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CONJUGATE HEAT TRANSFER ANALYSIS OF FLOATING PHOTOVOLTAIC PANELS WITH HYBRID NATURAL CONVECTION COOLING LOOPS AND SOLAR FILTER

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1. ABSTRACT

Floating photovoltaic panels have several advantages such as using the open water surface instead of large land areas. Exploiting the water body as a heat sink to cool the panels offers an additional advantage, leading to increased efficiency. This study focuses on the development of a numerical model for a hybrid system that combines a natural convection cooling loop with a solar filter feature. This added feature decreases the temperature of photovoltaic cells and optimises the spectral distribution of the incoming solar radiation. A conjugate heat transfer analysis shows that the cooling system is highly effective in dissipating heat and maximising the electrical output of floating photovoltaic panels. The study also optimises the thickness of the cooling channel to assess the effectiveness of nanofluids.

2. INTRODUCTION

Floating photovoltaic (FPV) system is an innovative solution to tackle the central problem of ground-mounted photovoltaic (PV) for expensive land requirements by utilising the water surface as the solar panel installation site [1]. The other advantages of a FPV system are reducing water evaporation and reducing the PV panels operating temperature, which is vital for the efficiency and resilience of solar panels.

A passive cooling method, such as a natural convection cooling loop (NCCL) system, is an alternative to complex and energy-consuming active cooling. Our earlier publications reported the testing of a successful experimental prototype of a passive cooling method for FPV [1, 2]. The results showed that the natural cooling loop effectively decreased the FPV temperature from 318.8 K to 314.3 K, resulting in a 17.84% increase in electrical efficiency under solar irradiation of approximately 1000 W/m^2 (noon time).

This study proposes a hybrid system for FPV panels that combines an NCCL with a solar filter. The purpose is to further reduce the temperature of FPV panels and optimise the spectral distribution of incoming solar radiation wavelengths reaching the panels. The computational fluid dynamics analysis is thus extended beyond the simulation of the circulation of the coolant within the NCCL, to also include the heat conduction across the PV layers and the effects of radiation absorption through the glass layers and the cooling fluid.

3. METHODOLOGY

Figure 1 shows the schematic design within the FPV system with the NCCL configuration. The cooling loop comprises three key components: a heat sink section at the loop's base, the PV module positioned above the heat sink section receiving solar energy, and a reservoir at the top of the loop. While solar thermal radiation is distributed over wavelengths ranging from 250 to 2500 nm, the c-Si PV cells can only convert solar irradiance within the range of approximately 325 to 1125 nm. Beyond this range, absorbed solar irradiance can only heat the panel, raising the c-Si PV cell temperature. The radiation filter above PV module is designed to absorb these non-useful solar irradiation wavelengths and reducing the c-Si PV cell temperature. The selection of cooling fluid in the radiation filter box is crucial; it should have high transmissivity within the 325 to 1125 nm wavelength range and high absorptivity (low transmissivity) outside this range.

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Equations (1)-(3) represent the governing equations of mass, momentum, and energy transport for the transient model, where u_i is the velocity vector and P, T, ρ, μ, Pr and c_p have their usual meanings. The source term $\dot{q}$ is incorporated into the energy equation to account for heat energy generation within each PV module layer associated with solar irradiation absorption.

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right) + \rho g_i \tag{2}$$

$$\frac{\partial}{\partial t}(\rho T) + \frac{\partial}{\partial x_j}(\rho u_j T) = \frac{\partial}{\partial x_j}\left(\frac{\mu}{Pr}\frac{\partial T}{\partial x_j}\right) + \frac{\dot{q}}{c_p} \tag{3}$$

Equation (4) shows the solar irradiance (G) as a function of time (t) corresponding to the starting time from 08:00 am until 04:00 pm ($0 \leq t \leq 28800\ s$) based on the established reference [1, 2].

$$G(t) = at^2 + bt + c$$
$$where\ a = -2.854 \times 10^{-6}\frac{W}{m^2 s^2};\ b = 7.747 \times 10^{-2}\frac{W}{m^2 s};\ and\ c = 493.4\frac{W}{m^2} \tag{4}$$

