Applied Thermal Engineering 73 (2014) 577–587

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Evaluation criteria for enhanced solar–coal hybrid power plant performance

Yawen Zhao*, Hui Hong, Hongguang Jin

Institute of Engineering Thermophysics, Chinese Academy of Sciences, P.O. Box 2706, Beijing 100190, PR China

HIGHLIGHTS

- New criteria to evaluate the solar hybrid power plant were developed.
- Typical solar–coal hybrid power plants were evaluated using the criteria.
- The integration principle of solar–coal hybrid systems was determined.
- The benefits of the solar–coal hybrid system are enhanced at lower solar radiation.

ARTICLE INFO

Article history:
Received 25 March 2014
Accepted 1 August 2014
Available online 12 August 2014

Keywords:
Solar–coal hybrid system
Evaluation criteria
Relative efficiency improvement
Saved collector area per solar power

ABSTRACT

Attention has been directed toward hybridizing solar energy with fossil power plants since the 1990s to improve reliability and efficiency. Appropriate evaluation criteria were important in the design and optimization of solar–fossil hybrid systems. Two new criteria to evaluate the improved thermodynamic performances in a solar hybrid power plant were developed in this study. Correlations determined the main factors influencing the improved thermodynamic performances. The proposed criteria can be used to effectively integrate solar–coal hybridization systems. Typical 100 MW–1000 MW coal-fired power plants hybridized with solar heat at approximately 300 °C, which was used to preheat the feed water before entering the boiler, were evaluated using the criteria. The integration principle of solar–coal hybrid systems was also determined. The proposed evaluation criteria may be simple and reasonable for solar–coal hybrid systems with multi-energy input, thus directing system performance enhancement.

1. Introduction

Inexhaustible solar energy has been considered an effective method to address the problems of fossil fuel shortage and environment pollution. The hybridization of solar energy with fossil power plants has attracted much attention in terms of near- and mid-term, sustainable solar thermal power plant development since the 1990s [1]. Electricity production cost can be reduced with an efficient thermal cycle compared with solar-only plants given similar field sizes. Using the existing infrastructure (and grid) of a conventional power station can limit technical and economic risks related to solar energy. Hybridizing solar energy with traditional coal-fired power plants is realistic and significant especially because the energy consumption structure in China is dominated by coal.

The Electric Power Research Institute [2,3] summarizes the major solar integration options for coal-fired plants, such as solar-superheated steam generation, solar saturated steam generation under different pressures, integration with the main steam, and injection into high- or low-pressure steam turbines in an existing coal-fired power plant, in its research on solar–coal hybrid power systems. Thirty percent to 40% solar heat-to-electricity efficiency can be attained, whereas the temperature of the collected solar heat is required to reach 400 °C–500 °C.

The Colorado Integrated Solar Project (CISP) [4] first integrated solar energy into a coal-fired power plant over a duration of seven months, from late May 2010 to December 2010. Solar heat heats the feed water and reduces coal use in electric power production. The solar integration scheme used in the CISP is effective and does not interfere with normal generation operations.

The thermodynamic and economic performances of solar–coal hybrid power have also been studied [5–8]. The results have shown that solar heat obtained at approximately 300 °C matches the water

* Corresponding author. Tel.: +86 10 825 430 28; fax: +86 10 826 228 54.
E-mail address: zhaoyawen@iet.cn (Y. Zhao).

http://dx.doi.org/10.1016/j.applthermaleng.2014.08.003
1359-4311/

fed back to the boiler. Replacing steam extractions with solar heat to heat feed water can increase the work output of a steam turbine. The thermal cycle of an efficient, traditional, coal-fired power plant can reduce solar electricity production cost compared with solar-only plants given the same field size. Hybridizing solar heat with coal-fired power plants potentially limits high coal consumption and the associated greenhouse gas emissions.

The integration of solar heat into typical coal-fired power plants has been simulated [9], and power plants with large capacities are conducive to solar integration. Replacing the different steam extractions of a typical coal-fired power plant with solar heat has been studied [10], and the most efficient position in the solar–coal hybrid system is at the feed water heater with the highest pressure. The thermodynamic and economic benefits in both power-boosting and fuel-saving models have also been presented [8].

Most previous research focuses on one or more case studies; however, investigations into general hybrid system integration are rare. Numerous traditional metrics used in fossil-only systems characterize and evaluate solar–coal hybrid power plants; however, appropriate evaluation criteria are important in system design and optimization. The heat inputs of both low-density solar energy and fossil fuel with high heat value are considered similar when system thermal efficiency is determined by "$W/(Q_{\mathrm{fuel}} + Q_{\mathrm{solar}})$". The energy loss during the transition from solar radiation to heat is ignored. System exergy efficiency is expressed as "$W/(E_{\mathrm{fuel}} + E_{\mathrm{solar}})$"; however, the method to calculate E_{solar} solar radiation exergy is disputed [11]. The sun surface is considered a blackbody with a temperature of 5800 K in classic methods, and E_{solar} [12] equals to 93%–95% × Q_{solar}. The results may suit the high-energy density solar radiation on the sun surface and not the solar radiation on earth after long-distance diffusion. Other studies measure hybrid cycle performances based on net solar-to-electricity efficiency, which is defined as "$(W_{\mathrm{hybrid}} - W_{\mathrm{coal}})/(\mathrm{DNI} \times S_{\mathrm{mir}})$" [13]. This efficiency can reflect the conversion of solar energy to net incremental solar work in a solar-fossil hybrid system. However, it cannot directly describe system performance improvements as a result of solar hybridization.

