Numerical analysis of effect of phase change thermal storage layer and annular fins on thermal performance of linear concentrating solar evacuated tubular collector

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Abstract. The effects of Phase Change Thermal Storage Layer (PCTSL) and annular fins on the thermal performance of linear concentrating solar evacuated tubular collector are numerically studied. July 15 and January 15 with relatively longer and shorter solar radiation durations are selected as the dates to simulate. Three types of linear concentrating solar evacuated tubular collectors with length of 400 mm are established, which are the traditional collector, the collector with PCTSL but without annular fins, and with PCTSL and annular fins. The results show that the maximum outlet transformer oil temperature of with PCTSL but without annular fins is 5.9 °C-10.7 °C lower than the traditional one, but the outlet oil temperature change rate of the collector with PCTSL is slow; the maximum temperature duration time of the collector with PCTSL but without annular fins is 2-2.5 hours longer than that of the traditional conditions; adding fins in PCTSL makes the outlet oil temperature reach the peak more than 30 minutes earlier. The PCTSL and annular fins studied in this paper have greatly improved the thermal performance of solar collectors and have broad application prospects.

1. Introduction
The world generates major energy from fossil fuel based thermal power plant which uses coal, oil and natural gas. The fossil fuel based energy sources have a major impact on the climate change[1]. In the context of massive use of fossil energy, of which stocks are decreasing, the currently unreasonable energy structure will be changed in the near future to meet environmental requirements and mitigate carbon dioxide emissions[2,3]. According to the statistical data, developing countries have marked increases in energy consumption, and fossil fuels still contributes the most to the energy supply in these countries, such as China, India, Brazil and South Africa[4].

Various forms of thermal energy storage solutions have been developed, such as sensible heat storage, latent heat storage and thermo-chemical storage[5]. Since the phase change materials (PCMs) can store a large amount of heat during the phase change process, PCMs are attractive candidate for latent heat thermal energy storage. PCMs absorb and release heat within a small temperature variation, whose the amount of thermal energy stored per unit volume can be up to 5-14 times more than the sensible heat thermal energy storage, such as water, masonry, or rock[6]. However, PCMs usually have poor thermal conductivity which makes them limited in thermal applications. The methods of
improving the thermal conductivity of PCM include dispersing high thermal conductivity fins into PCMs, use of porous matrix and nanoparticles and so on[7].

PCMs represent a storage medium for storing solar energy during high solar intensity and releasing heat during low solar radiation and at night[8]. Simultaneously, the structural design of solar energy storage plays a significant role in charge and discharge of energy. The extensively studied solar collector configuration reported in literature is evacuated tubular collector (ETC) integrated with compound parabolic concentrator (CPC) based phase change thermal storage layer (PCTSL). Mishra et al. (2017)[9] experimentally studied the thermal modeling of evacuated tubular collectors connected in series without and with concentrator. Liu et al. [10] presented a low-cost all-glass evacuated tubular solar steam generator with simplified CPC, which can produce steam exceeding 200 °C with pressure ranging from 0.10 to 0.55 MPa. Winston et al. [11] reported a new generation of advanced evacuated tube solar collectors capable of delivering efficient high temperature performance without tracking or tilt adjustment is being developed as an alternative to tracking collectors for temperatures up to and even exceeding 250 °C.

In order to promote the insufficient of low thermal conductivity of the available PCMs, the research on efficient heat transfer of solar collectors equipped with PCMs using different conductivity enhancement techniques is performing. Khan et al. [12] indicated solar collectors integrated with PCMs produced better results in recent years, and they studied innovative concepts of integrating PCMs in flat plate (water/air), evacuated tube, and photovoltaic/thermal solar collectors. Allouhi et al.[13] proposed a detailed analysis of an improved Integrated Collector Storage Solar Water Heater (ICSSWH) and N-eicosane was considered as PCM in this application. Li and Zhai [14] established a solar collector/storage system designed for mid-temperature application, which PCM composited by erythritol and expanded graphite with melting temperature of 119 °C was filled in the aluminum pipes, and those pipes were placed inside the evacuated tubes. Although the application of PCMs in the solar collectors greatly improves the working efficiency of the collectors, the low thermal conductivity of PCMs also limits the heat collecting effect of the collectors. In order to promote the insufficient of low thermal conductivity of the available PCMs, the research on efficient heat transfer of solar collectors equipped with PCMs using different conductivity enhancement techniques is performing. Bazri et al. Mat et al. [15] and Abduljalil Al-Abidi et al. [16] presented a numerical investigation about heat transfer enhancement technique by using internal and external longitudinal fins for PCM melting in a triplex tube heat exchanger (TTHX).

