**Modeling and Performance analysis of a Fresnel concentrator solar photovoltaic thermal energy system integrated with nanofluid spectral splitter**

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**Abstract**

In this study, the design and one-dimensional numerical analysis of a concentrated photovoltaic thermal system incorporating a spectral-splitting nanofluid was carried out. The nanofluid's spectral transmittance with different loading concentrations of ZnO nanoparticles over the full spectrum was measured experimentally, and a model system using the nanofluid as a splitter developed. The design posited solar irradiation being appropriately concentrated by a linear 1300-mm-by-70-mm Fresnel lens on a series of seven 20-mm-outer-diameter and 16mm-inner-diameter tubes through which the nanofluid flowed, allowing a large beam of limited spectra to be transmitted to the PV below, with the rest absorbed and converted to thermal energy. The photo energy conversion dependency on the specific sample solution's thermophysical properties, and on environmental parameters and properties of the solar cell was investigated. A nanofluid with a 50 ppm concentration ratio achieved transmission of spectra closest to those most useful by the photovoltaic band-gap. The temperature profile, power output, and performance of the hybrid concentrated photovoltaic thermal system for different loading concentrations of ZnO nanoparticles were computed. Since the photovoltaic module was detached from the filtering channel and integrated with the heat exchange pipe, its surface temperature was much lower than the nanofluid and output water temperature. The combined efficiency of the system under the solar irradiance on a typical day reached a maximum value of 50.35%, 65.2%, 72.70%, 74.7%, and 85% for ZnO nanofluids with concentration ratios of 20 ppm, 50 ppm, 95 ppm, 200 ppm, and 500 ppm, respectively.

**Keywords:** Concentrated Photovoltaic thermal, modeling, nanofluid, spectral splitting, solar energy, System efficiency

1. **Introduction**

Solar energy is a welcome renewable energy source that can reduce fossil fuel dependency and meet energy needs. It can be collected and utilized by means of many processes, like photosynthesis, solar thermal conversion and the photovoltaic effect. The technologies identified to convert solar energy into a useful form of energy are solar cells, solar thermal collectors, concentrated solar power and concentrated photovoltaic/thermal systems (CPV/T) [[1-3](#_ENREF_1)]. Photovoltaic/thermal (PV/T) collectors are a promising solar technology which is capable of cogenerating useful thermal energy and electricity from the same aperture area. These systems have played a pivotal role in the transition towards energy sustainability, providing more energy than the conventional photovoltaic cell [[4](#_ENREF_4), [5](#_ENREF_5)]. Concentrating a large area of sunlight to focus a small beam on a solar energy process, using optical concentrators, allows for more incident irradiation and, therefore, more output power per unit area. The concentration of sunlight on photovoltaic cells (PV) and the consequent replacement of expensive PV panel arrays with cheap concentrating mirrors or lenses can reduce the cost of solar electricity [[6](#_ENREF_6), [7](#_ENREF_7)].

Spectral energy at or near the band-gap of the semiconductor is utilized by PV cells for photoelectrical energy conversion, but the remaining photon energy is converted to thermal energy. This results in PV cell heating, which reduces their power production efficiency [[8](#_ENREF_8), [9](#_ENREF_9)]. An increase in solar radiation flux in CPV/T systems also leads to the increase of CPV/T system temperature which may lead to a high and precarious junction temperature unless the heat is used for an intended purpose or dissipated to the environment in time. When the PV cells' operating temperature is increased, not only is photo energy conversion efficiency decreased, but the PV cell material may also be damaged [[10](#_ENREF_10)]. One mechanism to solve this problem is spectral splitting: the photon energy usable by PV cells is utilized by the PV cells, and the remaining photons are engaged in thermal power generation [[11-15](#_ENREF_11)]. Nanofluid-based spectral splitting using low volume fractions of nanoparticles has become increasingly more popular for CPV/T applications due to the shift in the optical properties, inexpensively obtained. The loading of nanoparticles as optical filters for CPV/T systems will decrease transmittance, leading to a decrease in the short circuit current and lower electrical conversion efficiencies. Still, these powerfully absorbing nanofluids produce higher photothermal conversion efficiencies. The overall efficiency of the CPV/T system is dependent on the volume fraction of nanoparticles chosen [[16-18](#_ENREF_16)].

Nanofluids, thus, are typically employed for energy conversion efficiency enhancement since they exhibit high heat-transfer capabilities and optical properties [[19](#_ENREF_19)]. But, it is important to find one best kind of low cost nanofluid that can be applied to nanofluid-based spectral splitting CPV/T systems [[8](#_ENREF_8)].

As stated above, several methods are proposed in the literature to improve CPV/T system performance; employing a PV cooling system, using appropriate concentrators, and applying spectral filters are popular. Nanofluids offer a solution embodying all these characteristics.

