INTRODUCTION AND ANALYSIS OF A HYBRID SOLAR THERMAL POWER AND COOLING COGENERATION SYSTEM WITH LINEAR FRESNEL SOLAR COLLECTOR

Jinghui Song[1], Jishuai Ma[2] and Yanjun Dai[2]

[1] Electric Power Research Institute of Guangdong Power Grid Co., Ltd., Guangzhou (China)

[2] Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai (China)

Abstract

Based on the linear Fresnel concentration technology, a hybrid solar thermal power and cooling cogeneration system has been developed aiming for the solar thermal utilization in hot climate regions. The thermal from the solar Fresnel collectors can be used for air condition with high efficiency solar absorption cooling, and can also be used for power generation with Organic Rankine's cycle (ORC) cycle. It mainly consists of linear Fresnel solar collector, molten salt thermal storage tank, steam drum, ORC power generation equipment and absorption chiller. And this paper introduces the running modes under different kinds of solar radiation conditions. The system will turn on the heat storage mode when the incident solar rays are strong, and will switch to the heat release mode under poor insolation. Actually, we can choose to run the hybrid system in the mode of cooling or electricity generation in response to our needs. The Fresnel solar collector acts a crucial role in different running mode. Therefore, simulations on the mirror field and the absorber of the collector are operated respectively. On the basis of the results, we make the optimal operation strategies for the hybrid system. According to the analysis above, we can draw the conclusions. The hybrid solar thermal power and cooling cogeneration system is designed with several running modes, which guarantees the system runs stably and reliably.

Keywords: *solar thermal utilization, solar Fresnel collector, ORC cycle, absorption cooling, power generation*

---

1. Introduction

Solar energy is certainly the most considerable renewable and clean energy with the reserves of fossil energy decreasing, while the consumption increasing. Solar thermal utilization is quite an important way to use the generous energy from the sun. However, the traditional solar utilization manners in low temperature level area cannot meet the demand of industrial production. Various concentration technologies are needed to gather solar energy of high quality. The linear Fresnel solar collector with cavity receiver is an economical manner in middle temperature level area, compared with the trough solar collector which is relatively more mature. It concentrates sunlight with a series of discrete mirrors to heat the working fluid flowing through the cavity receiver up to about 300℃. The collected energy can be used to various processes, such as cooling, electricity generation, industrial heating and seawater desalinization.

Absorption refrigeration circulates with water or ammonia as the refrigerant are harmless to the environment and the ozone layer; And the cycle is driven by heat energy, which includes, in addition to the use of boiler’s steam, fuel’s combustion heat, waste heat, exhaust heat, solar energy and other low grade heat. The working medium mostly used in the absorption chiller is lithium bromide solution which performs well in operation.

doi:10.18086/swc.2015.10.12 Available at http://proceedings.ises.org

The entire device, except the pumps and valves, mainly consists of the heat exchangers, so that the machine works smoothly and noiselessly. Meanwhile, the refrigerator is running in a vacuum condition, and the structure is simple, safe, reliable and easy to install. The downside is that the solution of lithium bromide in the atmosphere has a very corrosive harm to metals, thus resulting in a higher requirement for the pipes of the equipment, and additional larger cooling load. 1.n lift cycle for Li-Br absorption chiller is an improved cycle based on single effect cycle and two stage cycle. In the cycle, the flow process of Li-Br solution is improved, making one part of the fluid circulate in the way of single effect cycle and the other part in the way of two stage cycle.

