Postprint: Off-Design Performance of Tower-Type Solar-Coal Complementary System

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Abstract

To conserve energy and protect the environment, solar-assisted coal-fired power generation systems have been developing rapidly. This paper proposes an integration scheme of solar tower with conventional coal-fired power plants for a 660 MW coal-fired unit in the Dunhuang region. A solar-coal complementary system model was established based on the TRNSYS simulation platform. Utilizing the meteorological database in TRNSYS software, the complementary system was simulated and analyzed under different irradiance intensities and various operating conditions in coal-saving operation mode, thereby obtaining the thermal performance for typical days and typical years and revealing the thermal characteristics of the solar-coal complementary system. The results indicate that the annual photoelectric conversion efficiency of the complementary system in this study is 15.36%. Compared with existing single solar thermal power generation technologies, the solar-coal complementation demonstrates certain advantages due to its higher cost-effectiveness. The findings provide new approaches and theoretical guidance for retrofitting existing coal-fired power stations.

Full Text

Preamble

Study on Off-design Performance of Tower Solar Energy Aided Coal-fired Power Generation System

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Abstract

To conserve fossil energy and protect the environment, solar-aided coal-fired power generation systems have developed rapidly. This paper proposes an integration scheme of tower solar energy collectors with a conventional 660 MW coal-fired power plant in the Dunhuang region. Based on the TRNSYS simulation platform, a model of the solar-aided coal-fired power generation system was established. Using meteorological data from the TRNSYS database, the complementary system was simulated and analyzed under varying solar radiation intensities and different turbine loads in coal-saving operation mode. The thermodynamic performance of the complementary system was obtained for typical days and a typical year, revealing its thermal characteristics. Results show that the annual solar-to-electric efficiency of the complementary system is 15.36%, which offers certain advantages due to lower costs compared to existing standalone solar thermal power generation technologies. The findings provide a new approach and theoretical guidance for retrofitting existing coal-fired power plants.

Keywords: Solar-aided coal-fired power generation system; Tower solar energy; Varying direct normal solar radiation; Varying turbine load; Thermodynamic performance

0 Introduction

Since the first Industrial Revolution, fossil energy has played a crucial role in human civilization. However, from the photochemical pollution in Europe in the 1950s to the current domestic haze problems, environmental pollution caused by fossil fuel consumption has seriously affected public health. Today, energy conservation and emission reduction have become international consensus, and developing diversified energy structures is a goal for all countries [1-3]. Solar energy has gradually gained attention due to its unique advantages: no greenhouse gas (primarily CO_2, NO) or toxic gas (SO_2, particulates) emissions; increased regional/national energy independence; and being a renewable energy source with abundant and low-cost energy [4]. Meanwhile, 70% of China' s electricity comes from thermal power plants. Constrained by resources and environment, energy conservation and emission reduction efforts are increasingly important, and many small to medium-sized coal-fired power plants with high coal consumption face shutdown. Therefore, complementary energy utilization has become an important development trend in energy systems [5-8]. China is rich in solar resources, and solar-aided coal-fired power generation systems have attracted growing attention.

In domestic research, Yang Yongping et al. [9-10] investigated the performance of complementary systems under design irradiation at different loads and discussed integration method selection under design conditions. Jin Hongguang et al. [11] studied the thermal complementation mechanism matching solar heat with turbine extraction steam temperature, finding that medium-low temperature solar energy (~300°C) from parabolic trough collectors matches the temperature of coal-fired power plant regenerative systems, and proposed that higher replacement stages of feedwater heaters yield higher collector field efficiency.

Western developed countries have made solar-coal hybrid power generation technology a primary direction of 21st-century energy research, conducting extensive studies. Teresita Larrain et al. [12] established a 100 MW system model of fossil-aided solar feedwater heating and studied it using climate parameters from the Chilean desert to find the minimum fossil fuel consumption at optimal hybrid system efficiency. Dimity Popov [13] used European Royal Economic Society fluid software to model a Rankine steam cycle, employing Fresnel solar collectors to directly heat feedwater and replace high-pressure heaters.

Due to the non-uniform and discontinuous temporal-spatial distribution of solar irradiation, combined with varying turbine loads, system performance deviates from design values, making off-design operation characteristic studies essential. This paper uses meteorological data from the TRNSYS software database [14] to simulate and analyze the complementary system under different irradiation intensities and operating conditions in coal-saving mode, obtaining thermodynamic performance for typical days and years to reveal the characteristics of solar-coal complementary systems. This study aims to provide a new approach and theoretical reference for retrofitting existing coal-fired power plants.

