Modeling and experimental investigation on a direct steam generation solar collector with flat plate thermal concentration

Jingkang Liang\textsuperscript{1}, Xu Ji\textsuperscript{2}, Jingyang Han\textsuperscript{2} and Yunfeng Wang\textsuperscript{2}

Abstract
Currently, steam generation using solar energy mostly relies on optical concentration, which is a costly system, to generate the high temperature needed for water evaporation. Here, the development of a low-cost and scalable approach based on thermal concentration for solar steam generation is reported. The system was demonstrated to be capable of generating 100–120°C steam under ambient air conditions without optical concentration. A solar thermal efficiency could be achieved up to 13% at an average solar irradiance of only 670 W m\textsuperscript{-2}. The new solar steam generation system, with its simple structure, great effectiveness, and low cost, holds the promise of significantly expanding the application domain of solar thermal systems.

Keywords
Direct steam generation, thermal concentration, flat plate, solar energy, heat transfer

Introduction
Of the many available sources of renewable energy, solar thermal energy is the most abundant, the efficient use of which could have a broad impact on human life (Farjana et al., 2018). While the low-temperature solar thermal technology is relatively well developed and

\textsuperscript{1}School of Physical and Electronic Information, Yunnan Normal University, Kunming, China
\textsuperscript{2}Solar Energy Research Institute, Yunnan Normal University, Kunming, China

Corresponding author:
Xu Ji, Solar Energy Research Institute, Yunnan Normal University, Kunming 650500, Yunnan, China.
Email: jixu@ynnu.edu.cn

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has been commercialized (Evangelisti et al., 2019), there is an urgent demand to develop technologies for medium-temperature solar steam generation for a broad range of applications such as desalination (Ahmed et al., 2019), absorption/adsorption refrigeration (Bataineh and Taamneh, 2016; Fernandes et al., 2014; Ghafoor and Munir, 2015), textile printing and dyeing (Lauterbach et al., 2012), medical sterilization (Kaseman et al., 2012), agricultural products, and food processing (Mekhilef et al., 2011).

Current methods of generating medium-temperature solar steam mainly rely on high optical concentration that focuses on the low-density solar irradiance to generate a high local temperature for water evaporation (De Sá et al., 2018). Many steam generation systems developed in the last few decades are based on concentrating solar collectors such as parabolic trough collector (Sandá et al., 2019; Souha et al., 2019) and compound parabolic concentrator (Liu et al., 2014; Pranesh et al., 2019). These solar steam generation systems could generate medium-temperature solar steam of 100–200°C, with the thermal efficiency usually of 30–50%. However, these solar concentrators require not only high-quality curved optical mirrors that are difficult to fabricate but also a complex solar-tracking system, resulting in high construction and operating costs (Bushra and Hartmann, 2019).

Non-concentrating flat plate solar collectors have much simpler structures and are easy to operate. However, they were only suitable to supply hot water of temperature 60–80°C due to the low energy density (Pandey and Chaurasiya, 2017). In recent years, researchers have proposed some flat and porous solar collectors for highly efficient solar steam generation (Ghasemi et al., 2014; Ni et al., 2016; Zhou et al., 2016, 2017). These porous solar collectors are in direct contact with the water, absorbing solar energy and generating local heating for water evaporation. To ensure efficient solar steam generation, these solar collectors are required to have the following features: broadband and efficient solar absorption, reduced thermal conductivity for localized water heating, hydrophilicity for efficient water supply, and porous structures for vapor channels (Hu et al., 2017). For example, Gang Chen’s group in MIT designed a carbon foam structure for solar steam generation at low optical concentration in open air, with the thermal efficiency up to 85% at 10 kW m⁻² solar illumination (Ghasemi et al., 2014; Ni et al., 2016). More impressively, Hu et al. (2017) proposed graphene oxide-based aerogels as solar absorbers for steam generation, which has achieved the same thermal efficiency as Gang Chen’s group at a much smaller solar illumination of only 1 kW m⁻². These novel solar absorbers, although being impressive with high thermal efficiency, suffer from a few problems such as the high cost and complexity in the fabrication and the limited lifetime of the solar absorbers. For example, scaling and fouling could be problems hindering the desalination applications of these porous solar absorbers.

