Efficient Solar Cooling by Using Variable-Effect LiBr-H_2O Absorption Chiller and Linear Fresnel Solar Collector with Cavity Receiver

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Abstract

A solar cooling system, which mainly consists of a variable-effect LiBr-H_2O absorption chiller and arrays of linear Fresnel solar collector, has been investigated and analyzed by experiment. The 50 kW variable-effect absorption chiller, which can work from single to double effect mode continuously, depending on the temperature level of the linear Fresnel solar collector array, can obtain a COP span of 0.6–1.15. Compared to the conventional single- and double-effect solar absorption cooling, the solar variable-effect cooling is capable of operating for a longer time, leading to more cooling output. Such solar cooling plant has been tested and analyzed in depth. The experimental results show that thermal efficiency of the linear Fresnel solar collector is approximately 58.8%, and the operation temperature is as high as 147 ℃. Thermal COP of the variable-effect LiBr-H_2O absorption chiller varies between 0.84–1.05 depending on the solar collector temperature. The solar cooling plant can convert solar radiation to cooling output accompanied by a solar COP span of 0.41–0.53 under given conditions.

Keywords: Solar cooling, variable effect, absorption chiller, Linear Fresnel solar collector, performance evaluation.

1. Introduction

Solar cooling is a promising approach to shift the peak of power grid due to its ability of converting effective solar radiation to cooling production which reducing the energy demand of city power grid. So far, it has been recognized as one of the best substitutes of conventional cooling, and is attracting more and more attention worldwide, especially in the regions with the hot and humid climate (Winston et al., 2014). Conventionally, a solar cooling plant is configured by single-effect LiBr-H_2O absorption chiller driven by stationary solar collectors (e.g. non-tracking flat plate or evacuated tubular solar collectors), or by double-effect LiBr-H_2O absorption chiller driven by concentrated solar collectors (e.g. trough or linear Fresnel solar collectors). For the first option, the conversion efficiency from solar radiation to cooling production (i.e. solar COP) is lower than 0.3. For the second option, the solar COP can be greatly upgraded due to the higher COP of double-effect chiller and high flux contributed by concentrated solar collector, however, the operation time of cooling output is limited because of a high driving temperature required by double-effect absorption chiller. To reach the target of high efficiency and longer time of solar cooling, it is urgent to develop a novel absorption chiller and the corresponding concentrated solar collector.

The predominant merit of linear Fresnel reflector (LFR) solar collector is the decrement manufacturing, operation and maintenance costs (Gharbi et al., 2011). LFR solar collector is becoming a potential method for solar thermal cooling and mid-temperature industrial utilization due to its simplicity in structural design and low investment cost. Chemisana et al. (2011, 2013) carried out a solar cooling system driven by LFR solar collector which provided thermal energy to a double effect LiBr-H_2O absorption chiller, where the rated COP of 1.35 and 150-170 ℃ driving temperature of chiller can be observed. The results showed that the LFR solar thermal cooling system has advantages and disadvantages. The advantageous is that a higher solar cooling COP can be realized with LFR solar collector under good conditions of solar irradiance. However, the disadvantageous in the system may be somewhat complex and expensive compared with the non-tracking solar cooling system. When comparing to evacuated tubular LFR collector, cavity receiver has its merits in cost benefit, and thermal stability, especially for pressure water cycle. Zhou et al., 2017 assessed

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the performance of a single/double hybrid effect absorption cooling system driven by linear Fresnel solar collectors with latent thermal storage, based on the parametric optimization. The variable-effect absorption refrigeration cycle previously proposed by Xu et al. (2013) indicates the COP of variable effect cycle increases with driving temperature. Based on the concept design, a 50 kW prototype of variable effect LiBr-H_2O absorption chiller was built and tested (Xu and Wang, 2016).

To date few reports of such similar detailed analysis of the performance in LFR solar thermal cooling system combined with the variable-effect absorption chiller has been produced. In this paper, an integrated LFR solar thermal cooling system with a variable-effect absorption chiller is introduced and studied experimentally. The individual test was carried out for major components including LFR solar collector arrays, and the variable-effect chiller. Finally, the solar COP of the entire cooling system was evaluated by dynamic test.

