Ammonia modification of activated carbon to enhance carbon dioxide adsorption: Effect of pre-oxidation

Mohammad Saleh Shafeeyan, Wan Mohd Ashri Wan Daud*, Amirhossein Houshmand, Arash Arami-Niya

Department of Chemical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

A commercial granular activated carbon (GAC) was subjected to thermal treatment with ammonia for obtaining an efficient carbon dioxide (CO2) adsorbent. In general, CO2 adsorption capacity of activated carbon can be increased by introduction of basic nitrogen functionalities onto the carbon surface. In this work, the effect of oxygen surface groups before introduction of basic nitrogen functionalities to the carbon surface on CO2 adsorption capacity was investigated. For this purpose two different approaches of ammonia treatment without preliminary oxidation and amination of oxidized samples were studied. Modified carbons were characterized by elemental analysis and Fourier Transform Infrared spectroscopy (FT-IR) to study the impact of changes in surface chemistry and formation of specific surface groups on adsorption properties. The texture of the samples was characterized by conducting N2 adsorption/desorption at −196 °C. CO2 capture performance of the samples was investigated using a thermogravimetric analysis (TGA). It was found that in both modification techniques, the presence of nitrogen functionalities on carbon surface generally increased the CO2 adsorption capacity. The results indicated that oxidation followed by high temperature ammonia treatment (800 °C) considerably enhanced the CO2 uptake at higher temperatures.

1. Introduction

It is widely accepted that carbon dioxide (CO2) is the most important greenhouse gas with the largest impact on climate change [1,2]. The increase in the atmospheric level of CO2, has led to the search for technologies designed to capture CO2 from point source emissions and stabilize its concentration in the atmosphere [3–5]. To date, most of commercial CO2 capture plants use amine-based processes and wet scrubbing systems [6,7], but they have serious drawbacks, such as high energy requirements and corrosion of process equipment [1,2,8–11]. Adsorption is considered as one of the most viable options that can be applied to carry out the separation of CO2 as it could reduce the cost associated with the capture step [4,10–13]. Among all adsorbents, activated carbons are being proposed as suitable candidates for CO2 capture: they are inexpensive, less sensitive to moisture, present a high CO2 adsorption capacity at ambient pressure and, moreover, they are easy to regenerate [14,15].

The CO2 adsorption performance of activated carbon is strongly influenced by the modification of surface chemistry [16]. The basic nature of the sorbents is expected to be favorable for their application in the adsorption of an acidic gas, such as CO2 [17,18]. It has been recognized that introduction of basic nitrogen functionalities into the carbon surface can increase the capacity of activated carbon to adsorb CO2 [13–5,9–11,17–22]. One of the most common procedures used for creation of nitrogen surface groups is the reaction with nitrogen containing reagents (such as NH3 and amines) [19,23–28]. The objective of ammonia treatment is to increase the basicity of activated carbon by introducing basic nitrogen functionalities to the carbon surface [27–31]. Several authors have studied thermal treatment of carbons in an ammonia atmosphere [24,26–28,32]. Plaza et al. [16,18] proposed the modification of activated carbon with gaseous ammonia as a suitable technique to produce efficient CO2 adsorbents.

Although the presence of acidic oxygen functionalities individually is undesirable for CO2 adsorption, before introduction of nitrogen functionalities onto the carbon surface the carbon is usually oxidized. The main reason for surface oxidation and development of oxygen surface groups is the role of these functionalities as an intermediate stage to develop some oxygenated anchoring sites before introducing nitrogen functionalities to the carbon surface [24,33]. When the oxidized carbons are treated...
with ammonia at high temperatures, the free radicals (such as NH₂, NH, and atomic hydrogen) which were created during ammonia decomposition may attack to the surface oxides and active sites present on the carbon surface to form nitrogen containing functional groups [26,27,29,32]. Mangum et al. [25] modified activated carbon fiber (ACF) with dry ammonia and demonstrated that reactivity of ammonia gas with carbon surface and consequent formation of N-containing functionalities increase with the oxygen content of precursor carbon.

