FEM analysis of novel Fresnel sheet solar concentrating system for TEG

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Abstract: The expensive manufacturing process and low efficiency at the high working temperature of photovoltaic cells necessitate the need for an alternate solar energy generation system. In this study, a concentrated solar thermal system that works on the principle of the Seebeck effect has been selected for electrical energy conversion. Standard Thermal Electric Generator (TEG) of material Bismuth Telluride is considered for harvesting energy from concentrated solar irradiance. In this research work, a Fresnel sheet concentrator has been used as the concentrating medium due to its low weight and easy installation. The solar simulator experiment is carried out on the Bismuth Telluride TEG module (type TEP1-12656-0.6) to find out its output characteristics curve with respect to irradiance. In this connection, high temperature is maintained at the top of the TEG by using fresnel concentrator and low temperature is maintained at the bottom by utilising the Flow Channel concept. Analysis of the flow channel is done in detail using ANSYS version 15. Results are discussed. Based on this result, the water flow rate has been optimised and it is found that the high temperature at the top of the TEG is not constant due to solar irradiance uncertainty. A complete cost analysis is performed and the payback period of the proposed model is found out to be considerably less compared to the conventional solar panel system. Hence, in this manner, the most abundant renewable energy like solar energy is made use efficiently as well as economically, without causing any harm to the environmental well-being.

Keywords: TEG, Solar concentrator, Fresnel Sheet, ANSYS Simulation, Flow channel

1. Introduction

Energy is the most unsurpassed gift given to humanity ever. The broad classification of energy are renewable and non-renewable sources. Non-Renewable energy sources lead to environmental as well as an ecological imbalance to the well-being of the society. Renewable Energy carriers seem to be a
promising contender. Of all the types of Renewable energy sources, Solar Energy or sunlight is the most abundant and environmentally friendly one. The energy in solar radiation hits the Earth at a steady rate of 10,000 times greater than the rate at which humanity uses energy. The challenge is to find practical and economical ways of channelling energy to human use from its natural state [1]. The two types of Solar energy are photovoltaic solar technology and solar thermal technology. Solar thermal technology is generally used to harvest the thermal energy from solar irradiances and utilized for electricity generation via photovoltaic cell panels, heat generation using collectors, etc. In this study, Solar thermal technology is utilized for heat generation purposes. Fresnel sheet is used for harvesting the solar irradiance as it proved to be a better alternative to the Glaze type, Parabolic type solar Collectors.

In contrast with other concentrating devices, Fresnel lenses have some advantages such as small volume, lightweight, high optical quality, and lower manufacturing and capital costs which make them one of the best options [2]. Fresnel lenses have widespread applications in generating power from solar radiation [3], hydrogen generation [4], as well as solar-pumped lasers [5]. Fresnel lenses are widely used for harvesting solar energy for the purpose of solar cookers.

The majority of the Fresnel moulded lenses are fabricated from plastic owing to the difficulties involved in the fabrication of huge optical glass lenses. Since the solar cells become inefficient at high working temperatures, a suitable alternative such as a TE Module is employed. The combination of Fresnel lenses and TE Modules are becoming more and more popular due to their efficient outputs and economical status. W.T.Xie [6] has summarized the applications of concentrated solar energy using Fresnel lenses such as solar power generation [7–9, 10–14, 28], hydrogen generation [15], photo-bio reactors as well as photochemical reactions [16, 17], surface modification of metallic materials [18–20], solar lighting [21] and solar-pumped laser [22–24]. Tae-Yong Park, et. al [25] has proposed a solar-energy collection system for cube satellite applications using a commercial PMMA (PolyMethyl MethAcrylate) Fresnel lens system, which provides an enhanced power generation efficiency compared to the multiarray lens system.

A study conducted by Gang Wu, et. al[26] demonstrates a multi-stage humidification-dehumidification (HDH) solar desalination system heated directly by a cylindrical Fresnel lens concentrator. The experimental results showed that the maximum yield of the unit is about 3.4 kg/h, the maximum gained output ratio (GOR) is about 2.1 when the average intensity of solar radiation is about 867 W/m².

