Experimental study on the influence of coal powders on the performance of water-based polymer drilling fluid

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Abstract
Coal powders, as cuttings, invade the drilling fluid along a coal seam during coalbed methane development, thereby changing the properties of the drilling fluid. Therefore, this work aims to investigate the influence of coal powders on drilling fluid performance. The powders of lignite, anthracite, and contrasting shale were added to a water-based polymer drilling fluid. Then, the rheology, filtration, lubricity, and adhesiveness were measured, and the natural degradation, as well as the wettability were further evaluated. The results show that some parameters of the drilling fluid, including viscosity, lubrication coefficient, adhesion coefficient, contact angle, and surface tension, increase after adding coal powders, while other parameters, such as filtration loss and natural degradation, decrease. Compared with lignite and shale, anthracite powders, with the lowest mineral content, exhibit the smallest change in the rheological property, lubricity, adhesion, and natural degradation of the drilling fluid. Moreover, the content and size of the coal powders generally have opposing effects on the drilling fluid. When the coal powder content reaches 3 wt.%, the surface tension and contact angle of the drilling fluid show more evident changes than other parameters. Based on the analysis of the stress intensity factor, the drilling fluid with coal powders exceeding 100 mesh can reduce the capillary force in microfractures, and in combination with other factors (such as reduced filtration loss and sealing and supporting of the microfractures), improves wellbore stability. Therefore, coal powders with suitable particle

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sizes and concentration levels are expected to become a new drilling fluid material to protect coal field reservoirs.

**Keywords**
Drilling along coal seam, coal powders, polymer drilling fluid, stress intensity factor, reservoir protection

**Introduction**

With the development of the global economy, the demand for energy is increasing (Boycheva et al., 2020; Kivi et al., 2018; Li et al., 2017). Unconventional energy sources, such as coalbed methane (CBM), shale gas, and tight sandstone gas, have replaced some conventional energy sources (Akhtarmanesh et al., 2013; Lu et al., 2017; Shen et al., 2019; Wu et al., 2020; Zhong et al., 2011). In recent decades, CBM has become an important energy source worldwide (Cai et al., 2016; Chen et al., 2018; Law and Curtis, 2002; Zhang et al., 2020; Zheng et al., 2018). China has rich coalfield reservoirs containing large quantities of CBM. As an unconventional energy source, CBM has the advantages of being clean, as well as environmentally friendly, and thus, it is widely exploited and used. PetroChina Coalbed Methane Co., Ltd has been continuously intensifying the exploration and development of CBM, and it has achieved an increase in the average annual production and sales equivalent to $50 \times 10^4$ t of oil, with an annual output of $200 \times 10^4$ t upon the completion of the construction of an unconventional gas field in 2019 (Wen et al., 2019).

Presently, the common mining method entails the collection and utilization of CBM resources by drilling in coal reservoirs, and several technical problems remain in the exploration and development of CBM drilling (Lyu et al., 2019; Sun et al., 2020; Tian et al., 2020; Yue et al., 2018). Coal is a soft, compact material with multiscale fractures as the main flow channel (Zhou et al., 2020a, 2020b). The mechanical strength of coal is low, and it can easily collapse and break (Bu et al., 2019; Huang and Honaker, 2016). Micro-cracks, pores, and joints are considerably developed in coal (Barone et al., 2019); its formation pore pressure is low and leaks easily (Yilmaz, 2019). When drilling along the coal seam, it becomes soaked with drilling fluid if the conventional potassium chloride drilling fluid is used, and the coal seam severely swells or collapses (Chen et al., 2019), while the undue drilling fluid pollutes the reservoir. Therefore, the drilling fluid should encompass safe drilling and reservoir protection functions in the CBM drilling process (Lv et al., 2019). Drilling fluid technology is considered as an ideal, effective, and economic approach to solve the contemporary drilling problem of coal reservoirs (Cai et al., 2011; Lyu et al., 2019).

