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ScienceDirect
Energy Procedia 75 (2015) 540 – 546
Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

Performance analysis of a novel cascade integrated solar combined cycle system

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Abstract

This paper proposed a novel cascade integrated solar combined cycle system, in which concentration solar collector (e.g. parabolic troughs) as direct steam generator and non-concentration collector (e.g. evacuated tubes) are hybrid with combined cycle power plant. Cascaded integration of solar into the combined cycle is achieved in the proposed system. This study analyzes the thermodynamic and economic performance as well as energy conversion characteristics of the proposed hybrid system. The result indicates that the low-cost and high-efficiency solar heat-to-power conversions for this hybrid system are achieved.

Keywords: cascade integrated solar combined cycle system; direct steam generator; evacuated tubes; performance analysis;

1. Introduction

Solar energy is considered to be a promising energy due to its infinite reserves and cleanness nature. It may be one of the most effective routes to solve the three significant issues of energy shortage, environment pollution and greenhouse effect caused by exploitation and utilization of fossil fuels. However, due to the drawbacks of solar energy such as instability, intermission and low energy density, solar-only thermal technology is low in solar-to-power efficiency, high investment costs and so on. To improve the thermodynamic and economic performances of the conventional solar-only thermal power systems, solar energy is integrated to a combined cycle in several ways to decrease the fossil fuel consumption and emissions[1-2]. This is accomplished in an integrated solar combined cycle (ISCC) system.

Integrated solar combined cycle (ISCC) systems coupling with direct steam generation (DSG) technology are considered a very promising alternative to the solar-only power generation systems. Conventional ISCC systems with direct steam generation (DSG) have only one-stage solar input, leading to low solar input and poor performance under design and off-design conditions. The two-stage ISCC-DSG system which consisted of two DSG solar fields with different working temperature was proposed

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Peer-review under responsibility of Applied Energy Innovation Institute
doi:10.1016/j.egypro.2015.07.449

[3]. The two-stage DSG solar fields were put into the combined cycle power plant, which have different pressure levels, to replace two-stage evaporators to vaporize feedwatwer.

Based on the two-stage ISCC-DSG system, in order to further reduce the cost, a cascade integrated solar combined cycle system is proposed in this paper. The key feature of the proposed system is the non-concentrated solar collectors are used to supply (solar) heat to lower stage turbine while the concentration collectors are used for higher stage of turbines. Figure 1 shows the schematic diagram of a cascade ISCC system with a non-concentration evacuated tube collector field and a concentration DSG solar field. As shown in Fig.1, concentration DSG solar fields can take place of high pressure evaporator to generate saturated steam at high temperature and pressure while evacuated tube collectors replace low pressure evaporator to generate saturated steam at low temperature and pressure. Compared with concentration solar collectors, non-concentration solar collector could collect total solar radiation (both direct and diffuse radiation), costs less and requires less area of land. The new system is expected to achieve a better thermal and economic performance with the low-cost and high-efficiency solar heat-to-power conversion.

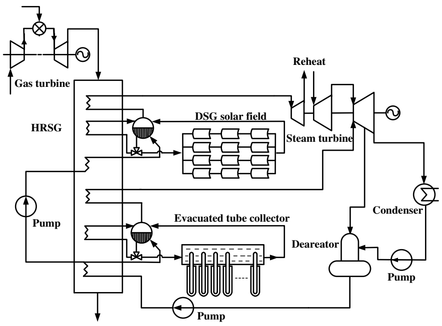

Fig. 1. Schematic diagram of the proposed cascade ISCC system

2. The thermal output from a non-concentration solar field

Thermal output from a non-concentration solar field depends on the solar radiation input and field's structure parameters (i.e. array pitch and inclination angle). It is assumed that there is an area of land 360,000 m^2 (600m×600m), which is located at 34°S (latitude) and 138°E (longitude), near Adelaide, South Australia. The land is used to install concentration collectors (i.e. PT collectors) or non-concentration collectors (i.e. ET collectors) for integrated solar combined cycle system purposes. One ET collector unit is made of 8 evacuated tubes (length of 2 m, width of 1.085 m), and generates useful solar heat at 150°C. The total annual solar heat absorbed is calculated by Bird Clear Sky process simulation software, which is exploited by US Renewable Resource Data Centre (RReDC).

Figure 2 exhibits the effect of inclination angle on the annual absorbed solar heat per unit area for the first row of collectors. The annual absorbed solar heat per unit area can reach the peak value when the inclination angle is 33°. Considering the shading by the front array, the annual absorbed solar heat for rows behind, if assuming they were set at the same angle as the first row, is influenced by the array pitch. Figure 3 presents the effect of inclination angle on the annual absorbed solar heat when the array pitch is different. Shading factor is calculated using the method in [our new Applied Thermal Eng paper]. When the array pitch ranges from 1.5m to 4m, the maximum annual absorbed solar heat can be obtained as the inclination angle is 42°, 32°, 17°, 4°, respectively.

