Solar-Coal Hybrid Thermal Power Generation —an Efficient Way to Use Solar Energy in China

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Abstract- **To solve the problem of high initial investment and low thermal performance for solar alone thermal power plant, solar/fossil fuels hybrid power system has become a trend of solar thermal power generation in recent years. China is rich in coal and solar energy. At present, coal is the main resource in generating electricity in China. Therefore, solar integrated with conventional coal-fired power generation cycles is considered the best way in China. As an option for easy operation and control flexibility, solar aided feedwater heating of a coal-fired power generation system is discussed and analyzed in this paper. Compared to the common hybrid power system, the main feature of this generation system is, the thermal oil carrying solar energy replaces the extraction steam to heat the feed water and the steam thus saved can continue to do work. Because the solar heat does not enter the turbine, the efficiency (of solar to power) is not limited by the temperature of the solar heat. The performance of the integrated system with different replacements is analyzed based on an example and the impact of solar collector areas and DNI (direct normal irradiation) on the performance of the generation system is discussed as well. The results show that the new integrated system not only contributes to increasing the efficiency of the conventional power station and reducing its emission of greenhouse gases, but also increases the efficiency of solar to electricity; further LEC is also reduced considerably compared with solar only thermal power system. However, the results also indicate that the replacement type, solar collector areas and DNI have great influence on the generation system.**

Keywords- Solar Energy; Coal-Fired Thermal Power Generation; Hybrid; Performance

I. INTRODUCTION

Nowadays, electricity is mainly generated by consuming fossil fuel, which has serious negative impacts on our environment. As a clean, free and non-depleting source, solar thermal power is receiving more and more attention. Since solar energy has relatively low intensity, instability and periodicity, generally speaking, its utilization is costly. In order to make use of solar energy more effectively, many solutions of solar and fossil fuel hybrid power generation system have been put forward by scholars [1-5]. Studies on solar integrated with coal-fired conventional power plant still stay on the stage of the design of integration [5-10].

China is rich in coal and solar energy. At present, coal is the main resource in generating electricity in China. Therefore, solar power integrated with conventional coal-fired power generation cycles is considered the best way in China.

Solar energy has been proposed with various utilizations in conventional steam power plants like feedwater heating, superheating/reheating of steam and air preheating [5-10]. In these combined approaches, as an option for easy operation and control flexibility, solar aided feedwater heating of a coal-fired power generation system is discussed in this paper. In the integrated system, thermal oil carrying solar energy replaces the extraction steam to heat the feed water and the steam thus saved can continue to generate work. Comparing to the existing systems, the new integrated system reduces exergy losses in regenerative heater and achieves energy cascade utilization.

II. THE MODE OF SOLAR-COAL HYBRID THERMAL POWER GENERATION SYSTEM

In both solar thermal power system and conventional power system, heat is always taken as the energy carrier. In the integrated system, the subsystems of solar collectors and conventional coal-fired power generation are coupled by heat. In the conventional coal-fired power system, the endothermic process of working fluid water can be divided into three stages: preheated, vaporized and superheated, and its temperature ranges from tens degree to hundreds of degree. This provides a very diverse way for the integration of solar energy and convention power system. Among the numerous integrations, applying the thermal oil carrying solar energy in regenerative system of convention coal fired power station is relatively easy and feasible. In conventional power system, in order to reduce the temperature difference of boiler heat absorption and heat transfer, the extraction steam is normally used to preheat feed water entering the boiler, which has a large sum of exergy loss. To reduce the exergy loss, the thermal oil carrying solar energy replaces the extraction steam to heat the feed water and the steam thus saved can continue to generate work.

Fig.1 is a schematic diagram of the integrated system, in which the replacement type can be adjusted. The working temperature of oil depends on the temperature of the feed water, which is heated commonly at a lower temperature than that heated in solar only thermal power system. The feed water is heated in the oil-water exchanger by thermal oil carrying solar energy. Owing to the instability of solar energy, the heat energy collected by the solar field is also instable. Therefore, the control system needs to adjust the flow rate of feed water to match the heat collected by the solar field and thus to make the output temperature of feed water meet the design requirements.

