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Thermodynamic and Techno-economic Analysis of Solar-Steam Hybrid Driven Flue Gas Desulfurization Wastewater Zero Liquid Discharge System

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ABSTRACT

Zero liquid discharge (ZLD) of flue gas desulfurization (FGD) wastewater from coal-fired power plants (CFPPs) provides an approach to comply with the increasingly stringent environmental regulations. However, traditional ZLD systems are commonly subject to high operating cost. A solar-auxiliary steam hybrid driven ZLD system is thereby proposed in the present work. Thermodynamic and economic analysis models were established. A case study in a 600 MW CFPP was carried out under the meteorological conditions of a typical city in China. It is found that the lowest levelized cost of wastewater treatment (LCOW) obtained was approximately 10.1 \$/t, and the cost could be reduced by marginally 8.0% by utilizing hybrid heat sources. A parametric study was further performed to investigate the impact of key variables on the LCOW, and indicated that auxiliary steam cost had the largest impact.

Keywords: FGD wastewater, zero liquid discharge, solar energy utilization, economic analysis

1. INTRODUCTION

Flue gas desulfurization (FGD) wastewater is the terminal wastewater of coal-fired power plants (CFPPs), which is characterized by high suspend solids, high salinity, complicated composition, and significant fluctuation [1]. Zero liquid discharge (ZLD) of FGD wastewater is one of the pathways for clean production of CFPPs to comply with the ever-strictly environmental regulations [2,3]. Thermal processes are essential for conventional ZLD systems, but the considerable energy consumption and high capital and operating costs have been the major stumbling block to their wide application [4,5]. Solar thermal utilization is a development trend in the desalination industry [6]. Since solar energy is one of the clean and cheap energy sources, the greenhouse gas emissions of the FGD wastewater treatment system can be greatly reduced and the cost of wastewater treatment is expected to be decreased by utilizing solar energy as the heat source.

Valuable researches have been carried out on solar driven desalination/distillation/ZLD systems. A ZLD distillation system that consisted of freeze desalination and membrane distillation-crystallization was proposed by Lu et al. [7], and 50% heating energy of this system could be supplied by solar panels. An integrated solar-energy based system was proposed by Demir et al. [8] for electricity and fresh water production, and the electricity generation capacity and daily fresh water production were 13.5 MW and 3,958 tons respectively. Menon et al. [9] provided a novel photo-thermal device to enhance solar evaporation for ZLD, and it could enhance evaporation by more than 100% and result in a better conversion efficiency of 43%. Information about the ongoing researches on solar distillation system was collected by Ranjan et al. [10], and the cost of desalination through solar stills was estimated in the range of 14 to 23.7 \$/m^3. Najafi et al. [11] proposed a ZLD wastewater treatment plant using hybrid solar energy-natural gas supply, and demonstrated that the cost was higher than it would be without solar power. Panagopoulos et al. [12] conducted techno-economic analysis of a solar driven MED system integrated with vapor compression to mitigate cost of brine treatment.

Process development of treatment chains has been done by the authors [13] to address the economic challenges of FGD wastewater ZLD. However, to the best of our knowledge, research on the integration of solar energy and plant auxiliary steam to achieve a low cost ZLD system in the field of FGD wastewater treatment has not been reported. Hence, the objective of the present work is to explore the performance and economic feasibility of a novel solar-auxiliary steam hybrid driven FGD wastewater ZLD system based on thermodynamic and economic analysis.

2. MATERIALS AND METHOGOLOGY

2.1 System description

As is shown in Fig. 1, the present system contains parabolic through collectors (PTCs) and the forced circulation multi-effect distillation (FC-MEDC) unit. Detailed process description of the FC-MEDC technology can be found in Ref. [13]. FGD wastewater, after being pretreated and softened, enters the FC-MEDC unit to be concentrated and distilled. A pusher centrifuge is applied downstream the FC-MEDC for the recovery of salt crystals. Moreover, a closed demineralized water loop is designed for absorbing the heat from solar field to generate low-pressure steam for driving the FC-MEDC. When the solar field cannot provide enough steam, the auxiliary steam available in CFPPs will be introduced as supplement heat source.

