Effect of Nanoparticle Adsorption on the Pore Structure of a Coalbed Methane Reservoir: A Laboratory Experimental Study

Lan Wang, Zhiping Li, Gangtao Mao, Yan Zhang, and Feng Peng Lai

ABSTRACT: Coalbed methane (CBM) is an important unconventional energy resource, and its micropore structure has a vital impact on its exploitation. Based on the nuclear magnetic resonance (NMR) experiment, the low-temperature liquid nitrogen adsorption experiment, and the contact angle experiment, in this paper, we investigated the influence of nanofluids on the micropore structure of a CBM reservoir from many aspects. The influence of different adsorption mechanisms of TiO$_2$ nanoparticles on the surface wettability of rock samples was analyzed. The influence of nanoparticle adsorption on the drainage and distribution of liquid in the rock sample was discussed in depth. In addition, the effects of nanofluid treatment on the micropore structure were investigated by comparing the data of low-temperature liquid nitrogen adsorption experiments, including the pore diameter, pore volume, and specific surface area (SSA). The experimental results show that the treatment of nanofluids helps to open the micropores and greatly increases the SSA, pore diameter, and pore volume of the sample. The maximum increase percentages of SSA, pore volume, and pore diameter are 228.12, 80.65, and 18.89%, respectively. It is found that the adsorption of particles is conducive to enhancing the water wettability of the pore throat surface and reducing the damage to water locks.

1. INTRODUCTION

According to the research and statistics of the International Energy Agency, the amount of coalbed methane (CBM) resources in the world is huge, reaching 260 $\times$ 10$^{12}$ $\text{m}^3$, with Russia, Canada, China, and the United States as the main producers. Due to the characteristics of strong plasticity and natural fracture of coal reservoirs, developers usually recover CBM by means of hydraulic fracturing and fracture expansion. In recent years, many technologies for the exploitation of CBM have been developed, including the fracturing transformation of coal seam roof, floor, and interlayer. The main technologies include indirect fracturing, acidizing fracturing for oxidizable coal seam, multipulse stamping fracturing, and liquid nitrogen fracturing technology. It is known that fracturing is an important step in CBM development, which determines whether CBM can be developed efficiently.

The selection of fracturing fluid according to the characteristics of the coal reservoir is also the focus of many researchers. Improving the matching of fracturing fluid and coal reservoir fracturing technology can improve the fracturing efficiency. Fracturing fluid injection can not only transform the fracture shape of the reservoir but also have a certain impact on the reservoir properties of seepage. The reservoir properties will change in all aspects after fracturing fluid seepage. This problem is illustrated by investigating several commonly used coal reservoir fracturing fluids. The first is active hydraulic fracturing fluid, which is composed of clean water, active agent, antiscratch agent, and drainage aid. This fracturing fluid has relatively light pollution to coal reservoirs and can be produced together with formation water during drainage and gas production. The other common type of fracturing fluid is the cross-linked gel fracturing fluid. Due to the presence of a cross-linking system, this fracturing fluid has strong sand carrying capacity. However, when the gel breaking and degradation of fracturing fluid in the reservoir is incomplete, the residue adsorption will seriously pollute the reservoir. Due to the small size and surface activity of nanoparticles, they can adsorb on the solid surface. In this paper, water-based TiO$_2$ nanofluids were used to study the influence of nanoparticles adsorbed on the reservoir pore characteristics. In addition, the adsorption performance of nanoparticles on the water lock phenomenon of coal reservoirs was also studied.

Researchers have carried out some important experimental and theoretical studies on the changes of the solid surface, which...
adsorbed the nanoparticles.\textsuperscript{16} They found that nanoparticles adsorb on the surface to form an adsorption layer, which changes the wettability of the rock and the adsorption/desorption performance of gas.\textsuperscript{17} Therefore, the adsorption layer in the coal reservoir may have a drag reduction, which makes water in coal easier to discharge that is conducive to the desorption and exploitation of CBM.\textsuperscript{18} This process of changing surface wettability through the adsorption layer is called the dehumidification process. Generally, there are two influencing factors: the first is the property of the adsorption material and the other is the microstructure formed on the surface of the adsorption layer. Researchers confirmed through experiments that there is a flow slip effect on the hydrophobic solid surface. They believe that the rough hydrophobic surface with a regular structure is more conducive to the flow slip effect than the smooth hydrophobic surface. The stronger the hydrophobicity, the more obvious the flow slip effect and the longer the slip length.\textsuperscript{19−21}

Based on the theoretical basis, in this paper, we carried out systematic experiments to investigate the influence of the adsorption of metal oxide (TiO\textsubscript{2}) nanoparticles on the pore structures of high-order coal. Also, the influence of the nanoparticle adsorption layer on the flow of water in rock is evaluated.

