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# Preliminary experimental study of post-combustion carbon capture integrated with solar thermal collectors

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## HIGHLIGHTS

- A solar assisted chemical absorption pilot system with two types of collectors (parabolic trough and linear Fresnel reflector) has been constructed.
- Performance of two types of solar collectors has been investigated and compared at steady and transient states.
- The operations of the pilot system with and without solar assisted have been tested.
- The pilot system responds to the temperature of the heat transfer fluid regularly.

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## ABSTRACT

The amine-based chemical absorption for $CO_2$ capture normally needs to extract steam from the steam turbine cycle for solvent regeneration. Integrating solar thermal energy enables the reduction of steam extraction and therefore, can reduce the energy penalty caused by $CO_2$ capture. In this paper, a pilot system of the solar thermal energy assisted chemical absorption was built to investigate the system performance. Two types of solar thermal energy collectors, parabolic trough and linear Fresnel reflector, were tested. It was found that the values of operation parameters can meet the requirements of designed setting parameters, and the solar collectors can provide the thermal energy required by the reboiler, while its contribution was mainly determined by solar irradiation. The solvent regeneration was investigated by varying the heat input. The results show that the response time of the reboiler heat duty is longer than those of the reboiler temperature and desorber pressure. This work provides a better understanding about the overall operation and control of the system.



## 1. Introduction

Coal-fired electricity generation produces roughly a quarter of the $CO_2$ gas emission in the world. According to the scenario of IEA New Policies (based on commitments in the Copenhagen Accord) in the *World Energy Outlook 2012*, the $CO_2$ emission from world-wide coal-fired generation is projected to grow by 18% from 2010 to 2020 [1]. Thus, reducing $CO_2$ emission coming from coal-fired generation presents a significant challenge.

Carbon capture and storage (CCS) has been proposed as a means of reducing greenhouse gas emissions from fossil-fueled power plants [2–5], and will play an important role as a transition step towards low-carbon energy generation. Among the several main approaches for CCS implementation in power plants, post-combustion carbon capture (PCC) is one of the most favored options due to its technology maturity and the possibility for retrofitting the existing plants. Now there have been many PCC demonstration plants all over the world [6–8].

However, the main barrier for the PCC technology is the high energy penalty. Taking amine-based chemical absorption as an example, it needs 3.0–3.6 GJ thermal energy to capture 1 ton $CO_2$ [9], which results in an efficiency penalty up to 10% of the low heating value of fuel [10].

Renewable energy, such as solar energy, has already been widely used in industrial applications for drying, heating and even cooling. In order to achieve a high efficiency, integrating solar energy into power plants has been considered as a promising

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**Nomenclature**

| | | | |
|---|---|---|---|
| DNI | direct normal irradiation, W/m$^2$ | $h_{abs}$ | heat of absorption, MJ/kg $CO_2$ |
| $A$ | aperture areas of the collector, m$^2$ | $q_{sens}$ | sensible heat, MJ/kg $CO_2$ |
| $\theta$ | incident angle of the collector, ° | $q_{vap}$ | vaporization heat, MJ/kg $CO_2$ |
| $Q_u$ | absorbed useful thermal energy by collectors, kW | $\alpha_{rich}$ | $CO_2$ loading of the rich solutions, mol $CO_2$/mol MEA |
| $\eta$ | efficiency of the collectors | $\alpha_{lean}$ | $CO_2$ loading of the lean solutions, mol $CO_2$/mol MEA |
| $q_{re}$ | specific regeneration heat, MJ/kg $CO_2$ | $C_{oil}$ | specific heat of heat transfer oil, kJ/(kg °C) |
| $Q_{loss}$ | heat loss of the system, kW | $\rho_{oil}$ | density of heat transfer oil, kg/m$^3$ |
| $q_{des}$ | absorption heat, MJ/kg $CO_2$ | $V_{oil}$ | volume flow rate of heat transfer oil, m$^3$/h |

option [11,12]. Using solar thermal energy (STE) to compensate the energy penalty caused by carbon capture is a new concept and has attracted more and more attention [13–18]. Due to the temperature for solvent regeneration ranging from 100 to 120 °C, most of the concentrating solar collectors have the ability to provide the demand temperature of thermal energy. The studied ideas include partially or totally compensating of PCC reboiler duty by STE directly. Cohen et al. [15] performed a preliminary feasibility study on a nominal solar-assisted carbon capture (SPCC) plant based on a very roughly estimated size and cost of solar collectors. Qadir et al., Mokhtar et al. and Li et al. [16–18] performed technical feasibility study and economic assessment on SPCC. The main difference of economic analysis model is the boundary condition such as location, electricity price, carbon tax, cost of solar collector and incentive. Apart from the low temperature STE utilization in PCC system, medium to high temperature STE can also be collected and used for feedwater heating while low pressure steam extracted from low-pressure turbine for post-combustion $CO_2$ capture [19–23].

