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A Fast Approach for Preparation of Adsorbent from Reed Black Liquor and Its Performance in Equilibrium and Kinetic Gas Separation

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A new approach using reed pulping black liquor by hydrothermal reaction followed by fast carbonization at 350 °C in fluidized bed reactor for 5 minutes was proposed in this paper. The BET specific surface area generated at optimum conditions reached 390 m² g⁻¹. The CO₂ selectivity over CH₄ and N₂ comparable to commercial activated carbons was obtained. The isosteric enthalpies of adsorption for CO₂, CH₄ and N₂ on the resultant carbon sample prepared at optimum conditions show surface heterogeneity. The kinetic results indicate its potential for separation of carbon dioxide from carbon dioxide/methane mixture.

Key words: reed, black liquor, carbon adsorbent, kinetic CO₂/CH₄ separation

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Introduction

With the growing demand for paper pulp in developing countries such as China, production of paper using reed as a resource is regarded as one of the most profitable approaches for high-value conversion of biomass due to the shortage of wood-derived resources in China. ¹, ² However, the major technical hurdle of non-wood pulping is the severe environmental pollution caused by the black liquid due to poor performance of alkaline recovery. ³ Exploring new approaches besides alkaline recovery for effective utilization of this hazardous material has attracted much attention. Processing routes, such as steam water gasification, ⁴ supercritical water gasification ⁵ and pyrolysis ⁶ have been extensively studied. Among those processes, hydrothermal carbonization of black liquor is an approach to effectively decrease COD (Chemical Oxygen Demand) and biomass content in black liquor with relatively little environmental impact. ⁷ The obtained carbons from hydrothermal carbonization have been reported to be utilized as solid fuels. ⁸ Preparation of adsorbents from hydrothermal carbonization is also a good approach for high-value conversion of biomass in aqueous solution. ⁷ However, the specific surface area of the carbon from hydrothermal reaction is generally low, which significantly limits its application. ⁷ In order to further increase the specific surface area of adsorbent, the thermal carbonization treatment will be generally applied. The most common reactor for thermal carbonization is the fixed bed reactor, which usually has rather high carbonization temperature and long reaction time. In the present work, the fluidized bed reactor was employed for thermal carbonization due to its yielding of uniform product, because of its efficient heat and mass transfer that minimize temperature variation and ensure good mixing. ⁹ These advantages are so compelling that the application of a fluidized bed reactor for the carbonization step can be very attractive for carbon-based adsorbent production. In addition, to the best of our knowledge, the study of a fast approach for preparation of carbon adsorbents from reed black liquor with large specific surface area and their direct application for gas separation has not been reported as yet.

Experimental section

Preparation of carbon adsorbent

The adsorbent was produced by hydrothermal reaction of 150 mL black liquor from pulping of reed in an autoclave at 200 °C for 48 hours, which
is optimized time for relatively high yield of carbon adsorbent. The detailed pulping conditions of black liquor could be found in our previous work.\textsuperscript{3,10} The products from the reaction were then filtered and sieved to about 0.15–0.3 mm in size after oven-drying at 110 °C for 4 hours. The solids were then carbonized at different temperatures in fluidized bed reactor. The detailed configurations, dimensions and operational parameters can be found in our previous works.\textsuperscript{9–11} The carbon produced from hydrothermal reaction at 200 °C is denoted as Hydro-RL-200, the carbons produced from further carbonization in fluidized bed reactor at 200 °C, 250 °C and 350 °C are denoted RL-200, RL-250 and RL-350, respectively. Table 1 lists the elementary composition of black liquor before and after carbonization, and the activated carbon prepared from fluidized bed reactor. With hydrothermal treatment, the carbon composition increased from 45 to 62 %. When the precursor was carbonized in fluidized bed, carbon composition could reach 88 %. This indicates that hydrothermal treatment and carbonization facilitate removal of volatile materials from precursors. The yield of activated carbon prepared from fluidized bed was about 40 %.

Table 1 – Comparison of elementary compositions of different precursors

| Sample  | C  | H  | N  | O (by difference) |
|---------|----|----|----|-------------------|
| BLB     | 44 | 6  | 0.5| 50                |
| BLA     | 62 | 5  | 0.5| 32                |
| Activated carbon | 88 | 0.5 | 0.5 | 10                |

Characterization of resultant carbon adsorbents

High-pressure adsorption measurements were conducted on a standard static volumetric method apparatus. The detailed rig information and operating conditions could be found in our previous works.\textsuperscript{12} High-purity grade methane (99.9 %), nitrogen (99.9 %), and carbon dioxide (99 %) supplied by Jingcheng Gas Co. Ltd. were used in these measurements.