The objective of the numerical simulation of this paper is to study the effect of PCTSL and annular fins on thermal performance of linear concentrating solar evacuated tubular collector. The linear concentrating solar evacuated tubular collectors with/without annular PCTSL and with/without annular fans are modeled with CFD (Computational Fluid Dynamics) simulations based on the finite element method (FEM) to analyze and explain the temperature field and energy distribution of collectors during the charge and discharge process.

2. Numerical simulation

2.1. Physical model and computational domain

Three different types of linear concentrating solar evacuated tubular collectors integrated with evacuated tube, CPC and PCTSL. These designed collectors mainly consist of two concentric cylinders which are the inner tube and outer tube with a total length of 400 mm. The inner tube is stainless steel tube with an inner diameter of 15 mm and a thickness of 2 mm. The outer one is made of Perspex and has an outside diameter of 80 mm. The three cases are:

Case A: it is the collector without PCTSL and without fins. There is the evacuated layer between the inner tube and the outer tube of the collector without PCTSL. The selective absorbing coating is located on the outer surface of the inner tube.

Case B: it is the collector with PCTSL and without fins. The annular place between the inner and middle tube is filled PCM which is a composite molten salt (60 wt% NaNO3 – 40 wt% KNO3). Its
evacuated layer is located between the middle tube and the outer tube. The selective absorbing coating is located on the outer surface of the middle tube.

Case C: it is the collector with PCTSL and without fins. Annular fans, an enhanced heat transfer structure, inside the annular PCTSL. Ten fins 2 mm thick and 38 mm interval are equally welded to the outer surface of the inner tube, and its top is 2 mm from the middle tube for the local natural convection of the melted PCM. The selective absorbing coating is located on the outer surface of the middle tube.

The data of these models are shown in Table 1. In view of the corrosive nature of the molten salt, stainless steel is selected as the material of the inner tube, the fin and the middle tube. Transformer oil employed as the heat transfer fluid (HTF) is injected with a constant injection velocity of 0.01 m/s enables a laminar flow in the inner tube (Reynolds number based on tube diameter is calculated to be much lower than 2300).

Table 1. Specifications and data input for a models

| Parameters                                      | Value     |
|------------------------------------------------|-----------|
| Diameter of the inner tube                     | 80mm      |
| Diameter of the middle tube                    | 60mm      |
| Diameter of the outer tube                     | 15mm      |
| Length of tubes                                | 400mm     |
| Thickness of stainless steel                   | 2mm       |
| Thickness of Perspex                           | 2mm       |
| Solar transmissivity of the outer tube [9]     | 0.95      |
| Solar absorptivity of the selective absorbing coating [17] | 0.93      |
| Concentration ration of CPC [18]               | 3         |

Under the radiation of the sun, a part of the sunlight is directly passes through the evacuated layer and irradiated onto the selective absorbing coating to be absorbed and converted into heat; the other part of the sunlight is reflected by CPC, and then linearly focused on a selective absorbing coating. The heat converted by the solar collectors in this study is directly transported by the transformer oil in the inner tube (case A), or absorbed by PCTSL and then slowly transferred to the transformer oil flowing in the inner tube (case B and case C). In order to simplify the simulation, the following assumptions are made:

1. Adding solar transmissivity of the outer tube, solar absorptivity of the selective absorbing coating and the heat loss coefficient the evacuated layer, ignoring the evacuated layer in the calculation model;
2. The PCM is uniformly distributed and isotropic in PCTSL.
3. The physical properties of PCM, Perspex tubes and stainless steel tubes remain stable under the simulation conditions.
4. Under the sunlight radiation, it is assumed that the solar radiation obtained by entire outer surface of the selective absorbing coating of the collector is uniform.
5. Ignoring the change of the concentration ratio caused by the change of the radius of the selective absorbing coating.

2.2. PCMs selection
The mixed molten salt of 60 wt% NaNO3 – 40 wt% KNO3 is selected as thermal storage phase change material. The phase-change temperature and latent heat of phase change meet the requirements of the heat storage and exothermic process of the three types of solar collectors in this study after all-day sunlight radiation. And the mixed molten salt can maintain a stable physical property parameter below 600 °C that is much higher than the simulated temperature of the study. The physical properties of the mixed molten salt are shown in Table 2.
2.3. Governing equations

This study mainly involved three physical fields of fluid heat transfer, solid heat transfer and phase change heat transfer in the simulation process.

In fluid heat transfer, using the following heat equation to simulate heat transfer in a fluid:

\[
\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot q = Q + Q_p + Q_{vd}
\]

where \( \rho \) is the density of working medium, kg/m\(^3\); \( C_p \) is the heat capacity at constant pressure, J/(kg·K); \( u \) is the transformer oil inlet speed, m/s; \( Q, Q_p, Q_{vd} \) are heat source item, viscous dissipation heat and the heat generated by the pressure work, respectively, W/m\(^3\). \( q \) is the conductive heat flux, W/m\(^2\).