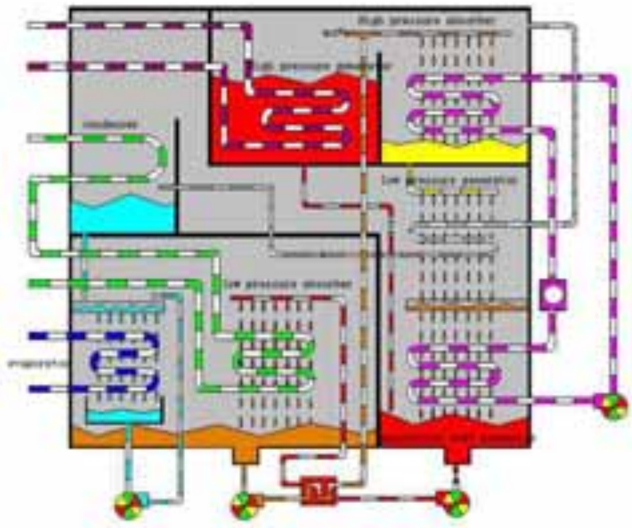


Fig. 1 Flow diagram of the 1.n lift cycle

The organic Rankine's cycle (ORC) is similar to the ordinary Rankine's cycle except that it uses the organic fluid not water as the working medium whose boiling temperature is low and the vapor pressure is high. The ORC may utilize the heat resource of low grade in power generation. The working medium absorbs heat from the heat resource and vaporizes quickly which is to drive the turbine.

In the solar thermal power generation field, heat storage is quite important to ensure the whole system operate continuously and effectively. The material storing the heat is more likely to be the phase change material (PCM) and nitrate is the common choice. Most nitrate's melting point is about 300℃ and the outstanding advantage of the salt is the low price, and low corrosivity and stable physical performance below 500 ℃. The disadvantage is that the heat of solution is small (only 20-30 kcal / kg), and the thermal conductivity is low[only 0.7 kcal / (m • h • ℃)], so that it would be overheated partially. However, compared with other molten salts, nitrates are still in the ascendant.

Solar salt is a kind of composite of nitrates which is the best choice in solar thermal molten salt power generation. Because it has the highest upper limit temperature (600 ℃), so it can keep the steam turbine operating at peak efficiency. In addition, it is one of the cheapest nitrate molten salt. But the Solar salt's freezing point is too high (220 ℃), comparing with the synthetic oil whose freezing point is only about 10 ℃ (Therminol VP-1,13 ℃). Therefore, some protective measures aiming at the high freezing point need to be taken to increase the strength of pipes, valves and other facilities, which would increase the operational and management costs. Given this, ternary molten salt Hitec (142 ℃), Hitec XL (120 ℃) are compounded, the freezing points of which are reduced a lot, and the upper limit temperature is decreased little. Thus, the synthetic molten salt has a broad application prospects in solar thermal power generation.

2. Hybrid system

2.1 Components

This solar thermal system is to achieve the functions including cooling, power generation, heat storage, domestic hot water preparation and many other features. Four linear Fresnel solar collectors in series are applied in the system, the absorber of which has a half cylinder trough cavity. The refrigerator is 1.n lift Li-Br absorption chiller, with a cooling capacity of 50kW. Organic Rankine's cycle power generator is used and the organic working fluid is R11, and generating power is 5kW. The refrigerator and power generator are designed and positioned in parallel and sharing one cooling tower, not working at the same time due to the limited collector area. The thermal storage use the hitec molten salt as the medium, storing heat according to the phase change latent heat. In addition, the system incorporates a drum for generating stable and high quality steam, equipped with an electric heater as an auxiliary heat source. Furthermore, a plate heat exchangers is assembled to produce domestic hot water through heat exchange with the steam drum.

