Engineering properties of ceramsite proppant and its application on hydraulic fracture for a coalbed methane well
Mingjun Zou1, Miao Zhang2, Jiaqi Wu3, Yuanzheng Liu1

1. College of Geosciences and Engineering, North China University of Water Resources and Electric Power, Zhengzhou, 450045, China
2. Henan Province Research Institute of Coal Geological Prospecting, Zhengzhou 450052, China

Abstract: Ceramsite is a porous engineering material with some basic mineral constituents, and has advantages of low density, high sphericity and high flow conductivity. It should be a good attempt to be adopted in hydraulic fracture, but related researches are really weak. In this paper, laboratory experiments are conducted on ceramsite, coated ceramsite and other typical proppants, which indicates that the coated ceramsite is the best proppant. Then, a coalbed methane well located in the soft coal area in Qinshui basin of China is selected as the research object, numerical simulations and statistic analyses are both conducted to obtain the granularity proportion and parameter optimization by using coated ceramsite. Some findings are achieved. Numerical simulation indicates that the granularity proportion for coated ceramsites of 40/60, 16/40 and 12/20 mesh should choose 1:6:2, which can receive a biggest proppant concentration and strongest flow conductivity. Construction parameters are all optimized for a best fracture performance. Micro seismic monitoring indicates that the actual fracture performance matches well with the simulated result. Drainage performance comparisons reveal that coated ceramsite is suitable for soft coal areas, and can achieve good drainage performances.

Key words: Ceramsite; hydraulic fracture; granularity proportion; flow conductivity; coalbed methane

1 Introduction

Reservoir reconstruction is essential before coalbed methane (CBM) draining (Gale et al. 2007). As one of the effective reservoir reconstructions, hydraulic fracture technology can stimulate the reservoir, propagate the proppant to the region far away, and support the cleat effectively (Akulich 2008; Chuprakov et al. 2011), which has been carried out extensively (Potluri et al. 2005; Li et al. 2018). Statistical analyses for fourteen thousand wells with commercial productions in the world show that more than 90 % wells have carried out hydraulic fracture technology (Ye 2006).

Numerical simulation has been adopted in hydraulic fracture extensively to predict fracture performances and adjust construction parameters. Mendelssohn (1984) reviewed both coupled fluid/solid three-dimensional fracture models in linear elastic fracture mechanics applicable to the growth of fractures. Lee et al. (1994) reformulated a three-dimensional hydraulic fracture simulator by using the finite element methodology and a newly adapted fixed grid. Adachi and Detournay (2008) described the solution of the plane strain problem of a hydraulic fracture propagating in a permeable, linear elastic medium. Zhang et al. (2012) established a 3D non-linear fluid-solid coupling model for horizontal fracture of vertical well with the ABAQUS code. Settgast et al. (2012) described the development of a computational capability focused on the creation, characterization, maintenance, and active management of optimal fracture networks for energy extraction from enhanced geothermal systems. Nagel et al. (2013) performed numerical simulations by using continuum and discrete element modeling approaches in both mechanical-only and fully coupled, hydro-mechanical modes. Morgan and Aral (2015) built a hydraulic fracturing model by using the discontinuous deformation analysis. Profit et al. (2016) proposed a novel numerical approach to predict the propagation of hydraulic fractures in tight shale reservoirs. Li et al. (2018) proposed a numerical method with digital-image-based technique for hydro-fracture simulation, and investigated effects of brittleness on hydraulic fractures in shale.

1 Corresponding authors: E-mail: zoumingjun2008@163.com (M. Zou), wujwangyi@163.com (J. Wu).
All those works indicate that numerical simulation is convenient and effective to obtain performances of hydraulic fracture in both conventional and unconventional reservoirs (Wang et al. 2017). Meanwhile, some field and laboratory experiments are also conducted to investigate fracture performance, such as CT scanning technology (Jia et al. 2013; Ma and Chen 2014; Zou et al. 2016), scanning electron microscope technology (Hu et al. 2015), seismic monitoring (Sleefe et al. 1995; Li et al. 1998), tiltmeter technology (Olson et al. 1997), and others (Teufel and Clark 1984; Van Den Hoek et al. 1993; Fan and Zhang 2014; Lin et al. 2017).

Above researches mainly focus on models or reservoirs of hydraulic fracture, while the proppant types are rarely taken into consideration. Quartz sand is always selected as a conventional proppant during hydraulic fracturing, and has been studied extensively on migration mechanism, fracture performance and others (Ruggieri and Gianelli 1999; Gilabert et al. 2012; Ding et al. 2013; Esswein et al. 2013). However, some CBM exploitation practices indicate that quartz sand has some disadvantages, such as low sphericity, high density, low compressive strength, all which may reduce both migration ability and flow conductivity, and may be not efficient in some areas, especially in those soft coal areas (Bowker 2003).

