Thermal Performance of Two-Phase Closed Thermosyphon in Application of Concentrated Thermoelectric Power Generator Using Phase Change Material Thermal Storage

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ABSTRACT

With the increasing energy demand due to growing world population and industrialization, utilizing concentrated solar energy for thermal and electrical power generation will be the future renewable power source to minimize the reliance on fossil fuel and reduce carbon dioxide emission. Besides using Concentrated Photovoltaic (CPV) system, Concentrated Thermoelectric generator (CTEG) will be another viable option for sustainable power generation. The CTEG system utilizes concentrated solar flux as a heat source to the thermoelectric generating (TEG) module in generating direct current thermoelectricity which can be easily converted to alternating power using an inverter. By maintaining a temperature difference between the hot and cold sides of the thermoelectric cells (Seebeck effect), thermoelectricity is generated where its magnitude is a function of temperature difference. The main challenge is the effectiveness of excess heat removal which accumulated at the cold side of the thermoelectric cell to achieve greater power generation. Using acting cooling mechanisms are not energy efficient proposal as it requires power in operating them and significantly reduces the total power output generated. A passive cooling system which uses two phase closed thermosyphon and phase change material thermal storage are proposed in the paper for operating CTEG system through passive cooling and achieving constant cooling. Two-phase closed thermosyphon is implemented as an effective heat transporting device for transferring excess heat from heated TEG module to the cooled PCM storage tank for heat storage. The aim of this investigation is to evaluate the thermal performance of the proposed system utilizing two phase closed thermosyphon as passive heat transportation device. The numerical simulation showed that solar concentration of 75 Sun's is able to deliver maximum temperature difference of 150\textdegree C and does not exceed the thermoelectric cell’s malfunction temperature of 250\textdegree C as recommended by the manufacturers. The working fluid used in the thermosyphon was Acetone and its filling ratio was designated at 40\% of the evaporator volume. Paraffin wax was selected as PCM with melting point of 47\textdegree C and acceptably high latent heat storage was selected in the thermal storage. The passive cooling mechanisms consist of PCM storage tank, heat pipe-based heat transfer system for transporting heat from TEG modules to the PCM storage tank during the daytime and a similar heat pipe-based system for discharging heat from PCM storage tank to the cooler ambient during the night time.

Keywords: two-phase closed thermosyphon, thermoelectric generator, thermal storage, paraffin wax

1. INTRODUCTION

Thermoelectric generator (TEG) is a single state electrical power generator where it requires a temperature difference across the hot and cold side of the thermoelectric cell (TEC) for thermoelectricity generation. Concentrated thermoelectric generator (CTEG) system uses concentrated solar energy as a sustainable heat source and obtains high solar heat flux to increase the TEC hot side temperature. The waste heat at the cold side of the TECs must be effectively dissipated to achieve greater temperature difference for higher power generation. Active cooling methods such as using electric fan and water pump would seem to be good thermal management solutions where they have gained popularity in electronic cooling with good thermal control and compact installation. However, the main drawback is power consumption which required for operating and reduces the total power generated by the system. Hence, passive cooling approaches would seem to be more reliable method for a sustainable power generator in spite of the lower cooling rate. Problem arises on passive cooling devices (i.e. heat sinks) are very
reliance on the ambient conditions and variation. Weather fluctuations such as wind speed and surrounding temperature can significantly affect the natural convection heat transfer performance and pose a limitation on the passive cooling of concentrating solar applications. To improve the existing passive cooling deficiencies, the authors have implemented phase change material thermal storage concept. Using encapsulated heat exchanging unit in the storage tank filled with phase change material (PCM), external ambient conditions would not be able to influence the constant cooling stability. The main challenge in this proposal is the requirement of effective heat transfer mechanism where it can transport large amount of heat over a certain distance within the system, from the heated TECs to the PCM thermal storage tank for heat storage.

In this paper, two-phase closed thermosyphons (TPCTs) are implemented to the proposed passive cooling system using PCM thermal storage. The objective of TPCT is to dissipate large amount of excess heat accumulated on the cold side of TEC to the PCM thermal storage which avoid cell damage and attain greater temperature difference. The aim of this study is to assess the thermal performance of the concentrated thermoelectric generator (TEG-PCM) system using TPCT as heat transporting device. Maximum temperature difference across the TEG must not exceed the maximum operating cell temperature of 250°C which recommended by TEG manufacturer.

