PERFORMANCE ENHANCEMENT OF COCENTRIC PHOTOVOLTAIC THERMAL RECEIVER SYSTEMS BY USING EFFECTIVE COOLING METHODS

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ABSTRACT

In the present study, a novel geothermal based cooling technology is developed for the cooling of PV and CPV system, which are named as earth water heat exchanger (EWHE) and earth air heat exchanger (EAHE). For the development of such technology, the simulations were carried out in TRNSYS by coupling EWHE with unglazed PV panels. The simulation results showed that the performance of the coupled (unglazed PV/T+ EWHE) system hardly depends on the EWHE pipe material and pipe diameter. Thus, instead of using expensive galvanized iron (GI) and steel pipes, cheaper pipe material could be used with smaller diameters, like 12 mm, to achieve optimum performance. Further simulation studies were carried out on glazed PV/T systems with EWHE cooling by developing one dimensional mathematical model using MATLAB vR12a. The analytical models were developed for two types of glazed PV/T systems i.e. tube-and-sheet and broad water channel. To validate these two models with the simulated one. It was observed that, with the use of EWHE cooling, the electrical efficiency of tube-and-sheet PV/T system is increased by 1.5% as compared to without cooling.

Keyword, *TRANSYS,CPV,MATLAB,EWHE*

1. INTRODUCTION

The energy consumption in the world has increased over the decades. In 1973, the primary energy consumption was 6,101 million tonnes (Mtoe) and it has grown up to 13,699 Mtoe in the year 2014. Electrical energy is a high grade form of energy which is being used directly in day to day life. And the demand of electricity is increasing at the rate of 3% per year due to globalization and the increase in technology for human comfort. If the current trend of global energy use-demand continues, the supply of fossil fuels is predicted to be exhausted within the next centuries. A report by International energy agency in 2001, estimated that with the existing rate of consumption, the oil reserves will last up to the year 2100 and the coal reserves will exhaust in the next 170-200 years. Burning fossil fuels releases stored greenhouse gases and lead to an increase in global warming. This disturbs the global carbon cycle, and leads to an increase in atmospheric CO2 levels. The intergovernmental panel on climate change also estimated that the global average atmospheric temperature has increased by 0.6 °C in the last century and with the existing pace of carbon emissions, it will increase by 1.4 to 5.8 °C by 2100. The developed nations have signed a pact to decrease their carbon emissions in coming years.

1.1 SOLAR ENERGY

The Sun is the primary source of energy for life on Earth. Being a hot gaseous matter, the effective temperature of the Sun‘s surface is 5778 K which radiates 63 MW/m2 energy in all the directions. The Earth receives only 1.7×1014 kW of energy. It is estimated that 84 minutes of solar radiation falling on the earth would cover the energy demand of the world for the whole year. India, on an average, has 300 sunny days per year and receives an average hourly radiation of 200 MW/km2. The India energy portal estimated that around 12.5% of India‘s land mass, or 413,000 km2, could be used for harnessing solar energy. Solar energy in general and photovoltaic (PV) in particular can provide a good source of producing clean energy for such areas. The area could be further increased by the use of rooftop solar PV systems. The solar PV growth in India has been slow since its inception, but gained pace after the announcement of Jawaharlal Nehru national solar mission and later national solar mission. For instance, the overall cumulative capacity of solar power in the country during 2009 was 9.13 MW but it has grown to 9012.85 MW in year 2016-17 and expected to grow up to 1,00,000 MW by 2022 as per the target of national solar mission..

1.2 Photovoltaic systems

Solar energy can be harnessed to produce electricity in two ways, PV and concentrating solar power (CSP). The PV technology works on the PV effect which was first discovered by the physicist Edmund Becquerel in 1839 who recommended that sunlight can be converted directly into electricity using semiconductor devices known as PV cells. The PV effect works on the principle of photon energy where photons with less than 1100 nm of wavelength has ample energy to break the bond in the semiconductors, creating a free electron and a free hole. These movements of electrons generate electricity when connected with external loads The PV cells are made-up of semiconductor materials having high absorption characteristics of solar radiation matching with the solar spectrum. PV system uses various semiconductor materials and technologies such as crystalline silicon, cadmium telluride, gallium arsenide, chalcopyrite films of copper indium selenide, etc. Now silicon solar cells (SCs) represent 40% of the world, SCs production and yield efficiencies varies between 9 to 18%. PV technology can be thin films or wafer based technology.

