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Research Article

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Study of an Integrated Tower Solar Energy Combined Cycle System with the Simultaneous Integration Solar Energy with Top and Bottom Cycle

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Abstract

In this paper, based on a conventional integrated solar combined cycle system (ISCC), a novel integrated tower solar energy combined cycle system (ITSCC) with the simultaneous integration the solar energy with top and bottom cycle of combined cycle system is proposed. The system models are developed and different system performance evaluation indices are proposed. Then in the condition of the same solar radiation the thermal performance of new system is analyzed and compared with the reference ISCC system and gas-steam combined cycle (GTCC) system. Furthermore, the operating characteristics of the new system in the summer solstice are deeply investigated in consideration of the heat variation from direct solar radiation and the effect of the ambient temperature change on the solar collector system. The efficiency of solar energy utilization and the thermodynamic properties of different systems are analyzed. The result shows that, in the summer solstice the natural gas input of new system is less 3.28% than that of GTCC system and the net output power is increased by 1.5%, the solar-to-electric efficiency and the exergy efficiency can achieve 27.3% and 28.4%, respectively. In addition, the annual performance of new system is also better than that of the reference system.

Keywords: ISCC; Tower Solar Energy; Thermodynamic Performance Analysis; Energy Efficiency; Operation Characteristic

Introduction

Fossil fuels have played an important role in the world energy structure for a long time. But with the excessive consumption of fossil energy, the increasingly prominent environmental pollution problems have occurred. The solar energy has the largest reserves of renewable energy and its large-scale and efficient utilization has become the inevitable requirements of adjusting the world's energy structure and sustainable development. The independent solar energy power plants apply the lens of concentrating solar power (CSP) unit to reflect the sunlight and converge the lower energy density of solar energy together, which can heat the working medium (water or air) of the thermal cycle system, then the process of solar-to-electric conversion is completed [1]. The research and operational experiences of some built solar thermal power generation systems show that independent solar energy power plants have the low thermal efficiency and need to add the thermal storage unit, which will result in the relatively high construction cost, due to the limitations of the solar energy characteristics and working medium temperature [2].

The traditional integrated solar combined cycle system (ISCC) can improve the solar radiation-to-electricity conversion efficiency, save cost and reduce fossil fuel consumption by integrating the solar energy. Several ISCC plants have successfully operated in the world. For example, the world's first ISCC is the Iranian Yazd power plant (its installed capacity is 467 MW and net electric generation is 17 MW). Other ISCC systems are either under construction like Agua Prieta II power station or in the planning phase including Palmdale, Victorville 2, Abdaliya power station [3] etc. Now the technology of integrated solar combined cycle system (ISCC) has been applied around the world, and is developing toward the larger capacity and higher efficiency.

For the process of the sunlight to thermal energy conversion, the trough solar collector technology is the most mature at present and has the highest degree of commercial application, which has been adopted in several operated ISCC power stations. The tower solar collector technology is another kind of solar heat energy concentration way that can massively convert the solar radiation energy into the thermal energy, which may be widely used in the future. By adopting the central collector method both the collecting temperature and concentration ratio of the tower solar collector are higher than those of the trough solar collector technology. In this paper, the thermodynamic performance of the integrated tower solar gas-steam combined cycle (ITSCC) is mainly studied.

ITSCC system is currently in the stage of the theoretical research, and there are no real commercial operation examples. According to the integration location in ISCC systems the tower solar collectors can be classified into two types which are integration with Brayton cycle (gas turbine) and integration with Ranking cycle (heat recovery steam generator), respectively. The integration with Brayton cycle is to use the solar thermal energy to heat the high-pressure air of the compressor outlet and then the heated air flows into the combustion chamber and participates in the combustion reaction, by this way the natural gas input can be reduced because the combustion initial temperature is increased. The integration with the Rankine cycle is to use the solar thermal energy to heat the feed water or steam in the heat recovery steam generator (HRSG), which can improve the net output power of steam turbine. However, when the solar energy is integrated with the Rankine cycle, the selection of the type of solar energy heat-collection (trough type or tower solar collector) requires considering the amount of solar energy input in the ISCC system according to the reserve capacity of steam turbine. And it can be known that the over sizing of the steam turbine is 40 percent without effect on the normal operation of steam turbine, which may greatly limit the contribution rate of solar energy in the ISCC system [4-9]. However, heating the compressed air by using the solar energy only reduces the consumption of natural gas of gas turbine, which has little effect on the output powers of both gas turbine and steam turbine. Meanwhile, some researches indicate that the solar-to-electric efficiency of integrating the solar energy with Brayton cycle is higher than that of integrating the solar energy with Rankine cycle. Therefore, it can be considerable to integrate the solar thermal energy with Brayton cycle, which not only can improve the solar-to-electric efficiency, but also can reduce the consumption of natural gas.

As the major part of ISCC system is gas-steam combined cycle system and the solar collector system plays a complementary role. It has to require that the capacity of combined cycle is large enough, so that it can bear the fluctuations caused by the integrated solar energy. At present, the gas turbines applied in most of combined cycle power plants have a large output power and high efficiency, which can integrate with more solar thermal energy and make the integrated solar system achieve a higher solar-to-electric efficiency. Whereas, the compressed air at the compressor outlet of heavy duty gas turbine has a high temperature and a large mass flow (For example, the compressor outlet air temperature and mass flow rate of a typical F class gas turbine are 400 °C and 600kg/s, respectively), so the solar energy in some periods of a day cannot be adequately used. For the foregoing situation, it can be considered that both the technology and application of adopting the molten salt as the middle heat conduction media to directly heat the compressed air are not mature and the structure of heavy duty gas turbine is not suitable to be modified. This research proposes a novel integration case in which after the molten salt as the middle heat conduction media is used to heat the compressed air, there is a part of unused waste heat to be introduced into the heat recovery steam generator to heat and evaporate the high pressure feed water, At the same time, it can use the molten salt to collect solar energy with the low energy flow density for integration with the Rankine cycle. In this paper, the tower solar collector model is built by referring to the Gem solar power station and the new integrated tower solar combined cycle system, which integrates a PG9351FA gas turbine with a triple-pressure reheat heat recovery steam generator, is proposed and simulated with EBSILON and TRNSYS software. In the process of simulation, the operating conditions of the ISCC system will change according to the actual situation of DNI (Direct Normal Irradiance), ambient temperature and solar azimuth in the area of Dun Huang. And both the thermal characteristic and feasibility of the new system are deeply investigated by comparing with the GTCC system in terms of solar-to-electric efficiency, natural gas input and net power capacity.

