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Dynamic Simulation of a Novel Solar Heating System Based on Hybrid Photovoltaic/Thermal Collectors (PVT)

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Abstract

In this paper, the authors aim at improving the knowledge on this topic presenting a dynamic model of a solar heating system based on PVT technology. With respect to the papers mentioned above, the layout proposed includes all the components required for operating the sys-tem. The TRNSYS simulation platform of the PVT cogeneration heating system has been established for researching the system performance of PVT solar cogeneration heating system. The inlet and outlet temperature, the electrical power output of PVT collector, heat consumption, outlet temperatures of auxiliary heat source and outlet temperatures of heat storage tank of PVT collector have been studied in this paper. The results of this investigation may be summarized as follows. The PVT collector 32m^2 in size in the system can achieve annual power output of 131kWh electric energy. The heat gain of heat collector system between 12 am and 6 pm on the typical day， when the auxiliary heat source is not turned on can meet the load demand. Indoor temperature varies between 16.3~19.5℃ on the typical day, fluctuation of indoor temperature s impacted by outdoor ambient temperature and solar radiation. The entire heating season that the solar fraction of this solar heating system is 31.7%, which is close to the design value of 30%.

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Keywords: Solar heating system; Hybrid photovoltaic/thermal collector; Trnsys; Dynamic simulation

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1. Introduction

Along with the increasing seriousness problem of environmental pollution and energy shortage, the application of renewable energy is attracted more and more attention by researchers around the world. As a kind of renewable energy sources, solar energy can offers a technical solution to generate electricity and heat in solar panels and/or photovoltaic-thermal panels. However, the relatively low efficiency limits the development of the photovoltaic panels, especially for areas that don't have high solar potential. As we all know that, the temperature of the cell affects the electricity generation of the photovoltaic panels, cell cooling was proposed as a solution in the photovoltaic-thermal panels (PVT). Thus, both electricity and heat are obtained. Air and water are considered as the fluids heated in the PVT collectors and which can be used for space heating or in the industrial application.

In recent years, there are numerous researches on the detailed analytical and experimental studies of PVT panels in different countries, intended to find out the solutions for increasing the efficiency of these panels. Vries [1] designed a PVT combi-panel through three thermal models, the experimental results showed that the single-covered basic combi-panel is to be preferred compared to the uncovered combi-panel and double covered combi-panel. Further-more, by increasing the heat transfer coefficient of the adhesive layer between cells and absorber could increase the electrical and thermal efficiencies. Zondag et al [2] developed a mathematical model with seven different design types to find out the best performance for the electrical and thermal efficiency. The conclusion of experimental results was that the PV-on-sheet-and-tube design in a solar heating system is a good choice, which is easier to construct. Tiwari et al. [3] studied introduced different configurations of PVT system from the thermal and electrical points of view, which included air collectors and water heaters. Boubekri et al. [4] developed a mathematical model to test the electrical performance of a collecting hybrid PV/T water collector. The results showed the overall efficiency of the collector was effected by the inclination angle, the flow mass rate of water and the conduction heat transfer coefficient in the adhesive layer. Radziemska [5] proposed one model for the performance analysis of hybrid PV/T integrated system, based on the energy and exergy transfer analysis. Because in this system the production of electricity is the main priority, it is necessary to operate the PV modules at low temperature, which diminishes the value of the harvested heat. In this case the exergetic efficiency is very small. Kalogirou et al. [6] simulated the industry of PV/T systems with water heat extraction in three cities with different latitudes. The results showed that while the electricity generation is higher for polycrystalline so-lar cells, the thermal contributions are slightly higher for amorphous solar cells. Chow [7], reviewed the trend for the technology development of flat-plate PVT collector systems for building-integration installations. The concentrator-type PVT could be suitable for medium to high-temperature hot water systems. Adnan et al. [8] also researched several types of flat plate PV/T collectors from the design and performance points of view. They point out that the flat plate PV/T solar collectors will be developed for building integrated applications in the near future. A three dimensional heat transfer model was designed for the Active Solar Panel Initiative System (ASPIS) to validate the prediction of component temperatures for concentrating photovoltaic systems [9]. Mishra et al. [10] estimated an integrated IPVTS system based on basic energy balance for various configurations with constant collection temperature. It was concluded that the energy gained from the IPVTS systems decreases with the increasing the temperature of constant collection. On the other hand, decreasing the collector area covered by the PV module will increase the thermal energy gain. Caluianu et al. [11] designed a two-dimensional steady-state thermal model of a photovoltaic module, the experimental results showed that the interaction of boundary layer would effect on the profiles of velocity and temperature of the air at the exit section, and velocity and temperature would change along with the increase of the channel width.