2. Description of the solar cooling system

The solar cooling system investigated in this paper is composed of a 50 kW variable-effect absorption chiller and LFR solar collector arrays with total aperture area of 144 m^2. In fact, the solar cooling system is originally a small part of a solar tri-generation system, for heating, cooling and power generation by using an ORC generator, shown in Fig. 1. Specifically, LFR solar collector arrays convert effective solar radiation to intermediate temperature heat, and then the heat is charged into a steam manifold that produces steam for the variable-effect absorption chiller (cooling), the ORC generator (power), and the domestic water (hot water). In this paper, the authors only focus on performance of the variable-effect absorption chiller driven by high-temperature steam heated by LFR solar collector arrays, outlined in Fig. 1.

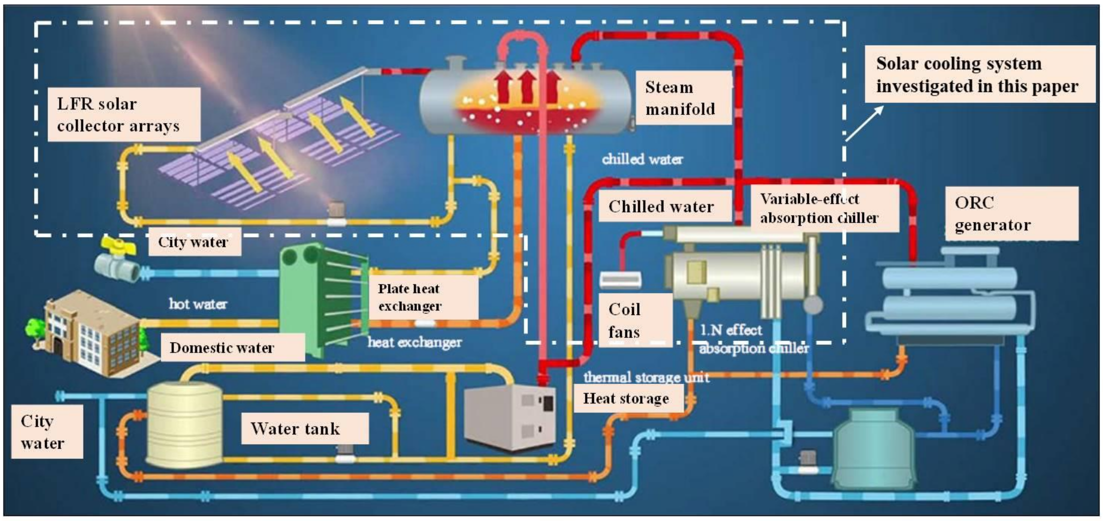
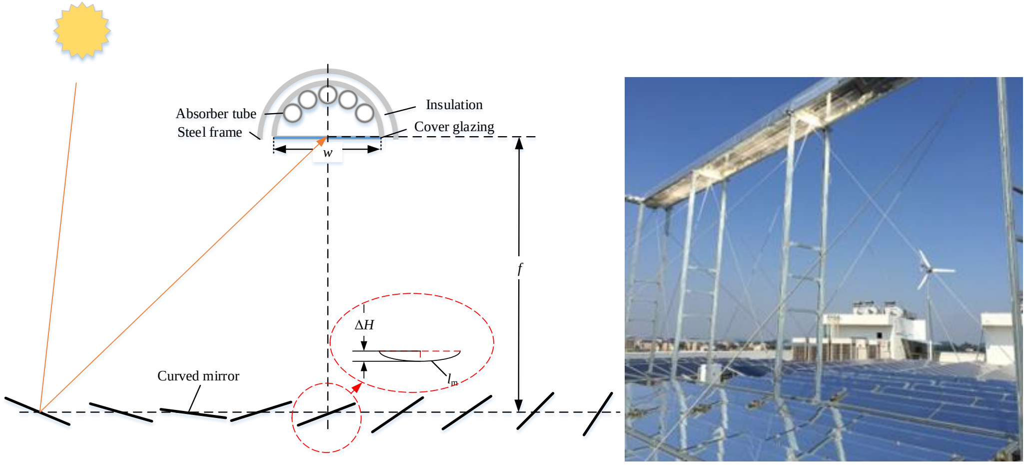


Fig. 1: Schematic diagram of the solar cooling plant with a variable-effect absorption chiller and LFR solar collectors

2.1. LFR solar collectors

A prototype of LFR solar collector employed steel tubular absorbers coated with selective absorption film was developed and serves as the thermal source. The schematic and prototype of LFR solar collectors are shown in Fig. 2.