Systems Descriptions

GTCC System without Integration with Solar Energy

Fig. 1 shows the flowchart of GTCC system without integration with solar energy. The GTCC system is composed of a PG9351FA gas turbine with a triple-pressure reheat HRSG. The air is compressed in the compressor, and burned with the natural gas in combustion chamber to generate the flue gas that flows into gas turbine to produce the electric power; meanwhile part of the compressed air is extracted to cool the turbine blades. The gas turbine exhaust gas with the temperature of 609 °C flows through the HRSG to heat the high pressure, intermediate pressure and low pressure feed water or steam. The feed waters with different pressure levels flow through economizers, evaporators, super heaters and reheaters, respectively, to produce the steams with different pressures to produce the electric power in steam turbine. In the end, the exhaust gas from the HRSG is discharged into the environment.

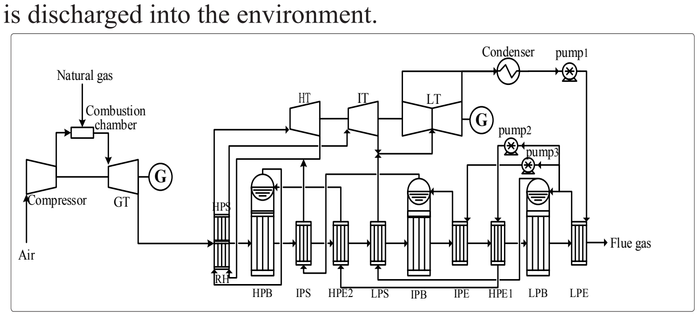


Figure 1: The flowchart of the GTCC system

The Novel ITSCC system (New system)

Fig. 2 shows the novel ITSCC system flowchart. The molten salt selected as the intermediate heat conduction media is heated by the solar energy for 2.5 hours between morning and afternoon when the DNI is relatively low, then the heated molten salt flows through valve 1 into the heat exchanger 2 and releases the thermal energy to part of the high pressure feed water from the HRSG to produce steam. After releasing the heat energy, the molten salt is pumped into the tank to continue to participate in cycle, and the acquired high pressure saturated steam is mixed with another part of high pressure saturated steam from the HRSG to participate in the thermal cycle. When the value of DNI is over 200 W/m^2 that is relatively high, the molten salt heated by the solar energy flows through the valve 2, heat exchanger 1, heat exchanger 2, respectively, to heat the compressed air and high pressure feed water. The heated compressed air flows into the combustion chamber to participate in the combustion, and the saturated high pressure steam returns into the HRSG to be heated to the superheated steam, and the molten salt is pumped into the molten salt tank to continue to participate in the cycle. In most of the time of one day, the tower solar energy system is mainly integrated with the top cycle (Brayton cycle) in the new system, only when the DNI is quite low, the solar energy and the waste heat of molten salt after heating the compressed air are integrated with the bottom cycle (Rankine cycle). Considering the characteristics of the integration of solar energy with both the Brayton cycle and the Rankine cycle, the new system proposed in this paper makes a more rational use of solar energy. When the solar energy is sufficient, after the molten salt flowing through the heat exchanger 1, it should make its outlet temperature unchanged, at this time the working condition of bottom cycle is not affected by the volatility of solar energy but can maintain a stable and safe state. Therefore, the system will further improve the net power generation capacity of ISCC system on the basis of saving the natural gas input, which also reduces the influence of solar energy input with large energy flow density on steam turbine operating conditions.

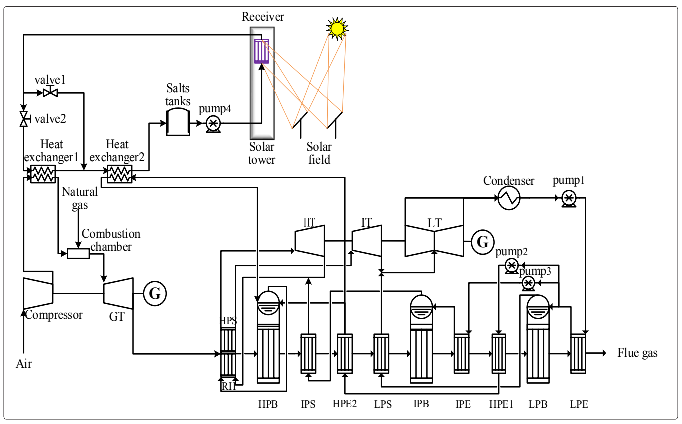


Figure 2: The flowchart of the new system (ITSCC)

The simulation of new system should follow the following several principles:

1. In order to ensure the normal operation of the system, the temperature of the molten salt after heating the compressed air does not exceed the maximum operating temperature (around 565 °C), so it needs to consider the maximum amount of the absorbed heat by the compressed air. According to the calculation, the maximum absorbed heat of the compressed air is about 85 MW, and when the molten salt reaches the maximum temperature, the mass flow of the molten salt cannot be over 360 kg/s.
2. When the DNI is less than 280 W/m^2, the temperature of molten salt should be kept at 414 °C. The molten salt is pumped into the bottom cycle to heat the high pressure saturated water, at this time the molten salt applies the variable flow operation mode. When the DNI is more than 280 W/m^2, the molten salt firstly heats the compressed air of the top cycle, then the waste heat is used to heat the high pressure saturated water, in this situation the mass flow of the molten salt remains constant.
3. The new system can realize the stable operation, by regulating the quantities of high pressure, intermediate pressure and low pressure feed water to maintain the pinch point temperature difference, the approach point temperature difference and the heat transfer temperature difference constant.

