Water Block Damage And Its Solutions For Tight Gas Reservoirs In Dabei-Keshen Area

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Abstract

Water block damage may arise in tight gas reservoirs in Dabei-Keshen area as the reservoir is associated with low porosity, low permeability and strong capillary forces, which results in worthless industrial exploitation. To investigate the mechanism of water block and put forward corresponding measures, water block index (WBI) is developed to estimate the damage degree of water block and thermo-stable surfactant systems are optimized to clean up water block through interfacial tension tests, wettability tests and spontaneous imbibition. The result of WBI for core samples from the targeted zone is 70%, belonging to the type of strong water block. Sensitivity analysis shows that matrix permeability and displacement pressure are in positive correlation with WBI, while water saturation, content of clays, fluid viscosity and interfacial tension are in negative correlation with WBI. Thermo-stable surfactant systems JY-2(0.05FS-31+15%methanol) and JY-3(0.5%HSC-25+15%methanol) are preferentially optimized. And JY-3 works best to reduce WBI from 66.2% to 30.4%. Surfactant in composite system contributes to reducing interfacial tension and altering wettability, and methanol is benefit for reducing water saturation through accelerating evaporation in a short time. This synergy promotes the clean-up process of water blocks. Based on the study of mechanism of water blocks and experimental results, we are able to provide reference for economic and efficient development of gas fields.

Introduction

Tight gas reservoirs in China contain large amount of resources with ultra-low permeability, porosity and productivity. It must be successfully stimulated to produce commercial productivity (Khlaifat et al. 2011). However, many problems may arise during the process of stimulation, including fines migration, incompatible fluid, water block, etc. Among these problems, water block seriously limits the successful development of tight gas reservoirs, and problems become more complicated when encounters high temperature and high pressure. Dabei-Keshen area is a typical HT/HP tight gas reservoir and the targeted zone mainly consists of feldspar sandstone, litharenite and arcose. Multi high angle fractures grew in the formation where feldspars and calcites are the main interstitial fillings. Clays consist of kaolinite (67~74%), illite mixed with smectite (16~22%) and chlorite, which results in the increase of connate water saturation and flow resistance due to high content of illite and smectite. The petrophysical properties of the reservoir include permeability (0.011×10^{-3}-$0.424\times10^{-3}\mu m^2$), porosity (2.09-7.91%), drainage pressure (1-8MPa), average pore radius (0.1μm), contact angle (18~40°), pressure coefficient (1.54-1.65), temperature (2.10°C/100 m), etc. It can be concluded that the target zone is a HT/HP and low

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porosity and permeability formation, and water block may exist during the process of stimulation (Xu 2016; Mei 2014).

There have been numerous experimental and field studies (Penny et al. 1983, Bennion et al. 2006, Liu et al. 2015; Rostami et al. 2016) on water block trapping. Ding and Kantzas (2003) studied the imbibition mechanism with NMR technique and attributed the cause of water block to capillary forces. Mahadevan and Sharma (2005) studied the affecting factors of water block, including permeability, wettability, and temperature on clean-up of water block by measuring relative gas permeability with Berea sandstone and Texas Cream limestone cores. Based on the analysis of these factors, many formulas have been proposed to clean up water block in consideration of reducing interfacial tension, altering wettability and reducing water saturation (Adejare et al. 2012; Tang and Firoozabadi 2002; Fahes and Firoozabadi 2007; Fernandez et al. 2011; Liu 2015; Li 2017; Jiye et al. 2016; Yuan et al. 2016;). But few studies of water block characteristics on tight gas reservoirs with HT/HP were conducted as it is difficult to simulate HT/HP conditions.

In this study, we focused on core's relative gas permeability from Dabei-Keshen area to investigate the cause of water block and put forward corresponding measures. First of all, water block index was initially established to evaluate the damage degree of water block and then five factors related to water block were systematically analysed. Then, four kinds of composite surfactant system were used to optimize the thermos-stable surfactant through interfacial tension, wettability and spontaneous imbibition tests. Finally, the optimized surfactant was used to prevent water block by measuring water block index.

Materials and Apparatus

Materials: 25 core samples (D=2.54cm, L=4.06-5.08cm) selected from 6 wells (5850.3-5885.8m) in Dabei-Keshen; 4 surfactants purchased from 3M Corporation in USA.

