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Relation between relative permeability and hydrate saturation in Shenhu area, South China Sea*

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Abstract: Nuclear magnetic resonance measurements in hydrate-bearing sandstone samples from the Shenhu area, South China Sea were used to study the effect of gas hydrates on the sandstone permeability. The hydrate-bearing samples contain pore-filling hydrates. The data show that the pore-filling hydrates greatly affect the formation permeability while depending on many factors that also bear on permeability; furthermore, with increasing hydrate saturation, the formation permeability decreases. We used the Masuda model and an exponent N = 7.9718 to formulate the empirical equation that describes the relation between relative permeability and hydrate saturation for the Shenhu area samples.

Keywords: Gas hydrate, permeability, NMR, Shenhu area

Introduction

Permeability represents the ability of fluids to pass through rocks and depends on rock porosity, the pore geometry in the fluid flow direction, particle size and arrangement, and so on, whereas it is independent of the fluid properties. Presently, the main methods to obtain the permeability of rock formations include core testing, wireline testing, drill-pipe testing, and well-test analysis (An et al., 2005). Using well-logging data to calculate permeability is the most commonly used and economical method. Especially, nuclear magnetic resonance (NMR) logging technology greatly improves the precision of formation permeability estimates (Wang and Li, 2001).

In hydrate-bearing formations, the formation and decomposition of hydrates affects the pore characteristics, which directly affects the permeability. Thus, the study of the relation between permeability and hydrates is critical in the analysis of hydrate-bearing formations. Besides the porosity characteristics of a formation, the permeability of hydrate-bearing porous media is affected by the gas hydrate growth patterns, occurrence, and saturation (Sakamoto et al., 2007, 2007, 2009; Kumar et al., 2010; Minagawa et al., 2008, 2012; Liu et al., 2011; Song et al., 2010; Zhao et al., 2011). The gas hydrates in Shenhu area are pore-filling hydrates. Most current studies of the permeability of hydrate-bearing porous media have simulated the sedimentary environment and synthetic hydrates. For, it is difficult to perform a comprehensive characterization of the actual underground conditions. Hence, the study of actual hydrate-bearing sandstone samples can help understand the relation of pore-filling hydrates and formation

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permeability.

In this study, we first obtained NMR spectra on actual samples from the Shenhu area, South China Sea and analyzed the effect of pore-filling hydrates on the formation permeability. Based on the data, we established an empirical equation for the relation between relative permeability and hydrate saturation suitable for the Shenhu area samples.

Geological setting

Shenhu area is an important gas hydrates exploration area in the Baiyun sag, Pearl River Mouth (PRM) Basin, on the northern slope of South China Sea (Figure 1). The PRM Basin has been subsiding since the Middle Miocene. In response to high deposition rates, the formation consists of lacustrine mudstones up to several kilometers thick, which favors the development of gas hydrates. Many geophysical and geochemical indications for gas hydrates were reported in the early geological surveys of the basin. In 2007, the Guangzhou Marine Geological Survey (GMGS) executed a gas hydrate drilling expedition, and gas hydrates were discovered in core samples. The hydrate-bearing sandstone samples used in this study are from this drilling expedition.

