independent. Yao et al. [4] expanded the applicability of the system under extremely cold conditions by introducing steam injection cycle into multi heat source (photovoltaic, photothermal and air source) heat pump system, and gave three operation modes and operation strategies of the system, compared with the related products produced by Gree company, it is found that the efficiency of this cycle is higher. Zhou et al. [5] experimentally tested the operation effect of the photovoltaic photothermal radiation refrigeration heat pump system designed by them in summer, which proved that the system can operate stably and efficiently, and has reference significance for the large-scale application of combined heat, power and cooling on buildings. Liang et al. [6] studied the operation characteristics of direct expansion solar heat pump system with photovoltaic

Selection and peer-review under responsibility of the scientific committee of the 13_{th} Int. Conf. on Applied Energy (ICAE2021).

photothermal module with pressure welding channel under refrigeration mode. The results show that it can effectively meet the refrigeration demand in summer. However, the requirements of pressure welding process are high, and the cooling effect is not as good as that of heat pipe. Obalanlege et al. [7] conducted experiments by using the control variable method to study the effects of irradiation intensity, cooling water flow, buffer tank size and other parameters on the operation performance of non-direct expansion photovoltaic photothermal heat pump system under short cycle operation. Du et al. [8,9] carried out experiments and Simulation Analysis on the micro heat pipe photovoltaic photothermal air heat pump system designed by him, and the results show that the system has excellent performance. Micro heat pipe can control the cost, and has high heat transfer and high-pressure bearing capacity, which can effectively take away the heat of photovoltaic cells and improve the overall efficiency. Zhou et al. [10] designed a multi heat source heat pump system integrating micro heat pipe photovoltaic photothermal modules and carried out experimental research. The results show that the system can meet the heating demand under low irradiation conditions. Chen et al. [11] analyzed the energy consumption, environmental protection, economy and robustness of photovoltaic photothermal ground source heat pump system with energy storage, combined with energy saving ratio (ESR), emission reduction ratio (ERR), adjustable ratio (AR) and annual cost saving ratio (ACSR), The above indexes are weighted into comprehensive performance index, and the influence on the change of system parameters is evaluated. Sommerfeldt et al. [12] analyzed the performance and economy of heat pump technology with buried pipe heat storage under residential conditions. The results show that due to the introduction of photovoltaic photothermal module, the floor area of buried pipe will be reduced and the system cost will be significantly reduced, which is conducive to the promotion of heat pump and long-term heat storage technology. Cui et al. [13] used Monte Carlo method to analyze the economy of a conventional non direct expansion photovoltaic photothermal heat pump system with the help of software. The results show that the solar heat pump system has economic benefits and return on investment. Ozcan et al. [14] conducted advanced analysis on photovoltaic air source heat pump with battery energy storage, studied the mechanism of available power loss of the system from the perspective of the second law of thermodynamics, and provided guidance for energy conservation.

It can be seen that photovoltaic photothermal coupled heat pump technology is a feasible technology to realize zero emission of building energy consumption, and has a good development prospect. Based on this technology, according to the climate conditions in Tianjin, China, a zero-carbon energy system suitable for single family villas is proposed, and the performance of the system is evaluated by TRNSYS software.

2. LCPV/T COUPLED HEAT PUMP COGENERATION SYSTEM

2.1 Villa model introduction

In this paper, TRNSYS software is used as the simulation platform, and the building model is completed by TRNBuild module in TRNSYS. TRNBuild is used to build the building load model. Table 1 shows the villa model parameters. The villa building model has a set area of about 300 m2, including six areas: living room, master bedroom, secondary bedroom, bathroom, study and kitchen.

