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Dynamic performance analysis of façade-integrated tri-functional photovoltaic/thermal solar collector

Dynamic performance analysis of façade-integrated tri-functional photovoltaic/thermal solar collector

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Abstract. Research on building-integrated photovoltaic/thermal (BiPV/T) technology has been conducted for years because the system can provide electric power and thermal energy simultaneously. A façade-integrated tri-functional PV/T collector system is presented and studied in this paper. The collector can work in PV/water-heating mode or PV/air-heating mode. Besides, it can also work in the composite mode that air and water be heated simultaneously. So optimum work mode of the collecor can be chosen for different energy demands. The collector can be combined with the southern wall of building, then it operates as PV-Trombe wall for passive room heating and electricity generation in winter, and for domestic water heating and electricity generation in other seasons. For the different working modes, theoretical research is carried out and dynamic model of the collector and building are developed. Based on the models, the performance of collector and the thermal behavior of the room are investigated under different climates conditions.

Keywords: photovoltaic/thermal collector; tri-functional; composite heating

1. Introduction

Passive air heating system can provide heat for a building interior by air natural circulation and has been researched and used widely due to the advantage of easy operation, easily combining with the building and its low cost [1]. The passive heating solar system combined with buildings has various forms, such as the traditional Trombe wall [2], PV-Trombe wall [3], Barra-Costantini wall improved by adopting metal panel [4] and Trombe wall system with solar air collectors [5] et al. Passive air heating system can reduce energy consumption for space heating in winter, but it has no significant effect in other seasons or even causes the buildings overheat during summer days [6]. It was found that after water tubes were attached to the rear surface of the absorber, the solar energy absorbed by the absorber plane could be removed by the water flow in the tubes and then the building overheating problems can be alleviated or even solved [7]. A dual-function solar collector can work in both air and water heating modes has been mentioned, and the thermal performance under different operating modes has been investigated [8].

Now a novel tri-functional PV/T solar collector is presented in the present study. The design of this collector is based on the sheet-and-tube solar water collector and single pass flat plat PV/T air collector. In order to apply this novel tri-functional PV/T solar collector to real life, what we going to do is simulation to confirm the feasibility of this collector in the building and how to integrate the tri-functional PV/T solar collector with building.

2. The introduction of theoretical model

2.1. Structure of the system

A virtual building that the indoor temperature can be control based on the general practical architectural features was designed. The room is of the dimension of 3.6 m×4.8 m×2.8 m. The structure of the tri-functional PV/T solar collector consists of the following components: glass cover, Polycrystalline silicon photovoltaic cells, Aluminium plate, Copper tubes, air inlet, air outlet, and the insulation layer. The illustrative diagrams of the building -integrated dual-function solar collector system is presented in figure 1. The PV cells are packaged and attached to the absorber plate with a packing factor of 0.59. The effective irradiation-collector area of the collector is 1.95 m × 0.91 m and the cell area is 1.05 m2. The PV panel consists of 72 pieces of cells and the rest of the absorber plate is covered by black painted surface.

Between the glass cover and the PV cells, there is an air gap to reduce the heat loss from upper surface. Copper tubes are welded at the bottom of the absorber plate. The air flow is of the dimension of 194 cm (length) × 93 cm (width) ×2 cm (height). The backboard is composed of 2 cm glass fibre along with iron plates for both inside and outside of the channel sides. Two opening vents with dimension of 36 cm × 12 cm are positioned at the top and bottom of the blackboard of the module for the air heating mode of the collector. In PV/air-heating mode, the collector is connected to a ventilation system and both ends of the copper tubes are closed. While in PV/water-heating mode, the inlet and outlet of the air flow channel are closed and a water tank is connected.