In the study, we designed and investigated the integration of concentrated solar irradiation, to achieve higher incident light on the system, with PV cooling and with spectral splitting, to use the full spectrum in an optimum way. The general objective of the study was to design an efficient concentrated hybrid photovoltaic thermal energy system. We also developed a model and investigated the energy conversion performance for the specific physical properties of the system. The study will help satisfy the green energy needs of households, industry and enterprises as an alternative solar electrical and thermal conversion technology. It also contributes to promoting proper green energy harvesting design with multi-purpose use of space and to developing technology with practical applications.

1. **Methodology**

We propose a CPV/T which converts full-spectrum incident sunlight to both electricity and thermal energy. It constitutes an immediate solution to using the entire solar spectrum for electricity in the PV band and for thermal energy from the heat waste and radiation outside the PV band, for purposes of higher temperature water heating. The concentrating system contains a Fresnel lens, PV cell, nanofluid flowing in glass tubes, and heat exchangers attached to the PV cell and in the form of a coil immersed in a water tank as shown in Fig.1. Incident sunlight is firstly concentrated by the Fresnel lens. The concentrated sunlight focuses on the nanofluid flowing in quartz tubes. The photons which can be converted most efficiently by the PV are transmitted to the PV module. The low-energy photons, which cannot be converted by the PV, and high-energy photons, which would be converted inefficiently, are absorbed and converted to thermal energy. The electrical energy converted by the PV is recorded directly. The heat pipe attached to the PV module is used as waste thermal energy collector. This energy is extracted by fluid flowing in the pipe which is directed to the heat exchange water tank. The outlet water temperature from the pipe attached to the PV module is the inlet water temperature for the water tank. Finally, the tank's outlet water temperature is determined to calculate the actual thermal energy derived from the full spectrum collected by the CPV/T system. When the system is operating, water first flows through the heat exchanger attached to the PV module, and then flows to the heat exchange water tank to be further heated to a higher temperature.

A one-dimensional numerical model was developed for simulation purposes to determine the temperature, electrical output, thermal power, and performance of the whole system. The Fresnel lens's geometry, spectral splitting nanofluid tubes, heat exchangers, and PV orientation were designed to obtain the optimal system performance. The nanofluid's optical properties were experimentally measured and used as input to the model to determine the absorption and transmission of radiation in the spectral splitting of the CPV/T system. The system was designed in such a way that the visible light could be transmitted and light in the low and high wavelength spectrum could be absorbed by the nanofluid. The zinc oxide nanofluid was prepared using a two-step method with water and ethylene glycol (EG) in a 50%:50% ratio. 1 mg, 2.5 mg, 4.75 mg, 10 mg and 25 mg of nano powder ZnO were poured into a 50-ml water-glycol solution and ultrasonically stirred for 30 minutes. In the following, the samples are represented by the letters A, B, C, D, E and F where A is simply a solution of water and EG, that is, A (0 ppm) and B (20 ppm), C (50 ppm), D (95 ppm), E (200 ppm) and F (500 ppm).

1. **Model description**

The proposed CPV/T system is composed of a linear Fresnel lens, a side by side channel of seven quartz tubes through which the nanofluid flows, a silicon PV module, a heat exchange pipe attached to the PV, and an aluminum plate as shown in Figs. 1 and 2. A linear Fresnel lens made of polymethyl-methacrylate with dimensions 760x1300x5 mm is used to concentrate the light rays on the upper surface of the nanofluid flowing through the tubes. Seven quartz tubes with an inner diameter of 16 mm and an outer diameter of 20 mm and 760mm in length are used for spectral splitting nanofluid flow. The nanofluid is used for both spectral filtering and as an intermediate thermal energy exchange

The incident concentrated light from the Fresnel lens strikes the top surface area of the tubes. This implies that the effective light exposure surface area of the filtering channel is about 0.167 m2, and the concentration ratio is 5.916. Four monocrystalline silicon photovoltaic modules each 190x380x35 mm in size, with cell efficiency 21.5% and 10 w power at standard test conditions (1000 w/m2 solar radiation intensity, 25 environmental temperature and air mass 1.5) are placed under the tubes. The effective area of the PV module is 0.288 m2, and the geometric concentration ratio is 3.43. The nanofluid absorbs spectral radiation, preventing it from reaching the solar cell, before flowing into a heat exchange water tank and passing through a copper coil. It releases thermal energy while flowing in the coil immersed in the insulated water tank. The thermal power and thermal efficiency of the system are determined by using the outlet and inlet temperature of water from the water tank heat exchanger. The nanofluid is finally collected in a nanofluid tank completing the cycle, ready for spectral filtering next day.

