Performance analysis of a high concentrating photovoltaic/thermal system with a water spray cooling device

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Abstract. A high concentrating photovoltaic/thermal system based on a water spray cooling device has been investigated in this paper. The system uses point-focus Fresnel lens as a concentrator with a concentration ratio over 1000. Both of the numerical thermal and electrical models have been developed to investigate the performance of the system. Moreover, the spray cooling has been used to solve the problem of high heat flux transfer and get good temperature uniformity, which is considered as an efficient method to develop the electrical efficiency and thermal efficiency. The results show that the overall efficiency is mainly influenced by water mass flow.

Keywords: solar energy; photovoltaic/thermal; concentrating system; spray cooling

1. Introduction

Facing the challenges of energy shortage and environmental pollution, photovoltaic power generation is an effective way to alleviate the problems. Photovoltaic technology has improved in the last ten years. However, photovoltaic system still has two urgent problems, including the high cost of photovoltaic systems and the low photoelectric conversion efficiency, which constrain the wide application of photovoltaic technology. Currently, concentration technology has been developed [1, 2], which can cut down the cell area to reduce the cost of the system. When sunlight reaches concentrating photovoltaic (CPV) system, the energy is not only converted into electric energy but also extra heat, which can cause the temperature rising of the cells. As the temperature of solar cells increases, the cell efficiency decreases. Therefore, a cooling system is used to cool the cells meanwhile the excess heat can be used as a heat source [3]. This concentrating photovoltaic thermal (CPV/T) system attracts a great deal of researchers’ attention [4, 5], because the CPV/T system can produce electric energy using a low-cost concentrator but also supply hot water for thermal application. Schuetz designs a photovoltaic system based on compound parabolic concentrator, which is a 7 times concentration system using silicon photovoltaic cells with system power efficiency of 7.9% [6]. Joe S. Coventry introduces a concentrating photovoltaic/thermal solar collector with a concentration ratio of 37, which shows thermal efficiency around 58% and electrical efficiency about 11% [7]. In order to solve the low electrical efficiency, multi-junction cells have been researched, because of their high electrical conversion efficiency [8-10]. As MOVPE technology improves, GaAs cells have a large potential for CPV/T system. Li Ming analyses a trough concentrating photovoltaic/thermal system using GaAs cells, which are much better than silicon cells [11].

Compare with low concentrating PV/T system, the high concentrating PV/T (HCPV/T) system demands better tracking and cooling technologies. When the geometric concentration ratio reaches 500
or even 1000, it is hard to achieve a uniform radiation flux distribution and an acceptable temperature of solar cells, which severely affects the electrical efficiency of the HCPV/T system[12].

In order to solve the above problem, the paper presents a high concentrating photovoltaic/thermal (HCPV/T) system with a water spray cooling device, which can provide both electrical energy and usable heat. The operation of the system is dynamic actually, thus a dynamic numerical model suitable for the system simulation is developed in this paper. It can provide the performance analysis of the system, including thermal gain, electrical gain and efficiencies. And the influence of the concentration ratio and the mass flow rate is also discussed in this model.

2. Description of the HCPV/T system

Figure 1 shows the structure of the HCPV/T system using Fresnel lens. The HCPV/T system mainly consists of 3 parts, including a concentrating device, a cooling device and a tracking device. It converges the sunlight into a small cell area through the concentrator. And GaAs cells are cooled by the cooling system using water as the working fluid, through which the heat is collected for thermal applications.

Generally, the tracking device should be adopted in the concentrating system. The system can only use direct solar radiation, when the concentration ratio reaches more than 10. In order to make sure that the system is accurately tracked, a two axes tracking device is applied in the HCPV/T system. The tracking device follows the location of the sun both in azimuth and elevation. And the tracking accuracy is about 0.2°. A programmable logic controller device is designed to compute the sun position.