2. EXPERIMENTS

2.1. Experimental Materials and Fluids. The four coal samples used in this paper are from four different CBM production wells in the Zhao Zhuang mining area of Qinshui coalfield, Shanxi Province, China. The Zhao Zhuang mining area is rich in CBM and belongs to a high-order coal reservoir. Samples were cut into standard samples with a diameter of 2.51 cm and a length of 3−6 cm (Figure 1), which were placed in a 105 °C drying oven for 24 h for subsequent experiments. Table 1 contains some basic parameters of the experimental sample, including the length, diameter, and weight of the samples after drying. The nanofluid used in the experiment was prepared by nanoparticles and deionized water according to a mass concentration of 0.05%. Nanoparticles are easy to settle in the nanofluid dispersion. The experiment was carried out after nanoparticles were stably suspended in deionized water. The basic parameters of the fluids used in the experiment are shown in Table 2.

Figure 1. Core samples.

| sample | diameter (cm) | length (cm) | dry weight (g) | volume (cm\textsuperscript{3}) |
|--------|---------------|-------------|----------------|-----------------------------|
| C1     | 2.51          | 5.02        | 40.700         | 24.827                      |
| C2     | 2.51          | 5.05        | 44.981         | 24.975                      |
| C3     | 2.51          | 4.82        | 38.621         | 23.838                      |
| C4     | 2.51          | 4.95        | 33.998         | 24.481                      |

2.2. Centrifugation and NMR Experiments. This part of the experiment was completed using a centrifuge and an NMR instrument. The fluid distribution characteristics in the cores, after the centrifugal experiment at different speeds under the saturated state of deionized water and nanofluid, were compared. The centrifugal speeds set in the experiment were 200, 500, 1000, 1500, and 2000 rpm. The loose property of cores limits the higher centrifugal speed; it is known from the previous experiments in the same block that destructive cracks appeared in the sample above a speed of 2000 rpm.\textsuperscript{22,23} Therefore, the maximum centrifugal speed designed in this experiment was 2000 rpm. The centrifugal process lasted 40 min under each speed, and then the core was weighed. In addition, NMR experiments were carried out after every centrifugal step. Finally, the T\textsubscript{2} spectrum of fluid distribution in cores was drawn into curves for comparative analysis.

2.3. Low-Temperature Liquid Nitrogen Adsorption Experiment. The instrument used in this part of the experiment is a BSD-PS (M) specific surface analyzer provided by Beijing BSD Instruments Co., Ltd. The samples used in the experiment are shown in Figure 2. The samples labeled 1, 2, 3, and 4 in Figure 2 correspond to the core grinding in Figure 1, and the particle size of the sample is between 60 and 80 mesh. The samples labeled 1′, 2′, 3′, and 4′ in Figure 2 are also from the corresponding cores in Figure 1, but these four samples are obtained by soaking in the TiO\textsubscript{2} nanofluid for 24 h and drying.

Eight sets of experiments were conducted and the experimental results were compared and analyzed. The changes of the microstructure and specific surface area (SSA) of the pores after nanoparticle adsorption were obtained.

2.4. Contact Angle Test. The instrument for measuring the contact angle is shown in Figure 3. The main method of the experiment is the sessile drop method. In this method, a drop of deionized water is placed on the core surface, and then the contact angle is measured. The contact angle is calculated by the software provided with the instrument.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Centrifugation and NMR Experimental Results. The T\textsubscript{2} spectrum reveals the fluid distribution in the core under the conditions of different fluid saturations and different velocity centrifugations. The experimental results of the cores from different CBM wells are analyzed in detail, and the influence mechanism of the nanofluid on the distribution of the residual fluid in reservoirs in different well areas is obtained.

