

Numerical study on the electrical performance of photovoltaic panel with passive cooling of natural ventilation

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Abstract

Many researchers employed air or water for the active cooling of PV to achieve higher electrical efficiency, but additional energy consumption for fan or water pump may reduce the net power output. Therefore, this paper provided a study on the electrical performance of PV panel with passive fin cooling of natural ventilation with the consideration of the effect of PV panel tilt angle, solar radiation, air temperature and wind velocity as well as fin size on PV energy performance. The study showed that there existed a PV tilt angle resulting in the minimum electrical efficiency and the maximum power output. Higher intensity of solar radiation led to lower PV electrical efficiency and the efficiency dropped to the minimum around 11:40 during the day time in Beijing. The PV electrical efficiency decreased in linear with the increasing air temperature, but it increased with the increasing wind velocity. The effect of fin height on the electrical efficiency seemed to be very slight. The average electrical efficiency of PV panel with fins was 0.27~1.14% higher than that of PV panel without fins under various conditions in this study.

Keywords: Passive cooling, natural ventilation, PV panel, electrical performance

1. Introduction

With the rapid economic development, energy demand and consumption had been sharply increasing in the past two decades. Fossil fuel reserve has been proven to be very limited, therefore, the development and utilization of renewable energy becomes more and more important. Solar energy, as a green and renewable energy, has been widely used for solar-electricity generation with photovoltaic (PV) panel in recent years. In 2012, the global PV production was 36 GW and 63.9% of them were produced in China. The electrical efficiency of commercial PV products was mostly less than 20%. Many studies [1], [2] found that PV cell/working temperature had a great impact on the solar-to-electricity conversion efficiency (PV electrical efficiency), and the higher PV cell temperature was, the lower the electrical efficiency would be. Many studies [3]-[7] of active PV cooling, employing air, water or refrigerant to extract heat from PV and combining PV panel with heat storage or heat pump for PV/thermal (PV/T) system, have been carried out to improve PV energy performance. But those systems consumed extra energy to drive the cooling fluid, and the improvement of electricity production by active cooling was very slight compared with the extra energy consumption for fan, water pump and compressor. Passive cooling with no extra energy consumption could be an option to improve PV electrical performance, even the cooling effect and energy improvement was not as good as expected. Therefore, this paper provided a study on the electrical performance of PV panel with passive fin cooling of natural ventilation.

2. Numerical Models

Zondag *et al.* [8] built four numerical models for the simulation of PV/T collector: a 3-D dynamical model and three steady state models that are 3-D, 2-D and 1-D. The study showed that the 1-D steady

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state model performed almost as good as the others. Therefore, for this work, the 1-D steady state model was used for the simulation based on the following assumptions:

- The temperature at each layer was well distributed and the geometrical center was selected to be the representative node.
- The contact resistance between each layer was neglected.
- Based on the energy balance analysis of each layer, mathematic models were developed for the numerical simulations of PV energy performance.

The heat balance at the PV panel was given by

$$0 = I(\beta\tau)_c f_c A_p + I(\beta\tau)_p (1 - f_c) A_p - E + h_{p-m} (T_m - T_p) A_p + h_{p-a} (T_a - T_p) A_p + h_{p-sky} (T_{sky} - T_p) A_p \quad (1)$$

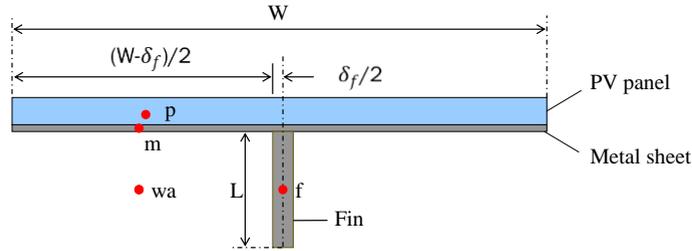


Fig. 1. Cross-sectional view of part PV panel with cooling fin.

where I was solar radiation; $(\beta\tau)_c$ and $(\beta\tau)_p$ were the effective absorptances of the solar cells “c” and PV base plate respectively; f_c was the ratio of cell area to PV panel area; A_p was the area of PV panel “p”; E was the electricity generation; h_{p-m} was the heat transfer coefficient between “p” and the metal sheet “m”; h_{p-a} was the convective heat transfer coefficient between “p” and the surrounding air “a”; h_{p-sky} was the radiative heat transfer coefficient between “p” and the sky; T_m , T_p , T_a and T_{sky} were the temperature of “m”, “p”, “a” and the sky respectively.