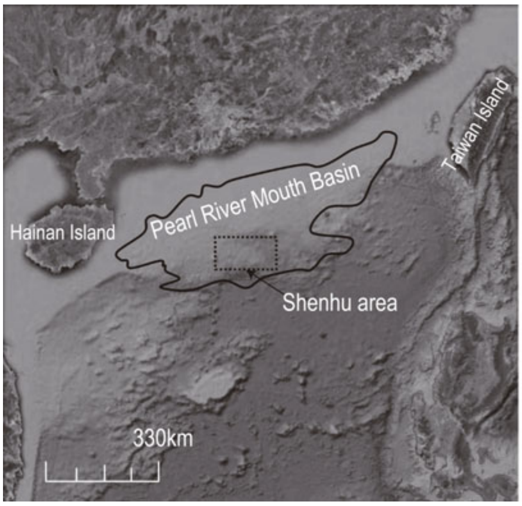
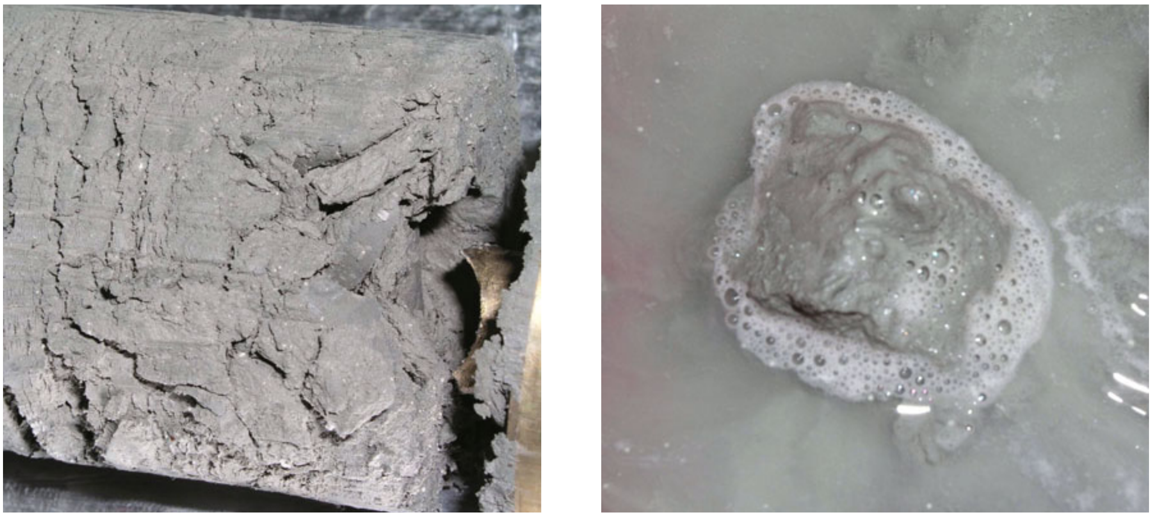


Fig.1 Location of Shenhu area in the northern slope of the South China Sea.

The gas hydrates of the Shenhu area are characterized as pore-filling hydrates. Biogenic methane that forms gas hydrates is found in the shallow porous beds. At the appropriate P–T conditions, methane and water form gas hydrates within the pores of the formation by mixing in situ. As shown in Figure 2a, pore-filling hydrates are uniformly dispersed within the pores. Hydrates are macroscopically observed; however, when the samples are immersed in water bubbles are coming out (Figure 2b).

The analysis of the cores showed that the gas hydrate-bearing sediments consist of silt (70%), sand (<10%), and clays (15%–30%) (Chen et al., 2011). Gases in the pore space of the sediments form the gas hydrates. Furthermore, the hydrate-free sediments have good permeability due to the large pore spaces and good pore connectivity. However, pore-filling gas hydrates change the pore characteristics and affect permeability, which suggests a close relation between the formation permeability and pore-filling gas hydrates.



(a) core

(b) sample immersed in water

Fig.2 Hydrate-bearing sandstone from the Shenhu area.

NMR measurements

NMR measurements are used to indirectly calculate permeability. Presently, the most commonly used models are the SDR model (Kenyon et al., 1992) and the Coates model, which is based on the T2 distribution (Coates et al., 1991). In this study, the hydrates in the sandstone samples decompose naturally, and the water produced by the decomposition saturates the sandstone. The SDR model is suitable for water-saturated rocks (Zou and Liu, 2011). Compared with the Coates model, the SDR model avoids errors due to the selection of T2 cutoff values in the calculation. Hence, we used the SDR model to calculate the sample permeability.

SDR model

In the SDR model, the permeability is calculated with the following equation (Kleinberg et al., 2003; Kenyon, 1992)

$$\kappa = c\varphi_{NMR}^{4} T_{2LM}^{2}, \tag{1}$$

where c is a coefficient related to lithology, φ_{NMR} is the NMR porosity, and T_{2LM} is the geometric mean of the T_2 distribution. In the NMR data, the magnitudes corresponding to the transverse relaxation times T_2 are transformed to pore components. By summing the pore components, we obtain the NMR porosity

$$\varphi_{NMR} = \sum_i m(T_{2i}), \tag{2}$$

where $m(T_{2i})$ is the magnitude corresponding to each transverse relaxation time T_2 and T_{2LM} is the comprehensive reflection of the relaxation time and porosity

$$T_{2LM} = 10^{\frac{1}{\varphi_{NMR}}\left(\sum_i \left[m(T_{2i})\log_{10} T_{2i}\right]\right)}. \tag{3}$$

In hydrate-bearing formations, the permeability at any hydrate saturation S_h is $\kappa(S_h)$, whereas the permeability of the hydrate-free formation is κ_0 . Thus, we define the relative permeability

$$\kappa_r = \kappa(S_h)/\kappa_0. \tag{4}$$

Using equation (1), we obtain

$$\kappa_r = \frac{\varphi_{NMR}^{4} T_{2LM}^{2}}{\varphi_{NMR_0}^{4} T_{2LM_0}^{2}}, \tag{5}$$

where φ_{NMR_0} and T_{2LM_0} are the NMR porosity and mean relaxation time of the hydrate-free formation, respectively.