Figure 4 shows the annual absorbed solar heat and the annual average solar collector efficiency as functions of the array pitch for ET collectors. The annual average solar collector efficiency is defined as annual absorbed solar heat divided by annual solar radiation that reaches the solar field. The annual absorbed solar heat and the annual average solar collector efficiency first increase then decrease with the increase of array pitch. When the array pitch is 3m, the maximize values (4289.63MJ/m^2, 53.3%) are achieved.

In conclusion, for the first row of collectors, the annual absorbed solar can reach the peak value (4584.3 MJ/m^2) when the inclination angle is 33°; for the rows behind of collectors, as the array pitch of 3m and the inclination angle of 17°, the maximum annual absorbed solar heat (4289.63MJ/m^2) can be obtained.

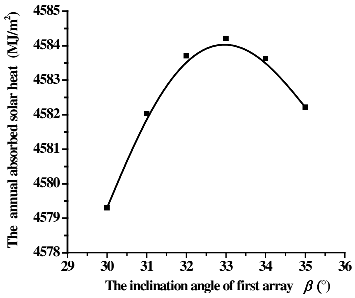

Fig. 2. Effect of inclination angle on the annual absorbed solar heat for the first array of collectors

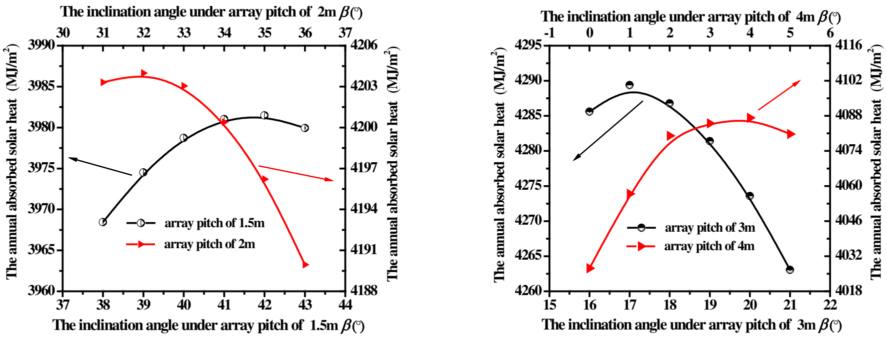

Fig. 3. Effect of inclination angle on the annual absorbed solar heat under different array pitch

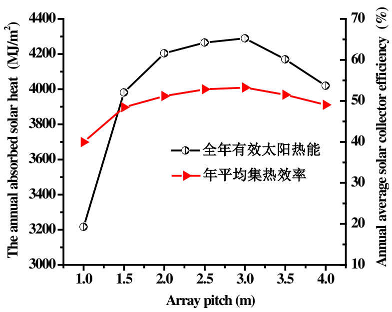

Fig. 4. Effect of array pitch on the annual absorbed solar heat and the annual average solar collector efficiency

3. Thermal performance analysis

3.1. Main assumptions

The cascade system to be analysed is a reference combined cycle gas turbine (CCGT) into which a DSG solar field of ET-150 (Euro trough collectors) and an evacuated tube collectors field introduced to supply latent heat for feedwater vaporization, as shown in Fig.1. The reference CCGT plant consists of a General Electric 7FA gas turbine, a dual-pressure, single reheat steam turbine and heat recovery steam generator (HRSG). The proposed cascade ISCC system is simulated by using the ASPEN PLUS code. The *DNI* of the design point is set to be 800W/m^2. The main technical parameters for the collector loop and assumptions for the simulation are given in reference [3].

3.2. Performance analysis and comparison

Table 1 presents the performances of the simulated cascade ISCC system, a conventional ISCC system with one-stage solar heat input and a reference CCGT system for comparison purposes. As shown in Table 1, for the proposed cascade ISCC system, solar heat input is higher than that in the conventional ISCC system, leading to a significant increase in net power output, so as to result to a thermal efficiency of 53.4%. Compared with the reference CCGT system for generating the same electricity, the fossil fuel saving ratio in the new ISCC system is 23.6%, 3.4%-points higher than that in the one-stage ISCC system.

The net solar-to-electricity efficiency is found to be 30.8%, higher than that in the one-stage ISCC system by 2.2%-points. From the second law point of view, the exergy efficiency of the cascade ISCC system is 60.9%, higher than that in the one-stage ISCC and CCGT systems by 4.3% and 12.2%, respectively. As the fuel based electricity efficiency is based on the fossil fuel input only, its value increases up to 74%.

It has been found that the use of different type of solar collectors would be resulting in upgrading low-grade solar thermal energy, reduction of irreversibility in cascade utilization and better thermal match in the heat recovery steam generator (HRSG). The cascade integrated solar combined cycle system takes advantages of both the high-efficiency heat-to-power conversion in the combined cycle gas turbine and the improvement of thermal performance.