1.1 Coal-fired Power Generation System

[Figure 1: see original paper] Schematic diagram of the coal-fired power generation system

This study uses a 660 MW supercritical coal-fired unit as the base system. The simplified schematic diagram of the coal-fired power generation system is shown in Figure 1. Table 1 presents the main parameters for five operating conditions: 100% load, 85% load, 75% load, 60% load, and 50% load.

Table 1 Main parameters of unit under five turbine loads
Power (MW) | Main steam pressure (MPa) | Main steam temperature (°C) | Reheat steam pressure (MPa) | Reheat steam temperature (°C) | Main steam flow (t/h) | Feedwater temperature (°C) | Exhaust steam pressure (kPa) | Exhaust steam enthalpy (kJ/kg)

1.2 Integration of Solar System and Boiler System

This study uses molten salt as the working fluid to absorb solar energy and transfer heat to the coal-fired power generation system for power generation through the turbine. The integration scheme includes two solar heaters. [Figure 2: see original paper] shows the schematic diagram of the tower solar system integrated with the boiler system of the base plant.

In coal-saving mode, the steam temperature at the high-temperature superheater outlet decreases. The #1 solar heater heats boiler extraction steam from the steam-water separator, which is then mixed with high-temperature superheater outlet steam to maintain constant main steam temperature (566°C) at the high-pressure cylinder inlet. Similarly, the high-temperature reheater outlet steam temperature decreases in coal-saving mode. The #2 solar heater heats high-temperature reheater outlet steam to maintain constant reheat steam temperature (566°C) at the intermediate-pressure cylinder inlet.

1.3 Solar-Coal Complementary System

This paper proposes a tower solar energy integration scheme with a conventional coal-fired power plant and investigates its thermodynamic performance in coal-saving operation mode (constant feedwater flow, reduced coal feeding). [Figure 3: see original paper] shows the schematic diagram of the solar-hybrid coal-fired power plant thermodynamic cycle.

The proposed solar-coal complementary system offers three main advantages:

(1) The system uses the #2 solar heater to heat reheat steam as the primary means of reheat steam temperature control, with the flue gas damper method as auxiliary regulation. This avoids potential failure of the damper method. The traditional flue gas damper approach for reheat steam temperature control has advantages of simple structure and convenient operation, adopted by many large power plant boilers. However, its disadvantages include excessive time delay in temperature regulation, nonlinear relationship between damper opening and steam temperature, and narrow effective opening range. Generally, flue gas dampers exhibit good regulation performance at 40%-60% opening, with good steam temperature control when flue gas share is 30%-70%. If flue gas share falls below 25% or exceeds 75%, the damper loses regulation capability and reheat steam temperature control fails, unable to maintain rated reheat temperature. Actual operation involves fluctuations in coal type and load, causing variations in flue gas composition and share, plus unstable solar resources, demanding higher sensitivity and speed from damper regulation.

(2) Compared with conventional schemes using solar energy to heat feedwater/condensate, this approach heats high-temperature steam. Since there is no change in regenerative extraction steam quantity, it does not affect steam flow, pressure, temperature, or work distribution throughout the turbine flow path, eliminating the need to recalculate and verify blade stages for safe operation.

(3) Supercritical once-through boilers have no steam drum and small heat storage capacity, making steam temperature changes more pronounced than drum boilers under the same disturbance level. This scheme effectively controls both main steam and reheat steam temperatures.

2 Model Development

The solar-coal complementary system model was built on the TRNSYS simulation platform. [Figure 4: see original paper] shows the simulation system of the solar-hybrid coal-fired power plant constructed using TRNSYS software.

2.1 Heliostat Field

The heliostat field model requires an efficiency matrix for calculating field efficiency. The matrix contains multiple data series, each comprising azimuth angle, zenith angle, and current field efficiency. The software uses linear interpolation to determine field efficiency at other positions. The more series the matrix contains, the better the fitting [14]. The power received by the receiver from the heliostat field, Q_{rec}, is calculated as:

$$Q_{rec} = \eta_{field} \cdot \rho_{field} \cdot A_{field} \cdot I$$

where:
- Q_{rec}: Power received by receiver from heliostat field (kJ/h)
- η_{field}: Field efficiency
- ρ_{field}: Mirror reflectivity
- A_{field}: Total heliostat mirror area (m^2)
- I: Direct normal irradiance ($\mathrm{kJ/h \cdot m^2}$)