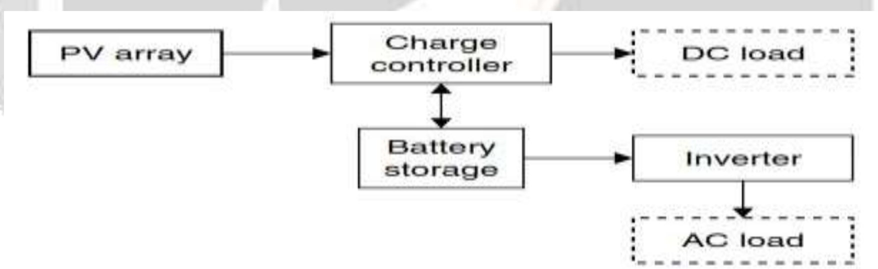

Fig. 1 Stand-alone PV system

1.2.1 Photovoltaic module characteristic curve

The PV module which is used in the solar power plant need to be tested for its efficiency and performance characteristics. The SCs are characterized by a PV module characteristic curve which is the current-voltage (I-V) curve as shown in Fig. 1.4. A typical I-V curve represents values of voltage and current under constant solar insolation and ambient temperature. This curve provides the required information of the PV module. The commonly used parameters of the I-V curve include electrical, thermal and physical characteristics of a SCs.

The main parameters of I-V curve are explained as below:-

<u>Short circuit current (Isc)</u>
It is the maximum current that PV module will produce corresponding to zero voltage.
<u>Open circuit voltage (Voc)</u>
It is the maximum voltage that PV module will produce corresponding to zero current.

Maximum power

It represents the maximum power obtained from the I-V curve at a constant solar insolation and ambient temperature conditions.

Fill Factor (FF)

It is the ratio of the maximum power to the product of open circuit voltage and short circuit current. This factor represents the quality of PV panel.

PV panel efficiency (ηe)

The instantaneous efficiency of the PV module is defined by the ratio of maximum power that can be obtained by the incident solar energy G (I) over that panel area (APV). Mathematically, it is represented as:

1.2.2 Concentrating photovoltaic system

The PV cells are flat and occupies a large area as the efficiency depends upon the same. The cost of the PV is still higher as compared to conventional sources of power generation due to the large size of panels.

Advantages

- Required less PV material for the same output as compared to normal PV system.
- Achieved high electrical efficiency up to 40% with multi-junction SCs.
- Low energy payback time.
- Low cost of electricity per watt of manufacturing capital.

Disadvantages

- Tracking is required.
- Proper cooling is required to maintain the uniform cell temperature.
- Lack of technology standardization.

1.3 Principle of geothermal cooling

Earth behaves as a huge collector-cum-storage medium of solar energy and can be used as daily or seasonal thermal storage medium. Because of the large heat capacity and insulation potential, the ground possesses many advantages for various applications. It is studied over time that the thermal losses from an underground reservoir are quite small and the annual heat losses amount to 10% of the total annual energy stored. Because of the large thermal capacity of the earth, The ground can therefore be used as a heat sink for cooling, especially during peak summers in dry and semi-arid regions like Rajasthan and Gujarat of India, where due to high solar insolation the ambient temperature reaches about 48 ºC. For such areas,

2. LITERATURE REVIEW

D. Reayet. Al. Heat pipes are hollow metal pipes whose inner surface is lined with a porous wick material which is soaked in a liquid coolant that transports heat by evaporating and condensing in a continuous cycle. Heat pipes can be classified according to their geometry, function and the methods used to transport the liquid from the condenser to the evaporator.

Peterson et.al. Because of their high thermal conductivity and high heat transfer characteristics, heat pipes have been extensively used for cooling of small electronic equipments. They are good alternatives to large heat sinks, especially in laptops where space is limited.

Singh et al. developed a miniature loop heat pipe with the flat disk shaped evaporator for thermal management of compact electronic equipments. The materials used for loop are copper with nickel wick and water is used as the working fluid. They showed that the system can dissipate maximum heat load of 70 W with evaporator temperature below 100±5 °C limits. From the literature, it is also observed that heat pipe cooling is also used by some researchers on PV and CPV systems.

Russell et.al has patented a CPV system with heat pipe to maintain constant temperature of SCs. The system contains linear Fresnel lenses focusing solar energy onto a string of SCs mounted on the heat pipe of circular cross-section, along its length.

Akbarzadeh and Wadowski. In their experiment heat pipe was made up of flat copper pipe having a finned condenser and SCs were mounted vertically on them at the end. The system was designed for 20 Suns concentration with parabolic trough collector of size 1 m×0.8 m. An experiment was conducted for a period of four hours. It was found that the surface temperature of SCs was maintained within 46 °C, as opposed to 84 °C in the same conditions but without heat pipe. It was reported that the power output was increased from 10.6 W to that of 20.6 W when heat pipe cooling was applied.

