Performance study of a static low-concentration evacuated tube solar collector for medium-temperature applications

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Abstract

With the development of the energy demands, solar energy medium-temperature applications (>80°C) for refrigeration, building heating, seawater desalination, thermal power generation etc. has become popular research fields. The article presents an investigation on a static low-concentration evacuated tube (LCET) solar collector for medium-temperature applications. Ray trace outcome at the incident angles between 0 and 60° shows that the average optical efficiency can reach 76.9%. The experimental testing was conducted in the medium temperature range of 80 and 140°C which indicates the instantaneous thermal efficiency is still larger than about 30.0%, and the instantaneous exergetic efficiency is >5.92%. The results comprehensively indicate the good performance of LCET solar collector for medium-temperature applications.

Keywords: solar energy; low-concentration; evacuated tube; medium-temperature; exergetic efficiency

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1 INTRODUCTION

Solar energy utilization, especially solar energy thermal utilization, has been an important component in renewable energy utilization. With the continuous advancements in society, medium temperature (~80–140°C) is inevitably required for solar energy applications in air conditioning, refrigeration, building heating, seawater desalination, thermal power generation etc [1–5]. For solar-driven cooling and air conditioning, the single-effect system gives best results in the temperature range >80°C [6]. According to [5], the thermal efficiencies of the ORC at different heat source temperatures of about 100, 90, 80 and 70°C are 8.2, 7.7, 7.4 and 4.6%, because of which the temperature larger than 80°C has a significant advantage. In addition, the multistage flash distillation plants usually operate at top brine temperatures of 90–120°C [7]. Therefore, the requirement of the medium temperature (>80°C) is obvious and significant. However, for the nonconcentration solar collector, for example evacuated tube and flat plate solar collector, with the temperature increasing, the thermal efficiency of the collector keeps down. Especially above 80°C, the thermal efficiency of the solar collector falls sharply. Therefore, it requires solar concentrators, as opposed to nonconcentration collectors [8].

On the other hand, although the high-concentration solar collectors can also meet the demand, they need a solar tracking system, which further escalates operation and management costs, and are usually suitable for large-scale integrated applications, such as high-temperature solar thermal power generation system. At the same time, the high-concentration solar collectors, such as tower concentration solar collector and dish concentration solar collector, can get much higher temperature, which is beyond these applications temperature above, and can cause more waste. What is more, high-concentration solar collectors can lead to more diffusion loss. Therefore, high-concentration
solar collectors also do not fit these medium-temperature applications.

Based on these above, researchers made series of related investigations on the low concentration rate solar collectors [9–13]. In the article, a low-concentration evacuated tube (LCET) solar collector is introduced and investigated. Its output can just meet the demand of these medium-temperature applications. In addition, it is a static solar collector without tracking system, and it has a larger acceptance angle. It can attain a temperature of over 80°C with higher thermal efficiency compared with non-concentration solar collector. With the rapid development in medium-temperature solar energy utilization, this research is very significant and interesting.

2 LCET SOLAR COLLECTOR STRUCTURE

A single LCET solar collector was shown in Figure 1. A cylindrical receiver is attached to the inside of the inner tube, and the heat absorbed by the receiver is conducted to the U-type pipe. Figure 2 shows a photograph of the LCET solar collector structure. The parabolic curve equations, expressed in centimeters, are given as

\[ y = \frac{1}{5}(x + 2)^2, \quad (-5.65 \leq x \leq 0) \]  
\[ y = \frac{1}{5}(x - 2)^2, \quad (0 < x \leq 5.65) \]

The focus of the 2 parabolic curves is \((\pm 2, 5/4)\). The absorber position is higher than that of the aperture. These reflectors can be pressed as a whole plate and are easy to transport and install due to the small size.

3 OPTICAL ANALYSIS

The LIGHTTOOL software was employed for ray tracing to evaluate the LCET solar collector optical performance at different incident angles. The incident angle is defined as the angle between the direction of the incident rays from the energy source and the direction perpendicular to the aperture of the concentrator. The model parameters are listed in Table 1.

3.1 Ray tracing analysis

In Figure 3a, a large portion of the incoming rays perpendicular to the aperture of the solar collector can reach the absorber and be concentrate on the bottom of the absorber. Figure 3b shows the LCET solar collector ray-tracing diagram at ray incident angle of 10°. The lost rays are obviously less than those of Figure 3a. Simultaneously, the incidence rays on the right side are reflected on the absorber, and no rays can pass through the gap from the right side.

The LCET solar collector ray-tracing diagram at ray incident angle of 20° (Figure 4a) shows that the incident rays gather density is higher at the lower section of the right side. When the incident angle is 30° (Figure 4b), the ray-tracing result is similar to that at an incident angle of 20°. However, the higher flux distribution is now at the middle section of the right side of the absorber.