2.2 Receiver

In tower solar systems, the receiver is a photothermal conversion device. Molten salt (LiCl & KCl) is selected as the heat transfer fluid with a composition ratio of 0.595:0.405 and operating temperature range of 355-1400°C. The molten salt tower receiver outlet temperature is designed as a constant 620°C. The receiver outlet state depends on inlet molten salt state and input radiation. Both receiver body and piping heat losses are included in the model [15]. The receiver model equations are:

$$T_{abs} = \frac{T_{in} + T_{out}}{2} + 273.15$$

$$Q_{abs} = \eta_{opt} \cdot Q_{rec} - Q_{rad,loss}$$

$$Q_{rad,loss} = \frac{3600 \cdot \epsilon_{abs} \cdot A_{abs} \cdot \sigma \cdot T_{abs}^4}{1000}$$

$$Q_{loss,pipe} = 3600 \cdot \epsilon_{pipe} \cdot A_{pipe} \cdot \sigma \cdot (T_{out} + 273.15)^4 + k_{pipe} \cdot A_{pipe} \cdot (T_{out} - T_{amb})$$

$$Q_{loss,cooling} = f_{cooling} \cdot Q_{abs}$$

$$Q_{net} = Q_{abs} - Q_{loss,pipe} - Q_{loss,cooling}$$

$$Q_{th} = \dot{m}_{salt} \cdot c_{salt} \cdot (T_{out} - T_{in})$$

$$\eta_{rec} = \frac{Q_{net}}{Q_{rec}}$$

where:
- T_{abs}: Average receiver temperature (°C)
- T_{in}: Receiver molten salt inlet temperature (°C)
- T_{out}: Receiver molten salt outlet temperature (°C)
- Q_{abs}: Power absorbed by receiver (kJ/h)
- η_{opt}: Optical efficiency
- $Q_{rad,loss}$: Receiver radiation loss (kJ/h)
- ϵ_{abs}: Receiver emissivity
- A_{abs}: Receiver aperture area (m^2)
- σ: Stefan-Boltzmann constant, 5.67×10^{-8} $\mathrm{W/(m^2 \cdot K^4)}$
- $Q_{loss,pipe}$: Piping heat loss (kJ/h)
- ϵ_{pipe}: Pipe emissivity
- A_{pipe}: Pipe surface area (m^2)
- k_{pipe}: Pipe convective heat transfer coefficient ($\mathrm{kJ/h \cdot m^{-2} \cdot K^{-1}}$)
- T_{amb}: Ambient temperature (°C)
- $Q_{loss,cooling}$: Receiver cooling loss (kJ/h)
- $f_{cooling}$: Receiver cooling loss coefficient
- Q_{net}: Net receiver power (kJ/h)
- Q_{th}: Molten salt tower thermal load (kJ/h)
- c_{salt}: Molten salt specific heat capacity ($\mathrm{kJ/kg \cdot K}$)
- $\dot{m}_{salt}$: Total molten salt mass flow rate (kg/h)
- η_{rec}: Receiver efficiency

2.3 Thermal Performance Indicators

Solar-to-electric efficiency is a key performance metric for evaluating the complementary system:

$$\eta_{se} = \frac{P_S}{Q_S} = \frac{P_Z - P_{ref}}{Q_{field}} = \frac{P_Z - P_{ref}}{\eta_{ref} \cdot Q_b}$$

where:
- η_{se}: Solar-to-electric efficiency

- P_S: Solar power output (W)
- Q_S: Total solar irradiation energy (kJ/h)
- P_Z: Complementary system output power (W)
- Q_{field}: Total solar irradiation energy received by heliostat field (kJ/h)
- Q_b: Total boiler thermal load (kJ/h)
- η_{ref}: Efficiency of reference original coal-fired power plant

Standard coal consumption rate is calculated as:

$$b_{sc} = \frac{m_{sc}}{E} \times 1000$$

where:
- b_{sc}: Standard coal consumption rate (g/kWh)
- m_{sc}: Coal consumption converted to standard coal (kg)
- E: Power plant electricity output (kWh)

3 Results and Analysis

In the design calculations, the power island design point was selected at 100% turbine load, with the heliostat field capacity reasonably matched to the power side. Based on typical annual irradiation data for Dunhuang region (40°N, 94°E) from the TRNSYS meteorological database (shown in [Figure 5: see original paper]), the design irradiation intensity was selected as 694 W/m^2 (2499 kJ/h · m^2). Table 2 provides detailed solar power system parameters at the design point.