CONCEPTUAL DESIGN

In this present design shows in Figure 1, two TPCTs or gravity-assisted wickless type of heat pipe are implemented in the CTEG-PCM system. The advantages of using TPCT are simple structural construction and the ability to transfer large quantity of heat with a small temperature drop that made it favorable as a heat transporting device in this proposed passive cooling concept.

Three TPCTs are utilized in the system where two of them (primary) are used for transferring heat from the TEG module to the PCM storage tank for heat absorption during the day. The third TCPT (secondary) is embedded in the PCM storage tank for transporting heat from the melted PCM to the cooler surrounding (PCM cooling) during the night in preparation for the next day cycle. Passive cooling cycle in this concept design is formulated through repetitive heat charging and discharging of the PCM thermal storage where TPCTs play important roles for effective heat transportation and dissipation.

Figure 2. Schematic TEG module and heat flow.

Figure 2 shows the schematic TEG module where the incoming heat source is delivered by the concentrated solar flux via Fresnel lens concentrator. The top panel (hot side) of the TEG module rapidly heat up and the bottom panel (cold side) requires effective cooling to achieve temperature difference for thermoelectricity generation. Copper material is used for heat collector and heat sink due to the high thermal conductivity (380 W/m K) and high corrosive resistance. Both copper blocks are used to sandwich the thermoelectric cell (TEC) to provide a temperature difference through the TEC’s top panel heating and bottom panel cooling for fulfilling the thermoelectricity generation criteria. Two TPCTs with evaporator sections (Outer diameter = 15.9mm) are thermally inserted into copper heat sink for transportation heat to the PCM storage tank during day time operation.
As mentioned earlier, one TPCT with evaporator section embedded in the PCM for removing the heat which stored in the melted PCM to the cooler surrounding during the night. It also acts as a thermal diode and is able to reject heat when the PCM temperature reaches its working fluid saturation temperature.

Figure 3. TEG module on the experimental prototype using heater as a heat source.

The PCM used in the thermal storage tank is paraffin wax. It is non-corrosive, readily off-the-shelves and has relatively high latent heat storage capacity (140kJ/kg) which make it attractive to be used in the thermal storage. Further information on the thermo-physical properties of the proposed paraffin wax are showed in table 1.

Table 2. Thermo-physical properties of proposed paraffin wax.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting temperature [°C]</td>
<td>47</td>
</tr>
<tr>
<td>Solid density [kg/m³]</td>
<td>880</td>
</tr>
<tr>
<td>Liquid density [kg/m³]</td>
<td>760</td>
</tr>
<tr>
<td>Latent heat capacity [kJ/kg]</td>
<td>140</td>
</tr>
<tr>
<td>Specific heat capacity [kJ/kg K]</td>
<td>2.9/2.2</td>
</tr>
<tr>
<td>Thermal conductivity [W/m K]</td>
<td>0.2</td>
</tr>
</tbody>
</table>

It is noted that Paraffin wax (PCM) has low thermal conductivity (0.2 W/m K) which may affect the heat exchanging performance by the thermosyphon condenser section. Approach taken for improving the PCM melting is by using long TPCT condenser section (1 evaporator length : 3 condenser length) incorporating aluminum fin attachments for providing a larger heat transfer surface area to improve the effective thermal conductivity within the PCM storage. TPCTs are tiled at 5° angles for facilitating the return of condensate to the evaporator. In addition, PCM storage tank is also required to be elevated above the TEG module to ensure the TPCT condenser section is above the evaporator section.

2. THERMAL PERFORMANCE MODELING

2.1. Energy Balance Analysis

The energy balance equation for the CTEG-PCM system is given by:

\[
Q_{inPC} = Q_{conv} + Q_{rad} + Q_{TEG} + Q_{cool}
\]  

The incoming solar radiation \( Q_{rad} \) is the solar radiant energy input on the collector area \( A_{col} \) of 80mm (length) and 40mm (width). The optical efficiency \( \eta_{opt} \) of Fresnel lens concentrator and the absorptive of the copper heat collector \( \eta_{abs} \) are assumed as 80% in this modeling. The concentrated heating power governed by solar concentration ratio (CR) on heat collector is written as:

\[
Q_{inPC} = \eta_{opt} \times \eta_{abs} \times Q_{rad} \times A_{col} \times CR
\]  

