Solar Energy Materials and Solar Cells 185 (2018) 494–504

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

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

Solar-assisted pressure-temperature swing adsorption for CO_2 capture: Effect of adsorbent materials

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ARTICLE INFO

Keywords:
Solar energy
Adsorbent materials
Carbon capture
PTSA
Energy efficiency

ABSTRACT

Because of the ability to utilize the low-grade solar thermal energy for regeneration, a CO_2 capture system characterized by solar-assisted pressure temperature swing adsorption (SOL-PTSA) is studied on the effects of adsorbent materials. A detailed cycle description is firstly presented within the diagram of adsorption isotherm for the energy-efficiency analysis. Typical adsorbent materials, including zeolites and chemical adsorbent, are assessed in terms of sensible heat and latent heat, etc. Then, the energy consumption and the second-law efficiency, which can be considered as lumped indicators from such material parameters, are chosen as performance indicators as well. The influence of separation temperature, desorption temperature, CO_2 concentration and CO_2 adsorption pressure on system performance are finally obtained. For the chosen three adsorbent materials, the energy consumption of SOL-PTSA system is at the range of 25.96–87.76 kJ/mol, and the corresponding second-law efficiencies are at the range of 9.18–26.89%. The effect of adsorbent materials on the energy-efficiency of SOL-PTSA system mainly depends on specific heat, CO_2 working capacity and cycle design. In addition, the integration options of solar energy into PTSA technology are also discussed from the standpoint of the utilization of solar grade heat due to two energy loads required for PTSA's operation.

1. Introduction

The global warming that caused by greenhouse gases has been regarded as one of the world's most serious shared environmental problems [1]. As a major greenhouse gas, carbon dioxide (CO_2) is emitted from a range of industries such as power plants and cement manufacturing. The increasing CO_2 content in the air has spurred academic researchers all over the world aiming to reduce anthropogenic CO_2 emissions. CO_2 capture and storage (CCS), extensive use of sustainable energy resources and improving the efficiency of energy conversion are recognized the three key technologies to mitigate climate change [2].

Among the methods developed for CCS, CO_2 adsorption technology is of great interest due to its low energy consumption, low costs and ease of application. CO_2 adsorption processes are mainly of two types according to the way in which the adsorbed amount is changed between the adsorption and desorption steps: by changing the pressure or/and the temperature [3,4].

Pressure-temperature swing adsorption (PTSA) process is a potential adsorption approach for CO_2 capture. The combination of pressure swing adsorption (PSA) and temperature swing adsorption (TSA) shows several significant advantages [5]. In the hybrid process of PTSA, the rise of pressure is needed in step of adsorption and temperature rise is required for regeneration in step of desorption [6]. Compared with TSA cycle, the operating cost of PTSA approach could be reduced because of lower regeneration temperature requirement [7]. Therefore, PTSA process is of interest because of its ability to directly utilize these low-grade thermal energy resources for regeneration.

So far, only a few of the adsorbent-based studies for CO_2 capture reported in the literature are based on TSA compared to PSA process. Tlili et al. [3] have performed the experimental work with zeolite 5A on a small laboratory column using TSA. Clausse et al. [8] have presented a numerical study by indirect TSA with desorption temperature ranging from 100 °C to 200 °C. Plaza et al. [9] have tested a commercial activated carbon and compared three different regeneration strategies (TSA, VSA and TVSA). Song et al. [5] have investigated an advanced PTSA process for CO_2 capture by integrating chemical heat transformer and pressure recovery. Ntiamoah et al. [10] have carried out the experiments and simulations using the CO_2 product as the regeneration

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https://doi.org/10.1016/j.solmat.2018.06.004
Received 14 September 2017; Received in revised form 19 April 2018; Accepted 4 June 2018
0927-0248/

Nomenclature

Symbol

C_{CO2}	amount of CO_2 capture per cycle (mol)
$C_{p,s}$	specific heat capacity of solid adsorbent (J/kgK)
$C_{p,a}$	specific heat capacity of adsorbed phase (J/kgK)
EC	energy consumption (kJ/mol)
Eff_{2nd}	second-law efficiency (%)
k_{air}	polytropic parameter
P	pressure (bar)
q	amount of CO_2 adsorption (mol/kg)
R	universal gas constant (8.314 J/molK)
Re_{CO2}	CO_2 recovery rate (%)
T	temperature (K)
V	volume of adsorber (m^3)
W	work consumption (kJ)
WC	working capacity (mol/kg)
y_{CO2}	CO_2 concentration (vol%)

Subscripts

ac	actual
ad	adsorption
atm	atmosphere
com	compressor
dep	depressurization
heat	heating
min	minimum

Greek letters

β	proportionality factor of CO_2 working capacity
ε	porosity
η_{unused}	percentage of unused bed (%)

Acronyms

CA	chemical adsorbent
CCS	CO_2 capture and storage
ORC	organic Rankine cycle
PSA	pressure swing adsorption
SOL-PTSA	solar-assisted pressure-temperature swing adsorption
TSA	temperature swing adsorption

purge gas in fixed bed TSA systems. Zhao et al. [11] have presented a comparative study on energy efficiency performance of VPSA and PTSA for CO_2 capture. Among these studies of TSA cycles, there are few studies that focus on the effect of adsorbent materials on the energy-efficiency performance of PTSA technology for CO_2 capture.

