A Review of Fundamental Research on Hydraulic Fracturing of Glutenite Reservoirs in China

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Abstract. There are abundant tight oil and gas resources in glutenite reservoirs in China, and hydraulic fracturing is essential for developing this kind of resources. At present, the basic scientific problems involved in hydraulic fracturing of glutenite reservoirs, including simulation of fracture propagation, proppant transport and fracture conductivity, are not systematically clarified yet. The deficiencies of existing research ideas and methods are summarized, then suggested solutions and development prospects are proposed. The analysis shows that for the fracture propagation experiment, the establishment of a scalable glutenite sample preparation method and the experimental parameter conversion method is an urgent problem to be solved. The particle flow code (PFC) method has advantages in simulating the fracture propagation in microscopic scale. However, the simulation of fracture propagation in oilfield scale faces the problem of cross-scale calculation, so establishing a fast and effective cross-scale simulation method is very important. For the proppant transport experiment, the key is to develop plates with unidirectional filtration and different roughness to simulate the hydraulic fracture surface of glutenite reservoirs. The CFD-DEM coupling method to simulate the proppant transport has a good prospect, but it is necessary to consider the special properties of the glutenite reservoirs, and improve the mathematical model and explore corresponding solution method. The key to the experimental research of the fracture conductivity is to make samples that meet the size and shape requirements. Downhole drilled core, man-made rock and 3D printing technique can be adopted for sample procession. For computer simulation of conductivity prediction, combining PFC with CFD method to predict the conductivity of glutenite is an important exploration direction in the future.

1. Introduction
As the exploitation of conventional oil-gas resources, it becomes increasingly difficult to exploit such reservoirs, and more and more attention has been paid to exploit unconventional resources[1]. In recent years, as a kind of unconventional resources, tight oil-gas has become a highlight area of global unconventional oil-gas exploration and development[2]. Glutenite is one of the important reservoirs bearing tight oil-gas resources. There are abundant tight glutenite oil-gas resources in China, which mainly distribute in the Mahu sag of Junggar basin, the Uriasti sag of Erlian basin and the Bohai Bay basin, etc (Table 1). It is reported in 2018 that the world's largest glutenite oil field had been discovered in Mahu sag, Xinjiang oilfield, where the reserve is proven to be 520 million tons. The mentioned oil
field will become one of important areas for increasing reserves and production of glutenite oil reservoirs in China\textsuperscript{[3]}. The glutenite reservoir generally has the characteristics of low porosity and low permeability\textsuperscript{[4]}. In order to realize its industrial exploitation, hydraulic fracturing must be carried out. In the process of sedimentation and diagenesis, the glutenite reservoir has formed clastic particles of different size distribution\textsuperscript{[5]}, which constitutes a rock structure composed of gravel-matrix-interface (figure 1) \textsuperscript{[6]}. Gravel is widely distributed, with different sizes and shapes. Gravel size is generally larger than 2mm and the maximum is more than 10 cm. The mineral composition and mechanical properties of the gravel are quite different from those of the matrix \textsuperscript{[7]}, which leads to the strong heterogeneity of the glutenite reservoir. In addition, the glutenite reservoir is generally buried deeper (generally more than 3000 meters). Also, the reservoir temperature is higher, and the gravel edge fracture and natural fracture may be more developed in glutenite, so the filtration in the process of glutenite fracturing is more serious\textsuperscript{[8]}. Therefore, compared with tight sandstone reservoirs, the special properties of glutenite reservoirs should be fully considered in hydraulic fracturing simulation research. This paper focuses on the basic research problems of fracture propagation, proppant transport, and fracture conductivity involved in hydraulic fracturing of glutenite, summarizes and analyzes the current research status and existing shortcomings, and puts forward the prospect of future research trends.