In this work, the development of an alternative approach based on low-cost and scalable thermal concentration for solar steam generation was reported. The solar irradiation was collected by a large-area heat absorption flat plate collector. The collected solar thermal energy is then concentrated through efficient heat conduction along a plate onto a steam generator pipe, generating a high temperature of 100–130°C for steam production. Through a prototype of the thermal-concentrating solar steam generation, this simple and effective method was demonstrated that there was a daily steam production of about 6.174 kg with an average solar irradiance of 896 W m⁻² for 5 h. The novel and cost-effective approach holds the promise in greatly expanding the feasibility and applicability of solar steam generation.
System design and model analysis

The sketch and the cross section of thermal-concentrating solar steam generation system are shown in Figure 1(a) and (b), respectively. The most critical components in the design are the thermal-concentrating flat plate solar collector and the steam generator pipe that lie at the center of the collector. The solar thermal-concentrating flat plate is made of a 0.35-mm-thick copper plate, coated with a thin layer of chrome solar selective absorber, achieving a solar absorptivity of more than 94%. The copper plate has a high thermal conductivity of $398 \text{ W m}^{-1}\text{ K}^{-1}$, ensuring efficient conduction of the collected thermal energy along the plate and concentrating onto the steam generator pipe. The concentrated thermal energy should have a sufficiently high energy density to generate medium-temperature solar steam from the room-temperature water through a proper design of the system, i.e. a balance among the solar flux density, collector area, water flow rate, and heat loss. In the following part, a systematic analysis will be conducted through modeling to explore the effect of various factors on the performance of the system and to find an optimum design of the solar steam generation system.

Thermal model on energy balance of the system

The energy balance of a system is shown in Figure 1(b). From the first law of thermodynamics, the total energy of this closed thermodynamic system should be conserved, i.e. the

![Figure 1](https://example.com/figure1.png)

**Figure 1.** (a) Sketch and design of the solar steam generation system based on thermal concentration and (b) the cross section and energy balance analysis on the solar steam generation system.
amount of useful energy collected by the system equals the absorbed solar energy minus the heat loss

\[ Q_U = Q_A - Q_L \] (1)

where \( Q_U \) is the amount of useful energy collected by the system, \( Q_L \) is the heat loss of the system, and \( Q_A \) is the absorbed solar energy which can be expressed as

\[ Q_A = Q_0 \tau \alpha = A_c G \tau \alpha \] (2)

where \( Q_0 \) is the incident solar energy, \( \tau \) is the transmission of solar radiation through the glass cover, \( \alpha \) is the absorption coefficient of the solar collector, \( A_c \) is the aperture area of solar collector, and \( G \) is the solar irradiance (W m\(^{-2}\)).

The useful energy collected by the system is used to evaporate water of the amount

\[ Q_U = \dot{m} h_{LV} \] (3)

where \( \dot{m} \) denotes the mass flow rate (kg s\(^{-1}\)) and \( h_{LV} \) is the total enthalpy of liquid–vapor phase change (specific heat + enthalpy of vaporization).

The solar thermal efficiency (\( \eta_{th} \)) can be defined as (Ghasemi et al., 2014)

\[ \eta_{th} = \frac{Q_U}{Q_0} = \frac{\dot{m} h_{LV}}{A_c G} \] (4)

The total heat loss \( Q_L \) includes three parts: the top heat loss \( Q_t \), the bottom heat loss \( Q_b \), and the side heat loss \( Q_e \)

\[ Q_L = Q_t + Q_b + Q_e \] (5)

\[
\begin{cases}
Q_t = A_a U_t (T_p - T_a) \\
Q_b = A_b U_b (T_p - T_a) \\
Q_e = A_e U_e (T_p - T_a)
\end{cases}
\] (6)

where the subscripts \( t, b, \) and \( e \) stand for the top, the bottom, and the sides of the solar collector, respectively; \( U \) is the heat loss coefficients; \( A_a, A_b, \) and \( A_e \) are the area of top, bottom, and the sides of the thermal-concentrating flat plate, respectively; and \( T_p \) and \( T_a \) are the flat plate temperature and the ambient temperature, respectively.