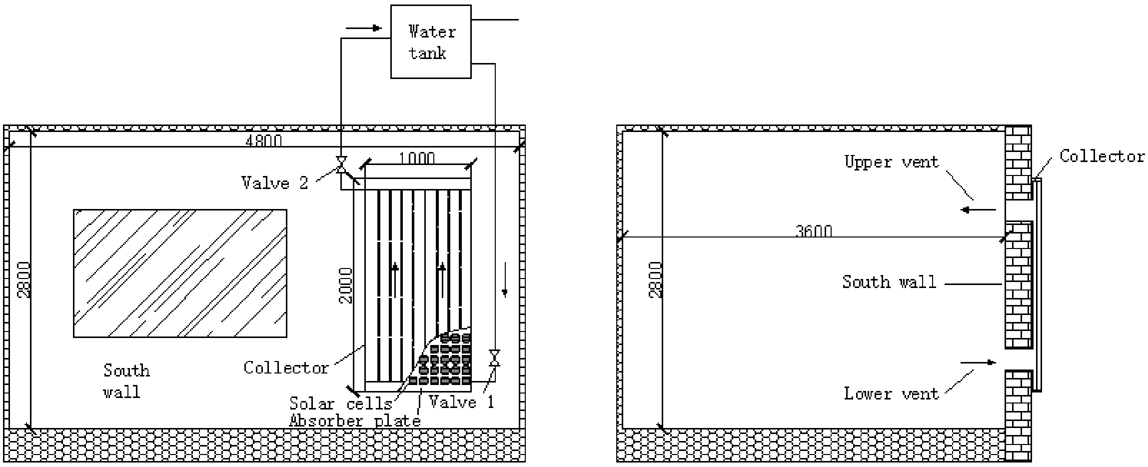

Figure 1. Illustrative diagrams of the building-integrated solar collector system.

2.2. Theoretical model of the building room

The envelop of the building is consisted of brick, and the thickness is 0.24 m, thermal conductivity is 0.84 W/(mK), specific heat is 835 J/kg K, density is 1920 kg/m^3. Absorptivity of the outside surface of the southern wall is 0.58. There is a window on the south wall which is of the dimension of 2.0 m (length) ×1.2 m (height). The solar radiation transmittance of the curtain is set to 0.3. A passive tri-functional photovoltaic/thermal solar collector module is installed on the outside of the southern wall. The depth of the air channel in the collector is 0.04m. The indoor temperatures in winter and summer are set to 18℃and 23℃. In the winter heating mode, indoor temperature is controlled as not lower than 18℃.

The heat flux through walls of the building envelope is determined by one-dimensional along its thickness, so the energy balance equation of the wall is given as

$$\rho_w c_w \frac{\partial T_w}{\partial t} = k_w \frac{\partial^2 T_w}{\partial x^2} \tag{1}$$

2.3. The theoretical model of the PV /passive air-heating mode

The essential components of the collector are the glass cover, backboard and the absorber plate. Under the assumption that the temperatures of the glass cover, absorber, and the back plate vary only in the direction of air flow, the energy equations were established. The temperatures of the air stream and essential components can be obtained by solving the equations. The scheme of heat transfer of the components of the collector is shown in Figure 2.

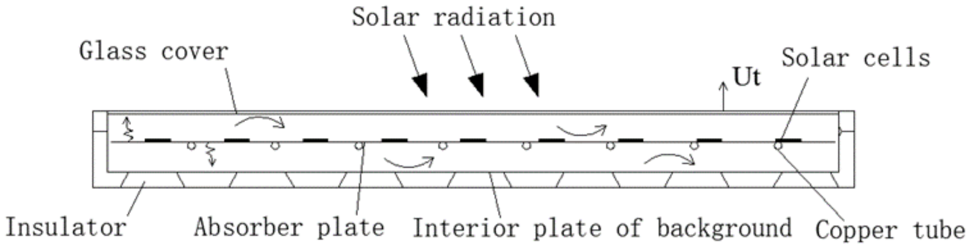

Figure 2. The schematic diagram of heat transfer process of PV/air heating.