At present, many high concentrating PV/T systems use continuous parabolic structure. However, this structure has a non-uniform distribution of light intensity, which can cause a temperature gradient and overheating in solar cells. It will greatly reduce the power output of the cells. Therefore, the Fresnel lens array structure is applied in this HCPV/T system, which can achieve a more uniform light intensity distribution.

In the concentrating system, the temperature of solar cells will increase fast under high solar intensity. As the temperature of solar cells increases, the electrical efficiency decreases. Therefore, a cooling device must be applied to cool and protect solar cells. The HCPV/T system uses water spray cooling device to control the mass flow.

![Figure 1. Photograph of the HCPV/T system using Fresnel lens.](image)

3. Mathematical analysis

A dynamic model is developed to simulate both the thermal and electrical performance, which is based on the control volume, finite difference approach for the water cooling system. The system can be represented by four corresponding points through solving the transient energy balance equations. The point ‘g’ is for solar cells, the point ‘c’ is for spray cooling device, the point ‘w’ is for water, and the point ‘i’ is for the insulation material.
The direct irradiance absorbed by GaAs cell layer is given by

\[ Q_g = \rho_c \alpha_g G - E_g \]  
\[ G = C_g R I_d A_g \]  

Where \( \rho_c \) is the reflectivity of the concentrator, \( \alpha_g \) is the absorptance of cells, \( C_g \) is the concentration ratio of the system.

The electrical generation is given by

\[ E_g = \rho_c r_g G \eta_{cell} \]  
\[ \eta_{cell} = \eta_r [1 - \beta_r (T_p - T_r)] \]  

Where \( r_g \) is the ratio of GaAs cell area to aperture area, \( \eta_r \) is the reference GaAs cell efficiency at the reference temperature \( T_r \), \( \beta_r \) is a temperature coefficient for GaAs.

The thermal resistances for the components of the system are given by

\[ R_{ga} = \frac{1}{(h_{ga} A_{ga})} \]  
\[ R_{ge} = \frac{1}{(h_{ge} A_{pe})} \]  
\[ R_{cg} = \frac{1}{(h_{cg} A_{cg})} \]  
\[ R_{ci} = \frac{1}{(h_{ci} A_{ci})} \]  
\[ R_{cw} = \frac{1}{(h_{cw} A_{cw})} \]  
\[ R_{ai} = \frac{1}{(h_{ai} A_{ai})} \]  

The heat transfer coefficients for the components of the system are given by

\[ h_{ga} = 3.8 u_a + 5.7 \]  
\[ h_{ge} = \varepsilon_g \sigma (T_g^2 + T_e^2) (T_g + T_e) \]  
\[ h_{cp} = k_c / \delta_c \]  
\[ h_{ci} = k_i / \delta_i \]  
\[ h_{cw} = N_u_D k_w / D_h \]  
\[ N_u_D = 4.7 R_e^{0.61} + Pr^{0.32} \]  

Therefore, the thermal resistance equations are considered for the HCPV/T system:

Solar cells: \[ M_g C_g \frac{\partial T_g}{\partial t} = k_g V_g \frac{\partial T_g}{\partial x^2} + \frac{T_{a-T_g}}{R_{ga}} + \frac{T_{e-T_g}}{R_{ge}} + \frac{T_{c-T_g}}{R_{cg}} + Q_g \]  

Spray cooling: \[ M_c C_c \frac{\partial T_c}{\partial t} = k_c V_c \frac{\partial T_c}{\partial x^2} + \frac{T_{a-T_c}}{R_{cg}} + \frac{T_{i-T_c}}{R_{ci}} + \frac{T_{w-T_c}}{R_{cw}} \]
Insulation: \[ M_i c_i \frac{dT_i}{dt} = \frac{T_c - T_i}{R_{ci}} + \frac{T_c - T_i}{R_{ci}} \] (19)

Water: \[ M_w c_w \frac{dT_w}{dt} = \frac{T_c - T_w}{R_{cw}} - m_w c_w \frac{dT_w}{dx} L \] (20)

The thermal output is given by
\[ Q_w = m_w c_w (T_{out} - T_{in}) \] (21)

Where \( T_{in} \) is inlet temperature and \( T_{out} \) is outlet temperature of water.