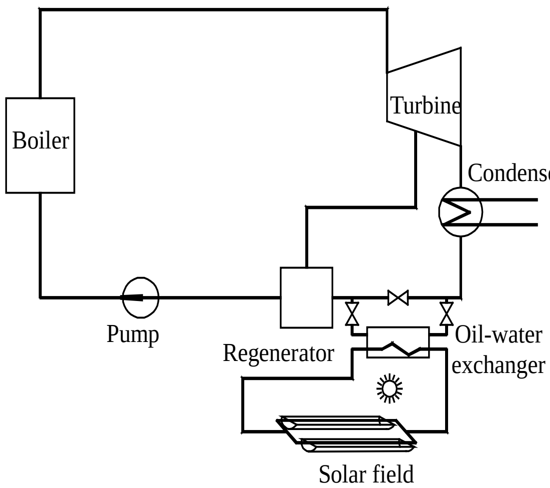

Fig. 1 A schematic diagram of the solar-coal hybrid thermal power generation system

III. ANALYSIS OF THE HYBRID POWER GENERATION SYSTEM

A. Solar Field

In this paper, the solar field model is based on a steady state. The heat capacity of the heat transfer fluid, absorbing tubes and connecting pipes are neglected. LS-2 parabolic trough collectors are chosen for this solar field. The thermal output of a solar field depends on the absorbed solar radiation incident on the collector reduced by the losses of the solar field. The direct normal irradiance (DNI) projected on the collector area can be expressed by:

$$Q_{Ld} = xI_{b,n}\cos\theta_i \cdot A_c \tag{1}$$

Solar radiation absorbed by the receiver tubes can be expressed as follows:

$$Q_{absorbed} = Q_{Ld} \cdot k \cdot \eta_0 \tag{2}$$

Where, k is the incidence angle modifier. It can be calculated with the angle of incident θ_i in degrees and two empirical constants c_1 and c_2 [1].

$$k = \max\left(1 - c_1 \cdot \frac{\theta_i}{\cos\theta_i} - c_2 \cdot \frac{\theta_i^{\,2}}{\cos\theta_i}, 0\right) \tag{3}$$

η_0 is the solar field efficiency considering the losses due to optics and imperfections. According to the literature [12-13] η_0=0.7133 including cleanliness correction factors.

The heat losses of the solar field include two parts: the absorbing tube heat losses and piping system heat losses. Both of them can be obtained from the corresponding empirical formula. For absorbing tube heat loss per unit aperture area, it can be calculated with the following the empirical formula [12].

$$Q_{loss,HCE} = \frac{a_0(T_0 - T_i) + \frac{a_1(T^2{}_0 - T^2{}_i)}{2} + \frac{a_2(T^3{}_0 - T^3{}_i)}{3} + \frac{a_3(T^4{}_0 - T^4{}_i)}{4} + I_{b,n}[b_0(T_0 - T_i) + \frac{b_1(T^3{}_0 - T^3{}_i)}{3}]}{(T_0 - T_i)W} \tag{4}$$

The empirical constants $a_0, a_1, a_2, a_3, b_0, b_1$ have been determined during collector tests[2].

For the heat loss of piping per unit aperture area, it is accounted for by the following empirical equation [12]:

$$Q_{loss,piping} = 0.01693\Delta T - 0.0001683\Delta T^2 + 6.78\times10^{-7}\Delta T^3 \tag{5}$$

Where, ΔT [°C] is the difference between the average field temperature and the ambient air temperature.

Thus, the net energy collected by the heat transfer fluid oil over the field is:

$$Q_{collected} = Q_{absorbed} - \left(Q_{loss,HCE} + Q_{loss,piping}\right)A_c \tag{6}$$

B. Power Generation

Applying the thermal oil carrying solar energy to replace the extraction steam to heat the feed water and the steam thus saved can continue to generate work. According to the necessary electrical load, the system can operate at a fuel-saving (fuel and emission reduction while keeping the same generating capacity) or power boosting mode (additional power generation with the same fuel consumption). In the analysis, the power booster operation mode was chosen for the hybrid power system [3]. Equivalence enthalpy descending analysis method [14] is used to calculate the extra work generated by the saved extraction steam.

The amount of the extraction steam replaced by the heat collected by solar field is calculated as:

$$x_i = \frac{Q_{collected}}{q_i} \tag{7}$$

The extra work generated by the saved extraction steam is expressed as:

$$\Delta E_i = x_i H_i \tag{8}$$

Where, H_i is the extra work generated by the 1 kg saved extraction steam stage *i*. According to the Literature [14], if the extraction steam *i* enters an open feed water heater, H_i is expressed by:

$$H_i = (h_i - h_n) - \sum_{r=1}^{i-1}\frac{\tau_r}{q_r}H_r \tag{9}$$

[1] Dudley et al.[11] determined the parameters $c_1 = -0.000884/1°$, $C_2 = 0.00005369/(1°)^2$

[2] The parameter a_0=-9.463033, a_1=0.3029616, a_2=-0.001386833, a_3=0.000006929243, b_0=0.0764961, b_1=0.0000001128818 are given by Angela M. Patnode [12].

