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Coupled natural convection and radiation heat transfer of hybrid solar energy conversion system

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ABSTRACT

A hybrid solar energy conversion system described in this study is designed to exceed the efficiency of each type of technology alone by combining advantages of concentrated solar power (CSP) technology and high performance concentrated photovoltaic (CPV) cells. This hybrid system can be tilted at different inclination angles to track the solar power at different latitudes and different time zones. Thermal management is important to CPV cells, as 1000× concentrated solar radiation onto CPV not only leads to higher performance but also generates more waste heat flux. In this work, the effects of natural convection with and without the interaction of surface radiation in the system consisting of PV cells, optical funnels and a heatsink were numerically investigated with an experimentally validated model. The influence of inclination on the overall flow structure and heat transfer was examined. Under the effect of these funnels, the heat transfer was enhanced when the heat was transferred through PV cells to funnels. At the same time, the separation flow between the spaces of funnels would take the heat to the ambient. The minimum average temperature of surrogate PV cells occurred at the inclination angle of 60°. When the inclination angle varied from 0° to 90°, the stagnation point moved from the downward surface of the heat sink towards the edge of heat sink. From 0° to 60°, the stagnation point was at the downward surface of heat sink and there was a dramatic decrease in the average temperature of the surrogate PV cells. When inclination angles were less than 60°, except that there was a separation region above substrate, the side flow could flow in and out freely between adjacent funnels and then formed a pair of separation bubble, or spiral node, on top of the funnels. At these inclination angles, flow velocity was found to be the dominant factor influencing heat transfer because the flow pattern (separation bubble) was the same on top of the funnels. However, at inclination angles of 60° to 90° the stagnation point occurred at the edge of the heat sink, and the surrogate PV temperature increased. When the inclination angle reached 90°, the flow was trapped and recirculated among funnels, and the vortical wake on top of the funnel disappeared. It can be concluded that from 60° to 90°, the dominant factor influencing heat transfer is funnel effect because the flow velocity stayed almost constant.

1. Introduction

Solar energy can be captured either as electricity by photovoltaic (PV) devices or as heat by concentrated solar power (CSP) systems. The former means are considered cost-effective, but cannot utilize the thermal spectrum. In addition, the storage of electricity is challenging. The latter has advantages of generating electricity from the stored heat (usually in the form of molten salt) even when the sun is not shining, but is pricy in construction and operation. Both CSP and PV utility-scale power stations have been in operation at various locations around the world since the 1980s. Currently, the largest CSP installation is the Solana Generating Station located near Gila Bend, AZ; a parabolic trough field with capacity of 280 MW and associated thermal storage. On the other hand, the largest PV installation is at the California Valley Solar Ranch: a 250 MW “solar farm” in San Luis Obispo County, CA.

Different from CSP plants that collect heat energy, systems with PV cells generate low-grade waste heat while solar energy is converted into electricity. Extreme temperature increase in PV cells (when waste heat cannot be dissipated efficiently) will not only lower the light-electricity conversion efficiency, but also damage

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Nomenclature

q_c	convective heat transfer rate (W/m^2)	T_w	average temperature of surrogate PV cells (°C)
k	thermal conductivity (W/(m·K))	T_a	ambient temperature (°C)
W	heatsink width (m)		

the cell and other module materials. Several papers [1–5] have addressed various ways for the cooling of PV cells. Recently, Tari [6,7] showed the possibilities of dissipating unwanted heat by the interaction of natural convection with thermal radiation for the vertical orientation of plate-finned heat sinks in two separate applications. Leung and Probert [8,9] experimentally studied the effect of orientation on heat exchangers. They found that the vertical and upward facing horizontal orientations of a heat sink were preferred for maximizing the natural convection heat transfer rate. As a result, these two orientations were investigated extensively under convective and radiative heat transfer effect. However, there are only a few works investigating inclined orientations under the interaction of natural convection and surface thermal radiation [10,11].

In 2014, Sharp Labs of America collaborated with University of Arizona and University of Missouri-Columbia aiming to combine advantages of CSP and PV technologies to achieve greater exergy, better dispatchability, and higher capacity factor at more reasonable costs than can be achieved by either technology alone. High heat flux waste heat need to be dissipated with the solar energy system running. Therefore, high efficiency cooling is required to keep the solar energy system working safely. To gain high PV cell efficiency, plated-finned heat sinks under forced convection are employed to keep our system working at a targeting low temperature of 75 °C. However, for the purposes of avoiding the maximum temperature of surrogate PV exceed the melting temperature of solder (167 °C) when any fan fails, heat rejection by natural convection and radiation need to be considered in order to ensure the all-time reliability of operation.