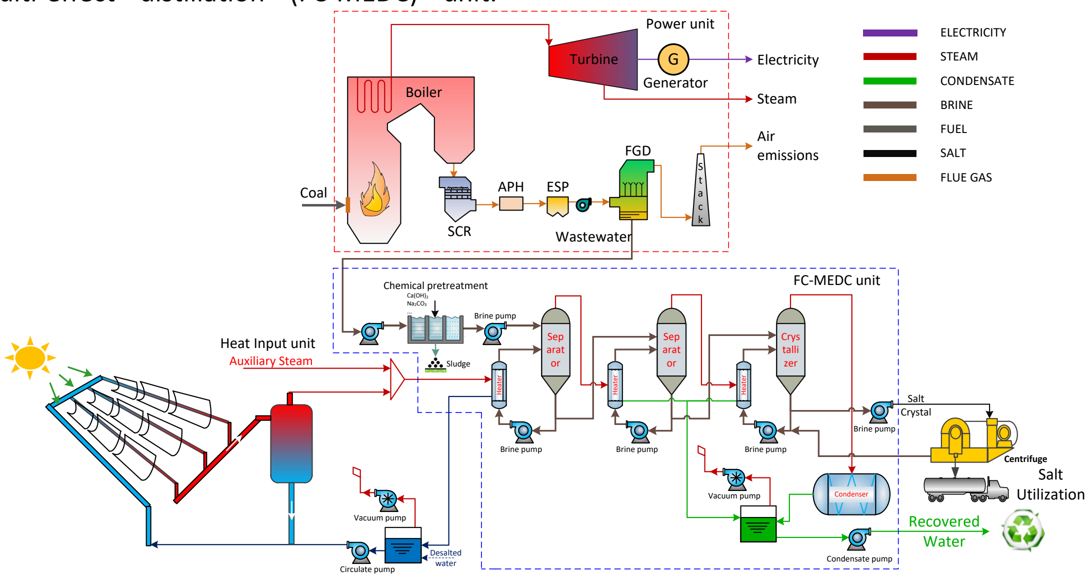


Fig 1 Schematic of the solar-auxiliary steam hybrid driven FGD wastewater ZLD system

2.2 System models

2.2.1 Thermodynamic models

The energy and mass balance model of the FC-MEDC unit can refer to Han et al. [13]. In seasonal design, the area of solar field (A_{SF}) can be designed by:

$$A_{SF} = \frac{Q_{th}}{\overline{DNI_s} \cdot \eta} \qquad (1)$$

where Q_{th} is the thermal energy that concentrate in PTCs needed to reach saturated condition, $\overline{DNI_s}$ is the seasonal average direct normal irradiance (DNI), and η is the comprehensive coefficient considering transmittance, absorptance and optical coefficient, which was set to be 0.7365 in the present work.

2.2.2 Economic models

Economic analysis is considered an essential step for evaluating the ZLD schemes. Here the levelized cost of wastewater treatment (LCOW), which considers both the capital expenditures and operating expenditures of the system, is defined to evaluate the cost of FGD wastewater treatment. It can be calculated as:

$$LCOW = \frac{[AF \times C_{cap} + C_{O\&M} + C_{chem} + C_{el}]_{FC\text{-}MEDC}}{TMW} + \frac{[AF \times C_{cap} + C_{O\&M} + C_{chem} + C_{el}]_{PTCs}}{TMW} + \frac{C_{stm}}{TMW} + \frac{[C_{ins} + C_{con} + C_{per}]_{overall}}{TMW} \qquad (2)$$

where C is the cost (\$), $O\&M$ refers to operation and maintenance and TMW is the total mass of FGD wastewater (t). AF in Eq. (2) is amortization factor and can be obtained by $AF = i(i+1)^n / ((i+1)^n - 1)$, where i and n represent nominal interest rate and plant lifetime, and were set to be 5% and 20 years in the present work, respectively. The *chemical* cost C_{chem} was assumed as 2.9 $/t [13], and *insurance* and *contingency* costs were 0.5% and 5% of the initial capital cost respectively. The land cost to construct this system was considered as zero. Detailed data for calculating other costs can be found in Refs. [11] and [13].