Table 1 Villa model parameters

Parameter	Numerical	Unit
Total area	300.40	m^2
Roof area	100	m^2
Living room area	104.13	m^2
Main bedroom area	50.4	m^2
Secondary bedroom area	41.07	m^2
Bathroom area	22.68	m^2
Study room area	45.6	m^2
Kitchen area	36.72	m^2
External wall heat transfer coefficient	2.815	W/(m^2·°C)
Internal wall heat transfer coefficient	0.652	W/(m^2·°C)
Floor heat transfer coefficient	0.313	W/(m^2·°C)
Air density	1.204	kg/m^3
Air specific heat capacity	1012	J/(kg·°C)
Air pressure	101,325	Pa
External window total area	90	m^2
External window heat transfer coefficient	5.68	W/(m^2·°C)
External window shading coefficient	0.20	W/(m^2·°C)
Computer power	300	W
Computer quantity	3	-
Personnel load	130	W
Number of persons	4	-

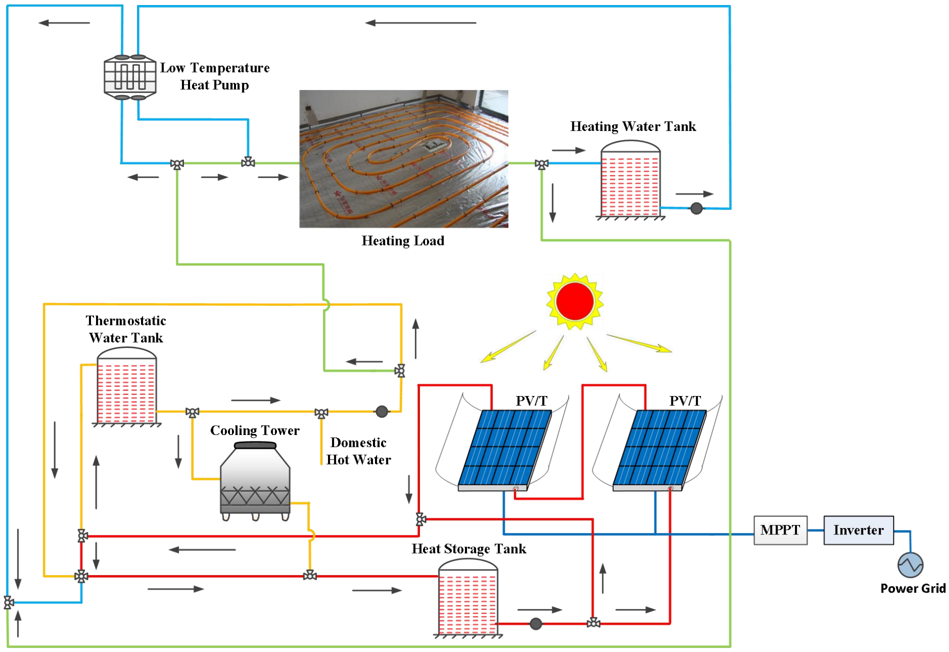

Fig 2 LCPV/T heat pump coupled cogeneration system of villa

2.2 LCPV/T and heat pump coupling system

The diagram of LCPV/T coupled heat pump cogeneration system is shown in Fig. 1. The system consists of four subsystems: LCPV/T subsystem, water source heat pump subsystem, heat dissipation terminal system and data test subsystem. LCPV/T subsystem includes PV/T module and CPC concentrator. PV/T receives solar irradiation and outputs electric energy and thermal energy. LCPV/T parameters are shown in Table 2. The water source heat pump subsystem adopts the traditional compressed water-water heat pump (WWHP), which is composed of evaporator, compressor, four-way valve, water pump and condenser. The water source heat pump system operating under the traditional mode has strict requirements for water quality and quantity. Therefore, the selected area of water source heat pump needs to have enough water, which limits the popularization and application of water source heat pump. However, in the LCPV/T coupled water source heat pump cogeneration system, the cooling water is continuously heated by solar energy and used as the heat source of evaporator to realize the closed circulation of water source, eliminate the restrictions on water quantity and quality, and significantly improve the cop of water source heat pump. The end heat dissipation device adopts capillary network, which is arranged below the surface of the room maintenance structure, and meets the requirements of comfort, space saving and energy saving.