![Figure 1. Cast slice picture of glutenite from Mahu sag](image)

**Table 1. Characteristics of tight oil-gas bearing glutenite reservoirs in China**

| Basin               | Geotectonic element | Formation                  | Resource type | Sedimentation type | Depth/\text{m} | Lithology                                      | Gravel size range/\text{cm} | Porosity/\text{%}          | Permeability/\text{mD} |
|---------------------|---------------------|----------------------------|----------------|-------------------|----------------|-----------------------------------------------|-----------------------------|-------------------------|------------------------|
| Junggar basin \textsuperscript{[9]} | Mahu sag            | Barkouquan                 | Oil            | Fan delta         | >3000          | Microconglomerate, cobblestone               | 0.25\text{~}~4              | 1.17\text{~}~16.4       | 0.01\text{~}~337       |
| Bohai Bay basin \textsuperscript{[10]} | Southeast edge of qinnan sag | Shahejie (S-I, S-II) | Oil            | Fan delta         | >3000          | Conglomerate, conglomerate sandstone, pebbled sandstone | 1\text{~}~5                  | 0.45\text{~}~34.7       | 0.01\text{~}~767       |
| Bohai Bay basin \textsuperscript{[11]} | Yanjia region of Dongying Sag | Shahejie (S-IV) | Oil            | Nearshore subaqueous fan | >3000          | Cobblestone, microconglomerate, psephitic sandstone, pebbled sandstone | 5\text{~}~10                  | 2.6\text{~}~16.5        | 0.065\text{~}~278      |
| Erlian basin \textsuperscript{[12]} | Uriasi sag          | Tenggeer (T-I)             | Oil            | Fan delta         | >1500          | Conglomerate, glutenite, psephitic sandstone | 2\text{~}~6                   | 7.9\text{~}~12.9        | 1.71\text{~}~4.4       |
2. Fracture propagation simulation

One of the keys of hydraulic fracturing design is to simulate the fracture propagation process. Hydraulic fracture morphology is affected by reservoir parameters, rock mechanics properties, fracturing fluid properties and operation parameters. The study of fracture propagation is of great significance for revealing the fracturing mechanics mechanism of glutenite reservoir and optimizing the fracturing parameters.

2.1. Physical experiment

Physical experiment is to simulate hydraulic fracturing process by pumping fracturing fluid into simulated wellbore under triaxial confining pressure in lab, and to analyze fracture propagation by direct observation or by means of some devices (AE instrument, CT scanner, etc.)[15]. Meng et al. (2010)[16] firstly did the true triaxial test for the glutenite rock sample and found that gravel had a significant impact on the fracture propagation path. Guo et al. (2011) [17] carried out experiments on four kinds of glutenite cores, and found that cements and gravel edge fractures had obvious effects on fracture pressure. Wang (2011) [18] found through experiments that cracks easily propagated around gravel and generated fracture networks. Ma et al. (2016) [19] discovered through experimental research that the fracture will terminate, penetrate, deflect or attract when it encounters a gravel (figure 2), and the fracture propagation resistance in gravel is large and the fracture width is small. Liu et al. (2016) [20] conducted hydraulic fracturing experiments on transparent samples of 3D-printed glutenite rocks (figure 3). Based on the mechanical properties and distribution characteristics of gravels in underground glutenite reservoir, Liu et al. (2017) [21] prepared the rock samples to carried out the fracturing experiments, and they also analyzed the fracture complexity by means of CT scanning and fractal theory. According to previous studies, it is known that the hydraulic fractures of glutenite are characterized by non-planar extension and complex fracture network. The hydraulic fracture morphology is mainly affected by in-situ stress, reservoir heterogeneity and fracturing operation parameters. At present, due to the limitation of experimental instruments and materials, the parameters such as confining pressure and pumping displacement in lab can not reach the levels of site fracturing operation, and the size of simulated wellbore is much smaller than the field value. Therefore, the similarity criterion[22] should be fully taken into account in the design of experimental scheme, and the method of conversion of experimental parameters should be established in accordance with the engineering background. In the aspect of sample preparation, we should fully consider the lithological and mechanical characteristics of glutenite reservoir. By adjusting the parameters such as water-cement ratio, sand particle volume and cement setting time, we can make samples which are closed to the actual situation, and even can use 3D printing technology to make very realistic samples. In addition, the well completion conditions should also be fully considered in design of physical simulation experiments.
2.2 Computer simulation

