sustainability

Article

Experimental Investigation of the Impact of Coal Fines Migration on Coal Core Water Flooding

Dapeng Gao [1,2], Yuewu Liu [1,2,*], Tianjiao Wang [3] and Daigang Wang [4,*]

[1] Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China; gaodapeng@imech.ac.cn
[2] University of Chinese Academy of Sciences, Beijing 100049, China
[3] CNPC Beijing Oilfield Machinery Co., LTD., Beijing 102206, China; wangtianjdri@cnpc.com.cn
[4] Beijing International Center for Gas Hydrate, Peking University, Beijing 100871, China
* Correspondence: lywu@imech.ac.cn (Y.L.); wwwdg2006@126.com (D.W.)

Received: 19 October 2018; Accepted: 5 November 2018; Published: 8 November 2018

Abstract: Coalbed Methane (CBM) has become an important gas resource in recent decades. The brittle property of coal matrix and overactive operation make the migration of coal fines inevitable. Blockage by coal fines that plugs flow paths is a non-negligible issue that results in a significant decline in gas production. By setting different experimental conditions with the following factors—coal fines concentration of the mixture displacing fluids, constant flow pump rate, inlet pressure, outlet pressure and confining pressure—six experimental schemes were designed to investigate the two-phase water and coal fines flow in natural core samples. When the differential pressure and flooding flow reach a pseudo-steady status, the equivalent permeability of coal samples can be approximately calculated considering coal fines migration. Furthermore, the influences of coal fines migration on the cleat opening and permeability variation are analyzed in the porous coal medium. The study will benefit CBM development and save pump maintenance costs. In this work, we found that maintaining the differential pressure for a longer period may result in new cleat openings and severe coal rock damage during the single-phase water flooding process. While coal fines may plug some natural cleats and pores, especially in the core samples with micro-cleats during the two-phase flooding stage, coal fines migration significantly reduces the equivalent permeability and dewatering ability of the coal rock in the earlier flooding. While enlarging the differential pressure in two-phase water and fines flooding, breakthrough of coal fines from the samples contributes to widened cleats. While coal fines are difficult to flood into the core pores for low-permeability core samples, coal fines gather in the inlet, and it is also difficult to reach the pseudo-steady status even under higher differential pressure. The damage to permeability mainly occurs in the early stage of coal fines migration, and an abrupt increase in the flow velocity can damage reservoirs and induce substantial coal fines generation. Thus, maintaining a stable effective strength and a controlled depressurization rate during drainage can effectively constrain coal fines output and decrease permeability damage within coal reservoirs.

Keywords: coal fines; flooding experiments; single-phase water flow; two-phase water and coal fines flow; permeability variation; cleat opening

1. Introduction

The development and use of coalbed methane (CBM) has a great significance for improving safety conditions to coal mining, alleviating the tight supply of conventional oil and gas, implementing a sustainable development strategy for the national economy, and protecting the atmosphere. Typically, a CBM production process consists of three stages: dewatering, stable production and decline, and those stages correspond to three flow phases: single-phase water flow, gas-water two-phase flow and single-phase gas flow [1]. During progressive dewatering (i.e., depressurizing), gas flows in the pore and cleat networks, and production rises to a peak for months or years [2]. Production from good gas wells can be high and stable for a long time. Although gas production is influenced by various factors, blockage by fines that plugs flow paths (i.e., pore throats, cleats and proppant packs) is a non-negligible issue that results in a significant decline in gas production. Coal fines are among the key issues that restrict the highly efficient production of coalbed methane. Because they cause blockages in reservoirs and accidents in wellbores [3]. Coal fines always agglomerate to migrate and plug flow paths in formation water. Fines generation has been summarized into five aspects [4–7]: (1) the tectonic effect, (2) fracturing, drilling and perforation, (3) hydraulic drag and lift due to fluid flow, (4) desorption of gas, and (5) increases in effective stress.

In the process of CBM development, coal fines migration can be caused by both coal internal factors and engineering factors, such as coal compositions and pore-cleat structures and intense dewatering [8]. In addition, it will lead to serious damage to CBM well performance [9,10]. Moving coal fines will be trapped in coal reservoir and bottomhole, so the hydraulic fractures' conductivity will gradually reduce around CBM wells, and that also leads to decay of CBM productivity [11,12]. Besides, coal fines will gradually deposit in bottomhole following the water drainage of CBM wells, and that sometimes results in submerging and blocking pumps, which seriously affect the performance of CBM wells [10,13]. CBM production is a process where the well bottom pressure continuously decreases by water drainage. In this process, not only a larger pressure drop area as possible is needed to provide energy for the subsequent CBM desorption and flow, but also whether the coal fines can be effectively discharged is very important, because coal fines stay in natural cleats and pores will plug gas migration paths and reduce the well performance [14,15]. Initial drainage and depressurization are the most serious stages of coal fines generation and migration [16]. The study of the coal fines impacts on the dewatering has a great significance to improve the CBM wells' performance [17,18]. Permeation experiments indicate that as upstream pressure increases, the instantaneous permeability of coal samples have different behaviors that represent three distinct stages of non-permeation, coal fines migration, and stable permeation/coal fines blockage. In the particle migration stage, fines in the fractures start to migrate and then deposit in narrower parts of the fractures (this migrating-deposition process repeats a few times). The permeability of the sample also repeatedly increases and then decreases [19]. The migration and deposition of particles will cause a major decline in permeability, and for a working CBM well, this will damage the CBM reservoir.