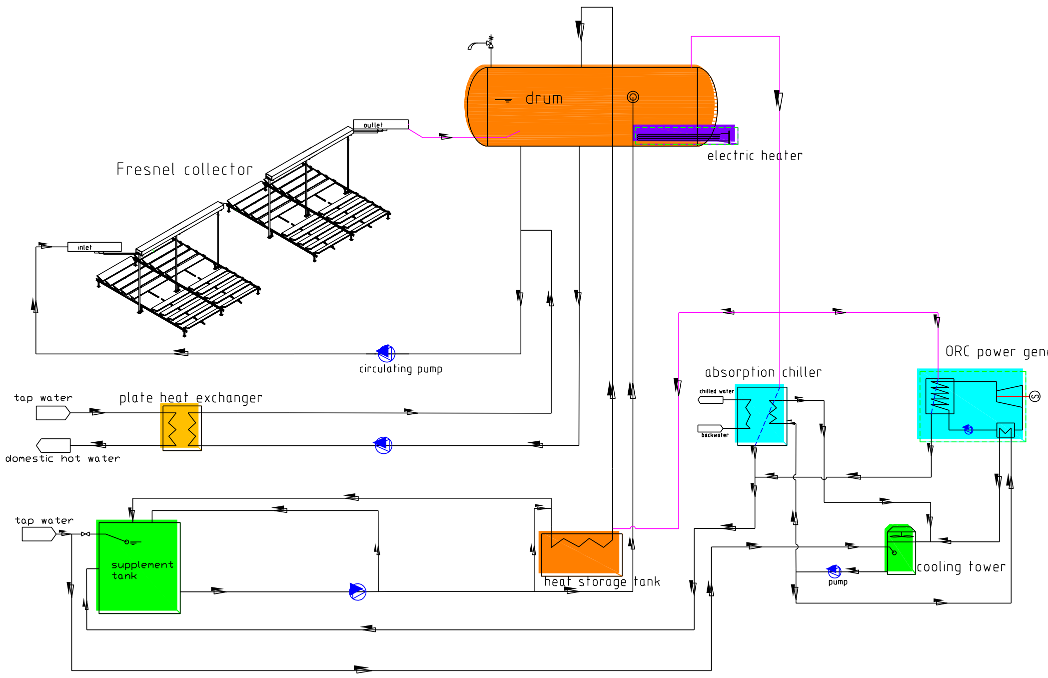


Fig. 2 schematic diagram of the hybrid system

2.2 System process

This system is a direct steam generation system (DSG), and the cycle working fluid is water. In the absorber of the collector, the water is heated to steam or mixture of water and vapor and flows into the drum where the vapor and the water are separated. The liquid water returns to the absorber through the drop tube. Meanwhile, the steam, heated by the electrical heater if necessary, runs out of the drum directly and entrances the terminal equipment, the refrigerator or the power generator. After driving the terminal equipment, the steam becomes liquid water and flows into the supplement tank. A circulating pump is there to deliver the water from the tank to the drum, where the steam and the water mix together to generate the steam that meets the demand. When the collector can't provide sufficient heat to produce steam, the electrical heater is enabled for additional heating.

When the solar radiation is intense, the steam generated in the drum is of high quality and surplus to drive the terminals. The heat that is spare from the steam would be stored in the heat storage tank. The water coming out of the tank returns to the supplement tank, mixing with the backwater from the terminals, and returns to the drum. When the solar radiation is weak, the heat storage tank, probably in combination with the collectors, could heat the water into steam for driving the terminals. If the terminals and the heat storage tank are not in use, the high temperature steam or water is switched into the plate heat exchanger to produce domestic hot water.

2.3 Running modes

The system is endowed with great flexibility to achieve variable functions and is able to runs in several operation modes which are switched through controlling the valves. Table 1 is a scan of all running modes.

Table 1 Seven running modes of the hybrid system

[1]	C-T	Collector mode	Collectors provide the complete production needs of steam.
[2]	C⊕E-T	Auxiliary heating mode	Collectors, joint with electric heater, provide heat for the steam generation
[3]	C-T∥S	Heat storage mode 1	The steam provides heat for the terminal and heat storage tank in parallel.
[4]	C-S	Heat storage mode 2	The steam provides heat only for the heat storage tank.
[5]	C⊕S-T	Exothermal mode 1	Collectors and the heat storage tank in series provide heat for steam generation.
[6]	S-T	Exothermal mode 2	Only the heat storage tank provides heat for steam generation.
[7]	C-D	DHW mode	The steam heated by the collectors is used to produce domestic hot water.