Ceramsite is an inert, heat-resistant, porous material that is made via the calcination of carbonaceous claystone in an oxidizing environment, with basic mineral constituents of mullite, hematite, quartz, and kaolinite (Hartman et al. 2007). It has many advantages of low density, high sphericity, high flow conductivity and others (Zhang and Zhou 2000), and has been applied in many areas of construction profession and chemical industry (He and Wang 2011; Hou and Tian 2013). Meanwhile, ceramsite can be coated over the surface by using resins, to obtain a lower density and higher compressive strength, which is called coated ceramsite. Although coated ceramsite should be very efficient in hydraulic fracture, especially for those soft coal areas, limited literatures can be found.

In this paper, coated ceramsite is selected as the fracture proppant, and a typical CBM well located in the soft coal area in Gaohe block of Qinshui basin of China is chosen as the target. Numerical simulation is performed to obtain migration regularity and granularity proportion of coated ceramsite, and construction parameters are calculated and optimized, all which can guide the hydraulic fracture in the future.

2 Engineering properties of proppants

Ceramsite, coated ceramsite and other conventional materials of quartz sand and walnut shell with different meshes are all prepared for laboratory experiments.

2.1 Sphericity

Sphericity can be measured as follows. Firstly, particles are picked partly and randomly from samples, lay in a single layer, and then taped. Secondly, the scanning electron microscope is used to observe the particles on the tape and magnified images are then captured. Finally, magnified images are used to compare with the standard charts, and the sample sphericity is determined.

| Table 1 Engineering properties of quartz sand, walnut shell, ceramsite and coated ceramsite |
|---------------------------------|-------|--------|--------|--------|--------|--------|--------|--------|
| Type                            | Walnut shell | Quartz sand | Ceramsite | Coated ceramsite |
| Mesh   | 16/40 | 12/20 | 16/40 | 40/60 | 16/40 | 40/60 | 12/20 | 16/40 | 40/60 |
| Sphericity | 0.5 | 0.7 | 0.7 | 0.7 | 0.9 | 0.9 | 0.8 | 0.8 | 0.8 |
| Acid solubility/ %              | 5.5 | 4.0 | 5.0 | 5.3 | 3.7 | 5.1 | 5.3 | 5.2 | 5.1 |
| Turbidity/ mg/L                 | 10.0 | 55.0 | 50.0 | 56.0 | 49.0 | 55.0 | 42.5 | 45.6 | 46.9 |
| Particle density/ g/cm³         | 1.2 | 2.6 | 2.6 | 2.7 | 2.6 | 2.6 | 1.9 | 1.9 | 2.0 |
| Bulk density/ g/cm³            | 0.7 | 1.6 | 1.6 | 1.6 | 1.5 | 1.5 | 1.1 | 1.1 | 1.1 |
| Compressive strength/ %         | 0.5 | 12.0 | 12.0 | 11.0 | 3.0 | 2.3 | 19.4 | 10.1 | 8.3 |

Sphericity for different proppants is listed in Table 1. To increase flow conductivity, sphericity should be close to 1. As shown in Table 1, the sphericity of ceramsite and coated ceramsite is 0.9 and 0.8, respectively, which is much higher than that of quartz sand or walnut shell.
2.2 Acid solubility and turbidity

Acid solubility is the ratio of dissolved weight to total weight, which is used to examine contents of carbonate, feldspar, iron oxide and clay. Turbidity is tested by shaking a given volumetric proppant in the specified volumetric distilled water, and is used to test contents of dust, mud or inorganic matter over the surface. Results of acid solubility and turbidity for four proppants are listed in Table 1. It shows that the two parameters for ceramsite or coated ceramsite are both lower than those for walnut shell or quartz sand.

2.3 Bulk density and particle density

Bulk density is the ratio of proppant weight to total volume, and particle density is the ratio of proppant weight to particle volume. Densities for four proppants are listed in Table 1. To be pumped easily, a low density is needed. It shows that the bulk or particle density of walnut shell is the lowest, and that of quartz sand is the highest.

2.4 Compressive strength

Compressive strength is the ability to prevent damage during hydraulic fracturing. It is tested by using a given volumetric proppant under a certain pressure (22 MPa is adopted in this study), and higher values can help to receive bigger fracture widths. Results for four proppants are listed in Table 1. As can be seen, the value of coated ceramsite is the highest, while the value of walnut shell is the lowest.