The array of LFR collector consists of 8 individual LFR collector units, where each unit contains 12 rows of curved mirrors. The curved mirror was designed with an arch height of ΔH = 3 mm. To reduce the effect of shading and blocking caused by adjacent mirrors on the optical efficiency of LFR collector, the distance between adjacent rows was set to be 7 cm based on the model proposed by Mathur et al. (1991). The semi-circle cavity receiver with reasonable optical efficiency, relatively low investment, operation, and maintenance costs (Xie et al., 2012) was located at the latitude of 4 m, where the semi-circle receiver is comprised of five copper pipes with the inner diameter of 38 mm. Selective black chromium coating was covered on the surface of absorber pipes with a ultra-white glass of 3 mm thickness. Besides, phenolic foam serves as the insulation material between absorber and steel frame to minimize the conductive heat loss. The structure and other main parameters of LFR collector are shown in Table.1.



(a) (b)

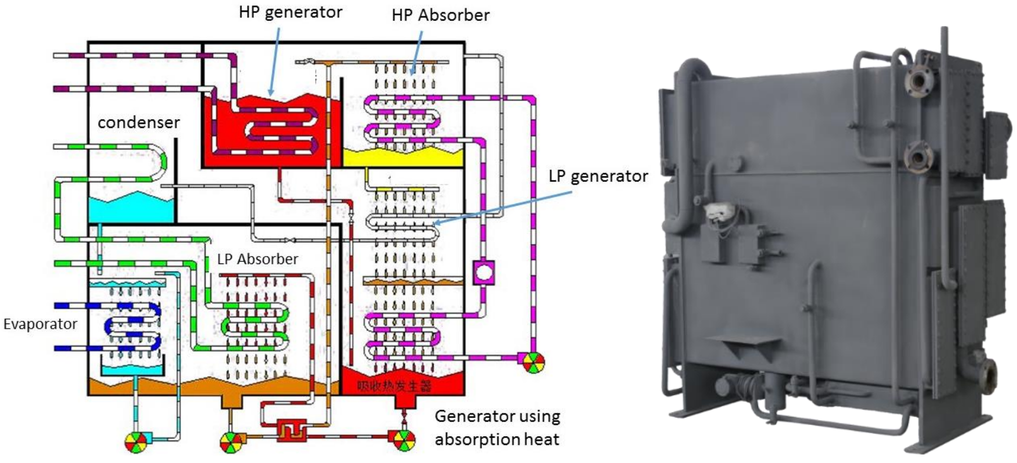
Fig. 2: The schematic and photograph of LFR solar collectors: (a) schematic of the LFR solar collector, and (b) the prototype

Table 1: The geometric and thermos-physical properties of the LFR solar collector array

Component	Parameters	Value
Mirror array	Number of units	8
	Collector area of each unit	18 m^2
Curved mirror	Arch height	3 mm
	Mirror length	3 m
	Mirror width	50 cm
	Distance of the adjacent mirrors	7 cm
Cavity receiver	Altitude	4 m
	Inner diameter (D_i) of absorber tube	38 mm
	Aperture width (w)	53 cm
	Aperture area	1.59 m^2 (each LFR unit)
	Thickness of the cover glazing	3 mm
	Absorptivity	0.85
	Emissivity (at 353 K)	0.5

2.2. Variable-effect absorption chiller

The variable effect absorption chiller, which is configured by adding an additional low pressure generator for harvesting the absorption heat, is the main section to improve the solar cooling efficiency. As is shown in Fig. 3, the main components of the chiller are presented. Fig. 3a (Xu et al., 2016) shows the thermodynamic cycle of the variable-effect absorption cooling. The variable absorption cooling works in three processes: (1) if the temperature of heat resource is enough high (> 140 ℃), it works in double effect mode, and the chiller is a double effect absorption chiller; (2) if the temperature of heat resource is less than 100 ℃, it works in single effect mode; (3) if the temperature level is in the range of 100-140 ℃, the chiller works in the 1.N effect mode, namely, it can work almost linearly from single to double effect depending on the temperature level, thus the cooling output can be increased, in comparison with the normal single effect or double effect chiller, especially for solar cooling application. The key for realizing variable-effect absorption cooling is that the internal absorption heat recovery in the high pressure absorber, even when the temperature level can not effect complete operation of high pressure generator, it can still contribute some for cooling production by using the heat from the high pressure absorber to the additional low pressure generator. The detailed thermodynamic process of the solar energy conversion and the cooling production is investigated. The prototype of the variable-effect absorption chiller is shown in Fig. 3b. The detailed parameters of the 50 kW variable-effect absorption chiller were reported by Xu et al., 2015.