Apparatus: DCAT11 interfacial tension meter, DSA-30 contact angle meter, self-made spontaneous device, HT/HP acidizing simulation device, displacement simulation device.

Methods

Damage Degree of Water Block. 11 cores were applied to evaluate damage degree of water blocks by testing the relative gas permeability. The experimental procedure was as follows:

(1) Dry the cores in the oven at 50°C for 24 hours;

(2) Take out the cores, record the dry weight m_0 and calculate initial gas permeability K_0 using steady state method as listed in **Eq. 1**;

(3) Set the sample in the core holder and flood it with simulated formation water with a salinity of 62000 mg/L, record the wet weight m_1;

(4) Flood the core with N_2 for 50-60 hours until the weight of the core ceases to change, set confining pressure as 4MPa and constant injecting pressure to be 2 MPa;

(5) Record the flow rate and weight the core per 1-2 hours, record as m_i (i=2,3,…n);

(6) Calculate S_w (**Eq. 2**) for a given time, and calculate K_i for gas phase under different water saturation according to SY/T 5345-2007;

(7) Calculate the damage degree of water blocks according to **Eq. 3** and plot S_w vs. K_{rg} (K_g/K_0).

$$K_i = \frac{Q_g C(P) V_d L}{A} \frac{\Delta \ln\left(\frac{P_{inlet}^2 - P_{initial}^2}{P_{inlet}^2 - P_{outlet}^2}\right)}{\Delta t}, \ldots\ldots(1)$$

$$S_w = \frac{m_i - m_0}{m_1 - m_0}, \ldots\ldots(2)$$

$$WBI = \frac{K_0 - K_n}{K_0} \times 100\% \ldots\ldots(3)$$

Criterion for damage degree of water block index (WBI) is listed in **Table 1**.

Table 1—Criterion for damage degree of water block.

WBI, %	0-30	30-60	60-90	>90
Damage degree	Weak	Neutral	Severe	Extremely severe

Optimization of Thermo-Stable Surfactants System. DCAT11 interfacial tension meter was firstly used to measure the interfacial tension of four kinds of composite surfactants system according to platinum plate method. DSA-30 contact angle meter was then used to measure the contact angle before and after adding surfactants. Finally, self-made spontaneous imbibition device (**Figure 1**) was employed to observe the variation law of S_w.

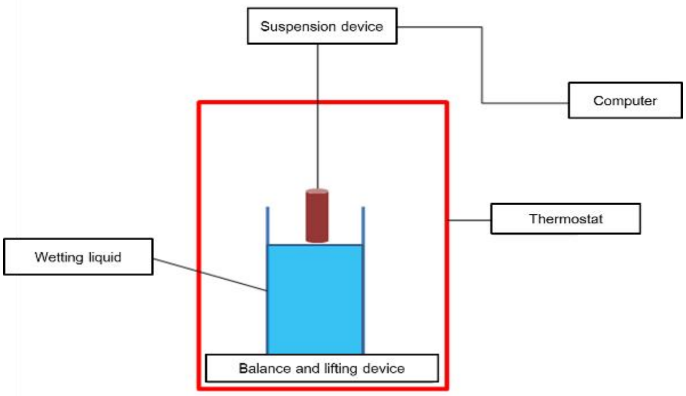


Figure 1—apparatus of spontaneous imbibition.

Clean-up of Water Block. The optimized composite surfactant system was utilized to clean up water block and the procedure was as follows:

(1) Evacuate the core in the sealed container and saturate it with simulated formation water;
(2) Set the sample in the core holder and heat it to 160°C, flood the core with 2PV surfactants, and then cool down to room temperature;
(3) Take out the core sample and weight it;
(4) Place the sample in the core holder again and flood it with N_2, measure the flow rate and weight until the weight stops changing;
(5) Calculate relative gas permeability under different water saturation.

Results and Discussion

Damage Degree of Water Block. 11 cores (as listed in **Table 2**) were selected to evaluate water block index (WBI) and relative gas permeability (K_{rg}). The average value of WBI is 69.8%, which indicates that the damage from water block is extremely severe.

Table 2—Results of WBI for 11 cores.