Of these heat losses, the heat loss coefficient of the top glass cover can be estimated using an empirical formula proposed by Klein (1975) as

\[ U_t = \left\{ \frac{N}{\frac{\xi_p}{T_p} \left[ \frac{T_p - T_a}{N + f} \right]^2 + \frac{1}{h_w}} \right\}^{-1} + \frac{\sigma (T_p + T_a) (T_p^2 + T_a^2)}{(\xi_p + 0.00591 N h_w)^{N + f}} + \frac{2N + f - 1 + 0.122 \xi_p}{\xi_c} - N \] (7)

where \( N \) is the number of glass layers; \( f = (1 + 0.089 h_w - 0.1166 h_w \xi_p)(1 + 0.07866 N) \); \( h_w \) is the air convective heat transfer coefficient; \( \xi_p \) and \( \xi_c \) are the emissivity of the thermal
concentrating flat plate and the glass cover, respectively; $c = 520(1 - 0.000051\beta^2)$ for the tilt angle of $0^\circ < \beta < 70^\circ$ for the solar collector plate; and $\sigma$ is the Stefan–Boltzmann constant. Klein’s formula, which considers conductive, convective, and radiative heat losses, is the most widely used one to estimate heat loss coefficient of the top covers of flat plate solar collectors.

When the thermal insulation layers at the bottom and sides of the steam generator are sufficiently thick, the temperature of the outer surface of the insulation layers can be assumed to be the same with the ambient temperature. The heat loss through the thermal insulation layers is thus dominated by heat conduction, with the heat loss coefficient for the bottom and sides of the steam generator expressed as

$$U_b = U_e = \frac{\lambda}{\delta}$$

where $\lambda$ and $\delta$ are the thermal conductivity and thickness of the thermal insulation layer, respectively.

**Effects of various factors on thermal performance of the system**

Using the thermal model described above, the effects of a few factors including the thermal-concentrating flat plate area $A_c$, the thickness of thermal insulation layer $\delta$, and the temperature of the thermal concentrating flat plate $T_p$, on the thermal performance of the system can now be analyzed. To study the effects of some factors on the thermal performance, some conditions have been assumed as below:

- The temperature of $T_p$ and $T_a$ can be acquired by measurement;
- Due to the good thermal conductivity of the thermal concentrating plate made from copper, the temperature of plate $T_p$ is assumed to be uniform for the whole flat plate.

Figure 2(a) shows the heat loss from the top ($Q_t$), the bottom ($Q_b$), and the sides ($Q_s$) of the device as a function of the aperture area of solar collector $A_c$. In this calculation, the air convective heat transfer coefficient $h_w$ is taken as $4$ W m$^{-1}$ K$^{-1}$; the thermal conductivity of the thermal insulation layer $\lambda$ is $0.044$ W m$^{-1}$ K$^{-1}$; the average temperature of the thermal concentrating flat plate and ambient are $100$ and $24^\circ$C, respectively. The results show that all the heat losses increase with the flat plate area $A_c$, especially the top heat loss, which takes $>80\%$ of the total heat loss, the bottom takes approximately $16\%$ of the total heat loss and the heat loss from the sides can be negligible, while the area of thermal concentrating flat plate is enlarged to $7$ m$^2$. Therefore, it is critically important to reduce the top heat loss to improve the overall efficiency of the system.

Figure 2(b) shows the heat loss from the bottom as a function of the thermal insulation layer thickness for several thermal conductivities of the thermal insulation layer. It shows that the heat loss is less when the thermal conductivity $\lambda$ is smaller and the insulation layer is thicker. However, the heat loss will approach a constant value as the thickness further increases. Therefore, for a thermal insulation material with $\lambda < 0.06$ W m$^{-1}$ K$^{-1}$, the insulation layer thickness should be chosen as $\sim 50$ mm: a thinner layer would not be sufficient to reduce the heat loss while a thicker layer would not make much difference.
Figure 2(c) shows the heat loss from the top cover per unit area of the solar collector area as a function of the solar collector plate temperature $T_p$. We can see that the heat loss increases dramatically by 2–4 times as $T_p$ increases from 60 to 120°C. For the low-temperature solar thermal collectors at a working temperature of 60–70°C, the single-glazing glass cover would be sufficient as the heat loss is relatively small at such low temperatures. However, for the medium-temperature solar steam generation application, a double-glazing glass cover would be necessary to reduce the total heat loss and thus to increase the overall thermal efficiency. It is obvious when the temperature $T_p$ increases to 130°C, the heat loss almost reduces by half with using the double-glazing glass cover.