The specific surface area and porosities of the carbon samples were determined by nitrogen gas adsorption at 77 K at a saturation pressure of 1 bar using a Micromeritics ASAP 2020 Automated Gas Sorption System. Carbon samples that were activated by Jingcheng Gas Co. Ltd. were used in these works.

Optimization of appropriate preparation conditions

Of the factors which affect the surface area of the carbons produced, the hydrothermal temperature and the carbonization temperature are the most important. The specific surface area of carbons produced from black liquor increases slightly with an increase in hydrothermal temperature, and a maximum BET specific surface area of approximate 100 m\(^2\) g\(^{-1}\) was observed at 200 °C. Further increase in hydrothermal temperature does not significantly increase the carbon surface area, and thus carbons produced at 200 °C were selected for preparation of activated carbons.

Fig. 1 shows the thermogravimetric analysis curve of Hydro-BL-200 indicating that the weight loss is divided into three general stages. These stages correspond to the elimination of loosely
bound moisture at around 100 °C (stage 1), the elimination of fixed water around 280 °C (stage 2), and the degradation and elimination of organic polymers around 350–450 °C (stage 3). In this work, Hydro-BL-200 was carbonized at different temperatures in fluidized bed reactor. Fig. 2 indicates that the carbonization treatment significantly increases the surface area when the carbonization temperature exceeds 350 °C, at which stage the specific surface area of the carbon (RL-350) reaches around 390 m² g⁻¹. In terms of nitrogen adsorption isotherms, according to Brunauer-Deming-Deming-Teller (BDDT) classification, the RL-350 exhibits a type I isotherm. The adsorption occurs at relatively low pressure, indicating the existence of micropores. The nitrogen adsorption/desorption isotherm of RL-350 is greater than that of Hydro-RL-200 indicating that the increased pore volume is mainly due to the removal of volatile materials during the carbonization of Hydro-RL-200 in fluidized reactor. Fig. 3 shows pressure drop and burn-off rate of Hydro-RL-200 as a function of carbonization time in the fluidized bed at 350 °C. It shows that the burn-off rate does not change appreciably after the first 5 minutes of carbonization, neither does the pressure drop. This means that, after the volatile matter had been completely removed in the first 5 minutes of carbonization, the volatilization was largely reduced. In this paper, we adopted 350 °C and 5 minutes as optimum carbonization temperature and reaction time in fluidized bed reactor.

Characterization of the resulting carbons

The pore size distribution (NLDFT, Non-Linear Density Functional Theory) assuming slit pore geometry) of RL-350 is shown in Fig. 4. The results indicate that RL-350 has a narrow pore size distribution, which mainly distributes in the microporous region in the range of 0.6–1.2 nm. In addition, it also possesses pores that belong to mesoporous region (>2 nm). The porosity parameters obtained from N₂ adsorption on RL-350 are summarized as follows: pore volume is 0.16 m³ g⁻¹, micropore area

Fig. 1 – Differential thermogravimetric analysis curve of Hydro-BL-200

Fig. 2 – BET specific surface area as a function of activation temperature and N₂ adsorption/desorption isotherms of different activated carbon samples

Fig. 3 – Pressure drop and burn off as function of carbonization time

Fig. 4 – DFT pore size distribution in microporous and mesoporous region of RL-350
is 270 m$^2$ g$^{-1}$ and average pore width is 2.04 nm. The SEM morphology of Hydro-RL-200 and RL-350 is shown in Fig. 5 a and b, respectively. Both Hydro-BL-200 and RL-350 carbons are seen to have relatively irregular carbon spheres. In addition, each carbon sphere tends to aggregate and form larger particles. After Hydro-BL-200 was carbonized in fluidized bed reactor, a further tendency of aggregation and forming of large porous particles was also observed. This suggests that the carbonization facilitates removal of volatile materials and formation of larger particles with intra-spaces, which in turn contributes to the increase in specific surface area of the resultant carbons. This result agrees with that of BET specific surface area analysis, in which the specific surface area of RL-350 significantly increased.