Experimental setup

To prevent the decomposition of the gas hydrates, the sample was placed in liquid nitrogen jars prior to the experiments, as shown in Figures 3c and 3d.

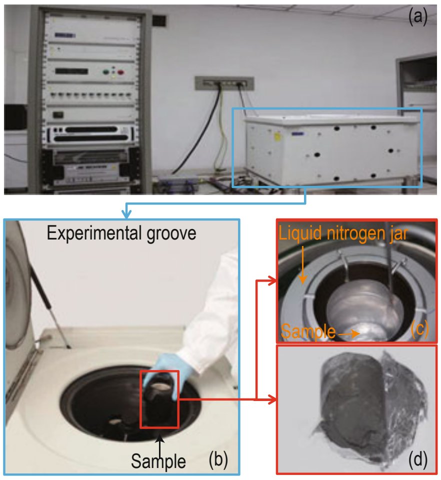


Fig.3 (a)NMR system. (b)Experimental groove. (c)Sample in the tinfoil stored in the liquid nitrogen jar. (d)Close-up view of the sample.

The experimental apparatus consists of a temperature control unit to maintain the temperature at 5 °C during the experiment, an OXFORD MARAN DRX2 NMR system (Figure 3a), and a data logger. The experimental parameters are listed in Table 1. The experimental procedure is:

1) The experimental groove keeps constant temperature of 5 °C by adjusting the temperature control device;

2) Open the NMR system, which comes to a steady state when the temperature reaches to 35 °C;

3) Take out the sample from the liquid nitrogen jar. Divide the sample into two pieces of equal size. Put one piece back into the liquid nitrogen jar. The other

Table 1 NMR experimental parameters

Test temperature (°C)	Waiting time (s)	Echo spacing (s)	Number of echoes	Number of scans	Field frequency (MHz)
5	6	0.3	2048	16	2

one is packed with insulation plastic and put into the experimental groove (Figure 3b);

4) Make the specimen decompose naturally. Meanwhile repeat the NMR measurements. Operate the data logger manually to record each result.

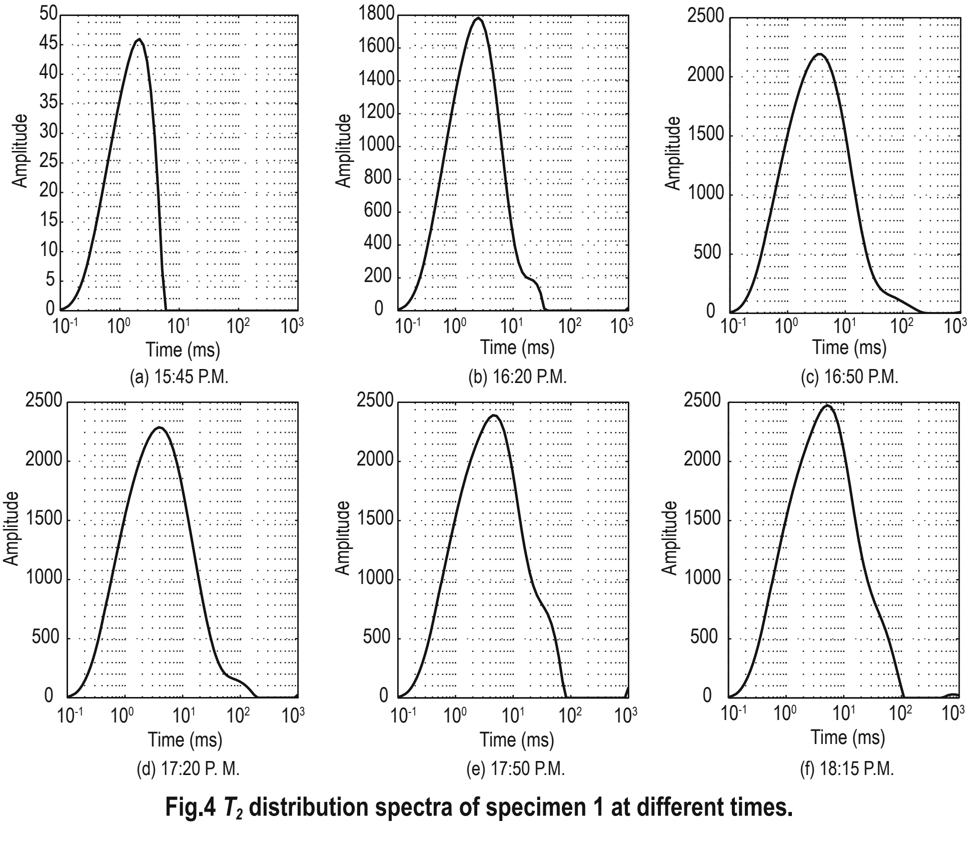
5) After the measurements of the first specimen, repeat the operation to the second specimen.