CBM desorption from coal matrices usually involves flow through micro-scale or even nano-scale micro-fracture networks. To achieve better drilling effects, many scholars have studied the damage mechanism of CBM reservoirs, as well as the drilling fluid for reservoir protection, and prepared the corresponding drilling fluid suitable for CBM. Barr (2009) introduced the guiding design principles of drilling fluids for CBM reservoirs, and thought it should be based on aspects such as nearby well data, reservoir characteristics, coal rank, drilling fluid rheology, shale rolling recovery experiment, and methylene blue content. Baltoiu et al. (2008) designed a drilling fluid, which could keep the horizontal well stable
and also reduce leak-age; it has been successfully used in two 1000 m long horizontal wells. Gentzis et al. (2009) discovered that two treatment agents could form thin mud cakes on the surface of a coal rock with strong plugging capability, and they could duly maintain their stability, as well as reduce leak-age. Barr (2009) designed a drilling fluid applied in the Wyoming CBM project, which reduced the existing problems of mud rings, collapse of shale, and long total drilling time in the area. Cai et al. (2011) introduced an environmentally- friendly and bio-degradable drilling fluid for CBM; they tested it to evaluate the polymer type and concentration, as well as enzyme type and concentration on the viscosity and breaking behaviors of this drilling fluid. Zheng et al. (2018) studied the fuzzy ball drilling fluid, which has now been successfully applied to approximately 1000 CBM wells to prevent collapse and block leakage in the Ordos stable block, and they discovered that the drilling fluid could significantly increase the wall thickness, thereby keeping the wall stable (Vryzas and Kelessidis, 2017). It is ideal to use low solid degradable drilling fluid systems in coal seams (Yang et al., 2018).

The performance of drilling fluid needs to meet certain requirements: firstly, the drilling fluid needs to form a thin and dense mud cake on the borehole to prevent it from invading the coal seam, balance the formation pressure, and ensure the safety of the drilling process (Shi et al., 2019). Secondly, coal is loose and fragile, thereby easily forming numerous cuttings. Based on the stable formation pressure, drilling fluid requires effective suspension of cuttings. Thirdly, when the drilling fluid encounters the coal seam, it must resist the interference of certain coal powders. When drilling, the cuttings and coal powders mix into the drilling fluid, and the large cuttings are removed through a solid control device, while the small coal powders mix into the drilling fluid. These mixed substances have a certain impact on the performance of the drilling fluid; therefore, it is necessary to study the influence of coal powders on water-based polymer drilling fluids, which is one of the key technologies to ensure safe CBM drilling.

Coal powders produced in the process of drilling along coal seam are mainly divided into two types (Lyu et al., 2020; Xiao et al., 2018): (1) The primary coal powders, which are produced by coalification and structural deformation in the process of geological evolution. This part of coal powders mainly exists on the fault surface, interlayer sliding surface, and coal fractures. Primary coal powders always exist in the coal reservoir before CBM development, and they move with the fluid in the fracture. (2) Secondary coal powders are produced by mechanical damage, mainly including the coal powders produced by the grinding of the coal seam by tools during drilling. Figure 1 shows the diameter data of drilling cuttings logging of three different types of coal structure intervals of the X-2 CBM well.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Mass concentration of drilling cuttings with different particle sizes from the X-2 well, including three different types of coal structures. (a) primary coal, (b) cataclastic coal, and (c) fragmented-mylonitized coal.
(Lyu et al., 2019) in Qinshui Basin, Shanxi Province, China. It is evident from Figure 1 that in the primary structure coal (a), the particle size is mainly 1.0–0.5 mm, followed by 0.5–0.25 mm; in the cataclastic coal (b), the particle size is mainly 1.0–0.5 mm, followed by 2.36–1.0 mm; while in the fragmented coal and mylonitized coal (c), the particle size is mainly >2.36 mm, followed by 2.36–1.0 mm.