*Cold water tank*

*Fresnel lens*

*PV module and Heat exchange*

*Heat Exchange tank*

*h=72cm*

*Pump*

*Filtering tube*

*Pump*

*Hot water*

Fig. 1. Schematic representation of the proposed CPVT system.

The homogeneity of the photons impinging on the CPV module, dimensional specification of the model elements, and the optimal distance between the filtering and PV module was studied using Tracepro. The lumped thermal capacitance method was applied for the energy equations in each layer of the subsystem to determine the power collected and the overall performance of the whole system

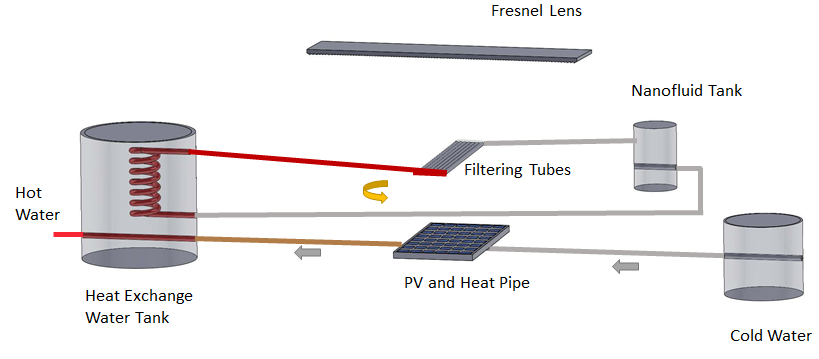


Fig. 2. 3D diagram of the CPV/T model.

1. **Mathematical modeling**

A model was formulated to evaluate the spectral splitting CPV/T system. The model analysis was performed by applying energy balance equations for the concentrator, spectral filtering, PV module layers, and heat exchangers. With these, it was possible to predict the temperature, the electrical and thermal powers, and the electrical and thermal efficiencies of the CPV/T. The amount of solar radiation reaching the PV module's surface is a function of the geometric concentration ratio *CR,* the intensity *I* of the direct normal irradiation and optical efficiency of the Fresnel lens, the transmittance of the nanofluid flow and the surface area of the PV module.

### Assumptions to simplify the CPV/T model system in this study are:

1. One dimensional uniform temperature distribution of the system is assumed due to the small area of the protective aluminum frame attached to the Fresnel lens, the filtering tube channel and the PV module [[21](#_ENREF_21), [22](#_ENREF_22)].
2. The nanofluid and water inlet temperature to the exchange attached to the PV module was taken equal to the ambient temperature.
3. Reflection of sunlight is ignored since we used a Fresnel lens, quartz tube, and glass with high transmittance [[23](#_ENREF_23)].
4. The thermophysical properties of the model elements are independent of temperature [[24](#_ENREF_24)].
5. The nanofluid flow is turbulent, uniform, and incompressible [[25](#_ENREF_25)].
6. Heat loss is ignored due to the insulation material [[22](#_ENREF_22)].

The power coming to the system through the Fresnel lens is [[26](#_ENREF_26), [27](#_ENREF_27)].

where *I* is the spectral solar radiation intensity with air mass 1.5, is the wavelength, and is surface area of the Fresnel lens. The total amount of power incident to the [nano](https://www.sciencedirect.com/topics/engineering/beam-splitter)fluid splitter can be calculated by Eq. (2) [[27](#_ENREF_27), [28](#_ENREF_28)].

where and are the concentration ratio and the effective surface area of the nanofluid splitter tubes, and the transmittance of the Fresnel concentrator. More than 99% of the surface solar flux is contained in the spectral region between 300 nm initial wavelength and 2500 nm final wavelength, hence solar radiation energy apart from this band can be ignored [[27-29](#_ENREF_27)]. Transparent quartz tubes are used to hold the nanofluid to reduce optical loss. This solar energy is equal to the thermal energy absorbed by the nanofluid, the transmitted energy to the PV module and the energy loss.

The power absorbed by the nanofluid is [[27](#_ENREF_27), [29](#_ENREF_29)].

where is the optical efficiency of the concentrator, is the transmittance of the tube, and is the absorbance of the nanofluid at wave length, λ. Solar radiation absorbed by the nanofluid is equal to the thermal energy transferred to the water while the nanofluid is flowing inside the coil and the energy lost. The insulation layer exchanges the heat by conduction with the heat exchanger and by convection with the ambient air.

The power transmitted from the nanofluid filtering tube channel to the PV module integrated with the heat pipe sub system is [[27-29](#_ENREF_27)]:

where and are the geometrical concentration ratio and area of the PV surface, respectively, and is the transmittance of the nanofluid. Total solar energy transmitted to the PV module is equal to the sum of the produced electric power, the heat dissipated to the ambient through convection and radiation and the thermal energy conducted to the heat exchanger attached to the PV, the three forms of energy into which it is transferred. The outflowing water from the heat exchange attached to the PV module is connected to the heat exchange water tank for further heating. According to the radiation transfer model, the spectral reflectivity, absorptivity and transmittance of the nanofluid filter depend on the wavelength of the incident light and the incidence angle. Therefore the power in each layer is affected by the optical property of the material selected and its geometry.