![Fig. 1 Flow conductivities with different meshes under two flow rates for ceramsite (left) and coated ceramsite (right)](image)

2.5 Flow conductivity

Flow conductivity is the product of permeability and fracture width. Flow conductivity experiments for four proppants with different meshes under two flow rates of 10 and 5 ml/min are conducted, and data of elapsed time, inlet temperature, outlet temperature, inlet pressure, outlet pressure, closure pressure and flow conductivity are all recorded. Then, important relationships between closure pressure and flow conductivity are thereby plotted as shown in Figs. 1 and 2.
Flow conductivity comparisons for different proppants with same mesh are conducted. Take 16/40 mesh under the flow rate of 10 ml/min as an example, the flow conductivity of walnut shell varies from 96.2 to 123.6 $\eta m^2$•cm, that of quartz sand is from 174.4 to 231.9 $\eta m^2$•cm, that of ceramsite is between 208.7 and 322.3 $\eta m^2$•cm, and that of coated ceramsite is from 91.3 to 569.2 $\eta m^2$•cm. It indicates that the flow conductivity of coated ceramsite is the highest, and the value of ceramsite is higher than that of quartz sand or walnut shell.

2.6 Comparison

Engineering properties of quartz sand, walnut shell, ceramsite and coated ceramsite with 16/40 mesh are selected to compare in Table 2. It shows that the ceramsite or coated ceramsite are generally better than quartz sand or walnut shell, while the coated ceramsite is much better than ceramsite. As a result, coated ceramsite can be used in hydraulic fracture.

Table 2 Comparisons for engineering properties of quartz sand, walnut shell, ceramsite and coated ceramsite with 16/40 mesh

| Property           | Walnut shell | Quartz sand | Ceramsite | Coated ceramsite | Comparison                                      |
|--------------------|--------------|-------------|-----------|------------------|------------------------------------------------|
| Sphericity         | 0.5          | 0.7         | 0.9       | 0.8              | Ceramsite is the best; coated ceramsite is better|
| Acid solubility/ % | 5.5          | 5.0         | 3.7       | 5.2              |                                                 |
| Turbidity/ mg/L    | 10.0         | 50.0        | 49.0      | 45.6             | Walnut shell is the best; coated ceramsite is better|
| Bulk density/ g/cm³| 0.7          | 1.6         | 1.5       | 1.1              |                                                 |
| Particle density/ g/cm³ | 1.2   | 2.6         | 2.6       | 1.9              |                                                 |
| Compressive strength/ % | 0.5 | 12.0        | 3.0       | 10.1             | Walnut shell is the best; ceramsite is better   |
| Flow conductivity/  | 96.2/123.6   | 174.4/231.9 | 208.7/322.3| 91.3/569.2       | Coated ceramsite is the best                    |
3 Case study

3.1 Geological setting

Gaohe block in Qinshui basin of China is selected as the research area, which is a typical and soft coal area with low permeability, and the practice indicates that the conventional hydraulic fracture by using quartz sand cannot receive good fracture and drainage performances (Zhang et al. 2015). A CBM well named well QS01 located in the block is chosen as the target well. Modified from Wei et al (2007), the well location and structural framework of the research area are shown in Fig. 3.

![Fig. 3 Well location and structural framework](image)

Stratum trend in the research area is mainly SN-NNE. Coal seam No.3 is the reservoir pending hydraulic fracture in this case, and it occurs in the lower part of the Shanxi formation. It is laterally stable and ranges in a thickness from 5.1 to 7.2 m, with an average of 6.0 m. The net coal thickness increases from 4.8 to 7.2 m. There are 1~3 layers of carbonaceous mudstone and mudstone within the coal bed. The roof is main mudstone or silty mudstone, while fine or medium-grain sandstone is found occasionally. The floor
rock is main siltstone or mudstone.

Well QS01 in the research area is between cities of Changzhi and Zhangzhi, as shown in Fig. 3. By using well drilling, some parameters are obtained. The depth range is from 527.8 to 534.8 m. The thickness, maximum well deflection and hole enlargement ratio are 7.0 m, 1.6° and 90 %, respectively. After drilling, well cementation is finished by using casing pipe, and data are shown in Table 3.

| Parameter       | External diameter /mm | Thickness /mm | Internal diameter /mm | Steel grade | Landing depth /m | Cementing quality |
|-----------------|-----------------------|---------------|-----------------------|-------------|------------------|-------------------|
| Surface casing  | 244.5                 | 8.9           | 226.6                 | J55         | 172.8            | Qualified         |
| Production casing| 139.7                 | 7.7           | 124.3                 | N80         | 590.6            | Qualified         |

After well cementation, well testing is conducted to check buried depth, locations of roof and floor, coal seam thickness and porosity, etc. Then, perforation is finished by using 102 gun and 127 bullet, with a hole count of 16 m. Combined with some field and laboratory experiments, main reservoir parameters of coal seam No.3 and roof/floor in the research area are listed in Table 4.