The numerical simulation is an important method to study fracture propagation. The computational models mainly include 2D model, pseudo-3D model and fully-3D model. The traditional models of fracture propagation include PKN, CGD and Palmer model. In recent years, the reservoir properties and operation conditions of hydraulic fracturing are becoming increasingly complex, resulting in more complex fracture propagation paths during fracturing process. Some numerical methods have been put into applications, which mainly include the following 4 types: finite element method (FEM), extended finite element method (XFEM), discrete element method (DEM) and boundary element method (BEM). Among them, the XFEM and the DEM have advantages in solving the mechanical problems of heterogeneous materials, while the BEM is good at simulating fracture propagation on the oilfield scale. Displacement discontinuity method (DDM) is a kind of BEM, which has been widely used in the simulation of multi-cluster fracture propagation on the oilfield scale in shale gas fracturing.

Rock failure process analysis (RFPA) is a numerical simulation method based on the FEM and statistical damage theory, which can be used to simulate the failure process of heterogeneous materials. Some scholars used this method to study the fracture propagation of glutenite reservoir. For example, Wang (2011) based on RFPA research found that multi-branch fractures and fracture networks were produced in the glutenite fracturing, which was consistent with the results of physical simulation. Li et al. (2013) found that a hydraulic fracture encounter a gravel mainly have four propagation modes, which are consistent with the experimental results in reference [19]. Zhang (2016) inspected the influence of horizontal in-situ stress difference, gravel size, gravel content, gravel strength, distance between gravel and borehole, and well type on fracture propagation. Liu et al. (2018) found that for glutenite with strong brittleness and great difference in strength between gravel and...
matrix, the fracture should be extended around gravel as far as possible to promote fracture bifurcation and form complex fracture network. Some scholars have used other numerical methods to reveal the mechanism of fracture propagation of glutenite. For example, Zhao (2011)\textsuperscript{[31]} used plane stress analysis method and found that the extension pressure increases along with the increase of gravel particle size, and the extension pressure of circular gravel is higher than that of elliptical gravel. Luo et al. (2013)\textsuperscript{[32]} used the critical energy release rate as the judgment criterion of fracture propagation. As per his calculation, it is found that the gravel size, the gravel content and the fracture toughness difference between gravel and matrix play important roles in causing the irregularity in the fracture propagation and pressure fluctuation. Ju et al. (2016)\textsuperscript{[33]} established a 3D heterogeneous numerical model based on the reconstruction of CT scanning images of glutenite, and simulate the fracture propagation of glutenite using the continuum-discrete element method (CDEM) (figure 5). The simulation results were found in good agreement with the experimental results in reference [21]. Yu et al. (2016)\textsuperscript{[34]} took into consideration the damage mechanics, fracture mechanics and other theories, established a mathematical model of fracture propagation in glutenite coupling micro-damage method and FEM.

In summary, the methods that can be used to study the fracture propagation of glutenite on micro-scale mainly include RFPA and CDEM methods. However, the RFPA method has poor computational stability and does not allow to be redeveloped. In RFPA, the gravel particles are assumed to be circular. The reservoir model constructed is relatively simple and inconsistent with the actual situation. The CDEM method can be effectively used in combination with 3D heterogeneous model of glutenite, but this method has not yet been fully disclosed to the public. Researches indicate that the particle flow code (PFC)\textsuperscript{[35]} has the potential to simulate the fracture propagation of glutenite. The PFC method takes particles as the basic element and uses DEM to simulate the movement, deformation and failure of particles. Wang et al. (2014)\textsuperscript{[36]} used PFC to simulate fracture propagation in homogeneous reservoirs,
and analyzed the influence of micro-rock mechanics parameters on fracture pressure and fracture morphology. Wang et al. (2017)\cite{37} used PFC method to study the fracture propagation patterns under different distributions of coal cleats. They found that hydraulic fractures not only communicate cleats, but also produce a large area of rock failure in the nearby matrix (figure 6). For the simulation of fracture propagation in glutenite reservoir, the construction of reservoir rock model is very important. The idea of building asphalt mixture or concrete model based on PFC can be considered to apply to construct the glutenite reservoir rock model\cite{38} \cite{39} \cite{40}. Specifically, based on image processing technology, the geometric model of the specimen can be established, and then introduce it into the PFC to preliminarily establish the physical model of glutenite (figure 7). The established model can truly reflect the quantity, shape and size of the gravels. On this basis, the micro-mechanical parameters of the gravel and the matrix are assigned to characterize the macro-mechanical characteristics of the glutenite. After the above work, a realistic rock model of glutenite reservoir is created to simulate the fracture propagation.

