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Advanced thermal management of a solar cell by a nano-coated heat pipe plate: A thermal assessment

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ABSTRACT

The significant temperature effect on solar cells results in loss of photovoltaic (PV) efficiency by up to 20–25%, which may over-negate the efforts in technology development for promoting PV efficiency. This motivates studies in thermal management for solar cells. This study concerns the thermal assessment of an advanced system composed by a solar cell and a nano-coated heat pipe plate for thermal management. Solar cell temperature and the corresponding evaporative heat flux are evaluated based on a conjugated heat transfer model. It indicates that the solar cell can be cooled down to be below 40 °C and suffers no temperature effect due to the use of the heat pipe plate. The heat pipe plate can provide sufficient cooling to the solar cell under different solar irradiance. The analytical and experimental results show that the maximum evaporative heat flux of the current heat pipe plate is around 450 W/m^2. However, the practical heat removal flux at the condenser is 390 W/m^2. The loss of cooling energy is due to the gathered vapour at the condenser section, which prevents the liquid-vapour circulation inside the vacuum chamber of the device. By using additional cooling strategies (i.e. heat sink, PCMs, water jacket) at the condenser section, the heat removal ability can be further improved.

1. Introduction

The temperature effect on solar cells indicates the loss of photovoltaic (PV) efficiency and energy yield due to the increase of the panel temperature [1–3]. The significant temperature rise of the PV panel under different operating conditions has been extensively investigated [4–8]. It is worth mentioning that solar cells in intensive solar radiation have a panel temperature of 50–70 °C, leading to an efficiency loss of 10–25% [9–11]. Although the temperature effect varies for different categories of solar cells, the significant influence on the PV efficiency may still over-negate the improvement of efficiency by technology and materials developments of solar cells [8].

The electrical performance of solar cells under different temperatures has been studied. It is concluded that the open-circuit voltage and electricity output decrease with the increasing of the panel temperature [12,13]. In another word, the electrical performance can be largely or even completely recovered by providing cooling energy to solar cells. To achieve that, various cooling methods for solar cells have been developed. Common strategies of cooling for solar cells include passive cooling, phase change materials (PCMs) based thermal energy storage and active cooling [14].

Passive cooling makes use of air flow between the panels and the roof tiles for heat removal. However, the cooling effect is not significant because of the restrained natural convection. As a result, the solar cell temperature can be lowered by 5–10 °C [15,16]. PCMs based thermal energy storage provides cooling energy by storing heat in PCMs. However, the poor thermal conductivity of the PCMs has significantly affected the heat charging process [17–19]. Active cooling uses forced convection of liquid driven by a pumping system to remove heat from the solar panel. Apparently, it has a relatively higher cooling energy and thus can cool the solar panel efficiently [20,21]. However, issues such as non-uniform temperature distributions and the increment in capital cost due to the electricity consumption are still issues that need to be resolved.

Advanced thermal management approaches have being developed in the last 1–2 decades. Impressive examples include thermal radiation cooling and evaporative heat transfer by a plate-type heat pipe. With designed nano-domes on solar panels, thermal energy can be radiated to the outer space in the form of electromagnetic wave. Fan et al. [22–24] has done substantial work on this. Their results show that the panel temperature reduction can be as high as 18.3 °C in theory and 13.0 °C in the experiments. The merit of the promising technology lies in its sufficient cold energy supply to the solar cells without energy consumption. Nevertheless, it is still a challenge to cut the manufacturing cost to enable the technology to be widely used in the future.

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In comparison, heat pipe technology is much simpler and techno-economic to be used for thermal management of solar cells. By integrating a flat-type heat pipe, large amount of cooling energy can be provided to solar cells by liquid evaporation inside the vacuum chamber of the heat pipe. Conventional heat pipe with fins [25,26], micro heat pipe arrays [27,28] and pulsating heat pipe [29,30] has been investigated. According the results, the induced PV efficiency can be improved by 9% at most. This implies a recovery of the efficiency loss (due to the temperature rise on PV panel) by ~36%. To further enhance the cooling effect, Du et al. [8,31] have invented a novel heat pipe plate by incorporating microgrooves with nano-coated compressed metal foams as the internal structure. With the use of the device, the temperature rise of solar cells can be reduced by 46%, indicating an efficiency loss recovery of approximately 56% [31].

Our previous research in [8,31] reveals the experimental results of the cooling effect for single solar cell and arrays of solar cells by the heat pipe plate, respectively. This study concerns the thermal assessment of the solar cell system integrated with the nano-coated heat pipe plate. The PV panel temperature and the evaporative heat flux are evaluated. The thermal assessment of the integrated system indicates the nano-coated heat pipe plate is able to provide sufficient cooling energy to the solar cell in different situations.