Sample No.	Porosity(%)	$K_l(10^{-3}\ \mu m^2)$	$K_g(10^{-3}\ \mu m^2)$	S_{wir}(%)	WBI(%)
1	6.41	0.092	0.032	35.82	65.59
2	6.51	0.098	0.029	41.68	70.41
3	7.91	0.424	0.231	29.78	45.52
4	5.05	0.061	0.019	34.96	68.85
6	3.07	0.013	0.003	42.14	76.92
7	3.34	0.011	0.002	46.51	81.82
11	2.09	0.016	0.002	49.76	87.50
12	2.49	0.021	0.003	48.69	85.71
18	6.47	0.083	0.031	34.74	62.65
21	6.53	0.115	0.044	36.85	61.73
22	5.61	0.151	0.058	31.74	61.59

Sensitivity Analysis. Sensitivity analysis was performed to investigate the effect of water saturation, matrix permeability, and content of clays.

Water Saturation**.** **Figure 2** shows the results of relative gas permeability under different water saturation. When S_w is between 40% and 80%, K_{rg} decreases drastically and the concave curves is observed. While for the high S_w (80~100%), K_{rg} is less than 15% for all 11 curves and its change interval is relatively small. Figure 2 reveals that the damage degree of water block increases significantly in the early time and then remains stable while the pore volume is almost occupied by water.

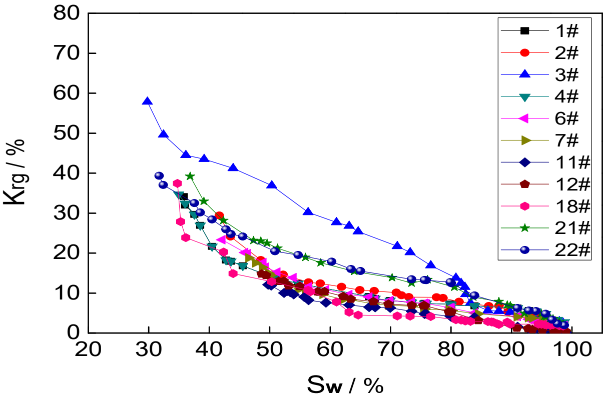
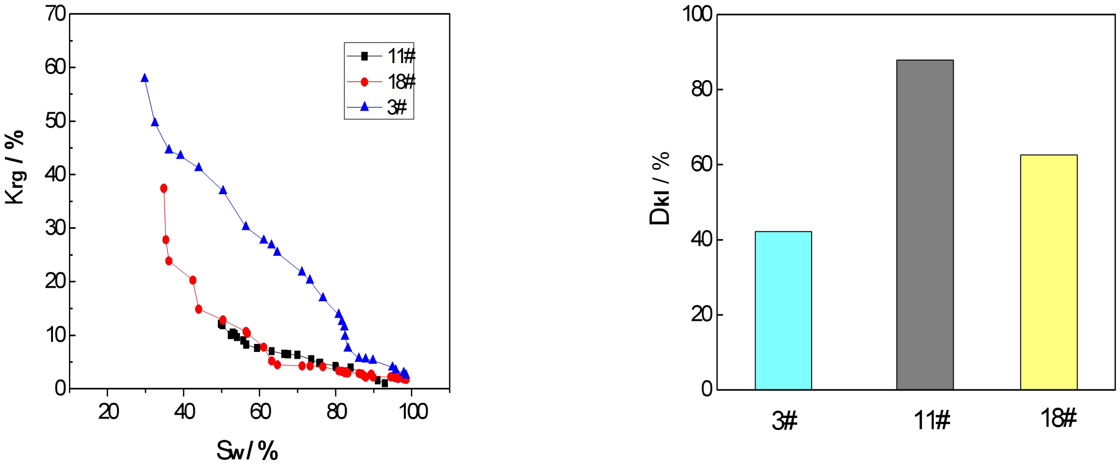


Figure 2—Relative gas permeability under different S_w.

Matrix Permeability**.** **Figure 3a** and **3b** present the results of K_{rg} and WBI for three cores (#11, #18, #3), whose matrix permeability is 0.016×10^{-3}, 0.031×10^{-3} and $0.424\times10^{-3}\mu m^2$, respectively. The results indicates that K_{rg} is in positive correlation with matrix permeability while WBI displays the negative law. This is subjected to the higher porosity and higher matrix permeability as the capillary force is lower, so the invaded fluid is more easily to be displaced. As a result, the fluid retained in the cores is less, which decreases the damage degree of water block.