Results and discussion

To compare the results and perform error analysis, the sandstone sample was divided into two pieces of equal size, named specimen 1 and 2. The same parameters were used for both. During the experiments, the specimens decomposed naturally, and we repeated the NMR measurements, measuring each echo train and simultaneously generating the T2 distribution. The experiment for specimen 1 lasted 6 h (15:30–18:30) and 3 h for specimen 2 (20:00–23:00). Eighty groups of valid data were measured for each specimen.

Taking specimen 1, for example, Figure 4 shows six T_2 distribution spectra at the initial, intermediate, and final stage, respectively. As we can see from the figure, at the initial stage, the range in the T_2 spectra is 0.1–10 ms with peak position less than 4 ms; therefore, the sample pores are mainly occupied by clay-bound water. As the experiment progressed, the T_2 distribution range expanded with the peak position gradually shifting to the right. At the intermediate stage, the capillary-bound water in the pores increased and more free water was present at the final stage. This suggests that during the experiment, the hydrates in the sample decomposed naturally, increasing the specimen porosity, and improving the pore connectivity. In addition, the T_2 distribution at different times is a single peak. This suggests that the specimen pore radius is relatively simple, and the hydrates are distributed uniformly.

Equations (2) and (3) are used to calculate the T_2 distribution and, subsequently, the NMR porosity, and the geometric means. In specimen 1, for example, the NMR porosity is shown as a function of time (Figure 5). The data in Figure 5 suggest that the porosity gradually increases, which is consistent with the above analysis. At the initial stage, the regularity of the porosity is relatively poor. This may be due to instrument instability. In addition, the poor pore connectivity at the initial stage may not release in time the generated gas from the gas hydrates, thus affecting the experimental results. At the final stage, the porosity gradually stabilizes, and therefore, we infer that the hydrates have completely decomposed.



(a) 15:45 P.M.

(b) 16:20 P.M.

(c) 16:50 P.M.

(d) 17:20 P. M.

(e) 17:50 P.M.

(f) 18:15 P.M.

Fig.4 T_2 distribution spectra of specimen 1 at different times.

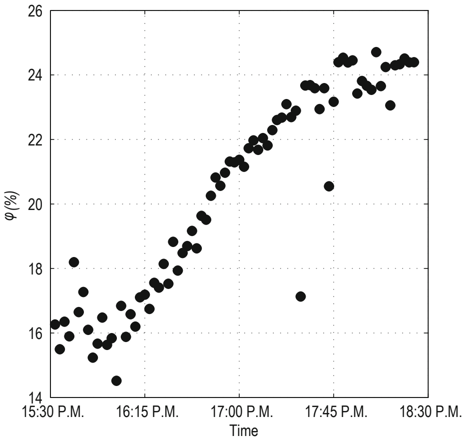


Fig.5 NMR porosity versus time for specimen 1. Black dots represent the NMR porosity calculated from the experimental data.

When the hydrates in the specimens completely decomposed in the final stage, we calculate the NMR porosity φ_{NMR_0} and the geometric mean of the T_2 distribution T_{2LM_0} for the hydrate-free sandstones. Hence, by using equation (5), the relative permeability of the samples is obtained. Because the hydrates occupy pore spaces, the hydrate saturation S_h during the experiment can be calculated by using the NMR porosity of the hydrate-bearing and hydrate-free formation

$$S_h = 1 - \frac{\varphi_{NMR}}{\varphi_{NMR_0}}. \tag{6}$$

Thus, we can establish the relation between relative permeability and hydrate saturation, as is shown in Figure 6. We can see that the relative permeability versus hydrate saturation of the two specimens shows apparent regularity. The relative permeability decreases with increasing hydrate saturation in both specimens.