(a) (b)

Fig. 4: The variable-effect absorption chiller: (a) Flow streams and (b) a prototype

3. Performance indexes

3.1. LFR solar collector

Optical efficiency η_{o} of LFR solar collector can be introduced with respect to cosine efficiency, end loss, reflectivity of mirror, and absorptivity of the absorber. The similar theoretical models (Morin et al., 2012) are used to predict the solar-to-thermal performance of the proposed LFR solar collectors. According to energy balance, the heat absorbed by cavity receiver is equal to the difference of the heat reflected to cavity surface by mirrors and heat loss of cavity, which is shown as the following relationship:

$$\eta_{\mathrm{th}} = F_R \left[\eta_0 - \frac{U_L (T_{\mathrm{i,LFR}} - T_{\mathrm{amb}})}{C I_{\mathrm{b}}} \right] \qquad \text{(eq. 1)}$$

where F_R is the heat removal factor of the solar collector. $T_{\mathrm{i,LFR}}$ is inlet temperature of pressure hot water. I_{b} is direct normal irradiance (DNI). U_L is heat loss coefficient between HTF and ambience. T_{amb} is ambient temperature. Geometric concentration ratio C of the LFR collector is defined as the ratio of collecting area A_{c} and absorber area A_{a} of the receiver.

Thermal efficiency represents the ratio between absorbed energy by cavity receiver and total energy received by mirror fields in steady state or sufficiently good quasi steady state condition. Thermal efficiency can be calculated by

$$\eta_{\mathrm{th}} = \frac{\dot{m}c_p\left(T_{\mathrm{o,LFR}} - T_{\mathrm{i,LFR}}\right)}{I_{\mathrm{b}}A_{\mathrm{c}}} \quad \text{(eq. 2)}$$

where $\dot{m}$ is mass flow rate of pressure water. c_p is specific heat of HTF. $T_{\mathrm{o,LFR}}$ represents the outlet temperature of the LFR collector array.

The heat loss coefficient of LFR solar collector can be expressed as

$$F_R U_L = \frac{Q_{\mathrm{loss}}}{A_{\mathrm{a}}\left(T_{\mathrm{i,LFR}} - T_{\mathrm{amb}}\right)} = \frac{\dot{m}c_p\left(T_{\mathrm{i,LFR}} - T_{\mathrm{o,LFR}}\right)}{A_{\mathrm{a}}\left(T_{\mathrm{i,LFR}} - T_{\mathrm{amb}}\right)} \quad \text{(eq. 3)}$$

3.2. Variable-effect absorption chiller

Cooling capacity is calculated by

$$Q_{\mathrm{chw}} = \dot{m}_{\mathrm{chw}} c_{p\mathrm{chw}} (T_{\mathrm{chw,in}} - T_{\mathrm{chw,out}}) \quad \text{(eq. 4)}$$

where $\dot{m}_{\mathrm{chw}}$ is defined as the flow rate of chilled water. $c_{p\mathrm{chw}}$ denotes specific heat of chilled water. $T_{\mathrm{chw,in}}$ and $T_{\mathrm{chw,out}}$ are the inlet and outlet temperatures of chilled water.

Input power of the pressure hot water is calculated in terms of flow rate of hot water ($\dot{m}_{\mathrm{hw}}$), specific heat of hot water ($c_{p\mathrm{hw}}$), inlet and outlet temperatures ($T_{\mathrm{hw,in}}$ and $T_{\mathrm{hw,out}}$) of hot water. The equation can be expressed by

$$Q_{\mathrm{hw}} = \dot{m}_{\mathrm{hw}} c_{p\mathrm{hw}} (T_{\mathrm{hw,in}} - T_{\mathrm{hw,out}}) \quad \text{(eq. 5)}$$

