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Historical and recent development of concentrating photovoltaic cooling technologies

Sanjeev Jakhar, M.S. Soni *, Nikhil Gakkhar

Center for Renewable Energy and Environment Development (CREED), Department of Mechanical Engineering, BITS, Pilani, Rajasthan, India

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ABSTRACT

Solar photovoltaic (PV) is a commercially proven technology to generate electricity directly from the Sun. However, the major limitation of PV technology is its lower efficiency and higher cost as compared to conventional power generation techniques. These problems can be overcome by concentrating photovoltaic (CPV), which is the fastest growing technology due to its lower cost and higher electrical conversion efficiency (of about 40%). Nevertheless, with the increase in the concentration ratio (CR), the solar cell temperature increases, results in decrease in its efficiency and lifespan. This problem of rise in temperature can be overcome by using a proper cooling technology. In this paper review work of various cooling technologies available for CPV systems has been presented. Cooling technology should be reliable, maintain low and uniform cell temperature, easy to operate and efficient in nature.

Contents

1. Introduction

Today's most of the energy requirements are met by fossil fuels. If the current trends of global energy use-demand continues, the supply of fossil fuels is predicted to be exhausted within next couple of centuries [1]. Burning fossil fuels release stored

* Corresponding author. Tel.: +91 1596 515634; fax: +91 1596 244183.
E-mail address: mssoni@pilani.bits-pilani.ac.in (M.S. Soni).

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greenhouse gases and lead to an increase in global warming. In recent times there has been a significant revival of interest in renewable energy to tackle the above problems. Among various renewable energy sources, solar energy is an abundant energy source which provides 4000 trillion kW h of insolation per day. Solar energy can be harnessed to produce electricity in two ways, photovoltaic (PV) and concentrating solar power (CSP) [2–4]. The PV technology works on PV effect which was first discovered by the physicist Edmund Becquerel in 1839 who recommended that sunlight can be converted directly into electricity using semiconductor devices known as PV cells. Photons below a threshold wavelength have enough energy to break an electron-hole bond in the semiconductor crystal, which in turn can drive current in a circuit. Out of total solar insolation, only 10–20% is converted into electrical energy while the remaining solar radiation is either converted into heat or is reflected back [5]. The cost of the photovoltaic is still higher as compared to conventional sources of power generation. The cost of solar PV based electricity generation can be reduced by cheaper concentrating mirrors or lenses which concentrate solar radiation on a smaller area, thus reducing the required solar cells (SCs) area for the same output [6–8]. These CPV systems are classified according to the CR of solar radiation incident on it. This ratio is usually referred as 'Suns', indicate the number of times the solar radiation is concentrated. It can vary from 1 to 40 Suns for low, 40 to 300 Suns for medium and 300 to 2000 Suns for high CPV systems [9].

Nevertheless, with the increase in CR, the cell temperature increases which in turns reduce the bond energy and the band gap of a cell, resulting in degradation of the open circuit voltage. The CPV cells will also exhibit long-term degradation if they are exposed to higher temperatures for long duration, reducing the lifespan rapidly [10–14]. Research studies show that the operating temperature is one of the key factors that influence the conversion efficiency. The correlations between PV operating temperature and its efficiency has been discussed by Skoplaki and Palyvos [15]. They concluded that for most of the PV cells with a base temperature of 25 °C, the average decrease in efficiency is of the order of 0.45% per degree rise in operating temperature. Nishioka et al. [16] presented the relation between temperature coefficients and conversion efficiency of triple junction SCs and found the conversion efficiency to be decreased by 0.248% at 1 Sun and 0.098% at 200 Suns for per degree rise in operating temperature. These two studies show that the temperature control is very important and crucial factor to improve the efficiency and life span of the SCs. The rise in operating temperature of PV and CPV cells can be controlled by using cooling technologies.

