INFLUENCE OF ACTIVE WATER STREAM, IRRADIANCE, AMBIENT TEMPERATURE, AND WIND SPEED ON THE EFFICIENCY OF FRESNEL LENS BASED TWO STAGE PVT SYSTEM

by

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Influence of wind speed, mass-flow rate of water, irradiance, and ambient temperature on concentrated photovoltaic thermal module (PVT) equipped with linear Fresnel lens as primary optic element and convex lens as secondary optic element have been investigated in this study. Influence of these parameters on module performance in terms of thermal efficiency and electrical efficiency are also examined during investigation. The thermal efficiency and electrical efficiency without consideration of parameters was found to be 14.3% and 51.2%, respectively. With consideration of mentioned four parameters, the results reveal that electrical efficiency of 17.2% and thermal efficiency of 55.3% can be achieved for designed set-up. Thus, there is 20% and 8% increase in electrical efficiency and thermal efficiency, respectively. The electrical efficiency increases with increase in flluid-flow rate, wind speed, and irradiance. Electrical efficiency decreases with increase in ambient temperature. The thermal efficiency increases with increment in water mass-flow rate, irradiance, and ambient temperature. However, with increase in wind speed, the thermal efficiency decreases.

Key words: *heat exchanger, PVT, Fresnel lens, thermal efficiency, electrical efficiency*

Introduction

Sun is provider of green energy and the major source of future global energy is going to be solar energy. A concentrated photovoltaic thermal (CPVT) system converts solar energy to electrical energy through photovoltaic cells and its heat removal system at back of solar cells carries thermal energy to heat exchanger where it can further be utilized for various domestic or industrial purposes like air conditioning or solar desalination [1, 2]. The solar concentrator choice has to be made primarily between Fresnel lens, parabolic trough, parabolic concentrator, or CPC. Out of these Fresnel lenses have certain advantages like light weight, simple structure, low cost, and ease for manufacturing [3]. Invent of poly-methyl-meth-acrylate (PMMA) provided great impetus to Fresnel technology in 1950's. It is thermally stable, resistant to sunlight and its refraction index is almost near to that of glass [4]. In-