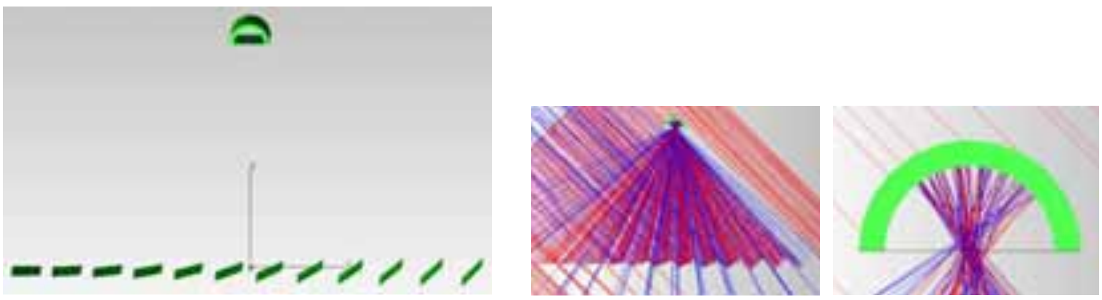
Note: The symbol ⊕ means the two equipment are in series while ∥ in parallel.

3. Simulation

In the hybrid system, the solar collector plays a pivotal role in operation modes. And the performance of it has an essential effect on the refrigerator and power generator. Therefore, it is necessary to figure out the characteristics of the linear Fresnel collector. Simulation software TracePro and Fluent are used to establish the optical model and the heat transfer model of the collector respectively.

3.1 Optical simulation

First, according to the design parameters of the reflective mirrors and the cavity absorber, as well as the mirrors' slant angles in different incident angle of light, establish the mirror field and absorber model in TracePro's workspace (see Figure 3 (a)), and define the surface properties and light source. Then ray tracing simulation is carried on(see Figure 3 (b)) and the radiation energy distribution on the glass cover and the inner wall of the cavity is obtained.



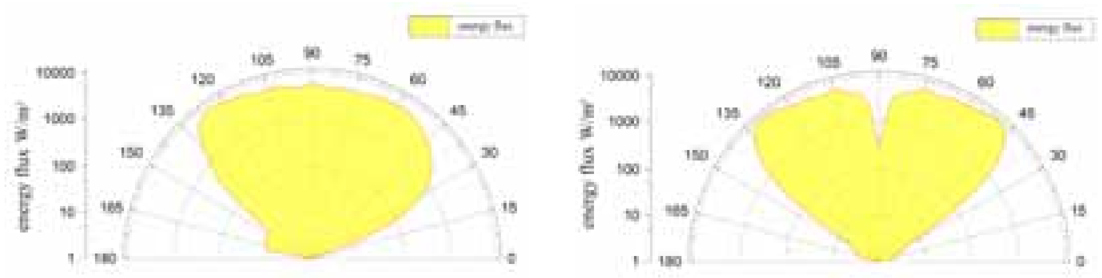
(a) (b)

Fig. 3 Geometry model of the collector and the ray tracing （$\alpha = 45°$）

The lights reflected by the mirror field converge onto the absorber, forming a facula of high energy density along the glass cover. Part of the lights reflected by the glass cover, most lights transmit through and disperse on the semi-circular inner wall of the absorber uniformly.

3.1.1 Energy flux density distribution

In the middle of the cavity absorber, take a cross section perpendicular to the longitudinal direction of the cavity, and the energy flux density distribution in polar coordinates is presented in Figure 4 and Figure 5(a). The incident angles are 45°and 90° respectively.