It has been reported that CO₂ adsorption capacity of activated carbon decreases with increasing adsorption temperature due to the physical nature of the adsorption process [4,11,15,16,18,19,21,22]. As in CO₂ capture plants, generally separation from the flue gas streams should be carried out at relatively high temperature (up to 100 °C) [1,12,22], the main objective of this work is to develop an adsorbent with high adsorption capacity at higher temperatures. To develop such an adsorbent, previous works have mainly focused on zeolite-based adsorbents due to their promising results in CO₂ separation from gas mixtures. However, the presence of water inhibits the CO₂ adsorption capacity of these materials [12,34]. Accordingly, in this study oxidation preceding high temperature amination is proposed as a suitable modification technique for improving the capture performance of activated carbons at relatively high temperature.

2. Experimental

2.1. Activated carbon sample

A commercial palm shell-based granular activated carbon (GAC) was used as starting material for the preparation of CO₂ adsorbent. The precursor was ground and sieved to the US mesh size 20–35 (850–500 μm) for all further treatments. In order to eliminate fines, it was then thoroughly washed with distilled-deionized water (DDW), dried at 105 °C for 24 h to remove moisture, and stored in a vacuumed desiccator until use. The following is a brief outline of the process used for the modification of these samples.

2.2. Ammonia modification

In order to ascertain if the presence of oxygen surface groups before amination could improve the CO₂ adsorption capacity in some way, two different approaches were studied. These included ammonia treatment of carbons that were heat treated under nitrogen (named without preliminary oxidation) and amination of oxidized samples (named with preliminary oxidation). Furthermore, in attempt to produce carbon adsorbents with different amount and type of N-containing functionalities, ammonia treatment was performed at two different temperatures for both methods.

Ammonia modification without pre oxidation consisted of placing around 1 g of activated carbon in a tubular quartz reactor under a flow of 75 cm³ min⁻¹ nitrogen. The sample was heated in nitrogen flow using a heating rate of 10 °C min⁻¹. Once the temperature reached the desired value, the feed gas (nitrogen) was changed to reactive gas (pure ammonia) at the same flow rate. The sample was held at the final temperature for 2 h (soaking time) and then cooled down to 100 °C under the same cooling rate. Finally, the flow was switched from NH₃ to N₂ and the sample was cooled down to room temperature.

For ammonia treatment with pre oxidation, about 1 g sample was put into a quartz reactor. Air was then introduced and the reactor temperature was ramped (10 °C min⁻¹) to 400 °C. This temperature was selected for air oxidation as it was reported to be the optimum temperature for addition of surface oxygen groups [35–37]. The sample was held at this temperature for 2.5 h and then cooled down to room temperature before the gas was switched to pure ammonia. Both the air and NH₃ flow rates were set at 75 cm³ min⁻¹. Next, the sample was heated in ammonia atmosphere with a heating rate of 10 °C min⁻¹ until the desired temperature was reached and ammonia treatment was then performed with the same reaction conditions described above. The modified carbons were denoted on the basis of the type of pre treatment and final temperature of ammonia modification. For example OXA-800 represents ammonia treatment of oxidized sample at 800 °C, and HTA-400 shows ammonia modification of heat treated sample at 400 °C.

2.3. Chemical characterization of the samples

The obtained samples were characterized in terms of chemical composition and surface chemistry to detect and verify the existence of surface functional groups. Ultimate analysis was carried out using a PerkinElmer-2400-II CHNS/O elemental analyzer in order to determine the chemical composition of the carbon samples. It is important to mention that the elemental analysis here only analyzes the nitrogen, carbon, sulfur, and hydrogen content of carbon. The oxygen content was estimated by difference assuming that only five elements, C, H, N, S, and O, could be gasified from carbon samples. Proximate analysis was carried out with the aid of TGA to determine the amount of ash and volatile matter. The pH at the potential of zero charge (pHₚ₀) of each sample was estimated using a mass titration method proposed by Noh and Schwarz [38]. FTIR spectra of the carbon samples were taken with a PerkinElmer-2000 FTIR spectrometer using KBr disks prepared by mixing 0.5% of finely ground carbon sample in KBr. Pellet made of pure KBr was used as a reference sample for background measurements. The spectra were recorded from 4000 to 400 cm⁻¹ at a resolution of 4 cm⁻¹ [28].

