Comparison of low-field NMR and mercury intrusion porosimetry in characterizing pore size distributions of coals

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1. Introduction

The flow and permeability properties of gas and water in coals partly depend on the volume and distribution of void space within a coal, which can be regarded as a network of void volumes (pore body) connected by a network of smaller void channels (pore throats). Pore size distribution (PSD) characteristics of coal include the porosity, size and distribution of pore body and throat, connectivitity, tortuosity and pore/throat shape.

A variety of methods is available to measure PSD of coals, such as mercury porosimetry, nitrogen gas adsorption, high resolution electron microscopy (e.g. the SEM) and micro focus X-ray computed tomography (µCT), where the most commonly used methods are nitrogen gas adsorption and mercury porosimetry. Both of these methods result in intrusion–extrusion curves created by penetration of nitrogen or mercury into the degassed samples. From these curves, information about pore size, pore volume, and surface area can be obtained. Nitrogen gas adsorption is applicable on micro- (<0.01 µm) to mesopores (0.01–0.1 µm), while mercury porosimetry is applicable to characterize meso- to macropores (includes both pores >0.1 µm and fractures). There are many discussions about the application of mercury porosimetry on coals, however there is very little discussion about whether the method is applicable for all kinds of coals.

The traditional mercury porosimetry (MIP) adopts the intrusion/extrusion of mercury at a constant pressure, and it is effective for studying pore body characteristic of coals. However, this method is inadequate for the study of coal pore throat size [1], although it is clear that the permeability for any given porosity is a function of the throat size through which fluids must flow. To address this problem, the constant-rate-controlled mercury penetration method (CMP) was applied to describe the throat size distribution of rocks [2,3]. However, still little attention has been devoted to the use of CMP on coals.

Recently, some nondestructive analytical methods were used to study the PSD of coals. For example, as a direct experimental three-dimensional digitized imaging method, the µCT method makes it possible to analyze coal pores with a spatial resolution of several microns. There were some discussions on the applications of µCT for quantitative measurement of coal porosity and visual characterization of the geometry of the pores and throats [4–6]. Moreover, in the authors’ previous work [7] a low-field nuclear magnetic resonance spectral analysis (LFNMR) was proposed for characterizing coal porosity, pore geometry and connectivity. The µCT and LFNMR holds much potential for characterizing coal PSD.
This paper mainly focuses on the comparisons of LFNMR and mercury intrusion porosimetry (both MIP and CMP) in characterizing pore size distributions of coals. Comparisons are made on the same source samples throughout. Advantages and disadvantages of both methods in characterizing coal PSD are discussed. In order to validate the results, the \( \mu \)CT experiment results were also used.

2. Experimental

Seven coal samples with coal ranks from lignite through anthracite were used for this study. The general analyzed data of these samples such as the mean maximum vitrinite reflectances (\( R_o \)), porosities, medians of pore radius and permeabilities are listed in Table 1, and more detailed information about these samples is given in Yao et al. [6].

A set of LFNMR and \( \mu \)CT experiments were run in series on each sample. The experimental principle and process were specified in the authors’ previous work [6,7]. Following the above experiments, some of the samples were selected for either MIP or CMP analyses (Table 1). Only one method could be performed, as both methods destroy the coal samples. MIP measurements were performed using a Micromeritics Autopore IV 9420 Instrument (Micrometrics, USA) and by the Chinese Oil and Gas Industry Standard 5346-2005. The measurements run up to a pressure of 32 MPa, meaning that pore throats as small as 0.02 \( \mu \)m were penetrated. Mercury intrusion-extrusion curves were obtained for analyzing PSD. CMP were performed using an ASPE-730 mercury porosimetry instrument (Coretest Systems Corp., US). During the measurements, the constant mercury intrusion rate and maximum applied pressure were 0.00005 mL/min and 6.2 MPa, respectively.