Contrary to the conventional shale or mudstone cuttings, the negative effect of coal cuttings to drilling fluids is unclear, especially the influence on some special properties, such as the degradation and wettability of the drilling fluid; thus, further study is required in this regard. To accurately verify the effect of coal cuttings on water-based polymer drilling fluids, we add coal powders to the drilling fluid, and measure their performance after mixing the coal powders. Because the large particles below 60 mesh of coal cuttings mixed in the drilling fluid are removed by the solid control device in field drilling operation, only small particles remain in the drilling fluid. In this study, coal powders with different particle sizes (60–100 mesh and greater than 100 mesh) were selected, and the changes in performance of the treated drilling fluid were tested, which accurately reflect the impact of coal powders with different particle sizes in the drilling fluid on the water-based polymer drilling fluid. Specifically, two representative samples from coal field basins in China were selected in this study—the lignite from the Erlian Basin (hereinafter referred to as “lignite”) and the anthracite from the Qinshui Basin (hereinafter referred to as “anthracite”)—and they were added to the water-based polymer drilling fluid; the influence of coal powders on drilling safety and reservoir protection was investigated. Firstly, the components of samples were determined by X-ray diffraction (XRD) analysis, coal industry analysis, and element analysis. Secondly, the function of drilling safety was evaluated by testing the rheology, filtration, lubricity, and adhesiveness of the drilling fluid, and the drilling fluid reservoir protection function was evaluated by testing the natural degradation and wettability. Finally, the stress intensity factor was taken as an index to comprehensively ascertain the influence of coal powders mixed with drilling fluid on wellbore stability. In addition, the roof and floor of coal seam are usually shale or mudstone under the actual stratum conditions. For a comparative study, the shale samples from Longmaxi formation, Datianba village, Xiushan County, Chongqing (hereinafter referred to as “shale”) were simultaneously tested.

**Materials and instruments**

*Experimental materials*

Selected coal samples: More than half of the CBM wells in China are aimed at anthracite and lignite reservoirs. The lignite in the Erlian Basin and the anthracite in the Qinshui Basin are typical low-rank and high-rank coal products in China, respectively. Therefore, these two coal samples are selected for experiments. The samples are taken from lignite in the Erlian Basin and anthracite in the Qinshui Basin; the photos of the real object and scanning electron microscopy (SEM) are presented in Figure 2.

Drilling fluid materials and chemicals mainly include Sodium bentonite (Hangzhou bentonite technology development Co., Ltd.); Xanthan gum (XC), Modified starch (DFD), Sodium carbonate (Na₂CO₃), and low-viscosity polyanionic cellulose (LV-PAC) (Chongqing lihong fine chemical Co., Ltd.).
Experimental instrument

The main instruments used in the experimental research are as follows: X’Pert PRO diffractometer, ZNN-D6 six-speed rotating viscometer, ZNS-5A medium pressure filtration instrument, extreme pressure (EP) lubricator, NF-2 adhesion coefficient instrument, QBZY-1 automatic surface tension meter, HH-501 super constant temperature water-bathing, JC2000DM contact angle meter, as well as LC- MP-1A metallographic grinding and polishing machine, ZX 101 electric blast drying box.

Experimental methods

Sample composition test

The mineral content of lignite, anthracite, and shale was determined by k-value quantitative analysis with X’Pert diffractometer (Panalytical B. V., Almelo, The Netherlands)
(Chen et al., 2019; Shi et al., 2019), coal industry analysis; and element analysis of lignite and anthracite.

**Rheology and filtration test**

The above-mentioned lignite, anthracite, and shale samples were put into a mortar and crushed into powder, sieve 60–100 mesh and >100 mesh with standard sieve, and then placed in an electric blast drying box for standby use (powders as shown in Figure 3). The base formula of the water-based polymer drilling fluid as the base fluid in the experiment is: 1 wt.% sodium bentonite + 1 wt.% DFD + 2 wt.% LV-PAC + 0.3 wt.% XC + 0.05 wt.% Na2CO3.