A traditional ISCC system (Reference system)

Fig.3 shows the flowchart of a traditional ISCC system used as the reference system in this paper. In this system, the solar energy is integrated with the high pressure evaporator (HPB). Its solar energy field is similar with that of the new system, and the molten salt with high temperature directly exchanges the heat with part of the high pressure saturated water extracted from HRSG. Compared with the new system, the difference of this reference system is that the solar energy is only utilized to heat the high pressure saturated water of the bottom cycle, and its integration temperature is fixed. The system operates normally by changing the mass flow of the molten salt.

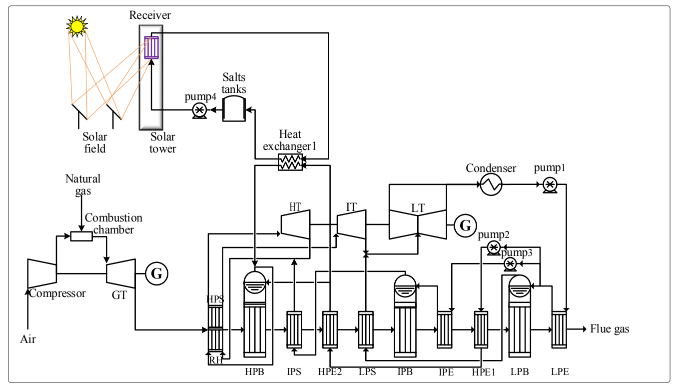


Figure 3: The flowchart of the reference system (ISCC)

ITSCC System Model

In this paper, the models of both the tower solar collector and gas-steam combined cycle are simulated with EBSILON software, and the meteorological data such as the solar irradiation, ambient temperature are acquired from the Trnsys studio.

The solar field model

The tower solar field layout refers to the Spanish Gemasolar independent solar energy power station (however, the new system doesn't have the heat storage system), which is the world's first large-scale solar power station with the molten salt to achieve all-day continuous power generation. The related parameters of the reference power station are shown in Table 1[10,11]. The net solar-to-electric conversion efficiency is about 16.6%. The solar field of the Gemasolar power station is large-scale, so it can receive the solar energy with the larger DNI value. Therefore, in the course of simulating the solar field, the amount of heliostats is 2060; the reflection area of lens is 237226 m^2.

Table 1: Solar field model design parameters

Solar field model	Gemasolar power station
The amount of heliostat	2650
The area of mirror (m^2)	306658
Received power (MW)	120
Net power generation (MW)	19.9
Molten salt component	60% $NaNO_3$ + 40% KNO_3
Molten salt working temperature (°C)	290-565
The height of tower(m)	140
The area of cylindrical receiver (m^2)	270
The angle of receiver (°C)	360
Concentration ratio	1136

In this paper, Dunhuang City, Gansu Province (east longitude 94.15°, latitude 40.13°) is selected as the geographical coordinates, and the day of summer solstice is selected as a typical day to simulate, and the relevant parameters are shown in Table 2.

Table 2: Gas turbine model design parameters

Gas turbine model	GE-PG9351FA
Rated ambient temperature(°C)	15
Natural gas input (kg/s)	14.08
Air mass flow rate (kg/s)	621.58
Cooling air ratio	0.21
Pressure ratio	15.4
Net power capacity (MW)	255.6
Compressed air temperature (°C)	404
Gas turbine initial temperature (°C)	1327
Fuel gas temperature (°C)	609.1
Gas turbine efficiency (%)	36.9

The simulation data such as DNI, ambient temperature (Ta) and other meteorological data can be obtained from the Trnsys Studio, including the solar radiation and other related data. The parameters of DNI need to be calculated according to the relevant mathematical model [12]. It is defined as follows:

$$DNI = \frac{GHI - DHI}{\cos(SZA)} \qquad (1)$$

Where, GHI refers to the global horizontal irradiance of solar energy, DHI refers to the diffuse horizontal irradiance of solar energy, both GHI and DHI have the same unit measurement (W/m^2), SZA refers to the solar zenith angle.

Fig.4 shows the variable DNI of the whole day of summer solstice in Dun Huang city, and Fig.5 shows the variable ambient temperatures.

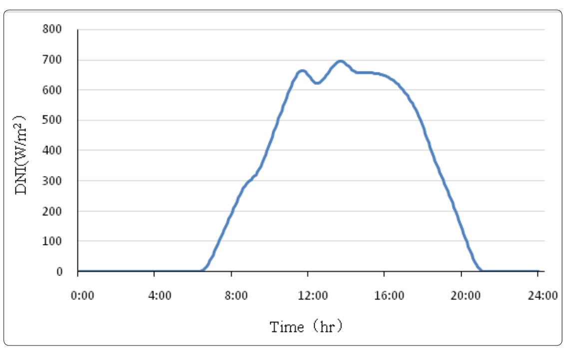


Figure 4: The flowchart of DNI variable trend in summer solstice

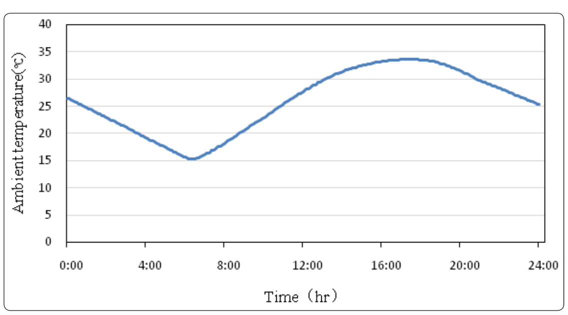


Figure 5: The ambient temperature variable trend in summer solstice

The Gas-Steam Combined Cycle (GTCC)

Gas Turbine Model

This paper builds the gas turbine model, and the related design parameters are shown in Table 2. When the tower solar energy is integrated with the Brayton cycle, the mass flow of the compressed air heated by the solar energy is 492 kg/s (404 °C) except for part of the air used for cooling the turbine blade. In the process of system simulation, the inlet air parameters of gas turbine keep unchanged, after integration with the solar energy, the initial temperature of the combustion gas before entering into gas turbine keeps at 1327 °C by adjusting the amount of natural gas inputted to the combustor in order to make the system operate normally.