2.4. Textural characterization of the samples

Textural characterization of the samples was carried out by conducting N₂ adsorption/desorption at −196 °C using a Micromeritics ASAP 2020 analyzer. The samples were degassed for 24 h under vacuum at 130 °C, prior to measurements. Experimental adsorption data over a relative pressure (P/P₀) range of 0.05–0.2 was used to calculate surface area values using the standard Brunauer, Emmett, and Teller (BET) method [39]. The total pore volume (Vtotal) was assessed from the amount of adsorbed N₂ near the saturation point (P/P₀ = 0.99). The classical Dubinin–Radushkevich (DR) equation in the relative pressure range of 10⁻³ to 10⁻¹ was used to evaluate the micropore volume (Vmicrometer) of the studied samples [40].

2.5. CO₂ capture measurement

Assessment of the CO₂ adsorption performance of the modified samples at atmospheric pressure was carried out using a TGA/SDT851 thermogravimetric analyser (TGA). Two different experiments were performed: isothermal and temperature-programmed (TP) CO₂ adsorption of the studied adsorbents. In the isothermal tests, about 10 mg of the adsorbent was placed in a small pan, heated up to 110 °C under pure N₂ flow (75 cm³ min⁻¹) and held isothermally for 1 h until the weight of the sample became stable. The temperature was then decreased to 30 °C and the gas was switched to pure CO₂ at the same flow rate. The sample was held isothermally at 30 °C for 1 h to achieve a complete saturation. The weight increase during this stage was considered as the CO₂ cap-
of the sorbents during the temperature-programmed adsorption test was monitored to evaluate the influence of temperature upon the CO2 adsorption capacity of the prepared samples.

3. Results and discussion

3.1. Chemical characterization

3.1.1. Ultimate analysis, proximate analysis and point of zero charge

Elemental analysis and pH_{PZC} results of the virgin and ammonia modified carbons are shown in Table 1. As can be seen from the table, reactions between the carbon surface and the radicals that were created during ammonia decomposition successfully incorporated nitrogen into the carbon structure. For instance, nitrogen content increased from 0.3 wt.% for virgin carbon to 3.1 wt.% and 4.6 wt.% for HTA-800 and OXA-800 samples, respectively. The differences in nitrogen content between the pre oxidized and pre heat treated samples indicated that the presence of oxygen functionalities on the carbon surface before ammonia treatment played an important role in determining the degree of nitrogen incorporation to the surface, and pre oxidation of carbons considerably enhanced the nitrogen incorporation during the ammonia treatment (Table 1). Thermal decomposition of these functionalities during the subsequent ammonia treatment leads to formation of active sites for ammonia molecules or nitrogen containing radicals to form nitrogen functional groups [24,33,41]. The reaction of ammonia with carboxylic acid sites present on the carbon surface can form ammonium salts that through dehydrogenation reaction(s) may lead to formation of amides and nitriles:

$$\text{COO}^+ \text{NH}_2^+ \rightarrow \text{CO-NH}_2^+ \text{H}_2\text{O}$$

Amines can also easily formed by the substitution of OH groups:

$$\text{OH} + \text{NH}_3 \rightarrow \text{NH}_2 + \text{H}_2\text{O}$$

In the reaction with ammonia at elevated temperatures ether-like oxygen surface groups are easily replaced by –NH– on the carbon surface that could readily lead to formation of imine and pyridine functionalities through dehydrogenation reaction(s) [26,29,42,43].

The results mentioned above agree quite well with proximate analysis data, where the pre oxidized samples presented a substantial increase in the volatile matter content, while the pre heat analysis data, where the pre oxidized samples presented a sub-

$$\text{VM FC* Ash C H N S O a}$$

The results of the elemental analysis are consistent with the pH_{PZC} data, where the incorporation of nitrogen functionalities tends giving a basic character to the aminated samples with the increase in pH_{PZC} values. It is important to mention that oxidized carbons treated with ammonia have a higher pH_{PZC} values compared to the pre heat treated samples. So it can be concluded that the presence of acidic functionalities was more favorable for incorporation of basic nitrogen surface groups.

3.1.2. FTIR analysis

To study the nature of the functional groups present on the surface of the samples, FTIR analysis was carried out. Fig. 1 shows the results of FTIR measurements taken for untreated carbon and modified samples (HTA-400, OXA-400, HTA-800, and OXA-800). In the spectrum of virgin carbon, several peaks were observed at the 3571, 1729, 1613, 1422, and 1140 cm$^{-1}$ which can be attributed to O–H stretching vibration [51], C=O groups moieties (in carboxylic and lactone structures) [52,53], C=C groups [54], aromatic ring [17], and C–O stretch of ethers [51], respectively. Furthermore, the spectrum exhibits two other peaks at 856 and 781 cm$^{-1}$, related to presence of C–H groups (located at the edges of aromatic ring) [55].