Zhang et al. [20] studied the formation of coal fines and the flow of different sized coal fines, under different cleat geometry and pump flow rate, by displacement experiments with coal rock cores containing artificial cleats. The correlation relation between cleat width, flow rate, coal fines size and coal fines output, coal permeability was studied. It had an important guiding significance to adopt control measures for coal production. Cao et al. [21] studied coal fines generation mechanism and factors in the process of CBM well dewatering by single-phase water flow displacement experiments. Li [22] studied the effect of coal fines components on their generation in CBM wells in the water and coal fines two-phase flow core flooding experiments. An investigation of their agglomerate behavior in deionized, standard saline and $NaHCO_3$ suspensions were conducted on different rank coals collected in the Ordos and Qinshui basins [23,24]. Measurements of the coal fines production and the impact of these fines on the permeability of two coals from the Bowen Basin, Australia, were performed at different flow conditions and pressure conditions [25]. The fines collected from each coal samples ranged in size from 1 μm to 14 μm. For both coal samples, during the first 50 h, the permeability decreases from 0.005 mD and 0.048 mD by 60.9% and 85%, respectively, followed by gradual decline with fluctuations. By the end of water injection, the permeability drops by 88% and 89%, respectively. This phenomenon is attributed to the counteraction between formation damage (cleats plugging and coal fines settlement) and breakthrough of coal fines from the samples (widened cleats). Gash (1991) [26] experimentally tested core flooding behaviors to evaluate the impact of coal fines on permeability and confirmed the formation damage was due to coal fines migration, because he observed the permeability recovery when the flow direction was reversed. Yao et al. (2016) [27] used reconstituted coal samples to investigate the effect of tectonically deformed coal types on the characteristics of coal fines generation. They suggested that granulated coal is more sensitive to flow velocity and reservoir effective stress than the undeformed coal, but the permeability variations were not measured in their experiments. Wei et al. (2015) [28] experimentally demonstrated the critical flux for coal fines generation and proposed a maximum water production for a particular CSG well. Guo et al. (2015, 2016) [6,29] conducted a series of core flooding tests using water to quantify the permeability variations caused by coal fines production. They concluded that the variation of permeability generally matches with the trend of coal fines production (i.e., more significant permeability drop corresponding to more coal fines production), and the permeability decreases continuously.

Therefore, we focus on the removal of large solids because it is more important. The purposes of this study are to estimate statics settling velocity and critical velocity, which are critical to the selection of appropriate operation [30–33]. The previous literatures mainly studied coal fines generation and migration in the original rock samples that produce coal fines by themselves, ignoring the coal fines flows into surrounding rock samples that do not produce coal fines but only provides a flow channel for coal fines. Besides, the impact of two-phase water and coal fines flow on the pore and cleats structures has few reports in the literatures. Therefore, this paper studies the influence of two-phase water and coal fines flow on coal samples' pores and cleats structures under different coal fines concentration and flooding conditions [34,35]. The experimental study can help investigate the coal fines generation and migration in the dewatering stage of CBM development. A series of water and coal fines flow experiments are conducted with natural coal rock cores under field conditions, and the coal fines concentration and flow rate are different in each experiment. Finally, the inlet pressure and the outlet pressure tested by each experiment are analyzed. When the inlet pressure and outlet pressure reach the pseudo-steady status, the equivalent permeability of the coal rock samples with coal fines migration can be calculated. Then, the influence of coal fines migration on the water flow ability of coal rock is analyzed.

2. Materials and Methods

2.1. Sample Preparation and Characterization

2.1.1. Coal Rocks

Two cube coal samples (sample size: 0.5 m × 0.5 m × 0.5 m) were both collected from CBM wells borehole in Chinese Qinshui field, and six cores (size: $\Phi = 2.5$ cm, $L = 2$ cm) are cut according to the Chinese professional standards by a line cutting machine through kerosene cooling. These samples possess similar mineral contents, which mainly includes kaolinite, with some quartz. The main component of coal rock is organic carbon, and the clay mineral content is about 10%. In addition, it also contains a certain amount of minerals such as quartz and feldspar. Among the clay minerals, the non-expanded clay minerals have a kaolinite, chlorite and illite content of 90%, while the expanded clay minerals have a content of about 10% less. The clay content in coal rock samples is mainly kaolinite content, and the kaolinite has low ion exchange capacity and low expansion. Few swelling minerals are present in the coal samples. Hence the swelling effect on coal permeability can be neglected.

As shown in Figure 1, No.1, No.2 and No.6 core samples have micro-cleats on the surfaces, and No.3 and No.4 core samples are tighter without any cleat, and No.5 core sample has obvious cross-cleats. These cores' initial permeability investigated by gas test is given in Table 1.

Table 1. Gas permeability of six core samples.

Schemes	**No.1**	**No.2**	**No.3**	**No.4**	**No.5**	**No.6**
Gas permeability/mD	0.33	0.27	0.20	0.02	0.46	0.24

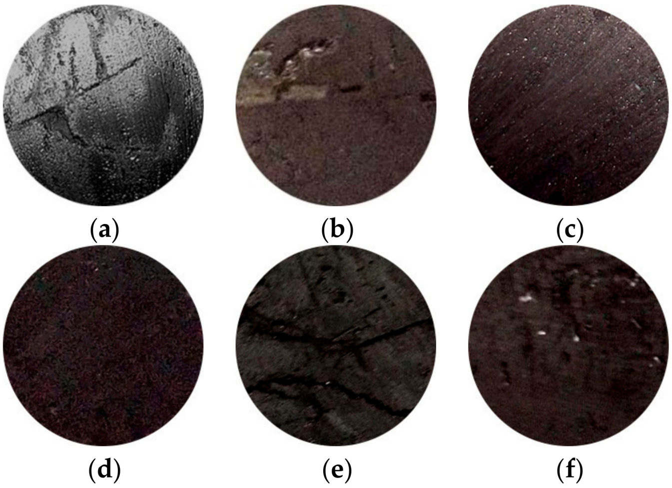


Figure 1. Upper surfaces of the six core samples before experiments. (**a**) No.1 core sample; (**b**) No.2 core sample; (**c**) No.3 core sample; (**d**) No.4 core sample; (**e**) No.5 core sample; (**f**) No.6 core sample.