Table 1. Thermal performances of the cascade ISCC system and reference systems

Parameters	Cascade ISCC	One-stage ISCC	CCGT
Natural gas exergy input, E_f (MW)	830.2	830.2	830.2
Solar heat input, Q_{sol} (MW)	309.1	249.3	-
Solar thermal share, X_{sol} (%)	27.8	23.7	-
Solar-to-electricity efficiency, η_{sol} (%)	30.8	28.6	-
Fossil fuel saving ratio, SR_f (%)	23.6	20.2	-
Net power output, W_{net} (MW)	594	568.7	453.7
Fuel based electricity efficiency, η_f (%)	74	70.8	56.5
System thermal efficiency, η_{th} (%)	53.4	54.1	56.5
Steam cycle thermal efficiency, η_{steam} (%)	40	38.8	37.1
System exergy efficiency, η_e (%)	60.9	58.4	54.3

4. Economic analysis

An economic analysis has been carried out to estimate the levelized cost of electricity (*LEC*) and payback period (*PBP*) of the proposed cascade ISCC system.

The levelized cost of electricity is calculated by:

$$LEC = \frac{fcr \cdot C_{TPC} + C_{O\&M} + C_{fuel}}{E_{net}} \tag{1}$$

where E_{net} is the annual net electricity; $fcr \cdot C_{TPC}$ represents the average annual investment, *fcr* is the average annual investment coefficient, *fcr* is calculated by:

$$fcr = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} = 8.88\% \tag{2}$$

where *i* is the interest rate(8%)，*n* is plant lifetime, assumed to be 30 years.

The payback period is the time by which the current value of all the income is equal to total plant cost:

$$R \cdot [(1+i)^{PBP} - 1] / [i \cdot (1+i)^{PBP}] = C_{TPC} \tag{3}$$

All the parameters and data used in the economic analysis are set according to several references [1, 4-6]. Table 2 shows the results of this economic analysis. We can conclude that: The total plant cost is 482.9 (10^6 \$), specific investment is 816 (\$/kW) , with a solar thermal share of 27.8%, the *LEC* is 0.06

$/kWh and the *PBP* is 5.5 year. The results show that the novel cascade ISCC system is economically superior to the conventional ISCC system.

Table 2. Economic analysis results of the cascade ISCC system

Parameters	Value
Net power output, W_{net} (MW)	594
Plant capacity factor (%)	77.4
Annual electricity production (10^6 kWh)	4023
Annual solar thermal energy input (10^6 kWh)	549.7
Annual fuel consumption (10^6 kWh)	7012
Total plant cost, C_{TPC} (10^6 \$)	482.9
Specific investment ($/kW)	816
Average annual investment, $fcr \cdot C_{TPC}$ (10^6 \$)	42.8
Annual operation and maintenance costs, $C_{O\&M}$ (10^6 \$)	19.2
Annual fuel costs, C_{fuel} (10^6 \$)	191.8
LEC ($/kWh)	0.06
PBP (year)	5.5

5. Conclusions

This paper proposed a cascade integrated solar combined cycle system which integrates concentration and non-concentration DSG technologies with combined cycle power plant at different energy levels. The novel system realizes cascade complementary between different temperature level of solar heat and combined cycle gas turbine, and provides a new way of solar energy and fossil fuel complementary utilization. The optimization of structure parameters for the evacuated tube solar fields was carried out. Thermal and economic performances of the whole system are analysed. The study shows that:

(1) For the first row of (non-concentration) collectors, the annual absorbed solar can reach the peak value (4584.3 MJ/m^2) when the inclination angle is 33^o; for the later arrays of collectors, as the array pitch of 3m and the inclination angle of 17^o, the maximum annual absorbed solar heat (4289.63MJ/m^2) can be obtained.

(2) Thermal performance analysis shows that the exergy efficiency of the cascade ISCC system is 60.9%, higher than that in the one-stage ISCC and CCGT systems by 4.3% and 12.2%, respectively. The fuel based electricity efficiency is up to 74%, higher than that in the one-stage ISCC and CCGT systems by 4.5% and 31%, respectively.

(3)As can be observed in economic analysis: The total plant cost is 482.9 (10^6 \$), the *LEC* is 0.06 $/kWh and the *PBP* is 5.5 year. The results show that the novel cascade ISCC system is economically superior to the conventional ISCC system.

Acknowledgements

The authors gratefully acknowledge the support of the National Natural Science Foundation of China (No. 51406049).

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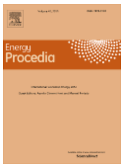

Biography

Yuanyuan Li, a doctor in Engineering Thermophysics. She holds her doctor degree from Institute of Engineering Thermophysics, Chinese Academy of Science (CAS) (Ph.D supervisor: Prof. Ruixian Cai, Academician of CAS). Yuanyuan Li mainly researches in solar and fossil fuel hybrid system integration.