Ammonia treatment caused some changes in the spectra of modified samples. In the range of 3376–3294, overlapping bands of O–H and N–H stretching vibrations was observed for all modified samples. These bands may be related to formation of hydrogen bonds between the adsorbed NH3 molecules and oxygen surface groups [56]. For both treatment methods, spectrum of low temperature modified samples (HTA-400, OXA-400), contains peaks at nitrogen content of 4.6 wt.% was obtained for the oxidized sample which was aminated at 800 °C. In the case of the pre heat treated carbons, the samples present lower oxygen content than the starting carbon and this amount decreases as the temperature of the heat treatment increases. That was attributed to the decomposition of oxygen functionalities as CO2 or CO during high temperature treatment in nitrogen atmosphere [44–46].

The pH_{PZC} values indicated that ammonia treatment increased the basic character of the modified samples in comparison with the virgin carbon. This increase in surface basicity may partly be a consequence of the formation of basic surface functionalities (e.g., nitrogen containing groups) that are capable of binding with protons. However, it can also be associated with decomposition of some oxygen containing acidic functionalities that can overshadow the $\pi$ electrons of graphene layers [47–50]. The results of the elemental analysis are consistent with the pH_{PZC} data, where the incorporation of nitrogen functionalities tends giving a basic character to the aminated samples with the increase in pH_{PZC} values. It is important to mention that oxidized carbons treated with ammonia have a higher pH_{PZC} values compared to the pre heat treated samples. So it can be concluded that the presence of acidic functionalities was more favorable for incorporation of basic nitrogen surface groups.
1665–1641 cm\(^{-1}\) and 2251–2265 cm\(^{-1}\) which can be assigned to cyclic amide functionality and nitrile groups, respectively [25,28]. But, as seen in Fig. 1, intensities of these bands were decreased by increasing the temperature of ammonia treatment (HTA-800, OXA-800). In addition, treatment with ammonia at elevated temperature lead to the presence of dominant peaks at 1334–1330 cm\(^{-1}\), which can be assigned to pyridine-like functionalities [24,27]. In the case of pre heat treated samples, due to decomposition of oxygen containing surface groups during thermal heating, the bands intensity associated with these groups gradually decreased with increasing the treatment temperature. For instance, the band related to carboxylic structure (at 1730–1723 cm\(^{-1}\)) diminished considerably when the higher temperature was applied.

It has been recognized [54] that as a result of oxygen chemisorption, cyclic anhydrides and carboxylic species are presented on the carbon surface. The reaction of NH\(_3\) with anhydride surface structures during the subsequent ammonia treatment can form surface ammonium salts of carboxylic acids that may lead to formation of amide structures through dehydration reaction [26,32]. In this way, the IR spectrum of pre oxidized carbons preferentially shows the presence of bands at 1381–1379 cm\(^{-1}\) (\(\delta_1\) of COO\(^{-}\)), as well as bands at 1451–1447 cm\(^{-1}\) (\(\delta_2\) of NH\(_2\)\(^{-}\)). A comparison of spectra between the pre oxidized and pre heat treated samples evidently showed the same bands shape at 1609–1584 cm\(^{-1}\) corresponding to the aromatic ring conjugated C=C and C=N groups [57]. There is also a sharp peak in the range of 1250–1235 cm\(^{-1}\), which could be a result of C–N stretching modes [28].

Some remaining C–O groups were found in the spectrum of pre oxidized samples (at 1147–1141 cm\(^{-1}\)). In opposite, no presence of these bands was observed for pre heat treated carbons. Disappearance of these acidic surface oxides bands confirms the pH result (Table 1), in that ammonia modification increased the pH values for pre heat treated samples. Compared to pre heat treated samples, oxidized carbons treated with ammonia exhibited an increase in the intensities of the bands associated with nitrogen containing species. Stronger signals in the regions at ∼1330 and ∼1660 cm\(^{-1}\), suggests that pre oxidation of samples followed by high temperature ammonia treatment significantly incorporates nitrogen onto the carbon surface with formation of pyridine-like and amides structures, respectively.