| Parameters                                      | Value   | Parameters                                      | Value   |
|------------------------------------------------|---------|------------------------------------------------|---------|
| Reservoir type                                 | CBM     | Fluid viscosity/ mPa-s                          | 0.8     |
| Buried depth/m                                 | 527.8-534.8 | Fluid compressibility/ MPa⁻¹                   | 4.4E-04 |
| Roof type                                      | Mudstone| Overall filtration/ 10⁻⁴m·min⁰.⁵                | 1.5     |
| Floor type                                     | Mudstone| Wall filtration/ 10⁻⁴m·min⁰.⁵                    | 5.4     |
| Poisson ratio of coal                          | 0.4     | Reservoir temperature/ °C                       | 24.2    |
| Poisson ratio of roof                          | 0.3     | Reservoir pressure/ MPa                        | 2.1     |
| Poisson ratio of floor                         | 0.3     | Burst pressure/ MPa                            | 29.3    |
| Elastic modulus of coal/ 10⁴MPa                | 0.2     | Porosity/ %                                    | 3.5     |
| Elastic modulus of floor/ 10⁴MPa               | 0.7     | Permeability/ mD                               | 0.2     |
| Elastic modulus of roof/ 10⁴MPa                | 0.7     |                                                |         |

3.2 Granularity proportion

FracproPT software is used to simulate fracture performances of well QS01 under different granularity proportions by using coated ceramsite. Three common proportions of 1:6:2, 1:1:1 and 3:1:2 for the ratio of respective coated ceramsites of 40/60, 16/40 and 12/20 mesh are designed according to the experience in the research area. Parameters used during simulations are listed in Table 4.

Simulated fracture performances under different proppant proportions are shown in Figs. 4-6. For three proportions, both fracture length and supported length vary quite small, with a maximum difference of about 2 m; both average concentration and flow conductivity vary obviously, with highest values generated by the proportion of 1:6:2. Therefore, the proportion of 1:6:2 can reach a best co-action for coated ceramsites of three meshes and a best fracture performance in the research area. As a result, the proportion of coated ceramsites of 40/60, 16/40 and 12/20 mesh should choose 1:6:2 during hydraulic fracturing.
Fig. 4 Simulation for fracture performance under the proportion of 1:1:1

Fracture length/ 211.6m  
Supported length/ 195.2m  
Average concentration/ 5.33kg/m²  
Dimensionless flow conductivity/ 2.279

Fig. 5 Simulation for fracture performance under the proportion of 1:6:2

Fracture length/ 210.8 m  
Supported length/ 196.3 m  
Average concentration/ 6.34kg/m²  
Dimensionless flow conductivity/ 2.558
3.3 Decisions for construction parameters

Construction parameters contain total proppant volume, each proppant volume, fracture fluid type, fluid injection rate, fluid injection volume, proppant concentration, etc. Before hydraulic fracturing, all these parameters should be optimized to receive a good fracture performance.

3.3.1 Total proppant volume

The proppant volume influences the supported fracture volume. If the proppant volume is too low, fractures cannot be supported well. If the proppant volume is too high, a large fluid injection rate and volume are needed, which may cause the fluid injected into the floor or roof and lead a failure hydraulic fracture. The proppant used in and around the research area is almost quartz sand, and the statistical analysis indicates that the optimal total sand volume is about 40 m³, which can obtain relatively good fracture and drainage performances (Liu et al. 2013).

Generally, the proppant volume is mainly influenced by the average radius of the proppant used in hydraulic fracture as expressed,

$$ Q = \frac{\pi}{6} r^3 (N_1 + N_2) \quad (1) $$

in which, $Q$ is the proppant volume; $r$ is the average radius of the proppant; $N_1$ is the number of the proppant in the direction of the minimum principal stress; $N_2$ is the number of the proppant in the direction of the maximum principal stress.

$N_1$ and $N_2$ in Eq. 1 can be expressed as follows,
\[
\begin{align*}
N_n &= \frac{\pi}{4} \left\lfloor \frac{W(x)}{r} \right\rfloor \cdot \left\lfloor \frac{1}{r} \right\rfloor \cdot \left\lfloor \frac{L_n}{r} \right\rfloor \cdot a \\
W(x) &= \frac{Q \cdot t_n (1 - C)}{0.6 \cdot a \cdot \left( \frac{GQ^3}{(1 - \nu)} \right)^{0.2} \cdot \mu \cdot H^4} t^{0.8}
\end{align*}
\]  

where, \[\left\lfloor \cdot \right\rfloor\] represents that the value in the bracket should be rounded up to the nearest integer; \(n\) means the directions of the principal stress; if \(n=1\), it represents the minimum principal stress; and if \(n=2\), it represents the maximum principal stress; \(a\) is the number of the fractures; \(H\) is the coal thickness; \(\nu\) is the Poisson's ratio; \(Q_n\) is the instantaneous volume in \(n\) direction; \(G\) is the shear modulus; \(t_n\) is the fracture time in \(n\) direction; \(C\) is the filtration coefficient; \(\mu\) is the viscosity of the fracture fluid; \(L_n\) is the fracture length in \(n\) direction.