2.1.2. Coal Fines

The quantity of coal fines required for these experiments exceeds the amount that can be easily recovered from production sites. Therefore, in this work we retrieve lumps of coal samples from the cube coal samples collected before, and then grind the coal samples into small size by using an electric grinder. The coal fines used in this study are screened by 100-mesh screens, which are equivalent to particle sizes (or sieve sizes) of 0.15 mm to 0.25 mm. The fine size distribution is coarse, and the particles larger than 3.0 mm in the sample account for about 50%; the fine size distribution is uneven, except for a large number of coarse particles, the coal rock samples contain more fine coal (less than 0.15 mm), and medium granularity (about 1 mm) coal content is small.

2.1.3. Displacement Fluids

The coal mining fluid of Qinshui CBM wells has a high salinity close to 8% salinity. Therefore, we made 8% salinity water (represents field water concentration) as the core flooding fluid, and the mass ratio of $NaCl:CaCl_2:MgCl_2\bullet 6H_2O$ is 7.0:0.6:0.4 in the fluid recipe. Besides, two kinds of water and coal fines mixture fluids are prepared, based on the coal fines concentration of fluid samples tested by distillation. According to production fluid samples taken from CBM wells, and the concentration of coal fines is tested by distillation, and it fluctuates between 0.004 g/cc and 0.01 g/cc. Hence, the coal fines concentrations of these two fluids are 0.004 g/cc and 0.01 g/cc, respectively.

2.2. Experimental Equipment and System

As shown in Figure 2, a constant flow ISCO pump (range: 0~20 MPa) is chosen as the pressure source, and the water is injected into a stirred vessel to mix with coal fines, and then the displacement fluid flow into a core holder for flooding. Three high precision sensors are installed to record the entrance pressure, outlet pressure and confining pressure of the core holder. Considering the initial formation pressure of coal reservoir, the fixed confining pressure is set to 5 MPa. These pressure data are obtained by multi-range pressure conversion system though converting electronic signals at different time, and they are stored by the computer data collection and control system.

When the inlet pressure and outlet pressure reach the pseudo-steady status, the equivalent permeability of the coal rock samples with coal fines migration can be calculated. Pseudo-steady is a kind of unsteady-state, which is close to steady state with pressure stabilization. When the confining pressure, inlet pressure, outlet pressure, pressure difference and flow rate are approximately constant, it can be regarded as the pseudo-steady state. At the same time, the output fluid volume from outlet is weighed when the pressure is measured, and the output fluid flows into the glass funnel, which has a filter membrane and a transparent flexible pipe, and then the coal fines from the outlet is observed.

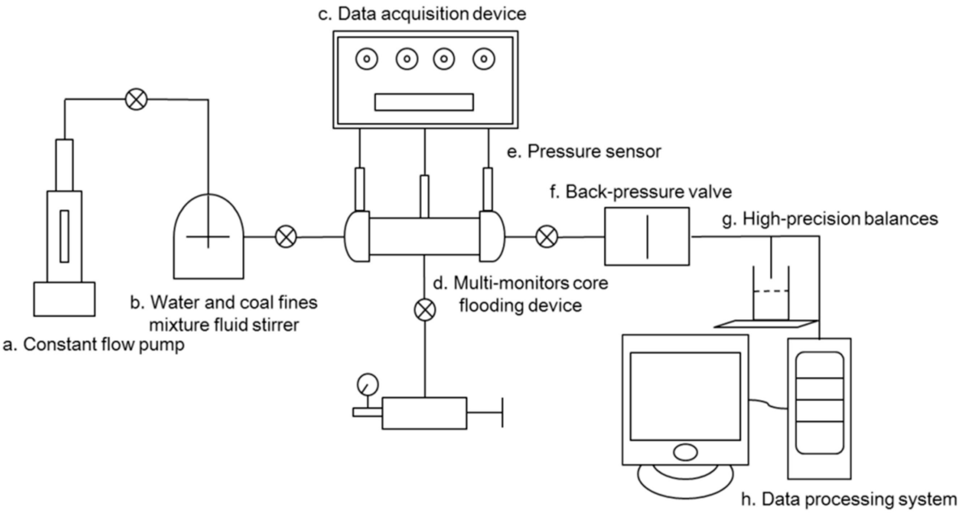


Figure 2. Experimental system.

2.3. Experimental Schemes and Workflow

Experimental schemes are designed with the six core samples prepared before, and there is a total of two variables in these experiments: a constant flow rate provided by the ISCO pump, and the concentration of coal fines in the two-phase displacement fluids. We designed each experiment scheme according to the cores' permeability and experiments' purposes. Our study focuses on Chinese Qinshui CBM reservoirs, which have high water rate at the early depressurization stage. A considerable amount of CBM wells with water rate (5 m^3/d to 25 m^3/d) show obvious fines gathering in the fluid output upon these two reservoirs' production data. Furthermore, according to the experimental comparability principles, the cross-sectional area proportion between the core and the underground perforated layer determine the flow rate proportion in the experiments and daily output. Hence, the flow rates are designed as 1 mL/min to 5 mL/min in different flooding stages.