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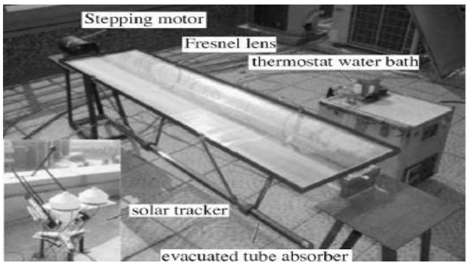
itial experiments on Fresnel lenses were performed for heating of water [5, 6]. Later experiments were done which proved high efficiency of Fresnel lens to the world. So, due to its high optical quality and other aforementioned characteristics it is preferred choice of solar system designers [7]. Huang *et al.* [8] focused on design of integrated small Fresnel lens and a strip photovoltaic cell. A software program was developed to study distribution of irradiance. This was done to get idea of optimum location of sun tracker and photovoltaic cell. Theoretical and experimental values were compared to check consistency. Pham *et al.* [9] presented a new concept in which they kept two Fresnel lens perpendicular to each other. These two Fresnel lens distributed direct sunlight more uniformly on receiver. Kairimi *et al.* [10] carried out research on CPVT using linear Fresnel lens. They performed tests on system with pure thermal arrangement and then with hybrid photovoltaic and thermal system. They found that hybrid systems had greater efficiency. After success of Fresnel lens as concentrator, Ning *et al.* [11] pioneered the concept of secondary optic element (SOE) thus making concentrator as a two stage system. The SOE is kept between solar cell and primary optic element (POE) to make radiation fall more uniformly. Chen *et al.* [12] developed three different varieties of SOE. They could achieve better uniformity of irradiation and they also obtained better optical efficiency. Ullah *et al.* [13] developed two stage CPVT systems to focus irradiation using concave and convex parabolic reflectors. Vu and Shin [14] combined a linear Fresnel lens with a special stepped thickness waveguide to focus irradiation for a day lighting system. There are many review papers describing the works done in field of CPVT. Daneshazarian *et al.* [15] presented a detailed review on CPVT systems. Tyagi *et al.* [16] presented review of research in field of PVT system including its various applications. Joshi *et al.* [17] carried out comprehensive review of PVT. Ju *et al.* [18] provided a review of CPVT systems with cooling methods. Cuce *et al.* [19] had also presented a review of cooling techniques used in PVT systems. Many researchers did experimental studies in order to improve η_{THE} and η_{ELE} of CPVT systems. Tan [20] experimentally proved that concentrated systems had better η_{THE} and η_{ELE} in comparison to systems without concentration. Abdelhamid *et al.* [21] studied two stage high-CPVT (HCPVT) systems. They experimentally verified the superiority of their system over conventional ones. Widyolar *et al.* [22] examined the effect of spectral beam splitting technology. They implemented this technology on parabolic troughs. Hussain and Kim [23] studied effect of W_{s} and flow rate on CPVT. Maximum η_{THE} and η_{ELE} of the collector were found to be 65.2% and 18.5%, respectively. Sornek *et al.* [24] studied effect of addition of Fresnel lens in BIPV. Distance of Fresnel lens from photovoltaic was determined experimentally. Shading effect of Fresnel lens on photovoltaic was taken care off. Xu *et al.* [25] performed experiments on HCPVT array. They achieved η_{THE} and η_{ELE} as 30% and 30%, respectively. Zhai *et al.* [26] compared performance of two collectors for CPVT. They found that η_{THE} for evacuated tube collector was 43.1% and for Fresnel lens collector was 52.1% .Thus they proved an increase in η_{THE} by 9% from evacuated tube to FL. Xu *et al.* [27] studied variation of η_{THE} and η_{ELE} with DNI, T_{ST}, W_{s}, T_{AT}, and flow rate on a high concentration PVT system. Maximum η_{THE} and η_{ELE} was found to be 60% and 28%, respectively. Kiyaee *et al.* [28] used novel design for advancement of a polymethyl methacrylate spectral splitting Fresnel lens (SSFL) for linear concentration. The spectral varied from 400-1150 nm to 800-1150 nm onto the silicon solar cell. Distinct SSFL were considered for directing the SSFL during investigation. Alzahrani *et al.* [29] check the durability of CPV systems by using optical and electrical characterizations of flawed SOG Fresnel lens. This method permits to approximate the percentage of the crack size to the whole Fresnel lens surface, and then approximate the optical performance and examine its impact on the electrical performance. Sova and Galstian [30] studied the experimental and theoretical analysis of a refractive Fresnel lens design based on the *modal control* principle. The recommended Fresnel lens can attain advanced optical powers when compared with a like but single aperture lens. For optimizing its working for distinct focal ranges a combined control mode is proposed. Theoretical modeling reveals the option of additional development of its aberrations by means of an optimized driving method. Ma *et al.* [31] developed an optimal transmittance-based Fresnel lens. They examined the focal length change during the tilt incidence *via* simulation and experiment. They concluded that the effective tilt incident angle can be enhanced from 7° to 32° by lifting the position of the receiver and adding a simple mirror secondary reflector. The experimental outcome demonstrate that the Fresnel solar concentrator is operating efficiently. Mohammadirad *et al.* [32] carried out experimental study on CPVT using linear Frensel lens. They determined position of Fresnel lens with respect to module experimentally and also compared the impact of focal lengths of Fresnel lens on performance of system. The collective impact of parameters on efficiency has rarely been investigated. For Fresnel lens based two stage system with convex lens as SOE, optimization of parameters has never been investigated. The study of optimization of these parameters helps in decision making process of planning of location of PVT plants. On the basis of our study, with knowledge of the level of solar irradiance, normal ambient temperature, and general wind speed at various places, we can compare and select most optimal site for installation of PVT plant. So, in present paper, Influence of various independent parameters like m_w, wind speed, ambient temperature, and irradiance on electrical and thermal efficiency have been discussed. Table 1 shows summary of some of related works in this field of CPVT.