Cheknane et al. Examined the role of gravity dependent copper heat pipe on silicon based CPV system with up to 500 Suns. As shown in Fig. 2.2, the gravity dependent heat pipe consisted of a sealed copper cylinder filled with a small amount of working fluid. The SCs were attached at the lower end of the heat pipe, and receive radiation from Fresnel lens concentrator. The working fluid is vaporized by the heat from SCs and the vapour rises up in the tube. The vapour gets condensed on the pipe walls by rejecting heat to the ambient air though large fins,

Huang et al. Designed a method to fabricate a novel hybrid-structure flat plate (NHSP) heat pipe for a beam radiation of 930 W/m2 CPV system. They used a sintered wick structure and a coronary-stent-like rhombic copper mesh to support the structure. They observed that the thermal resistance of NHSP heat pipe was less as compared to conventional heat pipes. They also reported that the NHSP heat pipe is proven to be better cooling technology for CPV system, which can increase photoelectric conversion efficiency by approximately 3.1%, compared to an aluminum substrate.

Lee and Baek Proposed a CPV cooling system using an insulated aluminium thermal absorber (width: 80 mm, length: 50 mm, height: 30 mm) having two heat pipes with distilled water as the working fluid. Triple junction (InGaP, InGaAs and Ge) SCs of 10×10mm was placed on the thermal absorber. Their results showed that the CPV cell temperature was 29.3, 33.3, 37.2 and 41.2 °C for 500, 600, 700 and 800 Suns respectively. They found electrical and thermal efficiency as 20% and 77% respectively.

Farahatet.al. Suggested the use of controlled gas heat pipes for cooling of PV cells. He used two types of evaporator shapes, i.e. round and square. He showed that the heat pipe cooling method can be successfully applied to the PV system.

Russell et.al. Patented a liquid immersion cooling system. In his design, he used optical concentrators focusing sunlight on an elongated pipe which is filled with electrically nonconductive thermally conductive liquid. He placed SCs inside the pipe and immersed in liquid having a refractive index suitable for concentrating the light onto the SCs array.

Abrahamyanet. al. They used an isotropic liquid dielectric as glycerin, butanol, acetone, dioxane, toluol, isopropyl alcohol and deionized water. Their experimental results showed that thin film of thickness 1 to 4 mm of dielectric increased the SCs efficiency by 40 to 60%.

Zhu et al. Proposed a liquid immersion cooling method for densely packed SCs under high CR. They found that the module was cooled to 35-45 °C for water flow velocity of 2.0-2.7 m/s at 16 °C inlet temperature of silicon oil. Their results showed that convective heat transfer coefficient can go beyond 3000 W/(m2 K) for a given range of velocities and found that experimental values were higher than simulated ones due to electricity to light conversion efficiency variation.

Liu et al. Developed an experimental system to dissipate heat from both the front and back surfaces of SCs by dielectric liquid immersions. They used a long arc xenon lamp as a source and dimethyl-silicon oil as the dielectric fluid. They observed that the temperature of cells can be reduced to 30 °C corresponding to 1000 W/(m2 K) heat transfer coefficient. They also achieved a uniform temperature distribution for the module in turbulent flow with a maximum temperature difference of less than 3 °C.

Han et al. Proposed a direct liquid immersion cooling system for CPV cells. They used deionized water, isopropyl alcohol, ethyl acetate, and dimethyl silicon as immersion liquids. The SCs were encapsulated between two sheets of

100×100 mm square and 3.3 mm thick Borofloat glass. They observed rise in efficiency from 8.5 to 15.2% for 1.5 mm thick liquid layer over the cell surface for 30 Suns, and concluded that the fluid inlet velocity and flow mode also influenced the SCs temperature.

Zhu et al. Designed a liquid immersion cooling system to eliminate the contact thermal resistance of back cooling for 250 Suns. They designed a system for ambient conditions of 900 W/m2 and 17 °C with inlet water temperature at 31 °C. They obtained 49 °C as peak temperature and 45 °C as uniform temperature of PV cell. They found a convective heat transfer coefficient to be approximately 6000 W/(m2 K).

Xiang et al. The system used a dish type concentrator with 250 Suns. The influences of inlet velocity and module geometric parameters were investigated by them. They found that the inlet velocity is inversely proportional to cell temperature. They observed that cell module, with fin height 4 mm with eleven fins, has the best thermal performance.

