Nondestructive quantification of moisture in powdered low-rank coal by a unilateral nuclear magnetic resonance scanner

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ABSTRACT
Moisture content in coal powder is a critical index because it controls the difficulty of coal handling and ultimately its combustion efficiency in coal-fired power plants. A unilateral proton nuclear magnetic resonance (NMR) scanner was applied in a laboratory to nondestructively quantify moisture content in powdered samples of brown and subbituminous coals. Due to the open geometry of the sensor unit, the scanner allows the nondestructive moisture quantification of a portion several millimeters below the surface of a large sample. Proton transverse relaxation was measured by the unilateral NMR scanner, and obtained moisture content values were compared with those by a conventional bilateral NMR apparatus. The comparison showed reasonable agreement with a root mean square residual of 4.1 wt.%H2O for a moisture content range of >12 wt.%H2O (wet basis). This moisture-quantification performance by unilateral NMR is sufficient for the quality control of wet coal having a critical value of approximately 30 wt.%H2O in terms of the handling property (flow-ability). Because unilateral NMR requires no specific sample preparation, such as sample insertion into tubes, the system is potentially applicable to in-situ nondestructive monitoring of the coal moisture in power plants to contribute to improved efficiency of handling and combustion.

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Introduction
The moisture content of low-rank coal is one of the most critical properties in coal-fired power plant operation (Luo, Zhang, and Chen 2017; Phiciato and Yaskuri 2019; Yu et al. 2013). A large moisture content can degrade the handling properties of powdered coal in the storage and transport facilities (e.g., hoppers) and also reduce the efficiency of combustion and gasification (Chen, Wu, and Agarwal 2000; Kim et al. 2013; Potter and Keogh 1981; Pusat, Akkoyunlu, and Erdem 2018; Rahman et al. 2017; Tahmasebi, Zheng, and Yu 2016; Xu et al. 2014). For example, the handling property (flow-ability) of wet brown coal powder drastically worsens when the moisture content exceeds a critical value of approximately 30 wt.%H2O in wet basis (Arima et al. 2018). Energy- and time-consuming special treatment (e.g., pre-drying) is needed for such wet coal. Therefore, a nondestructive and rapid method to monitor the moisture content of powdered coal being transported and stored in these plants is needed to judge whether special treatment is needed.

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This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
The low-field time-domain proton nuclear magnetic resonance (NMR) with a bilateral magnetic circuit has been used for the accurate moisture quantification of coal samples (Graebert and Michel 1990; Lynch and Webster 1979, 1980; Norinaga et al. 1998a, 1998b; Unsworth et al. 1988; Yao et al. 2010). The bilateral magnet arrangement was employed to obtain NMR signals with high signal-to-noise (S/N) ratios. A radio-frequency (RF) coil with a sample tube is placed between the two magnetic poles with a narrow gap, and a small sample is inserted into the tube. Thus, specific sample preparation, such as cutting a large sample into small pieces and inserting them into the sample tube, is required. This destructive and time-consuming sample preparation is a drawback when applying the NMR technique to the in-situ real-time nondestructive moisture monitoring in coal-fired power plants.

The NMR surface scanner employing a unilateral magnetic circuit (Blümich, Perlo, and Casanova 2008; Marble et al. 2007; Nicholls and De Los Santos 1991) potentially could be a solution for this need in power plants. With carefully designed unilateral magnet geometry, one side of a magnet with a planar RF coil is exposed to free space where large samples are placed (Blümich, Perlo, and Casanova 2008; Prado 2001). This single-sided or unilateral design enables the nondestructive surface scanning of large objects without specific sample preparation, such as cutting samples and inserting them into sample tubes. To test the applicability of unilateral NMR to coal moisture measurement, low-rank powdered coal samples from three localities were measured in a laboratory. The data obtained by unilateral NMR were quantitatively compared with those obtained by conventional methods (i.e., bilateral NMR and thermogravimetry) to evaluate the accuracy. On the basis of the data comparison, the moisture-quantification performance of the unilateral NMR technique was discussed and assessed whether it is sufficient for the quality control of wet coal having the above-mentioned critical value (i.e., approximately 30 wt.%H₂O).

