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Numerical analysis of direct distillation solar still coupled with a semitransparent photovoltaic module

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Abstract

Clean electrical energy and freshwater are two basic human needs that can be met by using solar energy properly. In this article, the goal is to produce electricity and freshwater simultaneously by installing a solar still coupled with a semi-transparent solar module. The coupled solar system was simulated in ANSYS Workbench 2022 software environment. To check the water yield, the system was simulated at different brackish water temperatures of 60 $^{\circ}C$, 70 $^{\circ}C$, and 80 $^{\circ}C$ and different solar intensities of 250, 500, 750, and 1000 W/m^2. Hence, ten case studies were defined and simulated according to radiation intensity and brackish water temperature. The results showed that the electrical power output is directly proportional to the solar intensity, however, as brackish water temperature rises the electrical power output slightly decreases since solar cell efficiency is inversely proportional to its temperature. Considering the freshwater production rate, it enhances by increasing the brackish water temperature. Based on the results obtained, it can be concluded that the coupled solar desalination unit, incorporating a semi-transparent solar module, is well-suited for regions in the southern part of the country characterized by abundant solar radiation.

Keywords: Renewable energy; Solar energy; Numerical simulation; Wind speed.

1. Introduction

The increasing need for energy has driven humanity towards using renewable energy sources. Renewable energies are relatively short-term reusable. Solar, wind, geothermal, tidal, biomass, and hydrogen are all part of renewable energies [1]. Among all renewable energy sources, solar energy stands out and is popular due to its advantages such as low conversion cost to electricity, availability throughout the day, and wide accessibility. For this reason, extensive studies have been conducted on solar energy, which has been used as a clean energy source for electricity generation and converting brackish water to fresh water.

Some researchers have evaluated the performance of different solar devices. Rahbar and Esfahani [2] determined the efficiency of a simple inclined solar desalination device using theoretical and numerical techniques. They reported similar trends for water production and convective heat transfer coefficient through numerical simulations compared to experimental data. Alagouz et al. [3] analyzed the performance of an inclined solar desalination device. Their results showed that the efficiency of the solar desalination device increases with a decrease in water mass and an increase in wind speed. Pormoideh et al. [4] numerically investigated a direct solar desalination device, studying the effects of dimension ratios, glass temperature, and brackish water temperature on parameters such as frictional, thermal, and concentration entropy. Their results indicated that the dimension ratio had an influence on the vapor transfer rate. Moreover, entropy increased with increasing glass and water surface temperatures. In another numerical study by Pormoideh et al. [5], they successfully increased the efficiency of a direct solar desalination device by 10% by using a porous sponge material. Amiri et al. [6] achieved a 17% improvement in the system's performance by employing a three-dimensional concentrator and using a shadow guard in the condenser section. Assari et al. [7] studied a bidirectional solar desalination device connected to an external reflector. Their results demonstrated an increase in efficiency by up to 32% with the external reflector.

Based on the previous studies, limited evaluation has been conducted on a solar desalination device coupled with a semi-transparent photovoltaic module, and so far, no numerical simulation has been performed on the coupled system of semi-transparent photovoltaic panels with a solar desalination device. Therefore, the objective of this research is to present a coupled model of these two solar systems and evaluate its performance under various operating conditions. To achieve this goal, simulation steps have been carried out using the ANSYS Fluent 2022 software environment.

2. Problem Description

The two-dimensional geometry of the problem, along with the dimensions, size, and boundary conditions, is depicted in Figure 1. According to Figure 1, two single-crystal solar cells with an efficiency of 20% and a size of 125*125 mm^2 are considered in the semi-transparent photovoltaic module. The geometric dimensions and optical properties of the semi-transparent photovoltaic module are summarized in Table 1 [8, 9]. Based on the applied boundary conditions, the following simplified assumptions are made:

1. The side walls of the solar desalination device are insulated.
2. The bottom part of the device containing the brackish water has a constant temperature.
3. The side walls of the photovoltaic module are opaque and adiabatic.
4. The problem is solved in a steady-state condition.
5. The fluid flow is laminar and incompressible.