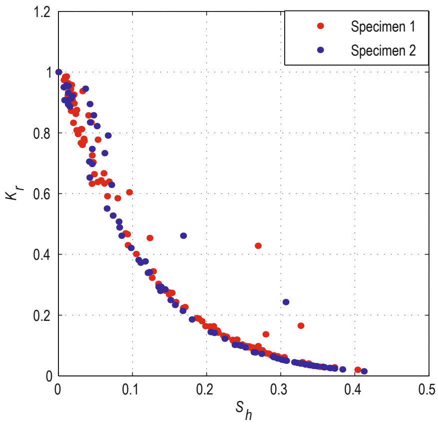


Fig.6 Relative permeability versus hydrate saturation in the two specimens.

From the experimental data, we infer that pore-filling hydrates strongly affect the formation permeability. When a formation contains hydrates, its permeability will decrease. Nonetheless, the effect of hydrates on the formation permeability is variable because the permeability of porous media is influenced by many other factors as well. Next, we analyze the factors that affect the permeability in hydrate-bearing formations using different models.

Pore-filling hydrates and formation permeability

Relative permeability models of hydrate-bearing formations

1. Parallel capillary model

To simulate porous media, Kleinberg et al. (2003) proposed a model consisting of a bundle of parallel capillaries with the same radius, which they called the parallel capillary model. When hydrates occupy pores, they surround the capillary walls. Thus, the porosity and capillary radius decrease, and the relative permeability as a function of hydrate saturation is

$$\kappa_r = \left(1 - S_h\right)^2, \tag{7}$$

where κ_r denotes the relative permeability and S_h is the hydrate saturation.

2. Kozeny grain model

Kleinberg et al. (2003) introduced the tortuosity of rock pores in the analysis of the permeability of hydrate-bearing formations. For pore spaces are irregular, and flow paths are not straight lines in porous media. Thus, the Kozeny grain model for hydrate-bearing formations was proposed. When hydrates occupy pores, the tortuosity changes, and we obtain

$$\kappa_r = \left(1 - S_h\right)^{n+1}, \tag{8}$$

where the exponent n equals 1.5 for $0 < S_h < 0.8$ (Spangenberg, 2001). For $S_h > 0.8$, the relative permeability of water is quite small, and the increase of n has only a minor effect.

3. Lawrence Berkeley National Laboratory Model (LBNL)

Moridis et al. (1998) proposed the LBNL relative permeability model

$$\kappa_r = \bar{S}_w^{1/2}\left[1-\left(1-\bar{S}_w^{1/m}\right)^m\right]^2, \tag{9}$$

with

$$\bar{S}_w = \frac{S_w - S_{rw}}{1-S_{rw}},$$

where S_{rw} is the irreducible water saturation, S_w is the water saturation, and m is the wettability for sandstones and equals 0.46 (Parker et al., 1987).

4. Masuda model

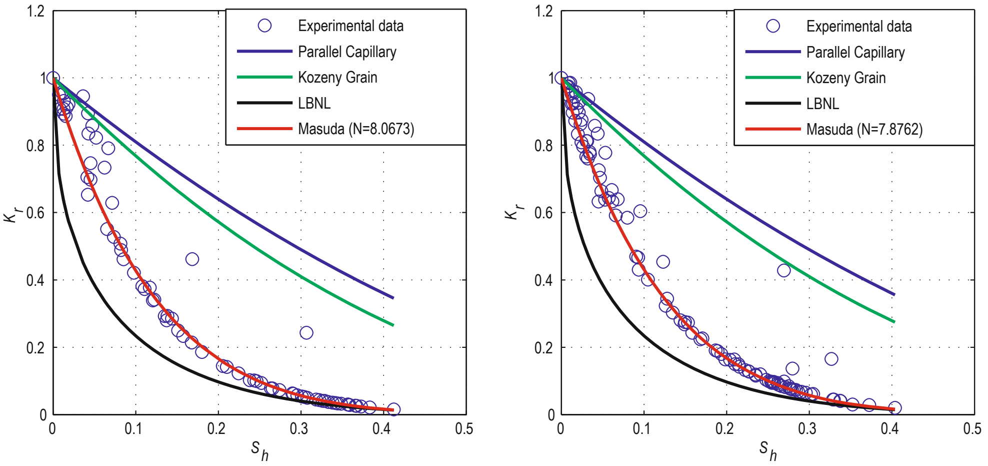
The Masuda model (Masuda et al., 1997) is an extension of the parallel capillary and Kozeny grain model. In this model, the relative permeability versus hydrate saturation of hydrate-bearing formations decreases exponentially. The effect of the hydrates on the formation permeability is reflected in the exponent. As the number of factors affecting the permeability of a formations increases, the exponent also increases. Hence, the Masuda model is of the form

