

CO₂ Capture for Low Temperature Heat Utilization Based on Advanced Coconut Shell Biochar

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ABSTRACT

In view of burgeoning carbon dioxide (CO₂) emission, adsorption post-combustion capture technology has drawn more attention. As the most critical part of capture technology, the selectivity of adsorbents with superb performance and appropriate economic benefit becomes a study hot button. Therefore, a new commercial biomass-derived activated carbon, i.e. coconut shell (CS), is developed, investigating the effects of adsorption and desorption temperatures for practical applications. Also, a solar-assisted coal-fired power plant integrated with temperature swing adsorption process is initially proposed for techno-economic assessment. Results show that CS has an excellent low-temperature adsorption capacity (1.19 mmol·g⁻¹ at 0 °C) and a relatively low desorption temperature (1.13 mmol·g⁻¹ at 80 °C). Compared with the system using monoethanolamine and zeolite 13X, carbon emission intensity, levelized cost of electricity and cost of CO₂ removed of the system using CS always show the best performances, corresponding to 93.19 g·kWh⁻¹, 62.32 USD·MWh⁻¹ and 18.67 USD·ton_{CO₂}⁻¹, respectively. CS may be a potential solution for carbon capture with low capital costs, low regeneration temperatures and high adsorption capacities.

Keywords: Coconut shell; High adsorption capacity; Low regeneration temperature; Solar energy

NONMENCLATURE

Abbreviations

TSA	Temperature Swing Adsorption
CS	Coconut Shell
SACFPP	Solar-assisted Coal-fired Power Plant
DAC	Direct Air Capture

MEA	Monoethanolamine
CEI	Carbon Emission Intensity
LCOE	Levelized Cost of Electricity
COA	Cost of CO ₂ Removed

1. INTRODUCTION

Greenhouse gases like CO₂ are released through coal combustion and transports, which cause global warming by trapping the sun's energy. Under the 2015 Paris Agreement, 197 countries agreed to take actions to keep temperature rising below 1.5 °C to avoid the negative impacts of climate change. More than 130 countries, including China, have pledged to reach "carbon neutrality" before mid-21st century. Hence, the demands for CO₂ emission reduction and capture technology are urgent.

CO₂ currently could be captured directly from flue gas in factories or from ambient air, namely direct air capture (DAC). Compared with DAC, post-combustion capture developed rapidly and occupied the main position due to the high energy consumption in light of low CO₂ partial pressure. As the most crucial part of capture process, the study of adsorbent with high efficiency and stability has received increasing attention. A wide variety of porous solid adsorbents have been explored for post-combustion carbon capture, such as zeolite, activated carbon and metal-organic frameworks. It's worth noting that biomass is also a promising candidate for its well-defined heterogeneous micro/nanostructures and morphology, which help create high porosity and controllable pore size. However, biochar-derived activated carbon has not been adequately reported despite its high CO₂ uptake. Lehmann [3] estimated that the utilization of biochar as adsorbent had the potential to absorb up to 1 gigaton of

greenhouse gases per year, which was more than 10% of total global emissions. Hence, biochar has the potential to play a leading role in carbon capture in the future.

For further application to practice, the techno-economic analysis on the CO₂ capture technology using adsorbents at the level of the coal-fired power plants has been investigated. The chemical absorption of solid amine-functionalized materials like monoethanolamine (MEA) has been widely investigated [4]. However, in view of the energy penalty and environmental impact of MEA during solvent regeneration [5], adsorption capture has been recognized as a promising CO₂ capture method for low investment cost and simple automatic operation [6]. Also, it was concluded that temperature swing adsorption (TSA) system based on physical adsorbent i.e. activated carbon was relatively more advantageous than that using MEA in terms of efficiency and cost for a natural gas combined cycle [7]. To further mitigate climate change, strategies integrated CO₂ capture and alternative energy, such as solar energy, could offer a bridge towards the long-term scenario, one dominated by renewable energy generation. However, quite few researches have been conducted to supply a techno-economic study of a solar-assisted power plant with CO₂ adsorption capture. Zhao [8] filled up the blank by integrating solar-assisted PTSA system into an 800MWe coal-fired power plant in 2019. Taking the availability of solar energy into consideration, which tends to favor TSA system, techno-economic assessment for solar-assisted coal-fired power plant (SACFPP) integrated with TSA is necessary for its potential promotion.