The screened lignite, anthracite, and shale sample powders were added into the prepared water-based polymer drilling fluid according to a certain mass fraction, the ZNN-D6 six-speed rotary viscometer was used to record the readings of 600 rpm and 300 rpm (θ_{600} and θ_{300}, respectively), which were used to evaluate the rheological properties of mud and measure the six-speed values to calculate apparent viscosity (AV), plastic viscosity (PV), and yield point (YP). Equations have been used in their fundamental form as shown below in equations (1) to (3) (Chen et al., 2019; Zhang et al., 2020). Additionally, the filtrate loss (FL) was measured with ZNS-5A medium pressure filtration instrument.

\[
AV = \frac{\theta_{600}}{2} \quad (1)
\]

\[
PV = \theta_{600} - \theta_{300} \quad (2)
\]

\[
YP = \frac{(2\theta_{300} - \theta_{600})}{2} \quad (3)
\]

**Lubricity and adhesion test**

The test objects include base fluid and drilling fluid with lignite coal powders, anthracite coal powders, and shale powders. An EP lubricator is used to test the lubrication performance of the different drilling fluids, according to the API standard, the torque is gradually increased.
at a speed of 1000 rpm/min; when the torque is increased to a certain value, the EP lubricator shakes violently. Here, the friction ring engages with the iron block, and the final data is recorded. The adhesion coefficient instrument is a kind of simulation test and analysis instrument, which is mainly used to monitor the friction coefficient between the drilling tool and the drilling fluid in the deep well to deal with the drilling fluid in time and improve its lubrication performance. The NF-2 adhesion coefficient instrument is used to test the adhesion coefficient of different drilling fluids (Chang et al., 2015).

**Natural degradation test**

The natural degradation method is mainly based on the molecular structure of the high molecular weight polymer in the drilling fluid, which gradually decomposes under the action of microorganisms over time, while the molecular weight changes from large to small until it is completely broken, and the viscosity of the drilling fluid gradually decreases during the degradation process. Therefore, the degradation of the drilling fluid can be evaluated by the viscosity (Lyu et al., 2019). The base fluid with added corresponding powders was stirred with frequency converter for 30 min, and the apparent viscosity of different drilling fluids was measured by the ZNN-D6 six-speed rotary viscometer, and then placed in the HH-501 super constant temperature water bath at a certain temperature (20°C). Taken out intermittently, the sample was measured at a certain temperature, and the natural degradation performance of the drilling fluid with added powders could be observed.

**Wettability test**

Wettability is one of the most important surface properties of a rock. It controls the size and direction of the capillary force and affects the migration of fine particles. The contact angle (θ) is usually used to describe the interaction among reservoir rock, oil/water, and gas (Hirasaki, 1991). Many scholars believe that, when θ < 75°, it is water wetting; when 105° > θ > 75°, it is neutral wetting; and when θ > 105°, it is oil wetting (Förch et al., 2009; Wu et al., 2001). The end face of the sample to be measured is ground with LC-MP-1A metallographic grinding and a polishing machine. Thereafter, the appropriate size samples are selected, put into the cut PVC pipe, and the bottom is wrapped with rubber mud. A certain proportion of quick drying adhesive is added. Next, the treated samples are placed at room temperature (32°C) until the quick drying adhesive solidifies. The contact angle is then measured by the JC2000DM contact angle meter (Chen et al., 2019; Lyu et al., 2019; Shi et al., 2019). To explore the influence of drilling fluid mixed with coal powders on the wettability of the samples, the contact angle of water, base fluid, and drilling fluid with 3 wt.% powder mixed with corresponding substances on the surface of the lignite, anthracite, and shale were evaluated.

The surface tension of liquid is the embodiment of intermolecular forces, while the value of the tension can reflect the physical and chemical properties of the liquid and its material composition. The surface tension has an important influence on the solubility and wettability of the liquid. The QBZY-1 automatic surface tension meter is used to test the surface tension of different types of drilling fluids by using the method of hanging piece, and the corresponding values are obtained.
Results and discussion

Sample composition analysis

XRD and the industrial analysis of lignite, anthracite, and shale samples show that: lignite maceral is mainly composed of a xylitic group (Figure 2(c)) and silk group (Figure 2(e)). The mineral content (61%) is high, mainly clay mineral, containing more quartz (32%) and kaolinite (23%) (Table 1); water content (17%) and volatile matter are higher (46%) (Table 2). The macerals of anthracite are mainly vitrinite (Figure 2(d) and (f)), while the main inorganic minerals are calcite (10%) and dickite (8%) (Table 1), as well as low ash content (8%) and high carbon content (91.1%) (Table 2). The quartz content in the shale of Longmaxi formation is as high as 60%, which easily causes shale hydration (Table 1).