The energy equation of absorber plate:

$$\rho_p c_p d_p \frac{\partial T_p}{\partial t} = k_p d_p \frac{\partial^2 T_p}{\partial z^2} - (hc_{pg} + hr_{pg})(T_p - T_g) - hc_{pf}(T_p - T_f) - (T_p - T_{pv}) + \alpha_p \tau_g S - \xi E_{pv} \quad (2)$$

The energy equation of air in the flow channel:

$$\rho_f c_f d \frac{\partial T_f}{\partial t} = \rho_f c_f u d \frac{dT_f}{dz} + hc_{pf}(T_p - T_f) + hc_{bf}(T_b - T_f) \quad (1)$$

2.4. The theoretical model of the PV /water-heating mode

The energy equation of water in the flow channel:

$$\frac{\dot{m} C_p}{w} \frac{dT_f}{dx} = hc_{pf}(T_p - T_f) + hc_{bf}(T_b - T_f) \quad (4)$$

2.5. Numerical Approaches

As a result of finite difference method, the energy equations are transformed into algebraic equations, which are solved by iteration method. In the solution procedure the initial condition and the instantaneous boundary conditions, such as solar radiation and ambient temperature, are set based on the experimental data. In this study, numerical simulation under unsteady state is run with FORTRAN.

3. Result and discussion

3.1. Study on winter operation performance of the system

Figure 3 shows the ambient temperature and solar radiation received by the vertical south surface on March 3th. The maximum solar irradiation is 617.8 W/m^2, and the total amount of radiation on the south wall throughout the day is 15.46 MJ/m^2. The maximum ambient temperature is 13.5℃ and the lowest is 1.5℃, the average ambient temperature is 6.3 ℃ throughout the day. Since the collector is in the passive heating mode, the heat quantity fluctuates greatly with the change of the solar irradiation and room temperature is difficult to reach a constant value, so the room temperature is set to no less than 18 ℃during the simulation. Figure 4 shows the Photovoltaic power generation. It can be seen that the power generation starts to rise at 9 am, drops to zero at 17 pm. The maximum output power can reach 48.3 W at about 13 pm of the day.

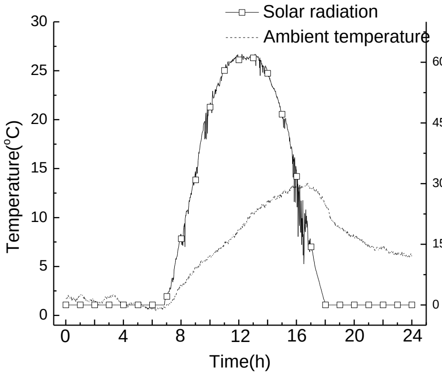

Figure 3. The curve of ambient temperature.

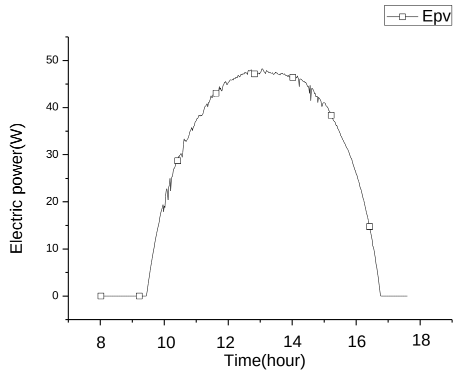

Figure 4. The curve of PV power.

Figure 5 shows the variation of indoor temperature of the building integrated with collector. It can be seen that the temperature is maintained at 18 ℃ from 0 am to 9:52 am and from 16:47 pm to 24 pm. The average indoor temperature is higher than 18 ℃ during the time from 9:52 am to 16:47 pm, and the maximum temperature reaches 21.2 ℃, which means that the room could keep the indoor air temperature by the use of the collector without additional power consumption. The air-conditioning system is started to keep the room at 18℃.

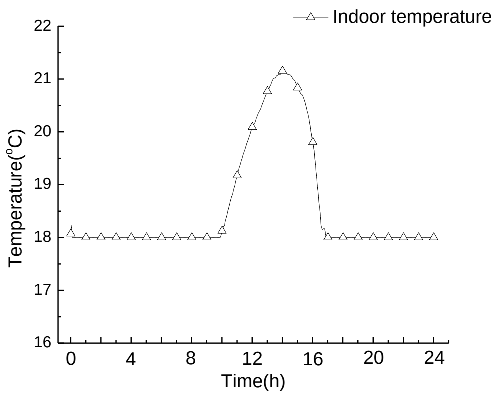

Figure 5. The average temperature of indoor air of the room.

