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Isotherm and Thermodynamic Analysis of Carbon Dioxide on Activated Carbon

Nor Adilla Rashidi[a], Suzana Yusup[a,]*, Azry Borhan[a]

[a]*Chemical Engineering Department, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 32610 Tronoh, Perak, Malaysia*

Abstract

In this study, commercial Norit® SX2 activated carbon has been evaluated as a solid adsorbent for carbon dioxide (CO_2) capture at the post-combustion conditions, which are at an ambient pressure and low temperatures (< 120°C). The CO_2 equilibrium adsorption capacity is assessed through a static volumetric technique. This solid adsorbent is characterized in terms of elemental analysis, nitrogen physisorption, as well as surface morphology. The CO_2 adsorptive property of the commercial Norit® SX2 demonstrates a reduction in the amount of CO_2 adsorbed at an elevated temperature, and accordingly, it indicates that CO_2 adsorption is a physical adsorption process and demonstrates a behavior of an exothermic reaction, which consistent with the thermodynamics analysis. Different isotherm models are applied to mathematically model the CO_2 adsorption, and on basis of the regression coefficient (R^2), the Freundlich model provides a perfect fit to the experimental data, owing to closeness of the R^2 to unity. The result obtained in this study can serve as a benchmark while searching for inexpensive and superior activated carbon production in future studies.

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Keywords: Activated carbon; CO_2 adsorption; Isotherm; Physisorption; Thermodynamics.

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1. Introduction

The climatic change is undeniably the main environmental problem in the 21st century that faces the mankind today. By now, Malaysia has experienced harsh weather events such as drought and flooding which results in economic losses and worsens the human health. Tangang et al. [1] projected that the global warming contributes to increase in surface temperature to 3-5°C by end of the 21st century. This warmer atmosphere drives ice and glacier melting, thus increases sea level to 95 cm, and may influence the rainfall pattern too [2]. These ecological damages are primarily contributed from the anthropogenic carbon dioxide (CO_2) emission from industrial sectors i.e. power plant, gas processing, refinery, chemical and petrochemical, iron and steel, as well as in cement manufacturing [3]. Due to rapid industrialization activity and prolong CO_2 atmospheric lifetime, the CO_2 concentration increases from 280 ppm in pre-industrial period to almost 400 ppm today, despite its recommended limit is at 350 ppm [4]. Since the estimated CO_2 concentration is beyond the upper limit, mitigating the CO_2 emission needs to be considered. Several methods have been introduced by researchers in tackling this problem, which include an improvement in energy efficiency, shift to lower carbon-fuel material and renewable energy, promote afforestation and reforestation, along with carbon capture and sequestration (CCS) [5]. Amongst these options, CCS is promising since it is capable to minimize the CO_2 emission from large point emission sources such as power sector, up to 85-90% [5, 6]. Capturing CO_2 from these power plants occurs in three different routes, viz.,

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* Corresponding author. Tel.: +6-05-368-7642 ; fax: +6-05-368-8205.
E-mail address: drsuzana_yusuf@petronas.com.my

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post-combustion, pre-combustion, and oxy-fuel combustion. Between these techniques, the post-combustion route is extensively employed in industries for the CO_2 removal from an exhaust gas of fossil fuel combustion. Wide acceptance of this technology is associated with an easiness of retrofitting the existing power plant, and allows the combustion system to remain unchanged [5, 7]. Presently, conventional method for the post-combustion CO_2 capture is via amine scrubbing system. Throughout this technology, the flue gas which is at 40-60°C passes through an absorber column and reacts with aqueous amine solutions. Upon equilibrium, the CO_2-loaded amine solution is drained from the absorber and is transported to a stripper, whereby the CO_2 is released at higher temperature (> 100 °C) [8, 9]. Despite being extensively applied at the industrial scales, consumption of amine based solvent such as monoethanolamine has its own limitations, owing to high energy requirement for absorbent regeneration, equipment corrosion, and potential of solvent degradation [10]. Moreover, evaporation and amine loss to ambient air is a big challenge, as atmospheric degradation of the amine-based solvent produce a wide range of byproducts such as amide, aldehyde, nitrosamine, and nitramine, that jeopardizes both health and environmental aspect [11].

