Performance Analysis of Tower Solar Thermal Power System

Wei Wang[1, a], Wei Du[2,b], Rongrong Zhai [3,c*] and Miaomiao Zhao[4,d]

[1,2]Nari Group Corporation State Grid Electric Power Research Institute, Nanjing 211000, China

[3,4]School of Energy, Power and Mechanical Engineering, North China Electric Power University, Beijing 102206, China

[a]wangwei@sgepri.sgcc.com.cn, [b]duwei@sgepri.sgcc.com.cn, [c]zhairongrong01@163.com, [d]zhaomiaomiao13@163.com

Keywords: solar tower; molten salt heat storage; exergy efficiency

Abstract. With the development of industry, the large-scale exploitation and use of fossil fuels, especially coal, oil and natural gas, cause serious impact on the environment. Therefore, the development of renewable energy has become an important way to solve the problem between energy and environment. Solar energy, a kind of clean energy, with large reserves and distribution, has caused the wide attention of people. Solar tower thermal power generation technology is promising way to use solar energy to generate electric power. This paper established a system model of a 30 MW tower solar thermal power plant, analyzed the system by using the second thermodynamics law. In addition, the storage and release performances of the molten salt thermal storage subsystem under various irradiation have been explored.

Introduction

In recent years, the large-scale exploitation and use of fossil fuels, especially coal, oil and natural gas, cause serious impact on the environment[1]. Therefore, the development of renewable energy has become an important way to solve the problem between energy and environment[2]. Solar energy, a kind of clean energy, with large reserves and distribution, has caused the wide attention of people. Solar thermal generation is a way that using mirrors to focus the sunlight on the surface of the absorber and heating the feedwater to superheated steam, then the steam enter to the turbine to generate electric power[3]. In accordance with the solar concentrator, solar thermal power generation can be divided into parabolic trough thermal power generation, parabolic dish thermal power generation, central tower thermal power generation and linear Fresnel thermal power generation[4].

Solar tower thermal power generation technology, which is also referred to as central receiver technology, uses a large number of heliostats having a dual axis control system (one about the elevation axis and the other about the azimuthal axis). These heliostats reflect direct beam solar radiation to a receiver located at the top of a tower. In the receiver, heat transfer fluid absorbs heat and transfers this thermal energy to the power block to generate power[5]. Because of the intermittent property of solar energy, it is necessary to provide enough heat by the thermal storage system to replenish energy when the weather is cloud or in the evening.

Solar tower thermal power generation system is composed of three parts, which are the concentrating heat system, the thermal storage system and the power block.

Concentrating heat system is made up of concentrating subsystem and absorber subsystem. Concentrating subsystem is mainly composited by the heliostats, which includes the mirror, support structure, tracking driving mechanism and a control system. Concentrating subsystem is one of the key components in the solar tower thermal power generation, and it's also a main part of the investment in power plant. The function of heliostats is to achieve the best tracking of solar radiant energy by tracking control device, so that the solar radiation can be accurately focused and reflected to the heat absorber, which provides the solar energy for the entire power generation system, and is the basis of the solar thermal power generation. The more heliostats, the higher concentrating ratio will be, so the heat absorber temperature will be high.

