Experimental Study on a Solar Heat Concentrating Steam Generator

Qiangqiang Xu, Xu Ji, Jingyang Han, Changchun Yang, Ming Li

***Abstract*—**Replacing of complex solar concentrating unit, this paper designs a solar heat-concentrating medium-temperature steam-generating system. Solar radiation is collected by using a large solar collecting and heat concentrating plate and is converged to the metal evaporating pipe with high efficient heat transfer. In the meantime, the heat loss is reduced by employing a double-glazed cover and other heat insulating structures. Thus, a high temperature is reached in the metal evaporating pipe. The influences of the system's structure parameters on system performance are analyzed. The steam production rate and the steam production under different solar irradiance, solar collecting and heat concentrating plate area, solar collecting and heat concentrating plate temperature and heat loss are obtained. The results show that when solar irradiance is higher than 600 W/m^2, the effective heat collecting area is 7.6 m^2 and the double-glazing cover is adopted, the system heat loss amount is lower than the solar irradiance value. The stable steam is produced in the metal evaporating pipe at 100 ℃, 110 ℃, and 120 ℃, respectively. When the average solar irradiance is about 896 W/m^2, and the steaming cumulative time is about 5 hours, the daily steam production of the system is about 6.174 kg. In a single day, the solar irradiance is larger at noon, thus the steam production rate is large at that time. Before 9:00 and after 16:00, the solar irradiance is smaller, and the steam production rate is almost 0.

***Keywords*—**Heat concentrating, heat loss, medium temperature, solar steam production.

I. Introduction

SOLAR energy is a widely distributed renewable clean energy and is widely exploited by solar thermal utilization technology and photovoltaic power generation. Low-temperature solar thermal technology is mature and has been commercialized. However, there are huge demands for medium-temperature heat in many areas of human production and life, such as desalination, absorption/adsorption refrigeration, textile printing and dyeing, medical sterilization, agricultural products and food processing [1], [2]. Solar medium temperature steam is mainly achieved by solar concentrator, such as parabolic trough concentrator (PTC), etc. Zhang et al. [3]-[5] developed a steam generation system based on the U-shaped PTC. The system can generate medium temperature steam of 120-200 ℃ under the pressure of up to 0.75 MPa. Thomas [6], Kalogirous [7] and Zarza et al. [8] studied the steam production system by using PTC. Only 48.6% of the solar radiation energy was utilized for steam generation. The collection loss was about 41.5%, and the heat dissipation loss was about 6.9%. Pollerberg et al. [9] proposed a solar driven steam jet ejector chiller, which employed the parabolic trough concentrators to produce stably steam at a temperature of 100-180 ℃ as heat source. Riffa et al. [10] adopted a V-shaped solar trough collector to generate steam for desalination. The thermal efficiency of the collector reached 38% at the working temperature of 100 ℃. Ling et al. [11] employed solar PTC to dry agricultural products. The concentrator could supply hot steam below 200 ℃ for drying application. Ji et al. [12], [13] used PTC to increase the solar flux density, thus increasing the electric generation from unit area of solar cells and the outlet fluid temperature. The low concentrating compound parabolic concentrator (CPC) was also utilized to generate steam in medium temperature. Liu et al. [14] designed a low-cost all-glass vacuum tube solar steam generator based on CPC. The maximum steam temperature was over 200 ℃, and the pressure range was 0.10-0.55 MPa. Oommen et al. [15] proposed a CPC with an oversized reflector to generate steam for sterilization. The half-acceptance angle was 23.5°, and the heat efficiency of the collector was about 50%. Cai [16] built a printing and dyeing sludge drying prototype based on CPC. Its working temperature was 80-110 ℃. Li et al. [17] conducted comparative study on two novel intermediate temperature CPC solar collectors with the U-shape evacuated tubular absorber. Their working temperature ranged 80-250 ℃. However, the solar concentrators generally include high-quality curved optical mirrors, which are difficult to fabricate. Moreover, the medium concentrating PTC also is required to track the sun by a complex tracking system, resulting in high construction and operating costs [18]-[20].