The T\textsubscript{2} spectra of the four samples are shown in Figure 4. The results show that, for C1 and C4, when saturated with deionized water (a), the fluid in the macropores is not easy to discharge under the condition of low speed (<500 rpm). Of course, the fluid in the smaller pores is more difficult to discharge, as it needs a greater driving force. There are no macropores in C2, while
deionized water in the macropores of C3 is completely discharged at a lower speed (<500 rpm). Compared with the nanofluid, DW is easier to stay in the cores under the small centrifugal force. It was found that with increasing centrifugal speed, the fluid in the small pores increases. Because in the process of high-speed centrifugation, a part of the fluid in the macropores is extracted with centrifugal force and a small part of it overcomes the capillary pressure and then enters the small pores. At this time, the partly movable fluid in the pore throat is transformed into a movable fluid and redistributed in the pore throat of the core.

Through the mass comparison, it is clear that the fluid discharged at high speed is significantly less than that at low speed. The NMR experiment results show that at high speed, most of the fluid only changes the position in the internal pore throat of the core, that is, it transfers from a small pore throat to a smaller pore throat or even dead pore throat. This feature still exists in C3 and C4, with the exception of C2. The position of deionized water in C2 hardly changes under high-speed conditions, and only a small amount of deionized water is discharged. The reason for this phenomenon may be that there are no macropores in the rock sample itself, and the initial distribution of deionized water in small pores is stable. It is difficult to change the fluid distribution under the action of displacement pressure.

By observing the results of the centrifugal NMR experiment of saturated nanofluids (b) of the four cores, it was found that all of the fluids in the macropores are discharged under the condition of low rotating speed (<500 rpm). In particular, at a rotating speed of 200 rpm, all of the fluids in the macropores are discharged. Compared with deionized water, the pressure limit of nanofluids discharged from the macropores is lower. Combined with the previous theoretical study on the wettability change of the double nanoparticle adsorption structure, it is obvious that under the condition of low rotating speed, in the large pore throat, the hydrophobicity produced by the dual structure is greater than the change of the hydrophilic properties of nanoparticles on the wettability. Therefore, the adsorbed core shows enhanced hydrophobicity under the condition of low displacement pressure. With the increase of rotating speed, the fluid in the small pores continues to be discharged. After the rotating speed reaches 1500 rpm, the weight of the discharged liquid is very small. The change of the wave peak can still be seen in Figure 4. However, this peak is the change of small pores, so when we evaluate the weight of cores, the change of core weight is very small. At this time, the fluid only changes its position from small pores to smaller pores in the core.

Compared with the results of deionized water, it can be seen that the dual adsorption structure of nanoparticles is conducive to the discharge of fluid at low speed, but at high speed, the dual adsorption structure may be unstable due to the strong centrifugal force. At this time, the hydrophilic property of nanoparticles leads to the change of wettability of the pore and throat surfaces. The results show that the retention volume of the nanofluid is less than that of deionized water at high speed. Hence, in the process of reservoir fracturing, if the nanofluid fracturing fluid can be injected, it will be beneficial to the drainage and gas production of coal reservoirs and reduce the damage to water locks.

### 3.2. Analysis of the Low-Temperature Liquid Nitrogen Adsorption Experiment

The low-temperature liquid nitrogen adsorption experiment includes the results of the adsorption/desorption curve and pore size change. The experimental results of the four samples treated with the nanofluid are compared with the results of the untreated samples to obtain the effect of nanoparticle adsorption on the pore structure (Table 3).

#### 3.2.1. Pore Shape

Adsorption/desorption curves in Figure 5 are determined by the Barrett–Joyner Halenda (BJH) method through analyzing the desorption branch of adsorption data. It can be seen from the curves of the four samples that the adsorption curves belong to type III isotherms, are concave, and have no inflection point. The amount of adsorbed gas increases with the increase of the component pressure. The curve is concave because the interaction between the adsorbate molecules is stronger than that between the adsorbate and the
Figure 4. continued
adsorbent. The adsorption heat of the first layer is smaller than that of the adsorbate. So, it is difficult for the adsorbate to adsorb at the initial stage of adsorption. With the progress of adsorption, the adsorption shows self-acceleration, and the number of adsorption layers is not limited. The hysteresis loops of the four samples belong to H3 hysteresis loops. There is no obvious saturated adsorption platform for this kind of the hysteresis loop isotherm. The pores reflect include a flat slit structure, fracture, and wedge structure. There is no adsorption saturation in the region of high relative pressure. Among them, the hysteresis loops of samples 2 and 4 are small, which means that the pore diameters of samples 2 and 4 are relatively small and the connectivity is poor. There may be some open pores. However, the hysteresis loops of samples 1 and 3 are relatively large, indicating that the pore diameters of the two samples are large and there are many open pores and even fractures.