The above methods investigate the influence of gravel on fracture propagation on micro-scale. However, if we want to realize the oilfield scale, we will face the bottleneck problem of huge number of grids and long computational time. The key problem is that the gravel scale generally must be maintained at millimeter scale, while the oilfield scale is generally meter scale. In other words, if the fracture propagation at tens or even hundreds of meters level is studied on micro-scale, the number of discrete grids will increase by tens of thousands of times. Therefore, the establishment of a fast and effective cross-scale simulation method is the way to solve this bottleneck problem mentioned above. Cross-scale calculation has been involved in the fields such as material mechanics\cite{41} \cite{42}, formation seepage mechanics\cite{43}, meteorological prediction\cite{44}, cell mechanics\cite{45}, heat and mass transfer\cite{46}. The effective connection of coupled regions of multi-scale models is the key to the effective transmission of physical information such as force, displacement, energy and material defects between continuum matrix and micro-scale regions. It is also one of the key problems to be solved in multi-scale analysis. The failure and evolution of materials and the propagation of fractures belong to field of fracture mechanics in essence. At present, the main cross-scale analysis methods include coarse grain molecular dynamics method, quasi-continuous medium method, bridge domain method and hybrid method\cite{47}. These methods require large amount of CPU time, and the computational scale can be as low as molecular and atomic level. However, the scale of gravel in this paper is millimeter level, and gravel particles are widely distributed. In this case, the computational time will greatly increase because the grid number will be added at the location of each gravel. Therefore, the above methods are not suitable for the simulation of fracture propagation of glutenite. Concrete is a three-phase composite material composed of mortar-aggregate-interface (figure 8). Its material structure is almost the same as that of glutenite reservoir. Both of them face the problem of cross-scale calculation. Sun\cite{48} developed multi-grid adaptive technology and automatic image recognition technology for damage area. On this basis, he proposed an efficient simulation method for structural failure caused by concrete damage trans-scale evolution, which provides a new idea for numerical simulation of cross-scale fracture propagation in glutenite reservoirs.

On the other hand, the DDM method is only applicable to homogeneous media and cannot establish gravel model. Although the hydraulic fractures of glutenite can be very rough under the influence of gravel particles, the deviation of fracture trajectory can be neglected on oilfield scale. However, the effect of rough fracture surface of glutenite on the fluid flow should be considered. By improving the conventional governing equations of hydrodynamics in the fracture, the pressure drop formula in rough fracture considering the influence of gravels can be established based on physical experiments and mathematic method. In addition, the calculating method\cite{49} of filtration coefficient of glutenite can be established with the consideration of the influence of gravel particles. Then in theory, the influence of gravel particles can be introduced into fracture propagation model based on DDM method, thus the cross-scale mathematical problem can be avoided and the fracture propagation simulation of glutenite on oilfield scale can be realized by using modified DDM.
3. Proppant transport simulation

The proppant transport in the fracture is particularly important. The shape of proppant profile directly determines the fracture conductivity and even affects the oil-gas production after hydraulic fracturing treatment. In the past decade, scholars have carried out a lot of research on the simulation of proppant transport.

3.1. Experimental simulation

At present, the device with two paralleled visualization plates is widely used for research of proppant transport simulation under different fracture structure, pumping displacement, fracturing fluid viscosity, proppant particle size, proppant concentration and proppant filling mode, so as to guide the optimization
of fracturing operation parameters. Based on research of literature, the proppant transport simulation device has experienced the development from concentric cylinder and small vertical fracture device to large-scale narrow-slot experimental device. In China, Wen et al. (2012) [49] firstly developed a visualized large-size proppant transport simulation device, but the fracture is flat and its shape cannot be changed. Jia (2013) [50] developed a large-scale visualized proppant transport device with 90-degree branching joints. Wen et al. (2016) [51] took into consideration the fracture width, temperature, fracturing fluid filtration, lithology and other factors, and developed a new proppant transport simulation device (figure 9). Li et al. (2017) [52] developed a device which can simulate the proppant transport in the main fracture and multi-angle secondary fractures (figure 10).