During the research, the authors given the schematic diagram of heat supply system in the PVT cogeneration heating system, shown the simulation flow chart of PVT solar cogeneration heating system by TRNSYS simulation platform. The inlet and outlet temperature of PVT collector working fluid, the electrical power output of PVT collector, heat consumption, outlet temperatures of auxiliary heat source and outlet temperatures of heat storage tank with outdoor ambient temperature, the floor surface temperature and radiant floor coil inlet/outlet temperature with outdoor temperature have been studied in this paper.

2. System description

PVT cogeneration heating system is a combination of photovoltaic (PV) and hot water systems. As the battery cooling system of the PVT system collecting low grade heat energy, which was wasted, on PV modules while increasing power generation rates of the modules, it makes the cascaded utilization of energy come true and enhances the efficiency of the energy utilization. Figure 1 shows the schematic diagram of PVT cogeneration heating system. Principles of the system are as follows: the system adopts forced cooling mode to lower the temperature of PV panels, and enhance the photoelectric conversion efficiency of PV cells, and uses the thermal energy obtained as radiant heating source of the indoor floor. Given the intermittent characteristic of solar energy, the system adopts auxiliary heat source (electric heating) to ensure the normal operation of the heating system. Solar photoelectric conversion sys-tem, on the other hand, converts DC to AC via inverter, and boosts voltage to grid voltage, then accesses the electric energy boosted to standard voltage to the power grid via grid controller. To ensure the stability of power system operation, the system also achieve automatic switching between self-generated electricity and grid electricity.

Schematic diagram of heat supply system in the PVT cogeneration heating system is shown in Figure 1.

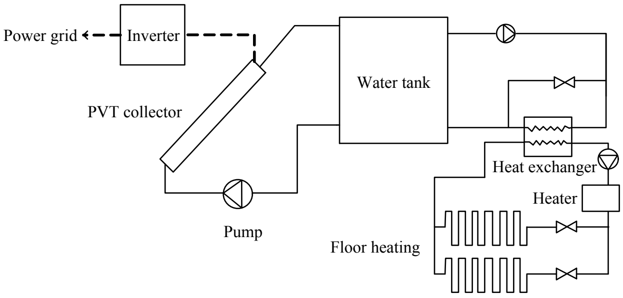

Fig. 1. Schematic diagram of heat supply system in the PVT cogeneration heating system.

Operating condition 1: during sunny winter daytime, PVT collector absorbs solar radiation to heat up the cold water in heating tank. Hot water in the heating tank can heat up the domestic hot water tank, when the temperature reaches the set value, the domestic water tank can sup-ply domestic hot water outward. Hot water used for heating enters the radiant floor coils by the action of heating circulating water pump, then the return water of heating system enters the bottom of heat storage tank, and this cycle repeats.

Operating condition 2: during night time or rainy days when there is no solar radiation, the col-lector stops working, and the heat storage tank directly supplies indoor heating. When the out-let water temperature of heating water tank cannot meet the heating needs, the electric heater at the heating water supply pipe is able to turn on to supplement heat.

Operating condition 3: during non-heating seasons, PVT collector stores the heat energy converted from the collected solar radiation in the heat storage tank, and the valve at the supply and return water of heating system is turned off. Hot water supply system operates normally, when the water temperature rises to a certain value, it starts to supply domestic hot water.