In this study, the Fresnel sheet is utilized for concentrating solar irradiance, which is harvested by the TEG modules, hence producing solar thermal energy. The TEG modules facilitate in increasing the temperature of water flowing in the tube, thereby turning cold water into hot water which can be used for a variety of purposes like bathing, domestic cleaning, space heating, cooking, etc.

### 2. Conceptual Design of Fresnel Sheet

#### Experimental Setup

This design involves a TEG being placed at the focal point of the Fresnel sheet. The hot side of the TEG consists of thermic fluid and cold side consists of water flowing at a rate of 0.002 Kg/s. Fresnel sheet is used to concentrate the solar irradiance on the TEG, thereby increasing the solar density value and hence the cold water flowing through the TEG gets heated up producing hot water.

**Case 1:** The Fresnel sheet was placed in such a way that the circular grooves side faced the Sun and the time taken for a jar of water to reach 60 degrees Celsius was calculated with the help of a cooking thermometer. The focal length was also measured with the help of a measuring tape in this case.

**Case 2:** In this case the Fresnel lens was placed in such a way that the circular grooves side faced away from the Sun and time taken to reach 60 degrees Celsius was calculated along with the focal length.

In both the cases it was found that the focal length remained unchanged. The time taken to reach the required temperature was much lesser when the Fresnel sheet was placed in such a way that the grooves side faced the Sun. Also, Spherical aberration was avoided in this case. Hence, Case 1 has been chosen for the experimental setup. The TEG is placed at the focal point to increase the heat transfer rate. The
high temperature is maintained at the top of the TEG using fresnel sheet concentrator and in the bottom, flow channel concept is utilised in order to maintain a constant low temperature.

2.1 Fresnel Sheet

A Fresnel sheet with a focal length of 200 cm, length of 140 cm, width of 109 cm and spot size of 8 cm is purchased and fabricated using a wooden frame of length 140 cm, width 109 cm and thickness 3.5 cm. The Fresnel sheet is framed with the wooden frame without affecting the circular grooves present in the sheet, which are highly responsible for the concentration of sunlight using some joining screws. From the specifications of Fresnel sheet the focal length was found to be 200 cm, so we need an support system to handle the framed Fresnel sheet and at the same time the focal length also to be considered while designing the support system. Four hollow concrete tubes of length 200cm are taken and a steel frame of same length and width of the framed Fresnel sheet is produced. Fasteners are used to connect the concrete tubes and the steel frame. After fabricating the support system, the Fresnel sheet is placed over the Steel frame and it was raised from the ground horizontally at a height of 200cm with respect to its focal length. The steel frame and the Fresnel sheet are connected using some flexible metallic wires. The optic centre distance was finally set at 300 cm. The entire setup is placed on the roof top over a clear sunny day in order to accommodate better experimental results.

Solar tracking was essential for efficient solar energy utilization. Thus an efficient Fresnel lens system has been developed in this paper.

2.2 TEG

To maximize efficiency and prevent damage to Thermoelectric Generator Modules (TEMs) the installation guidelines must be followed. TEMs thermally expand while operating under large temperature differences; specific hardware must be used to prevent unit damage due to this expansion. To ensure proper mounting, even pressure must be applied on both sides of the module.

A TEG module will generate power when a temperature difference, or $\Delta t$, is present between the hot side of the TEG module and the cold side of the module. A heat source should be applied to the hot side of the module, and a heat sink should be coupled to the cold side to create a $\Delta t$. The hot side of the module can be identified by the hot side marking on the face of the module. When heat is applied to the hot side and the cold side is coupled to a heat sink the positive output will be the red wire and the negative output will be the black wire. The hot side of the module is rated for a continuous temperature up to 330 °C (626 °F) and intermittent temperature up to 400 °C (752 °F). The cold side of the module cannot exceed 200 °C (392 °F) or the TEG module will degrade and fail. Temperature limits: 1) Temperature range of the hot side: -60 °C to 330 °C, Maximum 400 °C. 2) Temperature range of the Cold side: -60 °C to 180 °C, Maximum 200 °C. The dimensions of the TEG module used is as shown in figure 1.