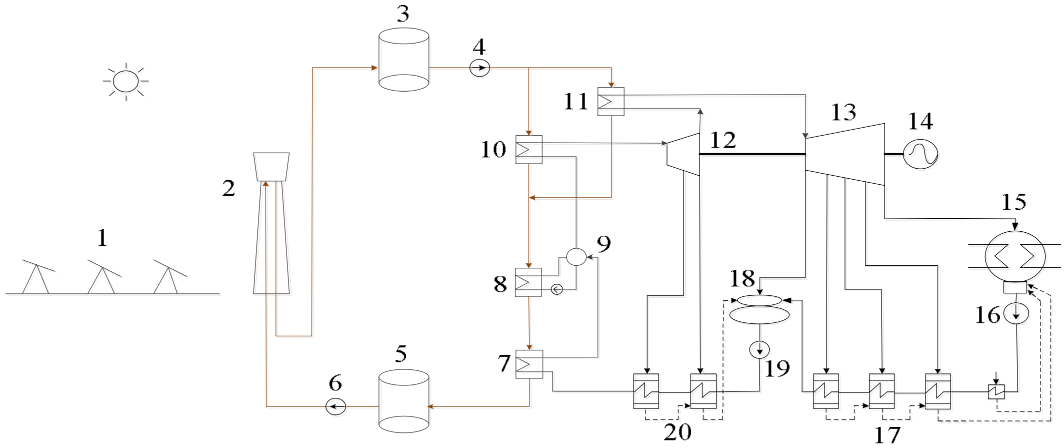
The absorber subsystem is composed of two parts, which are the tower and absorber located on the top of tower. Currently, the tower in solar tower thermal power station has reinforced concrete and steel frame two structure forms. And the height of tower depends on the scale of the heliostats field. Absorber is the device that can convert the solar energy into thermal energy, according to the shape of the absorber, there are divided into planar, globular shape, linear and cavity type. In the present world, most of the absorber is cavity type, because of its large heat absorbing surface and small heat loss.

Thermal storage system requires the working medium should have great performance of heat transfer and heat storage. At present, working medium are mainly water, steam, oil, molten salt, liquid sodium and other materials. In some earlier solar thermal power plant, oil is used as the thermal storage medium, but because of its low thermal storage temperature, flammable, volatile, and high cost. Therefore, the researchers quickly turned to molten salt. Molten salt is a kind of ideal thermal storage medium, which has the advantages of great heat transfer performance, high thermal storage temperature, low cost and so on. Therefore, molten salt as working medium in in the tower solar power plant has a broad application prospect, it can improve the efficiency, the stability and reliability of the system.

This paper established a system model of a 30 MW tower solar thermal power plant, analyzed the system by using the second thermodynamics law. In addition, the storage and release performances of the molten salt thermal storage subsystem under various irradiation have been explored.

Description of system

The system diagram of a 30 MW solar thermal power tower system studied in this paper is shown in Figure 1, the brown lines represent the molten salt and the black lines represent the steam and water in the figure. The system is composed of the concentrating system, the thermal collect and storage system and the power block. Concentrating system is composed of heliostat, absorber and other auxiliary devices. Heliostat locate around the tower arranged in a certain rule groups. Depending on the sun's position, each heliostat can adjust their own angle to track the sun to ensure that the sun light accurate focusing on the absorber located at the top of the tower. Thermal collect and storage system: the molten salt, which is composited of 40% KNO_3 and 60% $NaNO_3$, from the absorber first enter into the hot tank to heat the working medium to a certain temperature in the tank by the high temperature sensible heat of heat transfer fluid. Then molten salt pass through the superheater (or reheater), high temperature heat exchanger, low temperature heat exchanger, and cold tank, in which the low temperature sensible heat of heat transfer fluid is released to heat the working medium to a certain temperature in the tank, eventually return to the absorber to absorb heat once again. Power block is composed of solar drum, low temperature heat exchanger, high temperature heat exchanger, superheater, reheater, steam turbine, regenerator, deaerator and pump etc. Main steam firstly goes into the high pressure cylinder to work, after heated in the reheater to a certain temperature, the exhaust of high pressure cylinder enter to low pressure cylinder to work. Turbine exhaust steam pass through the condenser, feedwater pump to the low temperature heater and then enter the steam generator (high temperature heater and drum) to form saturated steam. Saturated steam enters the superheater to produce superheated steam (the main steam). After this cycle to achieve the purpose of thermal energy converted to power.