Table 1. Summary of experimental studies in field of photovoltaic and thermal systems

Author	Study	Major findings	Experimental set-up
Kairimi *et al.* [10]	CPVT with linear Frensel lens, comparison pure thermal and hybrid PVT efficiencies	The η_{TO} under linear concentration are 46.6% and 53% for pure thermal and integrated PVT, respectively	
Hussain and Kim [23]	Wind speed, flow rate, economic model	Maximum η_{THE} and η_{ELE} of the collector were found to be 65.2% and 18.5%, respectively	

⟶

Table 1. Continuation

Author	Study	Major findings	Experimental set-up
Sornek *et al.*, [24]	Building integrated photovoltaic distance of Fresnel lens from photovoltaic	Increase of 7% in η_{TO} was observed due to addition of Fresnel lens as concentrator	
Xu *et al.* [27]	Variation of η_{THE} and η_{ELE} with DNI and T_{AT}	Thermal efficiency (η_{THE}) and η_{ELE} was found to be 30% and 30%, respectively	
Zhai *et al.* [26]	Variation of η_{THE} with lens width, wind speed and ambient temperature	Thermal efficiency (η_{THE}) with evacuated tube collector was 43.1% and with Fresnel lens collector was 52.1%	
Xu *et al.* [25]	Variation of η_{THE} and η_{ELE} with DNI, T_{ST}, W_s, T_{AT}, and flow rate	Thermal efficiency (η_{THE}) and η_{ELE} was found to be 60% and 28%, respectively	
Perini *et al.* [33]	Optical model and thermal model with 2-D tracking	Lens optical losses were found as 47%. Total efficiency (η_{TO}) can be improved from 20% to 55% with evacuated receiver and insulation	

Experimental set-up

An experimental set-up with block diagram as depicted in fig. 1 and 3-D view as shown in fig. 2 was designed and developed to find out the effect of different parameters on the efficiency of a PVT panel as per set-up designed in congruence with [10, 23, 24]. Experimental set-up consists of two stage Fresnel lens, PVT, heat exchanger, water storage tank, and instruments for measurements. A comprehensive experiment was done to record parameters needed to calculate η_{THE} and η_{ELE}. Thus the overall efficiency of the PVT system was calculated. Figure 3 shows actual view of apparatus. The characteristics of CPVT system and measuring ranges of various instruments used are listed in tabs. 2 and 3, respectively.

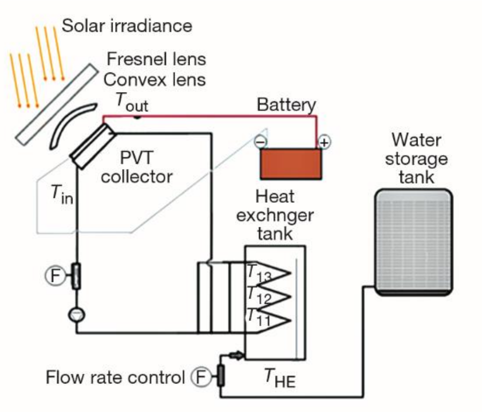


Figure 1. Block diagram of PVT system

Table 2. The CPVT characteristics

Parameter	Description	Value
Polycrystalline cell	I_{SC}, V_{OC}	0.88 A, 12 V
Fresnel lens	Material surface area	PMMA 0.3 × 0.4 m
Heat exchanger tank	Material, capacity	SS 304, 10 L
Thermal fluid	Type	water + ethylene glycerin
Absorber pipe	Material, diameter	Copper, 20 mm
Battery	Lead acid battery	12 V, 7 Ah
AC pump	rpm, power	2750, 125 W

Table 3. Range of instruments

Instruments	Range
Multi-meter as voltmeter	200 mV-1000 V
Multi-meter as ammeter	2 mA-10 A
Digital lux meter	200-200000 lumens
Flow meter	0.5-100 Lpm
Thermocouple	S type
Anemometer	1-60 m/s