It is useful to define a thermal concentration ratio (TCR), reflecting the degree of energy concentration for the solar steam generation system. One straightforward way to define the TCR is based on the geometry, i.e. the ratio between the solar collector area $A_c$ and the effective area of the steam generator pipe or the water evaporator pipe $A_s$:

$$C = \frac{A_c}{A_s} \quad (9)$$

which is called the geometric heat concentrating ratio.
In the thermal concentration solar steam generation system, the thermal concentrating solar collector and the steam generator pipe are the two most critical parts to collect, transfer, and utilize the solar thermal energy. When the effective area of the steam generator pipe is fixed, the heat concentrating ratio and the heat loss have direct impacts on the production rate of the steam and the thermal efficiency of the system.

Figure 2(d) shows the total absorbed solar energy $Q_A$, the heat loss $Q_L$, and the usable energy $Q_U$ as a function of the geometric heat concentrating ratio when the effective area of the steam generator pipe is 0.1 m², the thermal-concentrating flat plate temperature and the ambient temperature are 100 and 24°C, respectively. It shows that $Q_A$, $Q_L$, and $Q_U$ all increases with the geometric heat concentrating ratio $C$, the heat loss would be approximately 46% of the total absorbed energy while the concentrating ratio $C$ is 80. Therefore, reducing heat loss is critically important to improve the overall thermal efficiency of the system.

**Predicted steam production under different solar irradiances**

Figure 3 shows the predicted solar steam generation rate of the system as a function of solar irradiance, assuming a constant temperature of the thermal-concentrating flat plate $T_p$ as 100, 110, and 120°C, respectively. In the solar steam generation system, a double-glazing glass cover has been utilized, with the top surface area $A_o$ and effective collecting area $A_c$ being 8 and 7.6 m², respectively. The results suggest that the steam generation rate increases with solar irradiance. It would be impossible for the system to generate steam when the solar irradiance is approximately below 500 W m⁻², due to the large heat loss of the thermal concentrating plate even with a temperature of 100°C. During the process of steam generating, the temperature of thermal concentrating plate will increase gradually, if the plate temperature reaches 120°C, the minimum solar irradiance required to generate steam would be 600 W m⁻², which is necessary to balance the heat loss of the system. Keeping the solar collector plate temperature to a relatively lower level of 100°C is beneficial for more steam
production, as it induces less heat loss and can increase the overall thermal efficiency of the system. Actually, the plate temperature may usually reach 120°C, in which case the solar steam generation rate would be 1.38 kg h⁻¹ for the system, and 6.9 kg steam would be generated while the radiation duration is 5 h with solar irradiance above 600 W m⁻².

**Experimental demonstration and discussion**

A prototype of the solar steam generation system has been built and the feasibility of the thermal concentration approach for solar steam generation has also been demonstrated. The schematic and the photograph of experimental system are shown in Figure 4(a) and (b), respectively. The solar steam generator system consists of four thermal-concentrating flat plate solar collectors in series, and the details of the single solar collector have been given in Table 1. The thermal-concentrating solar steam generation system with a length of 3.8 m and a width of 2 m is tilted up toward south with an inclination angle of 45° from the ground. The steam generator pipe with smooth inner wall, having a diameter of 40 mm and made of copper, lies in the middle of the thermal-concentrating flat plate. The pipe is usually half-filled with water. Two steam exhaust pipes are inserted into the top of the steam generator pipe to collect the generated steam, which is then directed to a condenser and has its mass being measured there. Minimizing heat loss of the system is very important to improve thermal efficiency of the system. The bottom and all the sides of the collector are covered with thermal insulation materials, while the top is a double-glazing glass cover. The thermal insulation material is 50-mm-thick rubber foam, covered with aluminum foil, with a low thermal conductivity of 0.044 W m⁻¹ K⁻¹. The double-glazing glass cover is made of two 3-mm-thick glass plates with a 0.3-mm-thick air layer sandwiched between them. The transmittance rate of the glass cover is 94%, and the effective heat transfer coefficient through the glass cover is 4.26 W m⁻² K⁻¹ (Duffie and Beckman, 2013).