The electricity generation (W) was given by:

$$E = \eta_c f_c (\beta\tau)_c I A_p \quad (2)$$

where η_c was the temperature-dependent electrical efficiency of “c”.

$$\eta_c = \eta_{rc} [1 - \beta(T_p - T_{rc})] \quad (3)$$

where η_{rc} was the reference electrical efficiency at the reference operating temperature T_{rc} ; β was the temperature coefficient [9].

$$h_{p-m} = \frac{1}{R_{p-m}} \quad (4)$$

R_{p-m} was the thermal contact resistance between “p” and “m” ($0.04 \text{ m}^2 \text{ K/W}$).

According to Duffie and Beckman [9],

$$h_{p-a} = 2.8 + 3.0 \times u_{wind} \quad (5)$$

where u_{wind} was the wind velocity.

$$h_{p-sky} = \varepsilon_p \sigma (T_p^2 + T_{sky}^2) (T_p + T_{sky}) \quad (6)$$

where ε_p was the emittance of “p”; σ was the Stefan-Boltzmann constant.

$$T_{sky} = 0.0552 \times T_a^{1.5} \tag{7}$$

The heat balance at the metal sheet was given by:

$$0 = h_{p-a} (T_p - T_m) A_{p-m} + h_{m-f} (T_f - T_m) A_{m-f} + h_{m-wa} (T_{wa} - T_m) A_{m-wa} \tag{8}$$

where A_{p-m} was the contact area between “p” and “m”; A_{m-f} was the contact area between “m” and the fins “f”; A_{m-wa} was the contact area between “m” and the warm air “wa”; h_{m-f} was the conductive heat transfer coefficient between “m” and “f”; h_{m-wa} was the convective heat transfer coefficient between “m” and “wa”; T_f and T_{wa} were the temperature of “f” and “wa” respectively.

$$h_{m-f} = \frac{1}{\frac{x_m A_{m-f}}{2k_m \theta_m L} + \frac{y_f A_{m-f}}{k_f \theta_f L}} \tag{9}$$

$$x_m = W/4 \tag{10}$$

$$y_f = L/2 \tag{11}$$

where k_m was the thermal conductivity of “m” (200 W/(m·K)); θ_m was the thickness of “m” (2 mm); L was the height of “f” (80 mm); k_f was the thermal conductivity of “f” (210 W/(m·K)); θ_f was the thickness of “f” (2 mm); W was the width of “p” (10 mm).

$$h_{m-wa} = \frac{2k_m h_{p-a}}{2k_m + \theta_m h_{p-a}} \tag{12}$$

The heat balance at the fin was given by:

$$0 = h_{m-f} T_m (A_{m-f}) + h_{f-wa} T_m (A_{f-wa}) \tag{13}$$

where h_{f-wa} was the convective heat transfer coefficient between “f” and “wa” and was given by

$$h_{f-wa} = \frac{2k_f h_{p-a}}{\delta_m h_{p-a} + 2k_f} \tag{14}$$

The heat balance for the warm air between the fins was given by:

$$0 = h_{m-wa} (T_m - T_{wa}) A_{m-wa} + h_{f-wa} (T_f - T_{wa}) A_{f-wa} + m_{wa} c (T_a - T_{wa}) \tag{15}$$

where m_{wa} was the mass flow of “wa”; c was the specific heat capacity of air.