In glutenite reservoirs, firstly, fracturing fluid filtration is more serious, and its influence on the settlement and transport of proppant is so significant that it results in significant difference in proppant concentration between the front and tail of proppant profile in the fracture. However, at present, fracturing fluid filtration is simulated by drilling a certain number of filter holes on the glass plates of the simulation device [53], which is quite different with underground situation. In order to solve this problem, a plate with unidirectional permeability is considered in development to simulate the fracturing fluid leaking from fracture into the formation. Secondly, the roughness of the fracture surface of glutenite will increase the difficulties of proppant transport at the gravel edge. However, the current publicly reported proppant transport simulation device can not effectively consider the influence of gravel on proppant transport. Therefore, it is necessary to develop removable plates with different roughness to simulate highly rough fracture surfaces. Thirdly, the glutenite reservoir is deeply buried and has high closure pressure. The closure pressure has obvious influence on proppant transport. Under formation conditions, only when the fluid pressure in the fracture is greater than the closure pressure can the fracture be opened and provide a channel for proppant proppant. However, the fracture width is changed by adjusting the plates manually in the simulation device. As result, the fracture width is unchangeable during fracturing process, and the required fracturing discharge becomes significantly smaller. In order to solve this problem, it is necessary to develop a plate with high compressive capacity and adjustable fracture width to simulate proppant transport under different pumping displacement and net pressure conditions. Fourthly, researchers in the past found that complex fracture networks are easily induced in the near wellbore zone during the fracturing process. Therefore, it is worthwhile to study whether the proppant can get through the secondary fractures on different scales based on physical simulation results.

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1 large visualized flat panel, 2 liquid storage tank, 3 automatic sand filling device, 4 sand mixing tank, 5 U-shaped friction test pipeline, 6 Visual horizontal wellbore, 7 Visual vertical wellbore

Figure 9. 3D drawing of proppant transport simulation device [50]
3.2 Computer simulation

In essence, the proppant transport in fracture belongs to liquid-solid two-phase flow problem. The early mathematical model was mainly based on the settlement velocity formula under the equilibrium state of force and the relative velocity relationship between the liquid and solid phases to derive the movement of particles. It was difficult to effectively characterize the shape of the proppant profile\textsuperscript{[54]}. With the development of the computer technology, the computational fluid dynamics (CFD) method becomes a good tool for solving the law of liquid-solid two-phase flow problem considering fluid-solid coupling effect, making it possible to describe the proppant profile shape more accurately. Fluent is one of the CFD softwares\textsuperscript{[55]} and widely used to simulate proppant transport. In order to better describe the collision between proppant particles and to depict the mechanical behavior between the proppant particles and the fracture surface, computational fluid dynamics-discrete element method (CFD-DEM) coupling method has been used to numerically simulate the proppant transport (figure 11)\textsuperscript{[56]}, and can solve the trajectory of each proppant particle. The relevant softwares include PFC, open source program Liggghts-Openfoam and EDEM, etc.

In respect to the glutenite reservoirs, firstly, in the previous mathematical models, the rheological properties of fracturing fluid are difficult to be taken into account in the mathematical model, therefore unable to reflect the effect of proppant sedimentation and reservoir temperature on the dynamic filtration of fracturing fluid. Meanwhile the filtration loss of glutenite reservoirs is significantly serious, and the effective characterization of the fracturing fluid filtration in the flow process within the fracture becomes an urgent problem to be solved. Secondly, the fracture surface is currently regarded entirely smooth. There is no mathematical model of proppant transport which takes into consideration the effect of rough fracture surface. The complex mechanical behavior of proppant, fracturing fluid and rough fracture surface during proppant transport has not been effectively revealed.