Based on the cooling capacity and input power of pressure hot water, COP of the variable-effect absorption chiller can be expressed by

$$\mathrm{COP} = \frac{Q_{\mathrm{chw}}}{Q_{\mathrm{hw}}} \quad \text{(eq. 6)}$$

Considering the conversion performance from solar radiation to cooling production, the solar COP is defined as

$$\mathrm{COP_s} = \frac{Q_{\mathrm{chw}}}{I_{\mathrm{b}} A_{\mathrm{c}}} \quad \text{(eq. 7)}$$

4. Results and discussion

Thermal performance of the solar cooling system was tested under outdoor field conditions on the roof of a building in Guangzhou. In order to conduct a practical assessment, the variable-effect absorption chiller and the LFR solar collector array were experimented under dynamic conditions. In the testing system, physical measurement parameters should include all temperatures at the inlet and the outlet of all units, circulating volume flow rates, ambient temperature, and DNI. Platinum resistance thermometers (PT100) were used to measure all temperatures. All temperature sensors were calibrated to an absolute measuring error of 0.1 K and a relative deviation between each other less than 0.05 K. To minimize temperature measurement error, two temperature sensors were located as close as possible to the inlet and outlet locations. A pyrheliometer with the measuring error less than 5% were employed to measure DNI. The ambient temperature sensor was housed in a well-ventilated instrumentation shelter above the ground and with its door facing north in order to shield from direct irradiation. A set of Keithley 2700 served as the data logger, which collects and records the data of sensors with a time interval of 10 s.

Fig. 5 shows the variations of DNI and ambient temperature as a function of local time in the test day. As seen, it was typical cloudy day. The DNI varied in a span of 100-650 W/m^2 due to the cloudy weather condition and the mean ambient temperature is about 32 ℃.

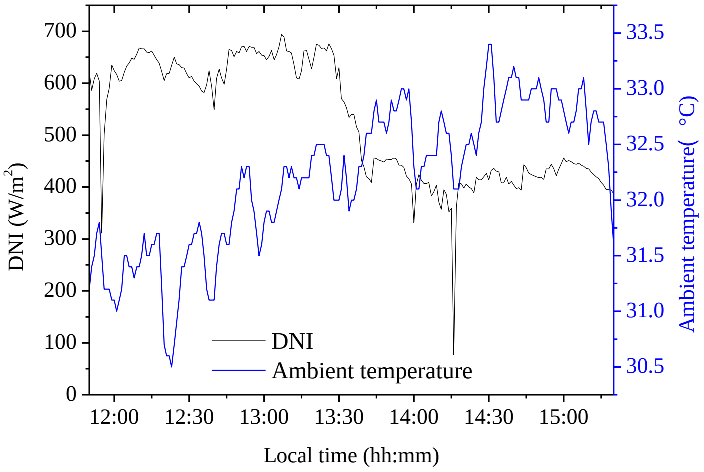


Fig. 5: DNI and ambient temperature as a function of local time

Fig. 6 shows the thermal performance of the LFR solar collector array including inlet and outlet temperatures, and thermal efficiency. The test results indicated that the peak temperature of the LFR solar collector array with cavity receiver can reach 150 ^{o}C under weather conditions shown in Fig. 5. It should be noted that the inlet and outlet temperatures of pressure hot water gradually increased, however, the DNI decreased hugely after 13:30. It is mainly contributed by the heat capacity of the steam manifold like storage tank. Thermal efficiency gradually decreased with the increasing temperature of hot water mainly due to the increasing heat loss of the cavity receiver.