As is shown in Fig. 3, the present system is composed of the linear Fresnel lens, spectral splitter, PV module, heat pipe water channel on the back of the PV cells, and water tank heat exchange. When the sunlight converged by the Fresnel lens passes through the quartz tubes filled with nanofluid, a portion of the solar energy is absorbed and converted into heat by the nanofluid, while the rest is transmitted to the PV module. The nanofluid in the tube is not only the spectral splitting filter, but also the medium for absorbing and transporting heat from the energy receiver.

The electrical power converted can be calculated by [[27](#_ENREF_27), [30](#_ENREF_30)]:

where FF and, are the open circuit voltage, fill factor and short-circuit current of the PV given by [[31](#_ENREF_31)]:

)

where is the optical response of the silicon solar cell [[32](#_ENREF_32)]. The open-circuit voltage can be calculated by equation Eq. (7).

where A′ and are the ideality factor and surface temperature of the solar cell, the Boltzmann constant, e the elementary charge, and the dark saturation current density, which is given by [[33](#_ENREF_33), [34](#_ENREF_34)]:

where is an empirical parameter. The filling factor is calculated using:

where, is the voltage at the maximum power point of the I - V curve given by:

where k is sn empirical parameter of the solar cell.

The electrical efficiency of the CPV/T system is calculated by

The short current of the PV module is used to calculate its corresponding open circuit voltage and fill factor based on the reported PV model [[34](#_ENREF_34)]. Finally, the electrical power output can be obtained through multiplying the current by open circuit voltage and fill factor.

The thermal power output from the system collected by the exchange integrated with the PV module, nanofluid, and the water tank can be determined by;

where and are the mass flow rate and the specific heat capacity of water and and are the outlet and inlet water temperature, respectively.

The thermal efficiency of the system is given by:

The overall efficiency of the system will be calculated by Eq. (14) [[35](#_ENREF_35)].

The merit function of the CPV/T system will be calculated by Eq. (15) using as a standard a 3:1 worth factor () of electricity to thermal energy to determine if the selected liquid would effectively convert sunlight into usable energy, as compared to the electrical power output of an unfiltered solar cell.

1. **Energy balance equations of the dynamic model**

### Applying the electrical equivalent circuit of the heat transfer in each layer of the CPV/T system and the setup of the differential equations is summarized as follows. The thermal resistance network circuit of the CPV/T model system is presented in Fig. 3.

The thermal capacitance is defined by Eq. (16) [[36](#_ENREF_36)]

where is the density, A the area, the thickness, and c the specific heat capacity of the circuit element in the model.

Energy equation of each sub system

1. The Fresnel lens layer

where , and are the thermal capacitance, temperature, absorptivity, and surface area of the Fresnel lens, respectively; is the incoming solar radiation striking the top surface area of the Fresnel lens; is the convective thermal resistance between the Fresnel lens and the ambient air; are the heat radiative resistance between the Fresnel lens and sky surface, and between the Fresnel lens and the filtering tube channel, respectively; and and are the ambient and sky temperature, respectively. , , and are given by Eqs. (18), (21), and (22), respectively [[29](#_ENREF_29), [37](#_ENREF_37)].

where is the surface area of the Fresnel lens, is the convective heat transfer coefficient between the Fresnel lens and ambient air defined by [[24](#_ENREF_24)]:

where is the wind speed, which was 2.6 m/s on the day of the experiment. The sky temperature is given by [[38](#_ENREF_38)].

where is the ambient temperature.

Fig. 3. The heat transfer mechanism and the corresponding electrical circuit model of the CPVT system.

The radiative thermal resistance between the concentrator and the sky and the filtering channel surface and top glass layer of the PV module are given by the two equations below.

where is the emissivity of the Fresnel lens 0.9, and the Stefan-Boltzman constant, which is

5.67 x 10-8w/m2.K4.

1. The spectral splitting nanofluid tube channel layer

where and are the thermal capacitance and temperature of the filtering tube channel, respectively; and are the radiative thermal resistance between the Fresnel lens and filtering tube channel and between the filtering tube channel and the top glass layer of the PV module given by Eqs. (24) and (25), respectively; and is the convective thermal resistance between the filtering channel and nanofluid, given by Eq. (27).