HRSG Model

The triple-pressure reheat HRSG model is built in this paper, and the related design parameters are shown in Table 3. When the solar energy is integrated with the bottom cycle, part of the high pressure feed water is extracted from the HPE2 to be heated by the solar energy, after that they are pumped into the HPS to participate in thermal cycle. In this process, the mass flow of the extracted feed water in the inlet HPE2 is constantly variable, and the stable operation of the system is maintained by regulating the high pressure, intermediate pressure feed water flow to keep the pinch point temperature difference and the approach point temperature difference of HRSG unchanged.

Table 3: HRSG model design parameter

HRSG model	Triple pressure reheat
High pressure steam mass flow rate (kg/s)	73.38
High pressure steam inlet pressure (bar)	164.35
High pressure steam inlet temperature (°C)	564.82
High pressure cylinder isentropic efficiency (%)	87.5
Intermediate pressure steam mass flow rate (kg/s)	8.7
Intermediate pressure steam inlet pressure (bar)	34.5
Intermediate pressure steam inlet temperature (°C)	564.8
Intermediate pressure cylinder isentropic efficiency (%)	89.5
Low pressure steam mass flow rate (kg/s)	19.12
Low pressure steam inlet pressure (bar)	3.96
Low pressure steam inlet temperature (°C)	272.48
Low pressure cylinder isentropic efficiency (%)	89
Pinch point temperature difference (°C)	12
Approach temperature point (°C)	8
Hot temperature difference (°C)	45
Fuel gas temperature (°C)	86.08
Net power capacity (MW)	134.76

Fig.6 shows the flowchart of GTCC system simulation which is simulated with the Ebsilon professional software.

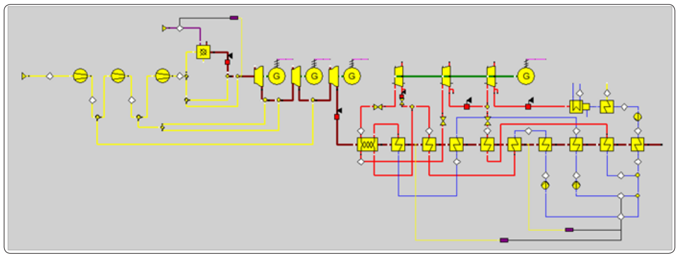


Figure 6: The flowchart of GTCC system simulation

Performance Analysis of the ITSCC System

In this section the performances of the ITSCC system are evaluated through both the energy and exergy analysis methods. The main evaluation indexes are as follows.

1) Net solar power generation $W_{Sol}\cdot net$:

$$W_{sol,net} = W_{net} - \frac{W_{GTCC} \times G_{f,ITSCC}}{G_{f,GTCC}} \quad (2)$$

Where, W_{net} denotes the net power generation of new system, kW; W_{GTCC} is the net power generation of GTCC system, kW; $G_{f,ITSSCC}$ and $G_{f,GTCC}$ are the fuel mass flow rates of new system and GTCC system, respectively, kg/s.

It is considered that the power consumption of the molten salt pump is part of the auxiliary power of the tower solar collector, and the net power generation calculation in the new system has been deducted from this part of the power consumption. As can be seen from the equation, when the solar energy is integrated with the bottom cycle, the net power generation of system increases and the input of natural gas are unchanged.

2) Net solar-to-electric efficiency $\eta Sol\cdot net$:

$$\eta_{Sol,net} = \frac{W_{Sol,net}}{DNI \times A_{area} \times N} \times 100\% \quad (3)$$

Where, DNI is the solar direct radiation intensity, W/m^2; A_{area} is the reflection area of a single reflector, m^2; N is the number of solar field reflectors.

3) Solar energy fractionα:

$$\alpha = \frac{W_{Sol,net}}{W_{net}} \times 100\% \quad (4)$$

4) Total net efficiency of the system η_{net} :

$$\eta_{net} = \frac{W_{net}}{DNI \times A_{area} \times N + G_{f,ITSCC} \times LHV_f} \times 100\% \quad (5)$$

Where, LHV_f refers to the lower heating value of natural gas, MJ/kg.

5) The exergy efficiency of solar-to-electric conversion $\eta_{Ex' Sol}$:

$$\eta_{Ex,Sol} = \frac{W_{Sol,net}}{DNI \times A_{area} \times N \times \psi} \times 100\% \quad (6)$$

Where, ψ is the energy grade of solar energy.

6) The equation of the energy grade of solar energy ψ is shown in following equation [13,14]:

$$\psi = 1 - \frac{4}{3} \times \frac{T_a}{T_s} + \frac{1}{3} \times \frac{T_a^4}{T_s^4} \quad (7)$$

Where, T_a is the ambient temperature, K; Ts is the solar surface temperature, and the value is 5770 K.

7) Total exergy efficiency of the system [14] $\eta Ex,net$:

$$\eta_{Ex,net} = \frac{W_{net}}{DNI \times A_{area} \times N \times \psi + Ex_f} \times 100\% \quad (8)$$

Where, Exf is the fuel exergy of natural gas, MJ/kg.

These above evaluation indexes changes with the change of the solar energy in the process of system simulation. They will be used to evaluate the overall performance of the new system.