3. RESULTS AND DISCUSSION

3.1 Seasonal design and TMY design

The design and simulation of the solar field in the typical Chinese area (Delingha, N37.22°, E97.23°) was based on typical meteorological year (TMY) data from SWERA [14], which is presented in Fig. 2. In seasonal design, the seasonal average DNI was calculated by averaging the DNI data of each season. Then the area of solar field can be calculated by Eq. (1). However, the meteorological data was not fully used with this method, so the minimum value of LCOW cannot be obtained effectively. Therefore, TMY design method was proposed in the present work. The area of the solar field was increased gradually and the LCOW was calculated accordingly. The design corresponding to the lowest LCOW was named as TMY design.

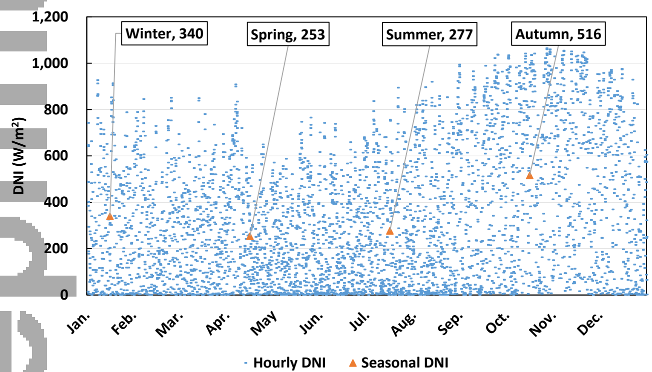


Fig 2 Hourly and seasonal variation of the DNI in Delingha, China

A typical 600 MW unit was selected, and the FGD wastewater flowrate was 20 t/h. The properties of the FGD wastewater are shown in Table 1. The auxiliary steam cost was estimated at 16.9 \$/t. The initial concentration of FGD wastewater was 5% and the corresponding GOR was 2.84 [13].

Table 1 Properties of typical FGD wastewater

pH	SS (mg/L)	COD (mg/L)	Na^+ (mg/L)	Ca^{2+} (mg/L)	Cl^- (mg/L)	TDS (mg/L)
6.80	13,487	444	9,686	1,447	17,339	46,559

As shown in Fig. 3, compared with adopting the design using auxiliary steam as the only heat source, the adoption of hybrid energy designs can reduce the LCOW. In these designs, TMY design had a maximum reduction of 8.0%, and the LCOW of TMY design and the design using auxiliary steam as the only heat source were 10.1 \$/t and 11.0 \$/t, respectively.

Fig. 4 illustrates that using TMY design can not only contribute to the lowest LCOW, but also require a minimum solar field area of about 13,500 m^2. Compared with utilizing the seasonal designs, adopting TMY design can reduce solar field area by up to about 50%.

