Journal of Cleaner Production 174 (2018) 53–64

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Analysis of flow separation effect in the case of the free-standing photovoltaic panel exposed to various operating conditions

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ARTICLE INFO

Article history:
Received 16 August 2017
Received in revised form
27 September 2017
Accepted 29 October 2017
Available online 2 November 2017

Keywords:
Photovoltaics
Fluid dynamics
Energy efficiency
Numerical analysis
Renewable energy

ABSTRACT

During its operation, a photovoltaic (PV) panel is exposed to various and in general, stochastic thermal and wind conditions, which have a significant influence on the PV panel operating temperature. The increased PV panel operating temperatures normally have an unfavorable effect on the PV panel performance and lifetime, thus various cooling methods were proposed in order to increase the photovoltaic energy conversion efficiency. A reasonable step before the consideration of a specific cooling strategy is to obtain a PV panel performance analysis with respect to its surroundings (specific geographical micro location) for various operating conditions. This paper presents such a study, which was conducted through an experimentally validated numerical model. Numerous CFD simulations regarding heat and fluid flow around a monocrystalline PV panel coupled with a heat flow simulation inside the PV panel elements were conducted. The aim of the paper was to investigate an effective heat transfer field and the variations in the PV panel temperatures with respect to various wind velocities and heat source conditions. A detailed study regarding pressure, viscous and body (buoyancy) forces as well as their effects on flow separation was also conducted. The study also investigated the changes in the effective heat transfer near the PV panel. The gained results in this study turned out to be useful for the consideration of a specific cooling strategy for PV panels, which can ultimately lead to an increase in PV panel efficiency and lifetime. Additionally, the conducted study could be used to improve the delivered electricity prediction from the PV system at a selected location defined by specific wind velocities and solar insolation distributions.

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1. Introduction

In recent years, the research community has increasingly been more focused on renewable energy systems. For example, authors in Lee et al. (2017) analyzed different sustainable energy strategies for Asia towards general energy transition. A novel hybrid energy system was proposed in Nižetić et al. (2015) for efficient use in residential applications regarding operation in typical Mediterranean climate conditions. Biomass fuel as a combination of cardboard/sawdust briquettes was considered in Lela et al. (2016) through a conducted experimental approach and showed potential. There are also other examples such as Vučina et al. (2015) and Wicki and Hansen (2017), that are focused on reducing the amount of fossil fuel dependence and decrease the consequential harmful effects to the environment. Among various renewable energy systems, photovoltaic (PV) technology Singh (2013) is becoming increasingly more attractive because of its relatively reasonable economic aspect. As PV technology is being increasingly used on large scales, any improvement or new development is particularly interesting and important. Additional improvements to existing PV technologies can be sought in several ways. The first group of improvements is related to novel materials which should be acceptable both from a technical and economic point of view Chen et al. (2016); Major et al. (2017). The second group of improvements is either related to the analysis of different working conditions regarding PV system performance or with the analysis of different cooling strategies for PV panels in order to increase energy

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https://doi.org/10.1016/j.jclepro.2017.10.310
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conversion efficiency. For example Baloch et al. (2015) considered converging channel heat exchangers for PV cooling with promising results. Nižetić et al. (2016a) analyzed a water spray cooling technique applied on PV panels, while authors in Teo et al. (2012) considered an active cooling technique for PV applications. This paper is concerned with the second group of improvements that have significant effects on PV panel performance.

During its operational lifetime, a PV panel is exposed to different radiation, thermal and wind conditions, i.e. operating conditions in general. The previous conditions often cause elevated PV panel operating temperatures which normally have a negative effect on PV panel performance and lifetime. The average drop in PV panel electrical efficiency in the case of crystalline silicon cells ranges from about 0.25%/°C to 0.5%/°C, Evans (1981), depending from the specific technology. The previous facts have led to proposals and developments of various cooling methods in recent years. A reasonable step before the consideration of a cooling method is to conduct an analysis of the general PV panel operating conditions in its surroundings, i.e. in the specific micro geographical location. The accurate prediction of the PV panel operating temperature is also important for estimating the energy potential of the selected location (delivered electricity), regardless if a cooling method is assumed to be applied or not.

The required analysis of the PV panel operating temperatures can be conducted through computational fluid dynamics (CFD) which can include both fluid flow and thermal analysis. The conditions of fluid dynamics around the PV panel have a direct influence on the heat transfer from the PV panel to the surroundings. The numerical modeling of fluid and thermal phenomena related to photovoltaics is thus an important feature that can provide useful data and insight into complex heat transfer and issues regarding fluid dynamics.