Simulation Results and Performance Analysis

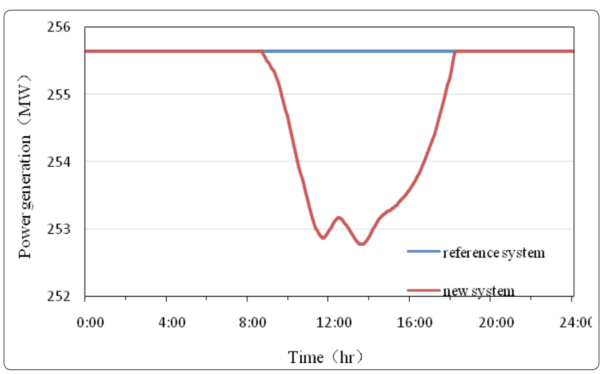
Simulation Results

This research takes five minutes as a time step to simulate a full-day operating condition of the new system and the reference ISCC system, with the enough consideration of the changes of DNI, solar azimuth angle and meteorological conditions. The variation rules of the output power, the amount of natural gas and the solar energy input are shown in Fig.7, Fig.8 and Fig.9, respectively. In addition, the fluctuating extremes of the thermal performance parameters over time for both the new system and the reference system are shown in Table 4.

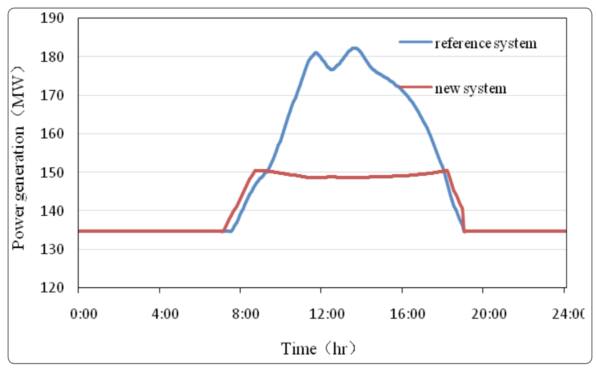
Table 4: The extremums of parameter fluctuations over time in the process of simulation

	GTCC system	The new system	Reference system
DNI (W/m²)	-	694	694
Ambient temperature (°C)	33.6	33.6	33.6
The top cycle power generation (MW)	255.6	252.9	255.6
The bottom cycle power generation (MW)	134.8	149.6	182.3
Total power generation (MW)	388.7	403.3	435.5
The compressed air temperature (°C)	404.7	522.8	404.7
Molten salt temperature before heat exchange (°C)	-	544.6	565
Molten salt temperature after heat exchange (°C)	-	361.8	361.8
High pressure saturated water temperature (°C)	-	349.8	349.8
Gas turbine flue gas temperature (°C)	609.1	606.7	609.1
Natural gas input (kg/s)	14.1	12.6	14.1
High pressure saturated water extraction (kg/s)	-	33.4	102.1
High pressure feed water (kg/s)	73.4	85.3	111.3
Saturated water mass flow rate of High pressure evaporator (kg/s)	73.4	51.4	9.0
The ratio of extraction water to high pressure feed water	-	0.39	0.92
Total feed water (kg/s)	101.2	109.5	128.6
The solar energy heat absorption of top cycle (MW)	-	63.6	-
The solar energy heat absorption of bottom cycle (MW)	-	29.4	92.8

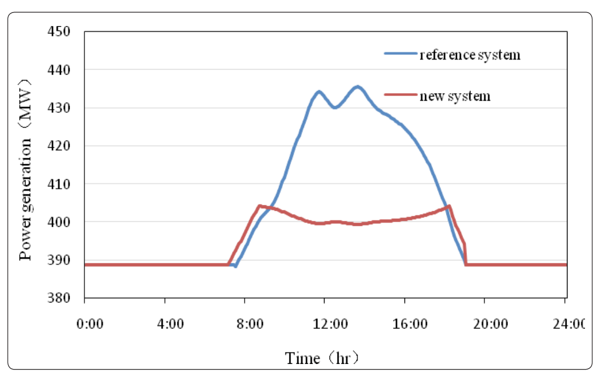
Fig.7 shows the top cycle, bottom cycle and total output powers of both the new system and the reference system. After the utilization of solar thermal energy, the new system has a significant decrease in the amount of output power generated by the top cycle(in the range of 0-1%) and the significant increase in the bottom cycle power generation (in the range of 0-11%) and an obvious increase of the total output power accordingly (in the range of 0-4%). For the reference system, because the solar thermal energy is fully integrated into the bottom cycle of the high-pressure evaporator, the power generation of the top cycle does not change. While the increasing range of power generation in the bottom cycle is very large (in the range of 0-35.3%), and its variation trend is similar with that of DNI. The capacity of the total power generation is basically the same as that of the bottom cycle power generation, and compared with the new system, the reference system can acquire more total power generation, but the change range of the output power generated by steam turbine has a great effect on the safety of the connected unit electric grid. Furthermore, the new system can utilize the solar energy with the lower energy flow density DNI, which can improve the solar energy utilization efficiency of system.



(a) The net power generation of top cycle



(b) The net power generation of bottom cycle



(c) Total power generation

Figure 7: The net power generation of new system and reference system comparison

Fig.8 shows the changes of the natural gas input quantities of both the new system and the reference system. It can be seen that different from the natural gas input unchanged in the reference system, the new system can save more natural gas fuel by using the solar energy. Taking into account of the changes in the total power generation, the new system can make the system net output power change more stable by reducing the amount of fuel, which may eliminate the impact of the frequently changed solar energy on the system.

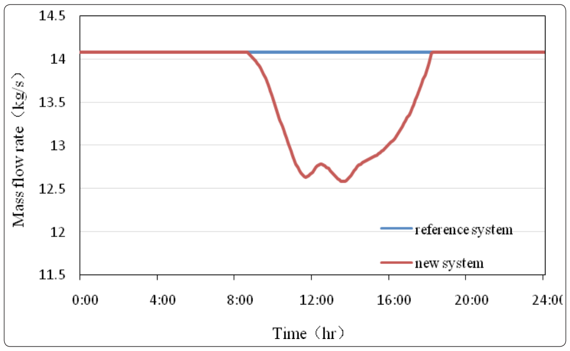


Figure 8: Natural gas input changing trend of new system and reference system over time

Fig.9 shows the solar heat load input changes of both the new system and the reference system. It shows the changes of solar heat input of top and bottom cycle of the new system compared with the reference system When the DNI meets the requirements, the solar heat energy entering the bottom cycle will remain unchanged, and the part beyond the required solar energy enters into the top cycle. When the bottom cycle achieves a stable condition, the solar energy input is 29.45 MW, and the maximum solar energy input entering the top cycle is 63.6 MW. The change trend of the absorbed solar heat entering into the bottom cycle in the reference system is consistent with that of DNI, the extreme value of heat input during this change is 92.8 MW. But in the reference system the solar heat energy integrated with the heat surface of HPB is too large and has an obvious fluctuation, which has the obvious effect on safety and stability operation of the bottom cycle system.