The location of Beijing was selected for study in this paper. To simplify the calculation and analysis, the time point, 12:00 on October 15th, was employed for numerical simulation. The solar radiation on tilt front surface of PV panel was given by [10]

$$I = I_b \left(\begin{aligned} &\cos S \cdot \sin \phi \cdot \sin \delta + \cos S \cdot \cos \phi \cdot \cos \delta \cdot \cos \omega + \sin S \cdot \sin \gamma \cdot \cos \delta \cdot \sin \omega \\ &+ \sin S \cdot \sin \phi \cdot \cos \delta \cdot \cos \omega \cdot \cos \gamma - \sin S \cdot \cos \gamma \cdot \sin \delta \cdot \cos \phi \end{aligned} \right) + I_d \left(\cos \frac{S}{2} \right)^2 \tag{16}$$

where I_d was the diffuse radiation on horizontal surface; I_b was the direct radiation on horizontal surface; S was the angle between the inclined plane and the horizontal plane (30°); ϕ was the geographical latitude (39.80° in Beijing); δ was the solar latitude (−9.60); ω was hour angle (0° at 12:00); γ was the azimuth angle (15°); α_s was the solar elevation.

$$I_d = C_1 (\sin \alpha_s)^{c_2} \tag{17}$$

$$\delta = 23.45 \sin\left(\frac{2\pi d}{365}\right) \tag{18}$$

$$\sin \alpha_s = \sin \phi \cdot \sin \delta + \cos \phi \cdot \cos \delta \cdot \cos \omega \tag{19}$$

3. Result and Analysis

3.1. Effect of PV panel inclination on the electrical efficiency

Fig. 2 showed the variation of PV electrical efficiency under different tilt angle of PV panel. It can be seen from Fig. 2 that the electrical efficiency decreased to the lowest point and then increased slightly with the increasing PV panel tilt angle. For PV panel with fins, the electrical efficiency was 14.7% responding to the tilt angle of 20°. It decreased with the increasing tilt angle and reached the minimum of 14.6% at the tilt angle of 45°. After that, the electrical efficiency turned to increase and reached 14.63% as the tilt angle increased to 60°. The average electrical efficiency was 14.6%. For PV panel without fins, the electrical efficiency was 14.5% responding to the tilt angle of 20°. It decreased with the increasing tilt angle and reached the minimum of 14.3% at the tilt angle of 45°. After that, the electrical efficiency turned to increase and reached 14.4% as the tilt angle increased to 60°. The average electrical efficiency was 14.4%. It can be concluded from Fig. 2 that the PV cooling fins led to an average efficiency increase by 0.27% in this case.

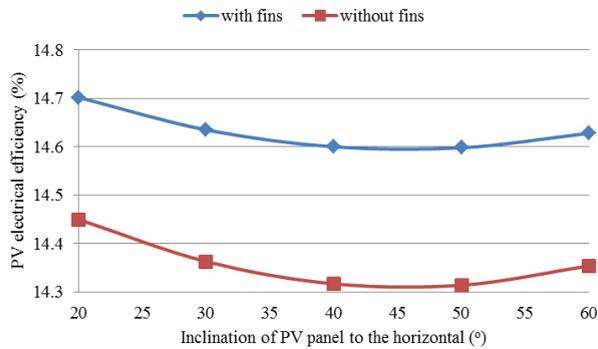


Fig. 2. Variation of electrical efficiency with PV panel tilt angle.

3.2. Variation of electrical efficiency during the day time

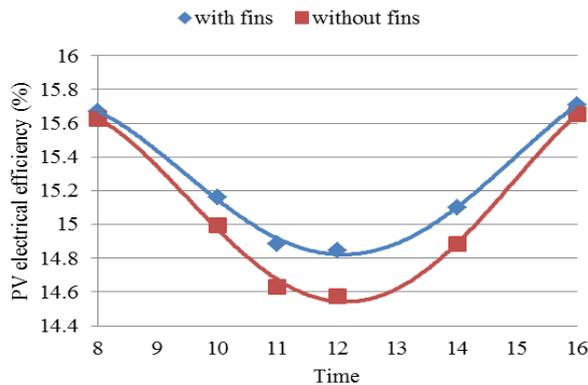


Fig. 3. Variation of electrical efficiency during the day time.

Fig. 3 showed the variation of PV electrical efficiency during the day time. It can be seen from Fig. 4 that the PV electrical efficiency decreased to the minimum before noon and then increased in the afternoon. For PV panel with fins, the electrical efficiency reduced from 15.7% at 8:00 to 14.9% at 12:00,

while it increased to 15.7% at 16:00. It reached the minimum of 14.8% around 11:40. The average electrical efficiency was 15.2%. For PV panel without fins, the efficiency decreased from 15.6% at 8:00 to 14.6% at 12:00, while it increased to 15.7% at 16:00. At about 11:40, it reached the minimum of 14.6%. The average electrical efficiency was 15.1%, 0.17% lower than that of PV with fins relatively.