Low-pressure adsorption of CO$_2$, CH$_4$, and N$_2$

The adsorption isotherms of different gases onto RL-350 are shown in Fig. 6. The Tóth equation$^{15}$ is used to correlate our experimental low-pressure equilibrium data of different gases.

The Tóth equation is as follows:

$$q = \frac{q_m^* P}{(b + P^t)^t}$$  \hspace{1cm} (1)

where $q_m^*$ is the adsorption saturation capacity (mmol g$^{-1}$), $b$ and $t$ are the constants in Tóth equation. The constants obtained from the Tóth model are listed in Table 2.

The enthalpy of adsorption is a significant property for characterization of the type of adsorption and degree of heterogeneity of a surface. The isosteric enthalpies of adsorption were not measured experimentally in this paper, but were estimated from the low-pressure adsorption equilibrium data by using the Clausius-Clapeyron equation:

$$\Delta H = RT^2 \left( \frac{d \ln P}{dT} \right)_n$$  \hspace{1cm} (2)

By using the low-pressure adsorption equilibrium data, we calculated the isosteric enthalpy of adsorption of RL-350 for CO$_2$, CH$_4$, and N$_2$, shown in Fig. 7. The isosteric enthalpy of adsorption of all the samples decreases with increase in loading be-
low 0.2 mmol g\(^{-1}\). This suggests that more energetic sites for carbon dioxide, methane and nitrogen at low loading are filled preferentially with less active sites filled as adsorption proceeds. The modest decrease in isosteric enthalpy with increase in loading of RL-350 in adsorbing CO\(_2\), CH\(_4\) and N\(_2\) indicates only mild heterogeneity for these three gases. The isosteric enthalpies of different gases on RL-350 are approximately 10 to 30 kJ mol\(^{-1}\), which generally falls below the range of isosteric enthalpies of physisorption of CO\(_2\), CH\(_4\) and N\(_2\) on adsorbents such as activated carbon. This is consistent with the non-polar nature of the carbonaceous surface.

### High-pressure adsorption of CO\(_2\), CH\(_4\), and N\(_2\)

In addition to the low-pressure adsorption, we also measured the high-pressure adsorption equilibrium of methane, carbon dioxide, and nitrogen on RL-350. We adopted the Peng-Robinson equation to determine fugacity and compressibility factor for those gases.

The high-pressure adsorption isotherms are shown in Fig. 8. The high-pressure isotherms obtained for carbon dioxide, methane and nitrogen onto RL-350 belong to type I of the IUPAC classification. At all pressures, carbon dioxide was the most strongly adsorbed gas, followed by methane and nitrogen.

Tóth equation was also chosen to model the high-pressure adsorption. The mathematical form of Tóth model at high pressure is as follows:

\[
n^\Omega = \frac{n_n^* BP}{[1 + (BP)^？]} = n + v_α \rho_g
\]  

\[
B = B^0 \exp \left(-\frac{\Delta H_0}{RT}\right)
\]

where \(n^\Omega\) is the absolute amount adsorbed in mmol g\(^{-1}\), \(n\) is the excess adsorption obtained from the measurement (mmol g\(^{-1}\)), \(n_n^*\) is the parameter that corresponds to full coverage of solid surface, \(v_α\) is the volume of adsorbate in the adsorbed phase in m\(^3\) g\(^{-1}\), \(\rho_g\) is the density of the bulk gas in mol m\(^{-3}\), \(B\) and \(f\) are constants from Tóth equation. \(\Delta H_0\) is isosteric heat of adsorption at zero loading, \(B^0\) is the infinite adsorption constant. We could obtain the
excessive adsorption formula to extrapolate the corresponding constants in equation:

$$n = \left( \frac{n_m^* B f}{\left\{ 1 + (B f)^{-1} \right\}^{1/2}} \right) \left( n_m^* - \frac{S^{3/2}}{(n_m^* A_l)^{1/2}} \rho_g \right)$$  \hspace{1cm} (4)

The detailed derivation of the model and definition of each constant could be found in literature. By fitting the excess adsorption data of different gases onto RL-350 with eq. 4, we obtained the constants of Tóth equation, and Table 3 shows the isosteric heat of adsorption at zero loading, $\Delta H^0$, and infinite adsorption constants $B_0$ of different gases. Fig. 8 shows that Tóth model is satisfactory in representing the experimental data of RL-350 in adsorbing carbon dioxide, methane and nitrogen under high pressure at different temperatures. The isosteric heat of adsorption with zero loading of RL-350 for adsorbing different gases is ordered as follows: carbon dioxide $>$ methane $>$ nitrogen, which generally agrees with the results calculated based on low-pressure equilibrium data.