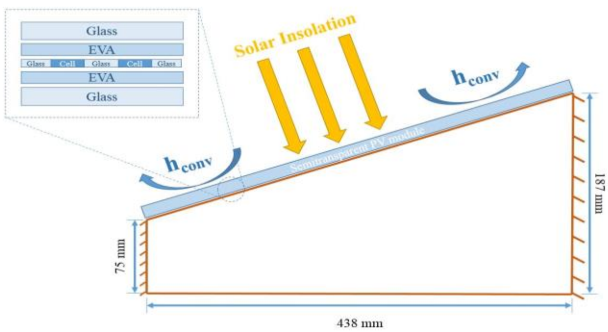

Figure 1. 2D representation of a solar still coupled with a semitransparent PV module

Table 1. The thermophysical and optical properties of the semitransparent PV system used in the current study [8, 9]

Materials	Thickness [mm]	Density [kg/m^3]	Thermal conductivity [W/m.K]	Specific heat [J/kg.K]	
Glass	3.0	3000	2	500	
EVA	0.5	960	0.35	2070	
Cell	0.2	2330	148	677	
	Absorptivity	Reflectivity	Transmissivity	Emissivity	Refractive index
Glass	0.04	0.04	0.92	0.9	1.526
EVA	0.08	0.02	0.9		1.45
Cell	0.9	0.08	0.02		3.69

Based on the assumptions made, boundary conditions can be classified based on operational parameters such as solar radiation intensity and seawater temperature. The solar radiation intensity is considered in the range of 250-1000 (W/m2). The temperature of the saline water is considered between 40-80 ˚C. The solar radiation intensity is divided into four different scenarios with values of 250, 500, 750, and 1000. Additionally, the temperature of the saline water is applied with values of 40, 50, 60, 70, and 80 ˚C. Based on this, there are 10 different operational conditions summarized in Table (2). The logic considered in the categorized scenarios is that the glass temperature should not exceed the water temperature (otherwise, the concept of solar desalination becomes meaningless). Therefore, after simulation and processing, some unsuitable case scenarios were not reported.

Table 2. Proposed case studies based on water temperature and solar intensity

Case number	Water temperature ($^{\circ}C$)	Solar intensity (W/m^2)
1	40	250
2	50	
3	40	500
4	50	
5	60	
6	50	750
7	60	
8	60	1000
9	70	
10	80	

The (1) below represent the solar cell efficiency as a function of temperature:

$$\eta_{PV} = \eta_{ref}\left(1 - \beta_{ref}(T_{cell} - T_{ref}) + 0.085\ln\left(\frac{I_{solar}}{I_{ref}}\right)\right) \tag{1}$$

The other main equations of the problem are summarized below. The continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{2}$$

The momentum equations in X and Y directions:

$$\rho(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y})=-\frac{\partial P}{\partial x}+\mu(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}) \quad (3)$$

$$\rho(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y})=-\frac{\partial P}{\partial y}+\mu(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2})+\rho\beta g(T-T_0)+\rho\beta^* g(C-C_0) \quad (4)$$

The energy equation:

$$(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y})=\alpha(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2})+S_h \quad (5)$$

The source term in (5) is due to the radiation effect.
The concentration equation is determined by the following relationship:

$$(\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y})=D_{AB}(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}) \quad (6)$$

The boundary conditions of the problem are needed to be defined as:
At the glass section:

$$u=0,\ v=0,\ C=0 \quad (7)$$

At the brackish water line:

$$u=0,\ v=0,\ T=T_w,\ C=1 \quad (8)$$

On the side walls of the solar still:

$$u=0,\ v=0,\ \frac{\partial T}{\partial x}=0,\ \frac{\partial C}{\partial x}=0 \quad (9)$$