As shown in Table 2, for the No.1 core, we wanted to study the pressure variation influenced by high coal fines concentration at high water rate, so the water rate was 5 mL/min and coal fines concentration was 0.01 g/cc. For the No.2 core, we wanted to study the pressure variation influenced by two different coal fines concentrations at medium water rate, so the water rate was 2 mL/min and coal fines concentrations were 0.004 g/cc and 0.01 g/cc, respectively. For the No.3 core, we wanted to study the pressure variation influenced by two different coal fines concentrations at high water rate, so the water rate was 5 mL/min and coal fines concentrations were 0.004 g/cc and 0.01 g/cc, respectively. For the No.4 core, because of its extreme low permeability and pressure pump limit, water flow rate was constrained at 1 mL/min, and the coal fines concentration is 0.004 g/cc. For the No.5 core, we wanted to study the pressure variation influenced by two different coal fines concentrations at two different water rates, so the water rate was 1 mL/min and 5 mL/min, coal fines concentrations were 0.004 g/cc and 0.01 g/cc, respectively. For the No.6 core, we wanted to study the pressure variation influenced by two different coal fines concentrations at two different water rates, so the water rate was 1 mL/min and 2 mL/min, coal fines concentrations were 0.004 g/cc and 0.01 g/cc, respectively. Four experimental schemes (i.e., No.2, No.3, No.5 and No.6 schemes) have the same concentration of coal fines in the two-phase displacement fluids, but different displacement flow rate. Moreover, No.1 scheme has a high flow rate and high coal fines concentration. On the contrary, No.4 scheme has a low flow rate and low coal fines concentration.

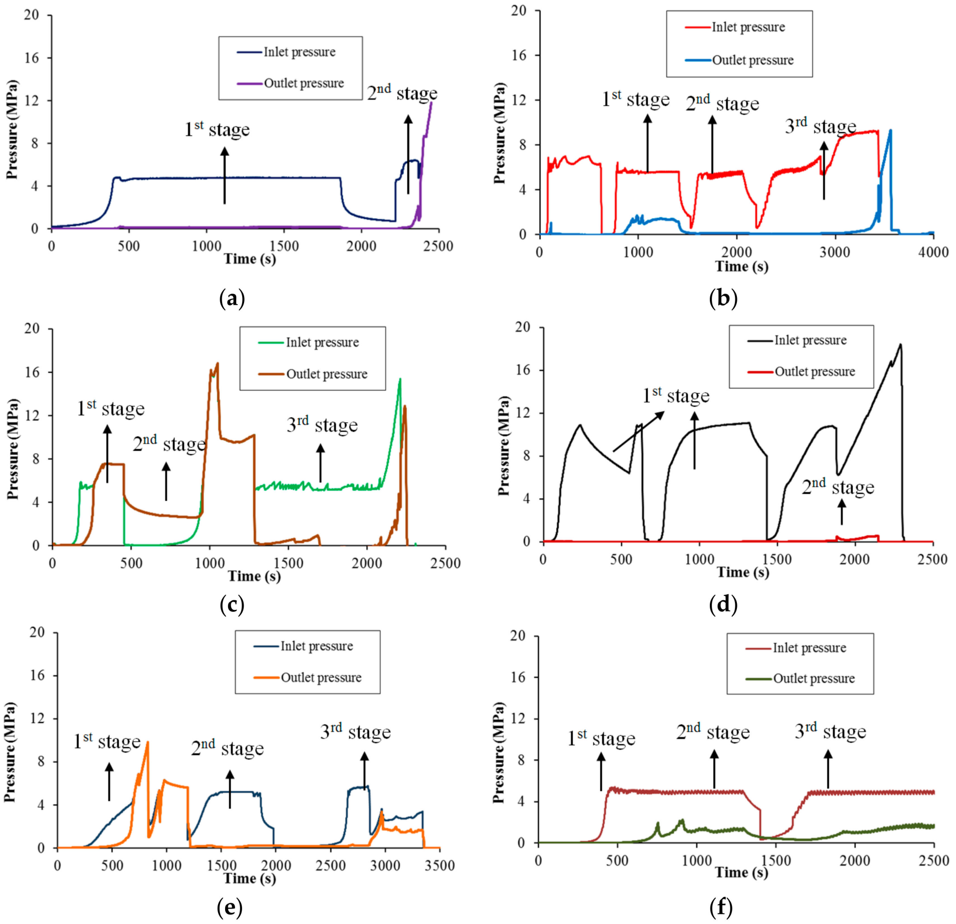
Table 2. Experimental schemes (The flow rate and coal fines concentration are designed).

Schemes	1st Stage (Single-Phase Water Flow)	2nd Stage (Two-Phase Water and Coal Fines Flow)	3rd Stage (Two-Phase Water and Coal Fines Flow)
	Water Flow Rate (mL/min)	**Water Flow Rate (mL/min), Coal Fines Concentration (g/cc)**	**Water Flow Rate (mL/min), Coal Fines Concentration (g/cc)**
No.1	2	5, 0.01	×
No.2	2	2, 0.004	2, 0.01
No.3	5	5, 0.004	1, 0.01
No.4	1	1, 0.004	×
No.5	1	1, 0.004	5, 0.01
No.6	1	1, 0.004	2, 0.01

3. Results and Discussion

3.1. Analysis of Pressures Variation

Experiments were conducted according to the experimental procedure and scheme designed above, and making use of real-time recording pressure data, the variations of inlet pressure and outlet pressure are shown in Figure 3. In every experiment, a part pseudo-steady status has been maintained for several minutes in each flooding stage, to approximately calculate the equivalent permeability of the coal rock samples with coal fines migration. According to the variations of inlet pressure and outlet pressure, the cleats' opening and coal fines blockage can be observed during displacement experiments.



(a) (b) (c) (d) (e) (f)

Figure 3. Pressures variation at different experiments. (**a**) No.1 core flooding experiment; (**b**) No.2 core flooding experiment; (**c**) No.3 core flooding experiment; (**d**) No.4 core flooding experiment; (**e**) No.5 core flooding experiment; (**f**) No.6 core flooding experiment.

