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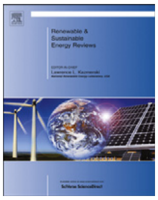

Opportunities and challenges in micro- and nano-technologies for concentrating photovoltaic cooling: A review

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ABSTRACT

Concentrating photovoltaic technology is one of the fastest growing solar energy technologies achieving electrical conversion efficiency in excess of 43%. The operating temperature of a solar cell strongly influences the performance of a photovoltaic system reducing its efficiency with a negative temperature coefficient. Thus, cooling systems represent a very important aspect in concentrating photovoltaic applications. This work presents an overview of micro- and nano-technologies applicable to passive CPV cooling and associated manufacturing technologies (such as monolithic applications). Among the different technologies, carbon nano-tubes and high-conductive coating are the most promising technologies to offer the best CPV cooling performance. A critical assessment of the technological review has also been made.

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1. Introduction

Up to now photovoltaic (PV) energy is still one of the most expensive energy source among both renewable and conventional sources. One promising approach to decrease PV costs is to reduce the amount of semiconductor materials needed. Some companies are manufacturing solar cell with thin silicon wafer to reduce costs [1]. Others use lenses or mirrors to concentrate sunlight onto cells: the replacement of semiconductor area with cheaper concentrating mirrors or lenses is a way to lower the cost of solar electricity. This solution is called *Concentrating Photovoltaic* (CPV).

Only a fraction of incoming sunlight striking any photovoltaic cell is converted into electrical energy. The rest of the absorbed energy converts into thermal energy within the cell [2]. At the end of 2011 the highest efficiencies of silicon single-junction cells [3] and for multi-junction cells [4] for one sun and AM1.5g spectrum were reported to be 25% and 34.1% respectively. While using with concentrating sunlight, increases in record efficiencies were reported which are 27.6% (AM1.5d, 92 suns) for Si cells [5] and 43.5% (AM1.5d, 418 suns) for multijunction cells [6]. Thus, a large amount of solar energy cannot be converted into electricity yet and is dissipated as heat.

The efficiency of any photovoltaic cell decreases with increasing temperature which is non-uniformly distributed across the cell. Martinelli and Stefancich [7] stated that "this fact can be viewed as a consequence of the second principle of thermodynamics imposing a limit on the conversion efficiency of energy coming from a source at a given temperature by a converter/sink having a finite temperature". Study has also shown that high temperature can cause long term degradation to the cell [8]. The rising temperature will also result in mechanical impact on the cell such as deformation on the cell surface, delamination of the transparent layer and development of micro-cracks on the cell. This is due to different thermal expansion coefficients of several different materials used to compose the cell structure. The temperature variation and, as a consequence, the different thermal expansion coefficients can lead to immediate failure in fragile components or to fatigue failure of the cell. This paper will review the state-of-the-art of the passive cooling systems that have been designed to overcome the thermal expansion and maintain the operating temperatures for concentrating photovoltaic systems.

2. Concentrating photovoltaic cooling

Cooling usually is not required in common flat PV systems and in the CPV systems with low concentration ratio ($CR \leq 5$); this is because of the large module surface and terrestrial energy flux of the sunlight. On the contrary, cooling is a real important aspect in medium and high concentrating CPV systems ($10\times < CR < 100\times$ and $CR > 100\times$ respectively), due to the significant reduction of the receiver surface and increase in the energy flux of the concentrated sunlight. Furthermore triple junction cells are particularly sensitive to temperature: the conversion efficiency of a three-junction cell can decrease 0.05% for every °C increase of cell temperature [9]. Taking into account a standard AM 1.5d solar insulation of 850 W/m^2 on a $500\times$ CPV system, optical losses of 20% and a cell efficiency of 30%, a heat power of 23.8 W/cm^2 must be dissipated by the cooling system. Several common cooling technologies, including fins, micro-channels and heat pipes, can be applied to the CPV systems, as reported by Royne et al. [2]

2.1. Passive cooling

Usually cooling systems are classified as *passive cooling* and *active cooling* depending on the cooling mechanism. Passive cooling does not require input of mechanical or electrical power as it acts through the exploitation of natural laws, whereas active cooling requires external energy to cool the solar cells.

Earlier review articles on cooling system for the CPV system stated that passive cooling was not feasible for any densely packed cells or for linear concentrators with concentration ratios above 20 suns [2]. There were very few passive cooling techniques available in the market as reported by Yeom and Shannon [10]. While reviewing micro-cooler, Yeom and Shannon discussed only a few passive cooling technologies for the CPV system.

Some theoretical researches have been published with the aim to investigate the opportunities of a passive approach for electronics cooling. In 2007, Tseng et al. [11] applied Taguchi's statistical method to optimise the passive cooling systems for electronic devices. According to the authors, application of Taguchi's method will contribute to the reduction of manufacturing costs of the electronic device. They demonstrated that openings in the mother board, power density and flow pattern are the most important parameters to determine the device's thermal behaviour. Furthermore, they stated that passive cooling is more reliable and even better than the inclusion of forced flow, and can reduce the damage probability caused by the cooling failures.

2.2. Active cooling

Active cooling is obtained using a fraction of the cell power output. Thus, a part of the energy output would not be available for further use. But active cooling is independent of the work conditions and is usually easily controllable than passive cooling. Micro-channels heat sink or impinging jets seemed to be the most promising technologies for active cooling of a CPV plant as reported by Royne et al. [2].

In 2009 Zhangbo et al. [8] presented new definitions for passive and active cooling. In their definition, active cooling referred only to the so-called photovoltaic/thermal collector (PV/T) technology: the heat produced by the PV is removed from the cell and it is re-used in other applications. This new "active cooling" concept does not include necessarily micro-channels or fluid jets impingement.