3. Simulation platform

Figure 2 shows the simulation flow chart of PVT solar cogeneration heating system. Modules in the TRNSYS model include input modules, output modules and specific modules. An In-put module consists of typical meteorological year reader (Type15-3) and building simulator (Type56), which are non-standard readers that can read specific loadable external information files from the logical unit numbers (external file). Among them, Type56 is able to establish the maintenance structure according to user needs as well as taking into consideration of cold air infiltration, personnel and equipment loads, etc. Output modules consist of data printer and real-time plotter, the former can export all data in forms of Excel, and the latter can carry out real-time plotting. In this systemsimulation, specific modules include PVT collector, heat storage tank, auxiliary heat source and radiant floor heating. Special modules in this systemare analyzed below.

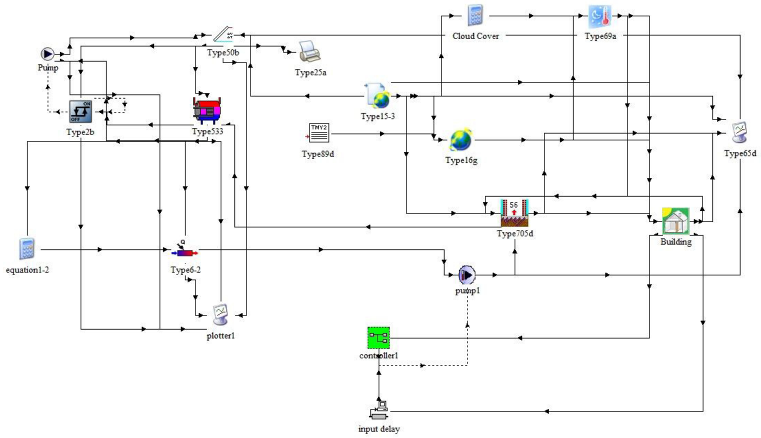

Fig. 2. Special modules.

3.1. PVT collector

PVT collector (Type50), whose performance determines the operation status of the entire sys-tem, is the most important component in solar systems. Type50 is composed of conventional flat plate collectors (Type1) and PV panels. As to photothermal part, heat collecting efficiency of the collector is calculated based on Hottel-Willer equation, and is expressed in the form of linear equation. Eq.1 is its efficiency expression.

$$\eta = (\tau\alpha)_{\mathrm{e}} - U_{\mathrm{L}} \frac{\left(T_{\mathrm{p}} - T_{a}\right)}{G_{t}} \tag{1}$$

Where T_p is the temperature of PV rear panel, ℃; T_a is the ambient temperature, ℃; G_t is the solar radiation value, W/m^2; $(\tau\alpha)_e$ is the effective product of transparent cover transmittance and absorption; and U_L is the total heat loss coefficient of collectors, W/m^2·K.

As to the photoelectric part, the maximum power point of PV cell under a certain amount of solar radiation and temperature should be determined first. PVT photovoltaic efficiency is defined as: the ratio of electric energy output by unit PV cell area to the incoming solar irradiance, that is

$$\eta_{\mathrm{e}} = \frac{Q_{\mathrm{e}}}{A_{\mathrm{c}} G_{\mathrm{t}}} = \eta_{\mathrm{ref}} \left[1 - \theta_{\mathrm{pv}} \left(T - T_{\mathrm{ref}}\right)\right] \tag{2}$$

Where A_c is the cover area of PV cell, m^2; Q_e is the output electric power, W; η_{ref} is the maximum power point of PV generation, which is set as 12%; θ_{pv} is the temperature coefficient of PV cell, which is set as 0.32%/K; T is the operating temperature, which is set as the panel center temperature; and T_{ref} is the standard operating temperature, which is set as 25℃.