3. Results and discussion

3.1. Pore size distribution by MIP

Mercury is a nonwetting fluid and thus will not penetrate pores by capillary action but will do so only by applying an external pressure. Mercury porosimetry is based on the gradual injection of liquid mercury into an evacuated pore system with external pressures. This process can then be converted to an equivalent pore radius, if required. Generally, increasing pressure makes smaller pores accessible to mercury [8]. Based on the assumption of cylindrical pores, the pore size distribution can be calculated by the Washburn Equation:

\[
R_c = \frac{\Delta \sigma \cos \theta}{P_c}.
\]  

(1)

where \( P_c \) is the absolute injection pressure, MPa; \( r_c \) is the pore radius (\( \mu \)m) when mercury enters at the pressure \( P_c \) (MPa); \( \theta \) is the contact angle between mercury and the pore surface (assumed to be 140° in the experiment); and \( \sigma \) is the interfacial tension of mercury (set to 0.48 J/m\(^2\)). After substitution, we have

\[
P_c = 0.735/r_c.
\]  

(2)

Eq. (2) enables cumulative injection volume to be inferred from the measured mercury injection curve. Invasion-extrusion curves from pressure-controlled MIP are shown in Fig. 1 and the characteristic PSD values are listed in Table 1. At the same time, representative \( \mu \)CT images of these coals are shown in Fig. 2. From these CT images, the developments of meso- and macro pores of the coals can be identified [6].

Sample LVB1 is a low volatile bituminous coal with \( R_o \) of 1.87%. The intrusion/extrusion curves of the coal are close to the axis of intrusion pressure with very steep slopes (Fig. 1), which means that porosity and connectivity are so poor that the pores are difficult to be intruded by liquid mercury. Bulk porosity and median pore radius analyzed by MIP are 4.0% and <0.023 \( \mu \)m, respectively (Table 1), which corresponds well to the porosity (4.3%) analyzed by Helium pycnometry. From the CT scan result, the coal pore is predominantly mesopores, while macropores (and fractures) cannot be identified (Fig. 2b). All the above results show that the LVB1 is a coal with low porosity, low permeability and poor pore connectivity. For this sample the MIP results correspond well to the results obtained by other methods.

Sample A2 is an anthracite with \( R_o \) of 2.69%, and a low porosity (5.43%) and permeability (1.20 mD). CT scan results show that the pores are predominantly mesopores, while macropores (and fractures) cannot be identified (Fig. 2d). Intrusion/extrusion curves of sample A2 are similar to those of LVB1, except that there is a hysteresis loop between the intrusion and extrusion curves. It was also found that the hysteresis loop did not close when the imposed pressure was reduced back to ambient. This means that

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Coal rank</th>
<th>( R_o ) (%)</th>
<th>( \phi ) (%)</th>
<th>( \phi_m ) (%)</th>
<th>( r ) (( \mu )m)</th>
<th>Permeability (mD)</th>
<th>Analysis methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Lignite</td>
<td>0.39</td>
<td>6.70</td>
<td>13.5</td>
<td>0.522</td>
<td>82.1</td>
<td>LFNMR, ( \mu )CT, MIP</td>
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<tr>
<td>HVB2</td>
<td>High volatile bituminous coal</td>
<td>1.01</td>
<td>5.20</td>
<td>/</td>
<td>/</td>
<td>3.09</td>
<td>LFNMR, ( \mu )CT, CMP</td>
</tr>
<tr>
<td>MVB1</td>
<td>Medium volatile bituminous coal</td>
<td>1.56</td>
<td>2.30</td>
<td>/</td>
<td>/</td>
<td>0.067</td>
<td>LFNMR, ( \mu )CT, CMP</td>
</tr>
<tr>
<td>LVB1</td>
<td>Low volatile bituminous coal</td>
<td>1.87</td>
<td>4.30</td>
<td>4.0</td>
<td>&lt;0.023</td>
<td>0.012</td>
<td>LFNMR, ( \mu )CT, MIP</td>
</tr>
<tr>
<td>SA2</td>
<td>Semianthracite</td>
<td>2.38</td>
<td>3.01</td>
<td>1.7</td>
<td>0.062</td>
<td>0.0044</td>
<td>LFNMR, ( \mu )CT, MIP</td>
</tr>
<tr>
<td>A2</td>
<td>Anthracite</td>
<td>2.69</td>
<td>5.43</td>
<td>5.1</td>
<td>&lt;0.022</td>
<td>1.20</td>
<td>LFNMR, ( \mu )CT, MIP</td>
</tr>
</tbody>
</table>

\* More detailed sample information and measure process are given in Yao et al. (2009); \( \phi \) is determined by helium expansion; \( \phi_m \) is determined by conventional mercury porosimetry (MIP); \( r \) is the median of pore radius analyzed by MIP.
not all of the intruded mercury has left the sample and some mercury has become entrapped in the void space of the porous medium. According to Gane et al. [9], the hysteresis behavior and entrapment of mercury are due to the pore shielding effect, which will be discussed below.