1-- filed of heliostats; 2-- heat absorbing tower; 3-- hot molten salt tank; 4-- high-temperature molten salt pump; 5-- cold molten salt tank; 6-- low-temperature molten salt pump: 7-- low-temperature heat exchanger; 8-- high-temperature heat exchanger; 9-- drum; 10-- superheater; 11-- reheater; 12-- high-pressure turbine; 13-- low-pressure turbine; 14-- generator; 15-- condenser; 16-- condensate pump; 17-- low-pressure heater; 18-- deaerator; 19-- feedwater pump; 20-- high-pressure heater

Fig. 1 System diagram of a 30 MW tower solar thermal power system

Exergy analysis of system

Difference of energy is not only the amount, but also grade level, so analyzing and evaluating thermal system should be from the view of the amount of energy and qualitative point of view, then proposing improvement measures. Exergy analysis is based on the second law of thermodynamics, and the evaluation index is exergy efficiency. Exergy efficiency of each equipment is equal to the ratio of received exergy and delivery exergy. For this article, studied solar thermal power generation system, the system comprises two circular loops: the molten salt circulation and steam/water circulation. This paper calculated exergy efficiencies of each equipment in these two circuits respectively.

This paper established a system model of a 30 MW tower solar thermal power plant by Ebsilon Professional software. In design point, the solar irradiation is 850 W / m^2, the area of mirrors field is 230,000 m^2, the working fluid is molten salt, the temperature of hot molten salt tank is 565 ˚C, and the temperature of cold molten salt tank is 290 ˚C. The pressure of main steam is 12.6 MPa and the temperature is 552 ˚C, and the feedwater reheat system adopts the mode that consists of two high-pressure heaters, three low-pressure heaters and one deaerator.

The values of get and paid of each equipment in the molten salt circulation are listed in Table 1 and the exergy efficiencies are shown in Figure 2 below.

Table 1 Exergy of each equipment in the molten salt circulation

Equipments	**Available（kW）**	**Cost（kW）**
Heat absorber	55159.29	118458.58
High-temperature molten salt pump	49.61	51.22
Low-temperature molten salt pump	582.31	672.66
Low-temperature heat exchanger	6526.54	6366.78
High-temperature heat exchanger	15121.41	15336.40
Superheater	12688.25	13425.07
Reheater	5935.08	6183.48

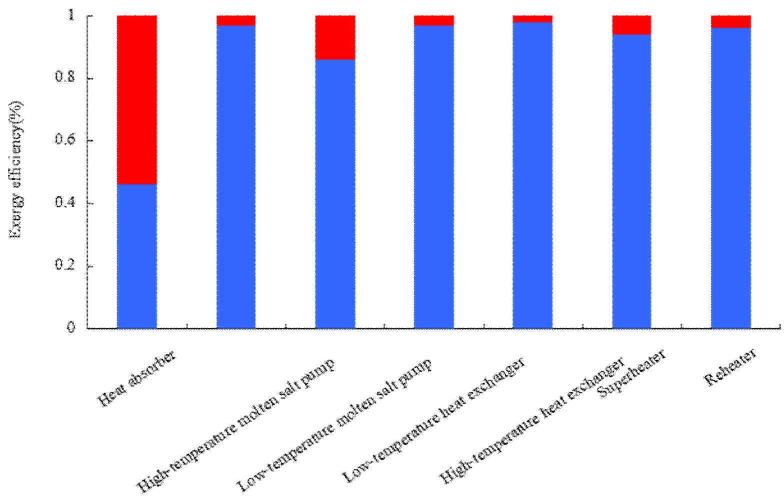


Fig. 2 Exergy efficiency of each equipment in the molten salt circulation

In the molten salt circulation, hot molten salt tank and cold molten salt tank are equipments that used to store the working fluid, not to analysis and calculate the exergy efficiency. For the heat absorber, the get of equipment is increasing the exergy of molten salt through the equipment, the cost of equipment is the exergy of solar heat that is put into the heat absorber. For pump, the get of equipment is increasing the exergy of molten salt through the equipment, the price is the pump power consumption. For the heat exchanger, the harvest is increased exergy of water or steam through the heat exchanger, the cost is reduced exergy of molten salt. Throughout the cycle, the lowest exergy efficiency is the exergy efficiency of heat absorber that is only 46%, so improve the heat absorber is essential to increase efficiency of the whole system, for example, improving material of heat absorber to improve insulation properties.