A linear PMMA Fresnel lens (size: 0.3 × 0.4 m) was mounted on aluminum frame with second stage convex lens of 0.3 m diameter. Asbestos sheet was used as base. It was given aluminum coating to provide strength. Slant frame was made of galvanized iron as galva nized iron is rust free. Aluminum stands were used for both Fresnel lens and convex lens. The

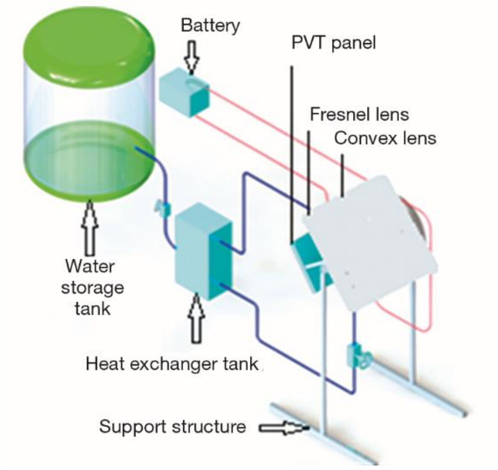


Figure 2. The 3-D view of set-up

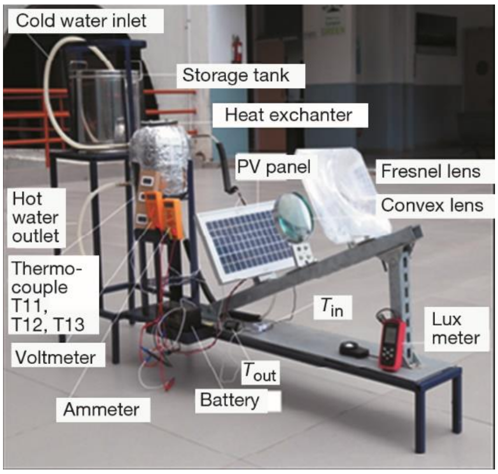


Figure 3. Photographic view of experimental set-up

distance between two lenses could be adjusted with help of screws. Combined frame to house water storage tank, heat exchanger, photovoltaic and lens was made of enamel coated iron. Forced water circulation using pump was used to extract heat from back of photovoltaic cells. Thirty nine pieces of polycrystalline photovoltaic cells were integrated with glue on the surface of copper collector (size: 400 × 200 mm). Beneath it, a serpentine copper pipe of 20 mm diameter was attached. Polycrystalline photovoltaic cells were used as polycrystalline cells are cost effective and service availability is more than mono crystalline cell modules. Series connection was implemented for these 39 cells to sum up the voltage of each cell. To provide dust protection photovoltaic cells were covered by plexi-glass. Plexi-glass also saves from transportation and installation damages to photovoltaic cells. Heat removal mechanism at back of photovoltaic cells along with insulation cladding was provided. Potentiometer attached with photovoltaic plate was used to vary resistance at equal intervals to get different values of V and I. Two digital multi-meters were used to measure voltage and current to get V-I characteristics. The heat exchanger tank has capacity to store 10 L of water. A battery of 12 V, 7 Ah was used to store electrical energy. Schottky diode was used to stop the reverse current. To build heat exchanger SS 304 food grade tank was used because it is rust free. The MS Stand was used and it was painted to protect from corrosion. Copper pipes were used as copper has good heat conductivity. Aluminum pipes were avoided as welding is not possible with aluminum. Rockwool insulation was used to cover the SS Tank to avoid loss of heat energy. As glass wool insulation has tendency to bruise hands, rockwool insulation was considered a better choice. Cladding was done with aluminum tape over the rock wool insulation. Aluminum cap gasket was used to cover the top of heat exchanger. A mixture of water and $C_2H_6O_2$ was used as working fluid with 50%/50% volume. Ethylene glycol has C_p about one half that of water and thus it lowers the C_p of water mixtures. The $C_2H_6O_2$ provides protection from freezing and boiling. The C_p of 50%/50% mixture at 26.7 °C is 0.815. Water storage tank was connected adjoining to heat exchanger tank to get next lot of water to be heated in heat exchanger tank. A 20 L steel tank was used for storage of water. To measure temperature, six *S*-type thermocouples were used. Three of these were installed at three intermediate points in heat exchanger tank to get average temperature inside the tank. Two were installed at entrance and exit of collector plate. Surface temperature of photovoltaic cells was obtained by a thermocouple pasted on surface of photovoltaic cells. A digital lux meter with inbuilt data logger MTQ1010D was used to measure light intensity and then record solar radiation. The specifications of digital lux meter used were model: MTQ1010D and range (200 to 2×10^7) Lux. Then IEEE conversion equation given below was used to convert lux into solar intensity in [Wm^{-2}].