The establishment of proppant transport model in glutenite reservoir remains still a challenging problem to solve. Thirdly, as in the experimental study, the current numerical simulation of proppant transport hardly takes into account the effect of fracture width. It assumes that the particles are laid on a single layer. In fact, during the fracturing process, the fracture width changes along the fracture length direction, and the proppant ratio also changes, leading to the variation in the number of proppant layers. Therefore, it is also worth of attention to understand the proppant distribution along the fracture width direction, which puts forward higher requirements for the construction of the mathematical model. Fourthly, the problem of numerical simulation of proppant transport in complex fracture network which contains a main fracture and many secondary fractures is still unsolved. Therefore, the simulation of proppant transport under complex fracture network of glutenite is also one of the important exploration directions in the future.

In a word, the proppant transport in glutenite is a complex scientific problem. It is of particular significance to accurately describe the mechanical behavior of particles and to characterize the trajectory of particles. In this sense, CFD-DEM numerical method will still be one of the important methods to study proppant transport in the future. However, considering the special reservoir properties of glutenite, it is necessary to improve the mathematical model and explore the solution searching method for the improved mathematical model.

![Figure 10. Device picture of proppant transport simulation under different secondary fracture angles\textsuperscript{[52]}](image-url)
Fracture conductivity refers to the ability of oil or gas to pass through the proppant pile under a closure pressure, which is numerically equal to the product of hydraulic fracture permeability and fracture width. The fracture conductivity is one of key factors to determine the oil-gas production.

4.1. Experimental simulation
Fracture conductivity is generally measured by fracture conductivity device (figure 12). The influence of the parameters such as rock type, proppant type, fracture structure, proppant concentration, closure pressure, test time, fluid properties and temperature on fracture conductivity, had been studied by the predecessors. At present, the conductivity experiments in the laboratory are generally carried out in accordance with the industry standard “Recommended Method for Evaluating Short-term Conductivity of Fracturing Proppant Filling Layer” (SY/T 6302-2009) in China. In the experiment, a rock plate and a steel plate clamping the proppant are often used to test the conductivity, in which the rock plate is generally ground into a flat surface. In respect to glutenite, the hydraulic fracture surface is very rough, and its effect on fracture conductivity is very significant. Therefore, the rough fracture surface is an important factor that must be taken into account when testing the fracture conductivity of glutenite.

So far as it is concerned, there are very few reports about conductivity test of glutenite in China. The key issue is how to prepare the glutenite plate samples which meet the experiment requirements. The original drilled core of glutenite can be processed into a sample in required size, or it can be manually made using sand and cement according to the characteristics of glutenite reservoir instead. The two rough fracture surfaces can be obtained by splitting the samples into two plates, and use them to clamp the proppants which are in the middle of the plates, then the fracture conductivity of glutenite can be tested. Furthermore, the effects of closure pressure, gravel size, gravel shape, gravel content and experimental time on the proppant embedment and fracture conductivity are needed to be researched. On the other hand, it is also worth exploring how to prepare the experimental samples of glutenite fracture conductivity using 3D printing technology.

4.2. Computer simulation
Based on the knowledge of elasticity and seepage mechanics, the predecessors have deduced a series of analytical models for calculating fracture conductivity. For example, Wu et al. (2013) established a calculation model of conductivity considering the proppant embedment, and discussed the influence of proppant layer number and proppant size on conductivity. Gao et al. (2015) established a calculation model of conductivity considering the effects of reservoir and proppant mechanical parameters, closure pressure, proppant size and other factors. Wang et al. (2015) established a long-term conductivity prediction model considering pressure dissolution diagenesis, proppant elastic deformation, proppant arrangement type and rock creep effect. However, the above prediction models failed to take into account the seepage characteristics of fluid in fracture and the mechanical properties of rock and proppant. In reaction to this, some scholars have carried out studies on the numerical simulation. By using the PFC, Deng et al. (2014) established a 3D shale clamping model with different proppants and different closure pressures (figure 13). The fracture width at different positions can be calculated.
and the interaction between proppants and the cementation of the rock are considered. Deng et al. (2017) used the lattice Boltzmann method (LBM) to simulate the fluid flow of single-phase fluid in the proppants, and the permeability of propping fracture was numerically calculated. The method was combined with PFC method to obtain the conductivity based on numerical solution. Zhang et al. (2017) calculated fracture conductivity using CFD-DEM coupling method, considered shale hydration, and validated the numerical model by physical conductivity test.