)

The emissivity of the glass used in the study is 0.95 and , the convective thermal resistance between the filtering channel and the nanofluid is determined by:

where is the thermal conductivity of the nanofluid and is the inner diameter of the tube ,  Nunf is the Nusselt number, which can be calculated using Eq. (28) [[38](#_ENREF_38)].

where φ is the particle concentration, and and are the Prandtl number and Reynolds number calculated by Eqs. (29) and (30), respectively [[39](#_ENREF_39)].

where is the velocity and the dynamic viscosity of the fluid. Since the nanoparticles used in this study are spherical with a diameter of about 5.3 nm and volumetric fraction ratio less than 4%, the dynamic viscosity of the nanofluid can be determined by Eq. (31) [[40](#_ENREF_40)]:

where is the viscosity of the base fluid, which is determined by [[41](#_ENREF_41)]:

where are the volume concentrations, and the densities, and and the dynamic viscosities of water and EG, respectively.

The specific thermal capacitance and density of the nanofluid are given by Eqs. (33) [[40](#_ENREF_40)]:

where is the concentration ratio of the specific sample solution, and the specific thermal capacitance and density of the nanoparticle, and and the specific thermal capacitance and density of the base fluid, respectively. The density of the base fluid can be calculated by:

Using the Maxwell expression for the spherical nanoparticles the thermal conductivity of the nanofluid is given by [[23](#_ENREF_23), [42](#_ENREF_42)]:

1. The nanofluid inside the filter channel layer

where , and are the thermal capacitance, temperature, and specific heat capacity of the nanofluid, respectively; is the power absorbed by the nanofluid; is the nanofluid mass flow rate, which is 0.0016 kg/s; and and are the outlet and inlet temperature of the nanofluid, respectively, with the inlet temperature assumed to be equal to that of the environment.

1. The top glass layer of the PV module

where, , , and are the thermal capacitance, temperature, absorptivity, and transmittance of the top glass layer of the PV module; is the power transmitted to the top surface of the PV module; and and are the radiative thermal resistance between the filtering tube channels and top glass layer of the PV module and the conductive thermal resistance between the PV and top glass layer, respectively.

Using the conduction heat transfer coefficient between two neighboring component layers m and n, which can be expressed by Eq. (39) [[43](#_ENREF_43), [44](#_ENREF_44)].

where and are the thickness of the layers *m* and *n* and and are the thermal conductivity of the respective layers. The conductive thermal resistance between the glass and the PV layer is given by [[24](#_ENREF_24), [45](#_ENREF_45)]:

where and are the heat conductive coefficient and contact area between the glass and PV module.

1. The PV module layer

where, and are the thermal capacitance, temperature and absorbance of the PV module, respectively; *Pele* is the electric power output of the PV module; and and are the conductive thermal resistance between the PV and top glass layer and TPT and PV layer, respectively.

1. The TPT (**Tedlar Polyester Tedlar**) layer

where and are the thermal capacitance and temperature of the TPT layer; is the conductive thermal resistance between the PV layer and TPT layer; is the conductive thermal resistance between the TPT layer and conducting pipe; and is the conductive thermal resistance between the TPT and insulator. The thermal resistance between these elements can be calculated using Eqs. (43) and (44) [[46](#_ENREF_46)]:

where is the heat conductive transfer coefficient and is the contact area between the TPT and tube conductor.

where and are the contact area between the TPT and insulator and heat conductive transfer coefficient, respectively. The contact area between the TPT and the tube is the product of the thickness of the TPT layer and length of the tube.

where n, , and are the number, thickness, and length of the pipe(s) integrated with the PV, respectively. The conductive heat transfer coefficient between the TPT and the conducting tube is determined by:

where is dependent on the tube spacing *w* and outer diameter of the tube

The conductive heat transfer coefficient between the TPT and the insulator is calculated by:

where and are the thermal conductivity and thickness of the insulator, respectively. The contact area between the TPT and insulator is given by:

where A is the area of TPT and w is the tube spacing.

1. The heat collecting pipe integrated with the PV module layer

where and are the thermal capacitance and temperature of the conducting pipe, respectively; is the conductive thermal resistance between the TPT and the conducting tube; is the conductive thermal resistance between the insulator and the conducting tube; and is the convective thermal resistance between the conducting tube and water flowing inside the tube.

The convective thermal resistance between the tube and the water will be determined by:

where and are outer diameter and length of the tube, respectively; and is the convective heat transfer coefficient, which can be determined by Eq. (52) [[47](#_ENREF_47)].

where is the Nusselt number, is the thermal conductivity of water, is the hydraulic diameter, which is the inner diameter of tube. The contact area of the tube with the insulator is

For the insulator layer with a thickness much larger than the outer diameter of the tube,

can be found from Eqs. (44), (45), and (48) above.