![Figure 1. Dimensions of TEG](image-url)
The thermoelectric modules will generate DC power as long as there’s a temperature difference across both sides of the module. The output power and efficiency will increase as the temperature difference increases across both sides of the module. Highly conductive graphite is applied to both sides of the module to increase thermal conductivity so there’s no need to apply thermal grease or other heat transfer compound during installation. The schematic diagram of the proposed experimental setup used in this study is shown in figure 2.

![Figure 2. Schematic Diagram of experimental setup](image)

3. Solar Simulator Experiment

A solar simulator is a device which provides illumination by approximating the natural sunlight. The purpose of solar simulator is to provide a controllable indoor facility in laboratory to test solar PV panels, sun screens etc., solar simulators are broadly classified into three different categories. They are continuous, flashed and pulsed. The continuous type simulator is the most common one in which the illumination is continuous with time. In solar simulators various types of lamps are used as light sources. Xenon arc lamp is the most commonly used light source, which offers high intensities and unfiltered spectrum that reasonably matches well with the sunlight. Light emitting diodes are recently used to produce solar simulators, which acts as a promising future technology of producing spectrally tailored artificial sunlight. The corresponding experimental setup is shown below in figure 3.

![Figure 3. Solar simulator experimental setup](image)
Hence the same simulator experiment is conducted with previously selected thermo electric generator (TEG) module to find out the various characteristics like power, intensity, irradiations plot etc., TEG modules was placed exposed to the light beam from solar simulator and the input illumination on the module was adjusted with the help of the adjusting knobs.

![Solar simulator output characteristics](image)

**Figure 4.** Solar simulator output characteristics

By analysing the plot between current, voltage and power the output power is analysed. This method is therefore proposed for the study of TEG. The obtained characteristics are shown in figure 4.

4. **ANSYS Simulations**

ANSYS is a 3D design simulation software. It is used to create computer models of structure, electronics or machine component to simulate strength, toughness, elasticity, temperature distribution, electromagnetism, fluid flow and many other attributes.

To solve an engineering problem there are mainly three ways

1. Theoretical approach
2. Numerical approach
3. Experimental approach

ANSYS is mostly utilised in the applications of aerospace industry, automotive industry, bio-mechanical industry, bridges, buildings, electronics appliances, heavy equipment and machinery, MEME-Microelectromechanical systems, sporting goods etc.

- Poisson ratio is defined as the ratio of change in width of a material to the change in length as a result of strain
- Poisson ratio for Hard material is from 0.1 to 0.3, for medium material it is from 0.3 to 0.7.
- CAE is used to perform problem analysis and generation of 3D model pre-processor, solution and post processor.
- In pre-processor, the types of analysis, material properties, geometric modelling, mesh, loading and boundary condition are mainly involved.
- In solution this phase is completely automatic.
- In Post processor the output form of solution phase is in the numerical form in result.

It is used in various applications such as structural analysis, Thermal analysis, Flow analysis, Dynamic analysis, vibration analysis, acoustics etc.
4.1 Boundary Conditions

*In Ansys fluent using the following boundary conditions:* Inlet velocity considered to be 30 m/s, as in general case the water flow in pipes have a pressure head of 5 bar, when they are converted to velocity head 30 m/s is obtained. As discussed earlier, the surface heat flow in TEG material is 6.2 W/cm², when calculated for 4 modules the TEG surface heat flux was set to be 24,800 W/m². The inlet temperature was set to be 300 K. The flow was assumed to be laminar and steady flow with the above boundary conditions.

*Boundary conditions:* the latitude of the place where the solar system must be considered for inclination about north-south direction i.e., the latitude of Coimbatore is 11.01°n, so the lens must be tilted about 15°+11.01° = 26.01° during summer and 11.01°-15° = -3.99° during winter.

*Initial condition:* The Fresnel lens specifications to keep constant. Lead telluride was chosen as the TEG module due to its high melting point and cost effectiveness.