Table 2 LCPV/T parameters

Parameter	Numerical	Unit
Total area of photovoltaic cell	60	m^2
PV/T panel area	0.9734	m^2
Specific heat capacity of fluid	4190	J/(kg·°C)
PV/T plate absorption rate	0.92	-
Number of glass covers	1	-
PV/T plate emissivity	0.09	-
Loss coefficient of bottom and edge	0.3	$W/(m^2\cdot°C)$
Absorption transmittance	0.9	-
PV panel temperature coefficient	0.0032	1/°C
CPC concentration ratio	4	-

When the system is running, the water in the heat storage tank is driven by the circulating pump to flow to the LCPV/T module and take away the heat. Then it is collected in front of the diverter valve and enters the constant temperature water tank or returns to the heat storage water tank to participate in the circulation again. The hot water in the thermostatic water tank is used for building heating and domestic hot water. The room temperature controller automatically adjusts the system operation mode according to the building temperature. The clean electric energy generated by PV cells is used for the power consumption of villa household appliances, air conditioning refrigeration and heat pump after inverter, and the excess electricity is input into the power grid for profit.

2.3 System evaluation index

The thermal performance of the proposed LCPV/T coupled heat pump cogeneration system is evaluated. Assuming that the system is in a stable state, ignoring the potential energy and kinetic energy of the system and ignoring the chemical reaction, the energy balance equation is established. Energy analysis is an analytical method based on the first law of thermodynamics. This method can evaluate how energy is consumed, and then determine a more effective integration mode of the system. The energy and efficiency of low power concentrating PV / T subsystem are calculated as follows:

$$E_{PV} = U_m * I_m \tag{1}$$

Where E_{PV} is the power generated by the LCPV/T subsystem, U_m represents the voltage generated by the photovoltaic cell, I_m represents the current of the photovoltaic cell.

$$Q_{th} = V_L \rho c (T_{L,out} - T_{L,in}) \tag{2}$$

Q_{th} represents the heat generated by the low power concentrating PV / T subsystem, V_L represents the volume flow of LCPV/T, ρ (kg / m^3) represents the density of water, and c (J/ kg ·°C)) represents the specific heat capacity, $T_{L,in}$ and $T_{L,out}$ respectively represent the inlet and outlet temperature of cooling water. The subscript L represents the LCPV/T subsystem, and the subscripts in and out represent the inlet and outlet respectively.

$$\eta_e = \frac{E_{PV}}{CGA_{PV}} = \frac{U_m * I_m}{CGA_{PV}} \tag{3}$$

$$\eta_{th} = \frac{Q_{th}}{CGA_{PV}} = \frac{V_L \rho c (T_{L,out} - T_{L,in})}{CGA_{PV}} \tag{4}$$

$$\eta_{all} = \eta_e + \eta_{th} \tag{5}$$

Among them, η_e,η_{th} and η_{all} represent the electrical efficiency, thermal efficiency and total efficiency of the LCPV/T subsystem respectively. C represents the condensing ratio of the concentrator. In this system, C = 4. G represents the solar irradiation intensity, A_{PV} is the effective photovoltaic cell area.

Coefficient of performance (COP) is an important evaluation index of water source heat pump subsystem. Use formula (6) to calculate the COP value of water source heat pump subsystem:

$$COP_{HP} = \frac{Q_c}{W_{HP}} = \frac{Q_c}{Q_c - Q_e} \tag{6}$$

Where W_{HP} is the instantaneous power consumption of compressor, Q_e is the transient heat of evaporator circulating water, Q_c is the circulating water heat of the condenser.

3. RESULTS

The installation area of photovoltaic modules is 99m^2. Taking the real weather data in Tianjin as the analog input value, the changes of main indexes of LCPV/T coupled heat pump system in the whole year are calculated.