A simple energy balance analysis of the system is shown in Figure 5 and conducted as follows.

The steam generator pipe is assumed as being half-filled with water at an initial temperature of 25°C. The energy required to evaporate this amount of water over a unit length of
the solar collector is calculated as

\[
J_1 = m(c_p \Delta T + \Delta H)
\]  

(10)

where \( m \) is the mass of water in per unit length of the water evaporator pipe; \( c_p \) and \( \Delta H \) are the specific heat and enthalpy of vaporization of water, respectively. Meanwhile, assuming an average solar irradiance \( q_i \) of 900 W m\(^{-2}\) and an energy efficiency \( \eta \) of 20\%, the amount of energy that effectively heats up the water is

\[
J_2 = \eta \cdot q_i \cdot t \cdot A_c
\]  

(11)

where \( t \) is the radiation duration. Equating \( J_1 \) and \( J_2 \), the time required to evaporate this amount of water is estimated to be \( \sim 1.25 \) h. This suggests that this design of the solar steam generation system is possible to work. It also suggests that the water needs to be refilled for about each 1 h.

The tests of the solar steam generation system under different weather conditions were conducted. During the tests, the solar irradiance, the temperatures of different components, and the steam production rate were closely monitored as a function of time. Figure 6(a) and (b) shows the temperatures of different components of the system under operation, including the thermal-concentrating flat plate solar collector, the steam generator pipe, the steam exhaust pipe, and the double-glazing glass cover, under a partly cloudy and a fully sunny weather condition. In the partly cloudy weather, the solar irradiance fluctuated between 150 and 1000 W m\(^{-2}\) from 10:00 to 15:00, with an average irradiance of 670 W m\(^{-2}\). In the fully sunny weather, the solar irradiance was always above 800 W m\(^{-2}\) from 10:00 to 15:00, with the peak irradiance of 1000 W m\(^{-2}\) and an average irradiance of 896 W m\(^{-2}\). The experimental conditions also are listed in Table 2.

It can be found that the temperature of the thermal-concentrating flat plate followed the solar radiation closely for both weather conditions. This is because of the high thermal

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**Table 1.** Some structural parameters of the thermal-concentrating flat plate solar collector.

| Item                          | Materials                                      | Thickness (mm) | Internal diameter (mm) | Length (m) | Width (m) |
|-------------------------------|------------------------------------------------|----------------|------------------------|------------|-----------|
| Thermal-concentrating flat plate | Copper coated with selective absorbent membrane | 0.35           | –                      | 0.95       | 2.00      |
| Water evaporator pipe        | Copper                                         | 1.50           | 40.00                  | 0.95       | –         |
| Steam exhaust pipe           | Copper                                         | 1.00           | 20.00                  | –          | 1.00      |

\[
\Delta H = 40.65 \text{ kJ mol}^{-1}
\]

Average solar irradiance \( \sim 900 \text{ W m}^{-2} \)

\[
\phi = 4 \text{ cm}
\]

Figure 5. Energy balance analysis of solar steam generation system based on thermal concentration.
The conductivity of the copper plate that ensures quick heat conduction and rapid thermal response of the thermal-concentrating flat plate. Comparatively, the temperature of the steam generator pipe is more constant, irrespective of the fluctuation of the solar irradiance. This is also easy to understand, since the large heat capacity and latent heat of liquid water

Figure 6. The variation of monitored temperatures (curves) of different components and solar irradiances (column bars) under different weather conditions: (a) partly cloudy and (b) fully sunny.