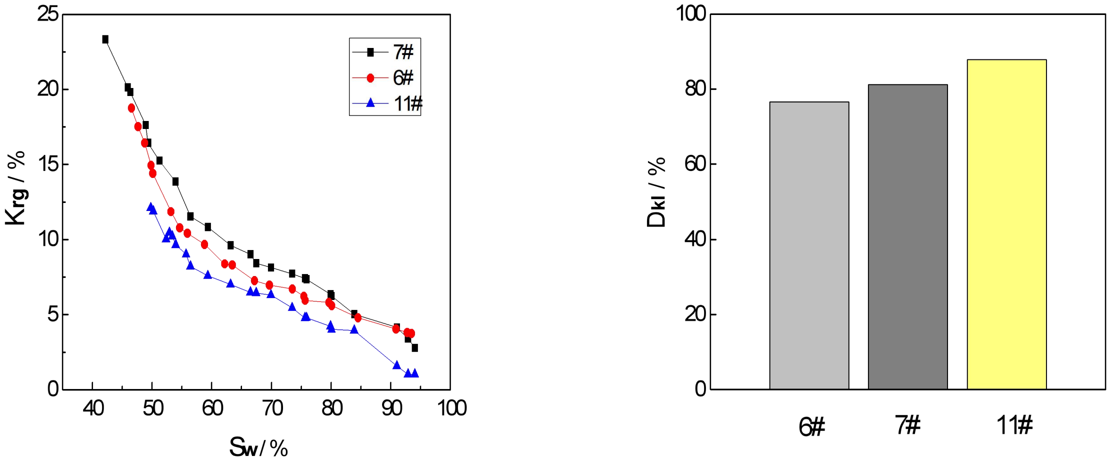


(a)

(b)

Figure 3—Results for #3, #18, #11. (a) Curves of relative permeability. (b) WBI.

Content of Clays**.** **Figure 4a** and **4b** show the results of K_{rg} and WBI for three cores (#6, #7, #11) whose matrix permeabilities are close but contents of clays are 14.9%, 20.1% and 23.6%, respectively. The results indicate that the degree of water block damage is more serious for the cores with higher content of clays, especially, when illites and smectites are rich. This is mainly attribute to the strong suction effect of illites and smectites, which induces the increase of water saturation and flow resistance. Therefore, the damage degree of water block increases.



(a)   (b)

Figure 4—Result for #6, #7, #11. (a) Curves of relative gas permeability. (b) WBI.

Displacement Pressure. The tests were performed at 1MPa and 2MPa (#4 and #5). **Figure 5** shows that the water saturation decreases with time. The results show that S_w is almost the same when t<200 min, but S_w of #5 decreases more rapidly as time increases. It can be concluded that displacement pressure mainly affects the clean-up time, and higher pressure tends to lower S_w and WBI.

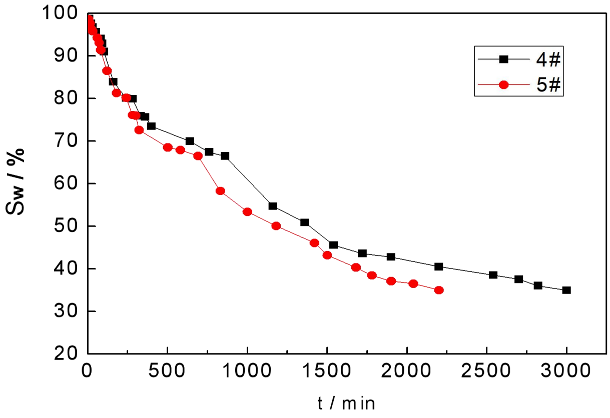


Figure 5—Saturation curves of 4# and 5#.

Fluid Type. Three cores were employed to compare the effect of different fluid type to WBI. The result presented in **Table 3** shows that the order of damage degree was surfactant JY-2 < simulated formation water (A) < filtrate of guar gum fracturing fluid (B). The main differences among these fluids are viscosity and interfacial tension. The invaded fluid is more difficult to be displaced if the viscosity and interfacial tension are higher.

Table 3—Results of WBI for different liquids.

No.	Fluid type	S_{wir} (%)	M (mpa/s)	σ (mN/m)	WBI (%)
#15	A	38.62	1.48	48.24	68.42
#16	B	51.35	4.00	62.61	90.24
#25	JY-2	21.51	1.42	20.58	37.25

Water block damage and sensitivity analysis indicates that the main factors that affects water block can be divided into inertial ones and external ones. Among them, the lower water saturation, matrix permeability, content of clays (inertial factors) will result in less damage. Fluid type and displacement pressure are the external factors. Lower viscosity, lower interfacial tension and higher pressure will decrease degree of water block.