In this study, given the knowledge gap between various adsorbents and practical application in light of adsorption efficiency and cost, a novel coconut shell-based activated carbon is developed, along with techno-economic assessment applied to practice. To start with, the effects of adsorption/desorption temperatures on working performances are investigated. What's more, the concept of SACFPP is initially proposed for further techno-economic analysis of coconut shell (CS), which describes a new approach for reducing industrial CO₂ emission.

2. METHODS

2.1 Materials

The CS is purchased from Jingzhiyuan Water Treatment Materials LTD, Henan, China. The sample is activated through physical treatment, namely calcination in high-temperature N₂ atmosphere. What's more, this material has achieved industrial production. Hence, it

goes without saying that the cost of CS is cheap, showing a great possibility for practical utilization at a large scale.

2.2 Gravimetric CO₂ adsorption

CO₂ adsorption capacities and desorption reaction kinetics of CS are investigated with Netzsch STA 449 F3 thermal analyzer. Firstly, approximately 1.5 mg of the sample is heated to 120 °C for degass pre-treatment at 10 °C·min⁻¹ under a flow rate of 40 mL·min⁻¹ of N₂ and held for 1 h. To investigate the low-temperature adsorption performance of CS, the sample is cooled to various adsorption temperatures in the range of 0-30 °C at a rate of 5 °C·min⁻¹ under a flow rate of 40 mL·min⁻¹ of N₂ and remained for 1.5 h with the premixed gas containing 15% CO₂ in N₂. Similarly, after 1 h degass pre-treatment at 120 °C and 1.5 h CO₂ adsorption process with a premixed gas containing 15% CO₂ in N₂ at 25 °C, the sample is then heated to desorption temperatures i.e. 40-80 °C at a rate of 40 mL·min⁻¹ of N₂ and held for 1.5 h for desorption process in order to study the regeneration capacity at different temperatures. The CO₂ adsorption and desorption capacities of CS at different temperatures are calculated by the mass variation before and after adsorption/desorption process.

2.3 Techno-economic analysis

To further explore the potential of CS for a large-scale application, techno-economic analysis of a SACFPP integrated with CO₂ capture system is conducted. Concept of SACFPP integrated with TSA is initially proposed based on our previous work [7] and reference [8], which could take full advantages of low-temperature or cryogenic heat source. The schematic diagram is shown in Figure 1. The proposed system consists of a supercritical coal-fired power plant, along with a solar field and a CO₂ capture system. The basic information of this 800MW power plant is referring to [6]. For solar energy system, one typical city, i.e. Singapore, with tropical weather and possessing the actual solar field, is considered in this study, and the detailed meteorological data can be seen referring to [9]. Vacuum tube collectors (VTC) are taken into consideration in light of the low desorption temperatures of sorbents (<150 °C). And associated calculation could refer to the equations (1) and (2) referring to [2]. In terms of CO₂ capture system, the single adsorption column chosen for the system is 3.5 m for diameter and 2.0 m for length [1]. For SACFPP system, flue gas from power plant is firstly treated by cleaner, and then flows into the cooler in order to cool down to adsorption temperatures of the adsorbents by cooling water. Whereafter, CO₂ in the flue gas is

adsorbed by solid adsorbents in the fluidized bed. At the same time, residual flue gas without CO₂ emits into the atmosphere. By means of circulating continuously between adsorber and desorber in a closed loop, adsorb-saturated adsorbents could transport to desorber and start to regenerate at a high temperature. Regeneration heat required for desorption step is determined based on the basic properties of the selected adsorbents. The high purity CO₂ is ultimately compressed for further transportation and storage. The cyclone is used to separate CO₂ and adsorbents from adsorber. During desorption process, regeneration heat of adsorbent is provided from either solar thermal energy or the steam bleeding from turbine. At sunshine time, steam above desorption temperature is applied for adsorbent regeneration, which is heated in solar thermal collectors. However, when the sunshine isn't appropriate, regeneration energy is supplied by the steam extracted from the turbine. With the utilization of the steam from the turbine, practical amount of electricity produced decreases. Combining solar energy with electrical power, the whole system is able to operate steadily throughout the life cycle. In light of the annual maintenance time of the power plant, the system does not run in December, which has the worst solar radiation over the whole year. Therefore, the proposed system only operates 8016 h per year.