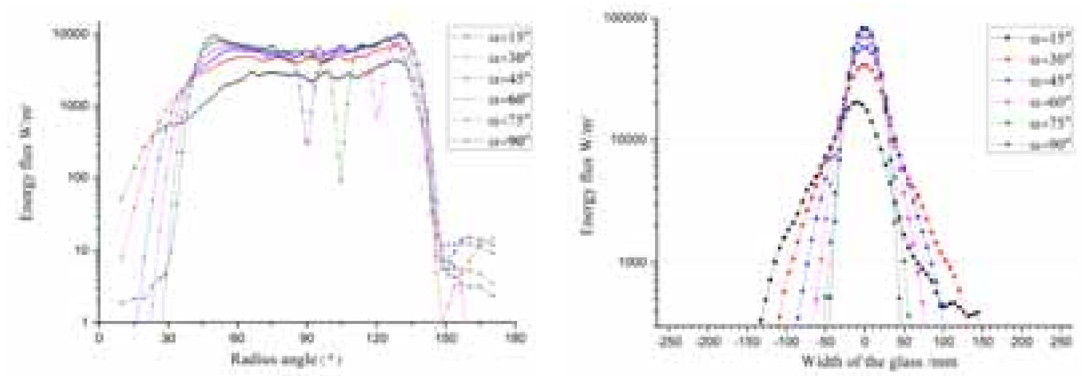
(a) $\alpha = 45°$ (b) $\alpha = 90°$

Fig. 4 Polar diagrams of the energy flux density on the inwall of the cavity

From Fig. 4 and Fig. 5(a) the characteristics of the energy flux density distribution on the cavity wall appear as follows: (a) with the rise of the incident angle, the energy density increases on the whole; (b) when the incident angle is 90° , there is a low ebb in the distribution of the energy flux density at the radius angle; The cause is the shadow the absorber project on the mirror field; (c) no matter how much the incident angle is, the energy falling on the cavity concentrate within the radius angle range of 30°-150°. Thus, the absorber's heat pipes should be arranged within the angular range.

3.1.2 Width of the facula

The width of the facula on the glass cover tells the concentration performance of the collector. Figure 5(b) shows the incident energy flux on the glass cover. As is seen, the width, the energy flux on the edge of which is 300W/m^2, decreases with the incident angle rising from 0° to 90°. According to the width of the facula, the geometric concentration ratio of the collector can be calculated (Table 2).



(a) on the inner wall of the cavity (b) on the glass cover

Fig. 5 Rectangular diagrams of the energy flux density on the absorber

Table 2 The facula width of the glass cover and the geometric concentrating ratio

Incident inclination angle	15°	30°	45°	60°	75°	90°
Facula's width/mm	285	240	190	145	110	95
concentration ratio	21.1	25.0	31.6	41.4	54.5	63.2

3.2 Heat transfer simulation

On the basis of the optical simulation's results, the appropriate distribution of the tubes in the cavity of the absorber is determined (see Fig. 6). There are five tubes that distributed within 30° ~150° where the heat flux energy is high and uniform. The boundary condition on the inner wall of the cavity is the energy flux distribution that is calculated in the optical simulation. Figure 7 shows the temperature contour on the cross section of the absorber. The aluminum fins between adjacent tubes transfer heat from the concentrated radiation to the tubes, however, is not able to deliver heat fleetly for the medium on both side of them perform weak in heat conduction.