The preferential adsorption of carbon dioxide indicates that RL-350 can be used for the separation of CO$_2$ from its mixture with methane and nitrogen. The variation of ideal selectivity of carbon dioxide relative to methane ($n_{CO_2}/n_{CH_4}$) and methane relative to nitrogen ($n_{CH_4}/n_{N_2}$) at 293 K are shown in Fig. 9. In Table 4, the ideal selectivities of $n_{CO_2}/n_{CH_4}$ and $n_{CH_4}/n_{N_2}$ on different commercial adsorbents are compared at room temperature at pressures below 5 bar. We see that the ideal selectivity $n_{CO_2}/n_{CH_4}$ and $n_{CH_4}/n_{N_2}$ of our samples is comparable to or even better than that of the commercial activated carbons, and carbon molecular sieves for preferentially adsorbing carbon dioxide to methane and nitrogen. Considering our less harsh preparation conditions (activation temperature below 400 °C) and relatively good CO$_2$ selectivity performance, our process shows a promising approach in preparing carbonaceous adsorbents for gas separation with low environmental impact.

| Gas   | Temperature | $t$ | $n_m^*$ | $B^0$ | $\Delta H^0$ |
|------|-------------|-----|---------|-------|--------------|
| CO$_2$ | 293 K  | 0.27 | 2.1 | $4 \cdot 10^{-5}$ | 22 |
|      | 273 K  | 0.25 | 2.6 |            |           |
| CH$_4$ | 293 K  | 0.58 | 1.3 |            |           |
|      | 283 K  | 0.71 | 1.4 | $3 \cdot 10^{-5}$ | 17 |
|      | 273 K  | 0.63 | 1.4 |            |           |
| N$_2$  | 293 K  | 0.42 | 1.7 |            | 11 |
|      | 283 K  | 0.49 | 1.7 | $2 \cdot 10^{-3}$ |           |
|      | 273 K  | 0.47 | 1.9 |            |           |
Dynamic adsorption experiments of CO₂/CH₄ mixtures in the packed bed reactor

Although the equilibrium results indicate good ideal selectivity of prepared activated carbon towards CO₂/CH₄ mixtures, the dynamic adsorption experiments in the packed bed reactor were conducted to validate its potential for gas separation. In this paper, RL-350 was used in the packed bed reactor for dynamic separation of CO₂ from CH₄. The gas was considered to flow isothermally through the packed bed of spherical pellets; plug flow was supposed to be appropriate in our system. Mass balances for gases in the bed of porosity εₚ resulted in the following equation:

\[ \varepsilon_b \frac{\partial c}{\partial t} + u \frac{\partial c}{\partial z} - D_z \frac{\partial^2 c}{\partial z^2} = -R \]  

(5)

where \( c \) is concentration of adsorbent in the gas phase, \( D_z \) is the axial dispersion coefficient, \( u \) is the superficial fluid velocity. The terms on the left hand side are transient, flux and diffusion flux, respectively. The term on the right hand side is the source term, which represents the diffusion of the gas from bulk phase to the surface of the pores and is calculated as:

\[ \varepsilon_p \frac{\partial c_p}{\partial t} + \rho_s \frac{\partial n_s}{\partial t} = \alpha k_{overall}(c - c_p) \]  

(6)

where \( c \) and \( c_p \) are the concentration of adsorbent in the gas phase and the average concentration in the pores of the adsorbent, respectively, \( n_s \) is the average adsorbent loading, \( \alpha \) is the specific surface area per unit bed volume, \( \rho_s \) is the adsorbent density, and \( k_{overall} \) is the overall mass transfer coefficient. The initial and boundary conditions appropriate for the breakthrough curve simulation are:

\[ c(t = 0) = 0, \quad n_s(t = 0) = 0, \quad c_p(t = 0) = 0 \]  

\[ \frac{\partial c}{\partial z} \bigg|_{z=0} = 0 \]  

\[ \frac{\partial c}{\partial z} \bigg|_{z=L} = 0 \]  

\( k_{overall} \) can be calculated as the sum of film and pore mass transfer coefficients. We used Sherwood number \( Sh \) to estimate the film coefficient as follows:

\[ Sh = 2 + 1.1Re^{0.6}Sc^{0.33} \]  