**Samples and Methods**

**Sample Description**

The following samples from three localities were chosen in the present study as water-rich low-rank coals: two brown coals (Loy Yang, Australia, and Mae Moh, Thailand) and a sub-bituminous coal (Adaro, Indonesia). The moisture contents of the raw coals as received are approximately 54, 31, and 18 wt.% for the Loy Yang, Mae Moh, and Adaro coals, respectively. The raw coals were crushed by a pin mill machine followed by sieving to obtain powdered samples (grain diameter, 350–500 μm). The powders were slightly heated using a hot plate for a specific duration to prepare samples with a broad range of moisture contents. Each sample lot with a specific moisture content was then stored in two glass tubes to prevent water evaporation during measurements. The glass tube sizes were 15-mL tube with an outside diameter of 25 mm (Fig. 1b), and 1-mL tube with an outside diameter of 8 mm.

The moisture contents of the coal powder samples were measured by conventional thermogravimetry (Thermo Plus 2000, Rigaku Corp., Tokyo, Japan). A small amount of the powder (approximately 10 mg) was sampled from each glass tube and heated for 60 min at 107°C (basically according to Japanese Industrial Standard (JIS) M 8812 for the
moisture analysis of coal samples). The observed weight loss obtained by the thermo-gravimetry was taken to be the ground truth for the moisture content of each powder sample (Lynch and Webster 1980). The thermogravimetry revealed that the powder samples stored in the glass tubes covered a wide range (7–54 wt.%) of the moisture contents. In the present study, the moisture contents are expressed in terms of the wet basis that is, the percentage ratio of the mass of the contained water to the mass of the wet coal.

Free and bound water is important because they could significantly degrade the handling properties of coals (Arima et al. 2018). The extensive low-temperature differential scanning calorimetry (DSC) (Norinaga et al. 1998a) down to −140°C was performed for the powder samples from the three localities (Nakashima Y., unpublished data). Free and bound water was identified as exothermic reaction peaks between 0 and −30°C and −30 to −140°C, respectively. The DSC results showed that (i) as for the two brown coals (Loy Yang and Mae Moh), both free and bound water existed for the wet samples of approximately >20 wt.% and (ii) although no free water was detected, bound water occurred in the relatively wet samples of approximately >17 wt.% for the Adaro samples.

**Unilateral NMR**

The unilateral NMR surface scanner used in this study was a Minispec ProFiler System (Bruker BioSpin GmbH, Rheinstetten, Germany), consisting of a spectrometer, personal computer, pre-amplifier, and sensor. The sensor unit (Fig. 1) with a permanent magnet and RF coil probe is compact, easy to use, and capable of measuring the time-domain relaxation process of mobile protons (1H nuclei), such as water and fat molecules, in samples (Räntzsch,
Wilhelm, and Guthausen 2016; Todt et al. 2006). The outstanding advantage of the unilateral system over a conventional bilateral system is the open geometry of the unilateral magnetic circuit (Blümich, Perlo, and Casanova 2008; Chang, Chen, and Hwang 2006). Therefore, unilateral NMR allows us to nondestructively scan the inside of a large object placed on the sensor unit, while bilateral NMR requires time-consuming sample preparation (e.g., sample cutting for insertion into narrow sample tubes).

Each powdered coal sample stored in a 15-mL glass tube with an outside diameter of 25 mm was measured at room temperature (approximately 25°C) using unilateral NMR (Fig. 1b). The conventional Carr Purcell Meiboom Gill (CPMG) pulse sequence (Blümich, Perlo, and Casanova 2008; Hürlimann and Griffin 2000) was employed to acquire the proton transverse relaxation data. The total number of powdered coal samples measured was 25. The detailed acquisition conditions were as follows: the proton Larmor frequency was 16.4 MHz, the durations of the 90° and 180° pulses were both 4.7 μs, the echo spacing was 0.05 ms, the sequence repetition time was 0.5 s (i.e., the $T_1$ full relaxation condition, where $T_1$ refers to the spin-lattice relaxation time), and the number of stacked signals was 256. Thus, an NMR measurement time of 128 s (0.5 s × 256 times) was required for each coal sample. No RF shield cloth (Nakashima 2015, 2019) was used to reduce the environmental RF noise during NMR measurements at the laboratory.