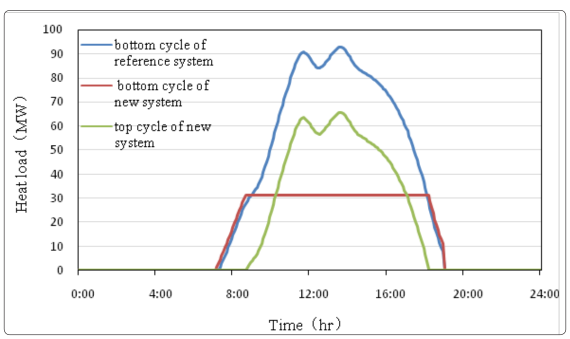


Figure 9: Solar heat input changing trend of new system and reference system over time

The Performance Analysis of Different Systems

According to the new system performance evaluation indices and the new system simulation results, the performances of both the new system and the reference system in the different times of a day can be evaluated. The variation rules over time of the specific evaluation indices, which include the solar net power generation, the solar power fraction, the net efficiency and energy efficiency of solar-to-electric conversion, are shown in Fig.10, Fig.11, Fig.12, and Fig.13, Fig.14. Table 5 shows the extremes of parameter fluctuations over time for both the new system and the reference system. The related performance indices of both the new system and the reference system in the day of summer solstice are shown in Table 6, including the natural gas input, power generation, net efficiency and energy efficiency of solar-to-electric conversion and system and so on.

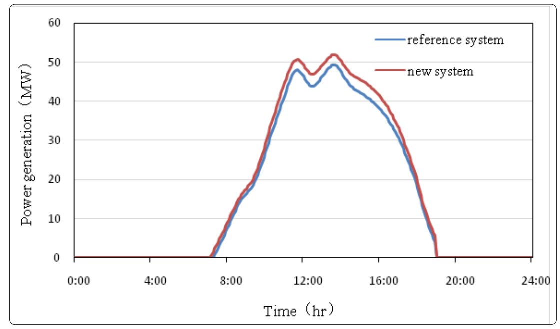


Figure 10: Solar net power generation changing trend of new system and reference system over time

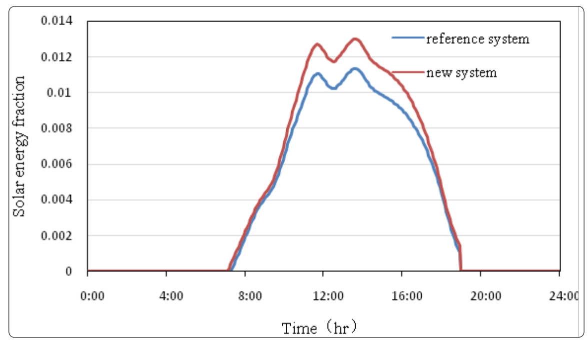
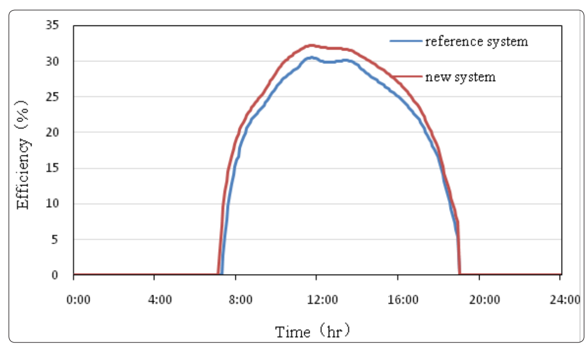
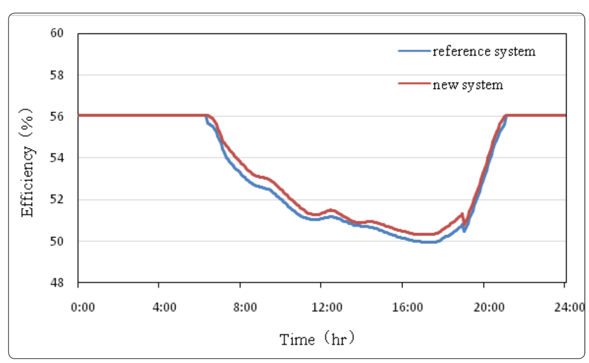


Figure 11: Solar energy fraction changing trend of new system and reference system overtime

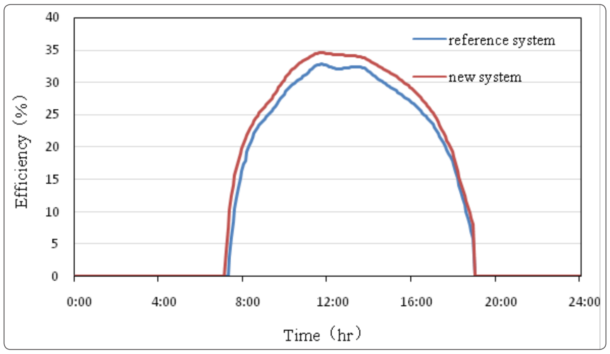


(a) Solar -to-electric net efficiency

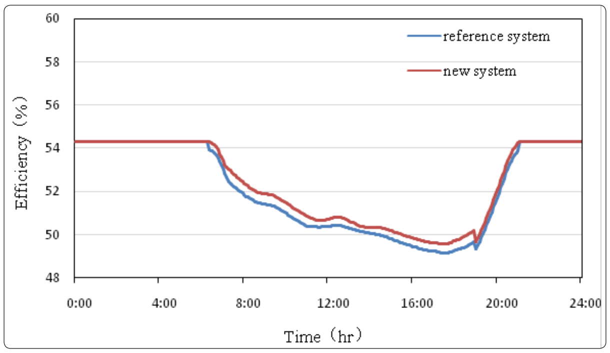


(b) System net efficiency

Figure 12: System net efficiency changing trend of new system and reference system overtime