Optimization of Composite Surfactant System. Wettability alteration and reduction of interfacial tension are two major means to clean up water block. Selecting proper surfactant is the most economical method to clean up water block. Combined with the geological properties of targeted zone, four kinds of composite surfactants system were used for further assessment. They are JY-1 (0.05% FC4430+15% methanol), JY-2 (0.05% FS-31+15% methanol), JY-3 (0.5% HSC-25+15% methanol), and JY-4 (0.5% F108+15% methanol). Among them, FC4430 and FS-31 are fluorocarbon surfactants, HSC-25 is cationic surfactant and F108 is bio surfactant. Three sets of tests were conducted to optimize the appropriate system, including interfacial tension tests, wettability tests and spontaneous imbibition tests.

***Interfacial Tension Tests*. Table 4** shows the interfacial tension of four composite surfactants at 180°C and 25°C. The results presented in the table indicate that they are all thermos-stable under both conditions. The interfacial tensions at 180°C is improved slightly than that at 25°C. Four systems all meet the requirements.

Table 4—Interfacial tension of composite surfactants.

No.	σ(mN/m) 180°C	σ(mN/m) 25°C
JY-1	20.34	19.86
JY-2	20.58	19.88
JY-3	22.81	22.41
JY-4	26.16	25.42

***Wettability Tests*. Figure 6** shows the result of wettability alteration by measuring the contact angle before and after adding surfactants. The contact angles were transferred from 20~30° to 60~65° by injecting JY-1 and JY-4, and the contact angles increased to 70~78°by injecting JY-2 and JY-3. The result indicates that JY-2 and JY-3 are more effective for wettability alteration.

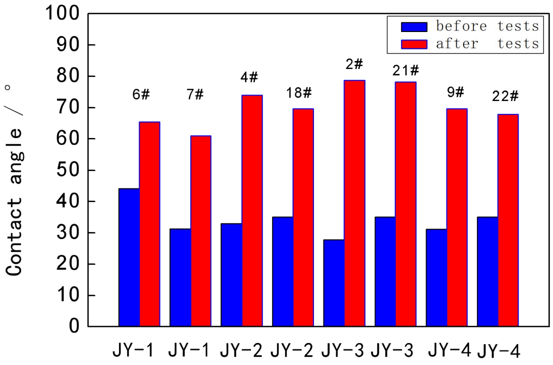
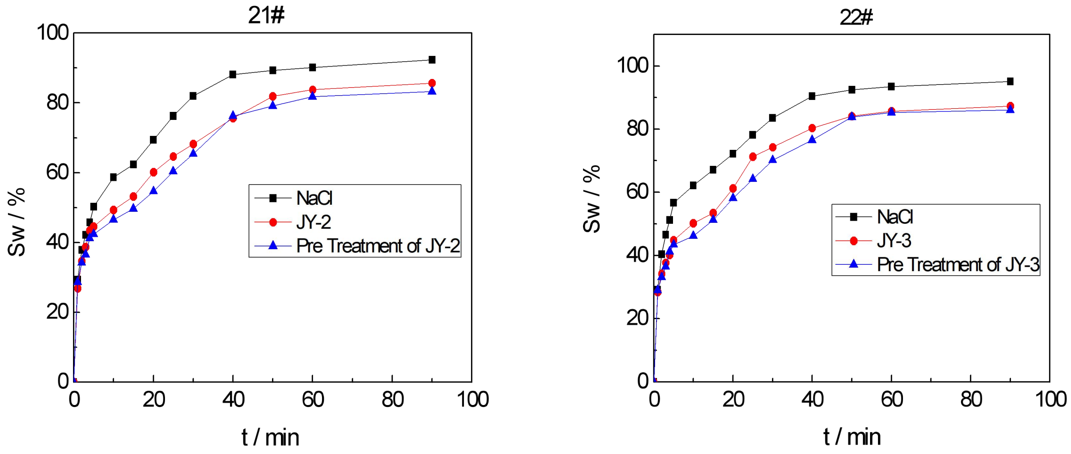


Figure 6—Wettability before and after adding surfactants.