The principle of the moisture quantification in coal samples using NMR proton relaxometry is simple and straightforward (Graebert and Michel 1990; Lynch and Webster 1980). The proton relaxation signal increases linearly as the amount of proton-bearing substance in the sensed region increases; the signal intensity can be converted into a water fraction when a reference sample with known proton concentration is measured. In the CPMG experiments, the obtained time-series data, $f(t)$, was assumed to obey a simple mono-exponential model, as

$$f(t) = M_0 \exp(-t/T_2)$$

where $t$ is time, $M_0$ is the signal intensity at $t = 0$, and $T_2$ is the transverse relaxation time (i.e., spin-spin relaxation time) of protons. The values of $M_0$ and $T_2$ were determined from Eq. (1) using the least squares method. The quantity $M_0$ was converted into water volume fraction by normalization using the $M_0$ value for a bulk H$_2$O sample (dilute CuSO$_4$ aqueous solution). The water weight fraction is readily calculated when the water volume fraction value is divided by the specific gravity of the bulk coal powder sample.

Before the coal moisture was measured, several benchmark experiments were performed to test the basic performance of the unilateral NMR system in Fig. 1. The tests consisted of the following three experiments:

(i) The sensed region of the RF probe in the x-, y-, and z-directions of Fig. 1a was determined by measuring silicon rubber sheets stacked in various thicknesses. A photo of the experiment is shown in the Electronic Supplementary Material (ESM) as Fig. ESM1a. The details of the experimental method using silicon rubber sheets are described elsewhere (Nakashima 2015).

(ii) One of the drawbacks of the unilateral magnetic circuit is the low S/N ratio compared with a conventional bilateral magnet (Anferova et al. 2004). This
drawback can be mitigated by increasing the number of stacked signals at the cost of increased total measurement time. To demonstrate the successful reduction of the random noise with increasing stack number, CPMG signals for a Loy Yang coal sample were measured (Fig. 1b) with various signal stacking numbers. The result was also compared with that obtained by a conventional bilateral NMR apparatus with high S/N ratio.

(iii) The accuracy of the proton quantification was examined using phantoms of CuSO₄ aqueous solutions (H₂O-D₂O mixture) with known proton (i.e., H₂O) volume fractions. The linear dependence of the CPMG signal intensity on the H₂O volume fraction was confirmed. A photo of the experiment is shown in Fig. ESM2a.

**Bilateral NMR**

The low-field time-domain NMR with a bilateral magnetic circuit has been used for the moisture quantification of coal samples (Graebert and Michel 1990; Lynch and Webster 1979, 1980; Norinaga et al. 1998a, 1998b; Unsworth et al. 1988; Yao et al. 2010). Although specific sample preparation (inserting samples into tubes) is required, the bilateral NMR ensures reliable moisture measurements with high S/N ratios. The powdered coal samples, each confined in a 1-mL tube with an outside diameter of 8 mm, were also measured by a conventional bilateral NMR apparatus. The purpose was to check the performance of the unilateral NMR in Fig. 1.

The bilateral NMR used in the present study was an NMS120 proton spectrometer (Bruker BioSpin GmbH, Rheinstetten, Germany) with a Larmor frequency of 20 MHz. The detailed specification is noted elsewhere (Nakashima 2001). A transient free induction decay (FID) signal after a single 90° RF pulse was measured for each sample at 27°C. The detailed conditions for the FID measurements are as follows: the duration of the 90° pulse was 2.9 μs, the receiver dead time was 7 μs, the sampling rate was 50 ns, the sequence repetition time was 0.5 s for the coal samples (i.e., T1 full relaxation condition), and the number of stacked signals was 256.

**Results**

The results for the benchmark experiments are shown in Figs. 2–4 and ESM1-2. As for the determination of the sensed region, examples of the raw CPMG data for silicon rubber sheets stacked in the z-direction are shown in Fig. ESM1b. The fitted signal intensity M₀ for Eq. (1) monotonically increases with increasing thickness of the stacked rubber. According to Nakashima (2015), thresholds of 10 and 90% were applied to the normalized M₀ values in Fig. 2 and ESM1cd. As a result, the dimensions of the sensed region of the sensor unit of Fig. 1a were determined to be 18, 6, and 3.4 mm in the x-, y-, and z-directions, respectively.