Rheology and fluid loss

It is evident from Table 3 and Figure 4 that for the same powders, the apparent viscosity of the powders with small particle sizes increases faster than that with large particle sizes added to the base fluid. For the same particle size, with the addition of powders, the more is added, the higher the apparent viscosity is, and the growth rate is larger at the beginning, although it decelerates later. With the addition of coal powders and shale powders, the apparent viscosity increases to a certain extent. At the same particle size, the increase of lignite viscosity is the largest, relative to the base fluid, with anthracite the smallest, and shale in the middle.

In the above-stated experiments, it can be understood that based on the increase in viscosity, the hydration degree is higher as the powders with smaller particle sizes are more fully in contact with water. As the quantity of the powders added is increased, AV also increases; thus, the friction and structural bearing capacity between coal particles and clay particles increases to enhance the AV and PV of the drilling fluid. As the solid phase in the drilling fluid, fine coal particles account for a large proportion in the mud cake. The coal powders with strong hydrophobicity embedded in the mud cake form a dense mesh chain

Table 1. X-powder diffraction analysis results of three samples.

| Sample  | Iliite | Chlorite | Dickite | Feldspar | Kaolinite | Quartz | Calcite | Dolomite | Amorphous |
|---------|--------|----------|---------|----------|-----------|--------|---------|----------|-----------|
| Lignite | 5      |          | 23      | 32       | 1         |        |         |          | 39        |
| Anthracite | 3      | 8        |         | 3        | 10        | 76     |         |          |           |
| Shale   | 15     | 11       | 6       | 60       | 5         | 3      |         |          |           |

Table 2. Industrial analysis statistics of two kinds of coal samples.

| Sample  | Proximate analysis (%) | Ultimate analysis (%) |
|---------|------------------------|-----------------------|
|         | Moisture | Ash | Volatile | Fixed carbon | Carbon | Hydrogen | Nitrogen | Oxygen and sulfur |
| Lignite | 17       | 15  | 46       | 22           | 70.2   | 5.2      | 1.8      | 22.8       |
| Anthracite | 2        | 8   | 5        | 85           | 91.1   | 3.5      | 1.3      | 4.1        |
structure, thereby marginally reducing filtration (Figure 5). At the same particle size, the AV of lignite increases the most because lignite is rich in clay minerals, which contacts with the water in the drilling fluid, and expands, thereby increasing the viscosity. The clay mineral content of the Longmaxi shale sample is medium, and its viscosity increases moderately. The content of clay minerals in anthracite is very low, and the clay minerals in contact with the

**Table 3.** Rheological properties and filtration loss with different mass fractions of powders.

| Sample                          | Powders size (mesh) | Mass fraction (%) | AV (mPa·s) | PV (mPa·s) | YP (Pa) | FL (mL) |
|---------------------------------|---------------------|-------------------|------------|------------|---------|--------|
| Base fluid                      | /                   | 0                 | 46.5       | 27         | 19.5    | 10.9   |
| Base fluid + lignite powders    | 60–100              | 0.5               | 49         | 30         | 19      | 9.3    |
|                                 |                     | 1.5               | 49.7       | 29         | 20.5    | 9.1    |
|                                 |                     | 3                 | 50         | 28         | 22      | 9.0    |
|                                 | >100                | 0.5               | 49.5       | 29         | 20.5    | 9.2    |
|                                 |                     | 1.5               | 50.5       | 29         | 21.5    | 9.0    |
|                                 |                     | 3                 | 51         | 28         | 23      | 8.8    |
| Base fluid + anthracite powders | 60–100              | 0.5               | 47.5       | 30         | 17.5    | 9.6    |
|                                 |                     | 1.5               | 47.8       | 29         | 19      | 9.3    |
|                                 |                     | 3                 | 48.5       | 28         | 20.5    | 9.2    |
|                                 | >100                | 0.5               | 48         | 29         | 19      | 9.4    |
|                                 |                     | 1.5               | 48.7       | 29         | 20      | 9.3    |
|                                 |                     | 3                 | 49.5       | 28         | 21.5    | 9.2    |
| Base fluid + shale powder       | 60–100              | 0.5               | 48         | 30         | 18      | 9.4    |
|                                 |                     | 1.5               | 48.5       | 29         | 19.5    | 9.2    |
|                                 |                     | 3                 | 49         | 28         | 21      | 9.1    |
|                                 | >100                | 0.5               | 48.5       | 29         | 19.5    | 9.3    |
|                                 |                     | 1.5               | 49.5       | 29         | 20.5    | 9.1    |
|                                 |                     | 3                 | 50         | 28         | 22      | 9.0    |