Due to numerous side effects of the amine scrubbing, alternative to this conventional technology should be pursued. Since the condition of post-combustion is only at atmospheric pressure, membrane separation and cryogenic distillation is impractical for the CO_2 removal. Due to low pressure of the flue gas, driving force for the membrane separation is low as well [12]. Meanwhile, cryogenic distillation that includes a cooling step and enables liquefied CO_2 production is unfavorable for the post-combustion CO_2 capture, as it requires high energy requirement for the refrigeration stage [5, 12, 13]. Due to limitation of these technologies, solid adsorption has been proposed due to its plenteous advantages such as low energy requirement for regeneration, better CO_2 adsorption capacity, high selectivity, low equipment cost, and easy to handle. Lower energy penalty in the adsorption-desorption process is owed to absence in water and low heat capacity of the solid adsorbent [14]. Amongst the low-temperature adsorbents, activated carbon presents several benefits such as hydrophobic in nature, inexpensive, and less regeneration energy [15]. In this present study, performance of the CO_2 adsorption onto the commercial activated carbon is evaluated at an ambient pressure and at temperature range of 25-100 °C. Besides, the CO_2 adsorption isotherm is assessed through several models. This isotherm analysis is significant as it defines the gas-solid adsorption behavior and to assist in the process optimization and design [6, 16]. The typical isotherm of gas adsorption onto solid adsorbent is illustrated in Figure 1.

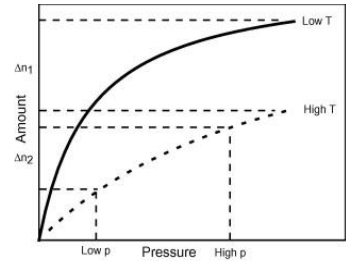

Fig. 1: Typical gas-solid physisorption isotherm [16]

2. Experimental

2.1. Material and Characterization

In this study, the commercial multi-purpose Norit® SX2 activated carbon supplied by Sigma Aldrich (M) Sdn. Bhd. was used. This activated carbon which is in powdered form had been produced from peat-based resources, and was steam-activated and acid washed. The textural properties of the activated carbon in terms of surface area and porosity were evaluated by nitrogen physisorption at -196°C by using a Micromeritics Tristar II apparatus. Prior to the measurement, carbon sample was outgassed at 350°C for four hours, to remove the physically adsorbed moisture and contaminant from the surface. Elemental structures of this solid adsorbent were identified through an ultimate analysis, using a CHNS/O analyzer (Perkin Elmer PE2400). Moreover, the surface morphology was analyzed via Field Emission Scanning Electron Microscopy (FESEM). In the FESEM analysis, a small portion of the sample was mounted to the sample holder by using a double-sided adhesive tape [17].

2.2. CO_2 Adsorption Measurement

The volumetric adsorption of purified CO_2 (99.8% purity) was performed by using a High Pressure Volumetric Analyzer from the Particulate System. Prior to CO_2 adsorption, about 0.3-0.4 g of the carbon sample was placed inside a 2 cm^3 sample cylinder, and degassed at 150°C for 8 hours under a vacuum condition, to ensure all impurities were removed from the carbon structures. A filter gasket of size 60 μm was placed on top of the sample cylinder, to prevent the fine particles to enter the valve [18]. Upon completion of the degassing step, the samples were cooled to ambient temperature and readied for subsequent adsorption stage at temperature range of 25-100°C. At low temperature of 25-50°C, the sample temperature was regulated by Julabo re-circulating water bath, whereas at elevated temperature (100 °C), a furnace was used to control the temperature. The CO_2 adsorption process