3.2.2. Basic Pore Parameters. The adsorption capacity of nitrogen increased under different partial pressures, but the curve shape did not change significantly. The reason for this result is that the adsorption of nanoparticles in the pores increases the SSA and so the adsorption capacity of nitrogen increases. However, as the adsorption of nanoparticles did not change the pore shape, the shape of the curve did not change. The average pore diameter and specific surface data in Table 3 are determined by the Brunauer–Emmett–Teller (BET) method in the low-temperature liquid nitrogen adsorption experiment. It can also be seen from Table 3 that the adsorption of nanoparticles has a small effect on the average pore size but can greatly affect the SSA. The result illustrates that the adsorption of nanoparticles will not greatly affect the SSA. The result illustrates that the adsorption of nanoparticles will not cause pore blockage and reservoir damage. Among them, the change of SSA of samples 1 and 3 is the most obvious. The reason for this result may be that nanoparticles produce single-layer or even multilayer adsorption on the pore surface, which greatly increases the roughness of the inner surface of the pore. The increase of the specific surface of samples 2 and 4 is not obvious. Because the adsorption of nanoparticles on the pore surface is mostly single-layer tight adsorption, the effect on the increase of surface roughness is not obvious.

The pore size distribution of the four samples in Figure 6 reflects the change of the internal pore size of the samples after nanofluid treatment. The main pore diameters of the four samples are between 1 and 10 nm, and the peak value of pore distribution is also in this range. This indicates that the pore distribution of the samples is relatively uniform. It can be seen from the figures that nanofluids have the greatest impact on sample 1, especially the micropores. The peak pore distribution of sample 3 also increased after nanofluid treatment. However, the increase of sample 1 was mainly in the micropores, while the mesopore and micropore spaces of sample 3 increased. It means that the nanofluid treatment is helpful to open the micropores and mesopores of samples 1 and 3. The distribution trend of samples 2 and 4 is hardly affected by nanofluids, and the pore distribution in each part increases slightly. Table 4 shows the effects of nanofluids on the pore diameter, SSA, and pore volume. Except for a small negative effect on the apertures of samples 1 and 4, other effects are positive. Therefore, in the field experiment, the nanoparticles are evenly dispersed in the injection fluid, such as fracturing fluid, which is conducive to the micromodification of CBM reservoirs, so as to reduce the difficulty of CBM recovery and reservoir damage. Nanoparticles can greatly increase the pore volume and specific surface area, which is beneficial to the flow of fluids in porous media. In addition, the increase of pore volume has a certain probability to increase the connectivity between pores. This part of the research is worthy of further experimental investigation.

3.3. Analysis of the Contact Angle Test. 3.3.1. Influence Mechanism of Nanoparticle Adsorption on Wettability. In the microporous channel system of the CBM reservoir, the main stress effects include the action of nanoparticles and the pore wall, the action of nanoparticles and the aquifer on the pore wall, the action of the aquifer and the pore wall, and the interaction between nanoparticles and liquid molecules.