4.2 Modelling of Flow Channel for experimental setup

To attain the maximum temperature difference for the power output in Thermal electric generator, flow channel concept is utilised. The channel setup was made with aluminium sheet and the thickness of the sheet was 1.5 mm. It was folded by bending operations and edges were joined with the help of arc welding. For the water flow, the tray was drilled on the two sides and by help of the FTA and MTA it was connected. To prevent leakage, it was sealed with the help of M seal. In the bottom, tray fins were placed for effective heat transfer. The fins were welded by the spot-welding process and small gaps are provided for the water flow between each fins. The main duct is connected with the converging duct at both the section at a length of 11 cm on each side and other dimensions were set with consideration that converging / diverging angle is maintained to be less than 10°. The design was made as a CAD model using Fusion360 software. After initial sketching, the model was developed by extrusion, mirroring etc. The final developed model is as shown in the Fig. 5.

*Type of mesh:* Mesh is used to subdivide the model into a number of smaller areas called elements. Elements connects all the characteristics point called nodes. Here, a coarse type mesh is made use, the number of elements are 608 and the number of nodes are 900 from the mesh analysis.

![Figure 5. CAD model of Flow Channel](image)

It is observed that the proposed system fails, because of the water stagnation in the tray and the thickness factor design fails. So the design and material of the flow channel system is altered. Using solid works the design is modified and is analysed with the help of ANSYS software. Flow channel
system was made with the copper sheet and with a thickness of 0.2mm and it was bent to the required shape and it was weld by the gas welding due to the thickness concern. Flow guide was also welded and it was arranged at proper angle for better water flow. Water enters the one end and it moves towards another end. Both ends water flowing arrangements are done and picks the heat and provide good heat transfer.

5. Results and Discussion

5.1 Calculation of efficiency of Fresnel sheet setup

From the experimental study, the effectiveness of the Fresnel sheet setup is calculated in this section.

Area of the Fresnel lens = 1.4 x 1.09 = 1.526m²

Solar Irradiance input = 314 x 1.526 = 479.164 W

Assuming the transmissivity through air at constant temperature of 260 degree Celsius to be 0.75. Hence, Considering transmissivity, the radiation input = 0.75 x 479.164 = 359.373W.

**With Fresnel sheet:**

During the time 2:55pm to 3:05 pm,

\[ Q = mc\Delta T + \text{(mass change x Latent Heat)} \]

\[ Q = 400 \times 10^{-3} \times 10^{-3} \times 1000 \times 4178(38-28) + 2 \times 10^{-3} \times 10^{-3} \times 100 \times 2246 \times 103 \]

\[ Q = 21204 \text{ J} / (10 \text{ min}) \]

\[ Q = 35.34 \text{ W} \]

**Without Fresnel sheet:**

During the time 3:15pm to 3:25 pm,

\[ Q = mc\Delta T + \text{(mass change x Latent Heat)} \]

\[ Q = 399 \times 10^{-3} \times 10^{-3} \times 4178(33-30) + 4 \times 10^{-3} \times 10 \times 1000 \times 1000 \times 2246 \]

\[ Q = 9196.31J/10\text{min} \]

\[ Q = 14.98W \]

Thus excess heat power of around 20W is generated due to the presence of Fresnel sheet.

**Effectiveness of Fresnel sheet:**

\[ \frac{35.34}{14.98} = 2.36. \]

**Sheet Efficiency:** 35.34/359.373 = 0.09833 = 9.8%

Thus effectiveness thus calculated can be considered a suitable condition for solar energy utilization. However, the efficiency of the sheet comes around 10%. The low efficiency of the sheet is due to various reasons such as:

1) Change in position of the sun, i.e., change in position of spot size
2) Convective heat transfer losses due to open beaker and high wind velocity
3) Conductive heat loss from beaker to ground
4) Inefficient medium for capturing heat energy

5.2 Cost estimation of Solar Thermal Electric System
Table 1. Cost estimation of Solar Thermal Electric System

| Components         | Description and Quantity                      | Cost (Rs.) |
|--------------------|-----------------------------------------------|------------|
| Fresnel sheet      | Focal length: 200cm, Width:109 cm, Spot size:8 cm, Length:140 cm, Qty: 1 no | 5000 +300 (freight charges) =5300 |
| TEG Module         | Material: lead telluride(PbTe), Melting point:1190 K, Hot Junction:550°C, Cold junction: 40°C, Qty: 200 no’s | 40000     |
| Concrete tubes     | Qty:10(approx.)                                | 200        |
| Frame              | Qty:1, Material: Wood                         | 100        |
| Fasteners          | Qty:15(approx.)                               | 100        |
| Class C chopper circuit | Qty:1                                      | 500        |
| Total              |                                                | 46200      |

The above table is significantly used to find out the payback period of our proposed system and made a comparison with the commercially available one.