According to the pressure variation curves in Figure 3, different displacement stages can be classified. When the inlet pressure and outlet pressure keep stable for enough time, equivalent permeability can be calculated approximately according to flow rate and the pressure differences under fluid–solid two-phase flow model, and the flow rates and equivalent permeability calculated at different flooding stages are shown in Table 3. Under the same pressure variation, the decreased rate of permeability is consistent with the decrease of water production capacity.

Table 3. Flow rates and equivalent permeability at different flooding stages.

Schemes	**Items**	**1st Stage (Single-Phase Water Flow)**		**2nd Stage (Two-Phase Water and Coal Fines Flow)**		**3rd Stage (Two-Phase Water and Coal Fines Flow)**	
		Pseudo-Steady Flow	**Cleat-Open**	**Pseudo-Steady Flow**	**Cleat-Open**	**Pseudo-Steady Flow**	**Cleat-Open**
1	Flow rate (mL/min)	2		5	5		
	Coal fines concentration (g/cc)	0	×	0.01	0.01	×	×
	Permeability (mD)	0.30		0.23	/		
2	Flow rate (mL/min)	2		2		2	2
	Coal fines concentration (g/cc)	0	×	0.004	×	0.01	0.01
	Permeability (mD)	0.16		0.13		0.08	/
3	Flow rate (mL/min)		5		5	1	1
	Coal fines concentration (g/cc)	×	0	×	0.004	0.004	0.004
	Permeability (mD)		/		/	0.13	/
4	Flow rate (mL/min)	1		1			
	Coal fines concentration (g/cc)	0	×	0.004	×	×	×
	Permeability (mD)	0.06		0.06			
5	Flow rate (mL/min)		1	1		2	2
	Coal fines concentration (g/cc)	×	0	0.004	×	0.01	0.01
	Permeability (mD)		/	0.14		0.13	/
6	Flow rate (mL/min)	1		1		2	5
	Coal fines concentration (g/cc)	0	×	0.004	×	0.01	0.01
	Permeability (mD)	0.19		0.20		0.16	/

Note: '×' means there is no cleat-open or pseudo-steady flow appeared in the experiment, and '/' means permeability cannot be calculated for core samples with cleat-open channel.

3.2. Analysis of Pore and Cleat Change

As shown in Figure 4, several cores are damaged due to coal fines migration and high pressure difference after the experiments, and some obvious opening cleats can be observed. Among these samples, No.1 core is relatively complete only with slight damage; however, there are two obvious cross-cleats in the middle, and a small piece of coal rock falls off in the intersection, as shown in Figure 4a. No.2 core and No.3 core are also relatively complete samples after the two-phase water and coal fines flooding experiments; however, there are obvious cross-fractures at the around edge, and some small pieces of coal rock falls off, as shown in Figure 4b,c. No.4 core is crushed seriously after displacement test, as shown in Figure 4d. The surface fractures have existed in No.5 core before the test, but the fractures seriously expanded to some pieces of rock peeled off, as shown in Figure 4e. The upper part of No.6 core falls off, and the whole structure of the core is destroyed obviously after test, as shown in Figure 4f.

3.3. Analysis of Permeability Variation

The mechanism of permeability variation in the water flow test has been discussed in previous literature. Stress, gas adsorption/desorption, mineral dissolution and precipitation, fines migration and clay swelling are the factors that can alter coal permeability. As the sample is covered by epoxy and no confining pressure is applied, there is no compression effect resulting from the variation of effective stress and no creep effect resulting from external stress. Also, the sample is exposed to only water during the test, so there is no gas adsorption/desorption effect either. The coal samples contain little swelling clay, which suggests that clay swelling should not be a cause for the permeability variation. Therefore, the possible mechanisms inducing permeability variation could be the mineral dissolution/precipitation fines migration and pore pressure variation.

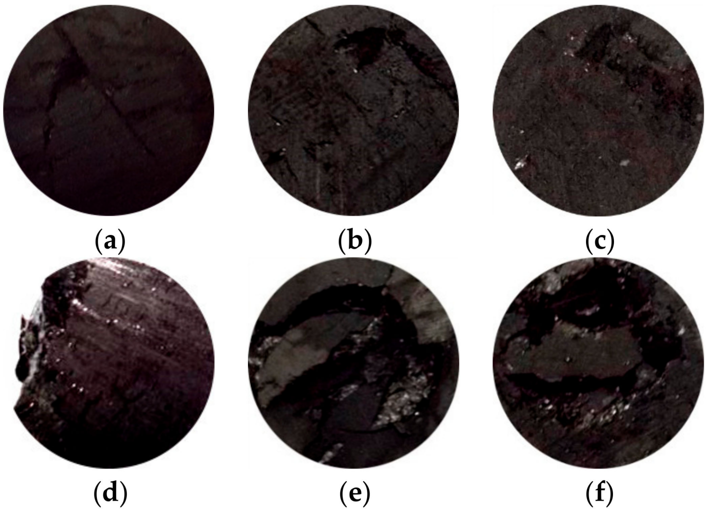


Figure 4. Upper surfaces of the six samples after experiments. (**a**) No.1 core sample; (**b**) No.2 core sample; (**c**) No.3 core sample; (**d**) No.4 core sample; (**e**) No.5 core sample; (**f**) No.6 core sample.