If the extraction steam *i* enters a closed feed water heater H_i is expressed by:

$$H_i = h_i - h_{i-1}(1 - \frac{\gamma_{i-1}}{q_{i-1}} H_{i-1}) \tag{10}$$

Defining the efficiency of solar to electricity with the Equation (11), the results with different replacement types are shown in Table 3.

$$\eta_{se} = \frac{\Delta E_i}{Q_{Ld}} \tag{11}$$

The annual performance can be obtained by solving the above equations at every time step. In this paper, since only hourly meteorological data are available, so the following calculations are based on this working time intervals.

C. Economics

In order to show the economical effect of the new integrated system, the "levelized electricity costs" (LEC) and the static payback time are calculated.

The LEC is calculated as follows:

$$\text{LEC} = \frac{(CC \cdot AF) + O\&M + FUEL - C}{E_{annual}} \tag{12}$$

Where CC is the total capital cost; AF, the annual factor; $O\&M$, the annual operating and maintenance cost; $FUEL$, fuel cost; C, other receipts; E_{annual}, annual net electricity generation in kWh. In this study, the mainly related data used are shown in the Table 1.

TABLE I MAINLY RELATED DATA USED IN THIS STUDY

solar fields (￥/m^2)	2000
$O\&M$ (￥/m^2)	50
standard coal cost (￥/ ton)	850
Cost of land	Not considered
Oil-water exchanger	Not considered
Solar electric power price (￥/ kWh)	1.09
auxiliary power percent of solar system	8%
interest rate	6%
lifetime (year)	25
annual factor	0.0782

IV. AN EXAMPLE

In this section, a solar energy integrated with a 125 MW coal fired conventional power generation unit is taken as an example to analyze. The simplified scheme of the original generation unit is shown in Fig. 2. The specific standard coal consumption of electricity generating is 333.6 g/kWh. The other related parameters of the original generation unit are shown in Table 2.

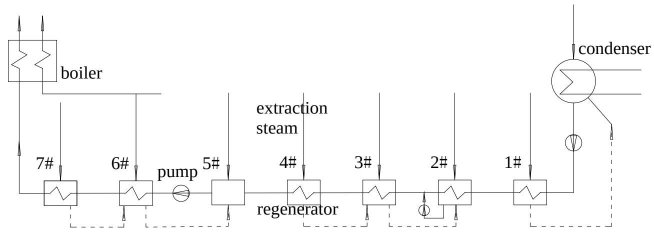

Fig. 2 Simplified scheme of the 125MW coal-fired conventional power unit

TABLE II MAINLY RELATED DATA USED IN THIS STUDY EXTRACTION STEAM PARAMETERS OF THE UNIT ANNUAL PERFORMANCE WITH DIFFERENT REPLACEMENT TYPES

	Pressure Mpa	**Temperature** ℃	**Enthalpy kJ/kg**	**Flow** t/h	**Water Enthalpy at Regenerative Beater outlet** kJ/kg
primary steam	13.24	550	3467	395	
Extraction steam No.7	3.64	375.4	3164	17.39	1039.6
Extraction steam No.6	2.55	331	3083	45.53	946.2
Extraction steam No.5	0.77	394	3256	6.56	667.4
Extraction steam No.4	0.46	326	3120	14.9	609.2
Extraction steam No.3	0.25	255	2980	19.72	509.1
Extraction steam No.2	0.07	135	2749	15.18	357.9
Extraction steam No.1	0.016	55	2541	9.33	212.7
exhaust steam	0.005	33	2420	266.4	136.3

In the hybrid thermal power system, solar energy collected by a solar field with 4710 m^2 aperture area replaces the extraction steam to heat the feed water and the saved steam continue to generate work.

The power plant location is set in Lhasa, China. The hourly meteorological data are used in the following calculations. In order to simplify the problem, we only take solar energy replacing the extraction steam No. 7 as an example to illustrate. The same method can also be applied in other replacements. Based on the typical year meteorological data, daily DNI, thermal output of the solar field and the solar power generation for extraction steam No. 7 replaced by solar energy are shown in Fig. 3. The annual performance with different replacement types are listed in Table 3.