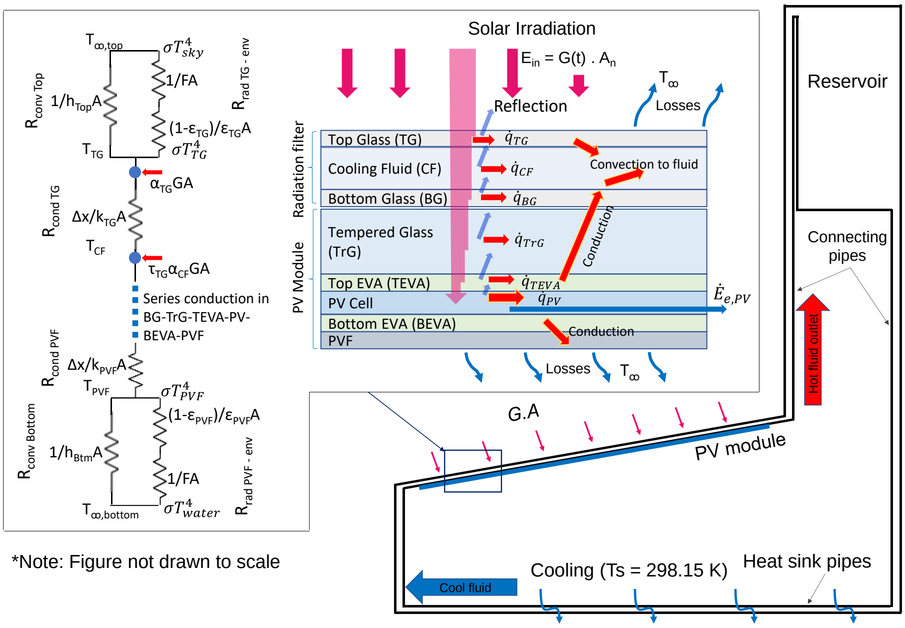

Fig. 1 Schematic design of the FPV with NCCL and solar filter system.

The electrical energy of the PV cell ($\dot{E}_{e,PV}$) in this model is determined by the fill factor (FF), the open-circuit voltage (V_{OC}), and the short-circuit current (I_{SC}), where they are the function of temperature (T) and spectral response (SR_λ) as shown in Equation (5).

$$\dot{E}_{e,PV} = FF.V_{OC}.I_{SC} = \left(FF_{ref} + C_{FF}(T - T_{ref})\right).\left(V_{ref} + C_V(T - T_{ref})\right).A\int_0^\infty SR_\lambda(\lambda)G_\lambda(\lambda)d\lambda \tag{5}$$

The finite-volume CFD code Fluent has been employed in conjugate heat transfer mode, to simulate the natural convection through the cooling loop and heat conduction through the PV cell layers shown in Figure 1, and the effects of thermal radiation and electrical generation are modelled through the inclusion of appropriate expressions for $\dot{\boldsymbol{q}}$ in the regions of the solid and fluid layers (Figure 1).

4. RESULTS

Here, we test the use of pure water and 5 ppm Ag-water nanofluid as cooling fluids. The thickness of the cooling passage, above the PV panel, was varied between 1-20 mm. The thicker passage absorbs more solar irradiance, reducing the energy reaching the c-Si PV cell, but also lowers the cell temperature. Thus, optimising the thickness of the transparent thermal box is crucial.

Figure 2 shows the average temperature of the PV cell for the entire daily cycle. The temperature of the PV cell rises over time, indicating that it absorbs heat from solar irradiance. This absorption is low in the morning, reaches its maximum at noon, and decreases in the afternoon.