(8)

where \( Re \) and \( Sc \) are Reynolds and Schmidt number, respectively. The pore mass transfer coefficient can be calculated as follows:

\[ k_p = \frac{5\alpha}{r^2\left(\frac{1}{D_k} + \frac{1}{D_m} + \frac{\tau}{D_k}\right)} \]  

(9)

where \( r \) is the particle radius, \( D_k \) is Knudsen diffusivity, \( D_m \) is molecular diffusivity, \( \tau \) is tortuosity factor, and Peclet number is used to calculate the dispersion coefficient \( D_z \). Partial differential equations must be rearranged into the dimensionless form and the following dimensionless variables were used to make the governing equations dimensionless:

Gas concentration: \( c^* = \frac{c}{c_0}; \quad c_p^* = \frac{c_p}{c_0} \)

Time: \( t^* = \frac{t}{1/u_z} \)
Distance in axial direction: \( z^* = \frac{z}{l} \)

Radius of pellet: \( r^* = \frac{r}{r_p} \)

The governing equations are then cast into the following form:

\[
\begin{align*}
\frac{\partial c^*}{\partial t} + A \frac{\partial c^*}{\partial z} - \frac{1}{Pe} \frac{\partial^2 c^*}{\partial z^2} + B(c^* - c^*_p) &= 0 \quad (10) \\
\frac{\partial c^*_p}{\partial t} + C(c^* - c^*_p) &= 0 \quad (11)
\end{align*}
\]

where \( A, B \) and \( C \), respectively, are:

\[
A = -\frac{1}{\epsilon_b}, \quad (12)
\]

\[
B = \frac{15 k_{\text{overall}} (1 - \epsilon_b)}{\epsilon_b r_p u (k_{\text{overall}} + 5\alpha (1/D_b + 1/D_m))}, \quad (13)
\]

\[
C = \frac{k_{\text{overall}}}{au (k_{\text{overall}} + 5\alpha (1/D_b + 1/D_m))}, \quad (14)
\]

\[
\frac{2 N_m (1 - \alpha)}{10^5 r_{\text{micro}}^2} - \frac{15\alpha (1/D_b + 1/D_m)^2}{r_p^2}
\]

\( N_m \) is the parameter that corresponds to full coverage of solid surface from Langmuir adsorption equation, \( r_{\text{micro}} \) is average micropore diameter, \( l \) is length of the bed.

Experimental breakthrough curves are shown in Fig. 10. The reasonable agreement is obtained between experimental results and our modeling indicating the acceptable approximation. Although our equilibrium results show ideal selectivity of \( \text{CO}_2/\text{CH}_4 \) in the range of approximately 3–3.6, the difference of the breakthrough time between \( \text{CO}_2 \) and \( \text{CH}_4 \) is not pronounced, indicating that the dynamic separation using the prepared RL-350 pellet performs relatively poorly in separating \( \text{CO}_2 \) and \( \text{CH}_4 \) using single adsorption bed reactor and experimental conditions investigated. This also indicates that the real selectivity of \( \text{CO}_2/\text{CH}_4 \) in the real dynamic separation is much less than 3–3.6. This may point to the need for further modification of the prepared carbon adsorbent e.g., by surface modification with functional groups or further modification of the process e.g., by increasing retention time in the column to increase the real selectivity of \( \text{CO}_2 \) vs. \( \text{CH}_4 \).

**Conclusions**

Carbon adsorbents were produced from biomass, i.e. from reed pulping black liquor by hydrothermal treatment at 200 °C followed by fast carbonization in fluidized bed at 350 °C for 5 minutes. The BET specific surface area of carbon at optimum conditions was 390 m\(^2\) g\(^{-1}\). The adsorption of carbon dioxide, methane and nitrogen at pressures up to 2 MPa and at different temperatures was measured and represented with the Tóth equation together with Peng-Robinson equation of state for determination of the gas phase fugacity. The sample RL-350 showed good performance in preferential adsorption of \( \text{CO}_2 \) vs. \( \text{CH}_4 \) below 5 bar at 293 K. The calculated isosteric enthalpies of adsorption for different gases on RL-350 indicated mildly heterogeneous surfaces. The kinetic results indicate its potential for separation of carbon dioxide from carbon dioxide/methane mixture.

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