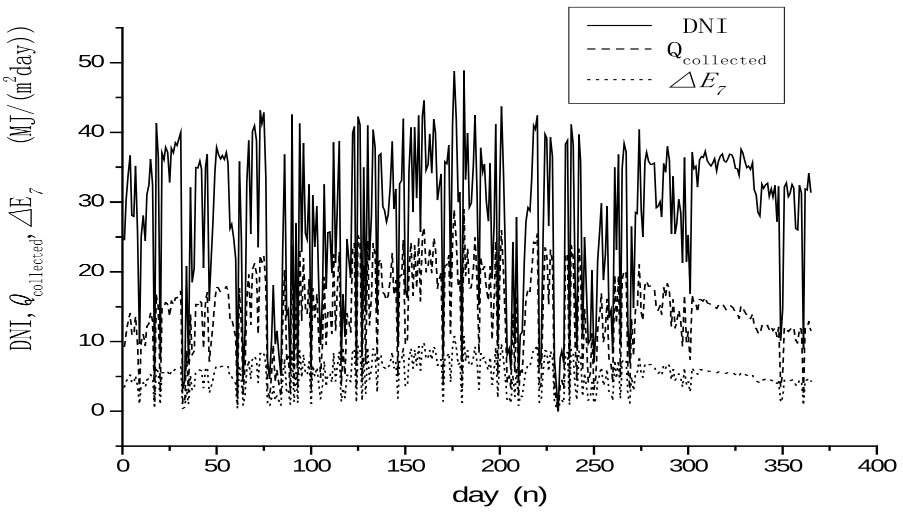

Fig. 3 Daily DNI, thermal output of solar field, solar power generation for extraction steam No.7 replaced by solar energy

TABLE III ANNUAL PERFORMANCE WITH DIFFERENT REPLACEMENT TYPES

The Extraction Steam Replaced	No.1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
Solar Collector Working Temperature (℃)	52	79	115	143	162	199.5	240
Solar-to-Electric Efficiency	0.027	0.069	0.116	0.138	0.149	0.180	0.189
Annual Thermal Output of Solar Field (kwh/m²/year)	1510	1505	1498	1490	1484	1467	1440
Annual Power Generation (*10⁵kwh/year)	3.59	9.18	15.5	18.5	19.9	24.1	25.3
LEC(￥/ kwh)	2.71	1.06	0.63	0.53	0.49	0.40	0.38
Payback (year)	75.7	13.8	7.1	5.8	5.4	4.3	4.1

*solar field aperture area is 4710 m^2

It can be seen from Table 3, for the same solar aperture area, different replacements result in different performances. The higher grade extraction steam is replaced, the higher working temperature of solar field is needed, and thermal output of solar field decreases when working temperature rises. As the loss of thermal output is not enough to offset the extra work generated by the saved extraction steam，the LEC and payback also decreases. From this we can conclude that, for this solar aperture area, the higher grade extraction steam is replaced, the more annual power generation and the better economical efficiency will be.

In order to obtain how solar field aperture area effects on the performance of the solar-coal hybrid thermal power system, different replacements with different solar field aperture areas are calculated and the results are presented in Fig. 4.

From it we can see that, when the solar aperture area is relative small, extraction steam No. 7 replaced would obtain a higher power generation, solar-to-electric efficiency and lower LEC than extraction steam No. 6 replaced. However, for the replacement type that extraction steam No. 7 replaced, when the collector aperture area increases to a certain degree, any further increase of the collector area will make solar power efficiency decrease rapidly, LEC increases rapidly and the growth rate of annual power

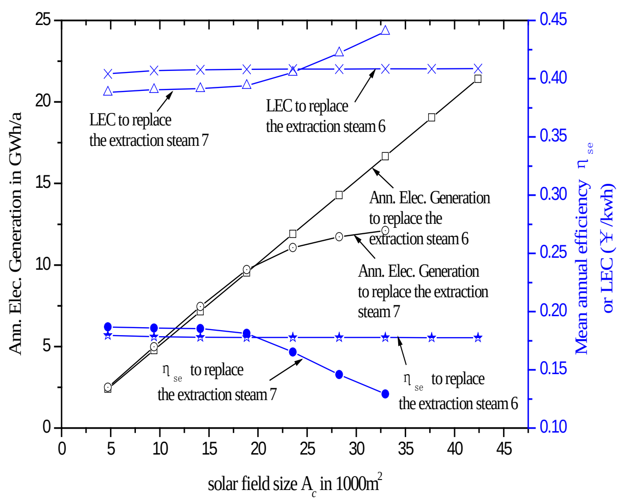

Fig. 4 Performance of the solar-coal hybrid thermal power system with different replacements and collector aperture areas