Methodology

To determine impact of change of rate of flow of fluid, four rates were chosen for experimental study (0.5, 1, 1.5, and 2 Lpm). Parameters were noted and η_{THE} and η_{ELE} were calculated for all readings. To determine impact of change of wind speed, different time slots over days were selected when wind speed was 0-1 m/s, 1-2 m/s, and 2-3 m/s. Thus, parameters were noted and η_{THE} and η_{ELE} were calculated. To study impact of irradiance on η_{THE} and η_{ELE} parameters were noted at different levels of irradiance to obtain corresponding efficiencies. Lastly, to study effect of ambient temperature on η_{THE} and η_{ELE}, experiments were conducted on different days with different ambient temperatures and efficiencies were calculated respectively.

Uncertainity analysis

The occurrence of random errors may lead to contradiction between experimentally attained data and its real values. So, it is necessary to measure the maximum probable error during the experiment. The technique proposed by Kline and McClintock [34] is utilized in present work to determine the change in provisional results. The uncertainity in measurement of different quantities is listed in tab. 4.

Table 4. The uncertainity in measurement of different quantities

Measurement	Instrument	Uncertainty
Temperature	Thermocouple	±1 °C
Solar intensity	Digital lux meter	±1 W/m^2
Voltage	Voltmeter	±0.01 V
Current	Ammeter	±0.01 A
Dimensions	Measuring tape	±1 mm at each edge

Uncertainty in thermal efficiency

Instantaneous efficiency for solar concentrating collector is:

$$\eta_{TH} = \dot{m}\frac{C_p\,\Delta T}{GA_c}100 \tag{1}$$

Based on theory of experimental error, the error propagation formula is:

$$\frac{\Delta u}{u} = \frac{\partial f}{\partial u_1}\frac{\Delta u_1}{u} + \frac{\partial f}{\partial u_2}\frac{\Delta u_2}{u} + \ldots + \frac{\partial f}{\partial u_n}\frac{\Delta u_n}{u} \tag{2}$$

where $u = f(u_1, u_2, \ldots, u_n)$ and $u_1, u_2, \ldots, u_n$ are the directly measured data. Substituting (1) in (2) the relative error of thermal efficiency is:

$$\frac{\delta\eta_{\mathrm{TH}}}{\eta_{\mathrm{TH}}}=\sqrt{\left(\frac{\partial\dot{m}}{\dot{m}}\right)^2+\left(\frac{\partial T}{T}\right)^2+\left(\frac{\delta G}{G}\right)^2}=\sqrt{\left(\frac{0.2}{10}\right)^2+\left(\frac{1}{25}\right)^2+\left(\frac{1}{830}\right)^2}=$$

$$=\sqrt{\left(\frac{0.2}{10}\right)^2+\left(\frac{1}{25}\right)^2+\left(\frac{1}{830}\right)^2}=\sqrt{(0.03)^2+(0.04)^2+(0.0012)^2}$$