Sample SA2 is a semi-anthracite with $R_o$ of 2.38%. The porosity and permeability of the coal are lower than those of samples LVB1 and A2, while the pore radius of SA2 is larger than that of LVB1 and A2 (Table 1). From the CT scan image, it was found that both mesopores and macropores (including a few microfractures) are developed in the coals (Fig. 2a). Moreover, it was found that bulk porosity (1.7%, by MIP) is distinctly lower than porosity determined from helium expansion (3.01%), and the hysteresis loop between the intrusion and extrusion curves is large (Fig. 1), indicating that the pore shielding effect is significant for the MIP analysis. Thus, the underestimation of porosity resulted by two reasons. One reason is pore shielding effect during MIP analysis. For another reason, some portion of the meso- and macro-pores is accessible to He, but not to Hg.

Sample L1 is a lignite with $R_o$ of 0.39%. In contrast to the coals discussed above, the CT scan image shows that L1 has well-developed macropores and fractures (Fig. 2a). The intrusion curve of the coal has a low slop, and the maximum intruded mercury saturation is up to 87% (Fig. 1). This is consistent with the interpretation that well-developed fractures and pores resulted in the high permeability (82.1 mD) and high porosity of the sample (Table 1). It needs to note that the porosity and PSD analyzed by MIP disclose suspect results. As shown in Fig. 1, the extrusion curve is totally separated from the intrusion curve indicating extremely low withdrawal efficiency. The withdrawal efficiency is generally thought to be controlled by various aspects of pore geometry, such as the effective pore throat size, pore throat size heterogeneity, the ratio of pore body size to neighboring pore throat size, and the pore coordination number [10]. It is apparent from the intrusion/extrusion curves of the sample that the liquid mercury fails to be discharged from coal pores or that some liquid mercury was entrapped in the void space of the coal. This is because the coal pore structure that has been destroyed by high-pressure mercury intrusion, blocks the mercury withdrawal. The bulk porosity determined by MIP (13.5%) is distinctly higher than that of helium porosity (6.7%) (Table 1). One possible reason of this difference relates to the applied high pressure that had induced new interparticle pores or ectogenic fractures in the coal. These artificial pores or fractures add to the value of measured bulk porosity. This phenomenon was also found in other research on coal and other porous materials [9,11]. Another possible explanation is that the increased porosity by MIP is related to the pore compression of the coal. Thus, these results confirm the inadequacy of MIP for research on the pore structure of lignite or other coals with very open structure.

### 3.2. Comparison of results of LFNMR and MIP

LFNMR denotes NMR measurements in a very low external magnetic field. In the low magnetic field, the number of hydrogen atoms present within the pore fluid of a rock can be detected by means of a relationship between relaxation distribution and relaxation time. Thus, the physical properties of the rock and the flow characteristics of the pore fluids can be determined [12].

The application of LFNMR in studying pore types of coals is based on the fact that the relaxation time of hydrogen atoms present within pores is positively correlated to the pore size ($V/S$). This relationship can be expressed as:

$$1/T_2 = \rho_2 (S/V)$$

where $T_2$ is the transverse relaxation time resulted from surface interactions; and $\rho_2$ is a constant representing the transverse relaxation strength. $S/V$ refers to the surface to volume ratio of the analyzed solids.

According to Eq. (3), a $T_2$ distribution corresponds to a pore size distribution with the smallest pores having the shortest relaxation times and the largest pores having the longest relaxation times. The details of the application of LFNMR in characterizing coal pore types, pore structures, porosity and permeability can be found in the authors’ previous work [7]. In this study, the $T_2$ spectra distributions are compared with the pore size distributions obtained by MIP for four coal samples (Fig. 3).

For sample L1, the CT image reveals well-developed mesopores, macropores and fractures (Fig. 2a), which corresponds well with the results from LFNMR (Fig. 3a). The $T_2$ spectrum distribution of L1 is trimodal with three peaks representing the mesopores, macropores and fractures, respectively. Similarly, in the results from MIP the percentages of meso-, macropores and fractures are...
Fig. 3. Comparison of pore size distribution by NMR relaxation (left: a, c, e and g) and mercury intrusion porosimetry (right: b, d, f and h) of four coals: L1: (a)–(b), LVB1: (c)–(d), SA2: (e)–(f), and A2: (g)–(h).
15%, 58% and 27%, respectively (Fig. 3b). However, when comparing Fig. 3a and b, it is evident that there are obviously overestimations of the percentages of macropores and fractures (>0.1 μm) volumes by MIP. This is because the intrusion of mercury in the lignite has induced swelling of compressible samples which causes an apparent increase in void volume. This result is also confirmed by the intrusion/extrusion curves (Fig. 1) and the difference between porosity and bulk porosity (Table 1). These results mean that the MIP method is inappropriate for characterizing coal fractures.