The values of get and paid of each equipment in the steam/water circulation are listed in Table 2 and the exergy efficiencies are shown in Figure 3 below.

Table 2 Exergy of each equipment in the steam/water circulation

Equipments	**Available（kW）**	**Cost（kW）**
Low-temperature heat exchanger	6366.78	6526.53
High-temperature heat exchanger	15121.41	15336.39
Superheater	12688.25	13425.07
High-pressure turbine	8831.46	9422.23
reheater	5935.07	6183.48
Low-pressure turbine	22418.54	24710.21
Condensate pump	22.51	28.13
Low-pressure heater	2286.00	2629.47
Deaerator	1154.37	1286.18
Feedwater pump	402.66	473.62
High-pressure heater	3454.39	3742.20

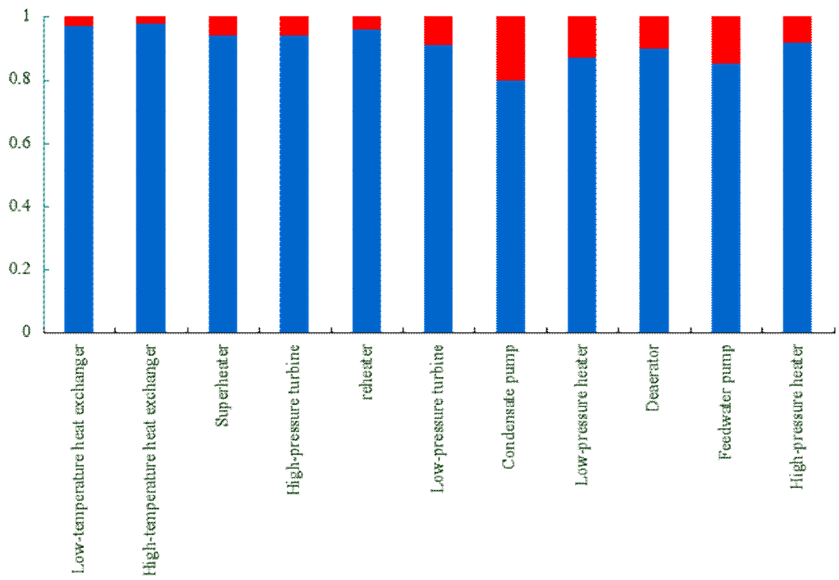


Fig. 3 Exergy efficiency of each equipment in the water/steam circulation

In the steam/water cycle, the condenser is used to cool the exhaust steam of turbine and reduce final parameters of cycle, so it does not need to analyze the exergy efficiency. The get of high-pressure and low-pressure turbine is the work, and the cost is reduced exergy of steam. For high-pressure and low-pressure heater and deaerator, the harvest is adding the exergy of water, and the cost is reducing the exergy of steam. In this cycle, the exergy efficiency of condensate pump and feedwater pump are lower, 80% and 85% respectively, so increasing performance of pump can help improve the efficiency of overall cycle. Exergy efficiencies of the rest equipments are above 90%, but there is still room for improvement, such as improving the type of heat exchanger to improve performance of heat transfer.