In Figure 5a, when the incident angle is 40°, some of the left rays are clearly concentrated at the lower section of the left side, and no ray is reflected directly out of the left aperture. In addition, the concentration position of the incident rays at the right side of the absorber moves forward to the higher right absorber section. At this incident angle, most of the incoming rays can

![Figure 1. Cross-sectional schematic diagram of the single LCET solar collector.](image1)

![Figure 2. Photograph of the LCET solar collector structure.](image2)

### Table 1. Model parameters of the LCET solar collector.

| Parameters                        | Value |
|-----------------------------------|-------|
| Reflective reflectivity, \(\rho_R\)| 0.84  |
| Absorber absorptivity, \(a_{inner}\)| 0.96  |
| Aperture diameter (mm), \(D_{inner}\)| 37.0  |
| Aperture width (mm), \(D\)        | 113.0 |
reach the absorber. Figure 5b shows that when the incident angle is 50°, the rays reflected by the right reflector all miss the absorber, and the only incoming rays that finally reach the absorber all come from the left reflector and the top, which inevitably lead to lower optical efficiency. Figure 5c shows the resultant ray-tracing diagram at 60° incident angle, which is similar to that at an incident angle of 50°. In addition, small portion of the rays pass through the gap directly without being reflected by the left reflector and then are reflected by the right reflector to exit the solar collector.

3.2 Optical efficiency and proportion of rays reaching the absorber

The variation in optical efficiencies and the rays reaching the LCET solar collector absorber at different incident angles was shown in Figure 6. The overall average optical efficiency between the incident angles of 0 and 60° can reach 76.9%, which is a very attractive value for medium-temperature applications. With the increase in incident angles, the optical efficiency and the proportion of rays reaching the absorber increase gradually, and the optical efficiency peak value of 85.3% and the 97.4% for the rays reaching the absorber occur at an incident angle of 45° because nearly all rays reach the absorber here. The optical efficiency and the proportion of rays that reach the absorber decrease rapidly when the incident angle reaches about 50°. The lowest value of 79.7% for the proportion of rays reaching the absorber appears at this angle of 50°, which is even lower than that of the 0° incident angle (80.7%). This situation happens because the rays reflected by the right reflector cannot reach the absorber, and the absorber can collect only the rays directly from the top and those being reflected by the left reflector (Figure 5b). When the incident angle continues to increase, the rays reflected by the right reflector is still unable to reach the absorber, but the proportion of rays reflected by the right reflector becomes less than that at the incident angle of 50°. Therefore, the optical efficiency and the rays that reach the absorber tend to increase up to the 60° incident angle. When the incidence angle is larger than 60°, the shadow will occur on the array. But due to the structure of reflector, the performance of the concentrator is similar with that of the common evacuated tube solar collector without reflector when the incidence angle is larger than 60°C.
4 EXPERIMENTAL STUDY

In order to further evaluate the performance of the LCET solar energy collector for medium-temperature applications, the experiment was designed and the transfer heat oil was used to as the fluid to attain higher temperature in Hefei (Anhui Province, People’s Republic of China; 31°53’N, 117°15’E).

4.1 Experimental system
A schematic diagram of the LCET solar collector experiment rig is shown in Figure 7. The system primarily consists of the LCET solar collectors, one circulating pump, one storage tank and other components. The heat transfer oil is circulated between the collector and the storage tank.

The LCET solar collector has 12 vacuum tubes. The entire solar collector has a heating-collection area of 2 m². The specific LCET solar collector structural parameters and materials with U-pipe are shown in Table 2. The U-type pipes in each collector are assembled into four groups parallel to one another, and each group contains three series of U-type pipes, shown in Figure 8. The test equipment components are shown in Table 3.

4.2 Experimental results and discussion
The LCET solar collector was tested in Hefei, and faced south at a tilt angle of 32°. The initial inlet oil temperature of the LCET solar collector was 80°C and the final temperature was 140°C.

For the LCET solar collector, the instantaneous heat input to the circulated heat transfer oil in the collector (\(\dot{Q}_{col}\)) at any given time is given as follows:

\[
\dot{Q}_{col} = \dot{m}_{oil} \cdot c \Delta T
\]

where \(\Delta T\) is the temperature difference between the outlet and inlet of the solar collector. \(\dot{m}_{oil}\) is the flow rate of the heat transfer oil. \(c\) is the specific heat capacity of the oil. The instantaneous thermal efficiency \(\eta_{\text{col}}\) is calculated by

\[
\eta_{\text{col}} = \frac{\dot{Q}_{col}}{G A_c}
\]

where \(G\) is the instantaneous solar irradiance (W/m²) on the surface of 32° tilt angle and \(A_c\) is the total area of the collector.