Ambient energy losses by convection \( Q_{conv} \) and radiative \( Q_{rad} \) heat transfer will be accounted in the net energy absorbed into the system.

\[
Q_{conv} = h_{wall} \times A_{wall} \times (T_{col} - T_{amb})
\]

\[
Q_{rad} = \alpha_{wall} \times A_{wall} \times (T_{col}^4 - T_{amb}^4)
\]

The assumption made for heat losses to the surrounding by the copper absorber plate is through convention and radiation heat transfer under the ambient conditions of wind speed \( V_{col} \) of 2m/s and ambient temperature \( T_{amb} \) at 20°C. The Stefan-Boltzmann’s constant \( (\sigma = 5.67 \times 10^{-8} \text{Wm}^{-2}\text{K}^{-4}) \) is applied to radiation heat transfer and convective heat transfer coefficient for top surface of the solar collector plate which is estimated by \( h_{wall} = 5.7 + 3.8V_{col} \) (McAdam, 1954).
2.2. Thermoelectric Generator Module

The commercially available thermoelectric cells used in the module are Bismuth Telluride (Bi$_2$Te$_3$) which is widely used as thermoelectric units. Two of the mentioned TECs with dimensions of 40mm (length) x 40mm (width) x 4mm (height) were electrically connected in series arrangement. The thermal resistance for single TEC of 0.75°C/W is determined through experiment test.

The thermal resistances for copper heat collector and heat spreader have similar in contact area as TECs:

$$R_{2-4} = \frac{R_{4-\infty}}{R_{2-4} \cdot R_{4-\infty}}$$  \hspace{1cm} (8)

The thermal resistance for TEG:

$$R_{2-1} = \frac{R_{4-2}}{R_{2-4} \cdot R_{4-2}}$$  \hspace{1cm} (9)

2.3. Two-Phase Closed Thermosyphon

Figure 7 shows the experimental prototype fabricated in RMIT University. Only two thermosyphons were used in the prototype for examine the passive cooling concept. For validating the experiment results, the framework of this modeling will solely base on thermal performance of one primary TPCT. In the scope of this study on cooling performance, secondary TPCT embedded in the PCM storage tank will not be included in the model.

The thermal resistance for the wall of thermosyphon:

The thermal resistance of TPCT wall is a function of TPCT’s sectional length and pipe thickness.

**Evaporator section:**

$$R_{2-1} = \frac{1}{2 \pi d \delta}$$  \hspace{1cm} (10)

**Condenser section:**

$$R_{1-\infty} = \frac{1}{2 \pi d \delta}$$  \hspace{1cm} (11)

**Heat transfer within TPCT:**

The selected working fluid is Acetone. It has
lower boiling point (55°C) at atmospheric pressure and latent heat of vapourization of 527kJ/kg. The designated saturated temperature for the cooling system is 60°C. The thermal resistances for convective heat transfer of vapourization and condensation of working fluid are shown below.

Evaporator section:
\[ R_{g-e} = \frac{L}{h_{conv} A_{eva}} \quad (12) \]

Condenser section:
\[ R_{g-c} = \frac{L}{h_{conv} A_{cva}} \quad (13) \]

The heat transfer coefficient within the TPCT is assumed under the working condition where only minimum fill volume of the working fluid is required for maintaining liquid film on the wall of the TPCT. The simplified average heat transfer coefficients for both evaporator and condenser sections are given by the Nusselt analysis (Faghri, 1995).

Evaporator section:
\[ h_e = \left[ \frac{2^{1/2} \ln \left( \frac{D_e}{d_{eva}} \right)}{h_{eva} \left( 1 - \frac{D_e}{D_{eva}} \right)} \right]^{1/4} \quad (14) \]

Condenser section:
\[ h_c = \left[ \frac{2^{1/2} \ln \left( \frac{D_c}{d_{cva}} \right)}{h_{cva} \left( 1 - \frac{D_c}{D_{cva}} \right)} \right]^{1/4} \quad (15) \]

Thermal resistance between the condenser fin attachment and PCM:

Paraffin wax will undergo phase change (solid-liquid) upon reaching its melting point under constant heat dissipation by the thermosyphon condenser. It is noted that conduction heat transfer will gradually diminish as natural convection heat transfer grow rapidly during liquid state transition. For modeling simplification, only pure conduction is assumed throughout the phase changing process. The thermal resistance for solid PCM within the aluminum fin gap is given by:

\[ R_{B-g} = \frac{L}{h_{fina} A_{fina}} + \frac{L}{h_{pcm} A_{pcm}} \quad (16) \]

The latent heat fusion (\(H = 140\)kJ/kg) of PCM must be accounted for at the melting point (\(T_{melt} = 47°C\)). The conditional governing equations for heat storage in the PCM thermal storage are given as:

Solid phase: \(T_{amb} \leq T_{pcm} < T_{melt} \)
\[ Q_{pcm} = m_{pcm} c_p (T_{pcm} - T_{amb}) \quad (17) \]

Solid-liquid Phase: \(T_{pcm} = T_{melt} \)

\[ Q_{pcm} = m_{pcm} c_p (T_{pcm} - T_{amb}) + H \]

Liquid Phase: \(T_{pcm} > T_{melt} \)
\[ Q_{pcm} = M_{pcm} \left[ C_1 (T_{melt} - T_{amb}) + H \right] \]
\[ + M_{pcm} C_1 (T_{melt} - T_{amb}) \quad (19) \]

3. NUMERICAL RESULTS

The numerical models for the CTEG-PCM system had been completely developed in MATLAB programming software. The numerical results simulated the thermal performance of CTEG-PCM prototype under experimental conditions. Different solar concentrations will be simulated to determine the optimum concentration for delivering the maximum TEC temperature difference.

Figure 7 shows the overall thermal performance of TEG-PCM system under 75 suns over 1700s (30mins) duration. The maximum TEC hot side temperature in the TEG module reached 240°C where the maximum temperature limit recommended by TEC manufacturer is 250°C. Hence the maximum solar concentration (CR) for this configuration is 75 which the aperture diameter of the Fresnel lens should be sized at 560mm. The TEC cold side temperature has maintained at 88°C and attained a constant TEC temperature difference of 152°C over the period. Both temperature on the TEC hot and cold side decrease rapidly when the evaporator temperature reaches the saturation temperature (60°C) of the working fluid in the TPCT. The significant drop at the TEC cold side shows that waste heat had effectively transferred from the evaporator section to the condensation section embedded in the PCM thermal storage for heat.
dissipation. The dissipated heat was absorbed by the PCM as sensible heat before 200 seconds and thereafter latent heat absorption upon reaching the melting point (47°C). The PCM temperatures (T9 and T10) located at 10mm and 50mm above the TPCT condenser were designated to capture melting performance during heat absorption. T9 rised gradually and latter become plateau due to the latent heat of fusion (melting). T10 was unchanged during the period of 30 minutes due to the poor thermal conductivity. At this plateau region, PCM continued to absorb dissipated heat despite there was no rise in temperature.

![Figure 9. Temperature difference and power output for 2 TECs under different solar concentrations.](image)

The thermoelectric cells in the TEG module are made of Bismuth Telluride (Bi₂Te₃) which has high Seebeck coefficient (~190µV/K) and high figure of merit (~2x10⁻³ K⁻¹) (Slack G.A, 1994). The maximum theoretical power output was 9.5W under maximum temperature difference of 152°C. Further temperature difference cannot be achieved in the existing configuration as the TEC hot side panel temperature will exceed the maximum operating temperature (250°C). Using working fluid with lower saturation temperature and higher latent heat of vaporization in TPCT can further attain greater temperature difference for higher thermoelectric power output.

4. CONCLUSION

In this present study, the thermal performance of the concentrated thermoelectric generator utilizing two phase close thermosyphon as heat transfer device has been investigated numerically. Some conclusions are drawn as follows:

- TPCT has shown to be an effective heat transporting device due to simple structural construction and it can be easily bent to fit and connect between the CTEG system and PCM thermal storage.
- The simulation had shown that using passive devices; TPCT and PCM thermal storage are able to maintain a temperature difference of 152°C and produce 9.5W of thermoelectric power.
- Although PCM provides large amount of heat storing capacity and enable constant cooling on TEG cold side panel, more researches need to be done on improving the thermal conductivity to maximize the heat absorption rate.
- More researches need to be done on working fluid selection for lowering the cold side temperature of the TEC to achieve greater temperature difference.

REFERENCES