For directly showing the performance of CS, a representative chemical absorbent such as MEA with high absorption capacity and common for commercial use, and another physical adsorbent i.e. zeolite 13X is selected for comparison. Zeolite 13X and CS share the same adsorption system. As for MEA, the absorption system could refer to [2]. For SACFPP with CO₂ capture system using three different adsorbents, the technology and economic evaluation are conducted in terms of three parameters, namely carbon emission intensity (CEI), levelized cost of electricity (LCOE) and cost of CO₂ removed (COA). CEI is used to assess different system designs, which is significant as a criterion of technical viability for various process parameters. LCOE is considered as a widely used tool when comparing costs of different technologies during economic life. Meanwhile, COA is an important comparison parameter for carbon capture and storage. The equations of these parameters could refer to [8].

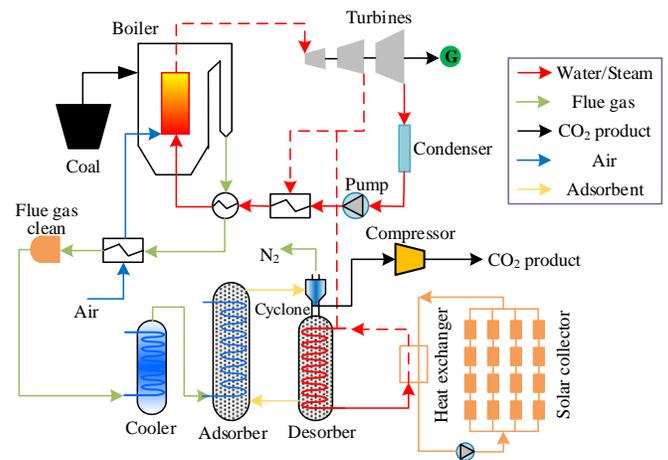


Fig. 1. Schematic diagram of SACFPP integrated with TSA process.

3. RESULTS AND DISCUSSION

3.1 Effects of adsorption temperatures

The CO₂ adsorption capacities of CS at different temperatures i.e. 0-30 °C are investigated with 15% CO₂ partial pressure. As shown in Figure 2, the CO₂ adsorption capacity performs incrementally whilst temperature reduces. Especially, CS shows a relatively high adsorption capacity of 1.19 mmol·g⁻¹ at 0 °C. Also, the adsorption performance declines dramatically at 30 °C, i.e. 0.80 mmol·g⁻¹, with 32.77% decrease compared with that at 0 °C. The comparison of working capacities at various adsorption temperatures indicate the excellent performance of CS at low temperature, showing the potential of integrating with low-temperature heat source e.g. evaporation heat of heat pump.

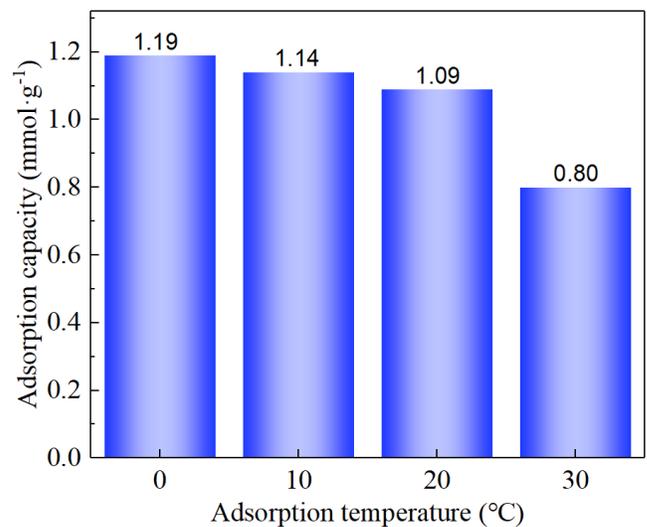


Fig. 2. The CO₂ adsorption performances of CS at different adsorption temperatures with 15% CO₂ partial pressure.

3.2 Effects of desorption temperatures

A relative low desorption temperature is of great significance for the practical application of CO₂ adsorption capture technology in light of energy consumption during regeneration process of the adsorbents. Meanwhile, low-grade heat source such as solar energy and condensation heat of heat pump could be taken into consideration [10]. To further investigate the effect of desorption temperatures, the temperature interval of 40 °C to 80 °C is selected for exploring the adsorption performances of CS. The results are exhibited in Figure 3. The CO₂ desorption capacity of CS increases with the increase of desorption temperature, which agrees with other solid adsorbents. With the desorption temperature increases from 40 °C to 80 °C, the desorption capacity rises rapidly from 0.54 mmol·g⁻¹ to 1.13 mmol·g⁻¹, with a 52.21% increase. Also, it's worth noting that CS has capacity to desorb completely at 80 °C when it adsorbs at 25 °C, which is a relatively low temperature compared with other physical adsorbents.