The annual electric power and thermal power of LCPV/T system are shown in Fig. 2 and Fig. 3. The annual maximum electric power can reach about 30kW and the maximum thermal power can reach about 220kw. By comparing the two figures, it can be found that the trend of heat and power production is basically the same. The power generation capacity and heat generation capacity of LCPV/T system are directly affected by the direct solar irradiation.

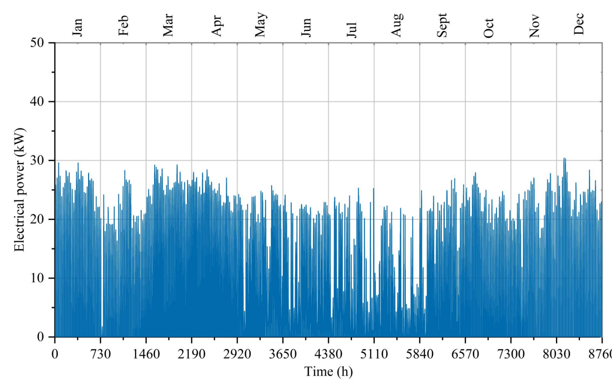

Fig. 2 Annual electric power of LCPV/T system

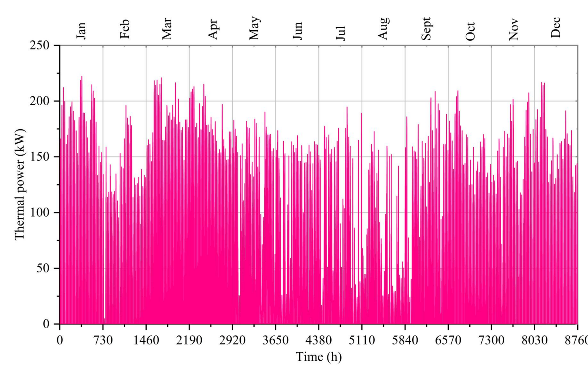

Fig. 3 Annual thermal power of LCPV/T system

The monthly electricity and heat production throughout the year are shown in Fig. 4. It can be seen that the change trend of thermal power output is basically the same. The heat and power generation are high in three months in spring, and the heat and power generation are not significantly affected when the temperature is low in winter. The data show that LCPV/T system can improve the comprehensive utilization

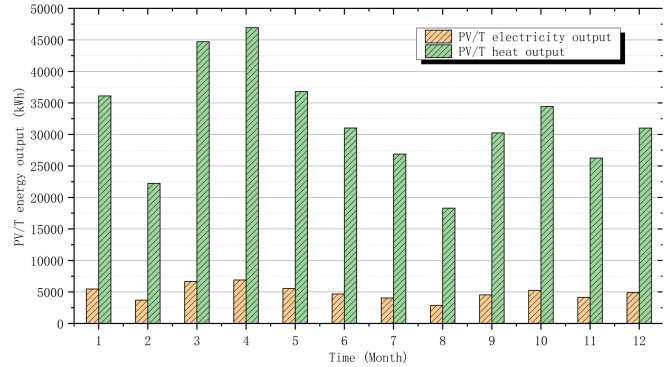

Fig. 4 Monthly power and heat production of LCPV/T system throughout the year

efficiency of the whole system. The power generation of LCPV/T system can fully meet the annual power load of the villa. The villa has heating demand from October to April of the next year, of which the building heat load reached 6400kwh in December, and the system can fully meet the building heating load throughout the year. Therefore, the solar cogeneration system designed in this paper for villa buildings can realize load matching and meet the diversified needs of users, whether from the perspective of the power load of the system itself or the matching of the heat load borne by the system.