Then, the thermal efficiency is
\[ \eta_t = \frac{Q_w}{G} = \frac{m_w c_w (T_{out} - T_{in})}{G} \] (22)

The electrical efficiency is
\[ \eta_e = \frac{E_g}{G} \] (23)

The total efficiency can be given by
\[ \eta_o = \eta_t + \eta_e \] (24)

4. Results and discussion

In order to know the performance of the HCPV/T system under different mass flow rate and concentration ratio, some parameters are assumed. The concentration ratio is 1000, direct irradiance is 800 W/m², and inlet temperature is 20 °C. The relevant parameter of the system is listed in Table 1.

Table 1. Mass, specific heat and conductivity of the system components.

| Component         | Specific heat (Jkg⁻¹K⁻¹) | Conductivity(Wm⁻¹K⁻¹) |
|-------------------|---------------------------|-----------------------|
| Solar cells       | 326                       | 46                    |
| Cooling device    | 903                       | 237                   |
| Insulation        | 795                       | 0.034                 |
| Water             | 4181                      | 0.63                  |

Other data includes: \( \varepsilon_p = 0.85 \), \( \alpha_p = 0.95 \), \( u_a = 3.5 \) m/s, \( L = 0.14 \) m, \( \eta_r = 0.366 \), \( \beta_r = 0.0026 \) °C⁻¹, \( T_r = 25 \) °C.

As shown in Fig.2 and Fig.3, the performance of the PV/T changes rapidly in this model, when the mass flow rate is less than 1.0 g/s. As the mass flow rate decreases from 1.0 g/s to 0.1 g/s, the electrical efficiency of GaAs cells will drop rapidly as shown in Fig.1; the temperature of GaAs cells increases fast as shown in Fig.3 If the mass flow rate is lower than 0.1 g/s, GaAs cells will be damaged because of the high temperature. This is mainly because with the mass flow rate less than 1.0 g/s, part of the water flow in the cooling device will evaporate and boil; therefore GaAs cells and the cooling device temperature rise, leading to rapid decline in the photoelectric conversion efficiency of GaAs cells. When the mass flow rate increases from 1.0 g/s to 5.0 g/s, GaAs cells can be better cooled.
Fig. 2. Thermal and electrical efficiency of different mass flow rate.

Fig. 3. Temperature of different mass flow rate

As shown in Fig.4, when the concentration ratio is less than 2000, the thermal efficiency has no significant change. However, the electrical efficiency decreases, if the concentration ratio continues to increase. It is mainly because solar radiation flux focusing on the surface of GaAs cells is too high. So part of the thermal energy can’t be taken away, which causes the temperature of GaAs cells rising, as shown in Fig.5. The electrical efficiency will be lower than 20% with the concentration ratio at about 2000. However, the temperature of GaAs cells will be up to or more, which is not conducive to the long-term use of the cells. Therefore, the selection of concentration ratio should consider the operation of the system.
Fig. 4. Thermal and electrical efficiency of different concentration ratio

Fig. 5. Temperature of different concentration ratio

5. Conclusions

This paper presents a HCPV/T system using Fresnel lens, which can provide a uniform light intensity distribution. GaAs cells are cooled by water spray cooling device, through which the heat can be collected for thermal application. Hence, the total solar utilization efficiency is greatly increased.

In order to study the performance of HCPV/T system, a dynamic model is developed, which can perform complete energy flow analysis on the system. It shows instantaneous thermal efficiency around 47% and electrical efficiency around 20% – 25%. The simulation results also indicate that this system is strongly influenced by the concentration ratio and the mass flow rate. Then the mass flow rate and the concentration ratio selection should comprehensively consider the operation of the system.
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