Non-concentrating solar plate collector is of simple structure and is usually employed to supply the hot water at the temperature of 60-80 ℃ [21]-[23]. However, the heat loss is large if it works at a higher temperature. Thus, it is hardly for solar plate collector to produce steam. In 2016, Chen Gang [24], [25] at the MIT designed a direct vapor generating structure that floats on the surface of the water. The floating vapor generating structure consists of three layers three layers. The bottom layer is styrofoam, which floats the entire structure on the water surface and also isolates the heat transfer from the intermediate metal to the water. The middle layer is metal (copper) collector with selective absorption coating on its upper surface. The top layer is a packing bubble film, used to reduce the heat loss of the intermediate metal absorbing layer to the

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ambient, meanwhile allows the external solar radiation penetration. The diameter of the vapor generating structure is 10 cm and has a 1mm x 1mm slot in the center. The slot is filled with the wick, whose end is dipped into the water. The siphon force of the wick sucks water to the metal collector's surface, thereby water is heated into vapor. This study provides a new idea of solar concentrating heating, which is to converge the solar irradiation on the whole floating structure's area to the wick by heat transfer, instead of light concentration. Furthermore, a small amount of water is directly heated to vapor, avoiding that the energy is utilized to heat simultaneously a large amount of water. It is avoided that a high proportion of energy is used for water temperature rise. Therefore, the steam production rate is raised significantly. Based on the structure, Zhou et al. [26]-[28] conducted relevant researches to improve the solar radiation absorption material and the mass transfer. Utilizing the proposed solar desalination equipment with three-dimensional porous membrane and self-assembled aluminum nanoparticles, the energy efficiency was up to 90%, and the salinity of water was reduced by four orders of magnitude. Neumann et al. [29] demonstrated the use of broadband light-absorbing nanoparticles as solar photothermal heaters to generate high-temperature steam. Ni et al. [30] studied an approach to reduce surface losses by localizing high temperatures to the interior of the receiver. The measured vapor generation efficiencies were 69% at solar concentrations of 10 sun using nanoparticles (graphitized carbon black, carbon black, and graphene) suspended in water (nanofluids). Muhammad et al. [31] enabled strong surface evaporation when the bulk fluid was still subcooled. Gold nanofluid (0.04 w%) increased photothermal conversion efficiency by 95%.

This paper designed and constructed a solar heat-concentrating medium-temperature steam-generating unit (SHMSU) without light concentrating equipment. The solar irradiation is collected by a large-area solar collecting and heat concentrating plate and converges to a metal evaporating pipe by high efficient heat transfer so as to reaches the temperature of 100-130 °C for steam production. The relationship between collector's temperature and solar irradiation, heat collecting area, heat loss is discussed. It provides a way for low-cost heat-concentrating solar steam generation without light concentrating equipment.

II. Experimental System Description

The solar heat concentrating medium temperature steam generator consists of solar heat-concentrating medium-temperature steam-generating unit (SHMSU) without light concentrating equipment, feed water tank, valves, steam collecting pipe and brackets, as in Fig. 1. Among them, the SHMSU includes solar collecting and heat concentrating plate, metal evaporating pipe, double-glazing cover, heat insulating material, and steam exhaust pipe, etc., as shown in Fig. 2. The solar radiation collected by the metal solar collecting and heat concentrating plate will converge to the metal evaporating pipe and heat the water in the pipe to cause vaporization phase transition. The SHMSU works at higher temperatures, so reducing their heat loss to the environment is very important. The bottom and sides of the device are heat insulating material and the top is double-glazing cover to minimize heat loss. The height of the liquid level in the metal evaporating pipe is determined according to the working temperature, the amount of heat collected, heating as little liquid as possible, and the favor of the vaporization phase transition. The area of the solar collecting and heat concentrating plate and the heat concentrating ratio are determined according to the target temperature and the heat loss.

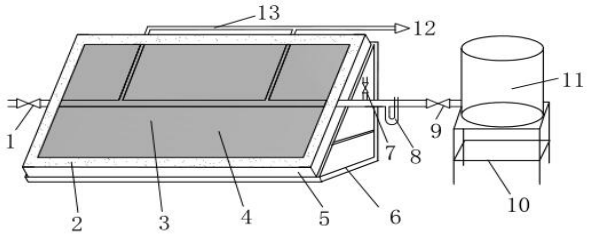


Fig. 1 Schematic diagram of solar heat concentrating medium temperature steam generator. 1,7,9. Valve, 2. Thermal insulation structure, 3. Heat collecting structure, 4. Double-glazing cover, 5. Stainless steel metal shell, 6,10. Bracket, 8. Water level tube, 11. Feed water tank, 12. Medium-temperature steam outlet, 13. Steam collecting pipe