3.2. Heat storage tank

Heat storage tank Type4 is used to simulate the part of temperature stratified heat storage tank. Studies have shown that the combination of temperature stratified heat storage tank to solar collector system can effectively enhance the efficiency of the system. The model considers the energy release during fluid flow, but ignores the loss of this process. The temperature of each node in the tank can be obtained by unsteady energy balance equation. Energy balance equation for the i-th layer is

$$M_i C_p \frac{dT_i}{d\vartheta} = \alpha_i M_H C_p \left(T_H - T_i\right) + \beta_i M_L C_p \left(T_L - T_i\right) + U_s \left(T_a - T_i\right) + \Gamma_i \tag{3}$$

Where T_H is the tank top temperature, ℃; T_L is the tank bottom temperature, ℃; T_i is the i-th layer tank temperature, ℃; U_s is the total heat loss of heat storage tank, W/(m^2·K); M_H is the tank top inlet flow, kg/s; M_L is the tank bottom inlet flow, kg/s; and M_i is the i-th layer tank flow, kg/s.

When $\gamma_i > 0$, $\Gamma_i = \gamma_i C_p \left(t_{i-1} - t_i\right)$; and when $\gamma_i < 0$, $\Gamma_i = \gamma_i C_p \left(t_i - t_{i+1}\right)$. Values of parameters α_i and β_i are related to the location of the i-th layer tank. When i represents the tank top, α_i is taken as 1; otherwise, $\alpha_i = 0$. In contrast, when i represents the tank bottom, β_i is taken as 1; otherwise, $\beta_i = 0$. Control function γ_i can be expressed as

$$\gamma_i = M_H \sum_{j=1}^{i-1} \alpha_j - M_L \sum_{j=i+1}^{N} \beta_j \tag{4}$$

The nodes are intermixed and the extent of intermixing is related to the collector flow, load flow, as well as the size of instantaneous value of control function.

3.3. Auxiliary heat source

Auxiliary heat source Type6 is an essential component in solar systems, which is used to ensure the 24-hour operation of the entire system, especially when solar energy is insufficient. Startup of auxiliary heat source can be controlled by internal or external controller. When the inlet temperature of the auxiliary heat source is lower than the set temperature T_{set} of the system, Type6, which heats up the outlet temperature to T_{set} value, can be within the maximum power range.

When the inlet temperature of auxiliary heat source is higher than T_{set} value, then $T_i = T_o$, $Q_{max} = 0$.

Otherwise, when the inlet temperature of auxiliary heat source is below T_{set} value, auxiliary heat source outlet temperature T_o can be written as

$$T_o = \frac{\left(Q_{\max}\eta_{aux} + M_i C_{pf} T_i + U_{aux} T_a - \frac{U_{aux} T_i}{2}\right)}{\left(M_i C_{pf} + \frac{U_{aux}}{2}\right)} \tag{5}$$

Where Q_{max} is the maximum heating power of auxiliary heat source, W;   is the auxiliary heater efficiency; T_a is the ambient temperature, ℃; T_i is the working fluid inlet temperature, ℃; U_{aux} is the total heat loss coefficient, W/(m^2·K); and M_i is the working fluid inlet mass flow, kg/s.

3.4. Radiant floor coils

Radiant floor coil module Type705d is a module simulating floor coil performance which is used in combination with the building model simulator Type56. Type56 can build retaining structure including walls, windows, floors and roofs according to user needs, and it allows users to add layer materials and corresponding thickness of each layer in the retaining structure freely. Meanwhile, it can take into account cold air infiltration, personnel and equipment loads, etc. Radiant floor module Type705d can be added in the floor when the retaining structure is added with active layer. The module can calculate the heat gain in the room based on the radiant tube diameter, spacing, working fluid inlet temperature and flow. Type56 is a non-standard reader that can read specific building information files (building.bui) from the logical unit numbers (external file).

4. Results and discussion

Through the PVT solar cogeneration heating system simulation platform built based on TRNSYS in the preceding section, the operating status of the system in typical rural residence in a township is simulated and analyzed.

Figure 3 shows the change graphs of solar radiation and ambient temperature over entire heating season (from October 15th to March 15th). For solar PVT systems, major environmental parameters influencing the system are the amount of solar radiation and ambient temperature. In TRNSYS system, the required meteorological data are read in by typical meteorological year (EPW) reader Type15; then meteorological graphs are generated through real-time plotter Type65.

