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The development of a thermo-economic evaluation method for solar aided power generation

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ABSTRACT

In this paper, a method is derived for evaluating the thermo-economic performance of solar aided power generation (SAPG) hybrid systems. These systems can achieve emissions reduction and energy savings compared to conventional coal-fired power generation systems. In the discussed model of SAPG hybrid system, various stages of heating feed-water in a conventional coal-fired power plant steam Rankine system are replaced by steam injected from solar direct steam generation (DSG). In order to determine the thermo-economic viability of SAPG compared to conventional power generation, convenient methods are required for evaluating the performance of SAPG systems. Therefore, an analysis method is developed which involves defining a generalized steam–water distribution matrix equation. This matrix approach simplifies the traditional thermal calculation and has a one-to-one correspondence with the system structure. As a case study, the proposed method is successfully used to solve the case of a 600 MW power generation system with the integration of DSG. A comparison of the case study system with (SAPG) and without (non-SAPG) the integration of the solar DSG shows thermo-economic benefits to the hybridised system. If the state parameters are taken as variables, this method can be used to study the effects of changes in system, equipment, operation, and load on the thermal economy of the integrated system.

1. Introduction

Conventional coal-fired power plants, a popular way of supplying electricity worldwide, are under pressure to reduce greenhouse gas and pollution emissions at a time when civilization's demand for energy is growing at a higher rate than ever before. The only method to solve this dilemma is to find an alternative energy resource which is both clean and efficient. Solar energy has come to our attention as a choice, but this low-grade energy has failed to meet this demand due to limitations of high storage cost and intermittency. However, the research on solar energy has led to the development of alternative ways of turning solar energy into electricity. One of the alternative ways is via hybridization technologies of solar thermal energy with conventional coal-fired power plants, generally referred to as solar aided power generation (SAPG). Because of the potential in SAPG to solve the mentioned issues, SAPG is attracting increasing attention. In related research, SAPG proved to have excellent performance in both thermodynamic efficiency and the efficiency of converting solar energy into electricity [1].

Prior research on the basic theory and application of SAPG has obtained many results. Initial work on the application of solar energy in power generation was performed in 1975 by Zoschak [2] who proposed various applications for solar energy as an auxiliary heat source in the regenerative Rankine power plant. These applications include heating feed-water, evaporation of water, superheating of steam, and preheating air. Later work is focused on the thermodynamic advantages of solar aided power generation. Ying and Hu [3] describe that for a SAPG system, the exergy merit index of the energy hits extremely high values and is far superior to the corresponding exergy efficiencies in other power systems with the same waste heat as the heat source alone, and SAPG can run more efficiently than a conventional power plant. An analysis of annual performance of a SAPG system at design points under various load conditions was conducted by Hou et al.

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Nomenclature

D_{df1}	first-stage drain water flux
D_{df4}	flux of drain water which flows into the fourth-stage heater
D_{f6}	flux of steam for consumers
D_{wf3}	superheater spray water flux
D_{sg4}	flux of shaft gland leak steam which flows into the steam pipeline of fourth-stage heater
D_{sg7}	flux of shaft gland leak steam which flows into the steam pipeline of seventh-stage heater
D_{sg8}	flux of shaft gland leak steam which flows into the steam pipeline of shaft gland heater
D_{f5}	flux of steam generated at the continuous blowdown flash tank
D_i	i_th-stage extraction steam flux
h_i	specific enthalpy of i_th-stage extraction steam
h_{wi}	outlet water specific enthalpy of the i-stage heater
h_{dfi}	drain water specific enthalpy
D_{dfi}	drain water flux
D_{si}	flux of working medium which flows through the solar collector system
τ_i	feed-water enthalpy rise of heaters
D_{fw}	flux of water which flows into the boiler
h_{swc}	inlet water enthalpy of collector system
N_s	turbine internal shaft power of hybrid system
N	turbine internal shaft power in thermal power unit
D_0	flux of steam which flows into the HP cylinder
h_0	specific enthalpy of steam which flows into the HP cylinder
Q_b	heat from the boiler
Q_{sc}	the heat of working fluids in solar collectors
η_b	boiler efficiency
η_p	pipeline efficiency
η_m	mechanical efficiency
η_g	generator efficiency
Q_{abs}	instantaneous heat of collector field
I	instantaneous direct normal solar radiation intensity
S	total area of the collector mirror field
$\eta_{col}(t)$	instantaneous heat efficiency of collector field
$W(t)$	difference between the instantaneous output work before and after integrating system

[4,5], which considered a coal-fired power plant in both subcritical and supercritical conditions [6]. Wu et al. [7,8] simulated SAPG with various solar field areas and thermal energy storage capacity under hourly meteorology data and discussed performance of SAPG system in fuel-saving operation mode, by using a modified simulation model.