The microstress state of nanoparticles is related to the flow state and position. After the nanofluid is injected into the reservoir, during the flow process, the free nanoparticles in the liquid are captured by the rough wall of the reservoir pore throat.
due to motion collision and then adsorbed. The main functions of nanofluids in the reservoir with low flow velocity or in the stage of stewing and energy storage are Brownian action, van der Waals action, and electrostatic action.\(^25\)–\(^27\)

In steady nanofluids, nanoparticles are usually evenly dispersed, indicating that they are in an equilibrium state and the effects of various forces are also in equilibrium. However, when nanofluids enter the reservoir and flow in micropores, the effect from the pore wall can be ignored. The main effect of adsorption comes from the Brownian motion of liquid molecules. When nanoparticles enter small pores, in other words, when the pore diameter of the reservoir is less than 100 nm, the adsorption increases the van der Waals effect and the electrostatic force effect from the pore wall.\(^28\)

In addition, the hydration layer on the surface of large and small pores has a great influence on the stress of nanoparticles. When nanoparticles enter the hydration layer, the interfacial tension between the hydration layer and the nanofluid has a certain impact on the adsorption of nanoparticles.\(^29\) According to the hydrophilicity and hydrophobicity of nanoparticles, the hydrophobic interfacial tension will help or prevent nanoparticles from entering the aqueous phase.

### 3.3.2. Schematic Diagram of the Adsorption Mechanism

It is known that TiO₂ nanoparticles are adsorptive on the core surface, and a single nanoparticle is easy to form aggregates.\(^30\) According to the scanning electron microscopy experiment of the researchers, it can be found that the adsorption of nanoparticles in the core throat has duality, that is, the nanoparticles adsorbed on the wall of the core throat have both a single-layer adsorption of nanoparticles and a layer of approximately spherical nanoparticle aggregates (Figure 7). These aggregates are basically irregularly arranged on the wall of the pore throat. There are two main mechanisms for the adsorption of nanoparticles on the pore throat surface to change.

![Figure 5. Adsorption/desorption curves of the samples (\(P/P_0\) refers to the ratio of the vapor pressure of N₂ to the saturation vapor pressure of N₂).](https://doi.org/10.1021/acsomega.1c06770)
The wettability. One is the properties of the nanoparticles and the other is the structural properties formed by the adsorption mode.\textsuperscript{31,32}

The results also show that the nanoparticle aggregate on the core slice surface and the double adsorption structure closely arranged on the aggregate surface can enhance the hydrophobic performance of the core slice surface and is the key factor leading to the strong hydrophobic performance of the core surface.

It is known from the literature that when the particles are adsorbed by a single-layer with closely arranged particles, the contact angle is calculated as follows\textsuperscript{33}

\[
\cos \theta_2 = (\pi - \theta_p) \cos \theta_p - 1 + \sin \theta_p
\]  

(1)

where \(\theta_2\) represents the apparent contact angle when only single-layer nanoparticles are adsorbed and \(\theta_p\) represents the plane center angle formed by the intersection of the wet water interface of the adsorbed particles and the adsorption contact point between particles and the core surface.

For double adsorbed structural surfaces, the calculation formula of the apparent contact angle is

\[
\cos \theta_{C-B} = f_1 \cos \theta_2 + f_1 - 1
\]  

(2)

where \(\cos \theta_{C-B}\) represents the apparent contact angle of the double adsorption structure and \(f_1\) refers to the proportion of the contact surface adsorbed by single-layer nanoparticles.

The wettability changes of the rock surface after nano fluid treatment were compared by the contact angle experiment.

Figure 8 reveals the influence of the nano fluid on the surface wettability of rocks. From the comparison diagram, it can be seen that the C4 sample has the largest change range of the contact angle. Among them, C1 and C3 change from being

\begin{table}
\centering
\caption{Effect of Nano fluids on the Pore Structure of the CBM Reservoir (\%)}
\begin{tabular}{|c|c|c|c|c|}
\hline
item & 1 & 2 & 3 & 4 \\
\hline
pore diameter & -5.61 & +11.43 & +18.89 & -1.45 \\
SSA & +228.12 & +30.77 & +118.57 & +8.30 \\
pore volume & +66.11 & +25 & +80.65 & +8.70 \\
\hline
\end{tabular}
\footnotesize{\textsuperscript{a}+ indicates increase and -- indicates decrease.}
\end{table}
hydrophilic to neutral, while C2 and C4 change from being neutral to hydrophilic. It may be caused by the differences in the adsorption of nanoparticles on the surface of samples. Because the nanoparticles are hydrophilic, if most of the nanoparticles are closely adsorbed on a single layer, the surface of the rock sample will change to hydrophilic. On the other hand, if most of the nanoparticles are adsorbed on the pore throat surface in a dual structure and if the hydrophobic properties caused by the dual structure are stronger than the changes caused by the hydrophilic properties of the nanoparticles themselves, then

**Figure 7.** Schematic diagram of single-layer tight adsorption and double adsorption of nanoparticles.

**Figure 8.** Comparison of the surface contact angle after nanofluid treatment.
the surface properties of the samples will be slightly changed from hydrophilic to neutral.