As an ideal alternative energy, solar energy has several advantages such as no pollution, a huge total radiant power and an endless supply [12,13]. Integration of solar energy utilization in fossil fuel-based power plant with CO_2 capture, also named as 'hybridization', can offer reduction of carbon emissions because of the lower carbon intensity of solar technologies. However, the concept of hybridization is novel, and there are a limited number of studies available in the literature. Li et al. [14] have assessed the feasibility of integrating solar energy into a power plant with amine-based chemical absorption for CO_2 capture. Parvareh et al. [15] have presented a review that focuses on the features of different solar thermal energy technologies to be integrated with the retrofitted power plant. Zhao et al. [16] have assessed existing options and measures of solar energy integration for the major classifications of CO_2 capture engineering by literature research. The trends of literature review have shown that the exiting researches of integration of solar energy utilization with CO_2 capture mainly focus on the technology of chemical absorption, rather than other approaches. However, PTSA process also has the potential to be integrated with solar energy utilization due to its ability to directly utilize low-grade thermal energy resources.

Given these backgrounds, there are few studies on the whole-chain analysis of solar-assisted pressure-temperature swing adsorption (SOL-PTSA) from material to system. As shown in Fig. 1, the energy analysis of SOL-PTSA cycle depends on material properties and external conditions. Therefore, the scenario of this study on solar energy materials is one kind of cutting-edge CO_2 capture systems featured by SOL-PTSA. To achieve a performance analysis from the materials to the systems, a detailed cycle description for the new system is presented in the diagram of adsorption isotherm. Three adsorbent materials, which are zeolites 5A, zeolites 13X and chemical adsorbent, are chosen for the energy-efficiency analysis of SOL-PTSA system regarding the energy consumption and the second-law efficiency. The influence of separation temperature, desorption temperature, CO_2 concentration and CO_2 adsorption pressure on the energy-efficiency of PTSA are also evaluated in the thermodynamic analysis. In addition, the integration options of solar energy into PTSA technology are also discussed from the point of the utilization of solar grade heat.

2. Solar-assisted CO_2 capture system and materials

2.1. Proposed system

A simplified diagram of the SOL-PTSA system is presented in Fig. 2. The novel system is composed of a solar heating system, a cooling tower and a PTSA system. The thermal energy required by regeneration process can be supported by solar thermal collectors, which are a special kind of heat exchangers that transform solar radiation energy to the internal energy of transport medium. The thermal energy of adsorption process is released by cooling water tower. Generally, step sequence of PTSA system is summarized in Table 1. For PTSA cycle, the five steps

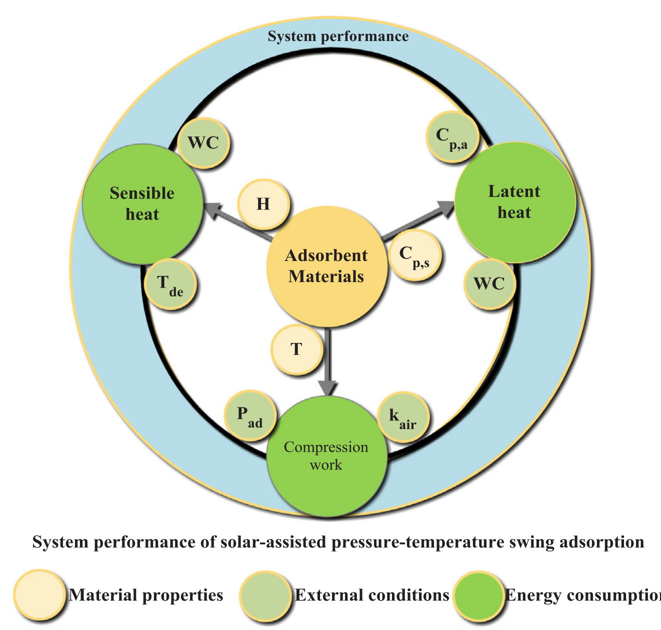

Fig. 1. Conditions for energy analysis of SOL-PTSA cycle.