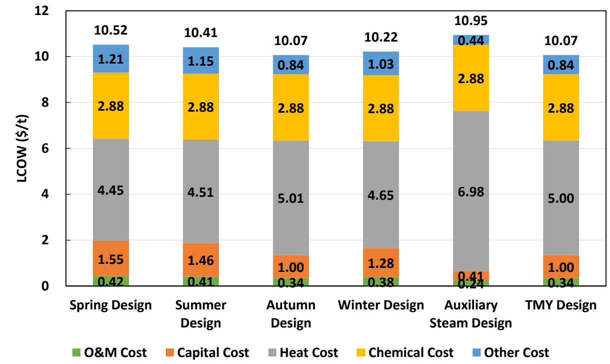


Fig 3 Comparison of LCOW in different scenarios

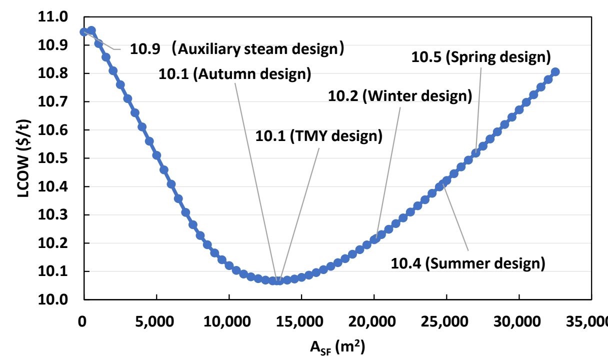
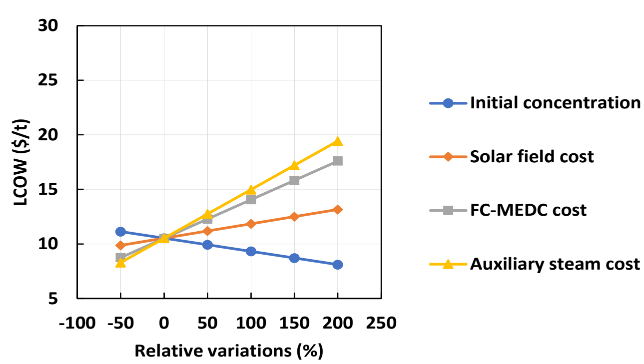


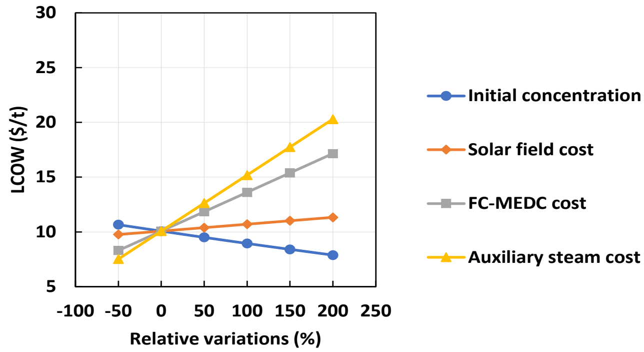
Fig 4 Variation of LCOW with increasing solar field area

3.2 Sensitivity analysis

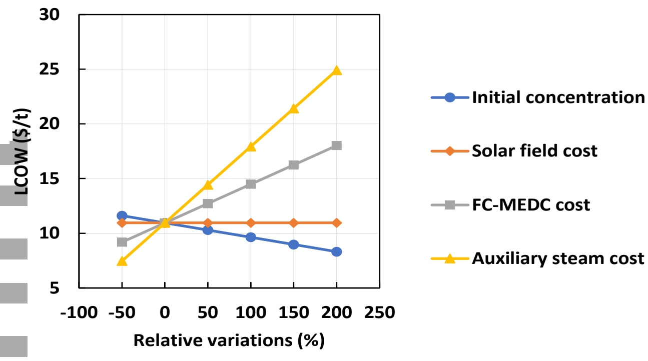
Fig. 5 shows the sensitivity analysis of wastewater treatment cost for seasonal designs (taking spring design as an example), TMY design and auxiliary steam design to the increase in some key parameters, including initial wastewater concentration, equipment cost and auxiliary steam cost. It is demonstrated that the LCOW was the most sensitive to the variation of auxiliary steam cost. Moreover, the solar-steam hybrid heat source design resulted in less sensitivity to steam cost variations than conventional design. The only difference between seasonal designs and TMY design was related to the area of solar field.



(a) Spring design



(b) TMY design



(c) Auxiliary steam design

Fig 5 Sensitivity analysis of LCOW in different scenarios

4. CONCLUSIONS

The application of FC-MEDC to achieve ZLD of FGD wastewater is reliable, and the utilization of solar energy might be a choice to reduce heat cost. A solar-auxiliary steam hybrid driven FGD wastewater ZLD system was proposed and system performance was investigated. The main conclusions are as follows:

1) The proposed system had a lower LCOW than conventional ZLD system. The minimum LCOW of 10.1 $/t could be achieved by introducing solar energy.

2) TMY design was more reasonable than seasonal designs. Compared with the seasonal designs, the LCOW and the area of solar field can be reduced by up to 8% and 50% under the TMY design, respectively.

3) The LCOW of the proposed system had the highest sensitivity to changes in auxiliary steam cost. A 50% increase in the cost of auxiliary steam would result in an increase in LCOW of approximately 25%.

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