Note: AV is the apparent viscosity; PV is the plastic viscosity; YP is the yield point; FL is the 30-min-filtration loss at 0.69 MPa.

**Figure 4.** Characteristics of apparent viscosity change caused by different amounts and powder sizes: (a) 60–100 mesh powders and (b) over 100 mesh powders.
water in the drilling fluid expand less, thereby lessening the rate of viscosity increase. From Figure 5, it is evident that as the anthracite coal powders at 3 wt.% compared to 1.5 wt.% over the 100 mesh are added to the drilling fluid, coal powder particles in the mud cake increase and the arrangement is more compact; thus, the filtration rate is low.

**Lubricity and adhesiveness**

It is evident from Table 4 and Figure 6 that after adding coal powders and shale powders into the base fluid, as the powder content increases, the lubrication coefficient increases and the lubricity decreases; however, the adhesion coefficient of the mud increases. When more powders are mixed into the fluid, the fluid becomes more viscous, further reducing the lubricity, and increasing the lubrication coefficient. After the mass fraction reaches a certain value, even if the mass fraction is increased further, its influence on lubricity is relatively weakened. It is shown that with the increase in the amount of powders added, the density of the drilling fluid increases, and the added particles deposit easily in the mud cake; the latter becomes thicker and its toughness deteriorates. This is because lignite and shale are mainly clay minerals, which affect the viscosity of drilling fluids and other parameters.

**Natural degradation**

It is observable from Figure 7(a) and (b) that under normal temperature and pressure conditions, the degradation of the drilling fluid after adding several kinds of powders is consistent on the whole, that is, with the extension of time, the apparent viscosity of the drilling fluid declines at a speed which is faster in the early stages and slower in the later stages. The viscosity of the water-based polymer drilling fluid is relatively high initially, and under the action of microorganisms, the polymer is broken and degraded, while the structure collapses and the microorganism rapidly propagates, thereby producing numerous metabolites that have an evident effect on the viscosity of the polymer solution, which decreases the viscosity, and with time extension, the remaining unbroken chains become less, and the rate of viscosity decrease decelerates. In addition, the gel breaking rate of the
base fluid is the largest, and the addition of three types of powders delays the degradation. Moreover, the influence of different types of powders on the natural degradation of the drilling fluid is different; lignite increases the most, followed by shale, and anthracite has the least impact on the degradation of the drilling fluid. This result may be due to the interaction environment between the matter and microorganisms in the rock.

**Contact angle test**

The contact angle is the angle of the solid rock–liquid–air three phase interface; it is difficult to control the time when the droplet contacts the sample surface during each measurement, and the sample surface cannot be absolutely the same flatness; thus, it is necessary to measure the influence of the drilling fluid on the wettability of the sample surface through statistical data many times. Figure 8 shows the statistical data of the contact angle of different rock sample surfaces with distilled water, base fluid, and drilling fluid mixed with corresponding powders. Figure 9 shows the typical contact angle measurement photos.