3.2. Textural characterization

As can be seen from this figure, the isotherms of all cases are type I according to the BDDT (Brunauer, Deming, Deming and Teller) Classification [58], indicating that the pore structure of the carbon samples is mainly composed of a well developed micropore volumes. It can be seen in Fig. 2 that all samples show hysteresis loops at \(P/P_0 > 0.4\), which indicates the presence of certain mesoporosity in the samples. Table 2 lists the apparent surface area \(S_{\text{BET}}\), total pore \(V_{\text{total}}\) and micropore \(V_{\text{micro}}\) volumes of the carbon samples which are good measures to investigate relative changes in pore characteristics of these materials.

It can be observed that ammonia treatment of heat treated samples develops the porous structure of the virgin carbon and causes an increase in BET surface area, total pore and micropore volumes of (HTA-400, HTA-800) samples compared to the untreated carbon. Furthermore, HTA samples presented an increase in the textural properties \((S_{\text{BET}}, V_{\text{total}}\) and \(V_{\text{micro}}\)) with the increase in treatment temperature from 400 to 800 °C. The observed increases in these parameters were primarily ascribed to the thermal decomposition of surface functional groups from the inside of pores leading to rather pores enlargement (preferentially creating micropores) upon pre heat treatment with nitrogen [24,26].

Apart from that, partial gasification of the studied adsorbents with free radicals that were created during ammonia decomposition can also have a contribution to development of the porous system [19,21,32,42,59–63]. As these radicals (atomic hydrogen, NH\(_2\) and NH) were generated at high temperature treatment, the textural characteristics developed with increasing treatment temperature. Therefore, the highest surface area \(S_{\text{BET}} = 889 \text{ m}^2 \text{ g}^{-1}\), pore volume \(V_p = 0.474 \text{ cm}^3 \text{ g}^{-1}\) and micropore \(V_{\text{micro}} = 0.442 \text{ cm}^3 \text{ g}^{-1}\) were observed for the HTA-800 sample. It seems that when partial gasification with ammonia radicals takes place, it acts mainly in the microporosity domain, thereby creating new micropore sites. As a consequence, the pre-heat treated carbons presented a slightly increase in micropore to total pore volume ratio compared to the untreated sample.

The results showed that low temperature ammonia modification of oxidized sample decreases the apparent surface area and total pore volume while high temperature treatment would lead to increase in these parameters. The initial decrease in porous texture properties is probably due to the partially blockage of the micropore entrances by oxygen that occurs during pre oxidation reaction. However it can also be associated to the collapse of some adjacent pore walls during pre oxidation stage leading to diminish in micropore volumes [49,64]. At higher temperature (OXA-800), the oxygen surface groups will decompose and as a consequence of leaving vacant sites the pores may become more accessible to free radicals after subsequent high temperature ammonia treatment [19,25]. Indeed, gasification with ammonia allows to the sample to recover its porosity and pore volumes even increased a little over that of the sample which had been modified at 400 °C.

![Fig. 2. \(N_2\) adsorption isotherms at \(-196^\circ\text{C}\) of the parent and modified activated carbons.](image)

<table>
<thead>
<tr>
<th>Sample</th>
<th>(S_{\text{BET}}) (m(^2) g(^{-1}))</th>
<th>(V_{\text{total}}) (cm(^3) g(^{-1}))</th>
<th>(V_{\text{micro}}) (cm(^3) g(^{-1}))</th>
<th>(V_{\text{micro}}/V_{\text{total}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated</td>
<td>768</td>
<td>0.387</td>
<td>0.358</td>
<td>0.92</td>
</tr>
<tr>
<td>OXA-400</td>
<td>723</td>
<td>0.376</td>
<td>0.343</td>
<td>0.91</td>
</tr>
<tr>
<td>OXA-800</td>
<td>826</td>
<td>0.428</td>
<td>0.396</td>
<td>0.92</td>
</tr>
<tr>
<td>HTA-400</td>
<td>858</td>
<td>0.462</td>
<td>0.431</td>
<td>0.93</td>
</tr>
<tr>
<td>HTA-800</td>
<td>889</td>
<td>0.474</td>
<td>0.442</td>
<td>0.93</td>
</tr>
</tbody>
</table>

![Table 2. Physical characteristics of activated carbon samples.](image)
at room temperature, the micropore volume was the dominant feature for increased adsorption of CO$_2$; the adsorbed amounts per unit micropore volume should approximately remain constant for all samples. However, Fig. 4 clearly shows that the adsorbed amount per unit micropore volume significantly changes from one sample to another.