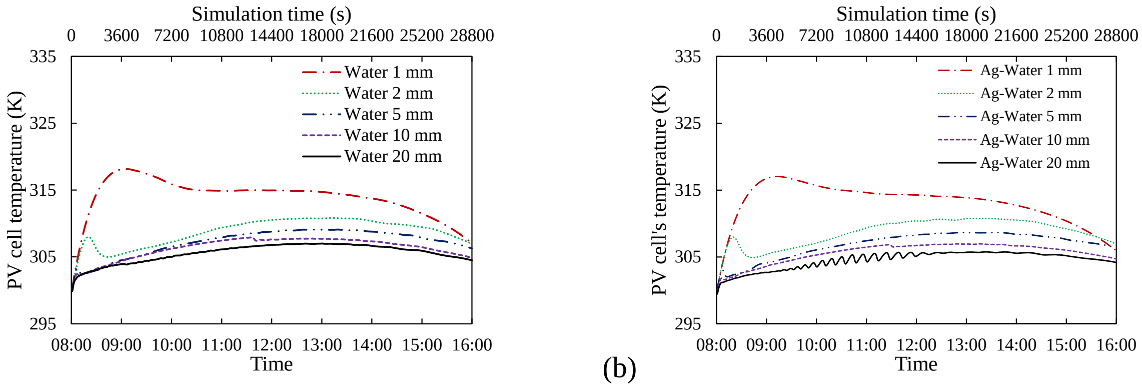

Fig. 2 Time history of PV cell temperature for different channel thicknesses in the NCCL system using (a) pure water and (b) 5 ppm Ag-water nanofluid

Figure 3 presents the relationship between PV cell temperatures and fluid absorptivity for pure water and Ag-water nanofluid. Increasing cooling channel thickness reduces PV cell temperature by absorbing more solar irradiance and increasing cooling. Ag nanoparticles in the nanofluid increase absorptivity and thermal conductivity, leading to a lower PV cell temperature, but also reduce the useful energy reaching the PV cell.

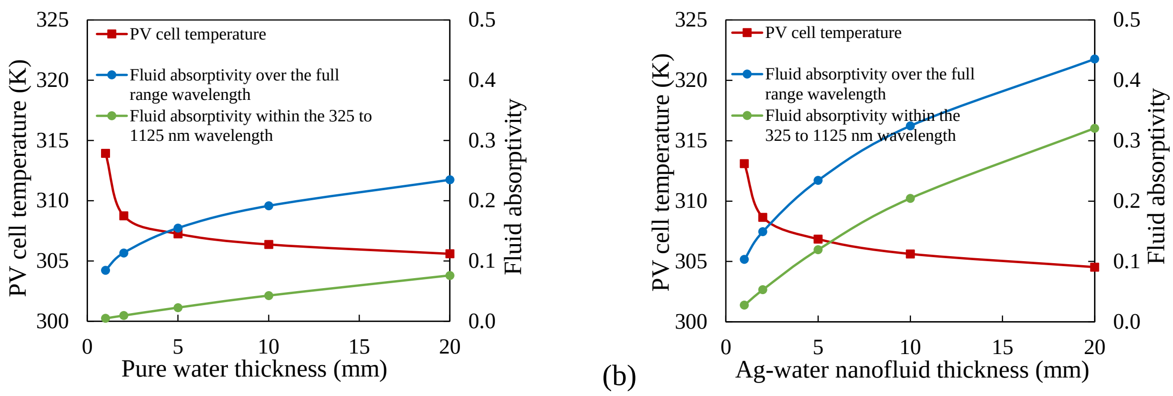

Fig. 3 PV cell temperature and fluid absorptivity of (a) pure water and (b) 5 ppm Ag-water nanofluid

5. CONCLUSIONS

In summary, the multi-physics thermal model assembled, shows this innovative natural convection cooling loop system effectively reduces cell temperatures and optimises the solar light irradiation. The findings highlight that Ag nanoparticles can reduce the PV cell temperature. However, the electrical efficiency of NCCL using 5 ppm Ag-water nanofluid is lower than pure water due to higher absorption in the useful wavelength range ($325 \leq \lambda \leq 1125$ nm) of c-Si PV cells. The presentation will include a wider range of thermal comparisons and animations of the temperature variation of the entire system over the daily cycle.

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