Applied Energy 200 (2017) 170–179

Contents lists available at ScienceDirect

Applied Energy

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

A novel solar energy integrated low-rank coal fired power generation using coal pre-drying and an absorption heat pump

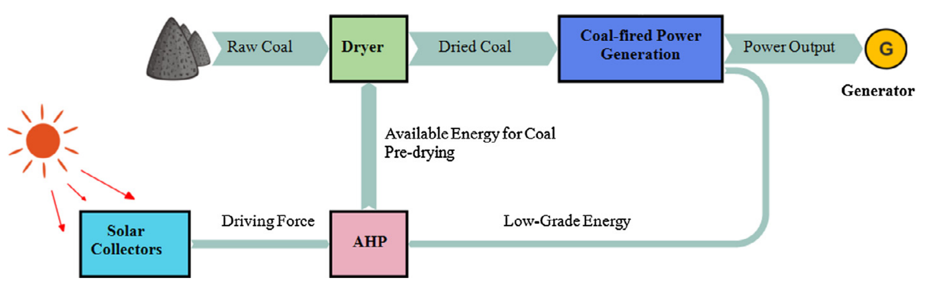
Cheng Xu, Pu Bai, Tuantuan Xin, Yue Hu, Gang Xu *, Yongping Yang *

National Thermal Power Engineering and Technology Research Center, North China Electric Power University, Beijing 102206, China

HIGHLIGHTS

- An improved solar energy integrated LRC fired power generation is proposed.
- High efficient and economic feasible solar energy conversion is achieved.
- Cold-end losses of the boiler and condenser are reduced.
- The energy and exergy efficiencies of the overall system are improved.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 8 February 2017
Received in revised form 17 April 2017
Accepted 6 May 2017

Keywords:
Absorption heat pump (AHP)
Coal pre-drying
Low-rank coal (LRC)
Solar thermal energy
Thermodynamic analysis
Economic analysis

ABSTRACT

A novel solar energy integrated low-rank coal (LRC) fired power generation using coal pre-drying and an absorption heat pump (AHP) was proposed. The proposed integrated system efficiently utilizes the solar energy collected from the parabolic trough to drive the AHP to absorb the low-grade waste heat of the steam cycle, achieving larger amount of heat with suitable temperature for coal's moisture removal prior to the furnace. Through employing the proposed system, the solar energy could be partially converted into the high-grade coal's heating value and the cold-end losses of the boiler and the steam cycle could be reduced simultaneously, leading to a high-efficient solar energy conversion together with a preferable overall thermal efficiency of the power generation. The results of the detailed thermodynamic and economic analyses showed that, using the proposed integrated concept in a typical 600 MW LRC-fired power plant could reduce the raw coal consumption by 4.6 kg/s with overall energy and exergy efficiencies improvement of 1.2 and 1.8 percentage points, respectively, as 73.0 MW_{th} solar thermal energy was introduced. The cost of the solar generated electric power could be as low as $0.044/kW h. This work provides an improved concept to further advance the solar energy conversion and utilisation in solar-hybrid coal-fired power generation.

1. Introduction

Coal is the most abundant fossil fuel on the planet and is expected to continue to play a key role in the future power generation. In China, coal accounts for over 90% of total fossil energy reserves and coal-fired power plants produce 73% of the electricity in the year of 2015 [1]. However, coal-fired power generation are major emitters of carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter (PM) of huge local and regional environmental and health impacts in China. Great efforts have been made to improve the energy efficiency of the coal-fired power generation and increase the share of the clean energy power generation in the nation's energy mix. As a clean, free and non-depleting resource, solar energy has been increasing its share in the global energy mix for power generation [1,2].

Parabolic trough based solar power is the most commercially available technology and accounts for more than 90% of the current

* Corresponding authors.
E-mail addresses: xgncepu@163.com (G. Xu), yypncepu@163.com (Y. Yang).

http://dx.doi.org/10.1016/j.apenergy.2017.05.078
0306-2619/

Nomenclature

Abbreviation

AHP	absorption heat pump
COP	coefficient of performance
CRF	capital recovery factor
CSP	concentrating solar plants
DNI	direct normal irradiance
FCI	fixed capital investment
O&M	operating and maintenance costs
ICC	installed capital costs
COE	cost of electricity
LRC	low-rank coal
LHV	lower heating value
SAPG	solar aided coal-fired power generation
SOPG	solar-only power generation