After fracturing of glutenite, the generated fracture is very rough, which results in the uneven distribution of the fracture width. At the same time, under the closure pressure, the interaction between fracture surface and proppant is more complex. Previous studies indicated that proppant embedment is more likely to occur in glutenite than in tight sandstone. Therefore, the influence of gravel should be fully taken into account in predicting the fracture conductivity of glutenite, so it is difficult to obtain the analytical solution of fracture conductivity considering the effect of gravels. In contrast, numerical simulation is an effective method. The size of gravel and that of the proppant is the same as the geometric scale of fracture width, which belongs to the millimeter scale. Therefore, there is no cross-scale calculation problem for numerical simulation of glutenite conductivity prediction. For this reason, the key to predicting the conductivity of glutenite lies in how to accurately characterize the influence of gravel in the model, to reveal the interaction mechanism between the rough fracture surface and proppant, and to predict the permeability of propping fracture under the condition of non-uniform filling of proppant in rough fracture.

There are some potential advantages of using PFC to predict the fracture width of glutenite. This method allows to fully consider the mechanical interaction between adjacent proppant particles, between proppant and rock particles, as well as between adjacent rock particles, and enables the establishment of the irregular gravel model to simulate the effect of proppant embedment and fracture width distribution on rough fracture surface. For the calculation of propping fracture permeability, the interaction between fluid and proppant should be fully taken into account based on coupled analysis. CFD method is recommended to be used to find the solutions of fluid flow. In summary, using CFD-PFC coupling method to calculate the fracture conductivity of glutenite is promised.

(a) Experimental device of fracture conductivity  (b) Shale plates after conductivity test

![Fig 12. Experimental device and sample of fracture conductivity test](image)
5. Conclusion

- There are some deficiencies in the experimental simulation of fracture propagation in glutenite, such as the imperfection of sample model making method and the inability of experimental results to quantitatively guide the optimization of fracturing operation parameters. Therefore, it is necessary to establish a popularized method for making glutenite samples and a parameter conversion method that meets the engineering background. For the computer simulation, the PFC method is a good tool for simulating the mechanical action of inhomogeneous medium, so it has a good prospect in terms of application in simulating micro-scale fracture propagation in glutenite. For oilfield scale simulation, the key is to establish a fast and effective cross-scale simulation method. Cross-scale evolution simulation of concrete damage based on FEM in field of civil engineering can be introduced to simulate the fracture propagation of glutenite on oilfield scale. In addition, the influence of gravel particles can be introduced into fracture propagation model based on DDM method which is oilfield scale to simulate the fracture propagation of glutenite.

- So far as it is concerned, neither physical simulation nor computer simulation of proppant transport in hydraulic fracture of glutenite reservoirs has been being reported. For experimental simulation, it is necessary to develop fracture plates with unidirectional permeability and different roughness to simulate the rough fracture surface of glutenite. In addition, it is also possible to consider the development of a physical model device with secondary fractures to study whether the proppant can get through the secondary fractures, and to improve the flat plate to provide a closure pressure loading function. The key of computer simulation is to improve the mathematical model of proppant transport, such as considering fracturing fluid filtration, rough fracture surface, proppant placement in the direction of fracture width, and proppant transport in the complex fracture networks. There is a good development prospect for using CFD-DEM coupling method to simulate proppant transport. It needs to take into consideration the special reservoir properties of glutenite, and it requires to improve the mathematical model and explore the solution of improved model.

- At present, there are few reports available about the experimental test of the conductivity of glutenite. The key lies in the preparation of the rough glutenite plates which meets the experimental size and shape requirements. The samples can be obtained based on the downhole core, man-made rock sample or 3D printing technology. For computer simulation, the current mathematical model of conductivity fails to reflect the influence of gravel. So far as it is concerned, it is still difficult to accurately describe the complex mechanical mechanism between the fracture surface and the proppant, and to depict the fracturing fluid flow in propping fracture by analytic model, while the PFC numerical simulation method is able to fully take into consideration the mechanical interaction between adjacent proppant particles, between the proppant and rock, as well as between adjacent rock particles. Therefore, combining CFD and PFC method to numerically solve the fracture conductivity will become one of the important directions in the future.
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