As shown in Fig. 3c–h, the pore size distributions of meso- and macropores analyzed by LFNMR correspond very well with the result obtained by MIP for samples LVB1, SA2 and A2. However, when comparing the MIP results to the results from the CT scan and LFNMR (Figs. 2 and 3), it was found that the percentage of macropores (including fractures) in sample SA2 is overestimated by the MIP, and, correspondingly the percentage of mesopores is underestimated (Fig. 3e and f).

The MIP results of the four coals show that MIP is usually suitable for quantifying coal PSD. However, there are also some drawbacks concerning the method. It is not possible to obtain the pore volume of closed pores or some micropores by MIP, which can induce an underestimation of total porosity and pore volume in common situations. In another situation, however, high-pressure intrusion by mercury may either deform or destroy the coal sample and eventually induce an increase in coal porosity due to the compressibility of the matrix and the micropore system. In this situation, the “capillary bundle pore-model” used in MIP is unsuitable. Thus, the pore compressibility of the coal structure must be considered when analyzing coal porosity and PSD. Results for sample L1 illustrate that porosity and macropore volume are typically underestimated by MIP. Moreover, it is also known that mercury can interact with various forms of carbon, ranging from activated carbons or unburned carbons derived from coal, to the relatively inert diamond surface [13–15]. The adsorption of mercury to the carbon surface can also impact the pore size determination by mercury intrusion.

Moreover, the pore shielding effect may induce uncertainty in the PSD analysis by MIP. It is the main reason for the results in the hysteresis behavior between intrusion and extrusion, and it is also the reason for the induced mercury entrapment in the coal. During the intrusion-extrusion processes, mercury selectively intrudes larger and then smaller pores with increasing pressure. After initially fully filling the void space with mercury, the mercury in turn first withdraws from the smaller and then from the larger pores. The pore shielding effects occur during the intrusion-extrusion processes. According to Wardlaw and McKellar [10] and Rigby and Edler [16], two kinds of pore shielding effects are commonly found in the coals, denoted as PSD models of A and B. For model-A, clusters of smaller pores occur in isolated domains in a continuous network of larger pores. When mercury is injected, it preferentially fills the larger elements first. With further increases in pressure the void volume becomes saturated with mercury. When the pressure is subsequently reduced, mercury initially withdraws only from the clusters of smaller voids. However, in model-A, the neighboring large pores isolates the small pores. As a result, the mercury is temporarily entrapped until the neighboring large pores are extruded. The hysteresis behavior in the samples of SA2 and A2 mainly belongs to the PSD model-A (Fig. 1). Different from model-A, model-B describes isolated clusters of large pores occurring in a continuous network of smaller pores. After initially fully filling the void space with mercury, the mercury initially withdraws from the smaller pores. However, at the stage where pressure had been reduced below the threshold for emptying the clusters of larger pores, these pore had already become disconnected by “snap-off” of the mercury meniscus and extensive residual mercury is retained. The mercury entrapment of sample L1 is typical of the PSD model-B (Fig. 1). It was found that both pore shielding effects are caused by the presence of spatially extended structural heterogeneities. This result agrees well with Rigby and Edler [16], who indicated that mercury entrapment is determined by the nature of the pore structure over macroscopic, and not microscopic, length scales. It was also found that pore shielding effects are commonly seen in the coal with a relatively wide PSD, but not in the coal with a narrow PSD. For example, sample L1 has wide PSD (Fig. 3a and b) and its pore shielding effect is distinct (Fig. 1). In contrast, sample LVB1 has a narrow PSD (Fig. 3c and d) and its pore shielding effect is negligible (Fig. 1).

In general, results show that LFNMR is an efficient tool for quantifying coal PSD. Moreover, it is easily-handled, convenient, fast, and, most importantly it is nondestructive. These advantages make it a powerful pore analysis method. The results from LFNMR agree well with the results by μCT and other traditional methods. In most situations, MIP results agree well with the results from LFNMR, however, some drawbacks such as the pore shielding effects and the destructive influence on samples can induce high uncertainty in the experimental results. MIP is not appropriate for analyzing lignite or other coals that have an open structure or well-developed fractures.