The effects of signal stacking on the random noise reduction for the unilateral NMR is shown in Fig. 3a. The S/N ratio evidently improves with increasing number of stacked sheets. The degree of the fluctuations of the 256-times stacked CPMG data by the unilateral NMR in Fig. 3a is generally the same as the singly stacked data for the bilateral NMR in Fig. 3b, suggesting that accurate unilateral NMR measurements can be performed by increasing the signal stacking number.
Figure 2. Sensitivity of the NMR sensor along the z-axis. The normalized CPMG signal intensity, $M_0$, is plotted as a function of the thickness of the silicon rubber sheets stacked in the z-direction. The solid curve is an eye guide. Details of the measurement are given in the caption of Fig. ESM1. The 10%- and 90%-sensitivity positions indicated by dotted lines show that the dimension of the sensed region of the sensor is approximately 3.4 mm in the z-direction.

Figure 3. Improvement of the S/N ratio by signal stacking. The sample is Loy Yang coal (53.7 wt%H$_2$O). The number of stacked CPMG signals is indicated. (a) Unilateral NMR (16.4 MHz) from Fig. 1 with an echo spacing of 0.05 ms. (b) Bilateral NMR (20 MHz) with an echo spacing of 0.08 ms. Although the sample volume within the sensed region of each NMR spectrometer is almost the same, the vertical scales of (a) and (b) are not exactly identical.
The performance test for the accuracy for the proton quantification by the unilateral NMR system in Fig. 1a is summarized in Figs. 4 and ESM2. The sample setting and examples of the raw CPMG data are shown in Fig. ESM2ab. Fitted $M_0$ values for the CPMG data were used to draw the calibration line (Fig. ESM2c). The results are converted to a cross-plot in Fig. 4, indicating that the root mean square residual is as small as 1.6 vol.% for the water fraction estimation. This demonstrates that the unilateral NMR of Fig. 1 is capable of proton quantification with a reasonable accuracy.

Examples of the raw CPMG data obtained by the unilateral NMR (Fig. 1b) are shown in Fig. ESM3 for three coal samples. The following preprocessing was applied to the raw data before the fitting using Eq. (1): (i) The initial echoes obtained by unilateral NMR are inevitably transient, and a deviation from the ideal exponential decay occurs (Hürlimann and Griffin 2000). Thus, the first two echoes were discarded in the present study. (ii) A non-zero signal can be seen for the nominally proton-free “blank” sample (i.e., ambient air) in Fig. ESM3. This is probably due to transient ringing derived from the strong 90° RF pulse (Fukushima and Roeder 1979) and to the intrinsic background noise of the spectrometer. This blank signal was subtracted from the CPMG data for the all coal samples before the application of Eq. (1).

Examples of the application of the mono-exponential model, Eq. (1), to the CPMG data are shown in Fig. 5. The fitted quantity $M_0$ for each coal sample in Fig. 5 was converted into a water volume fraction by division with that for a dilute CuSO$_4$ aqueous solution (=100 vol.%H$_2$O). Then, the water volume fraction was converted into a water weight fraction by dividing it by the specific gravity of the bulk powder sample in the glass tube. The obtained water weight fractions estimated by the unilateral NMR for the 25 coal samples are plotted in Fig. 6 against the ground truth that was obtained by

Figure 4. The accuracy of the proton measurement by the unilateral NMR of Fig. 1. This is a re-plot of Fig. ESM2c, obtained by rescaling the vertical axis using the calibration line.

The accuracy of the proton measurement by the unilateral NMR of Fig. 1. This is a re-plot of Fig. ESM2c, obtained by rescaling the vertical axis using the calibration line.
thermogravimetry. The slight but systematic overestimate for moisture by NMR can be seen in Fig. 6, which is also seen in Fig. 7 for bilateral NMR. The similar overestimate has been observed using a different low-field bilateral NMR spectrometer, JNM-MU25 (25 MHz for proton; JEOL Ltd., Tokyo, Japan), with respect to the same coal samples (Nakashima Y., unpublished data). This systematic overestimation by the three different NMR spectrometers compared with thermogravimetry is not an artifact but probably attributable to non-water mobile hydrogen (e.g., hydroxyl groups) in solid coal (Lynch, Barton, and Webster 1991; Norinaga et al. 1998b), which is undetectable in principle by thermogravimetry at 107°C. Thus, “water” or “moisture” measured by unilateral/bilateral NMR includes signals from the small amount of non-water mobile hydrogen as well as those from H$_2$O molecules.