1. The insulating material layer

where is the thermal capacitance and is the temperature of the insulator; is the conductive thermal resistance between the conducting tube and insulator; is the conductive thermal resistance between the TPT and insulator; and is the convective thermal resistance between the insulator and the environment.

1. The water flowing inside the pipe integrated with the PV module layer

where , , are the thermal capacitance, temperature, mass flow rate and specific heat capacitance of the water flowing inside the pipe; and are the outlet and inlet temperature of the water, respectively; and is the convective thermal resistance between the conducting tube and water, which can be calculated using Eq. (51). The mass flow rate of the water inside the pipe integrated with the PV module was adjusted to 0.00166 kg/s and the inlet temperature of the water was taken to be equal to the ambient temperature. The temperature of the water in the tube is the average of the inlet and outlet temperature of water in the tube.

1. The nanofluid flowing in the coil and immersed inside the water heater tank layer

where , , , and are the thermal capacitance, temperature, mass flow rate, and specific heat capacity of the nanofluid flowing in the coil immersed in the heat exchange water tank; and are the outlet and inlet temperature of the nanofluid, respectively; and is the convective thermal resistance between the nanofluid and the water in the water tank, which can be calculated by:

where is the heat transfer area between the coil and the water in the heat exchange tank, and is the convective thermal resistance between the nanofluid and water in the tank. Neglecting the thermal resistance of the wall of the coil since it is very thin, can be determined by [[24](#_ENREF_24), [47](#_ENREF_47)]:

where and are the outer and inner diameter of the coil, respectively, is the convective heat transfer coefficient between the water in the water tank and the wall of the coil, which can be described by Eq. (59) [[47](#_ENREF_47)]; and is the convective thermal resistance between the nanofluid and wall of the coil.

where is the thermal conductivity of water, is the inner diameter of the coil, and  is the correction coefficient of the bend effect given by:

where is the curvature radius of the spiral tube.

where is the volume expansion coefficient, which is/K, g the acceleration due to gravity, which is 9.8 m/s2, , and the dynamic viscosity, thermal conductivity, and specific heat capacity of the nanofluid, and the outer diameter of the coil, respectively.

1. The water tank layer

where and are the thermal capacitance and temperature of the water in the heat exchange tank, and is the convective thermal resistance between the nanofluid and water in the tank.

The parameters used in the simulation of our modeled system are shown in Table 1. Some of the parameters are based on measurements specific to the model system; some are taken from the literature, and others are properties of the materials used.

Table 1

Parameters used in the model

Fig. 4. Flowchart of CPV/T computation

1. **Results and discussion** 
   1. Energy allocation

The spectral transmittance of ZnO nanofluid with five different concentrations was measured using a V-670 spectrophotometer for different wavelengths ranging from 300--2500 nm at intervals of 5 nm. The sample solutions and the spectral transmittance measurements are presented in Fig. 5 below. The nanofluid highly absorbed the short- and long-wavelength radiation. Photons at these wavelength ranges are outside the usable PV electrical energy conversion band. The high concentration of nanofluid spectral filtering results in high absorbance, and the low concentration results in high transmittance of the spectra. Therefore, at some point between these two extremes, there lies an optimum concentration of nanofluid for the intended requirement that maximal thermal and electrical energy be generated. The results obtained show that the 50 ppm nanofluid solution transmits the spectra that best allow photons to excite electrons across the silicon solar cell band gap. So this concentration is to be preferred as it generates optimum amounts of both electrical and thermal energy.

|  |  |
| --- | --- |
| (a) |  |
|  | (b) |

Fig. 5. The nanofluid solution samples and their spectral transmittance: (a) Nanofluid sample solutions (b) the spectral transmittance of the samples

The photo energy conversion obtained with each sample solution depends on the thermophysical properties of the specific solution and its ZnO concentration, and on environmental parameters and the properties of the solar cell. To investigate this conversion, we determined important parameters specific to our samples from their base materials. The major findings using the parameters of the experiment and the model are summarized in Table 2 and Fig. 6. Then we applied the model we developed to analyze power output and system performance.

Table 2

Theormophysical parameters of the nanofluid determined based on the samples used

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| No | Sample | Viscosity  (Pa.s x10-3) | Density  (kg/m3) | Specific heat capacity  (J/kg.K) | Prandtl No  - | Re (x104) | Nu |
| 1 | 0 | 2.0100 | 1055.10 | 3324.9 | 18.20647 | 6.695012 | 16.66335 |
| 2 | 20 ppm | 2.0098 | 1055.19 | 3324.55 | 18.20548 | 6.695091 | 16.66342 |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |

Fig. 6 shows the thermal conductivity of the nanofluid solution calculated using equation 35. It demonstrates that the thermal conductivity of the fluid improves as more ZnO nanoparticles are loaded into the solution. The increase in thermal conductivity of the nanofluid enhances the heat transfer rate in the heat exchange water tank. In this study, the heat transfer rate was highest for a 500-ppm particle-loaded sample.