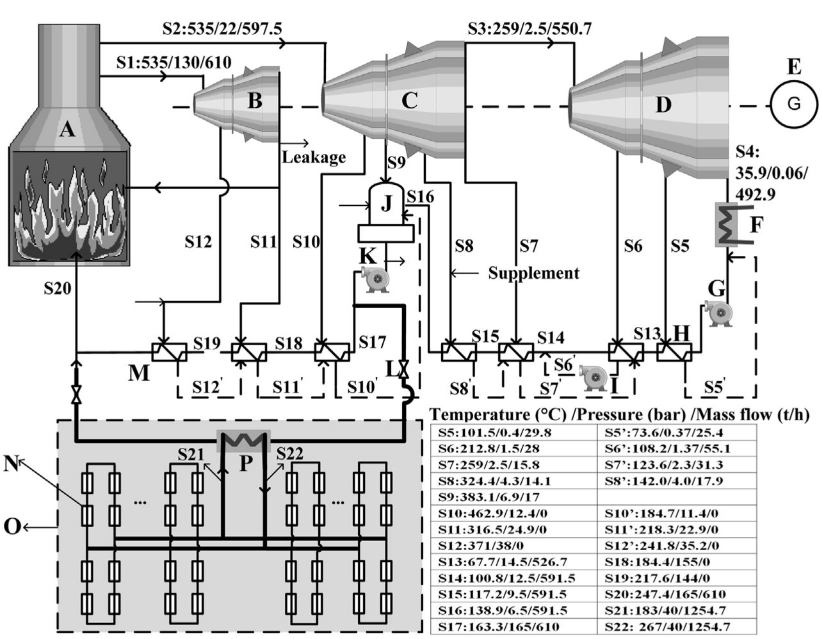
The objectives of this study are: (1) to propose new solar–coal hybrid system evaluation criteria; (2) to determine the performances of solar hybridization with 100 MW–1000 MW coal-fired power plants; and (3) to present the system design principle and integration method.

2. System description

In the solar–coal hybrid power plant (SCHPP), the typical coal-fired power plants were hybridized with solar heat at approximately 300 °C. The solar heat collected by the parabolic troughs can be utilized to replace one or more steam extractions, to preheat the feed water before the boiler.

Taking a typical 200 MW coal-fired power plant with first three high-pressure steam extractions replaced by solar heat for example, Fig. 1 depicts its flow sheet with the thermodynamic parameters such as temperature and pressure. The main steam is produced by the boiler (A) with a mass-flow rate of 610 ton/h at 130 bar and 535 °C, and reheat steam of 597.5 ton/h at 22 bar and 535 °C. The condensate water is pumped into the low-pressure feed water heaters (H) and the deaerator (J), raised the temperature up to 139 °C by the steam extractions from the mid and low-pressure turbines. In a water–oil heat exchanger (P), the feed water from the deaerator is further preheated to 247 °C by the solar heat at around 300 °C, collected by a series of parabolic troughs (N). Thus, the steam extractions are eliminated, and the work output of the steam turbines is enhanced when steam expands in the turbines compared with the coal-only plants. The joint of an oil-water heat exchanger incorporates the parabolic trough solar field into the thermal cycle of the coal-fired power plant.

When the collected solar heat can't satisfy the need for the high-pressure feed water heating, such as during night time and overcast



S5:101.5/0.4/29.8	S5':73.6/0.37/25.4
S6:212.8/1.5/28	S6':108.2/1.37/55.1
S7:259/2.5/15.8	S7':123.6/2.3/31.3
S8:324.4/4.3/14.1	S8':142.0/4.0/17.9
S9:383.1/6.9/17	
S10:462.9/12.4/0	S10':184.7/11.4/0
S11:316.5/24.9/0	S11':218.3/22.9/0
S12:371/38/0	S12':241.8/35.2/0
S13:67.7/14.5/526.7	S18:184.4/155/0
S14:100.8/12.5/591.5	S19:217.6/144/0
S15:117.2/9.5/591.5	S20:247.4/165/610
S16:138.9/6.5/591.5	S21:183/40/1254.7
S17:163.3/165/610	S22: 267/40/1254.7

A-Coal-fired boiler; B-High-pressure steam turbine; C-Mid-pressure steam turbine; D-Low-pressure steam turbine; E-Generator; F-Condenser；G-Condensate pump; H-Low-pressure feed water heater; I-Drain pump; J-Deaerator; K-High-pressure pump; L-Valve; M-High-pressure feed water heater; N-parabolic trough collectors; O-Solar feed water heater; P-Water-oil heat exchanger.

Fig. 1. Schematic diagram of the solar–coal hybrid system.