Examples of the raw FID data obtained by bilateral NMR are shown in Fig. ESM4. Signals from the mobile protons (e.g., water molecules) were extracted and converted into water fraction values according to the conventional technique (Lynch and Webster 1979, 1980; Norinaga et al. 1998a, 1998b; Unsworth et al. 1988), which is described in the caption of Fig. ESM4. The results of the moisture quantification by the bilateral NMR are plotted in Fig. 7 against the ground truth obtained by thermogravimetry.

**Figure 5.** Examples of CPMG data for three coal samples acquired by the unilateral NMR in Fig. 1. Each water fraction measured by thermogravimetry is indicated. The data for the 0.15 wt.% CuSO$_4$ solution sample is also shown. Fitting results by the mono-exponential model, Eq. (1), are superimposed.
Figure 6. Cross-plot of the water fraction values by thermogravimetry and by the CPMG method using the unilateral NMR of Fig. 1. The solid and broken lines refer to exact agreement and ±10 wt.% error, respectively.

Figure 7. Same as Fig. 6 but for the water fraction values by the FID method using bilateral NMR as the vertical scale.
A coal powder with a specific moisture content was prepared from the same sample lot and stored in two sample tubes (15-mL tube for unilateral NMR measurement and 1-mL tube for bilateral NMR measurement). Thermogravimetric analysis was performed for each tube and plotted in the horizontal axes of Figs. 6 and 7, depicting slight disagreement between samples with nominally the same moisture content. However, by neglecting this slight disagreement, it is possible to directly compare the moisture quantification results by the unilateral and bilateral NMR methods (Fig. 8). To discuss the measurement error more quantitatively, the root mean square residual for all 25 data points was calculated to be 5.8 wt.%; it was reduced to 4.1 wt.% for the 21 data points larger than 12 wt.% (the units of the horizontal axis of Fig. 8). Because the typical value of the specific gravity of the coal powder sample is 0.8, the value of 4.1 wt.% is converted into $4.1 \times 0.8 \approx 3.3$ vol.%. This water volume fraction value is similar to the measurement error of 1.6 vol.% determined using the H$_2$O-D$_2$O mixtures (Fig. 4), suggesting that the coal measurements were performed in a reliable manner.

**Discussion**

According to the benchmark experiments (Figs. 2–4 and ESM1-2) to evaluate the performance of the unilateral NMR scanner in Fig. 1, the sensor unit of the scanner system has a compact sensing region of approximately 18, 6, and 3.4 mm in the x-, y-, and z-directions, respectively. The sensing depth (distance from the RF coil to the center of the sensed region in the z-direction) was 2.8 mm if it is defined as the distance yielding
a normalized signal intensity of 50% in Fig. 2. The inevitably strong random noise due to the open geometry of the unilateral magnetic circuit could be suppressed simply by signal stacking (Fig. 3). As a result, the root mean square residual as the error for the proton detectability was as small as 1.6 vol.% (Fig. 4); that as the error for the coal-moisture detectability was 4.1 wt.% for the 21 data points larger than 12 wt.% in Fig. 8. These error levels are similar to those reported for other unilateral NMR scanners (Anferova et al. 2004; Nakashima 2019; Prado 2001; Todt et al. 2006). Thus, the accuracy of the present study is reasonable, and the unilateral NMR scanner of Fig. 1 is a promising apparatus for nondestructive coal-moisture quantification.

The main purpose of the present study is to assess whether the current state of the art of the unilateral NMR technique is sufficient for the in-situ quality control of wet coal in power plants. The handling property (flow-ability) of brown coal powder drastically worsens when the moisture content exceeds a critical value of approximately 30 wt.% H₂O in wet basis (Arima et al. 2018). Thus, it is desirable to quantify the coal moisture content at least down to 30 wt.%H₂O to judge whether special treatment (e.g., energy-consuming pre-drying) is needed. The ability to quantify moisture in coal samples by unilateral NMR was successfully confirmed, as shown in Fig. 8, which depicts reasonable agreement with the data obtained by conventional bilateral NMR. The measurement error (root mean square residual) of the moisture quantification was as small as 4.1 wt.% H₂O for the relatively wet 21 samples with moisture contents larger than 12 wt.% H₂O. Thus, the unilateral NMR apparatus covers the broad moisture range, including the critical value of 30 wt.%H₂O, with a reasonable measurement error. In conclusion, the unilateral NMR used in the present study would be applicable to the in-situ moisture quantification of wet brown coal to nondestructively evaluate its handling properties.