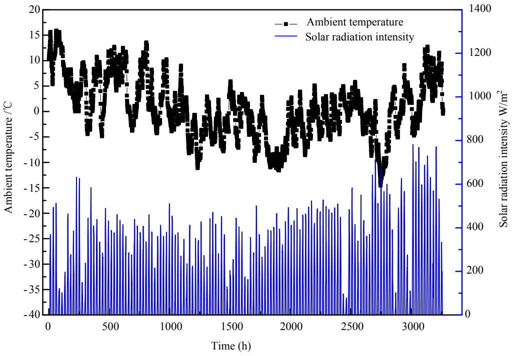

Fig. 3. Change graphs of solar radiation and ambient temperature in heating season.

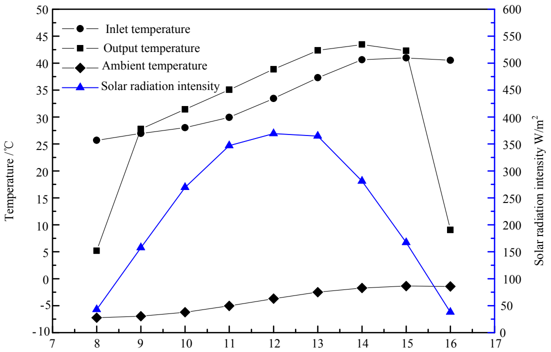

Fig. 4. Graphs of inlet and outlet temperature of PVT collector working fluid with solar radiation intensity.

Figure 4 shows the change graphs of inlet and outlet temperatures of PVT collector working fluid with solar radiation intensity and ambient temperatures on a typical day within heating season. As can be seen from the figure, on the typical day, average outdoor temperature is -4.6℃, and highest solar radiation intensity approaches 370 W/m^2, difference in inlet and outlet temperature of working fluid within PVT collector increases with the increase in solar radiation intensity, maximum difference in inlet and outlet temperature appears at 12 am, which reaches 5.42℃. It is worth noting that when the low solar radiation is less intense, after water flows through the collector, the collector dissipates heat to the environment as it is unable to gain more heat, resulting in a situation where working fluid inlet temperature is higher than the outlet temperature.

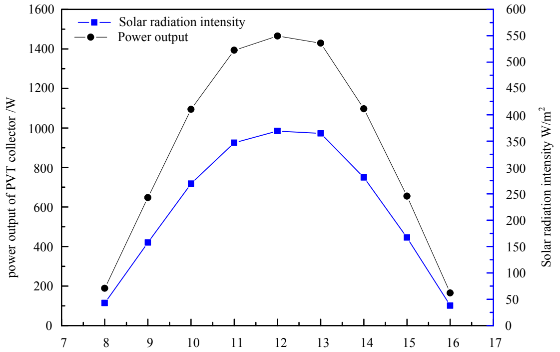

Fig. 5. Changes in electrical power output of PVT collector.

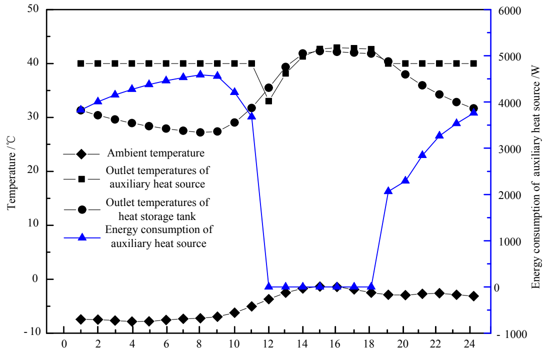

Fig. 6. Graphs of heat consumption, outlet temperatures of auxiliary heat source and outlet temperatures of heat storage tank with outdoor ambient temperature.