In the three models, stainless steel inner tubes and annular fins are applied to solid heat transfer, and the governing equations used in solid heat transfer are as follows:

\[
\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot q = Q + Q_{ed}
\]

where \( Q_{ed} \) are the heat source item and the thermoelastic damping, W/m\(^3\).

In two types of solar collectors with PCTSL, PCM is applied to phase change heat transfer during heat transfer. In the process of absorbing heat, the heat transfer control equations involved in PCTSL are given as Equation (3) - (6).

\[
\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot (\rho \alpha_m \frac{\partial \theta}{\partial T}) = Q + Q_p + Q_{vd}
\]

\[
\rho = \theta \rho_1 + (1 - \theta) \rho_2
\]

\[
C_p = \frac{1}{\rho} \left( \theta \rho_1 C_{p1} + (1 - \theta) \rho_2 C_{p2} \right) + L \frac{\partial \alpha_m}{\partial T}
\]

\[
k = \rho_1 \alpha_m
\]

where \( \rho, C_p \) and \( k \) are the density, the heat capacity and the thermal conductivity of the molten salt. The subscript 1 and 2 represent solid phase and liquid phase of the molten salt; \( \theta \) is the mass fraction of the solid phase (%); \( L \) represents the latent heat of phase change (kJ/kg); \( \alpha_m \) is the density change rate of the molten salt, which is calculated by Equation (7).

\[
\alpha_m = \frac{1}{2} \left( \frac{(1 - \theta) \rho_2 - \theta \rho_1}{\theta \rho_1 + (1 - \theta) \rho_2} \right)
\]

2.4. Initial and boundary conditions

Based on the above-mentioned assumptions and the solar radiation intensity of Jiaozuo city, a boundary heat source is provided on the selective absorbing coating of the solar collectors. According to the law of conservation of energy, the energy obtained by the solar collector is the difference between the solar radiant energy absorbed by the collector and the energy dissipated by the collector to the surrounding environment. The energy obtained per unit area per unit time can be calculated by Equation (8) [19]:

\[
q = G \times \tau \times \alpha - U_i \left( T_p - T_a \right)
\]
where \( q \) is the effective solar radiation absorbed by the selective absorbing coating (W/m²); \( G \) is the average solar radiation intensity per hour (W/m²); \( \tau \) is the solar transmittance of the outer Perspex tube; \( \alpha \) is the solar absorptivity of the selective absorbing coating; \( T_p \) is the surface temperature of the selective absorbing coating (°C); and \( T_a \) is the temperature of the outer Perspex tube (°C). In the present study, \( \tau = 0.95 \), \( \alpha = 0.93 \), and the concentration ration of CPC is 3.

According to the climatic conditions of Jiaozuo, July 15 of the summer with sufficient sunshine and the January 15 of the winter with short sunshine time were selected as the research time. From the above formulas, the variation curves of the solar radiation intensity of Jiaozuo local July 15 and January 15 is calculated as shown in Figure 1. The overall initial temperature of the collector is 22 °C [4]. The heat loss of the evacuated tube and the collector tube is set to 0.75 W/(m²·K)[19].

![Figure 1. The variation curves of the solar radiation intensity of Jiaozuo](image)

### 3. Results and discussion

#### 3.1. Comparison of the thermal performance of linear concentrating solar evacuated tubular collectors without PCTSL and with PCTSL

Two typical days of July 15 (summer) and January 15 (winter), with sufficient and short sunshine hours respectively, have been selected to simulate. Take the outlet temperature of the transformer oil at the outlet ends of the linear concentrating solar evacuated tubular collectors without PCTSL and with PCTSL. The output oil temperature curves are shown in Figure 2.

Based on the comparison of Figure 2, in the winter and summer, the outlet oil temperature of the collector without PCTSL reach the highest temperature of 89.2 °C and 101.6 °C, respectively; the oil outlet temperature of the collector with PCTSL reach the highest temperature of 83.3 °C and 90.9 °C, respectively. The maximum temperature difference between the outlet oil temperatures of the two types of collectors is 5.9 °C and 10.7 °C, respectively, in winter and summer. However, the outlet oil temperature change rate of the collector without PCTSL during the peak period is large, and the outlet oil temperature change rate of the collector with PCTSL during the peak period is slow, and the peak value is gently passed, maintaining a long time high temperature. When the outlet oil temperatures reaches 40 °C or above, the collector without PCTSL has 7 hours and 9 hours in the winter and summer seasons respectively; the collector with PCTSL has 8.5 hours and 10 hours in the winter and summer seasons, respectively, which is 1.5 hour and 1 hours longer than the collector without PCTSL. After sunset, the collector with PCTSL continues to heat the transformer oil for nearly 2 hours in the winter and for nearly 2.5 hours in the summer. There are some reasons for these phenomena: (1) with PCTSL, the heat capacity of PCM is so relatively high that the heat energy converted by sunlight can be stored per unit time, which satisfies the requirement for high solar radiation intensity at noon of the day; (2) heat stored in large quantities by PCTSL is output continuously and steadily, which embodies the stability of PCM in heat storage and heat release performance. Therefore, the collector with PCTSL can provide transformer oil with a stable temperature, and extend the heating time.
3.2. Thermal performance analysis of PCTSL with enhanced heat transfer structure: annular fins