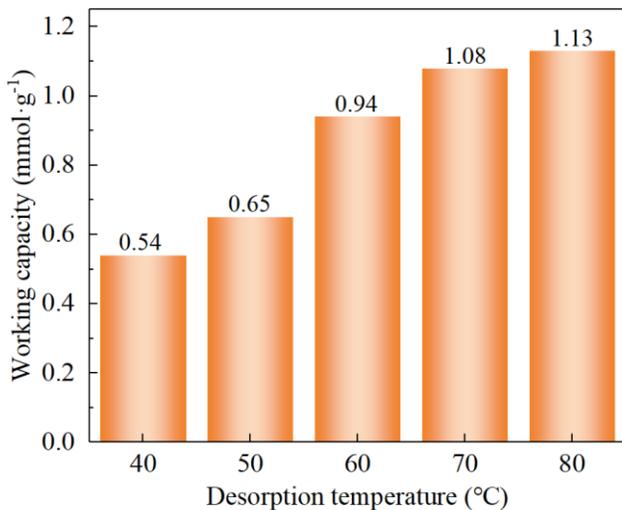


Fig. 3. The CO₂ desorption performances of CS at different desorption temperatures when adsorbed at 25 °C with 15 % CO₂ partial pressure.

3.3 Techno-economic results

The results of the techno-economic estimation are discussed in terms of CEI, LCOE and COA for comparing the effects of different desorption temperatures on the basis of the systems with or without solar energy technology. As shown in Figure 4 and 5, it's obvious that these three parameters rise with the increase of desorption temperatures in two systems, especially with a rapid rise from 70 °C to 80 °C. Also, with the utilization of solar energy system, techno-economic performances of SACFPP using CS are marginally lower than that

without solar energy system because capitalized cost of solar energy collectors could counteract extra electrical power for adsorbent regeneration.

What's more, information presented in Tables 1 [2, 7, 8, 11] is used to calculate the values of CEI, LCOE and COA for different sorbents, and the results are shown in Figure 6. When it comes to CEI, its value of CS is 93.19 g·kWh⁻¹, which is slightly less than that of zeolite 13X and signally lower than (35.66%) that of MEA in light of high regeneration energy caused by temperature difference between adsorption and desorption temperature. The LCOE of the SACFPP using CS is notably lower than that using zeolite and MEA, i.e. 62.32 USD·MWh⁻¹ compared with 69.59 and 68.34 USD·MWh⁻¹, on account of high desorption temperatures and high costs of material and equipment. Finally, the values of COA are related to the values of CEI and LCOE. The corresponding values of COA for the system using MEA, zeolite and CS are 29.65 USD·ton_{CO₂}⁻¹, 29.26 USD·ton_{CO₂}⁻¹ and 18.67 USD·ton_{CO₂}⁻¹, respectively.

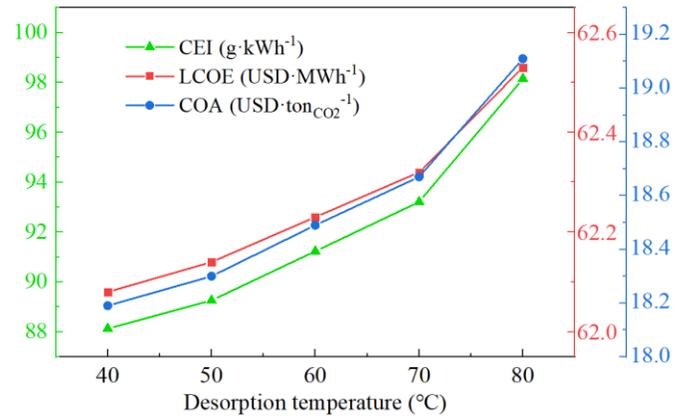


Fig. 4. Variations of CEI, LCOE and COA of CS at different desorption temperatures with solar energy.

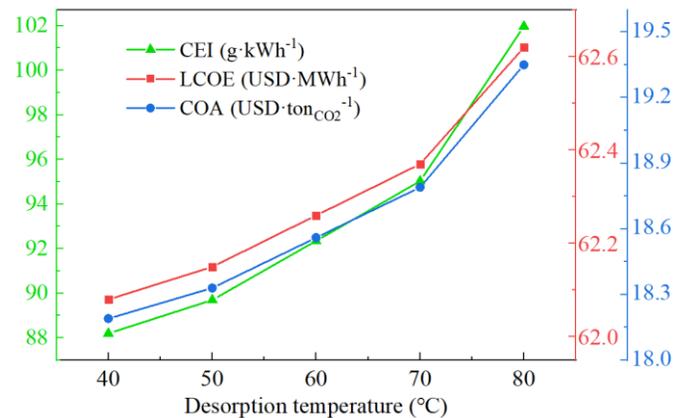


Fig. 5. Variations of CEI, LCOE and COA of CS at different desorption temperatures without solar energy.