Through the calculation of the apparent contact angle of the surface of the double adsorption structure, it can be seen that when the proportion of the contact surface adsorbed by single-layer nanoparticles is less than 50%, whether the nanoparticles are hydrophobic or hydrophilic, the adsorption of nanoparticles will change the core surface to being hydrophilic. Accordingly, the proportion of the single-layer adsorption of nanoparticles is usually dominated by double or multiple adsorptions. Therefore, the proportion of the single-layer adsorption contact surface is almost less than 50% in the current experimental and theoretical research. This is also the reason why the experimental results of most researchers reported that nanofluids help the core change from being hydrophobic to hydrophilic. However, in a few cases, the adsorption of nanoparticles can theoretically change the core surface to being hydrophobic. By washing the core surface with the nanofluid, the researchers obtained the experimental results that the long-term cumulative adsorption of nanoparticles may cause a hydrophobic phenomenon on the core surface. According to the apparent contact angle theory, the longer the scouring time, the higher the area proportion of monolayer adsorption and so there is a hydrophobic tendency. Of course, with the progress of nanotechnology, the theoretical mechanism for the change of the surface properties of nanofluid treatment will be more perfect, and various situations will be explained more reasonably. Thus, nanoparticles can also be more effectively applied in various industries.

Therefore, the properties and adsorption mechanism of nanoparticles have a very important impact on the wettability of reservoirs. It is very necessary to investigate the adsorption mechanism of nanoparticles in the follow-up research.

4. CONCLUSIONS

According to the results of three experimental studies, the following important understanding of the influence of nanofluids on the pore structure of CBM reservoirs is obtained

1. The nanofluid treatment has a great impact on the SSA and pore diameter of the sample, especially on micropores, which is the key pore structure of CBM reservoirs. The maximum increase percentages of SSA, pore volume, and pore diameter are 228.12, 80.65, and 18.89%, respectively.

2. The adsorption of nanoparticles is conducive to the discharge of liquid from the micropores of the core. The NRM experimental results show that the micropore wave peak saturated with nanofluid changes more obviously at the same centrifugal speed compared with deionized water.

3. The adsorption of TiO₂ nanoparticles enhances the water wettability of the core.

AUTHOR INFORMATION

Corresponding Author
Zhiping Li — School of Energy Resources, China University of Geosciences, Beijing 100083, People’s Republic of China; Beijing Key Laboratory of Unconventional Natural Gas Geology Evaluation and Development Engineering, Beijing 100083, People’s Republic of China; orcid.org/0000-0002-2276-2984; Email: lzp_cugb@163.com

Authors
Lan Wang — School of Energy Resources, China University of Geosciences, Beijing 100083, People’s Republic of China; Beijing Key Laboratory of Unconventional Natural Gas Geology Evaluation and Development Engineering, Beijing 100083, People’s Republic of China; Department of Civil and Environmental Engineering, School of Mining and Petroleum Engineering, University of Alberta, Edmonton, AB T6G 2W2, Canada
Gangtao Mao — School of Energy Resources, China University of Geosciences, Beijing 100083, People’s Republic of China; Beijing Key Laboratory of Unconventional Natural Gas Geology Evaluation and Development Engineering, Beijing 100083, People’s Republic of China
Yan Zhang — School of Energy Resources, China University of Geosciences, Beijing 100083, People’s Republic of China; Beijing Key Laboratory of Unconventional Natural Gas Geology Evaluation and Development Engineering, Beijing 100083, People’s Republic of China
Feng Peng Lai — School of Energy Resources, China University of Geosciences, Beijing 100083, People’s Republic of China; Beijing Key Laboratory of Unconventional Natural Gas Geology Evaluation and Development Engineering, Beijing 100083, People’s Republic of China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.1c06770

Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The staff of the Key Laboratory of China University of Geosciences (Beijing) and the colleagues of the research group helped with the experiments conducted in this paper. This work was also supported by the National Natural Science Foundation of China (51974282).