Sun et al. Designed a narrow rectangular channel receiver to reduce the liquid holdup with 9.1 Suns. The width of the channel was 6 cm and 5 cm for the upper and lower part respectively. They used silicon SCs of 5 cm × 4 cm with an active area of 19.5 cm2. They maintained the cell temperature in the range of 20-31 °C at 910 W/m2 DNI with 15 °C inlet temperature of silicon oil as a coolant.

Edenburn Presented a cost analysis of a CPV system with heat sink cooling for optimizing the cost of cooling geometry for CRs of 50, 92 and 170 Suns. Their results showed that SCs can maintain below 150 °C on extreme days at 92 Suns. They concluded that the cost of heat sink increases with increase in lens area.

MODELLING AND SIMULATION

3. Modelling and simulation of the PV/T and CPV/T systems with geothermal cooling

This presents TRNSYS and MATLAB modelling of unglazed and glazed PV/T system coupled with EWHE cooling for the climatic and ground conditions. An analysis has been carried out by varying its operating parameters for these systems. The purpose of TRNSYS modelling is to understand the transient behavior of unglazed PV/T system coupled with EWHE cooling in hot and dry climatic conditions with variation of key parameters. Besides, the results of TRNSYS modeling have also been used to decide the design of glazed PV/T system coupled with EWHE cooling. For the same, a detailed thermodynamic model has been presented using the first law of thermodynamics and energy balance.

3.1 Description of the TRNSYS software

TRNSYS is a tool which is used for modelling and simulation of complex systems to identify its transient behavior. The systems may be thermal (solar, refrigeration, etc.) or electrical (PV, wind, etc.) and can be solved using an inbuilt set of equations using a modular approach. The basic equations related to each component are subroutine through FORTAN language. Theses subroutines are called as Types and works as a single system component. The complex system can be made by joining all the Types together within the proper sequence. One of the advantages of this tool is that, the standard library has an extensive set of more than 150 components and models. Each component is denoted by 'Type X' where 'X' denotes the number. For instance, 'Type 3' represents a variable speed pump and can be used directly to solve the case of variablespeed pump.

3.1.2 Simulation methodology

In the current work, the transient modelling and simulation of unglazed PV/T with EWHE cooling was carried out using TRNSYS (v17.0). The adopted simulation methodology for this work is explained using the following steps:

1. The problem definition needs to be defined. It is very important to understand as much as possible about the problem being simulated in order to accurately define it. This stage involves collecting all the necessary data required for the simulation including design parameters, fluid properties and flow specifications, etc.

2. The simulation of unglazed PV/T system coupled with EWHE cooling requires climatic data such solar radiation, wind velocity, ambient temperature, relative humidity, etc. Weather data has been generated using inbuilt Meteonorm files provided within TRNSYS.

3. The component for unglazed PV/T collector is created using PV/T collectors in the electrical library which is termed as TESS library in the software.

4. Within the ground heat pump library of TRNSYS, EWHE is a horizontal heat exchanger model which interacts thermally with the ground. It considers convection between the inner surface of buried pipe to flowing water, conduction within the buried pipe and conduction between the external surface of buried pipe and earth.

3.2. Methodology

The methodology for system design and its parametric variation for the EWHE is discussed in this section. The simulation of unglazed PV/T coupled with EWHE system is carried out for 10 hours of system operation which is average sunshine hours as a conservative estimate during the peak summer period (June 21). To optimize the design parameters of such coupled system, the parametric simulation was performed for different mass flow rates for a fixed diameter and length of the HDPE pipe. This analysis gives the optimum flow rate of 0.018 kg/s for a 30 m HDPE pipe length and diameter of 12 mm. For three different EWHE pipe materials, i.e. galvanized iron (GI), HDPE and steel pipe, the simulation was carried out it shows that the performance of the coupled system hardly depends on the buried pipe material. Thus, among all the pipe materials discussed here, HDPE pipe is considered for the performance analysis as it is economical as compared to other two.

3.2.1 Effect of mass flow rate of cooling water

The effect of mass flow rate on the performance of unglazed PV/T along the EWHE pipe length of 30 m and a diameter of 25 mm for the HDPE pipe is shown in Fig. 3.9. It reveals that the temperature of PV goes up to 79.31 °C without any cooling. In case of EWHE cooling scenario, the PV temperature decreases significantly and it varies with different mass flow rates, i.e. 29.99 °C - 53.82°C for 0.01 kg/s, 28.54 °C - 47.13 °C for 0.018 kg/s and 28.33 °C - 46.29 °C for 0.026 kg/s. It is observed that with increase in mass flow rate the PV temperature decreases and becomes almost same for 0.018 kg/s, 0.022 kg/s and 0.026 kg/s. For the practical applications, 0.018 kg/s flow rate could be used as with increase in mass flow rate the pumping power required also increases.