After preliminary design calculations, PVT collector area is finalized as 32m^2 for this system. Figure 5 shows the changes in electrical power output of PVT collector. The impact of solar radiation intensity on PVT collector power output can be seen from the figure, the output power of PVT collector increases with the increase in solar radiation intensity. At 12 am, solar radiation intensity is about 370W/m^2, and the output power of PVT collector array reaches a maximum of about 1465W, which is equivalent to maximum unit area PVT collector output power of 45W.

It can be seen from the results of the full-year operating trend simulation in the system that the PVT collector 32m^2 in size in the system can achieve annual power output of 4,077,601W, i.e. 4,195kWh, which means that the unit square meter of PVT collector can output 131kWh electric energy yearly.

Figure 6 shows the changes in heat consumption, outlet temperature of auxiliary heat source, and the outlet temperature of heat storage tank in the heat collector system along with changes in outdoor ambient temperatures. As can be seen from the figure, startup of auxiliary heat source is consistent with the changes in outdoor ambient temperatures. When ambient temperature is higher, temperature of working fluid in the heat storage tank would meet the load demand, and startup of auxiliary heat source is unnecessary. Auxiliary heat source startup is opposite to the changes in solar radiation intensity; when solar radiation value is higher, heat storage tank would get more heat, so there is no need to start up auxiliary heat source. It can be found that the heat gain of heat collector system between 12 am and 6 pm on the typical day，when the auxiliary heat source is not turned on can meet the load demand. At rest times, heating with auxiliary heat source is needed according to the temperature of working fluid in the heat storage tank.

Figure 7 shows the graphs of floor surface temperatures, and inlet and outlet temperatures of radiant floor coil in the simulation building with the outdoor temperatures. Floor heating system in the system adopts intermittent operation mode, and design indoor heating temperature is 18℃. PID controller determines the output signal of heating water pump through the set value of temperature and monitoring of indoor temperature, and thereby meets the set requirements on indoor temperature. As can be seen from the figure, indoor temperature varies between 16.3~19.5℃ on the typical day, fluctuation of indoor temperature is impacted by outdoor ambient temperature and solar radiation. Highest value of indoor temperature appears at 14 pm, while the lowest value occurs at 6 am, indoor temperature basically meets the requirements. Floor surface temperature varies between 23~25℃, heat dissipating capacity per unit area of floor can reach up to 50W/m^2.

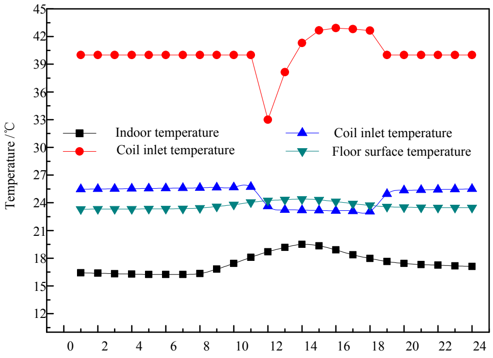

Fig. 7 Graphs of floor surface temperature and radiant floor coil inlet/outlet temperature with outdoor temperature.

It can be found through the analysis of simulation results of the entire heating season that the solar fraction of this solar heating system is 31.7%, which is close to the design value of 30%. This further illustrates the rationality of the present system design.

5. Conclusions

In this paper, the TRNSYS simulation platform of the PVT cogeneration heating system has been established for researching the system performance of PVT solar cogeneration heating system. The inlet and outlet temperature, the electrical power output of PVT collector, heat consumption, outlet temperatures of auxiliary heat source and outlet temperatures of heat storage tank of PVT collector have been studied in this paper. The results of this investigation may be summarized as follows.

(1) It can be seen from the results of the full-year operating trend simulation in the system that the PVT collector 32m^2 in size in the system can achieve annual power output of 4,077,601W, i.e. 4,195kWh, which means that the unit square meter of PVT collector can output 131kWh electric energy yearly.
(2) Indoor temperature varies between 16.3~19.5℃ on the typical day, fluctuation of indoor temperature is impacted by outdoor ambient temperature and solar radiation.
(3) It can be found through the analysis of simulation results of the entire heating season that the solar fraction of this solar heating system is 31.7%, which is close to the design value of 30%.

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