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Fig. 6. Thermal conductivity of the sample solution

The input local direct solar irradiation on August 19, 2020 (Taiwan, Taipei) is presented in Fig. 7. The solar radiation intensity increased to a maximum value of 842.96 w/m2 at noon and then dropped to 9.98 w/m2. The model analysis was carried out using these solar radiation intensity figures with the specified solar concentration on the filtering channel and the PV surface. Ray tracing and distribution on the tubes' upper surface and CPV/T are presented in Fig.7 b.

|  |  |
| --- | --- |
|  |  |
| a) b) | |
| Fig. 7. Hourly variation of solar irradiance on the typical day August 19/2020 and ray distribution on the module: (a) Solar irradiance on the typical day (b) ray distribution on the module | |

Applying Eqs. (1) and (2), the power collected by the concentrator and the amount of irradiative power reaching the top surface of the spectral filtering tube channel were determined using MATLAB. The solar spectral irradiance on the Fresnel lens and spectral response of the PV are presented in Fig. 8. Using the optical data for the nanoparticles' different loading concentrations, we numerically found the power absorbed by the nanofluid, power transmitted to the PV module integrated with the heat exchanger, and the short circuit current density. The least energy absorbed was observed with the base fluid and the most with the 500-ppm sample. As shown in Fig. 9 b, the power absorbed by the nanofluid increased as the concentration increased. The power absorbed by the base fluid and nanofluid with the highest concentration ratio was 163.97 w/m2 and 676.13 w/m2, respectively. This means that the spectral solar insolation on the surface of the PV module decreased. That value was 575.97 w/m2 for the base fluid and 89.63 w/m2 for the most concentrated nanofluid. This allocated power was used as input to the mathematical model to find the temperature profiles, power output, and performance of the CPV/T system.



Fig. 8. The solar spectral irradiance on the Fresnel lens and spectral response of the PV [[30](#_ENREF_30)].

|  |  |
| --- | --- |
|  |  |
| (a) | (b) |

Fig. 9. Solar irradiation utilization by the concentrated system: (a) The spectral distribution on the PV module surface (b) Daily power allocation for the different concentration samples

* 1. Temperature profile

The hourly varying temperature of each subsystem in the model was computed for the different nanofluid concentrations and is presented in Fig. 10. As in previously published research, our study indicates that the nanofluid's working temperature increases proportionally to the increase in the concentration of nanoparticles. Since the PV module is detached from the filtering channel and integrated with the heat exchange pipe, its surface temperature is much lower than the nanofluid temperature, even in the case of low-concentration samples. Each subsystem's surface or bulk temperature in the model affects the following layers' temperatures due to radiation, conduction, or convective heat transfer. In the case of the base fluid or a nanofluid with a low concentration ratio, our results show a smaller rise in the nanofluid’s temperature is accompanied by higher heat exchange-coupled PV module temperatures. This is due to the lesser absorption of energy by the filtering channel, leaving large amounts of energy free to strike the PV surface. But the heat pipe properly absorbs the waste heat energy. So, it is also found that the hourly varying surface temperature of the PV module is consistently less than that of the nanofluid flowing through the filter channel and heat exchange water tank for the base fluid and other nanoparticle loading concentration ratios. The output temperature of the water heated by the pipe attached to the PV and the heat exchange water tank increased as the concentration increased. The maximum output water temperature computed was at 14:00, and its value was 313.74 K, 315.90 K, 324.13 K, 332.56 K, 333.42 K, and 350.68 K for samples A, B, C, D, E, and F, respectively..

|  |  |
| --- | --- |
|  |  |
| a) Temperature variation of A | b) Temperature variation of B |

|  |  |  |
| --- | --- | --- |
|  | |  |
| c) Temperature variation for C | | d) Temperature variation for D |
|  |  | | |
| e) Temperature variation of E | f) Temperature variation of F | | |

Fig. 10. The temperature of each sub system in the model for the different concentrations

* 1. Power output

We numerically determined the system's electrical and thermal power output based on the proposed optical, electrical, and thermal models. The hourly varying electrical power output and short current density of the model are presented in figure 11. The highest power output and short circuit current was obtained for the base fluid, and the smallest value was for the 500 ppm sample solution. The result clearly shows the increase in loading concentration of nanoparticles decreases the electrical power output and short circuit current. The peak value of electric power for the sample A , B, C, D, E, and F are 183.81 w/m2, 167.14 w/m2, 129.57 w/m2, 108.34 w/m2, 106.67 w/m2 , 29.47 w/m2, respectively.

|  |  |  |
| --- | --- | --- |
|  |  | |
| (a) | | (b) |

Fig. 11. The hourly varying electrical power output and the short current density of the CPV/T system: (a) The electrical power output (b) The short current density

The hourly varying thermal power output of the model is presented in Fig. 12. As discussed above, the nanofluid in the filter channel absorbs energy from parts of the spectrum and then outflows into the coil immersed in a heat exchange water tank, which is the source of thermal power. The greater the nanoparticles' concentration, the more the absorption of energy from the spectrum, which directly contributes to the increases in thermal power output.