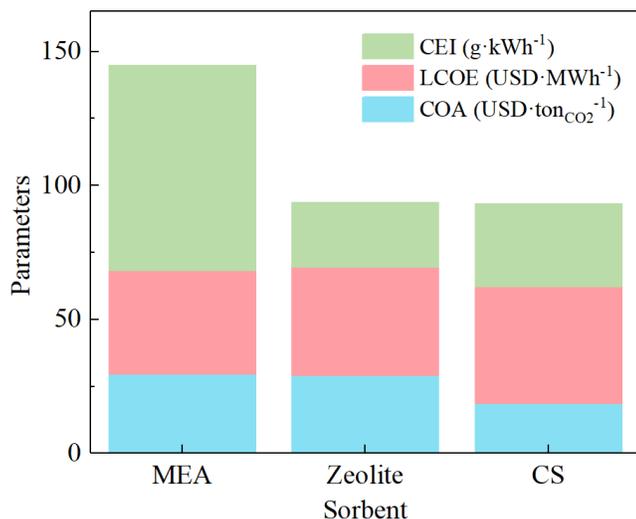


Fig. 6. Techno-economic performances of SACFPP with capture technology using MEA, zeolite and CS.

4. CONCLUSIONS

In this paper, the adsorption and desorption performances and techno-economic analysis are conducted based on biomass-based activated carbon, namely CS, which has achieved commercial production. Conclusions are yielded as follows:

(1) Based on adsorption experiments, the CO₂ adsorption capacity of CS decreases with the increase of adsorption temperature. Especially, it performs high adsorption capacity at low temperatures with 15% CO₂ partial pressure, i.e. 1.19 mmol·g⁻¹ at 0 °C. Meanwhile, CS could desorb completely at relative low temperature, up to 1.13 mmol·g⁻¹ at 80 °C.

(2) A new SACFPP system integrated with TSA technology is initially put forward. The increase of regeneration temperature has a negative influence on techno-economic indicators for the system with or without solar energy system. Employing the techno-economic comparison of the system using three different sorbents, including MEA, zeolite 13X and CS, applied potentials of CS are testified. With low desorption temperature, low capital investment, and high adsorption capacity, CEI, LCOE and COA values are 93.19 g·kWh⁻¹, 62.32 USD·MWh⁻¹, 18.67 USD·ton_{CO2}⁻¹, respectively, which always perform best among three sorbents.

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Table 1. Performance parameters and comparisons of MEA, zeolite 13X and CS.

Technology	MEA	Zeolite 13X	CS
Project life (years)	25	25	25
Construction period (years)	3	2	2
Operation time (h·year ⁻¹)	8016 ^a	8016 ^a	8016 ^a
Discount rate (%)	7	7	7
Operation and maintain cost (% of capital investment)	7	7	7
Equipment salvage value	0	0	0
Power plant			
Total specific investment (USD·kW ⁻¹)	1012.5	1012.5	1012.5
Price of coal (USD·ton ⁻¹)	95	95	95
Power output after CO ₂ capture (MW)	408.63 ^a	632.00 ^a	635.11 ^a
Sorbent system			
Cost of sorbent (USD·kg ⁻¹)	0.97	5.59	3.95 ^b
Capture capacity (mmol·g ⁻¹)	8.186	2.77	1.02
Desorption temperature (°C)	120	75	70
Regeneration energy (GJ·tonCO ₂ ⁻¹)	4.09	2.46	0.46 ^a
CO ₂ adsorption column (USD·column ⁻¹)	N	3606	3606
Bed void of adsorption column	N	0.37	0.37
Total cost of equipment (million USD)	620	N	N
Cost of compression system (USD·kW ⁻¹)	115.7	115.7	115.7
Approximate cost of exchanger (USD·exchanger ⁻¹)	1600 ^b	1600 ^b	1400 ^b
Cost of cyclone (USD·kW ⁻¹)	853.1	853.1	853.1
Solar fields			
Heat collector temperature (°C)	125	80	75
Approximate cost of ETC (USD·m ⁻²)	122.27	122.27	122.27

Notes: N=none; a: values calculated or measured by the author; b: values obtained from practical purchase.