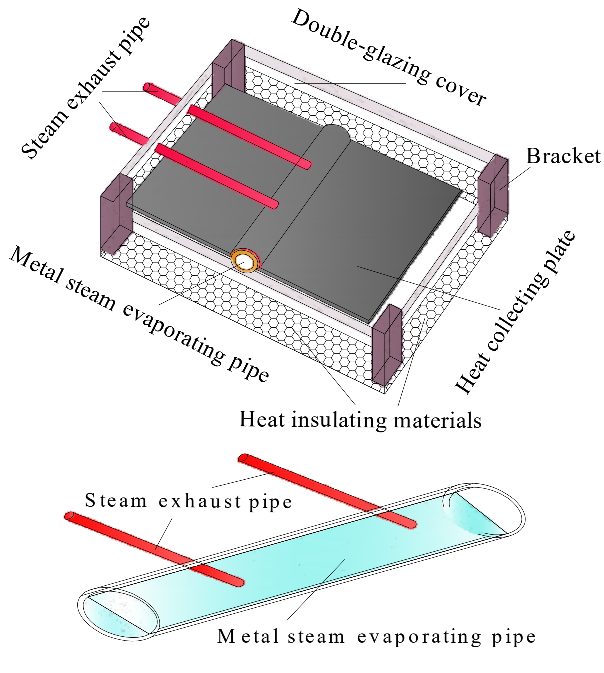


Fig. 2 Schematic diagram of SHMSU

Fig. 3 is the SHMSU experimental system. The solar collecting and heat concentrating plate is made of chrome amethyst copper with the thermal conductivity of 398 W/(m·K), the thickness of 0.35 mm, the surface area of about 7.6 m^2 and the absorptivity of more than 94%. The inclination angle between the solar collecting and heat concentrating plate and the ground is 45°. The metal evaporating pipe runs through the middle of the solar collecting and heat concentrating plate and has a diameter of 40 mm. There are two steam exhaust pipes connecting the metal evaporating pipe with the external steam collecting pipe. The heat insulating material is aluminum foil rubber insulation cotton with the thermal conductivity of 0.044W/(m·K), and the thickness of 50mm. The top cover adopts a sandwich glass of '3 mm +0.3 mm +3 mm'. The effective heat transfer coefficient is 4.26W/ (m^2·K), and the transmittance rate is 94%. The solar collecting and heat concentrating plate converges the collected solar energy to the metal evaporating pipe, and the water in the metal evaporating pipe is continuously heated. The water surface in the metal evaporating pipe always maintains at 1/2 of the cross section (the water is about 2.5 kg). In order to measure the steam production, the generated steam is passed to a storage bottle and is condensed.

Fig. 3 SHMSU experimental system

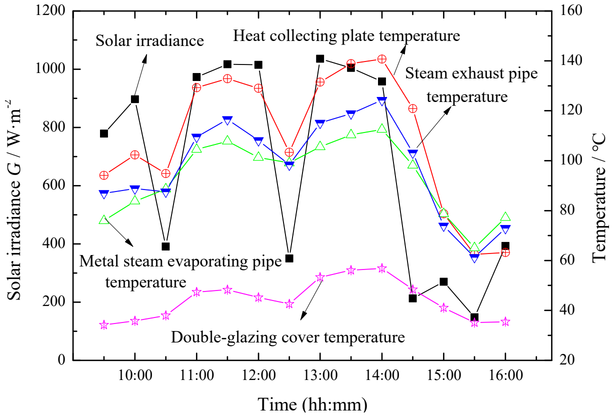
III. Results and Discussions

A. Component Temperature of SHMSU under Different Weather

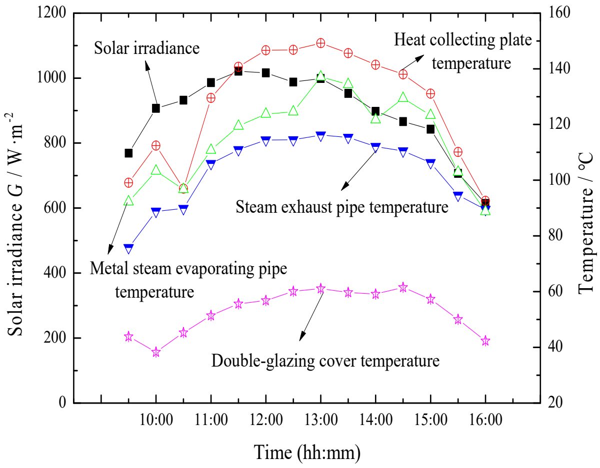
Fig. 4 shows the component temperature of SHMSU under different weather. During this period of 10:00-15:00, the temperatures of the solar collecting and heat concentrating plate, the metal evaporating pipe and the steam exhaust pipe follow the trend of solar radiation. The temperature of the solar collecting and heat concentrating plate is greatly affected by the solar radiation, and the metal evaporating pipe is somewhat less affected. The main reason is that when it is cloudy, the solar irradiance decreases, thereby the energy collected by the solar collecting and heat concentrating plate rapidly decreases, and the plate temperature decreases accordingly. The temperature of the metal evaporating pipe will also decrease, but the decline is relatively small. In the figure, the temperatures of the solar collecting and heat concentrating plate maintain above 100 ℃ in both weather from 11:00 to 15:00. Even, its temperature can maintain above 140 ℃ for a period of time at noon in sunny weather.