REFERENCES

(1) Clarkson, C. R.; Bustin, R. M. In Coalbed Methane: Current Evaluation Methods, Future Technical Challenges, SPE Unconventional Gas Conference. OnePetro, 2010.
(2) Mastalerz, M.; Glikson, M. V.; Golding, S. D. Coalbed Methane: Scientific, Environmental and Economic Evaluation; Springer Science & Business Media, 2013.
(3) Stromquist, M. Methods of stimulating water sensitive coal bed methane seams. U.S. Patent Application 10/811,745, filed Sept 29, 2005.
(4) Ma, H.; Chen, S.; Xue, D.; Chen, Y.; Chen, Z. Outlook for the coal industry and new coal production technologies. Adv. Geo-Energy Res. 2021, S, 119–120.
(5) Salmachi, A.; Sayyafzadeh, M.; Haghighi, M. Infill well placement optimization in coal bed methane reservoirs using genetic algorithm. Fuel 2013, 111, 248–258.
(6) Wu, Y. S.; Bai, B. J. In Modeling Particle Gel Propagation in Porous Media; SPE Annual Technical Conference and Exhibition. OnePetro, 2008.
(7) Snyder, S. G.; Jockel, D. W.; Lopez, A. W. In Improved Fracturing Technology for Coalbed Methane Gas Wells in Western Pennsylvania Increases Gas Production over Offset and Historic Wells in Mount Pleasant CBM Field, Eastern Regional Meeting. OnePetro, 2007.
(8) Xiao, B.; Zhang, S.; Zhang, J. In A Novel Nano-composite Fiber Laden Viscoelastic Fracturing Fluid for Coalbed Methane (CBM) Reservoir Stimulation: Laboratory Study and Test, SPE Asia Pacific Oil and Gas Conference and Exhibition, Jakarta, Indonesia, Oct 22–24, 2013.
(9) Jacobs, T. Energized fractures: shale revolution revisit the energized fracture. J. Pet. Technol. 2014, 66, 48−56.
(10) Ramruth, M.; Lyons, B.; Magill, D. P. In Hybrid Fracture Stimulation in under Pressured Coals, SPE Gas Technology Symposium, Calgary, Alberta, Canada, May 15−17, 2006.
(11) McNiel, B. W. In Hydraulic Fracturing Techniques Used for Stimulation of Coaled Methane Wells, SPE Eastern Regional Meeting, Columbus, Ohio, Oct 31−Nov 2, 1990.
(12) Choi, S. Enhancing Thermal Conductivity of Fluids with Nanoparticles; ASME: New York, 1995; p 99.
(13) Sonawane, S.; Bhandarkar, U.; Puranik, B.; Kumar, S. Assessment of Aviation Turbine Fuel-TiO2 Nanofluid for Heat Transfer Augmentation in Rocket Engines. Physiother. Res. Int. 2013, 18, 239−249.
(14) Zou, S.; Sun, C. X-ray microcomputed imaging of wettability characterization for multiphase flow in porous media: A review. Capillarity 2020, 3, 36−44.
(15) Dai, M.; Wang, J.; Wei, N.; Wang, X.; Xu, C. Experimental study on evaporation characteristics of diesel/ceirium nanofluid fuel droplets. Fuel 2019, 254, No. 115633.
(16) Chen, H.; Di, Q.; Ye, F.; Gu, C.; Zhang, J. Numerical simulation of drag reduction effects by hydrophobic nanoparticles adsorption method in water flooding processes. J. Nat. Gas Sci. Eng. 2016, 35, 1261−1269.
(17) Bai, F.; Wu, J.; Gong, G.; Guo, L. Biomimetic "water strider leg" with highly refined nanogroove structure and remarkable water-repellent performance. ACS Appl. Mater. Interfaces 2014, 6, 16237−16242.
(18) Pit, R.; Hervet, H.; Leger, L. Direct experimental evidence of slip in hexadecane: solid interfaces. Phys. Rev. Lett. 2000, 85, 980.
(19) Li, S.; Hou, S. A brief review of the correlation between electrical properties and wetting behavior in porous media. Capillarity 2019, 2, 53−56.