The outlet oil temperature change curves of the two types of collectors are shown in Figure 3. As can be seen in Figure 3, the heating time of the collector with PCTSL and annular fins for the transformer oil is approximately equal to that of the collector with PCTSL but without annular fins, however, the collector with PCTSL and annular fins can provide a higher temperature for the transformer oil during heating. The highest oil temperature in the winter and summer seasons can reach 85.1 °C and 93.9 °C, respectively, which is higher than the peak reached by the collector with PCTSL but without annular fins. At the same time, the collector with PCTSL and annular fins reaches the peak temperature of oil more than 30 minutes earlier than the collector with PCTSL but without annular fins. At 7:00-8:00, the outlet oil temperature variation curve of the collector with PCTSL and annular fins is superimposed with the curve of the collector with PCTSL but without annular fins, that is, the outlet oil temperature with low light intensity is equal to the outlet oil temperature with high light intensity.

Figure 2. Transformer oil outlet temperature daily evolutions for conditions of with and without PCTSL on both January 15 and July 15

Figure 3. Transformer oil outlet temperature daily evolutions for collectors with PCTSL conditions of with and without fins on both January 15 and July 15

Figure 4 is the three-dimensional temperature field of the axial section of the collector with PCTSL but without annular fins, which are (a1) and (a2), and the collector with PCTSL and annular fins, which are (b1) and (b2). The time is selected at the moment when the outlet oil temperature of the collector with PCTSL but without annular fins reaches a peak, that is, at 15:00 on January 15 and July 15. From the perspective of temperature distribution, the high temperature region of the collector with
PCTSL but without annular fins is mainly distributed the outer of PCTSL, and the temperature difference with the inner phase change material reaches about 85 °C; the high temperature region of the collector with PCTSL and annular fins is less distributed the outer of PCTSL, and the temperature difference between the inside and outside of PCTSL is about 60 °C, which is nearly 25 °C smaller than the collector with PCTSL but without annular fins. This implies that annular fins are added in the PCTSL to reduce the temperature difference between the inner and outer layers of PCTSL and improve the overall thermal conductivity of the thermal storage layer. The lower temperature of the PCTSL outer layer helps to improve the problem of the heat loss. At the same time, it can be seen that PCTSL without annular fins form a distinct temperature gradient layer, which makes the internal temperature distribution uneven and affects the heat storage performance; the internal temperature distribution of PCTSL with annular fins is relatively uniform, which is beneficial to the overall PCM inside PCTSL to actively play the role of heat storage, making full use of the thermal properties of PCM.

Figure 4. The three-dimensional temperature field of the axial section of the collector with PCTSL (℃): without annular fins (a1) on January 15 and (a2) on July 15; with annular fins (b1) on January 15 and (b2) on July 15.

4. Conclusions
This paper numerically studies the influences of PCTSL and annular fins on the linear concentrating solar evacuated tubular collectors. By analyzing the outlet oil temperature studied in this paper, the following conclusions are obtained: (1) Add PCTSL to the linear concentrating solar evacuated tubular collector, the peak value of the outlet oil temperature decreases. However, the outlet oil temperature change rate during the peak period is slow, and the peak value is gently passed, maintaining a long time high temperature. The heat stored in the PCTSL can stably heat the transformer oil in the inner tube, reducing the influence of external factors on the collector. (2) At the same solar radiation intensity, the outlet oil temperature of the collector with PCTSL but without annular fins reaches 40 °C or more for an increase of 1-1.5 hours compared to the collector without PCTSL and annular
fins. And the overall time that the collector with PCTSL but without annular fins heats the transformer oil is longer than the overall time of the collector without PCTSL and annular fins. (3) The collector with PCTSL and annular fins has a higher outlet oil temperature peak than the collector with PCTSL but without annular fins, and it is 30 minutes early to reach the peak temperature. The internal temperature distribution and energy distribution of PCTSL with annular fins are relatively uniform. The annular fin enhances the thermal conductivity of the PCTSL, improves the heat absorption and heat storage capacity of the collector, and reduces the heat loss of the collector.

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