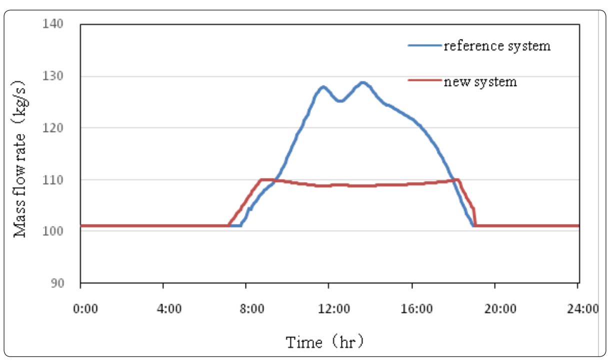


(a) Solar-to-electric exergy efficiency

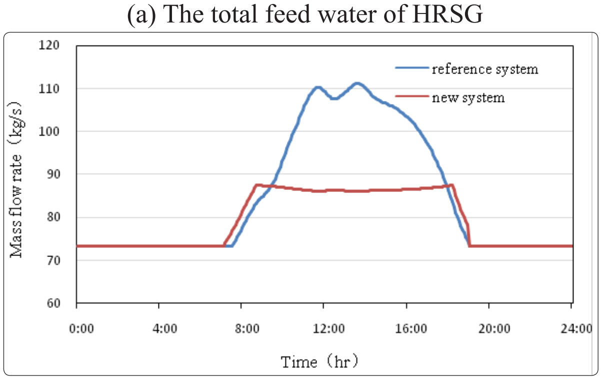


(b) System exergy efficiency

Figure 13: Exergy efficiency changing trend of new system and reference system over time



(a) The total feed water of HRSG



(b) The high pressure feed water

Figure 14: The feeding water mass flow rate changing trend of new system and reference system over time

Table 5: The analysis indexes in the day of summer solstice

	GTCC system	New system	Reference system
Solar net power generation (MW)	-	51.84	49.38
Solar power fraction (%)	-	13.0	11.3
Solar -to-electric net efficiency (%)	-	32.2	30.6
Net efficiency (%)	56.0	50.4	50.0
Solar-to-electric exergy efficiency (%)	-	34.6	32.8
Exergy efficiency (%)	54.3	49.7	49.2

Table 6: The thermal parameters in the day of summer solstice

Parameter	GTCC system	The new system	Reference system
Natural gas input quantity (kg)	1.22×10^6	1.18×10^6	1.22×10^6
Total power generation (MW•h)	9.33×10^3	9.47×10^3	9.63×10^3
Solar net power generation (MW•h)	-	391.75	363.54
Solar power fraction (%)	-	4.14	3.76
Solar-to-electric net efficiency (%)	-	27.3	25.4
Solar-to-electric exergy efficiency (%)	-	28.4	26.6
Net efficiency(%)	56.0	53.7	53.3
Exergy efficiency(%)	54.3	52.4	52.0

According to the variable performance indices above in one day, whatever from the perspective of solar energy utilization or the overall energy utilization of the system, the performance evaluation indices of the new system are higher than those of the reference ISCC system. And on the basis of the variable situation of performance indices above, the variation trend of new system is consistent of that of the reference system. The DNI value reaches 664 W/m^2 at 11:40 when the ambient temperature is 27 °C. It is the time that the solar energy has the maximums of both the solar light-to-electricity efficiency and exergy efficiency. At 13:40, DNI value reaches the maximum at 694 W/m^2 when the ambient temperature is 30 °C. It is the time that both the solar net power generation and the solar power fraction are the largest. When the DNI value is 546 W/m^2 and the ambient temperature is 33.6 °C. It is the time that system has the minimums of both the net energy and exergy efficiency, and the performances of both the new system and the reference system are less than those of the GTCC system.

As shown in Table 6, the total natural gas input of the new system reduces by 3.3% compared to that of the GTCC system and the reference system during the day of summer solstice, and the total net solar power generation, solar power fraction, the net efficiency and exergy efficiency of the light-to-electrical conversion process of the new system are also greater than those of the reference ISCC system. However, because the integration of solar energy with the top cycle results in the reduced natural gas input, the total power generation of system is less than that of the reference system ISCC. In terms of the total energy utilization, though the net efficiencies and exergy efficiencies of both the new system and reference system are less than those of GTCC system, the efficiency of energy utilization rate of the new system is still greater than that of the reference system, and its net efficiency and exergy efficiency are 0.4 percent higher than those of reference system.

When the solar energy is integrated into the HRSG, in addition to the utilization efficiency and working ability of solar energy, it should be also considered the effects of the solar energy integration with system on both the operational condition of HRSG and steam turbine. The integration of solar energy with the bottom cycle mainly has a great effect on the mass flow rates of feed water with different pressure levels, which may result in steam turbine divagating its rated condition and influence the safety of system operation. Because both the new system and the reference system are integrated into the high-pressure steam (feed water) side, this paper only analyzes both the feeding water mass flow rate and the total amount of water, and their mass flow rate variations are shown in Fig.12. The variation trends of both the total feed water flow and high pressure feed water flow in the reference system are basically the same as that of DNI, but its variable ranges of mass flow rate are increased by 27.4% and 51.6% respectively compared with the GTCC system, which seriously influences the steam turbine operating conditions, and even exceeds the margin of steam turbine capacity. Compared with the reference system, the solar energy is integrated into both the top cycle and the bottom cycle at the same time when the solar energy has a high energy density. At the time of integration with the top cycle, the feeding water mass flow rate of the bottom cycle is relatively stable and has little effect on the steam turbine. Especially when the mass flow rates of both the total feed water and high pressure feed water reach their peak value which are respectively increased by 8.2% and 16.2%, the new system can still operate safely. In addition, the amount of solar energy utilized by the reference system is close to the limited value and may even exceed the capacity limit. But the new system selects two heating surfaces as the integration locations, the solar thermal energy can be integrated with both the top cycle and the bottom cycle, more solar energy as an energy input can be used, which remarkably improves the integration potential of the GTCC system.