There is relatively large discrepancy between the unilateral and bilateral NMR, particularly for the dry Adaro and Mae Moh samples (≤12 wt.%H₂O in the units of the horizontal axis of Fig. 8). A similar discrepancy for the dry samples can be seen between unilateral NMR and thermogravimetry (Fig. 6). In contrast, no significant discrepancy was observed between bilateral NMR and thermogravimetry for all samples, including samples with ≤ 12 wt.% H₂O (Fig. 7), suggesting that the accuracy of the moisture quantification by unilateral NMR is somewhat worse for such dry samples. Probably this is a consequence of the relatively small T2 value of the dry samples (He et al. 2019; Prado 2001; Xu et al. 2017), which reduces the accuracy of the mono-exponential fitting due to the small number of CPMG data points acquired at a sampling rate of 0.05 ms. For example, effectively only 10 non-zero CPMG data points were used in fitting for the Adaro sample in Fig. 5. In contrast, a large number of FID data points (see Fig. ESM4) acquired quickly at a sampling rate of 50 ns is responsible for the negligible discrepancy in Fig. 7. Therefore, the unilateral NMR apparatus with a CPMG echo spacing of 0.05 ms could reduce the accuracy of the moisture quantification for relatively dry coal samples with equal to or less than 12 wt.%H₂O. However, it should be noted again that the present study demonstrates that the current state of the art of the unilateral NMR technique is sufficient for the moisture quantification for wet coals of > 30 wt.%H₂O, for which special treatment (e.g., pre-drying) is needed.

The less accurate moisture estimation mentioned above for the dry coal samples with equal to or less than 12 wt.%H₂O could be improved by the following advanced methods. (i) The use of the multi-exponential model (Liu et al. 2020) instead of the mono-exponential model, Eq. (1), would be more promising for the analysis of heterogeneous
natural coals having various pore diameters. Thus, if a large number of non-zero CPMG data points were acquired with an echo spacing much shorter than 0.05 ms, the application of the multi-exponential model to the CPMG data using the inverse Laplace transform (Anferova et al. 2004; Blümich, Perlo, and Casanova 2008) would improve the accuracy. (ii) Machine learning algorithms have been successfully applied to the low-field NMR data analysis (Greer, Chen, and Mandal 2018). Thus, if time-domain CPMG data such as Fig. 5 and Fig. ESM3 were provided as a large data set for numerous samples with known moisture content values, the application of machine learning to the large data set would enable more accurate moisture quantification.

The unilateral NMR system is portable and capable of scanning the inside of a large object to quantify moisture nondestructively. Although glass tubes were used in the present study (Fig. 1b) to prevent water evaporation during measurement, it is possible to scan the surfaces of a large pile of coal powder at a power plant. The following should be noted for the use of the unilateral NMR scanner for such in-situ moisture monitoring (Nicholls and De Los Santos 1991) aimed at more effective coal utilization:

(i) The CPMG data acquisition time for a sample was 128 s in the present study, which should be shortened for practical real-time monitoring. It would be possible to reduce the acquisition time to several seconds if the sensor unit is equipped with a RF noise shield cloth (Nakashima 2015). Enlargement of the sensed region by careful design of the magnetic circuit (Marble et al. 2007) to increase the signal intensity could be another possible solution.

(ii) The investigation depth is as shallow as several millimeters (Fig. 2) due to the small dimensions of the relatively small magnet used (Fig. 1). A deeper investigation depth (e.g., 3 cm) is available when a larger magnetic circuit is employed (Nakashima 2015, 2019).

Conclusions

A unilateral NMR scanner was successfully applied to the nondestructive quantification of the moisture content in low-rank coal powder samples in a laboratory. Comparison with the conventional bilateral NMR apparatus showed that the measurement error of moisture as the root mean square residual was as small as 4.1 wt.% for relatively water-rich (i.e., larger than 12 wt.%H₂O) samples. Because no specific sample preparation (e.g., inserting powders into sample tubes) is needed for measurement, the unilateral NMR system is a promising tool for the nondestructive in-situ moisture monitoring of water-rich coals for the improvement of handling and combustion efficiency in coal-fired power plants.

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