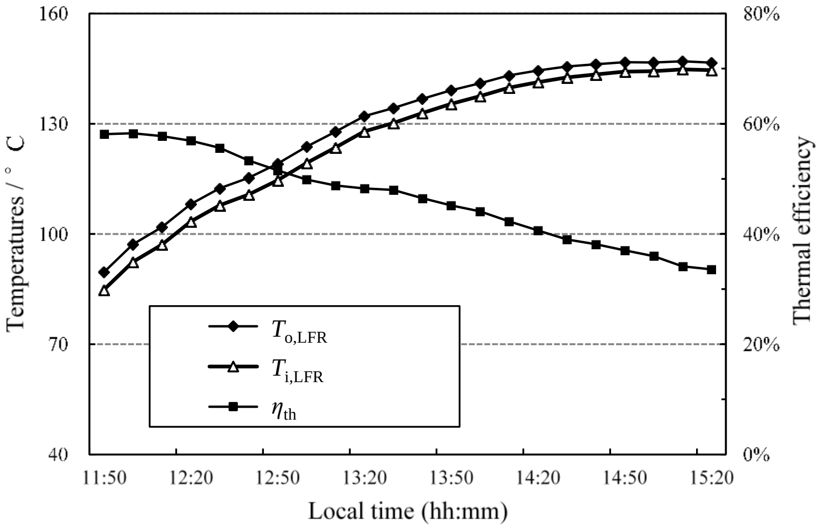


Fig. 6: Thermal performance of the LFR solar collector array

The details of performance of the variable-effect absorption chiller are depicted in Fig. 7. The cooling capacity of the variable-effect absorption chiller is around 50 kW, and the thermal COP of the chiller is about 1.05 during the operation period. During a typical cloudy day, the chiller COP varies from 0.84-1.05, much higher than the solar single effect absorption cooling system. It is found that the solar cooling system works well and the chiller COP is always above 0.8 during the given period. Fig. 8 further shows the variations of the system COP, indicating that 36-53% of solar radiation can be converted to cooling output. Also found is that the solar thermal efficiency for the Fresnel solar collector varies from 36-58% during the operation period, and the operation temperature is within the range of 90-147^{o}C. The cooling output changes (Q_{chw}) from 28-65.8 kW accordingly. It is important that the COP and the cooling output are almost linearly changing instead of step changing from single effect mode to double effect mode, and the operation time is also extended.

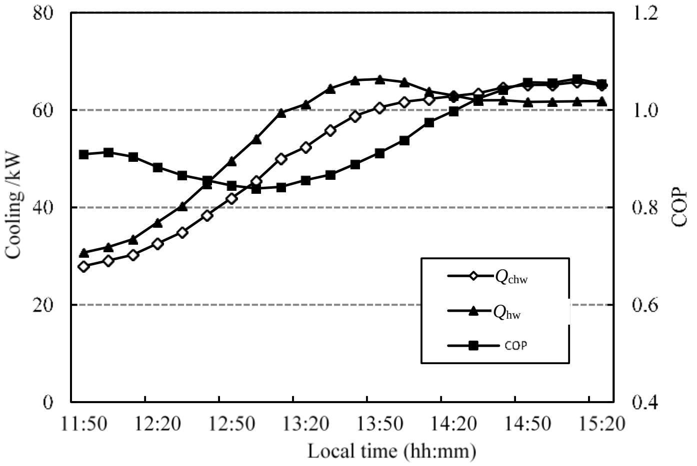


Fig. 7: Cooling output and chiller COP as a function of local time

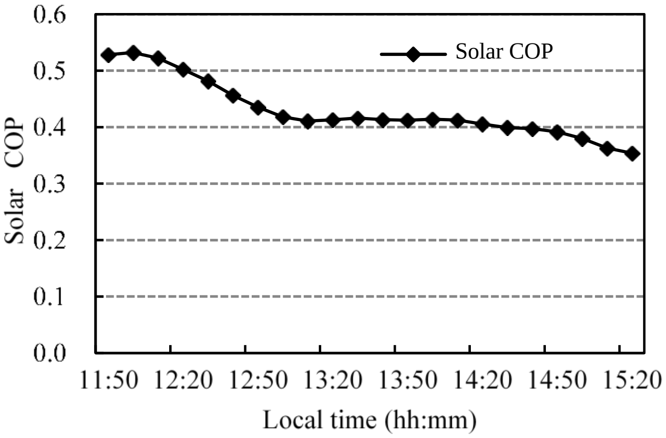


Fig. 8: Solar COP as a function of local time

5. Conclusions and Future work

A solar cooling system, composed of linear Fresnel reflector (LFR) solar collectors, a variable-effect absorption chiller and assistant components was established and investigated experimentally in this paper. A typical cloudy day test was conducted. The corresponding conclusions can be drawn:

(1) Thermal efficiency for the LFR solar collector varied from 36-58% during the operation period, and the operation temperature was in a temperature span of 90–147 ℃.

(2) The solar cooling system COP is about 0.4–0.5, indicating that this design and configuration for solar cooling can convert 40-50% of solar radiation to cooling output. The results show that the variable-effect absorption chiller is one of the best choices for improving solar cooling output and efficiency.

Future work will be focused on detailed whole day and entire summer season test, parametric optimization of such kind of solar cooling system, and cost benefit analysis.

6. Acknowledgment

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