3.3. Pore size distribution by CMP

For conventional pressure-controlled mercury porosimetry (MIP), mercury pressure is raised in increments and the injected mercury volume is measured periodically. This generates a pressure-controlled measurement of a mercury capillary curve, while for CMP the capillary pressure curve is measured by the rate-controlled injection of mercury into the sample where the injection rate is kept constant and the mercury capillary pressure is monitored [3]. The conventional (pressure-controlled) mercury capillary pressure curve is also called the total capillary pressure curve. An advantage of CMP is that the total capillary pressure curve (normal capillary pressure curve) can be divided into two sub-curves: one details the distribution of pore bodies and the other details the distribution of pore throats [3]. As a result, the size distributions of both pore bodies and pore throats can be obtained. The detailed principles and process of CMP are referred to Yuan and Swanson [3] and Toledo et al. [17].

The CMP results, including the mercury intrusion curves and PSD of three selected coals, are shown in Fig. 4. Sample A4 is an anthracite with $R_{v}$ of 2.70%. The coal was collected adjacent to an igneous dike where the contact metamorphism may have induced a change in the pore structure leading to the generation of secondary macropores and fractures in the coal [18]. As shown in Fig. 2e, well-developed pores and fractures are obvious in this sample, although some of them were filled with minerals. The coal has extremely high porosity (9%) and permeability (14.9 mD) (Table 1). In the CMP results, we found that the intrusion saturation is as high as 80% and the PSD is wide with well-developed pores (Fig. 4). Sample HVB2 is a high volatile bituminous coal with $R_{v}$ of 1.01%. The pores and fractures of HVB2 are not as well developed as those of sample A4, while some fractures can still be clearly identified in the CT scan image (Fig. 2f). The porosity (5.2%) and permeability (3.09 mD) of the coal are medium to high, which mainly relates to the development of fractures and some macropores (Fig. 4). Sample MVB1 is a medium volatile bituminous coal with $R_{v}$ of 1.56%. In contrast to the above two samples, MVB1 has very low porosity (2.3%) and permeability (0.067 mD) (Table 1). The CT scan result shows that pores are predominantly mesopores, and some pores are filled with minerals (Fig. 2g). The CMP results for all three samples have strong positive correlations with the results from mercury intrusion and PSD characteristics as shown in Fig. 4.
Furthermore, CMP can disclose much more information about pore and throat characteristics such as average pore body radius ($P_{rav}$), average pore throat radius ($P_{tav}$), average of dominating pore-throats ($P_{tdm}$), and low-threshold of dominating pore-throats ($P_{tdl}$) as listed in Table 2. Comparison of the $P_{rav}$, $P_{tav}$, and permeability data of the three coals shows that coal permeability relates not only to the volume of pore body but also and more importantly to the pore throat size (Tables 1 and 2). The influence of pore throat on permeability is further determined by analyzing the dominating pore-throats, which are defined as the pore-throats cumulatively combined contribute to 80% of the permeability. $P_{tdm}$ represents the main type of pore throats that effectively contributes to permeability, and $P_{tdl}$ gives the low-threshold value of pore throats that mainly contribute to permeability. Taking sample A4 as an example, the permeability of the coal mainly derives from the pores with pore throats >7.88 $\mu$m. The ratio of pore body to throat represents the connectivity of the pore system. The higher the value, the poorer the pore connectivity. The relatively low pore/throat ratio of sample A4 indicates that pores with various diameters are uniform and all are well developed. On the comprehensive consideration of $P_{rav}$, $P_{tav}$, and $P_{tdl}$, and as well as the Pore /throat (Table 2), the sample with the best PSD is A4 followed by HVB2 and MVB1.

![Fig. 4. Rate-controlled mercury intrusion curves and pore size distributions of three selected coals.](image1)

![Fig. 5. Comparison of pore size distribution analyzed by NMR relaxation (a) and constant-rate-controlled mercury porosimetry (b, c and d).](image2)