3. Results and discussion

The electrical output power and water efficiency for the entire integrated system are calculated and shown in Figure 2. From Figure 2, it can be observed that at the same solar intensity, the output power decreases slightly with an increase in the temperature of the saline water. This is because with higher water temperature, the air inside the solar device becomes hotter, resulting in solar cells operating at lower efficiency and consequently reducing the output power. It can also be concluded that the electrical output power is proportional to the solar intensity.
From the perspective of a solar desalination system, the increase in the temperature of saline water is of great importance in producing fresh water. Therefore, the solar radiation intensity may not appear to be directly related to the amount of fresh water produced, but its significant effect is evident with an increase in the temperature of saline water. For example, by examining cases 1 and 2, it can be inferred that increasing the water temperature from 40 to 50 degrees leads to an approximate 245% increase in the fresh water production efficiency.
Now, if we assume a constant water temperature (e.g., 50 degrees) and vary the solar intensity, the water efficiency decreases with an increase in solar intensity because the glass temperature becomes higher under intense radiation. This is an important finding that indicates a solar desalination system with a low initial temperature can have a negative impact on fresh water production. If the saline water is cold and the solar radiation intensity is high, the glass temperature quickly increases, resulting in a decrease in the evaporation rate.
To provide an estimation, cases 2 and 4 are compared, where the saline water temperature is constant at 50 degrees but the solar radiation intensity differs. If the solar radiation increases from 250 to 500 W/m², the efficiency decreases by approximately 32%. Similarly, comparing cases 4 and 6 with solar intensities of 500 and 750 W/m² respectively, it can be observed that the efficiency decreases by approximately 60%. This is because the saline water temperature is the same in both scenarios, but the radiation intensity is higher for scenario 6, resulting in a higher glass temperature and a lower fresh water production rate.
Therefore, increasing and maintaining the temperature of saline water is crucial in higher solar radiation levels during the operation of a solar desalination system.

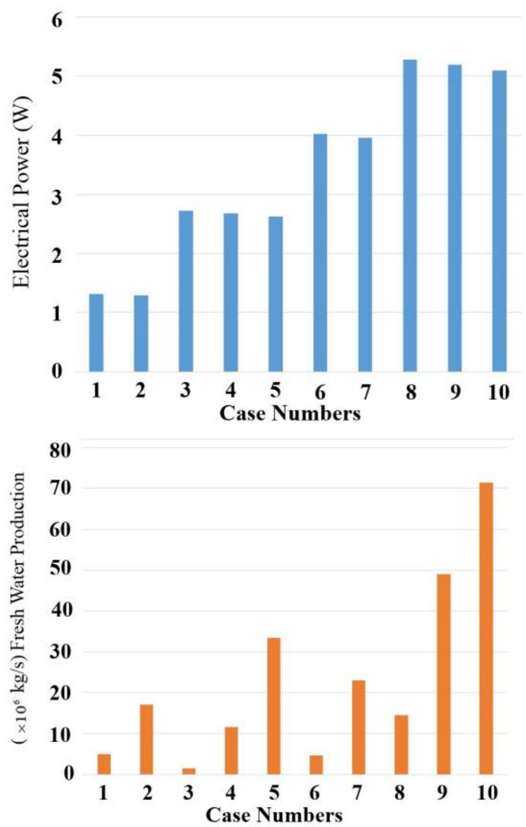

Figure 2. The electrical output power and water production rate for different case studies

4. System of Units

C	specie concentration (kg m^{-3})
D	Diffusivity (m^2 s^{-1})
g	acceleration of gravity (m s^{-2})
I	radiation intensity (W m^{-2})
P	pressure (Pa)
T	temperature (K)
t	time (s)
u, v, w	fluid velocity in Cartesian coordinates (m s^{-1})
x, y	Cartesian coordinates (m)

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
β^*	species expansion coefficient (m^3 kg^{-1})
β	thermal expansion coefficient (K^{-1})
μ	dynamic viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
η_{PV}	electrical efficiency

Subscripts

ref	reference

5. Conclusions

In this study, two separate systems, a solar desalination unit and a semi-transparent solar module, were coupled together, and their performance was numerically simulated under different solar intensities and varying temperatures of saline water. The results showed that firstly, the coupled solar system with suitable efficiency and a smaller footprint could be a novel design for residential or commercial use. Secondly, the production of fresh water significantly increased with an increase in the temperature of saline water, while the impact on the reduction of electricity production due to the system's temperature increase was negligible. The obtained results indicate that the coupled solar desalination unit with a semi-transparent solar module is suitable for southern regions of the country that have high solar radiation. It is recommended to investigate the effects of the number and placement of solar cells on the fresh water production and the swirls in future research.

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