(20) Phenrat, T.; Fagerlund, F.; Illangasekare, T.; Lowry, G. V.; Tilton, R. D. Polymer-modified Fe0 nanoparticles target entrapped NAPL in two-dimensional porous media: Effect of particle concentration, NAPL saturation, and injection strategy. Environ. Sci. Technol. 2011, 45, 6102−6109.
(21) Saleh, N.; Sirk, K.; Liu, Y.; Phenrat, T.; Dufour, B.; Matyjaszewski, K.; Lowry, G. V.; et al. Surface modifications enhance nanoiron transport and NAPL targeting in saturated porous media. Environ. Eng. Sci. 2007, 24, 45−57.
(22) Zhou, A.; Zhang, D.; Lai, F.; Wang, M.; Mao, G. Experimental investigation on the effect of ethanol on micropore structure and fluid distribution of coalbed methane reservoir. Energy Explor. Exploit. 2020, 38, 1631−1646.
(23) Mao, G.; Li, Z.; Lai, F.; Wei, H. Experimental investigation on the effect of organic solvents on gas development of coalbed methane reservoir. Fuel 2021, 287, No. 119497.
(24) Choi, C. H.; Ulmanella, U.; Kim, J.; Ho, C. M.; Kim, C. J. Effective slip and friction reduction in nanograted superhydrophobic microchannels. Phys. Fluids 2006, 18, No. 087105.
(25) Di, Q. F.; Shen, C.; Wang, Z. H.; Gu, C.; Shi, L.; Fanf, H. Experimental research on drag reduction of flow in micro-channels of rocks using nano-particle adsorption method. Acta Petrolei Sinica 2009, 30, 125−128.
(26) Li, H. J.; Li, Z. H.; Peng, Y. J.; Yang, Y. L.; Tang, Y. B.; Liu, Z. Pore structures and methane sorption characteristics of coal after extraction with tetrahydrofuran. J. Nat. Gas Sci. Eng. 2014, 19, 287−294.
(27) Jia, D.; Qiu, Y. K.; Li, C.; Cai, Y. D. Propagation of pressure drop in coalbed methane reservoir during drainage stage. Adv. Geo-Energy Res. 2019, 3, 387−395.
(28) Song, H.; Xu, J.; Fang, J.; Cao, Z.; Yang, L.; Li, T. Potential for mine water disposal in coal seam goaf: investigation of storage coefficients in the Shendong mining area. J. Cleaner Prod. 2020, 244, No. 118646.
(29) Fuhs, A. E.; Schetz, J. A. Handbook of Fluid Dynamics and Fluid Machinery: Experimental and Computational Fluid Dynamics, Volume II; John Wiley & Sons, Inc., 1996.
(30) Wang, L.; Li, Z.; Adenutsi, C. D.; Wang, C. An experimental study of the effect of three metallic oxide nanoparticles on oil-water relative permeability curves derived from the JBN and extended JBN methods. J. Pet. Sci. Eng. 2020, 192, No. 107257.
(31) Huang, T.; Han, J.; Agrawal, G.; Sookprasong, P. A. In Coupling Nanoparticles with Waterflooding to Increase Water Sweep Efficiency for High Fines-containing Reservoir-lab and Reservoir Simulation Results, SPE Annual Technical Conference and Exhibition. OnePetro, 2015.
(32) Sara, O. N.; Er, F.; Yapici, S.; Sahin, B. Effect of suspended CuO nanoparticles on mass transfer to a rotating disc electrode. Exp. Therm. Fluid Sci. 2011, 35, 558−564.
(33) Patankar, N. A. On the modeling of hydrophobic contact angles on rough surfaces. Langmuir 2019, 13, 1249−1253.
(34) Burton, Z.; Bhushan, B. Surface Characterization and Adhesion and Friction Properties of Hydrophobic Leaf Surfaces and Nano-patterned Polymers for Superhydrophobic Surfaces. In Applied Scanning Probe Methods III; Springer: Berlin, Heidelberg, 2006; pp 55−81.
(35) Wang, X.; Di, Q.; Zhang, R.; et al. Dual drag reduction mechanism of nanoparticle water-based dispersion in rock core microchannel and its experimental verification. J. Phys. 2012, 61, 000336−000342.