2. Conceptual development

Fig. 1 demonstrates the merits of thermal management for solar cells. Without solar illumination, solar cells are at ambient temperature and have the maximum PV efficiency. When the PV panels are exposed in solar radiation, the panel temperature increases significantly due to the accumulation of excess thermal energy on the panels [4], as can be seen in Fig. 1(a). In certain cases, the panel temperature can achieve 70 °C. As a result, the electrical performance of the solar cells is severely affected. For a solar cell that has a temperature coefficient of −0.5%/°C, the relative reduction of PV efficiency can be as high as 20–25%. This may negate the promotion of efficiency caused by the current technology developments, as shown in Fig. 1(b). Therefore, an advanced hybrid PV/Thermal management (PV/TM) system is proposed to be developed with the aim to recover the efficiency loss caused by the thermal issue on the panels.

The developed hybrid PV/TM system is shown in Fig. 2. By integrating a thermal management device at the rear of the PV panel, heat can be transported from the hot spots to a place where heat can be subsequently dissipated to the atmosphere. A heat pipe plate is used as the thermal management device due to its high efficiency of heat transfer induced by the liquid-vapour phase change of the working fluid inside the vacuum chamber. The internal structure is composed by arrays of micro-grooved channels and nano-coated compressed metal foams. Theoretically, the arrays of microgrooves supply more nucleate sites for bubble generation and growth, which increases the heat transfer ability of the device; while the compressed metal foams with nano coatings provide desired pore size and micro-roughness on the surface of the metal ligaments, leading to an improved liquid wicking in the porous media. With intense solar radiations, additional heat sinks are attached to the condenser section. As a result, the accumulated vapour at the cold end can condense efficiently to ensure adequate liquid wicking back to the evaporator. The vapour flow and wicking liquid flow are periodic, which enables the device to work continuously without energy consumption. Since liquid-vapour phase change of the working fluid inside the chamber of the heat pipe plate absorbs large quantities of thermal energy with an approximate constant vapour pressure, the heat pipe plate can remove heat from the hotspots efficiently and reduce the cell temperature uniformly.

3. Thermal assessment of the hybrid system

3.1. Analysis of the energy flow

Energy flow chart of the solar cells with the illumination of the standard light source is presented in Fig. 3. Without thermal management, the illuminated light (q_s) is partially converted into electricity (q_e) while the rest becomes thermal energy. Although part of the thermal energy is dissipated to the environment by means of natural convection (q_c) and thermal radiation (q_r), the cell temperature increases due to excess heat accumulated on the panel (Fig. 3(a)). However, by using heat pipe plate as the thermal management system, the excess thermal energy can be partly or fully removed (q_n), leading to a reduced temperature rise of the solar cells (Fig. 3(b)).

As a result, the energy balance of the solar cell with thermal management is written as:

$$q_s = q_c + q_r + q_e + q_n \tag{1}$$

Detailed calculations for q_e, q_c and q_r can be found in [4], based on which, the panel temperature can be expressed as in Eq. (2):

$$T_s = \frac{((1-\beta)\cdot\varepsilon_0\cdot Q_s - 2\cdot\varepsilon_1\cdot\sigma_{sb}\cdot(T_s^4 - T_a^4) - q_n)}{2\cdot h_c} + T_a \tag{2}$$

The above equation indicates that the cooling heat flux q_n is not a fixed value in the cooling process. Instead, it varies with the change of the solar cell temperature T_s, the operating conditions (i.e. the solar irradiance) and the thermal physical properties of the materials (i.e. the absorption rate of the PV panel).

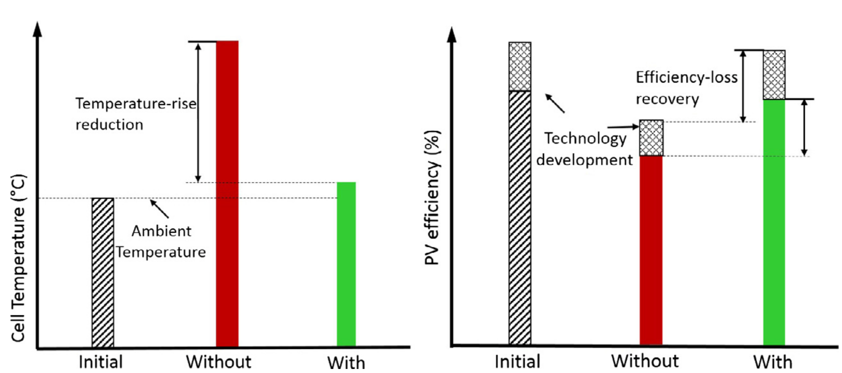

Fig. 1. The merits of thermal management for solar cells.