Table 2 Parameters of solar power system at design point
Heliostat mirror area | Molten salt mass flow rate | #1 solar heater molten salt inlet temperature | #1 solar heater molten salt outlet temperature | #2 solar heater molten salt inlet temperature | #2 solar heater molten salt outlet temperature | #1 solar heater boiler extraction outlet temperature | #2 solar heater reheat steam outlet temperature | Molten salt tower thermal load | Maximum instantaneous solar-to-electric efficiency

3.1 Off-design Operation

Five sliding pressure operating conditions were selected: 50% load, 60% load, 75% load, 85% load, and 100% load. [Figure 6: see original paper] shows the variation of molten salt tower inlet and outlet temperatures under different loads. The molten salt tower receiver outlet temperature is designed as a constant 620°C, so it remains unchanged at 620°C as load decreases. However, the molten salt tower inlet temperature increases with decreasing load because less steam flows for heat exchange with molten salt, reducing heat transfer. The molten salt temperature rise range decreases from 69°C at 100% load to 39.7°C at 50% load, meaning a certain number of heliostats remain unused, causing resource waste and significantly reduced solar-to-electric efficiency.

[Figure 7: see original paper] shows the variation of boiler heating surface thermal loads under different operating conditions. The horizontal axis (WW, Div, Back, Hsh, HRh, LSh, LRh, Eco) represents water wall, division platen, rear platen, high-temperature superheater, high-temperature reheater, low-temperature superheater, low-temperature reheater, and economizer, respectively. Figures a, c, e, g, i show the original system under five loads, while b, d, f, h, j show the complementary system under five loads. Compared to the original system, the thermal load change rates in descending order are LSh (HSh) > Back (Div) > LRh > HRh > Eco > WW. At different turbine loads, LSh and HSh thermal load change rates are similar, as are Back and Div. The maximum thermal load change rate is approximately 15%, and the minimum is about 1%.

[Figure 8: see original paper] compares standard coal consumption between the original and complementary systems under different loads. Coal consumption increases as load decreases. At 100% load, the complementary system reduces coal consumption by 7.7 g/kWh compared to the original system; at 50% load, the reduction is 6.5 g/kWh. This translates to efficiency improvements that decrease slightly with load: the complementary system improves overall plant efficiency by 1.07% at 100% load and 0.80% at 50% load.

3.2 Typical Day Thermal Performance

Four typical days were selected for analysis: spring equinox (March 20), summer solstice (June 21), autumn equinox (September 22), and winter solstice (December 21). [Figure 9: see original paper] shows the variation of solar-to-electric efficiency over time for these typical days.

The results show that spring and autumn equinoxes have similar solar utilization hours, with summer solstice being the highest. On winter solstice, the DNI values are too low to reach the required molten salt tower outlet temperature of 620°C, so the solar field does not operate throughout the day. On spring and autumn equinox days, the average daily solar-to-electric efficiency is approximately 18% at 100% load and about 10% at 50% load. On summer solstice, these values are approximately 21% at 100% load and 11% at 50% load. The efficiency variation trend correlates with daily solar irradiation patterns. At noon, although DNI is high, efficiency is not necessarily highest due to underutilization.

3.3 Annual Thermal Performance

To obtain annual operational performance data, the power plant was assumed to operate at 100% load throughout the year. [Figure 10: see original paper] shows the monthly solar utilization hours, which are lowest in winter due to low ambient temperatures (higher heat losses), large solar incidence angles (higher cosine losses), and low DNI values, resulting in the shortest complementary operation periods.

Table 3 Annual performance at design point
Solar annual utilization hours | Solar annual power generation | 3.72$×10^{7}$ kWh | Annual solar-to-electric efficiency | Annual coal savings

The complementary system utilizes solar energy for 2,047 hours annually, generating 3.72$×10^{7}$ kWh of solar electricity with an annual solar-to-electric efficiency of 15.36% and saving 10,414 tons of coal.

4 Conclusions

This paper proposes a tower solar energy integration scheme with a conventional 660 MW coal-fired power plant in the Dunhuang region. Based on the TRNSYS simulation platform, a solar-coal complementary system model was established and analyzed under coal-saving operation mode at varying irradiation intensities and operating conditions, yielding thermal performance data for typical seasonal days and a typical year. The results indicate:

1) At 100% load, the complementary system reduces coal consumption by 7.7 g/kWh and improves overall plant efficiency by 1.07% compared to the original system; at 50% load, it reduces coal consumption by 6.5 g/kWh and improves efficiency by 0.80%.
2) Under design power (100% load), the complementary system achieves high solar-to-electric efficiency and low coal consumption, outperforming the other four reference loads, with maximum instantaneous solar-to-electric efficiency reaching 23.16%.
3) Annual thermal performance analysis at the design point shows an annual solar-to-electric efficiency of 15.36%. Compared to existing standalone solar thermal power generation technologies, the solar-coal complementary approach offers cost advantages.

These achievements provide a new pathway and theoretical guidance for retrofitting existing coal-fired power plants.

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Note: Figure translations are in progress. See original paper for figures.