Two coal samples collected from Australia CBM fields are investigated [4,5], the permeability dropped significantly (by 60.9% and 85%, respectively for Sample 1 and Sample 2) in the water flooding process, followed by gradual decline with time, even if the differential pressure increased. The variations in coal permeability can be explained by the counteraction of four phenomena [36,37]: (1) the deposition and/or plugging of coal fines in cleats, damaging the permeability (i.e., entrapped coal fines); (2) the dilation of coal cleats by increased pore pressure (or decreased effective stress), resulting in permeability enhancement; (3) the discharge of coal fines widened the cleats, causing gradual permeability growth; and (4) the unplugging, redistribution and/or recapture of coal fines due to local pressure build-up, contributing to permeability fluctuations. In phenomenon (1), the settlement of coal fines would lead to gradual permeability decline as a result of narrowed cleats, while the clogging would contribute to abrupt permeability deterioration due to closure of cleats. Coal fines migration into the wellbores has resulted in pump issues and coal fines production, leading to a significant decline in production. To clean out the coal fines and replace the pumps on a continuous basis is a costly workover issue. Hence, a foamed remedial treatment was designed to displace the conductivity-plugging coal fines away from the wellbore and immobilize them with the foam also serving as a diverting agent. This has allowed the production and dewatering process to continue without any interruption [3].

In our work, two-phase water and coal fines flooding of No.2 coal sample is analyzed with the experimental results. The pressure fluctuation is obvious under 2 mL/min pump flow rate, and then the flow rate reduces to 1 mL/min. As proposed in the literatures [4,5,25,28], in pseudo-steady flow, the permeability of water is calculated based on Darcy's Law. However, the permeability of cleat with non-Darcy flow cannot be obtained by Darcy's Law. After several minutes, the displacement flow reaches a pseudo-steady state, and the coal equivalent permeability is 0.16 mD. After flooding by mixture fluid with 0.004 g/cc coal fines concentration, the differential pressure is gradually increased. It indicates that coal pores are blocked by coal fines, so the equivalent permeability decreases to 0.13 mD. The inlet pressure gradually increases after flooding by mixture fluid with 0.01 g/cc coal fines concentration, and the differential pressure is gradually increased. The coal pores are further blocked by more coal fines, and the equivalent permeability has a 50% drop to 0.08 mD. Finally, the differential pressure increases sharply, which indicates the coal core cleats gradually open, and the permeability does not make any sense.

Two-phase water and coal fines flooding of No.6 coal core sample is analyzed based on the experimental results. During the single water flooding stage, the inlet pressure and outlet pressure maintain steady for a long time, and the coal permeability is 0.19 mD. After flooding by mixture fluid with 0.004 g/cc coal fines concentration in 1 mL/min flow rate, the inlet pressure decreases a little, and the permeability is still 0.2 mD. However, differential pressure gradually increases after flooding by mixture fluid with 0.01 g/cc coal fines concentration, which obviously indicates that both coal pores and cleats have been blocked by coal fines, and the permeability decreased to 0.15 mD with a drop of 21%. After increasing the pump flow rate to 2 mL/min, the differential pressure is gradually decreased along with some coal fines flowing out. It indicates that some core pores and cleats blocked by coal fines have been washed throughout, and then the permeability increases to 0.17 mD. Finally, the pressure difference increases sharply, which indicates the coal core cleats gradually open, and the permeability does not make any sense.

When the coal cores have some micro-cleats visible on the surface, coal fines migration may cause the blockage of the micro-cleats and even pores, leading severe permeability decrease. In No.2 core flooding test, the core permeability decreases 19% when flooded using two-phase water and coal fines mixture fluids with 0.004 g/cc coal fines concentration, and the core permeability reduces 50% when flooded using two-phase water and coal fines mixture fluids with 0.01 g/cc coal fines concentration. If we keep the two-phase flow under constant differential pressure for a longer period, some wider cleats open gradually, and even some extremely high-permeability channels form. When the coal rock cores are crossed by some cleats directly, it is difficult to reach the pseudo-steady state during the single-phase water flooding process, so the equivalent permeability cannot be calculated accurately by Darcy law. Moreover, the inlet pressure and outlet pressure do not change obviously when flooded by two-phase water and coal fines mixture fluids with 0.004 g/cc coal fines concentration later, and the flow still cannot reach a pseudo-steady state. However, the outlet pressure decreases obviously when flooded by two-phase water and coal fines mixture fluids with 0.01 g/cc coal fines concentration in the third stage. This phenomenon indicates that the cleats have been blocked by the coal fines, to obtain the pseudo-steady flow state after a period of test. If the coal core has relatively low permeability without any cleat, outlet pressure will be low during the displacement, and inlet pressure increases with pressure holding is quite serious. The flow is still not stable even with a very little displacement flow rate. It is difficult for coal fines to enter the coal rock pore, and most gathered in the entrance after adding more coal fines. Although the differential pressure is high, the outlet pressure is still very low, and it is difficult to reach the pseudo-steady state.

4. Conclusions

Due to mechanical collision, liquid erosion, pressure fluctuations and other external forces, CBM well inevitably produce coal fines when drilling and production. Coal fines deposit at the well bottomhole, leading the pump-blockage accidents. The over-frequent pump repair impacts the methane desorption and production. Coal fines plug some pores and micro-cleats, and the dewatering rate reduces, which leads to gas performance damage in later development. However, coal fines migration may also help form high-permeability channel in the coal bed, and the reservoir pressure will decrease quickly along with dewatering.