It can be observed that the CO$_2$ capture capacity of the prepared samples at 105°C is about 2–3 times lower than that at 30°C. The observed decrease in the CO$_2$ adsorption capacity with increasing temperature for all samples is to be expected due to the exothermic character of physisorption where both the molecule diffusion rate and the surface adsorption energy increase with increasing temperature [4]. Similar behaviors have been reported for other activated carbon adsorbents with different precursors modified with ammonia [11,15,16,18,19,21,22].

In the case of the pre oxidized samples, the stronger interactions between the acidic gaseous CO$_2$ and the basic nitrogen groups present on the modified carbon surfaces results in a softer slope of the TP adsorption curve with temperature in comparison with pre heat treated carbons. Maximum CO$_2$ uptake by the modified carbons at 105°C is achieved for sample OXA-800, reaching values of up to 75.9 mg cm$^{-3}$ (30.1 mg-CO$_2$/g-adsorbent) due to the combined effect of fine pore structure and favorable surface chemistry (stronger basic character of the sorbent). Oxidation preceding high temperature ammonia treatment seems to be a suitable approach to enhance chemisorption by modifying the carbon surface without cancelling physisorption. This would be a promising result for the subsequent application of these sorbents, as they could be applied to the flue gas treatment if the capture unit is to be placed after the flue gas desulphurisation unit in the power plant.

3.3.3. Factors influencing CO$_2$ adsorption

It is interesting to mention that in comparison with the pre-heat-treated aminated samples, the pre oxidized carbons displayed enhanced ability to adsorb CO$_2$ at relatively high temperatures. However, the pre heat treated carbons presented the highest micropore volume, and therefore, they might be expected to exhibit higher capture capacities. In addition, Fig. 5 depicts the relationship between the amount of micropore volume and the CO$_2$ uptake of prepared samples at 30°C with significantly better regression coefficient than 105°C. This would seem to indicate that the effect of porosity development becomes less important as the adsorption temperature increases and the surface chemistry, particularly the presence of basic nitrogen functional groups, being more noticeable at higher temperatures.

The results mentioned above are in accordance with Fig. 6, where, the relationship between the nitrogen content of prepared...
adsorbents and their CO2 adsorption capacity at 105 °C displayed stronger linear correlation than 30 °C, demonstrating that formation of basic nitrogen functionalities plays a more active role at higher temperatures. It should be pointed out that although the nitrogen content of both pre oxidized samples are almost same (see Table 1), the high temperature modified sample (OXA-800) presents higher CO2 uptake at 105 °C than the other one (OX-400). Considering the fact that the nature of nitrogen functionalities differed with the temperature of ammonia treatment [25], it seems that apart from the amount of nitrogen functionalities incorporated (nitrogen content), CO2 capture capacity also depends on the type of the nitrogen surface groups introduced on to the carbon surface. According to the FTIR spectra presented in Fig. 1, the observed CO2 capture enhancement for sample OXA-800 is presumably due to the presence of amine groups and pyridine-like functionalities which particularly for the latter are appeared at high temperature modification [15,16,18,19,22,24,29].

4. Conclusion

In this work, the impact of changes in surface chemistry on CO2 adsorption performance of the modified activated carbon samples was studied. Two methods for producing activated carbon with basic surface were considered: ammonia treatment with preliminary oxidation and ammination of oxidized samples. In summary, modification of the surface chemistry had different effects on CO2 capture capacity depending on the methods employed. It was found that decomposition of oxygen containing functionalities can increase the reactivity of ammonia molecules or nitrogen containing radicals to form nitrogen containing functional groups. Introduction of basic nitrogen surface groups, particularly through oxidation followed by ammination significantly enhanced the adsorption ability of the carbon adsorbent towards CO2, mainly due to the increase in micropore volumes and surface basicity. Post-oxidation ammoniation treatment at 800 °C was proposed as a promising modification technique for the production of carbon-based CO2 adsorbents that can be operated particularly at relatively high temperatures.

References