Compared with coated ceramsite and quartz sand, their radii with the same granularity are same, and \(a\) depends on the fracture technology and has little relationship with the proppant type. Then, the following simplified relationship can be achieved in each direction,

\[
\frac{Q_c}{Q_q} \propto \frac{N_c}{N_q} \propto \frac{L_c}{L_q}
\]

(3)

where, \(Q_c\) is the proppant volume by using coated ceramsite; \(Q_q\) is the proppant volume by using quartz sand; \(N_c\) is the number of coated ceramsite; \(N_q\) is the number of quartz sand; \(L_c\) is the fracture length by using coated ceramsite; \(L_q\) is the fracture length by using quartz sand.

It can be seen from Eq. 3 that the proppant volume has a linear positive relationship with the fracture length. The simulated fracture length by using coated ceramide is about 211 m as shown in Fig. 5, and the fracture length by using conventional quartz sand in the place very close to well QS01 is about 133 m detected by micro seismic monitoring (Zhang et al. 2015). The ratio of 211 m and 133 m is about 1.59, and then the optimal total proppant volume with coated ceramide is about 63 m³ by using 40 m³ multiplied by 1.59.

### 3.3.2 Each proppant volume

As studied in Section 3.2, the optimal granularity proportion for three coated ceramites is 1:6:2. When the total proppant volume is 63 m³ as discussed above, the proppant volumes for coated ceramites of 40/60, 16/40 and 12/20 mesh are thereby 7, 42 and 14 m³, respectively. However, for those areas with soft coals (such as the research area), the proppant may be embedded into the coal matrix during hydraulic fracturing, then each proppant volume can be increased properly according to the fracture performance.

### 3.3.3 Fracture fluid type

Active water is used widely and frequently in hydraulic fracture and has lots of advantages of little damage, low price, wide supplement and mature technology (Zou et al. 2013). If some nitrogen is added into active water, the suspension property and proppant carrying capacity will be increased obviously, and a better fracturing performance will be obtained (Hou et al. 2017; Ranjith et al. 2018). As a result, active water with nitrogen is selected as the fracture fluid in the research area.

### 3.3.4 Fluid injection rate

Fluid injection rate influences the proppant carrying capacity and induced fracture geometry. Generally, a higher fluid injection rate may result in a bigger fracture volume and longer fracture length. However, the fluid may inject into the roof or floor if the fluid injection rate is too high, which reduces the construction efficiency.

According to the different stages in hydraulic fracturing, fracture fluid can be divided into ahead fluid,
carrier fluid and displacement fluid. Ahead fluid is the buffer fluid, and its function is to adjust absorptive capacity of the reservoir and increase injection efficiency of the fluid. Carrier fluid is used to carry proppant, and the displacement fluid can push proppant far away.

Data of monitored fracture lengths versus injection rates of ahead fluid, carrier fluid and displacement fluid in and around the research area are all collected and plotted from Liu et al (2013), as shown in Fig. 7a, 7b and 7c. Two obvious regions can be divided in each subfigure. In the upper region, fluid injection rates are relatively high and fracture lengths vary widely, which indicates that the fracture performance is not stable. In the lower region, fluid injection rates are low and fracture lengths vary narrowly, which indicates that the fracture performance is quite stable and good. Average fluid injection rate in the lower region in each subfigure is set as the optimized value. Then, 5.5, 6.0 and 4.5 m³/min are designed for injection rates of ahead fluid, carrier fluid and displacement fluid, respectively.

![Fig. 7 Relationships of fracture length versus injection rates of ahead fluid (a), carrier fluid (b) and displacement fluid (c) and fluid injection volume versus daily gas production (d)](image)

### 3.3.5 Total fluid injection volume

Actual daily gas productions and total fluid injection volumes in and around the research area are collected from Dai (2012) and plotted as shown in Fig. 7d. It shows that the scatter diagram can be divided into two regions. For the lower region, both the daily gas production and total fluid injection volume range widely, indicating that the fracture and drainage performances are neither stable nor good. While for the upper region, the daily gas production varies highly from 2000 to over 4000 m³, as the total fluid injection volume ranges narrowly from 420 to 580 m³, which indicates that the hydraulic fracture performs well. As a result, the total fluid injection volume is set as the average value of about 500 m³.