The origin of mobile coal fines and/or particles falls into categories: (1) large coal fines created during drilling and completion, (2) and small coal fine generated in production and migrate through cleats and hydraulic fractures into bottomhole. The former is large in particle size but has a small volume in total. The latter is small in particle size while has a large cumulative volume. Because large particles required a high liquid velocity to be removed to the surface, and they are the major causes of equipment failure. Small coal fines, although comprising the majority of migrating coal during back-flow after completion and during production, are easier to lift to the surface and require a low lifting velocity. The velocity that can remove large coal fines will not have difficulty lifitng small coal fines and will prevent them accumulating at well bottomhole. The new observation of our study is: "Maintaining the differential pressure for a longer period may result in new cleats openings and severe coal rock damage during the single-phase water flooding process; While coal fines may plug some natural cleats and pores especially in the core samples with micro-cleats during the two-phase flooding stage, so coal fines migration significantly reduces the equivalent permeability and dewatering ability of the coal rock in the earlier flooding; While enlarging the differential pressure in two-phase water and fines flooding, breakthrough of coal fines from the samples contributes to widened cleats." The other published reports only stated that coal fines generation and migration are the dominant causes for the rapid reduction of coal permeability, while the removal of coal fines from the samples contributes to slight permeability enhancement. They did not discuss the "cleat-open" phenomenon after a period of coal fines blockage in the pores, and the blockage of nature cleats has not been investigated in their previous experiments.

How to reduce the coal fines generation is the source to decrease the damage of coal fines migration, and it is crucial to achieve better CBM performance. The damage to the permeability mainly occurs in the early stage of coal fines migration. Thus, maintaining a stable effective strength and a controlled depressurization rate during drainage can effectively constrain coal fines output and decrease permeability damage within coal reservoirs. Generally, to avoid the blockage of coal cleats and reduce the damage of permeability, the depressurization rate and intensity should be controlled in the process of earlier dewatering. However, coal fines migration is inevitable in most CBM reservoirs, where it is necessary to find a better way to transport the coal fines from the bottomhole to the ground avoiding reiterative shut in and open. Subsequent studies can use the disc core to further observe the accumulation characteristics of coal powder in the radial seepage and the pressure changes along the path.

Author Contributions: Writing: D.G.; Providing case and idea: Y.L.; Providing revised advice: T.W., D.W.

Funding: The study was supported by Open Fund (PLN201711) of State Key Laboratory of Oil and Gas Reservoir Geology and Exploration (Southwest Petroleum University), National Natural Science Foundation of China (11702300), PetroChina Innovation Foundation (2017D-5007-0208) and the Key Laboratory of Fluid–Solid Coupling System Mechanics, Chinese Academy of Sciences.

Conflicts of Interest: The authors declare no conflict of competing interest.

References

1. Moore, T.A. Coalbed methane: A review. *Int. J. Coal Geol.* **2012**, *101*, 36–81. [CrossRef]
2. Salmachi, A.; Yarmohammadtooski, Z. Production data analysis of coalbed methane wells to estimate the time required to reach to peak of gas production. *Int. J. Coal Geol.* **2015**, *141*, 33–41. [CrossRef]
3. Magill, D.P.; Ramurthy, M.; Jordan, R.; Nguyen, P.D. Controlling coal-fines production in massively cavitated openhole coalbed-methane wells. In Proceedings of the SPE Asia Pacific Oil and Gas Conference and Exhibition Society of Petroleum Engineers, Brisbane, Australia, 18–20 October 2010.
4. Bai, T.; Chen, Z.; Aminossadati, S.M.; Li, L.; Liu, J.; Lu, H. Dimensional analysis and prediction of coal fines generation under two-phase flow conditions. *Fuel* **2017**, *194*, 460–479. [CrossRef]
5. Bai, T.; Chen, Z.; Aminossadati, S.M.; Pan, Z.; Liu, J.; Li, L. Characterization of coal fines generation: A micro-scale investigation. *J. Nat. Gas Sci. Eng.* **2015**, *27*, 862–875. [CrossRef]
6. Guo, Z.; Hussain, F.; Cinar, Y. Permeability variation associated with fines production from anthracite coal during water injection. *Int. J. Coal Geol.* **2015**, *147–148*, 46–57. [CrossRef]
7. Liu, H.L.; Wang, H.Y.; Liu, R.H.; Zhao, Q.; Zhang, X.W.; Yong, H. Unconventional oil and gas resources development status and key issues. *Nat. Gas Ind.* **2009**, *29*, 113–116.
8. Okotie, V.U.; Moore, R.L. Well production challenges and solutions in a mature, very low-pressure coalbed methane reservoir. In Proceedings of the SPE Annual Technical Conference and Exhibition, Calgary, AB, Canada, 19–21 October 2010.
9. Zhong, Z.Y.; Wu, X.D.; Han, G.Q.; He, L.P.; Xiong, X.F.; Wang, S.L. Experimental investigation on particle transport of coal fines in unsteady terrain slug flow. *J. Pet. Sci. Eng.* **2018**, *166*, 747–758. [CrossRef]
10. Chen, Z.H.; Wang, Y.B.; Sun, P. Destructive influences and effectively treatments of coal powder to high rank coal bed methane production. *J. China Coal Soc.* **2009**, *34*, 229–232.
11. Zou, Y.S.; Zhang, S.C.; Zhang, J. Experimental method to simulate coal fines migration and coal fines aggregation prevention in the hydraulic fracture. *Transp. Porous Med.* **2014**, *101*, 17–34. [CrossRef]