In addition, this paper takes an hour as a time step for both the new system and reference system to simulate working condition of the entire year of 8760 hours in Dunhuang area. Fig.15 shows the DNI distribution of the whole year in Dunhuang area. The detailed simulation results of annual condition are shown in Table 7. It can be seen that the new system has higher thermal performance than the reference system, which reflects the thermal performance advantages of the new system, except that the total power generation is slightly lower than that of the reference system.

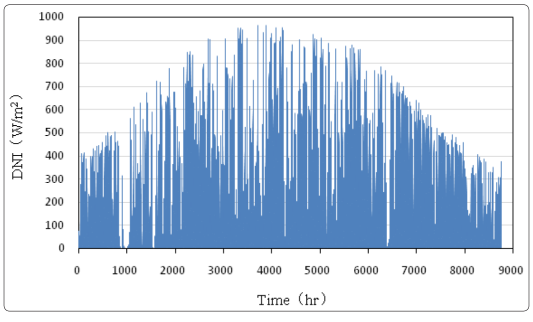


Figure 15:.Annual DNI variation in Dunhuang area

Table 7: Annual thermal performance parameters of the new system

Parameter	GTCC system	The new system	Reference system
Natural gas input quantity (kg)	4.44×108	4.39×108	4.44×108
Total power generation (MW•h)	3.41×106	3.43×106	3.47×106
Solar net power generation (MW•h)	-	7.17×104	6.75×104
Solar power fraction(%)	-	2.09	1.94
Solar-to-electric net efficiency (%)	-	25.1	23.6
Solar-to-electric exergy efficiency (%)	-	26.2	24.7
Net efficiency (%)	56.0	54.8	54.5
Exergy efficiency (%)	54.3	53.3	52.9

Conclusion

In this paper, a novel integrated tower solar combined cycle system based on GTCC system is proposed. The operational condition of the novel system in the day of summer solstice is simulated with Ebsilon Professional, and the relevant thermal performance parameter indices are acquired and compared with those of the GTCC system.

Results show that the solar energy will contribute 4.14% of net power to the new system in the day of summer solstice, and the total output power of the new system markedly improves 1.5 percent. Meanwhile, the solar heat to electricity efficiency in within the new system is markedly improved comparing with the independent solar energy power plants.

While the net energy efficiency (53.7%) and exergy efficiency (52.4%) of the new system are less than those of GTCC system, which are respectively decreased by 2.3% and 1.9% because the reduced efficiency in the conversion of solar radiation into heat causes less heat into the combined cycle to participate in thermal cycle. The traditional ISCC system used as the reference system in this paper, has higher total power generation than the new system in the same condition of solar radiation, however its solar net power generation and energy utilization efficiency are quite less than those of the new system.

In a conclusion, the integration solar energy with GTCC system can not only save the natural gas input but also increase the power generation, and improve the solar energy utilization efficiency. More solar energy can be integrated with the bottom cycle so as to improve the integration potential of introducing solar energy into combined cycle. At the same time, for the new system, due to that the solar heat input into bottom cycle is consistent, the bottom cycle system is less fluctuation after the integration with solar energy, but for the traditional ISCC system, the solar energy is only integrated into the heat surface of HPB, which can cause the large fluctuation of system operation effected by the solar energy. What's more, the economic advantage and the feasibility of the engineering construction of new system should be further analyzed in the future.

Acknowledgments
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Nomenclature
A: area, m^2
Aare: The Reflection Area of a Single Reflector, m^2
CSP: Concentrating Solar Power
DHI: Diffuse Horizontal Irradiance
DNI: Direct Normal Irradiance
GHI: Global Horizontal Irradiance
Exf: The Fuel Exergy of Natural Gas, MJ/Kg
$G_{f,GTCC}$: The Gas Mass Flow Rates of GTCC System, kg/s
$G_{f,ITSCC}$: The Gas Mass Flow Rates of ITSCC system, kg/s

GT: Gas Turbine
GTCC: Gas Turbine Combined Cycle
HPB: High Pressure Evaporator
*HPE*1: High Pressure Economizer1
*HPE*2: High Pressure Economizer2
HPS: High Pressure Super Heater
HRSG: Heat Recovery Steam Generator
HT: High Pressure Steam Turbine
IPS: Intermediate Pressure Super Heater
IPB: Intermediate Pressure Evaporator
IPE: Intermediate Pressure Economizer
ISCC: Integrated Solar Combined Cycle
IT: Intermediate Pressure Steam Turbine
ITSCC: Integrated Tower Solar Energy Combined Cycle
LHVf: Low Heating Value of Fuel, MJ/kg
LPB: Low Pressure Evaporator
LPE: Low Pressure Economizer
LPS: Low Pressure Super Heater
LT: Low Pressure Steam Turbine
N: The Number Of Solar Field Reflectors
RH: Re Heater
SZA: Solar Zenith Angle
T: Temperature
T_a: Ambient Temperature
T_s: The Solar Surface Temperature, K;
W: The Net Power Generation
W_{GTCC}: The Net Power Generation of GTCC System, MW
W_{net}: The Net Power Generation of New System, MW
$W_{Sol\cdot net}$: The Net Solar Power Generation, MW

Greek symbols
α Solar Energy Fraction
η Efficiency, %
ψ The Energy Grade of Solar Energy

Subscripts
a Ambient
area Reflection Area
Ex Exergy
f The Gas Fuel
GTCC Gas Turbine Combined Cycle
ITSCC Integrated Tower Solar Energy Combined Cycle
net Net Power (Efficiency)
s Solar Surface
Sol Solar

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