Proposed output power capacity = 1KW

The following calculation was done in order to obtain payback period of the proposed design:

**Radiation input to Fresnel lens = 280 W**

**Net radiation incident on target = 246.829 W**

**Efficiency of Fresnel lens = 246.829/280 = 88.15%**

**Std. Solar irradiance at Coimbatore = 5.86 KWh/m²/day**

**Area of Fresnel lens = 1.54 m²**

**Irradiance input at inclined lens = 1.54 x 5.86 = 9.0244 KWh / day**

**Heat energy/p to target material due to inclined lens = (0.881) x (9.024) = 7.95 KWh/day**

**Efficiency of central lens during AM/PM = 0.88 x 0.5 = 0.44**

**Heat power input due to central lens: 0.44 x 5.86 = 2.5784 KWh/ day**

**Total heat input**
at target: $7.95 + 2.5784 = 10.5284 \text{ KWh/day}$

Conventional TEG efficiency: 20%

Energy generated during the period: $0.2 \times 10.5284 = 2.10568 \text{ Kwh/day}$

Cost of 1 unit = Rs. 8

Money generated per day = $8 \times 2.10568 = \text{Rs. 16.84544}$

Money generated in one year = Rs. 6148.5856

Payback period

\[\frac{46200}{6148.5856} = 7.5139 \text{ years}\]

The payback period in the proposed system is considerably less than that of conventional solar system. Hence the proposed concentrated system can be considered as a candidate for an efficient solar thermal system.

5.3 Flow channel analysis

The solid domain as designed earlier using fusion 360 was converted to fluent domain and analysis was done in Ansys fluent using the following boundary conditions:

- Inlet velocity considered to be 30m/s, as in general case the water flow in pipes have a pressure head of 5bar, when they are converted to velocity head, 30m/s is obtained.
- As discussed earlier, the surface heat flow in TEG material is 6.2W/cm, when calculated for 4 modules the TEG surface heat flux was set to be 24,800W/m²
- The inlet temperature was set to be 300K
- The flow was assumed to be laminar and steady flow

With the above boundary conditions and considering maximum iterations to be 100, the problem was solved and the required contour was obtained.

It is found that there is no significant difference in temperature of Fluid flow through the channel i.e. The temperature is found to be constant at 300K. It is observed that the areas where TEG is in direct contact experiences a higher temperature of about 303K and the surround temperature decreases in a linear manner accordingly.

Thus, as Water temperature is found to be constant and the flow channel side of TEG is found to be maintained at 303K. It can be said that the designed flow channel (with 3 fins) works more efficiently compared to other 2 fins model and is sufficient to maintain considerable temperature difference across the junctions of the TEG module.

The Analysis output images are shown from figure 6 to figure 11.
Figure 7. Pressure

Figure 8. Turbulence Eddy Dissipation

Figure 9. Wall Heat transfer Coefficient

Figure 10. X contour
6. Conclusion

- The critical parameters of a Fresnel concentrated system were identified and suitable decisions and values were chosen for them.
- Necessary calculations were done to obtain the payback period which was found to be less than the conventional concentrated system stating that the concentrated system designed is efficient.
- The maximum power output from each TEG module was found out to be 5W which proves that the stated system has a significant potential in operating in higher efficiency zone compared to conventional solar cells.
- The flow channel system design has proved to be efficient in maintaining low temperature in the cool side.
- However, maintaining the temperature for a prolonged time has proved to be tough due to uncertainty in solar radiation. Hence a better design or improvement in the flow channel is required.
- In order to overcome this issue, a Thermic fluid reservoir or a Phase Change Material(PCM) can be utilised.

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