B. Steam Production within a Day under Different Weather

Fig. 5 shows the steam production within a day under different weather. In cloudy weather, the average full-day effective irradiance is about 670 W/m^2. The steam production of the SHMSU begins at 10:00. The steam production increases continuously, however the steam producing rate is relatively low. In sunny days, the average full-day effective irradiance is about 896 W/m^2. The steam production also increases continuously with a higher producing steam. After 15:00, the SHMSU almost no longer produces steam.

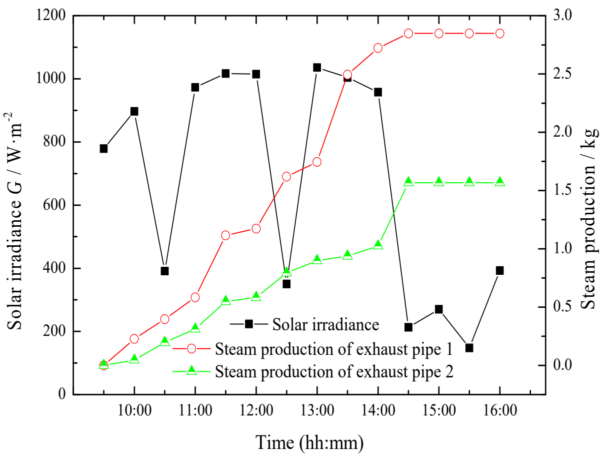


(a) Cloudy

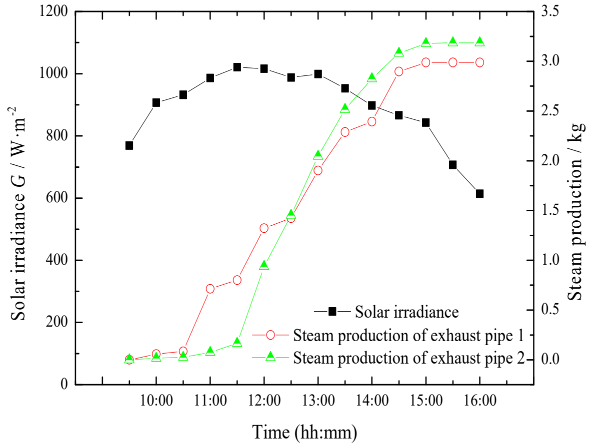


(b) Sunny

Fig. 4 Component temperature of SHMSU under different weather



(a) Cloudy

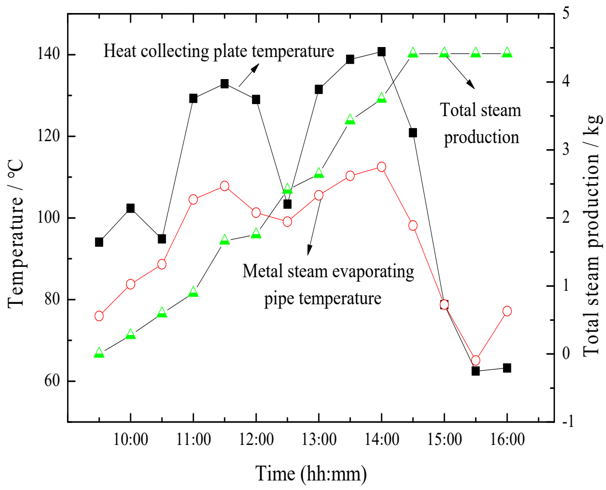


(b) Sunny

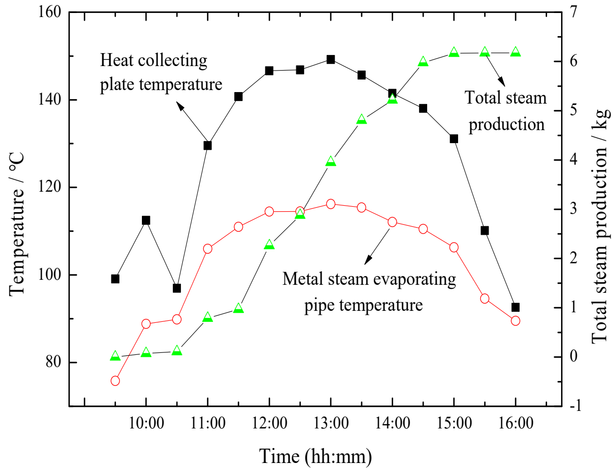
Fig. 5 Steam production of SHMSU under different weather

C.Influence of Solar Collecting and Heat Concentrating Plate Temperature on Daily Steam Production

Fig. 6 shows the influence of solar collecting and heat concentrating plate temperature on daily steam production. From 10:00, the steam production increased with the increase of the surface temperature of the solar collecting and heat concentrating plate. After 15:00, the temperature of the solar collecting and heat concentrating plate is low, the steam is no longer generated. The steam-generating time of the day is about 5h. In cloudy weather, the average temperature of the solar collecting and heat concentrating plate is 118 ℃, and the daily steam production is about 4.415 kg. In sunny days, the average temperature of the solar collecting and heat concentrating plate is 134 ℃, and the daily steam production is about 6.174 kg. Fig. 7 shows the steam generation by SHMSU.



(a) Cloudy



(b) Sunny

Fig. 6 Influence of solar collecting and heat concentrating plate temperature on daily steam production

Fig. 7 Steam generation by SHMSU

D.Steam Production in Different Periods of a Day