It is evident from the contact angle data in Figures 8 and 9 that in the contact angle test of the same rock sample surface with water, base fluid, and drilling fluid added with corresponding rock powders, the drilling fluid added with rock powders has the largest contact angle, while distilled water has the smallest, and the base fluid is in the middle. For the same liquid medium, the contact angle of anthracite is the largest, that of shale is the smallest, and that of lignite is in the middle. This shows that the contact angle increases and the
wettability of the surface of the coal block decreases when the powders are mixed into the drilling fluid. Compared with anthracite, lignite has a higher ash content. The ash content in coal mainly depends on the original mineral composition, which is mainly kaolinite, illite, and montmorillonite with strong ion exchange capacity and certain hydrophilicity. Therefore, when the ash content in coal is large, the wettability of coal to water is relatively strong; thus, the contact angle of anthracite exceeds that of lignite. Shale has the highest mineral content, among which quartz has the highest proportion, and quartz has strong hydrophilicity; hence, the contact angle is smaller than that of the two kinds of coal.

Figure 6. Variation characteristics of lubrication coefficient, adhesion coefficient, and surface tension of the drilling fluid after adding different types of powders.
Figure 7. Change of (a) apparent viscosity and (b) gel breaking rate of drilling fluid with time after mixing several powders.

Figure 8. Contact angle between different rock samples and drilling fluid: (a) lignite, (b) anthracite, and (c) shale.
Wellbore stability evaluation

Coal reservoirs have developed cleat, with features, including low porosity, low permeability, large surface area, and low mechanical strength (Purl et al., 1991). When a large number of fractures and other discontinuities develop in the reservoir, the discontinuities with different sizes and distributions are the main factors that affect the stability of the borehole wall (Figure 10). When the filtrate of drilling fluid enters the formation along the microfracture, it has two effects: ① Increase the pore pressure of the fracture surface; ② Lubricate the borehole surface, resulting in the pressure transmitted to the fracture tip. These two aspects promote the expansion of the original cracks and the propagation fractures of the surrounding rock. When the failure depth reaches a certain degree, the borehole collapses. The fracture propagation is the result of the comprehensive influence of geostress, fluid pressure between fractures, drilling fluid wettability, fracture toughness, and fracture geometry (Lu et al., 2012; Luo et al., 2020; Ma and Chen, 2015; Oleas et al., 2008). Figure 11 presents the schematic diagram of the drilling fluid passing through the fracture.

Capillary force in the fracture is:

\[ F = \frac{2r\cos\theta}{w} \] (4)
When using a water-based drilling fluid, the stress intensity factor around the wellbore is (Lu et al., 2012):

\[
K_I = \frac{-\sigma\sqrt{\pi H}}{\pi} + \frac{2P_f}{\pi H} \arcsin \frac{l}{H} + \frac{2r \cos \theta \cos \theta}{\sqrt{H - l}} \sqrt{H + l}
\]  

(5)

In Figure 11, as well as equations (4) and (5), \( K_I \) is the stress intensity factor, MPa·m\(^{0.5} \); \( \sigma \) is the minimum horizontal geostress, MPa; \( P_f \) is formation fluid pressure, MPa; \( F \) is the capillary force in the fractures, MPa; \( \theta \) is the contact angle, \(^{\circ} \); \( H \) is the half fracture height, m; \( l \) is the distance between the center of fracture and the front edge of drilling fluid in fractures, m; \( r \) is the liquid surface tension, N/m; and \( w \) is the fracture width, m.

The above-stated equation (5) is used to judge the expansion ability of the surrounding rock fracture and evaluate the borehole stability of the coal reservoir under different drilling fluids. Taking well X-2 in the Qinshui Basin as an example (Figure 10), the depth is 500 m, the minimum horizontal stress (\( \sigma \)) is 10 MPa, and the formation fluid pressure (\( P_f \)) is 5 MPa. Assume that the small fracture height (\( H \)) is 0.01 m, \( l \) is 0.005 m, and \( w \) is 0.0002 m.
The influence of the wetting characteristics (surface tension, contact angle) of the drilling fluid on the stability of the surrounding rock is analyzed.

When the surface tension of the drilling fluid is chosen as 30 mN/m, 50 mN/m, and 70 mN/m, a set of values is calculated by changing the degree of the contact angle, as shown in Figure 12(a). When the contact angle is 90°, the stress intensity factor is the smallest, and when the contact angle is approximately 0° and 180°, the stress intensity factor increases greatly.