So maximum uncertainty in thermal efficiency is 4.47%

Uncertainty in electrical efficiency

The electrical efficiency of the system can be calculated by:

$$\eta_{\mathrm{el}}=\frac{\text{Output power}}{\text{Input energy}}100\ ,\qquad \eta_{\mathrm{el}}=\frac{VI}{A_{\mathrm{PV}}G}100$$

Uncertainty in area = $L \times B$:

$$\frac{\delta A}{A}=\sqrt{\left(\frac{\partial L}{L}\right)^2+\left(\frac{\partial B}{B}\right)^2}==\sqrt{\left(\frac{2}{390}\right)^2+\left(\frac{2}{60}\right)^2}==\sqrt{0.00002629+0.00111111}=0.0337$$

Uncertainty in $P_{\max}$:

$$P = VI$$

$$\frac{\delta P_{\max}}{P_{\max}}=\sqrt{\left(\frac{\partial V}{V}\right)^2+\left(\frac{\partial I}{I}\right)^2}==\sqrt{\left(\frac{0.01}{4.23}\right)^2+\left(\frac{0.01}{0.80}\right)^2}=\sqrt{(0.00236)^2+(0.0125)^2}=0.0127$$

Uncertainty in electrical efficiency

$$\frac{\delta\eta e}{\eta e}=\sqrt{\left(\frac{\partial A}{A}\right)^2+\left(\frac{\delta P_{\max}}{P_{\max}}\right)^2}=\sqrt{(0.0337)^2+(0.0127)^2}=\sqrt{0.0012962}=0.036002$$

Hence, maximum relative error in electrical efficiency is 3.60%.

Results and discussion

Experiments were conducted with given set-up for various days. With most favorable days and considering all four parameters, η_{ELE} of 17.2% and η_{THE} of 55.3% could be achieved for designed set-up. Individual impact of each parameter is given in next sections.

Impact of change of rate of flow of water on efficiency

The rate of heat transfer of working fluid from absorber surface to heat exchanger is controlled by pipe flluid-flow rate**.** The graph of thermal efficiency (η_{THE}) *vs.* T_{HEW} with varying rates of flow (0.5, 1, 1.5, and 2 Lpm) at (G_{I} = 550 W/m^2) has been plotted. Figures 4 and 5 show variation of thermal efficiency**,** η_{THE}, and electrical efficiency, η_{ELE} with T_{HEW} at flow rates of of 0.5, 1, 1.5, and 2 Lpm, and at G_{I} of 550 W/m^2. Figure 4 shows that there is increase in η_{THE} with increase in flluid-flow rate. Figure 5 depicts that electrical efficiency increases with increase in flluid-flow rate.

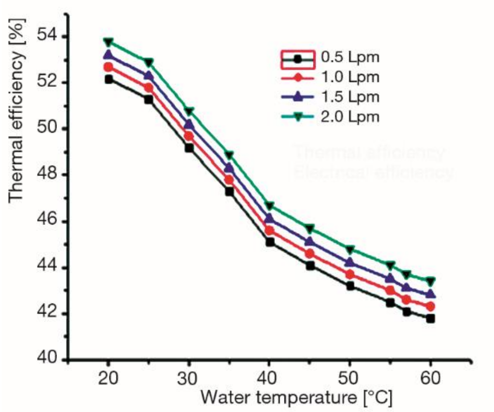


Figure 4. Thermal efficiency, η_{THE}, *vs.* T_{HEW} with varying rates of flow and at G_I of 550 W/m^2

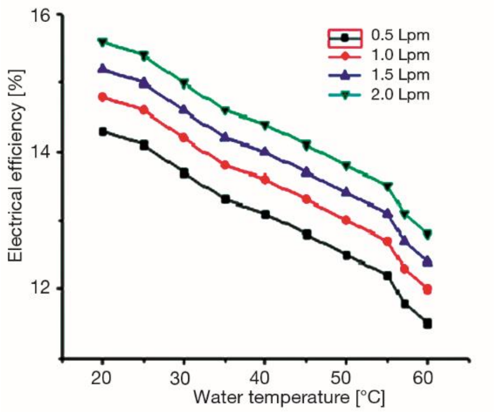


Figure 5. Electrical efficiency, η_{ELE}, *vs.* T_{HEW} with varying rates of flow and at G_I of 550 W/m^2

