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Review article

An overview of activated carbons utilization for the post-combustion carbon dioxide capture

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A B S T R A C T

The increase of carbon dioxide (CO_2) concentration in the ambient air has become the key factor in the pace of temperature rise, and accordingly, is a primary contributor towards global warming scenario. In view of this, the quick mitigation efforts associated with capturing CO_2 from fossil fuel combustion source must be implemented to alleviate environmental catastrophic events in future. Therefore, the purpose of this paper was to review the role and performances of activated carbon in capturing anthropogenic CO_2 flue gas prior to emission to air. Throughout this paper, the activated carbons which were proposed to be a separation medium for CO_2 capture are evaluated in terms of equilibrium adsorption capacity as well as the surface modification. The utilization of the activated carbons instead of current state-of-art technology, which is the chemical absorption is promising as it avoids higher energy penalty encountered in regeneration process and the consumption of corrosive chemical such as aqueous amine-based solvent. In addition, the investigation on the potential of activated carbons for post-combustion CO_2 capture is expected to confer scientists with critical information related to the future direction of the activated carbons in an industrial application, and as an alternative to conventional amine scrubbing process.

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1. Introduction

The increasing of carbon dioxide (CO_2) concentration in the atmosphere is viewed as a serious problem to all people around the world. In 2014, the CO_2 concentrations in ambient air approached 400 part per million (ppm) and it increased by 120 ppm from the CO_2 concentrations in the pre-industrial time [1]. With regard to

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this continual increased of CO_2 emission from fossil fuels such as oil, coal, and natural gas combustions that cater diverse purposes such as electricity generation, transportation, and industrial sector, deteriorations of both environmental and ecosystem conditions are likely to happen. In addition, with the never-ending emission of CO_2 gas to the surrounding, the Kyoto Protocol had been enforced in 2005 in which its core objective is to reduce the greenhouse gas concentrations primarily CO_2, methane (CH_4), and nitrous oxide (NO_x) in the atmosphere to a minimum level, by which catastrophic impacts towards the ecosystem can be evaded. In line with this policy, it has been reported that the CO_2 emissions from industrialized countries must be reduced to lesser than 6% by 2012 [2]. With regard to this, Malaysia affirms to take appropriate initiatives to decrease the level of CO_2 concentrations by 40% in 2020, with respect to its concentration level in 2005. In order to realize the vision, proper mitigation techniques must be addressed. In Malaysia, power plant sector has released significant amount of CO_2 pollutants, and in 2010, the total CO_2 emission from this sector almost reached 47.63 million tons, and thus accounted for 52.29% of the total CO_2 emission [3]. Since electricity generation is the prevailing contributor of CO_2 emission in Malaysia, the CO_2 capture should be implemented starting from this source. The present technology for CO_2 capture which is broadly adopted in the industry nowadays is the post-combustion system, whereby the flue gas separation takes place after the combustion process of fossil fuel. The benefits of this process include ease in retrofitting the existing power plants and flexibility of the process, whereby the power plant is still capable to operate even if there are malfunctions in the capturing system [4]. The conditions of flue gas streams from the coal and natural gas combustion are summarized in Table 1, and the simplified diagram of the post-combustion carbon capture is shown in Fig. 1. In post-combustion CO_2 capture, the temperature of the flue gases will cool down and the gas streams will undergo a pre-treatment scheme prior to capturing system. The purpose of pre-treatment system or known as gas cleaning is mostly to reduce the concentration of impurities in the flue gas such as nitrogen oxide, sulphur oxide, water vapour, and particulate matter [5]. In addition, Chen et al. [6] reported that typical temperature for the flue gas in post-combustion system is between 50 and 150 °C.

By far, chemical absorption with amine-based or ammonia-based absorbent receives the greatest attention due to its high process efficiency, and thus, is widely performed by industrialists. This process that commonly utilizes alkanolamine-functional groups such as monoethanolamine (MEA) will react with CO_2 from the flue gas in an absorber column at temperature between 40 and 60 °C and at ambient pressure [14,15]. During this stage, flue gas is introduced at the bottom part of the absorber unit whilst 20–30% MEA solution is added from the top [16]. By utilizing the amine-functional group, CO_2 absorption will take place through a chemical reaction mechanism, owing to acid-base ionic species in the solution [17]. Upon equilibrium, a rich-CO_2 solution will be regenerated in a stripper column at high temperature around 100–140 °C, in order to release the bonded CO_2 molecules from the absorbent [14,15,18]. Whilst purified CO_2 is compressed and sequestered, the regenerated amine-based solvent will be cooled and recycled to the absorption column [16,18]. The schematic diagram of the amine scrubbing process is illustrated in Fig. 2.