### 3.3.6 Fluid injection volume in each fracture stage

According to the experienced proportion of fluid injection volumes in different stages in the research area (Liu et al. 2013), fluid injection volumes of ahead fluid, carrier fluid and displacement fluid can be designed as 140, 350 and 10 m³, respectively, as an attempt.

### 3.3.7 Proppant concentration

Proppant concentration can be calculated as follows,
\[ r_c = \left( \frac{Q_c}{F_c} / c \right) \times 100\% \]  
\[(4)\]

in which, \( r_c \) is the proppant concentration by using coated ceramsite, \( \% \); \( Q_c \) is the total proppant volume by using coated ceramsite, \( m^3 \); \( F_c \) is the carrier fluid injection volume, \( m^3 \).

As studied before, the total proppant volume by using coated ceramsite is 63 \( m^3 \), and the carrier fluid injection volume is 350 \( m^3 \). Then, the proppant concentration by using coated ceramsite is calculated as 18 \%.

3.4 A summary for optimized construction parameters

As a summary, all optimized construction parameters are listed in Table 5, which will be set in hydraulic fracture in the later.

| Parameters                  | Value       | Parameters                  | Value               |
|-----------------------------|-------------|-----------------------------|---------------------|
| Injection rate              | 5.5\(m^3/min\) | Fracturing fluid type       | Active water with nitrogen |
| Carrier fluid               | 6.0\(m^3/min\) | Granularity proportion     | 1:6:2               |
| Displacement fluid          | 4.5\(m^3/min\) | Total proppant volume       | 63\(m^3\)          |
| Ahead fluid                 | 140\(m^3\)  | Each proppant volume        | 40/60 mesh          |
| Carrier fluid               | 350\(m^3\)  | 16/40 mesh                  | 42\(m^3\)          |
| Displacement fluid          | 10\(m^3\)   | 12/20 mesh                  | 14\(m^3\)          |
| Total fluid injection volume| 500\(m^3\)  | Proppant concentration      | 18\%               |

4 Evaluation for fracture performance

According to the optimized parameters in Section 3.4, hydraulic fracture is constructed. To evaluate the fracture performance, micro seismic monitoring and drainage performance comparison are both conducted.

Fig. 8 Micro seismic monitoring result (a: vertical view; b: lateral view)

4.1 Micro seismic monitoring

Results of micro seismic monitoring are shown in Fig. 8. Fig. 8a shows that the south side of the fracture length is about 200 m, which approaches with 211 m obtained by using numerical simulation in Fig.
5. Fig. 8b shows that the fracture fluid is mainly around the depth of about 530 m, which indicates that no proppant plug is occurred and little fracture fluid is injected into roof or floor.

### Fig. 9 Drainage curves for well QS01

#### 4.2 Drainage performance comparison

After hydraulic fracturing, well QS01 is drained, and the drainage curves are shown in Fig. 9, which shows that the daily gas production is about 830 m$^3$ at day 440. Althogh the daily gas production is not quite high, it still has a very obvious increase trend. For a comparison, drainage curves of another well QS02 near well QS01 fracutred by using quartz sand are also given in Fig. 10, which shows that the daily gas production is about 100 m$^3$ at day 440 and an obvious decrease trend can be recognized at the end of drainage. The comparison shows that the drainage performance of well QS01 is obviously higher than that of well QS02. Overall, drainage performance for the soft coal area is really not good by using quatz sand, however can be improved obviously by using a new proppant of coated ceramsite.

### Fig. 10 Drainage curves for well QS02

#### 5 Conclusion

Laboratory experiments are conducted on ceramsite, coated ceramsite and other typical proppants,
comparisons indicate that ceramsite or coated ceramsite is generally better than quartz sand or walnut shell, while coated ceramsite is much better than ceramsite. A CBM well located in the soft coal area of China is chosen as a case, and statistic analyses and numerical simulations are both conducted to obtain optimized parameters of hydraulic fracture. The following conclusions are achieved. The fracture fluid should use active water with nitrogen. Injection rates of ahead fluid, carrier fluid and displacement fluid should set as 5.5, 6.0, and 4.5 m³/min, respectively, and their injection volumes are 140, 350 and 10 m³, respectively, with a total fracture fluid volume of 500 m³. The optimal granularity proportion for coated ceramsites of 40/60, 16/40 and 12/20 mesh should select 1:6:2, which can receive a biggest proppant concentration and strongest flow conductivity. The optimal proppant volume by using coated ceramsite is about 63 m³, and the proppant volumes for coated ceramsites of 40/60, 16/40 and 12/20 mesh are 7, 42 and 14 m³, respectively. Average proppant concentration is designed as 18 %. Micro seismic monitoring shows that the maximum fracture length can reach about 200 m, which approximate to the simulation result of 211 m, indicating that the hydraulic fracture performs well. Comparisons for gas productions fractured by using coated ceramsite and quartz sand reveal that the coated ceramsite is much suitable for the soft coal areas, and can achieve a good drainage performance.