Symbols

A	area of the solar collectors (m^2)
f	scale factor
h	full-load operating hours (h/year)
k	discount rate
n	expected plant lifetime (year)
Q_c	heat released by the recycled water (kW)
Q_h	high-temperature heat flux (kW)
Q_t	heat required for pre-drying (kW)
Q_{loss}	heat losses of the dryer (kW)
r	average required heat for moisture evaporation (kJ/kg)
S	scale parameter
α	pre-drying degree
ψ	solar collector efficiency (%)

Subscripts

b	boiler
c	coal
cir	circulated water
rec	recycled water
col	collector
g	gas
r	reference
s	steam
w	water

concentrating solar plants (CSP) [3]. The synthetic oil is generally used as the heat transfer fluid, which could be heated to the temperatures of around 400 °C, to drive the Rankine cycle to transform the useful energy generated in receivers into electric power. This type of the solar power generation is termed as solar-only power generation (SOPG) and the thermal storage systems are required as a norm to guarantee the plants' continuous operation. Conrado et al. [4] established the mathematical models and experimental set-ups of the collector/receiver of a parabolic trough solar collector. Cheng et al. [5] developed a model to optimize the performance of parabolic trough solar collector (PTC) based on the particle swarm optimization (PSO) algorithm and the Monte Carlo ray-tracing (MCRT) method.

As an alternative, solar aided coal-fired power generation (SAPG), in which the solar thermal energy could be utilised to pre-heat the feed/condensed water and save the steam bleeds from the turbines, could solve the discontinuity of the SOPG and exhibits higher energy efficiency and lower initial investment cost [6,7]. Yan et al. [8] analysed the performance of the SAPG with different replacements under different operating conditions. It was found that solar thermal energy used to displace higher temperature extraction steam leads to greater solar thermal to power efficiency than that used to displace lower temperature extraction steam. Zhao et al. [9] used two new criteria, i.e., relative net solar-to-electricity efficiency improvement and saved collector area per solar power, to optimize the SAPG plant modified from different power capacity. Zhu et al. [10] developed the thermal models to evaluate the solar contribution of the SAPG plant and the overall system performance from the perspective of the second law of thermodynamics. Suresh et al. [11] employed the 4-E (namely energy, exergy, environment and economic) analyses approach to comprehensively assess the performance of SAPG power plants and obtained that the SAPG a thermodynamic and economic viable option for solar energy utilisation.

It may be noted that, many of the world sun-rich areas, such as Australia, USA and Northwest China, are normally with large deposits of low rank coals (LRCs) and are highly depend on coal-based power generation [12,13]. As an example, Zhundong coal with ~400 billion tonnes in reserves has been found and exploited in Xinjiang, where exhibits a large sunshine time of 2550–3500 h and a high average solar radiation of 5430–6670 MJ/m^2 per year, providing China with a secure energy sources for many decades to come [6,14]. LRCs account for almost half of the global coal reserves, and their long term future is predicated on their growing utilisation for power generation; however, LRCs generally content a high amount of moisture (20–60% by weight), rendering low energy output and low fuel efficiency as compared to the bituminous coals [15,16]. Coal pre-drying technology, which is decoupled from the coal firing and could evaporate part of the moisture content prior to the furnace, has been considered as an effective approach to upgrading the LRCs utilisation [17]. The energy for coal drying normally come from the internal energy within the power plant, e.g., boiler flue gas or steam bleeds from the turbines. Xu et al. [15] have optimized the steam bleeds with the condensation temperature range of 100–120 °C for coal pre-drying by incorporating a supplementary steam cycle, the superheat of the steam could be significantly reduced with the overall plant efficiency improvement of 1.5–1.8%. The 550 MW Coal Creek power plant utilised the low-grade heat from the cooling water ranging from 45 to 60 °C to evaporate part of the lignite moisture in an air fluidized bed dryer, improving 2.6–2.8% power plant efficiency [18]. Obviously, coal pre-drying is an energy intensive process while the required temperature is normally not high. The absorption heat pump (AHP) is such a device, which could be driven by the high-temperature thermal energy and release heat at an intermediate temperature with larger quantities [19], and as such, there exists a potential to effectively utilise the solar energy driven AHP for pre-drying in LRC power generation.

Against this backdrop, a highly integrated solar energy integrated LRC-fired power generation system, including the solar thermal collecting, coal pre-drying, AHP and the conventional steam power generation, was proposed. Different from the current SOPG and SAPG, the solar thermal energy collected from parabolic trough is efficiently utilised to drive the AHP to absorb the waste heat of the steam cycle, achieving larger amount of heat with suitable temperature for convective coal pre-drying. The