generation slows down. For example, when the collector aperture area is 30000 m^2, the power generation, solar-to-electric efficiency of No. 7 replaced will be lower than that of the situation when No. 6 replaced and LEC vice versa. The reason is that the flow of extraction steam No. 6 is larger than that of No. 7. When collector aperture area increases, the thermal power of solar field will eventually exceed the energy needed for heating feed water in regenerative heater. The larger the aperture area, the higher ratio of surplus energy will be. Therefore, from Fig. 4, we can determine which replacement and how big aperture areas are the best to be considered based on the specific case.

Since the DNI also has a great influence on the performance of the integrated system, the annual performances with different typical meteorological data are calculated and the results are listed in Table 4.

TABLE IV ANNUAL PERFORMANCE UNDER DIFFERENT DNI

	Typical Year	**Extremely High Radiation Year**	**Extremely Low Radiation Year**
Solar-to-electric efficiency	0.189	0.197	0.189
Power generation (kwh /year)	2,527,694	2,786,944	1,323,917
Solar field thermal output (kwh/m^2/year)	1440	1587.5	754
DNI (kwh/m^2/year)	2845	3008	1485
LEC (￥/kwh)	0.38	0.35	0.73

*The aperture area is 4710 m^2, extraction steam no.7 is replaced.

From the table we can see that, the annual performance and LEC vary from the extremely high radiation year to extremely low radiation year.

V. CONCLUSIONS

In this paper, a solar–coal hybrid power system is presented where solar (thermal) energy as an aiding heat source is integrated into the conventional coal-fired power generation cycles. The performance of the hybrid power system is analyzed with an example. In the hybrid power system, thermal oil carrying solar energy replaces the extraction steam to heat the feed water, the steam thus saved can continue to generate work. Compared with the solar only power generation system, the system overcomes the instability of solar only power system and shares the good stability of conventional coal-fired power plant. The influence of the replacement, solar collector aperture area and weather condition on the hybrid power system are analyzed.

The results show that, the efficiency of the conventional power station increases and its emission of the greenhouse gases reduces. Besides, the hybrid power system also increases the efficiency of light to electricity, and LEC reduces considerably compared with solar only thermal power plant. However, the results also show that, different replacements, solar collector areas, and DNI have great influence on the solar–coal hybrid power system. When the collector area is small, thermal output of the solar field without any surplus with extraction steam replaced, the higher grade extraction steam replaced, the better thermal performance and economical efficiency will be. When collector area increases to a critical value, the system performance will decrease rapidly with the increase of the collector area. Therefore, which replacement and how big aperture areas to be chosen need to analyze in combination with specific case. From the result we also can see that, the thermal output of the solar field depends on the value of DNI and its distribution. Even in the same area, LEC varies significantly from year to year. It should also be noticed that, since the analysis based on many specific parameters, the obtained results are only valid for the specifically defined conditions and may vary significantly from project to project.

Nomenclature

A_c	aperture area of solar field [m^2]
h_i	enthalpy of the extraction steam *i* [kJ/kg]
h_n	enthalpy of the exhaust steam [kJ/kg]
$I_{b,n}$	direct normal insolation (DNI) [W/m^2]
$Q_{absorbed}$	the heat absorbed by HCE tube [W]
Q_{Ld}	the direct solar radiations fall on the aperture of solar field [W]
$Q_{collected}$	energy collected by the HTF over the solar field [W]
$Q_{loss,HCE}$	the HCE heat loss of per unit length [W/m$_2$]
$Q_{loss,piinq}$	the thermal losses of the piping system in the solar field [W/m^2]
q_i	enthalpy drop of extraction steam No. *i* [kJ/kg]
x	row shadow factor[-]
x_i	the saved extraction steam No. *i* [kg/s]
T_i	inlet temperature of solar field[℃]
T_o	outlet temperature of solar field [℃]
γ_i	heat released by the drain in the feed water heater *i* [kJ/kg]
τ_i	enthalpy increase of feed water in regenerator *i* [kJ/kg]

θ_i	incident angle of collector aperture[°]
ΔE_i	the more work generated by the saved extraction steam No. i[W]
η_{se}	the efficiency of solar to electricity[-]

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