$$\kappa_r = \left(1-S_h\right)^N, \tag{10}$$

where N is between 2 and 15 (Liang et al., 2011).

Factors of pore-filling hydrates affecting formation permeability

To analyze the effect of pore-filling hydrates on the formation permeability, we fit the experimental data of the two samples with the abovementioned relative permeability models and compare the results in Figure 7.



(a) Sample 1

(b) Sample 2

Fig.7 Experimental vs model-derived data.

From Figure 7, we infer that the parallel capillary model and the Kozeny grain model do not fit the data, which suggests that the models underestimate the effect of pore-filling hydrates on the formation permeability. Thus, it is not enough to consider the effect of hydrates on the formation porosity and pore tortuosity. The LBNL model also does not fit the experimental data, especially at low hydrate saturation, probably, because the empirical wettability value is not applicable to the Shenhu area. The Masuda model best fits the experimental data by adjusting the exponent, which suggests that the Masuda model is better suited for the sandstones in this area. The exponent value for specimens 1 and 2 is 8.0673 and 7.8762, respectively, which strongly suggests that the effect of pore-filling hydrates on the formation permeability depends on many factors.

From the above, we conclude that pore-filling hydrates affect the formation porosity, pore tortuosity, and formation permeability. Moreover, hydrates affect the size and shape of the pores, the fluid flow direction, and finally the formation permeability. Clearly, a combination of factors contributes to the significant effect of the pore-filling hydrates on the formation permeability.

Empirical equation

We modified the Masuda model to formulate the empirical equation for the relation between relative permeability and hydrate saturation for the Shenhu area. The small difference between the two exponents (8.0673 and 7.8762) suggests that the measurements are reliable. The small difference is attributed to systematic and random errors. Because of the limited number of samples and experimental conditions, it is rather difficult to accurately assess and eliminate errors under reproducibility and repeatability conditions. Thus, errors were roughly eliminated by taking the average of the exponents of the two specimens. N = 7.9718 and the empirical equation that describes the relation between relative permeability and hydrate saturation is

$$\kappa_r = \left(1 - S_h\right)^{7.9718} \tag{11}$$

or

$$\kappa(S_h) / \kappa_0 = \left(1 - S_h\right)^{7.9718}, \tag{12}$$

where $\kappa(S_h)$ is the formation permeability, S_h is the hydrate saturation, and κ_o is the permeability of the hydrate-free formation.

3D seismic methods play a major role in the exploration of hydrate reservoirs. According to the BISQ porous medium model, changes in the formation permeability will affect the attenuation of seismic waves, which enables seismic wave attenuation attributes to become an important method in the recognition and quantitative analysis of hydrate reservoirs (Li et al., 2013). In the development stage, permeability is critical to successful depressurizing exploitation. Permeability variations will significantly influence the flow of gas and water in porous media, thereby affecting gas storage and exploitation. Thus, the empirical equation of the relation between relative permeability and hydrate saturation in the Shenhu area can help guide the exploration and development of hydrate reservoirs.

Conclusions

NMR data from core samples of hydrate-bearing sandstone samples from the Shenhu area suggest that pore-filling hydrates greatly affect the formation permeability, while also affecting many parameters that bear upon permeability. With increasing hydrate saturation, the formation permeability decreases rapidly. We found that the Masuda model best reproduces the experimental data and used it to formulate the empirical equation that describes the relation between relative permeability and hydrate saturation in the Shenhu area sandstones. However, because of the limited number of samples, the applicability and accuracy of the empirical equation remains moot. Nonetheless, because the Shenhu area pore-filling hydrates are rather typical, the derived empirical equation may have wide applicability.

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