Though STE assisted $CO_2$ capture is technically and economically feasible, there are still some challenges. There are different options to integrate STE in reboiler. One way is to use STE directly in reboiler. Its advantage is to reduce steam extraction and therefore there will be fewer disturbances in steam turbine cycle, which will result in higher efficiency. However, STE gained from solar collector is intermittent, and the fluctuation of STE will affect desorption. To overcome this problem, either energy storage or steam extraction can be used. However, in order to optimize the system, it is important to understand how the fluctuation of STE affects the performance of chemical absorption, which has not been done in the literature. It is also of importance to validate the simulation results and provide operation and control strategies for SPCC system by carrying out the experimental study.

In this paper, a STE assisted PCC pilot equipment was setup, two types of STE collectors were included, parabolic trough and linear Fresnel collectors. The operation of the solar collectors and the operation of the pilot system were presented. Meanwhile, parameters analyses as well as the dynamic characteristics of the solar collectors and the dynamic response of the integration system were discussed. The objective of the paper is to fill in the knowledge gap, and the results will provide guidelines and insights for the design of solar-assisted PCC.

## 2. Design of pilot system

### 2.1. PCC system

A pilot system was built in Tianjin University for STE assisted $CO_2$ capture based on chemical absorption as shown in Fig. 1a and 1b, and the main parameters are summarized in Table 1 [24].

The absorber and desorber, both with an internal diameter of 0.15 m, are filled with BX500 Gauze-structured packing, which heights are 2.2 m and 1.8 m, respectively. Both of the two columns have a collector plate and a redistributor in the middle of the packing. A demister is fixed above the packing of the absorber and the desorber to reduce the foaminess. The desorber is a thermosyphon column, in which a reboiler is used to strip $CO_2$ from rich solvent. The reboiler is a shell-and-tube heat exchanger, and the heat required by the regeneration is provided by the outer heat source. For each column, a condenser with a shell-and-tube heat exchanger is installed at the exit.

Flue gas is produced by mixing pure $N_2$ and $CO_2$ or $CO_2$ and air. Traces of $SO_2$ and other gas components are ignored. The $CO_2$ concentration in the flue gas is controlled by adjusting its flow rate. The mixed flue gas is preheated to a temperature around 40 °C. Before entering the absorber, the flue gas is fed into a tank filled with deionized water to control the moisture of the flue gas. The flow rate of flue gas at the absorber inlet is controlled by the valve of the blower in the bypass. To keep the water balance and reduce the solvent loss, the flue gas from the absorber outlet is condensed by the condenser.

The rich solvent from the bottom of the absorber is pumped into the desorber. A rich/lean heat exchanger is used to recover heat from the lean solvent. After passing the rich/lean heat exchanger, the lean solvent is further cooled to about 40 °C by a sub-cooler, and then sprayed into the top of the absorber. The flow rate of the rich/lean solvent can be controlled in two ways: by the frequency of the solvent pump or by the throttle valve in the pipeline.

In the design of the cooling water system, a water tank with 2.0 m$^3$ capacity is designed to maintain and store the cooling water. The flow rate of the cooling water to the sub-cooler and the condensers is controlled by the valves of each line.

### 2.2. Solar thermal collectors

Two types of solar collectors, parabolic trough collector (PTC) and linear Fresnel reflector (LFR) were constructed to supply heat to the reboiler. The PTC system is a module of 6.1 m long and 2.5 m aperture with a horizontal east–west single tracking. The collector consists of the foundation base, supporting structure, mirror supporting arm and absorber tube. The mirrors are supported by parabolic shaped cantilever arms. The reflector is made of parabolic shaped glass with silvered reflective coating on the back surface, and the reflectivity of the mirrors is more than 0.9. The focal length of the parabolic concentrator is 0.85 m. The LFR system is a self-built system, which is based on the secondary reflection of solar radiation, and the receiver is a compound parabolic collector (CPC). The LFR is fixed on a tracking system. The collectors are connected to the reboiler directly with the insulated pipeline. Considering the intermittence of solar energy, a 20 kW auxiliary electrical heater is installed to ensure the heat demand of the regeneration when solar energy is insufficient to meet the requirement. Synthetic oil is used as heat transfer fluid (HTF), and the flow rate is controlled by the valve of the inlets of

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