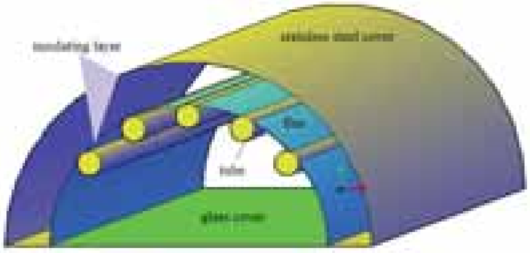


Fig.6 structure of the absorber

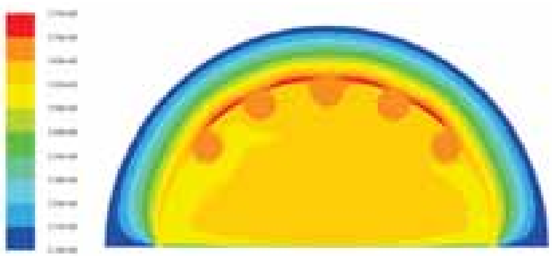


Fig.7 temperature contour of the absorber

The air's temperature is high and near to the water flowing through the tube, therefore the heat loss occurring on the glass cover is mainly in form of convection and radiation. Fig.8 shows the thermal efficiency and the heat loss ratio of the radiation of the absorber. The efficiency decreases with the rise of temperature of the water entering the tubes, and is about 54% when the water is 100℃. The pressure in the tube is high enough to ensure the water wouldn't vaporize. The radiation heat loss of the absorber maintains a steady level, about 1/3, which will rises slowly when the water's temperature is higher than 80℃. The convection heat transfer through the glass cover still dominates the whole heat loss of the absorber.

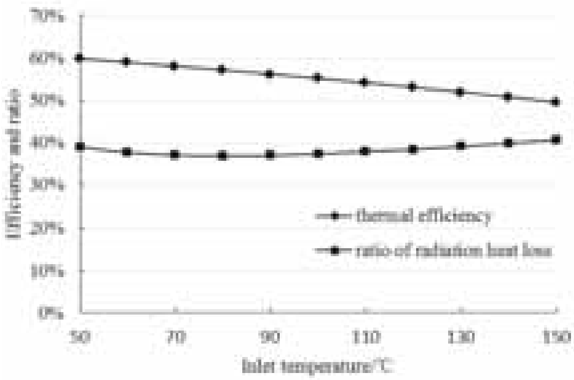


Fig.8 thermal efficiency and the heat loss ratio of the radiation of the absorber

The steam used in the terminals is about 120℃ where the efficiency of the collector is about 50%, so the heat collecting capacity of the collector is at least 2 times the steam heat consumption of the refrigerator and power generator. Considering the extra factors the simulation ignores, the practical efficiency is definitely lower than 50%, the mirrors' area of the collector is a key to guarantee the system performs well.

4. Conclusion

According to the introduction and simulation of the components and system, we could draw the conclusion as follows. The hybrid solar thermal power and cooling cogeneration system is designed with several running modes, which guarantees the system runs stably and reliably. In good weather condition, the system can meet the demand of cooling or electricity continuously. In poor condition, the storage unit works and can supply supplementary heat for at least one hour. The Fresnel collector performs well in light concentration. The light incident into the cavity is focused on the angular range 30°~150°, and the facula formed on the glass cover is 9.5mm at minimum. As to the heat transfer property, the temperature of the tubes and fins in the cavity distributes even and uniform. The thermal efficiency of the collector is about 55% when the inlet temperature of water is 100℃ more or less. When matching the collector with the refrigerator or power generator, the heat collecting capacity should be considered carefully. The flexibility and reliability are reflected mostly by using the heat storage tank.

5. References

[1] Jianming Liu, 2012. Technology of solar thermal power generation[M]. Beijing: House of Chemical Industry.

[2] Anica Trp et al, 2006. Numerical analysis of the thermal behavior of a shell-and-tube heat storage unit using phase change materials [J].Applied Thermal Engineering. 26, 1830–1839.

[3] Hamid Ait Adine et al, 2006. Analysis of the influence of operating conditions and geometric parameters on heat transfer in water-paraffin shell-and-tube latent thermal energy storage unit [J]. Applied Thermal Engineering.26, 1830–1839.

[4] Xian L et al, 2010. Numerical heat transfer analysis of the packed bed latent heat storage system based on an effective packed bed model. Energy, 35, 2022-32.

[5] Pablo Dolado et al, 2011. Characterization of melting and solidification in a real scale PCM-air heat exchanger: Numerical model and experimental validation [J]. Energy Conversion and Management. 52, 1890–1907