Recent work has considered the evaluation of SAPG. There are five aspects to the evaluation: the collector field side, turbine side, coal side, the second law of thermodynamics, and the experimental data. The results by Zhai et al. [9,10] show that the evaluation method based on the second law of thermodynamics is more practical and closer to actual plant operation data Another evaluation method proposed by Yang et al. [11] confirms the solar contribution to SAPG, which can be used to assign the individual cost components involving solar energy.

The aforementioned analysis gives different perspectives for the evaluation of SAPG. However, by now, the pattern of SAPG has developed into several different versions. Overviewing the various hybridization patterns, there are no universal and uniform equations to evaluate SAPG. Therefore, this paper aims to develop a new evaluation method for SAPG for a coal-fired power plant with a solar direct steam generation (DSG) system and this analysis method will involve deriving a generalized steam–water distribution matrix equation, having a one-to-one correspondence with the system structure.

It is typical for SAPG systems to include the integration of solar parabolic trough collectors. SAPG systems utilizing solar parabolic trough collectors are usually a two-circuit system. These two-circuit systems consist of the collector circuit and the Rankine cycle power block, with the two circuits connected via a heat exchanger. Another kind is a single-circuit system, such as SAPG with the integration of solar DSG, where the solar collectors is directly coupled to the power block. In either kind of SAPG system, solar energy is used to replace the extracted steam in order to heat the feedwater in a regenerative Rankine plant cycle. To establish the matrix equation for the SAPG systems, one of the key points is to know the inlet and outlet working flow fluxes and tempertures – these are heated by heat exchanger, as in the two-circuit system, or by solar energy directly, as in the DSG single-circuit system.

2. SAPG with direct steam generation

The discussed solar aided power generation (SAPG) system consists of a coal-fired power generation system and a solar direct steam generation (DSG) system. In such SAPG systems, solar steam can be supplied to replace extraction steam for heating feed water of the regenerative Rankine cycle system. The SAPG system discussed in this paper is shown in Fig. 1. This SAPG system includes the injection of solar steam to join the 1st-stage extraction steam, as well as to various stages of extraction, reheating or superheating steam. The system is based on the regenerative Rankine cycle. In Fig. 1, the stage division is illustrated by the dashed lines. The stage division depends on the boundary of the outlet feed water of the relevant heater. Without losing generality, the following assumptions are made:

(1) The drain water, D_{df1}, provides thermal energy for consumers from the drain pipeline of first-stage heater and the drain water, D_{df4}, flows into the system from the drain pipe of fourth-stage heater.
(2) The hot steam for consumers, D_{f6}, flows out of the turbine from the steam extraction pipeline of the sixth-stage heater and is condensed to water. The condensed-water flows into the main feed-water pipeline at the inlet of the fifth-stage heater.
(3) The superheater spray water, D_{wf3}, is taken at the outlet of feed water pump.
(4) The shaft gland leak steam, D_{sg4}, flows into the steam pipeline of fourth-stage heater, the shaft gland leak steam, D_{sg7}, flows into the steam pipeline of seventh-stage heater, and the shaft gland leak steam, D_{sg8}, flows into the steam pipeline of the shaft gland heater.
(5) The steam generated at the continuous blowdown flash tank, D_{f5}, flows into the steam side of the fifth-stage heater.

For the typical complementary power system shown in Fig. 1, the ith-stage extraction steam flux is denoted with D_i, e.g., for the 1st stage it is denoted with D_1, its specific enthalpy is denoted as h_i, the outlet water specific enthalpy of the ith-stage heater is denoted with h_{wi}, the drain water specific enthalpy is denoted with