Impact of variation of wind speed on efficiency

Heat losses arising from wind are attributed to wind speed. When wind speed, W_s, is high the convection heat losses increase and they overshadow the performance of collector. The graph of η_{THE} *vs.* T_{HEW} with varying wind speeds, 0-1, 1-2, and 2-3 m/s, at G_I of 550 W/m^2 has been plotted in fig. 6. The graph of η_{ELE} *vs.* T_{HEW} with varying wind speeds, 0-1, 1-2, and 2-3 m/s, at G_I = 550 W/m^2 has been plotted in fig. 7. From results in figs. 6 and 7 it is clear that with rise in wind speed, η_{THE} decreases and η_{ELE} increases.

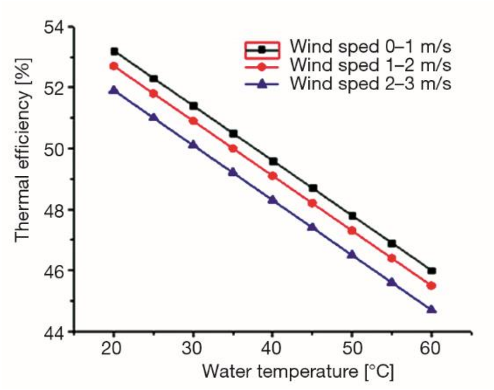


Figure 6. Thermal efficiency, η_{THE}, *vs.* T_{HEW} with varying wind speeds and at G_I of 550 W/m^2

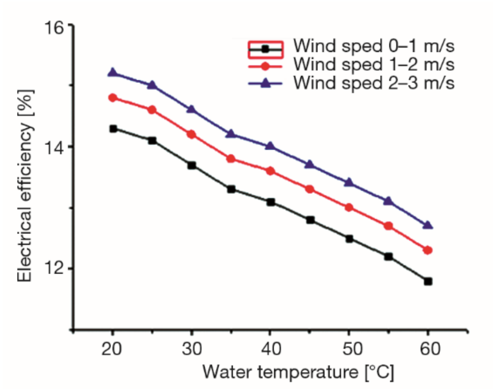


Figure 7. Electrical efficiency, η_{ELE}, *vs.* T_{HEW} with varying wind speeds and at G_I of 550 W/m^2

Impact of irradiance on efficiency

The thermal efficiency and electrical efficiency as function of solar irradiance is depicted in fig. 8. With higher irradiance higher thermal efficiency can be clearly observed. When irradiance reaches lower levels, the thermal efficiency falls sharply. Even though T_{ST} is higher than T_{HEW}, it is unable to transfer heat. This is primarily due to weak insulation which causes a greater part of heat to be lost to ambient.

With higher irradiance higher electrical efficiency can be obtained. With increasing irradiance electrical efficiency increases due to increased photovoltaic effect. After certain level the increase becomes less quick due to reduction in heat removal efficiency of thermal system.

Impact of ambient temperature on efficiency

The thermal efficiency and electrical efficiency as function of T_{AT} is depicted in fig. 9. Ambient temperature, T_{AT}, influences thermal efficiency as it shifts the heat loss between module and the ambient. The η_{THE} decreases if T_{AT} decreases. This is because of higher heat loss by greater temperature gradient between surface temperature of photovoltaic cells, T_{ST}, and T_{AT}. In order to reduce the influence of T_{AT} the thermal insulation of photovoltaic plate should be improved.

With increase in ambient temperature initially the electrical efficiency increases. Later it reaches an optimum value after which the excessive heating of cells leads to fall in electrical efficiency of module.