Table 2. Experimental conditions.

| Weathers       | Range of solar irradiance (W m⁻²) | Average irradiance (W m⁻²) | Ambient temperature (°C) | Wind speed (m s⁻¹) |
|----------------|----------------------------------|----------------------------|--------------------------|-------------------|
| Partly cloudy  | 150–1000                         | 670                        | 20–26                    | 0–3               |
| Full sunny     | >800                             | 896                        | 20–27                    | 0–3               |
in the pipe helps to maintain the pipe temperature slightly above 100°C. The steam exhaust pipe had a slightly higher temperature, ~10°C, compared to the steam generator pipe. Because of the highly efficient solar absorption and the excellent thermal insulation, the thermal-concentrating flat plate maintains a high temperature above 100°C in both weather conditions from 11:00 to 15:00. The temperature of the thermal-concentrating flat plate can be even above 140°C at noontime in a sunny weather.

Figure 7 shows the steam production of the system under different weather conditions, as compared to the temperatures of the thermal-concentrating flat plate and the steam generator pipe at different time of the day. The steam production of the system, as suggested in Figure 7, began at 10:00 and increased continuously until about 15:00, after which the system no longer produced steam. The rates of steam production for both weathers, as shown by the column bars in Figure 7, were in accordance with the temperatures of the thermal-concentrating flat plate and the steam generator pipe. In the partly cloudy weather, with an average solar irradiance of 670 W m⁻² and an average temperature of the thermal
concentrating flat plate as 118°C, the daily steam production was about 4.415 kg. In the sunny weather, with an average solar irradiance of 896 W m\(^{-2}\) and an average temperature of the thermal concentrating flat plate as 134°C, the daily steam production was about 6.174 kg. Based on the equation (4), the thermal efficiency of the system was evaluated as \(\sim 13\%\) for both weather conditions.

Many factors could affect the thermal efficiency of the solar steam generation system, such as the solar absorption efficiency, the heating of bulk liquid, etc. However, the most notable one that affects the thermal efficiency of the system is the thermal loss. With the system operating at the medium-temperature range (>100°C), excellent thermal insulation is critically important for the thermal efficiency of the system. In the system, the thermal loss from the top dominates, taking about 80% of the total heat loss, despite the double-glazing glass cover used. A more effective way to reduce the thermal conductivity of the glass cover without compromising its optical transmission will significantly reduce the thermal loss and thus improve the overall thermal efficiency of the system. Meanwhile, an optimum design of the system such as the geometric concentration ratio also affects the thermal efficiency. In the follow-up research, a more systematic study will be conducted to improve the system design for an even higher thermal efficiency. Nevertheless, despite the relatively low thermal efficiency of the current system (\(\sim 13\%\)) compared to a conventional solar steam generation system based on optical concentration (30–50%), the system clearly has shown its advantages of easy operation, low cost, and scalability.

Conclusions

A novel approach for medium-temperature solar steam generation based on thermal concentration instead of the conventional costly optical concentration has been designed and demonstrated. In the system, the solar collector with a large thermal-concentrating flat plate is used to collect the solar radiation and concentrate the thermal energy onto a small steam generator pipe, where the water is heated and the steam is generated. A heat transfer model of the solar collector has been proposed to discuss the effect of some parameters on the thermal performance. The results found that the thermal-concentrating flat plate area, the thickness of thermal insulation layer, and the temperature of the thermal concentrating flat plate can impact performance, but the heat loss of the collector is the most essential factor for the performance degradation. And according to the model, the steam production of the collector has been predicted, 6.9 kg steam would be generated while the radiation duration is 5 h with solar irradiance above 600 W m\(^{-2}\). Then, the experiments have been conducted under different weathers conditions. The daily steam production was about 4.415 and 6.174 kg for the partly cloudy and full sunny days, respectively. A thermal efficiency could be achieved up to 13% for an average solar irradiance as low as 670 W m\(^{-2}\). The research provides a new solution for cost-effective generation of medium-temperature steam from solar thermal energy, which could have a broad impact in expanding the flexibility and feasibility of solar steam generation after further reducing the heat loss of the system.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.
Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was financially supported by the research project 51766018 of the National Natural Science Foundation of China (NSFC), which is gratefully acknowledged by the authors.

ORCID iDs

Jingkang Liang https://orcid.org/0000-0001-9521-8923
Yunfeng Wang https://orcid.org/0000-0002-2986-0464

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