Analysis of heat storage system under various solar irradiation

Solar irradiation is existing in the daytime, but none is at night. Even in the same day, it also keeps changing overtime, so the analysis of system performance under various solar irradiation is necessary. Tower solar thermal power system studied in this paper has a molten salt heat storage subsystem, so it can ensure the output power of the system remain constant 30 MW. When the solar irradiation is changing, the flow rate of molten salt that flows from cold molten salt tank into heat absorber is changeable, and the flow rates of molten salt that out from the hot molten salt tank to exchange heat with steam or water is constant. Therefore, when solar irradiation is changing, just to analyze the heat storage and release performance of heat storage. When the solar irradiation DNI changes from 500 W / m^2 to 1000 W / m^2, the situation of heat storage and release is as shown in Table 3, "-" indicates the thermal energy of heat storage system is decreasing in the table.

Table 3 Heat storage and release of heat storage system under various solar irradiation

DNI (W/m^2)	Flow rate of molten salt that goes into the heat absorber tower (kg/s)	Flow rate of molten salt that exchange heat with steam or water (kg/s)	Heat storage and release of heat storage system (kW)
500	132.23	171.08	-16670
550	146.28	171.08	-10834
600	160.33	171.08	-4999
639	171.08	171.08	0
700	188.42	171.08	6675
750	202.47	171.08	12510
800	216.52	171.08	18345
850	230.56	171.08	24181
900	244.61	171.08	30017
950	258.66	171.08	35852
1000	272.7	171.08	41688

As it can be seen from Table 4, with the increase of the DNI, the flow rate of molten salt that goes into heat absorber tower continues to increase, while the flow rate of molten salt that exchange heat with steam or water remains 171.08 kg / s. When the DNI is 639 W / m^2, the flow rates of molten salt that goes in or out tank are equal, then the thermal energy is neither increased nor reduced, which means that the heat provided by the solar collector field can meet the thermal energy demand of steam-to-water cycle. When the DNI is lower than 639 W / m^2, the solar collector field and the heat storage system provided the heat demand of steam and water together, and the thermal energy of heat storage system is declining. When the DNI is higher than 639 W / m^2, part of the heat provided by the solar collector field is to provide energy to the side of steam/water, another is stored in the heat storage tank, and the heat stored is increasing with the DNI.

Conclusions

This paper established the model of a 30 MW tower solar thermal power system, and calculated exergy efficiencies of each equipment and analyzed the heat storage and release of thermal storage system under various solar irradiation. The conclusions are following:

(1)By calculating the exergy efficiency of each equipment in molten salt and steam/water circulation, it can be seen that the heat absorber has the lowest exergy efficiency, so improving structure and heat transfer performance of heat absorber is important to improve efficiency of overall system .

(2)DNI that is 639 W / m^2 is a critical point of the system, the thermal energy of heat storage system is neither to increase nor to reduce. When the DNI is less than 639 W / m^2, thermal energy of heat storage system is decreasing; when the DNI is greater than 639 W / m^2, thermal energy of heat storage system is increasing.

Acknowledgment

This work was supported by headquarters science and technology project of State Grid Corporation of China.

References

[1] Princiotta FT, Loughlin DH. Global climate change: the quantifiable sustainability challenge. J Air Waste Manage Assoc 2014;64:979–94.García Márquez, Gabriel. Love in the Time of Cholera. Translated by Edith Grossman. London: Cape, 1988.

[2] Su JF, Han W, Lin RM, et al. Tower type solar energy-based thermal power generation system with a two-stage heat storage and dual operating mode. Journal of Engineering for Thermal Energy & Power, 2009, 24(1): 132-137.

[3] Ranjan KR, Kaushik SC. Thermodynamic and economic feasibility of solar ponds for various thermal applications: a comprehensive review. Renewable Sustainable Energy Rev 2014;32:123–39.

[4] Gupta M K, Kaushik S C, Ranjan K R, et al. Thermodynamic performance evaluation of solar and other thermal power generation systems: A review. Renewable and Sustainable Energy Reviews, 2015, 50: 567-582.

[5] Srilakshmi G, Venkatesh V, Thirumalai N C, et al. Challenges and opportunities for Solar Tower technology in India. Renewable and Sustainable Energy Reviews, 2015, 45: 698-709.