Natural convection plays a key role in the fan failure condition. Various numerical methods have been employed to solve the different natural convections [12–17]. In order to estimate the heat transfer performance on such a cooling assembly, researchers have derived the empirical heat transfer rate and Nusselt number with the relationship of some non-dimensional numbers. Bejan and Lee [18] derived an analytical solution of the convection heat transfer rate for packages of electronic components, and found that if the heat transfer mechanism was natural convection, the maximum density of heat generating electronics (or Q/HLW) was proportional to $(T_{max} - T\infty)^{3/2}$ and $H^{-1/2}$. H, L and W are the fin height, the heatsink length and heatsink width, respectively. Mehrtash and Tari [10] scaled the equation with a factor obtained from the analysis of the simulation data which is $(H/L)^{0.32}$. Leung and Probert [8] obtained a similar relation in which they had an exponential fin effectiveness term that can be neglected in the cases where fins have high thermal conductivity. They used equations to calculate the average Nusselt number based on the product of modified average Grashof number with Prandtl number. However, these reports do not include the inclination angle effect. Inclined orientations are important for hybrid solar energy conversion system for at least two reasons: (i) at different latitudes and different time zones, the hybrid solar system needs to be tilted at different inclination angles in order to track solar power, thus the maximum temperature at the assembly needs to be estimated; (ii) because funnels are used on top of PV cells for optical purposes, which can affect the overall flow structure, natural convection and heat transfer need to be further investigated. In order to obtain the heat transfer performance of heat sink cooling assembly with different inclination angles, Fujii and Imura [19] studied the relation of $\overline{Nu}$ vs $Gr\mathrm{Pr}$ for the horizontal plate facing downwards and when the flat plate was inclined from the vertical. When the heat sink was inclined from the vertical, Tari and Mehrtash [20] assumed that the flow structure stayed the same. The only change was in the body force, where the effective body force became $\rho g cos\theta$. With the same rationale, they suggested the vertical case correlation for plate fin heat sinks with the same modification was expected to be valid at small inclination angles, as long as the flow structure stayed the same. However, their equation can only be applied when there is convective heat transfer effect. If the surface thermal radiation is included, their equations are not applicable to calculate the corresponding Nusselt number.

In this study, we validated our simulation results with the case when there was adiabatic boundary condition on top of cooling assembly without funnels. Then we applied our validated model to investigate the heat transfer performance of cases with funnels under various inclination angles. The average temperature of surrogate PV and average Nusselt number of cooling assembly were compared and discussed. We also studied the relationship between heat transfer and flow pattern at the heatsink side and funnel side.

2. Numerical method

The assembly of PV cells cooling in hybrid solar energy conversion system is schematically depicted in Fig. 1. Fig. 1a is the isometric view of the assembly and Fig. 1b is the side view from the cutting plane with dimensions. The heat sink was provided by Aavid Thermalloy, LLC. The funnels were provided by Sharp Laboratory of America. The numerical model dimensions of our cooling assembly were listed in Table 1. In this system, thermal management is important to PV cells, as 1000x concentrated solar radiation onto PV cells not only leads to higher performance but also larger heat loads (heat flux on PV cells is over 10^5 W/m^2). The module includes an optimized plate-fin heat sink, an aluminum substrate, fourteen equally spaced PV cells located on the substrate, and fourteen funnels attached to the surface of PV cells. The assembly shown in Fig. 1 is placed in a cubical room filled with air, with walls that are maintained at a constant temperature. The width, length and height of this cubical room are applied as 148.8 mm, 400 mm and 400 mm. Because the Rayleigh number of our cooling assembly is estimated to be 3.2×10^9 under a total power input of 84 W at the PV cells, the use of proper turbulence model to simulate this process is needed.

In the analysis (with ANSYS CFX), steady state solutions were obtained by using the Shear Stress Transport Model (SST) with natural convection and surface to surface radiation. From the ANSYS user manual for natural convection [21], they applied four turbulent models (Standard and RNG k-epsilon, Standard and SST k-omega) to study the natural convection in a tall cavity and compared with the experimental data [22]. SST model shows better agreement with their experiment. Thus, we used SST model for our study. Boussinesq approximation was applied to assume the