The instantaneous exergetic efficiency of the LCET solar collector is calculated as follows:

\[
e_{\text{col}} = \frac{\dot{E}_{\text{output}}}{\dot{E}_{\text{sun}}}\]

where \(\dot{E}_{\text{output}}\) is the exergy obtained by the collector [14].

\(\dot{E}_{\text{output}}\) can be written as

\[
\dot{E}_{\text{output}} = \dot{Q}_{\text{col}} \left(1 - \frac{T_a}{T_{\text{in}}}\right)
\]
\[ \dot{E}_{\text{sun}} = A_\text{c} G \left( 1 - \frac{T_\text{in}}{T_{\text{sun}}} \right) \]  

where \( T_{\text{sun}} \) is equal to 6000 K solar irradiance temperature in the exergetic evaluation of a solar collector.

Figure 9 shows the irradiance density is between 562.5 and 954.0 W/m² in the experiment, and the environment temperature is between 22.9 and 34.5 °C. The instantaneous thermal and exergetic efficiencies of the LCET solar collector are shown in Figure 10. When the inlet oil temperature is 80 °C, the instantaneous thermal and instantaneous exergetic efficiencies are 36.3 and 6.02%, respectively, and when the inlet oil temperature is 140 °C, they are 31.7 and 8.63%, respectively. Obviously, the instantaneous thermal efficiency curve shows a declining trend, but the lowest value is still larger than 30.0%. In addition, the instantaneous exergetic efficiency curve shows an increasing tendency, and the lowest and largest values are 5.92 and 8.82%, respectively. The instantaneous thermal and exergetic efficiencies all indicate superior performance in achieving medium-temperature applications.

### 4.3 Error analysis

Referring to [18], the relative error of the dependent variable \( y \) can calculate as follows:

\[ \text{RE} = \frac{dy}{y} = \frac{\partial f}{\partial x_1} \frac{dx_1}{y} + \frac{\partial f}{\partial x_2} \frac{dx_2}{y} + \ldots + \frac{\partial f}{\partial x_n} \frac{dx_n}{y} \]  

where \( x_i (i = 1, \ldots, n) \) is a variable of dependent variable \( y \), and \( \frac{\partial f}{\partial x} \) is the error-transfer coefficient of the variables.

The experimental relative mean error (RME) during the test period is expressed as

\[ \text{RME} = \sum \frac{|\text{RE}|}{N} \]  

Based on Equations (8)–(10), the RME of all variables are given in Table 4.

### 5 CONCLUSION

An LCET solar collector without tracking system employing heat transfer oil for medium-temperature applications, which has a large half-acceptable angle, has been introduced and investigated.

The ray tracing on the single LCET showed that the overall average optical efficiency could reach 76.9% between 0 and 60° incident angles, which is a very attractive value for medium-temperature applications.
The experimental result showed that the instantaneous thermal efficiency was larger than 30.0%, and the instantaneous exergetic efficiency was larger than 5.92% when the inlet temperature is between 80 and 140°C, which all indicated superior performance in achieving medium-temperature applications.

![Flowchart of the U-type pipes.](image)

**Figure 8.** Flowchart of the U-type pipes.

**Table 3.** Specifications of the test components.

| Test equipment            | Specification                  | Production site                              | Quantity | Position                                            |
|---------------------------|--------------------------------|----------------------------------------------|----------|-----------------------------------------------------|
| Pressure gauge            | 0–1.0 MPa                      | Hangzhou, China (Fuyang Huada Co.)           | 1        | Loop pump outlet                                    |
| Thermocouple             | 0.2 mm copper-constantan        | Made in laboratory, USTC                     | 3        | Collector inlet; outlet; environment temperature    |
| Pyranometer              | TBQ-2                          | Jinzhou, China (Sun Co.)                    | 1        | On tilted surface parallel to the CPC collector aperture plane |
| Flowmeter                 | LC-TE20                        | Pope Hefei Instrument Co., Ltd(China)        | 1        | Collector inlet                                    |
| Environmental temperature| JZH-1                          | Jinzhou, China (Sun Co.)                    | 1        | Near experimental rig                               |

Others: Data Acquisition Instrument: Agilent 34970A (USA), test computer and electrical wires, among others.

![Environmental parameters of the experiment.](image)

**Figure 9.** Environmental parameters of the experiment.

![Instantaneous thermal and exergetic efficiencies of the LCET solar collector.](image)

**Figure 10.** Instantaneous thermal and exergetic efficiencies of the LCET solar collector.

The experimental result showed that the instantaneous thermal efficiency was larger than 30.0%, and the instantaneous exergetic efficiency was larger than 5.92% when the inlet temperature is between 80 and 140°C, which all indicated superior performance in achieving medium-temperature applications.

**Table 4.** Experimental RME of the variables.

| Variables | ΔT | G  | Ō_{col} | η_{col} |
|-----------|----|----|---------|---------|
| RME       | 6.42% | 2.00% | 6.92% | 8.92% |
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