The cooling technologies which can be active or passive is an important aspect in case of CPV rather than normal PV as multi-junction cells are sensitive to cell temperature. The selection of cooling technology depends upon various parameters like area available for cooling, fluid flow rate and heat transfer coefficient. It should be reliable, easy to operate and efficient in nature. The design of cooling system for CPV depends upon direct normal irradiation (DNI) and CR. Various types of cooling technologies has been discussed in the literature which includes liquid immersion, microchannel heat sink, water cooling etc. Earlier articles on CPV system reported that the passive cooling for linear concentrator was insufficient for CR above 20 suns [17]. As reported by Yeom and Shannon [18] a very few passive cooling techniques were commercially available in the market. The active cooling systems for CPV which can overcome the existing challenges of passive system and are compatible with higher CR (above 100).

The main objectives of this study are to present and update current work in the area of CPV cooling technologies and recommend feasible research direction based on these efforts. CPV cooling technologies which are discussed in over last decade are reviewed extensively. Further, they are categorized according to various parameters like CR, cell temperature, cooling effect and heat transfer coefficient etc. The literature review is comprehended according to their research gaps, research scenario and findings. The present study differs from the existing studies due to the fact that (i) it covers an exhaustive review and discussion on CPV cooling technologies with main focus on active cooling systems. (ii) it discusses the advantages and disadvantages of various cooling technologies both commercially available as well as in research phase and are represented in a tabular form. (iii) the comparative study of CPV cooling is made as per their operating parameters like cell temperature, cell material, cooling effect etc. (iv) Finally, the present work explores from literature the key areas for research potential and recent development of CPV cooling along with its application and challenges during fabrication. At the end, future directions are given for the research work in this area and suitable recommendations are provided.

2. CPV cooling techniques

The various types of cooling technologies which have been implemented for CPV systems are discussed in the following sections. The classification is made according to the type used.

2.1. Heat pipe cooling

Heat pipes are hollow metal pipes whose inner surface is lined with a porous wick material which is soaked in a liquid coolant that transports heat by evaporating and condensing in a continuous cycle. Heat pipes can be classified according to their geometry, function and the methods used to transport the liquid from the condenser to the evaporator [19]. Because of their high thermal conductivity and high heat transfer characteristics, heat pipes have been extensively used for cooling of small electronic equipments. They are good alternatives to large heat sinks, especially in laptops where space is limited [20]. Singh et al. [21] developed a miniature loop heat pipe with the flat disk shaped evaporator for thermal management of compact electronic equipments. The materials used for loop are copper with nickel wick and water is used as the working fluid. They showed that the system can dissipate maximum heat load of 70 W with evaporator temperature below 100 ± 5 °C limits.

From the literature, it is also observed that heat pipe cooling is also used by some researchers on CPV systems. Russell [22] has patented a CPV system with heat pipe to maintain constant temperature of SCs. The system contains linear Fresnel lenses focusing solar energy onto a string of solar cells mounted on the heat pipe of circular cross-section, along its length, as shown in Fig. 1. Several pipes were arranged next to each other to form a panel. The heat pipe has an internal wick elongated lengthwise of the tube that draws out the liquid up to the evaporator. The heat was removed from the heat pipe by an internal liquid coolant flowing through the U shaped pipe maintaining a uniform temperature along the pipe.

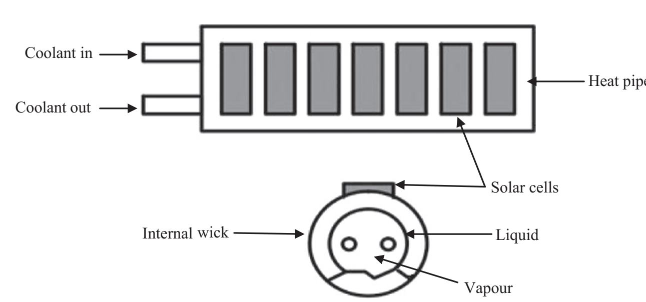

Fig. 1. Heat pipe cooling system for PV as proposed by Russel [22].