Fig. 12. The hourly varying thermal power output of the system

* 1. Energy conversion performance

The energy conversion efficiency of our model system is presented in Fig.13. The results show extensive time variation in thermal efficiency and the almost stable electrical energy efficiency of the system. The electrical efficiency of the CPV/T module without nanoparticles was 19.5%. This photoelectrical conversion efficiency of the CPV/T module decreased to 18.75%, 14.53%, 12.15% 11.96%, and 3.30% for the 20 ppm, 50 ppm, 95 ppm, 200 ppm and 500 ppm concentration ratio sample solutions, respectively. The decrease in electrical efficiency is mainly caused by solar insolation reductions on the CPV module's surface. The photons absorbed by the concentrated solutions contribute to an enhancement of thermal efficiency that compensates for the photoelectrical efficiency reduction. The maximum overall efficiency of the system computed was 46.83%, 50.35% , 65.21 %, 72.27 %, 74.69%, and 85.27% for samples A, B, C, D, E, and F, respectively.

The usefulness of the model's energy conversion was analyzed with the merit function and was found to increase in value from 1.076 to 1.184. over the samples A to F, respectively. This shows that the nanofluid filter effectively converts the absorbed light to useful energy.

|  |  |
| --- | --- |
|  |  |
| 1. Efficiency of A (base fluid) | 1. Efficiency of B(φ 20ppm) |
|  |  |
| 1. Efficiency of C (φ 50ppm) | 1. Efficiency of D(φ 95ppm) |
|  |  |
| 1. Efficiency of E (φ 200ppm) | 1. Efficiency of F (φ 500ppm) |

Fig. 13. The photon energy conversion efficiency of the model system.

1. **Conclusions**

We designed a linear Fresnel lens-based CPV/T system collecting an extremely wide light beam into an effective nanofluid filtering and PV module system integrated with a heat exchange pipe. The filtering tubes arranged in rows without a gap allow intense light striking the top surface to be transmitted or absorbed, contributing intended amounts of power to the required form of either photoelectrical or thermal energy conversion. In the study, we investigated the photon energy conversion's dependence on the specific sample solution's thermophysical properties and on environmental parameters and the properties of the solar cell. The prepared nanofluid's optical properties were measured by UV-VIS spectrometer, and light ray distribution and local solar irradiation information were obtained with Tracepro. These parameters were applied to the developed model to analyze the model's power output, system performance and energy benefits. The major findings are summarized below.

* A light beam focused by a Fresnel lens on sequentially-arranged filtering tubes of the optimum diameter without a gap, together with a PV module to which a heat exchanger is attached, can be employed as a resourceful photo energy conversion system. It is one novelty of our study that the light rays travel equal distances while propagating inside the tubes and distribute uniformly. Many other researchers, as far as it is our understanding, have used other forms of channel.
* Using optical data for the different loading concentrations of nanoparticles, we numerically found the power absorbed by the nanofluid and the power transmitted to the PV module integrated with the heat exchange. The use of a 50:50% water-ethylene glycol solution as a base fluid will filter out 19.58% of the total solar irradiation on the CPV/T system. It was also found that the nanofluid solution with concentration ratios of 20 ppm, 50 ppm, 95 ppm, 200 ppm, and 500 ppm will filter 22.94%, 42.43%, 50.59%, 52.08%, and 80.75% of the spectrum, respectively.
* We numerically determined the temperature profiles of the elements of the model system and found that the filtering tubes and nanofluid have the highest values. The peak temperature of the nanofluid is higher, by far, than the PV module’s peak temperature for all samples A to F, and the temperature of the water in the tank rises to a peak value at 14:00 of 313.73 K, 314.19 K , 324.12 K 332.56 K, 333.42 K, and 350.68 K, respectively..
* The combined efficiency of the system under the solar irradiance of a typical day with a geometrical concentration ratio of 5.8 at the filtering channel and 3.43 at the PV module reaches a maximum value of 50.35%, 65.2%, 72.70%, 74.7%, and 85% for a ZnO nanofluid of concentration ratios 20 ppm, 50 ppm, 95 ppm, 200 ppm, and 500 ppm, respectively.
* The usefulness of the model's energy conversion was analyzed by merit function and was found to increase in value from 1.076 to 1.184, over the samples A to F, respectively.