PV panel cooling techniques are usually based on forced or natural ventilation, heat pipe cooling, hydraulic cooling or a phase change material system. In general, cooling techniques can be divided into passive (do not require additional power input) and active (which requires a certain amount of energy to enable the cooling process) techniques. In Hasanuzzaman et al. (2016), a review of cooling technologies was given and the conclusion was that passive systems were only feasible for small scale use and more research was needed. While active systems are more attractive from a performance point of view, as they can efficiently use harvested heat, their economic viability is questionable. Researchers working on natural ventilated systems achieved PV temperatures in a range of 50–70 °C while a lower temperature range of 20–30 °C could be achieved through ventilated systems Du et al. (2013). Researchers do not often quantify the "parasitic" power consumption required for active systems, but a net power gain was achieved in a few quantified cases. Cooling methods can also consider temperature uniformity, this is also an important factor for improving PV panel performance Bahaidarah et al. (2016). Although passive cooling systems do not usually achieve as much cooling, the results from this paper can be used as a guide for developing improved passive cooling techniques. As mentioned in Hasanuzzaman et al. (2016), more research is required before a passive cooling system could be applied on a large scale. An example of a passive cooling technique was shown in Popovici et al. (2016) where an air cooled heat sink was analyzed. The heat sink was constructed as a ribbed wall attached at the back of the PV panel while placing the panel in a ventilated double skin facade. This paper aims to provide more insight into the heat transfer process for the herein analyzed and similar types of naturally ventilated stand-alone PV panels.

More than a few research papers have provided a contribution to understanding the causal relation between different thermal and fluid-flow operating conditions that affect PV panel performance. In Teo et al. (2012), the PV module temperature was practically shown to be a linear function of irradiation. The second important factor regarding heat transfer is wind velocity Jubayer et al. (2016). In addition to wind velocity, wind direction (i.e. PV panel orientation) is also an important factor. In Jubayer and Hangan (2014), the aerodynamic forces of the PV panel were investigated by CFD and it was shown that maximum overturning moments appear at wind directions of 45° and 135°. In Nižetić et al. (2016b), it was shown that the same wind directions corresponded to maximal heat convection losses regardless of wind speed and insolation. In Wilson and Paul (2011), a different PV panel (roof) mounting position was investigated, considering convective heat losses as a major cooling mechanism. CFD was used to test several different air gap heights and angular positions (with respect to horizontal position which ranged from 15° to 90°). It was shown that for natural convection, angular position had a significant effect on heat convection, but the convection was almost independent from angular position when a velocity magnitude was prescribed. While the mentioned paper used a 2D CFD, a similar study was conducted in Zhang et al. (2017) with the usage of 3D CFD but only for a single PV panel configuration (at different wind speeds and thermal radiation conditions). Another important key factor is turbulence intensity. Namely, in Arianmehr et al. (2014), it was shown that turbulence increased by simple groove means could improve convective heat transfer. The PV panel in a wind tunnel experiment was modeled with the usage of a flat aluminum plate parallel to the wind flow which is not a realistic situation. Nevertheless, the effect of turbulence on heat transfer was once more confirmed.

The main objective of this paper was to examine the heat and fluid flow conditions around the PV panel, the PV panel operating temperatures and the convective heat transfer between the PV panel and the surroundings for various thermal and wind conditions (i.e. various operating conditions). The main research contributions regarding this paper in comparison to previous similar studies were: (1) the recognition and analysis of a nonlinear relation between the flow field near the PV panel and heat source; (2) the investigation of an effective thermal conductivity field in the air surrounding the PV panel which was considered important for the development of novel cooling methods; and (3) the analysis of local temperature variations across the PV panel as a function of thermal and wind flow conditions. The analysis was obtained through the application of an already developed and experimentally validated CFD model by Nižetić et al. (2016b).

2. PV panel energy flows: overview

A schematic overview of the main energy flows in the case of a PV panel exposed to solar irradiation is illustrated in Fig. 1. The PV panel absorbs the energy from the solar radiation which can be divided into direct, reflected and diffuse radiation of which the direct solar radiation is the largest energy contributor (heat gain) to the PV panel. In stationary conditions, the sum of all incoming energy flows is equal to the sum of all outgoing energy flows (per unit time). Furthermore, a relatively small part of solar radiation energy is converted into electrical energy by the photoelectric effect which is the main characteristic of Si-based technology. While some of the radiation is directly reflected, most of the irradiated energy is converted into heat, thereby increasing the PV panel operating temperature. As the elements of the PV panel get heated, their temperature increases, and the PV panel operating temperature is higher than the surrounding air temperature as a result. The higher the PV panel operating temperature is, the higher the heat

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