<table>
<thead>
<tr>
<th>Sample</th>
<th>$P_{rav}$ ($\mu$m)</th>
<th>$P_{tav}$ ($\mu$m)</th>
<th>$P_{tdm}$ ($\mu$m)</th>
<th>$P_{tdl}$ ($\mu$m)</th>
<th>Pore /throat</th>
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<tbody>
<tr>
<td>A4</td>
<td>181</td>
<td>7.14</td>
<td>9.28</td>
<td>7.88</td>
<td>68.3</td>
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<td>HVB2</td>
<td>144</td>
<td>5.91</td>
<td>6.80</td>
<td>6.03</td>
<td>46.2</td>
</tr>
<tr>
<td>MVB1</td>
<td>132</td>
<td>2.22</td>
<td>1.51</td>
<td>1.29</td>
<td>71.8</td>
</tr>
</tbody>
</table>

$P_{rav}$, average pore body radius. $P_{tav}$, average pore throat radius; $P_{tdm}$, average of dominating pore-throats (dominating pore-throats are defined as the pore-throats that cumulative contribute 80% of the permeability); $P_{tdl}$, low-threshold of dominating pore-throats.
3.4. Results comparison between LFNMR and CMP

In Fig. 5, the $T_2$ spectra distributions are compared with the pore size distributions obtained by CMP for three coal samples. According to Yao et al. [7], each $T_2$ spectrum can be divided into two parts by a threshold (cutoff) of $T_{2c}$: the part with $T_2 < T_{2c}$ representing the adsorption pores (dominating by micro- and mesopores) that cannot be easily drained due to capillary forces and the second part with $T_2 > T_{2c}$ representing the transport pores (macropores and fractures) that can be drained. The calculated $T_{2c}$ values for samples A4, HV2B and MVB1 are 12.5, 31 and 11 ms, respectively [7]. As a result, for each $T_2$ spectrum the shadowed area represents the transport pores, and the remaining area represents the adsorption pores (Fig. 5a).

It was found that for characterizing of the distributions of macropores and fractures, the results of LFNMR are correlated well with those of CMP. For example, the $T_2$ spectrum of sample A4 has a wide and large peak, which indicates that the coal has a high porosity (mainly transport pores) and good connectivity (Fig. 5a). The pore throat distribution is uniform with the radius of 2–14 $\mu$m dominating (Fig. 5b) and with the pore body radius mainly ranging from 120 to 220 $\mu$m (Fig. 5c). Thus, at macropores scale (>0.1 $\mu$m), the CMP results agree well with the results by LFNMR. For sample HV2B, three kinds of pores (fractures, macropores and mesopores) are clearly distinguished in three $T_2$ spectrum peaks, where the fractures and macropores peaks correspond with the pore throat radius of about 8 $\mu$m and 2 $\mu$m in Fig. 5b. Similarly, for sample MVB1, the $T_2$ spectrum peak on the right corresponds with the pore throat radius of about 1.7 $\mu$m. However, for characterization of mesopores, the CMP results do not agree well with the LFNMR results. As shown in Fig. 5a, both samples HV2B and MVB1 have a mesopores peak on the left of the $T_2$ spectrum. This means that mesopores were distinguished by LFNMR method. In contrast, the mesopores information cannot be found in the pore throat distributions of the two samples (Fig. 5b). This is because that during the CMP analysis, the constant mercury intrusion rate is set to be 0.00005 mL/min, with which the maximum intrusion pressure is 6.2 MPa. According to Eq. (2), the measurable minimum pore radius is about 0.1 $\mu$m. As a result, mesopores information of coal cannot be distinguished by CMP methods.

4. Conclusion

The MIP is usually suitable for quantifying PSD of coal, however it has some uncertainties and drawbacks. On the one hand, high-pressure intrusion by mercury may either deform or destroy the coal sample and eventually induce inaccurate estimations of coal porosity, thus skewing of pore structure compressibility must be made in analyzing lignite or other coals with a very open structure or with well-developed fractures. On the other hand, during MIP measurements, two kinds of pore shielding effects were found in the coals with two different PSD models. In one model clusters of smaller pores occurs in isolated domains in a continuous network of larger pores, in which mercury may temporarily be entrapped during the extrusion process and a hysteresis loop between intrusion and extrusion curves is developed. In the second model the isolated clusters of large pores occurs in a continuous network of smaller pores, in which mercury is prone to be permanently shut off and isolated. Both pore shielding effects can result in uncertainty, while the influence by the latter effects is much more significant than the former effects.

The CMP method can provide much more detailed pore body and throat information of macropores, however it is deficient in analyzing the mesopores of coals.

After comparing the results by $\mu$CT and other traditional methods, it was found that LFNMR is an efficient tool for nondestructively quantifying coal PSD, and the method can provide much more accurate results than mercury porosimetry (both MIP and CMP).

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