Acknowledgments
The authors wish to acknowledge financial supports of this study by the National Natural Science Foundation of China under Grant No. 41702168.

References
Adachi JI, Detournay E (2008) Plane strain propagation of a hydraulic fracture in a permeable rock. Eng Fract Mech 75(16): 4666-4694.
Akulich AV (2008) Numerical simulation of hydraulic fracture crack propagation. Mos U Mech Bull 63(1): 6-12.
Bowker KA (2003) Recent developments of the Barnett shale play, Fort Worth Basin. West Texas Geol Soc Bull 42(6): 1-11.
Chuprakov DA, Akulich AV, Siebrits E, Thiercelin M (2011) Hydraulic-fracture propagation in a naturally fractured reservoir. SPE Prod Oper 26(1): 88-97.
Dai L (2012) Study on hydraulic fracturing design of coalbed methane. Xi’an: Yangtze University. (In Chinese)
Ding W, Zhu D, Cai J, Gong M, Chen F (2013) Analysis of the developmental characteristics and major regulating factors of fractures in marine-continental transitional shale-gas reservoirs: A case study of the Carboniferous-Permian strata in the southeastern Ordos Basin, central China. Mar Petrol Geol 45: 121-133.
Esswein EJ, Breitenstein M, Snawder J, Kiefer M, Sieber WK (2013) Occupational exposures to respirable crystalline silica during hydraulic fracturing. J Occup Environ Hyg 10(7): 347-356.
Fan T, Zhang G (2014) Laboratory investigation of hydraulic fracture networks in formations with continuous orthogonal fractures. Energy 74: 164-173.
Gale JFW, Reed RM, Holder J (2007) Natural fractures in the Barnett shale and their importance for hydraulic fracture treatments. AAPG Bull 91(4): 603-622.
Gilbert FA, Bö MD, Cantavella V, Sánchez E (2012) Fracture patterns of quartz particles in glass feldspar matrix. Mater Lett 72: 148-152.
Hartman M, Trnka O, Pohofely M (2007) Minimum and terminal velocities in fluidization of particulate ceramsite at ambient and elevated temperature. Ind Eng Chem Res 46(22): 7260-7266.
He J, Wang Q (2011) Technology research on waterworks sludge for ceramsite. Advan Mater Res 383: 3352-3355.
Hou H, Tian L (2013) Experimental study on high strength composite ceramsite using fly ash and waste glass. Appl Mech Mater 357: 1337-1342.
Hou P, Gao F, Ju Y, Yang Y, Gao Y, Liu J (2017) Effect of water and nitrogen fracturing fluids on initiation
and extension of fracture in hydraulic fracturing of porous rock. J Nat Gas Sci Eng 45: 38-52.

Hu Y, Devecgowda D, Striolo A, Phan A, Ho TA, Civan F, Sigal R (2015) The dynamics of hydraulic fracture water confined in nano-pores in shale reservoirs. J Unconv Oil Gas Resour 9: 31-39.

Jia L, Chen M, Sun L, Sun Z, Zhang W, Zhu Q, Sun Z, Jin Y (2013) Experimental study on propagation of hydraulic fracture in volcanic rocks using industrial CT technology. Petrol Explor Dev 40(3): 405-408.

Lee TS, Advani SH, Pak CK (1994) Three-dimensional hydraulic fracture simulation using fixed grid finite element algorithms. ASME J Energy Res Technol 116(1): 2-9.

Li Y, Cheng CH, Toksöz MN (1998) Seismic monitoring of the growth of a hydraulic fracture zone at Fenton Hill, New Mexico. Geophysics 63(1): 120-131.

Li Z, Li L, Li M, Zhang L, Zhang Z, Huang B, Tang C (2018) A numerical investigation on the effects of rock brittleness on the hydraulic fractures in the shale reservoir. J Nat Gas Sci Eng 50: 22-32.

Lin C, He J, Li X, Wan X, Zheng B (2017) An experimental investigation into the effects of the anisotropy of shale on hydraulic fracture propagation. Rock Mech Rock Eng 50: 543-554.