4. RESULTS AND DISCUSSION

4.1 Performance analysis of glazed PV/T systems coupled with EWHE and EAHE cooling

This chapter deals with performance analysis of glazed PV/T systems coupled with EWHE and EAHE systems. The developed mathematical models have been validated experimentally on an experimental set-up installed. India. As discussed in the previous chapters, the present study deals with the analysis of two types of PV/T systems i.e. tube-and-sheet PV/T and broad channel IPVTS systems. Following the experiment, the simulation was also carried out for parametric study by developing mathematical model and validating it with experimental results. Performance of coupled tube-and-sheet PV/T system with EWHE cooling has been evaluated on three consecutive days with different flow rates. In this section, the results of six days are discussed in details. Mass flow rate of cooling water through the tube-and-sheet PV/T and EWHE pipes was maintained at 0.017 kg/s, 0.025 kg/s and 0.033 kg/s for different respective days. Following this, the broad channel IPVTS system coupled with EWHE cooling was tested.

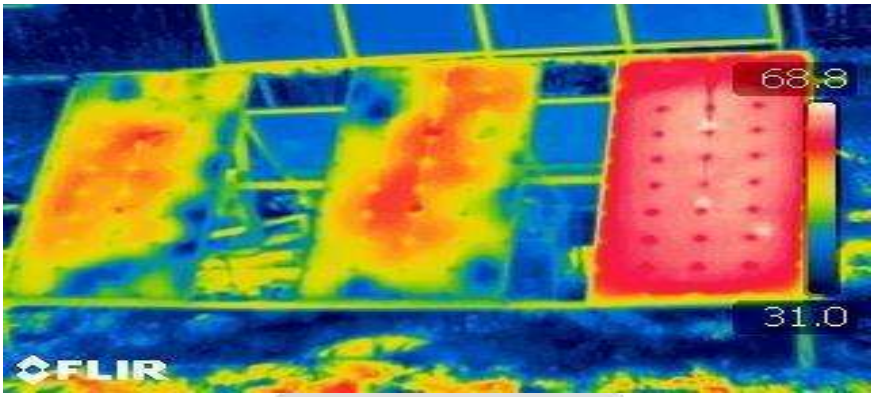

Fig. 4.1.PV panel temperature measured by FLIR

4.2 Performance analysis of glazed broad water channel PV/T (IPVTS) system coupled with EWHE cooling

The experimental study was performed under realistic conditions. The simulated values of SCs temperature, short-circuit current, open-circuit voltage, outlet temperatures of IPVTS and EWHE have been validated experimentally by conducting 6-hours experimental study on 20th September, 2016. The experiment was conducted for the mass flow of 0.033 kg/s. Fig. 4.9 represents the hourly variation in the solar radiation and ambient air temperature during the test day. The solar radiation and ambient air temperature ranges between 494 W/m2 to 953 W/m2 and 31.2 °C to 37.7 °C respectively. The IPVTS panel temperature with and without EWHE cooling for flow rate of 0.033 kg/s is shown in Fig. 4.10. It is observed that the PV panel temperature without any cooling ranges between 60.4 °C to 74.5 °C. Whereas, the IPVTS panel temperature drops with EWHE cooling and ranges from 39.27 °C to 46.11 °C and 41.70 °C to 49.32 °C for experimental and theoretical studies respectively.

5. CONCLUSION AND FUTURE SCOPE OF THE WORK

• From the simulation results of variation in pipe lengths it is observed that with increase in pipe length the PV temperature decreases and power output increases. Results showed that maximum drop in PV temperature have observed from 10 m to 50 m length as 60 °C to 42.89 °C. However for the length of 60 m the PV temperature is 41.59 °C which is little higher as compared to 50 m pipe length. Similar trend has been observed for the PV power output.

• Further analysis shows that with increase the pipe diameter the PV/T outlet temperature decreases gradually over a period of time but at the peak simulation hour the PV temperature for all the pipe diameters exhibits similar temperature drop. Thus smaller pipe diameter i.e. 12 mm may be used for the practical applications.

5.1 Future scope of work

• Experimental study may be carried out for the unglazed PV/T and glazed CPV/T systems coupled with EWHE cooling.

• The economic analysis and life cycle analysis can be recommended for further work, which will be required before commercialization of the system.
• Experimental study may be carried for the rooftop PV/T air collector with EAHE system for combined electrical power and space heating.

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