12. Nouri, A.; Vaziri, H.; Belhaj, H.; Islam, R. Sand-production prediction: A new set of criteria for modeling based on large-scale transient experiments and numerical investigation. *SPE J.* **2006**, *11*, 227–237. [CrossRef]
13. Liu, C.H.; Liu, X.F.; Zhou, C. Migration patterns of pulverized coal in coal reservoirs during the well drainage. *Coal Geol. Explor.* **2015**, *43*, 23–26.
14. Liu, S.G.; Hu, A.M.; Song, B.; Li, H.F. Early warning and prevention and control measures of coal dust concentration in coal bed gas wells. *J. China Coal Soc.* **2012**, *37*, 86–89.
15. Zou, J.; Rezaee, R. Effect of particle size on high-pressure methane adsorption of coal. *Pet. Res.* **2016**, *1*, 53–58. [CrossRef]
16. Liu, S.G.; Zhang, X.L.; Yuan, W.F.; Tian, X.Y. Pulverized coal output law of coal-bed methane wells and practice of drainage control and management. *J. China Coal Soc.* **2012**, *37*, 412–415.
17. Wang, Q.W.; Cao, D.Y.; Wang, T. Relationship between the stress-concentrated zone caused by cavity-completed wells and the coal powder output. *Coal Geol. Explor.* **2013**, *41*, 35–37.
18. Liu, X.F. Prediction of flowing bottom hole pressures for two-phase coalbed methane wells. *Acta Geol. Sin. Engl. Ed.* **2013**, *87*, 1412–1420.
19. Wei, Y.C.; Cao, D.Y.; Yuan, Y. Characteristics and controlling factors of pulverized coal during coalbed methane drainage in Hancheng area. *J. China Coal Soc.* **2013**, *38*, 1424–1429.
20. Zhang, G.S.; Tian, W.T.; Tao, S.; Bai, J.M.; Shi, H.N.; Cheng, H. Experimental research of coal grain migration rules of Coalbed Methane. *J. Oil Gas Technol.* **2011**, *33*, 105–108.
21. Cao, D.Y.; Yao, Z.; Li, X.M.; Wei, Y.C.; Hu, A.M.; Song, B. Rules of coal powder output under physical simulation experiments of single-phase water flow displacement. *J. China Coal Soc.* **2013**, *38*, 624–628.
22. Li, X.M.; Cao, D.Y.; Yao, Z.; Xiang, X.R.; Wang, X.L.; Wei, Y.C. Study on mechanism of pulverized coal discharge based on flow-state physical simulation. *Coal Sci. Technol.* **2015**, *43*, 76–79.
23. Lan, W.J.; Wang, H.X.; Yang, S.Y.; Zheng, C.; Liu, Y.X.; Chen, S.S. Study on the migration of pulverized coal in CBM wellbore. *J. Pet. Sci. Eng.* **2017**, *156*, 740–747. [CrossRef]
24. Shi, Q.M.; Qin, Y.; Zhou, B.Y.; Zhang, M.J.; Wu, M.; Wang, L.N. An experimental study of the agglomeration of coal fines in suspensions: Inspiration for controlling fines in coal reservoirs. *Fuel* **2018**, *211*, 110–120. [CrossRef]
25. Bai, T.; Chen, Z.; Aminossadati, S.M.; Rufford, T.E.; Liang, L. Experimental investigation on the impact of coal fines generation and migration on coal permeability. *J. Pet. Sci. Eng.* **2017**, *159*, 257–266. [CrossRef]
26. Gash, B.W. Measurement of rock properties in Coal for Coalbed Methane Production. In Proceedings of the 66th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers, Society of Petroleum Engineers, Dallas, TX, USA, 6–9 October 1991.
27. Yao, Z.; Cao, D.; Wei, Y.; Li, X.; Wang, X.; Zhang, X. Experimental analysis on the effect of tectonically deformed coal types on fines generation characteristics. *J. Pet. Sci. Eng.* **2016**, *146*, 350–359. [CrossRef]
28. Wei, C.; Zou, M.; Sun, Y.; Cai, Z.; Qi, Y. Experimental and applied analyses of particle migration in fractures of coalbed methane reservoirs. *J. Nat. Gas Sci. Eng.* **2015**, *23*, 399–406. [CrossRef]
29. Guo, Z.H.; Hussain, F.; Cinar, Y. Physical and analytical modelling of permeability damage in bituminous coal caused by fines migration during water production. *J. Nat. Gas Sci. Eng.* **2016**, *35*, 331–346. [CrossRef]
30. Han, G.; Ling, K.; Wu, H.; Gao, F.; Zhu, F.; Zhang, M. An experimental study of coal-fines migration in Coalbed-methane production wells. *J. Nat. Gas Sci. Eng.* **2015**, *26*, 1542–1548. [CrossRef]
31. Mitchell, T.R.; Leonardi, C.R. Micromechanical investigation of fines liberation and transport during coal seam dewatering. *J. Nat. Gas Sci. Eng.* **2016**, *35*, 1101–1120. [CrossRef]
32. Reydick, D.B.; Luc, G.; Turner, K.M. Steel X-ray µCT investigations of the effects of cleat demineralization by HCl acidizing on coal permeability. *J. Nat. Gas Sci. Eng.* **2018**, *55*, 206–218.
33. Niu, C.K.; Xia, W.C.; Peng, Y.L. Analysis of coal wettability by inverse gas chromatography and its guidance for coal flotation. *Fuel* **2018**, *228*, 290–296. [CrossRef]
34. Wang, Q.G.; Yin, W.D.; Yang, H.R.; Lu, J.F.; Zhao, B. Numerical study on the effect of fine coal accumulation in a coal beneficiation fluidized bed. *Powder Technol.* **2015**, *283*, 570–578. [CrossRef]
35. Zhang, N.; Chen, X.M.; Nicholson, T.; Peng, Y.J. The effect of froth on the dewatering of coals—An oscillatory rheology study. *Fuel* **2018**, *222*, 362–369. [CrossRef]

36. Zhang, S.H.; Tang, S.H.; Zhang, J.P.; Pan, Z.J. Pore structure characteristics of China sapropelic coal and their development influence factors. *J. Nat. Gas Sci. Eng.* **2018**, *53*, 370–384. [CrossRef]
37. Othman, F.; Yu, M.; Kamali, F.; Hussain, F. Fines migration during supercritical CO_2 injection in sandstone. *J. Nat. Gas Sci. Eng.* **2018**, *56*, 344–357. [CrossRef]