Table 1
Summary of flue gas conditions in post-combustion technology [10–13].

Components	Coal-fired flue gas[a]	Natural gas-fired flue gas
N_2 (vol%)	70–80	73–80
CO_2 (vol%)	11–15	3–8
H_2O (vol%)	5–12	7–14.6
O_2 (vol%)	3–6	4.45–15
SO_2 (ppm)	200–4000	<10
SO_3 (ppm)	0–20	–
NO_x (ppm)	200–800	50–70
CO (ppm)	50–$<$100	5–300
Hg/As (ppb)	1–7	–
Particulate matters (g/m^3)	5–20	–
Pressure (bar)	1	1
CO_2 partial pressure (bar)	0.12–0.15	0.05–0.1

[a] Before flue gas treatment—FGD and deNO_x.

Despite the good performance of absorption technology in capturing CO_2 which can be up to 98% efficiency [20], heavy consumption of amine-based solvent contributes towards equipment corrosion, and hence, requires special materials for equipment construction which can withstand corrosivity of these chemicals [21,22]. Moreover, the corrosivity and generation of chemically-unstable compounds during the heating process are difficult to handle than solid adsorbents [20]. In addition, a higher energy input is imposed during solvent regeneration process due to stronger chemical interaction between CO_2 and basic amine solvent [22,23]. Yu et al. [24] reported that the total energy consumption for solvent regeneration has accounted for 60% of the total energy consumption. Besides, it is reported that heat input to remove one ton CO_2 consumes about 2.5 to 3.6 GJ [16]. Furthermore, with regards to high volatility of these amine compounds, there is a possibility that a minor portion of these chemicals will be evaporated and released to ambient along with cleaner flue gas, and accordingly impacts the ecosystem. Moreover, another concern in utilizing the chemical absorption process is due to amine degradation, either through oxidative degradation or thermal degradation. The oxidative degradation causes the amine compounds to fragment into toxic derivatives such as organic acid, ammonia, and amide, whilst the thermal degradation that usually takes place in a stripping column tends to produce large molecular weight of the amine-chain products. The potential of the amine compounds to degrade and accumulate in solvent phase will result in poor CO_2 absorption capacity and kinetic rate, and thus necessitates a frequent injection of fresh absorbent and contributes to higher operating cost [19].

Due to the shortcomings of conventional amine scrubbing process in CO_2 removal from flue gas, solid adsorption process is proposed as an alternative to the current technology. The adsorption scheme is said to offer miscellaneous advantages including high adsorption capacity at ambient conditions, low regeneration cost, long-term stability, fast kinetics, evading in moisture removal from flue gas, and ease in terms of handling [25–27]. In addition, adsorption system is attractive since it can reduce the total energy consumption in regeneration process, owing to lower heat capacity of adsorbent as compared to water, as well as skipping the water evaporation stage [28]. This technology involves two stages which are CO_2 adsorption onto the material surfaces in an adsorption column via physical (physisorption) or chemical (chemisorption) bonding. Upon equilibrium, solid adsorbents will be regenerated through a pressure swing (PSA) or thermal swing (TSA) process, so that the adsorbed CO_2 molecules can be discharged from the carbon surfaces and the adsorbents can be reused for the next adsorption cycle [23,29]. In TSA system, regeneration process is performed by increasing the operating temperature, whilst PSA is a process where the CO_2 molecule is desorbed from carbon surface upon pressure reduction [30]. The flow diagram of the adsorption process for CO_2 removal from flue gas is shown in Fig. 3.

In considering the adsorption technology as an alternative to amine scrubbing process, there are a few guidelines that must be abided by researchers so that effectual separation process is attained. Accordingly, the selection of adsorbent should satisfy the following features which include high adsorption capacity, high