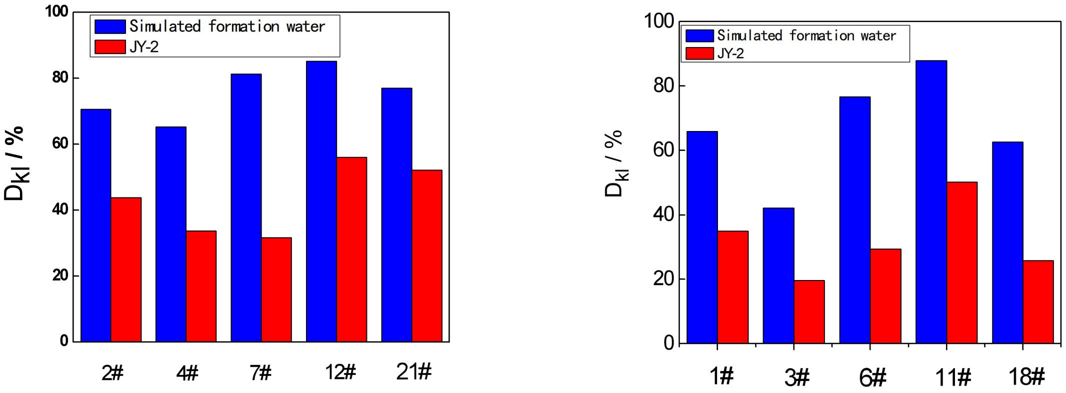
Spontaneous Imbibition Tests. Spontaneous imbibition tests were conducted to observe whether the surfactants could shorten the time of displacement so that water saturation could be decreased. **Figure 7a** and **7b** show the results of water saturation with time increasing. The imbibed fluid consists of simulated formation water, simulated formation water mixed with surfactants, and simulated formation water with pre-treated surfactants. The results indicate that water saturation and imbibition rate could be reduced by injecting mixed system and pre-treatment system. As a result, the imbibition process was prohibited to a certain extent. In other words, surfactants JY-2 and JY-3 are both able to reduce imbibition rate.



(a) (b)

Figure 7—Spontaneous imbibition curves. (a) #21. (b) #22.

Clean-Up of Water Block Damage. **Figure 8a** and **8b** show the result of WBI by injecting simulated formation water, JY-2 and JY-3. The average WBI for simulated formation water and JY-2 are reduced from more than 62.6% to 42.4%. And WBI for simulated formation water and JY-2 are reduced from 66.2% to less than 30.4%. The results indicate that the surfactants in the composite system reduce the interfacial tension and alter the wettability, leading to a considerable decrease in capillary force. Meanwhile, the methanol in the composite system can accelerate the evaporation process and reduce water saturation. Eventually, water block is effectively cleaned up through injecting composite surfactant system, and JY-3 is the best choice.



(a) (b)

Figure 8—Results of WBI. (a) JY-2. (b) JY-3.

Conclusions

1) Water block index, WBI, is applied to evaluate the damage degree of water block, and WBI of selective core samples from the targeted zone is 70%, belonging to the type of strong water block.
2) Sensitivity analysis shows that the factors that affects WBI are divided into inertial ones and external ones. Matrix permeability and displacement pressure are in positive correlation with WBI, while water saturation, content of clays, fluid viscosity and interfacial tension are in negative correlation with WBI.
3) Thermo-stable surfactant systems JY-2 (0.05 FS-31+15% methanol) and JY-3 (0.5% HSC-25+15% methanol) are optimized through interfacial tension tests, wettability tests and spontaneous imbibition tests. Surfactant in the composite system plays a role of reducing

interfacial tension and altering wettability, and methanol is favorable for reducing water saturation. They are mutually effective to clean up water block damage.

4) Composite system JY-3 works best to reduce WBI from 66.2% to less than 30.4%.

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Conflicts of Interest

The author(s) declare that they have no conflicting interests.

Nomenclature

Q_g = gas flow rate gas, cm^3/s
L = sample length, cm
A = sample cross sectional area, cm^2
$P_{inlet/outlet}$ = are inlet pressure and outlet pressure, respectively, MPa
m_i = i core weight at different S_w, respectively, g
V_d = downstream reservoir volume, mL
$P_{initial}$ = initial pore pressure, MPa
WBI = water block index, %
K_0 = initial gas permeability, $10^{-3}\mu m^2$
K_i = gas permeability at S_w, $10^{-3}\mu m^2$
K_n = gas permeability at S_{wi}, $10^{-3}\mu m^2$
K_{rg} = relative gas permeability, %.

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