Liu H, Sang S, Li M, Liu S, Xu H, Zhao Z, Xie Y (2013) Analysis on affecting factors and technique optimizing of fractured coalbed methane well. Coal Sci Technol 41(11): 98-102. (in Chinese with an English abstract)

Ma T, Chen P (2014) Study of meso-damage characteristics of shale hydration based on CT scanning technology. Petrol Explor Dev 41(2): 249-256.

Mendelsohn DA (1984) Review of hydraulic fracture modeling-part II: 3D modeling and vertical growth in layered rock. ASME J Energy Res Technol 106(4): 543-553.

Morgan WE, Aral MM (2015) An implicitly coupled hydro-geomechanical model for hydraulic fracture simulation with the discontinuous deformation analysis. Int J Rock Mech Min 73: 82-94.

Nagel NB, Sanchez-Nagel MA, Zhang F, Garcia X, Lee B (2013) Coupled numerical evaluations of the geomechanical interactions between a hydraulic fracture stimulation and a natural fracture system in shale formations. Rock Mech Rock Eng 46: 581-609.

Olson JE, Du Y, Du J (1997) Tiltmeter data inversion with continuous, non-uniform opening distributions: A new method for detecting hydraulic fracture geometry. Int J Rock Mech Min 34(3-4): 236.e1-236.e10.

Potluri NK, Zhu D, Hill A (2005) The effect of natural fractures on hydraulic fracture propagation. Paper SPE 94568, presented at SPE European Formation Damage Conference, Sheveningen, The Netherlands, 25-27 May.

Profit M, Dutko M, Yu J, Cole S, Angus D, Baird A (2016) Complementary hydro-mechanical coupled finite/discrete element and microseismic modelling to predict hydraulic fracture propagation in tight shale reservoirs. Comput Part Mech 3: 229-248.

Ranjith P, Wanniarchachi WAM, Perera MSA, Rathnaweera TD (2018) Investigation of the effect of foam flow rate on foam-based hydraulic fracturing of shale reservoir rocks with natural fractures: An experimental study. J Petrol Sci Eng 169: 518-531.

Ruggieri G, Gianelli G (1999) Multi-stage fluid circulation in a hydraulic fracture breccia of the Larderello geothermal field (Italy). J Volcanol Geoth Res 90(3-4): 241-261.

Settgas R, Johnson S, Fu P, Walsh SDC, Ryerson F (2012) Simulation of hydraulic fracture networks in three dimensions. Thirty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 30-February 1.

Sleeve GE, Warpinski NR, Engler BP (1995) The use of broadband microseisms for hydraulic fracture mapping. SPE Form Eval 10(4): 233-240.

Teufel LW, Clark JA (1984) Hydraulic fracture propagation in layered rock: experimental studies of fracture containment. Soc Petrol Eng J 21(4): 19-32.

Van Den Hoek PJ, Van Den Berg JTM, Shlyapbersky J (1993) Theoretical and experimental investigation of rock dilatancy near the tip of a propagating hydraulic fracture. Int J Rock Mech Min Geomech Abstr 30(7): 1261-1264.
Wang M, Feng YT, Wang CY (2017) Numerical investigation of initiation and propagation of hydraulic fracture using the coupled Bonded Particle-Lattice Boltzmann Method. Comput Struct 181: 32-40.

Wei C, Qin Y, Wang G, Fu X, Jiang B, Zhang Z (2007) Simulation study on evolution of coalbed methane reservoir in Qinshui basin, China. Int J Coal Geol 72: 53-69.

Ye J (2006) Advances in exploration and development of coalbed methane in China: A review. Geol Bull China 25(9): 1074-1078. (in Chinese with an English abstract)

Zhang J, Biao FJ, Zhang SC, Wang XX (2012) A numerical study on horizontal hydraulic fracture. J Petrol Explor Prod Technol 2: 7-13.

Zhang T, Song S, Liu C, Wang N (2015) Ground hydraulic fracture crack’s monitoring and identification methods in Gaohe mine. Coal Technol 34(04): 185-187. (in Chinese with an English abstract)

Zhang Y, Zhou Z (2000) Experimental study on the short term flow conductivity of the cracks filled with ceramsite fracturing proppant. J Xi’an Petrol Inst 15(5): 39-41. (in Chinese with an English abstract)

Zou M, Wei C, Fu X, Bao Y, Cai Z (2013) Investigating reservoir pressure transmission for three types of coalbed methane reservoirs in the Qinshui Basin in Shan’xi Province, China. Petrol Geosci 19: 375-383.

Zou Y, Zhang S, Zhou T, Zhou X, Guo T (2016) Experimental investigation into hydraulic fracture network propagation in gas shales using CT scanning technology. Rock Mech Rock Eng 49(1): 33-45.