When the contact angle is 60°, 70°, and 80°, by changing the surface tension, the corresponding change in stress intensity factor is obtained, as shown in Figure 12(b). It is evident that at certain contact angles, the stress intensity factor increases with the surface tension.

According to the contact angle and surface tension data of anthracite in the Qinshui Basin in this work, the stress intensity factors are obtained, as shown in Table 5.

From the calculation presented above in Figure 12 and Table 5, we can determine that to duly ensure the safety of the wellbore of the CBM, it is necessary to maximally reduce the stress intensity factor of the fractures around the wellbore as much as possible to guarantee safety.

1. When the contact angle is controlled at 105° > θ > 75° is neutral wetting, the stress intensity factor is small and the fractures do not expand easily.
2. With a constant contact angle, the smaller the surface tension, the lower the stress intensity factor, and the fractures do not expand easily, which ensures the safety of CBM well drilling.

3. For the coal powders mixed in the drilling fluid, based on borehole stability, firstly, because of the decrease in the capillary force, the stress intensity factor decreases. Secondly, the powders can enter into the micro-fractures, thereby reducing filtration loss and effectively sealing the micro-fractures. Lastly, the powder can enter into the micro-fractures, which can also support the micro-fractures longitudinally and strengthen stability.

According to the above-mentioned research, conventional drilling cuttings pollute the drilling fluid to a certain extent, which is unfavorable to safe drilling and needs to be addressed in a timely manner. It is discovered that the coal powder can make the wellbore more stable when appropriate particle sizes and concentrations are used.

Conclusions

1. When coal powders are mixed into a water-based polymer drilling fluid, the performance of the drilling fluid changes, although most of the indexes change minimally. For anthracite powders with less influence, the $AV$ of the drilling fluid increases slightly from 46.5–49.5 mPa·s, the filtration decreases from 10.9–9.2 mL, and the lubrication coefficient and adhesion coefficient increase from 0.28–0.35 and 0.1268–0.1944, respectively. To a certain extent, it increases the friction among the drilling fluid, the wellbore, and the cuttings, and reduces the drilling efficiency. In addition, the natural degradation is slower than that of the base fluid. The contact angle increases from 59–75°, while the surface tension increases from 51.2–58.5 mN/m. Based on reservoir protection, a single test result of drilling fluid performance cannot produce uniform results. In general, the performance of these changes needs to be comprehensively considered. When drilling along the coal seam, the key performance of the drilling fluid that is most likely to affect the smooth drilling process can be decided according to the actual conditions, such that the drilling fluid performance or drilling parameters can be adjusted in time.

2. The type, particle size, and concentration of coal powders have different effects on the performance of the drilling fluid, and the particle size of coal powders has a negative correlation with the apparent viscosity, lubrication coefficient, and adhesion coefficient of the drilling fluid, as well as a positive correlation with filtration loss. The effect of the amount and size of coal powders on these drilling fluid properties is opposite. The formation rock composition has apparent control effects on the performance of the drilling fluid. Herein, compared with lignite in the Erlian Basin and Chongqing shale, anthracite powders with the lowest mineral content in the Qinshui Basin exhibit the smallest change in the rheological property, lubricity, adhesion, and natural degradation of the drilling fluid.

3. Through the comprehensive evaluation of wellbore stability by the stress intensity factor, it is discovered that the closer the drilling fluid is to neutral wetting, the smaller the surface tension and the stress intensity factor. Especially, taking the X-2 well as an example, the stress intensity factor of the drilling fluid with 3 wt.% anthracite powders with particle sizes greater than 100 mesh is $8 \text{ MPa-m}^{0.5}$. Consequently, the fracture does not expand easily, which can ensure the safety of CBM well drilling. In addition, the comprehensive effect of coal powders, which includes reducing filtration loss, as well as
sealing and supporting microfractures, promotes wellbore stability. Hence, coal powders with suitable particle sizes and concentration levels are expected to become a new drilling fluid material to protect the reservoir under specific coal seam conditions.

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