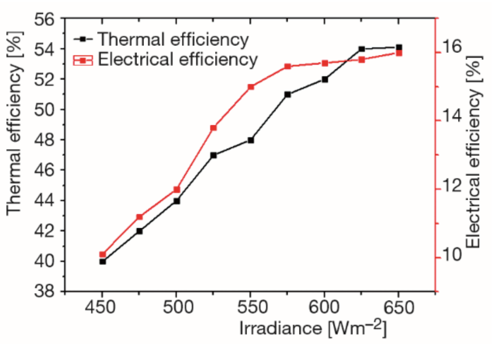


Figure 8. Impact of variation of G_I on thermal efficiency and electrical efficiency

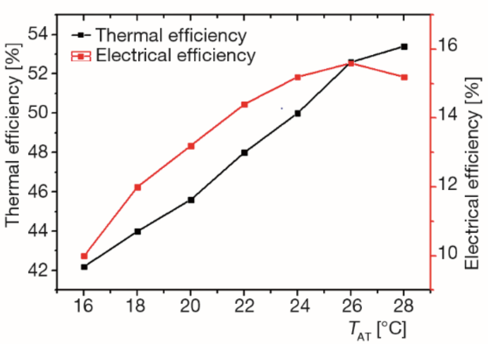


Figure 9. Impact of T_{AT} variation on thermal efficiency and electrical efficiency

Conclusions

A new concentrated PVT system equipped with linear Fresnel lens as POE and Convex Lens as SOE has been designed for experimental study. The system can cogenerate electrical energy and thermal energy simultaneously in a reliable way. The η_{ELE} and η_{THE} without consideration of parameters was found to be 14.3% and 51.2%, respectively. With consideration of four parameters, the results reveal that η_{ELE} of 17.2% and η_{THE} of 55.3% was achieved for designed set-up. Thus, there was 20% and 8% increase in η_{ELE} and η_{THE}, respectively. Influence of four parameters on η_{THE} and η_{ELE} has been investigated independently. Some of the useful conclusions drawn are enumerated below.

- Both η_{THE} and η_{ELE} increased with increase in m_w. Increase in m_w has very less effect on η_{THE} but due to reduction in T_{ST}, the η_{ELE} increases significantly. A suitable m_w should be chosen with complete evaluation of η_{THE} and energy consumption due to pump. It is worth noticing that the rate of removal of heat from back of photovoltaic cells can be enhanced by increasing m_w but only up to a threshold value.

- It was observed that with increase in W_s the η_{THE} decreased, however η_{ELE} increased. Decrease in η_{THE} for the highest W_s was result of additional heat loss from the surface of photovoltaic cells to the environment.
- It was observed that with increase in irradiance both η_{THE} and η_{ELE} increased.
- It was observed that due to rise in ambient temperature, the thermal efficiency increased though electrical efficiency decreased. The fall in electrical efficiency is attributed to lesser heat removal from photovoltaic cells surface due to lesser convection heat loss.
- The study of effect of these parameters helps in decision making process of planning of location of PVT plants. On the basis of present study, with knowledge of the level of solar irradiance, normal ambient temperature and general wind speed at various sites, we can compare and select most optimal site for installation of PVT plant.

Nomenclature

A_c – surface of concentrator
C_p – specific capacity, [Jkg^{-1}C^{-1}]
G – solar radiation intensity
G_I – solar radiation intensity
I – elektric current intensity
$\dot{m}_w$ – flluid-flow rate
P_{max} – maximum power
T_{ST} – surface temperature of photovoltaic cells
T_{HEW} – water temperature in heat exchanger tank
T_{AT} – ambient temperature
V – voltage
W_s – wind speed

Greek symbols

η_{THE} – thermal efficiency
η_{ELE} – electrical efficiency
η_{TO} – total efficiency

Acronyms

BIPV – building integrated photovoltaic thermal
CPC – compound parabolic concentrator
DNI – direct normal irradiance
HCPVT – high concentration photovoltaic thermal
POE – primary optic element
SOE – secondary optic element
FL – fresnel lens
HE – heat exchanger
PV – photovoltaic
SSFL – spectral splitting Fresnel lens

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