3.2. Thermal behavior of the system in PV/water heating mode

Figure 6 shows the ambient temperature and solar radiation received by the south-facing surface of September 1st. The maximum solar radiation is 419.5 W/m^2 and the total amount of radiation on the south wall is 9.9 MJ/m^2. The maximum ambient temperature is 34.9°C and the minimum is 25.5°C. The daily average ambient temperature is 28.8°C. Figure7 shows the PV electric power generation of the day. It can be seen that the power generation increases from 8 am and the maximum output power can reach 48 W at about 13 pm. The solar radiation in summer is greater than that in winter, so the electric power gain is earlier than winter.

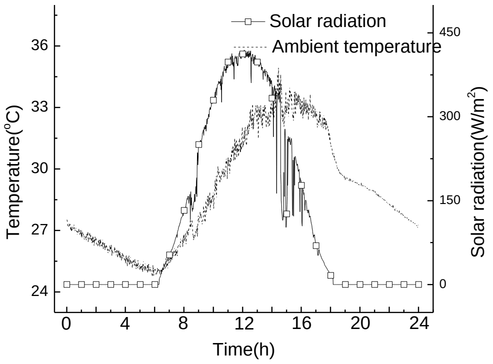

Figure 6. Solar radiation intensity and outdoor air temperature.

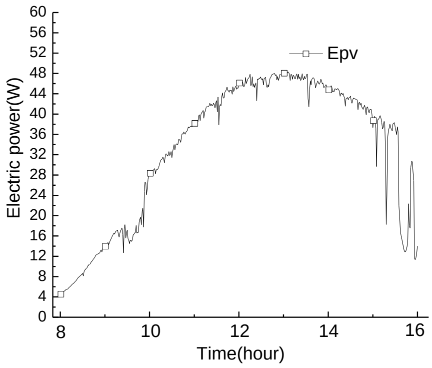

Figure 7. The curve of PV electric power generation.

Figure 8 shows the average water temperature in the tank from 8 am to 16 pm of the day. It can be seen that the temperature increases from 25.4 °C to 38.4 °C as a result of natural circulation. Therefore, the collector can not only generate electric power but also heat the water effectively when operating in the PV/water heating mode in summer.

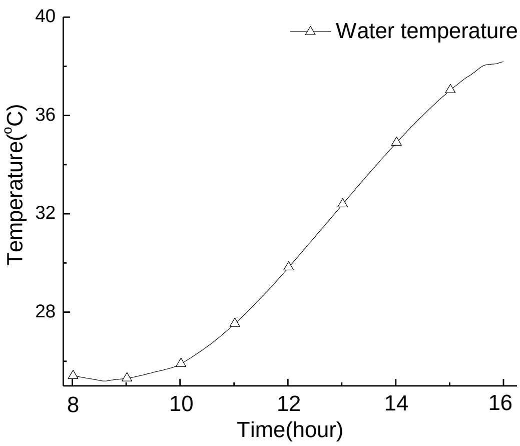

Figure 8. The water temperature in the water tank.

4. Conclusion

This paper designs a virtual building room integrated with a tri-function solar collector on the southern wall and establishes a theoretical model of the system. The theoretical model contains PV/passive air heating mode and the PV/water heating mode. The electric generation performance and thermal behavior of the two working modes have been theoretically studied.

1. The average indoor temperature is higher than 18 ℃ from 9:52 am to 16:47 pm in winter, which means that the room could keep the indoor air temperature by the use of the collector during this time without additional power consumption. In addition, electric power can be generated, the maximum output power can reach 48.3 W.

2. When the PV/water heating mode is operated in summer, the water in the tank can be heated up to 38.4 °C. The efficiency of photovoltaic power generation is about 10%.

It can be seen that the façade-integrated tri-functional photovoltaic/thermal solar collector works well both in winter and summer.

5. References

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