3.3. Effect of air temperature on the electrical efficiency

Fig. 4 showed the variation of PV electrical efficiency under different air temperature. It can be seen from Fig. 4 that the efficiency decreased in linear with the increasing air temperature. As the air temperature increased from 269.15K to 299.15K, the electrical efficiency decreased from 16.0% to 14.0% for PV panel with fins, while from 15.7% to 13.7% for PV panel without fins. Every 10K air temperature increase led to an electrical efficiency decrease by 0.7%. The average electrical efficiency of PV panel with fins was 0.28% higher than that of PV panel without fins.

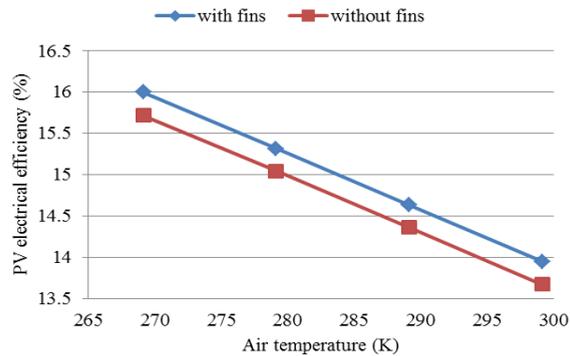


Fig. 4. Variation of electrical efficiency with air temperature.

3.4. Effect of PV panel inclination on electrical efficiency

Fig. 5 showed the variation of PV electrical efficiency under different wind velocity. Higher wind velocity led to better fin cooling and consequently better PV electrical performance. The electrical efficiencies were 14.6% and 14.4% for PV panel with and without fins respectively at the wind velocity of 3 m/s. As the wind velocity increased to 6 m/s, the efficiencies increased to 14.9% and 14.8% respectively. With every 1m/s increase of wind velocity, the efficiency increased by 0.08% and 0.14%, respectively.

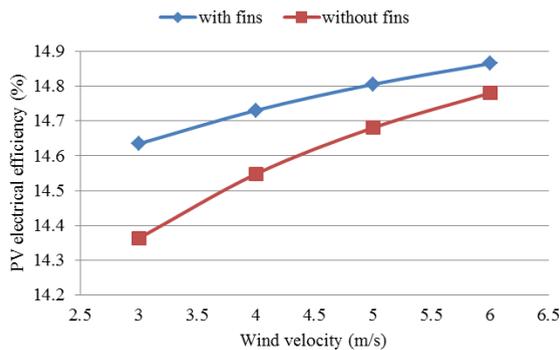


Fig. 5. Variation of electrical efficiency with wind velocity.

4. Conclusions

The paper presented a numerical study on the electrical performance of PV panel with passive cooling of natural ventilation. Numerical models were developed to investigate the effect of PV panel tilt angle, solar radiation, air temperature and wind velocity as well as fin size on the electrical efficiency and power

output. The study could be concluded that:

- 1) As the PV panel tilt angle increased, the electrical efficiency dropped to the minimum at the tilt angle of 45° and then rose slightly. The average electrical efficiency of PV panel with fins was 0.27% higher than that of PV panel without fins.
- 2) Higher intensity of solar radiation led to lower PV electrical efficiency. During the day time, the efficiency dropped to the minimum at around 11:40 and then went up for PV panels with and without fins. The average electrical efficiency of PV panel with fins was 1.13% higher than that of PV panel without fins.
- 3) The PV electrical efficiency decreased in linear with the increasing air temperature. Every 10K decrease in air temperature led to the increase of electrical efficiency by 0.68% for PV panels with and without fins. The average electrical efficiency of PV panel with fins was 0.28% higher than that of PV panel without fins.
- 4) Higher wind velocity led to better PV cooling effect as well as better electrical performance. Every 1 m/s increase in wind velocity led to the increase of electrical efficiency by 0.08% and 0.14% for PV panels with and without fins, respectively. The average electrical efficiency of PV panel with fins was 1.14% higher than that of PV panel without fins.

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