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Water blocking effect caused by the use of hydraulic methods for permeability enhancement in coal seams and methods for its removal

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ABSTRACT

To research techniques for removing the water blocking effect caused by hydraulic applications in coal seams, the use of surfactants is proposed, based on the mechanics of the water blocking effect. Centrifugal experiments were used to validate the effects of using surfactants; the results show that after dealing with vacuum saturation with water, the volume of micropores decreases, which results in a larger average pore size, and the volume of transitional pores, mesopores, macropores and total pores increases. Based on the distribution of pore size, the operation mode of "water infusion after gas extraction, then continuing gas extraction" is recommended to improve the volume of coal mine gas drainage. When the reflectance of vitrinite in coal samples is less than 1, using the surfactants Fast T, 1631, APG, BS can mitigate the damage caused by the water blocking effect. But when the reflectance of vitrinite is larger than 1.4, the damage caused by the water blocking effect can be increased. When the surfactant CMC is used in hydraulic applications, the capillary forces of coal samples are almost negative, which means the capillary force is in the same direction as the gas extraction. The direction of capillary forces benefits the gas flow. So, using CMC can play an active role in removing the water blocking effect. Centrifugal experiments confirm that using CMC can effectively remove the water blocking effect, which has a beneficial effect on improving the gas drainage volume.

1. Introduction

With the increase in mining scale and depth, most coal mines will develop the high-gas coal seams with low-permeability that exist in our country. The principal way to enhance gas drainage in high-gas and low-permeability coal seams is to relieve pressure and increase permeability [1,2]. Presently, hydraulic methods have been widely used to relieve pressure and increase permeability for industrial experiments by many mines in China, such as coal seam water infusion, hydraulic fracturing, hydraulic cutting, hydraulic slotting, hydraulic flushing and hydraulic pressing [3–8]. Following the application of hydraulic methods, the gas concentration and flow rate increase markedly at the initial extraction stage. However, after a period of time, the gas concentration and gas flow decay quickly, and there is possibly no gas extracted from the coal seam. This phenomenon can be explained by the water blocking effect. Because coal is a complex porous medium, with dual-pore structures [9], water flows into the deep parts of the coal mass through pore channels, under the application of external pressure. Water causes the gas to exist in a free state by competitive adsorption [10], which leads to an interface forming between water and gas. Under the effect of surface tension, this meniscus forms a capillary force directed toward the gas. The gas cannot be extracted from the coal seam when the coal seam energy and extraction pressure are not sufficiently large to overcome the capillary force, which gives rise to the water blocking effect [11].

In order to improve the effect of gas extraction, it is necessary to prevent and control the damage caused by the water blocking effect. Practical methods for removing the water blocking effect together with suggestions for improving the effect of hydraulic methods, and thereby the effectiveness of gas extraction systems, are explored and discussed in this paper.

2. Water blocking mechanism and removal method selection

2.1. Water blocking mechanism

The water blocking effect was first referenced in the field of petroleum exploitation [12]. When an externally-applied fluid flows

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along the pore channels into a deep reservoir, an additional capillary resistance appears at the gas/oil (water) interface. If the reservoir energy is not high enough to overcome the capillary force, the externally-applied fluid will block the flow channels, which leads to low permeability which eventually results in the phenomenon of lower reservoir recovery rate [13]. From the analysis above, it is found that the fundamental cause of the water blocking effect is the capillary force which can be described by the Laplace equation [14,15].

$$P_c = \frac{2\sigma \cos\theta}{r} \quad (1)$$

where P_C is the capillary force, σ is the surface tension (liquid/air), θ is the contact angle and r is the pore radius.

2.2. Removal method selection

According to Eq. (1), there are three basic ways to decrease the capillary force: (a) reduce the surface tension of the solution; (b) make the contact angle approach 90°; (c) increase the pore size.

Based on physical chemistry, surfactants can reduce the surface tension of a solution. Surfactants can also decrease the contact angle on the solid surface. If there is an interaction of reciprocal inhibition between the two effects, it will aggravate the damage caused by the water blocking effect. Therefore, the criteria for selection of the surfactant are identified as follows:

(1) Decrease the surface tension of the solution.
(2) Make the contact angle approach 90°.
(3) Make sure the pores in the coal will not close or shrink.

3. Coal samples and experimental methods

3.1. Reagents

According to the classification of surfactants, five types of surfactants were chosen for this experiment: polymer, anion, cationic, nonionic, zwitterion, etc. The reagents are shown in Table 1, in which water is defined as the contrast agent.

3.2. Sample preparation

Six coal samples were selected from the following mines: Guqiao mine of Huainan city, Qianqiu mine of Yima city, Fucun mine of Zaozhuang city, Shoushan No. 1 mine of Pingdingshan city, Xinfeng mine of Dengfeng city, Daning mine of Jincheng city. Detailed mark labels are shown in Table 2. After sampling, the coal samples were crushed. Approximately 2 g of the coal samples 0.2–0.25 mm in size were sifted for proximate analysis and approximately 10 g of the coal samples 0.2–0.25 mm in size were sifted for the reflectance of vitrinite in coal. Approximately 2 g of the coal samples less than 200 mesh occupying 80% were sifted for pressing tablets, which are 40 mm in diameter and 6 mm in thickness. Tablets of coal samples are shown in Fig. 1.

3.3. Experimental method

(1) Proximate analysis

Following the MT/T 1087-2008 test methods for proximate analysis of coal using instruments, we used a 5E-MAG6600 for proximate analysis through thermogravimetric analysis.

(2) Reflectance of vitrinite

Following the GB/T 16773-2008 method of preparing coal samples for coal petrographic analysis, we prepared polished sections with coal samples of 0.20–0.25 mm in size for determination of the reflectance of vitrinite in coal. The mean maximum reflectance of vitrinite in the coal samples was determined in accordance with the GB/T 6948-2008 method for microscopically determining the reflectance of vitrinite in coal samples. A microscope photometer made by German ZEISS is used to test reflectance of vitrinite.

(3) Solution surface tension and contact angle

Fig. 1. Tablets of coal samples.

Table 1
Reagents of laboratory.

Chemical name	Abbreviation	Type	Level	Remark
Dihydrogen monoxide	Water	Deion		Distilled water
Carboxymethyl cellulose	CMC	Polymer	Analytically pure	White powder
Sodium diethylhexyl sulfosuccinate	Fast T	Anion	Chemically pure	Light yellow viscous liquid
Cetyltrimethyl ammonium bromide	1631	Cationic	Analytically pure	White microcrystalline powder
Alkyl glucoside	APG	Nonionic	Chemically pure	Yellowish transparent liquid
N-Dodecyl-N,N-Dimethylglycine	BS	Zwitterion	Chemically pure	Yellowish transparent liquid

Table 2
Proximate analysis and reflectance of vitrinite in coal samples.

Coal mine	Moisture (wt.%, ad)	Ash (wt.%, ad)	Volatile matter (wt.%, daf)	Reflectance of vitrinite (%)
Guqiao mine	2.310	9.120	40.390	0.760
Qianqiu mine	8.330	10.190	37.700	0.852
Fucun mine	1.890	3.675	35.505	0.937
Shoushan No. 1 mine	1.350	7.410	22.815	1.363
Xinfeng mine	1.720	14.435	16.380	1.781
Daning mine	2.540	12.650	10.250	2.444