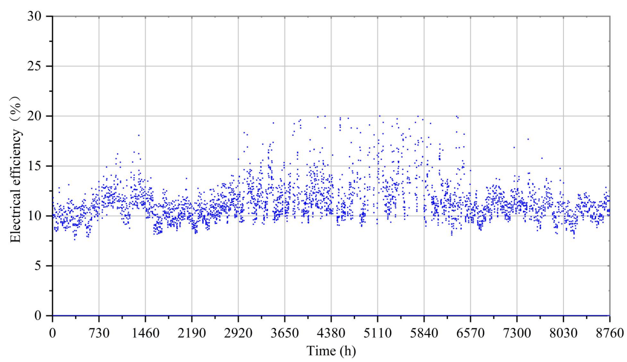

Fig. 5 Annual electric efficiency of LCPV/T system

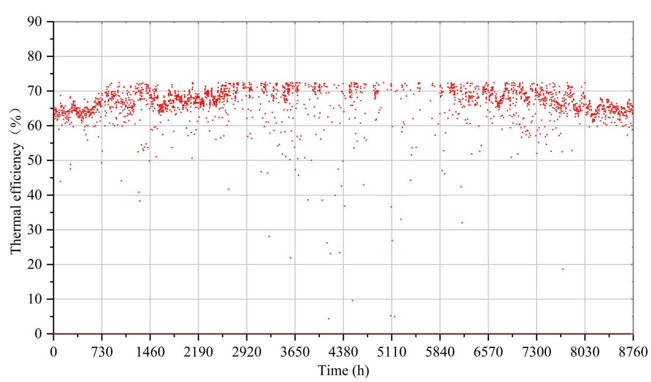

Fig. 6 Annual thermal efficiency of LCPV/T system

The annual thermal efficiency and electrical efficiency of LCPV/T system are shown in Fig. 5 and Fig. 6. The electric efficiency fluctuates around 12%, up to 20%, and there are many days with high electric efficiency in summer; The thermal efficiency varies in the range of 60-70%, which is higher in summer and lower in winter; The comprehensive utilization efficiency of solar energy varies in the range of 70-82%. In the heating mode, the auxiliary equipment is low-temperature water source heat pump. From the operation stage of low-temperature water source heat pump, the cop can reach 4 at most and fluctuate in the range of 2-4. During the operation of heat pump, the outlet water temperature at the load side is maintained above 40 °C, which can meet the needs of building heating heat load. This coupling mode can make rational use of low-temperature heat source and play obvious energy-saving effect.

4. CONCLUSIONS

According to the cogeneration characteristics of LCPV/T module, a non-direct expansion solar heat pump cogeneration system based on LCPV/T technology and water source heat pump technology is established in this paper. Taking the real weather data in Tianjin as the input, the villa energy supply system with an area of 300m2 is simulated and analyzed by using TRNSYS software. The main conclusions are as follows:

(1) The average electrical efficiency of LCPV/T system is about 12%, up to 20%, the average thermal efficiency of PVT module is 65%, and the comprehensive utilization efficiency of solar energy of module is as high as 75%.

(2) Through simulation calculation, the cop of heat pump is between 2-4, and the energy-saving attribute of the system is obvious.

(3) The simulation results show that the PV/T coupled heat pump cogeneration system can fully meet the power load of the villa and the heating heat load demand from October to April, and realize the self-sufficiency of energy consumption in quantity.

(4) The investment cost and income of the system are evaluated. The annual net income of the system is about 2816.1 yuan, with an investment payback period of about 9 years. After cost recovery, the system can continue to bring economic benefits for many years.

In terms of total energy consumption, LCPV/T coupled heat pump system can fully meet the power demand and heat load of the villa. In cloudy and rainy days, the power grid can be directly used to supply energy to the villa, and in the weather with sufficient radiation, the excess power can be connected to the grid for profit, so as to achieve the goal of zero carbon energy supply for the villa.

ACKNOWLEDGEMENT

This work was supported by the project "(KJ21-1-19) Research on Key Technologies of distributed solar cogeneration integrated energy system" of Tianjin Electric Power Research Institute.

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