The steam production per unit time in different periods of a single day is shown in Fig. 8. In this period of 12:00-15:00, the steam production per unit time is more due to large solar irradiation. Before 9:00 and after 16:00, the steam production per unit time is almost 0 due to no enough solar irradiation.

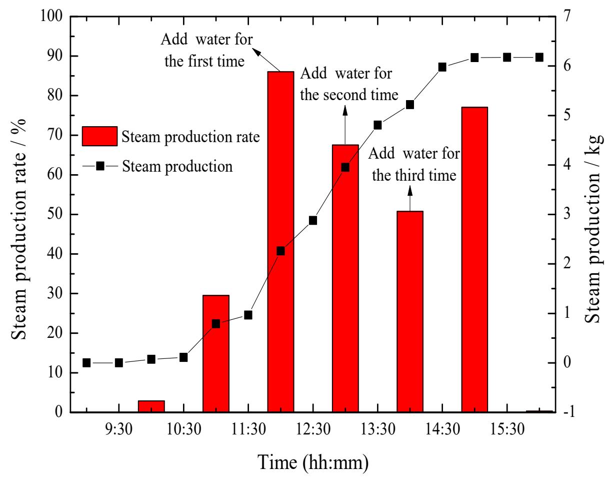


Fig. 8 Steam production per unit time

IV. Conclusions

A solar medium-temperature steam-generating system based on heat concentration, instead of light concentration, is proposed in this paper. A large solar collecting and heat concentrating plate is adopted to converge solar radiation to the metal evaporating pipe with high efficient heat transfer. Meanwhile, the heat loss was reduced by employing a double-glazed cover and other heat insulating structures. With the relevant experimental research, the following conclusions are drawn:

(1) The conditions for steam production are obtained. The solar irradiance is more than 600 W/m2, the thermal conductivity of the top glass cover is less than 6W/(m2·K), and the thickness of the heat insulation layer is as close to 50 mm as possible.

(2) The top heat loss is much larger than the bottom heat loss and the side heat loss. If the surface temperature of the solar collecting and heat concentrating plate is 100 °C and the ambient temperature is 24 °C, the top heat dissipation ratio is 82%, the bottom heat dissipation ratio is 16%, while the side heat dissipation ratio is only 2%. In order to steadily produce steam, the double-glazing cover should be used to reduce heat loss.

(3) The surface temperature of the solar collecting and heat concentrating plate is greatly affected by solar radiation. The steam productions of the system are about 4.415 kg and 6.174 kg in cloudy weather and sunny weather, respectively. In a single day, the steam production per unit time is more in the period of 12:00-15:00. Before 9:00 and after 16:00, the steam production per unit time is almost 0.

Acknowledgment

This work has been supported financially by the research project 51766018 of the National Natural Science Foundation of China, which is gratefully acknowledged by the author.

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