Numerical simulation study of oil-based cuttings re-injection induced fractures

Geng Tie¹, Bin Lin¹, Shuai Zhang², Kunkun Wu¹, Chengyun Ma², Yongeun Feng²*

1. EPS China Oilfield Services, Sanhe, Hebei 065201, China
2. College of Petroleum Engineering, China University of Petroleum (Beijing), Beijing 102249, China

Corresponding author’s e-mail: yfeng@cup.edu.cn

Abstract. Cuttings re-injection is an effective method to solve the accumulation of solid waste such as oil-based cuttings in offshore oil and gas fields, which has the advantages of low cost, high efficiency, and environmental safety. But, the slurry leakage events occur frequently due to the poor understanding of the fracture initiation and extension of cuttings re-injection in existing studies. This paper develops a rock cuttings intermittent re-injection simulator based on the open-source hydraulic fracturing software Pyfrac. The impact of different construction and formation parameters on the propagation of induced fractures was investigated through numerical simulations. The simulation results show that Young's modulus, Poisson's ratio and the magnitude of in-situ stress have less influence on the final scope of the fractures. The difference in-situ stress between the re-injection layer and the compartment, the viscosity of the re-injection fluid and the re-injection interval time have significant impacts on the length and height of the fracture. Therefore, in the actual construction process, the liquid viscosity and interval time can be adjusted to obtain the different scopes of induced fractures.

1. Introduction
Oil-based rock cuttings volume has increased significantly with the heavy use of oil-based drilling slurry in the development of shale gas and offshore oil. However, the treatment of oil-based cuttings has become a constraint for oil and gas development under the increasingly strict environmental requirements. Nowadays, the main methods of treating oil-based cuttings are incineration, landfill, chemical treatment, biological treatment[1-3]. All of these methods suffer from large floor space, low treatment efficiency and high cost. The Cuttings Re-injection is an oil-based cuttings treatment method. First, oil-based cuttings are grinded and mixed with water to form a slurry that can be injected into the
formation \(^{[14-15]}\). Then, the slurry is injected into the pre-selected formation in batches through a pump at a pressure higher than the formation fracture pressure. This method can permanently isolate oil-based cuttings in the formation and has the advantages of small occupation area, fast processing speed, low cost and no pollution. Although the cuttings re-injection method has been widely used in developed countries such as Europe and the United States, underground slurry leakage incidents often occur. The essential factor is the poor understanding of the propagation of the induced fractures during cuttings re-injection\(^{[6-8]}\).

Numerical simulations of hydraulic fracture extension have been carried out by a large number of scholars. However, there are fewer studies on the fracture extension of the cuttings re-injection process. In addition, the commonly used fracture numerical simulation software has the characteristics of difficult mesh partitioning, slow solving speed and difficult convergence \(^{[9-12]}\). In this paper, we developed a cuttings re-injection simulator based on the Pyfrac\(^{[13]}\) simulator and carried out a study on the extension of induced fractures during cuttings re-injection to investigate the interaction between the re-injection slurry and the formation, and to reveal the extension mechanism of the induced fractures.

2. Simulator introduction

The simulator used in this paper was developed based on the open-source software Pyfrac. It is a fully coupled implicit hydrodynamic solver based on an implicit level set algorithm. The fracture front edge is represented by a level set function and the new position of the fracture at the end of each time step is calculated iteratively by a fully implicit way. The fundamental mathematical model relies on a linear elastic hydraulic fracturing model that combines elasticity, linear fracture mechanics, and the Carter leakage model\(^{[13]}\).

2.1. Mathematical model

First, the rocks are assumed to be homogeneous, linearly elastic, and permeable in the model. Stiffness is a function of Young's modulus and Poisson's ratio. The fracture energy of rock is expressed by fracture toughness. The fluid in the fracture is assumed to be incompressible and the effect of gravity is neglected in the model.

2.1.1. Control equation. For planar fractures, the control equation is as follows \(^{[14,15]}\):

\[
p(x, y, t) = -\sigma_o(x, y) + \frac{E}{8\pi(1-\nu^2)} \int_{A_0} w(x', y', t) \frac{d A(x', y')}{[(x'-x)^2 + (y'-y)^2]^{3/2}}
\]

(1)

where \(p\) is fluid pressure, \(\sigma_o\) is far-field in-situ compressive stress, \(t\) is the fracture propagation time, \(E\) is Young's modulus, \(\nu\) is Poisson's ratio, and \(A\) is the fracture envelope area.

2.1.2. Continuity equation.

\[
\frac{\partial w}{\partial t} = \frac{1}{12\mu} \nabla \cdot (w \nabla p) - \frac{CH(t-t_0(x, y))}{\sqrt{t-t_0(x, y)}} + Q(t)\delta(x, y)
\]

(2)

where \(w\) is the fracture width; \(\mu\) is the slurry Dynamic viscosity; \(p\) is the fluid pressure; \(C\) is the Carter
leakage coefficient; $H$ is the Heaviside function; $\delta$ is the Dirac delta function; $Q$ is the injected rate$^{[16,17]}$.

2.1.3. Boundary conditions.
The model assumes that the fluid front is the front edge of the fracture, and the boundary conditions of the model are as follows$^{[18]}$:

$$w(x,t) = \begin{cases} K_1(x,t) = K_{ic} & \text{for } |V| > 0 \\ K_1(x,t) < K_{ic} & \text{for } |V| = 0 \end{cases} \text{ and } q(x,t) = 0 \text{ for } x \in C(t)$$ (3)

where $K_1$ is the mode I stress intensity factor; $K_{ic}$ is the fracture toughness; $V$ is the velocity of the fracture front; $C(t)$ is the fracture front.

2.2. Model algorithm
The model is implemented based on the Implicit Level Set Algorithm (ILSA) algorithm. The problem of large differences in the resolution of multi-scale structures in the fracture tip approximation can be avoided by coupling the fracture tip approximation solution with the fracture finite discretization. A brief introduction of the ILSA algorithm is given in this section, please refer to references for the specific implementation. ILSA algorithm calculation mainly includes discretization method, elastic hydrodynamic solution, fracture extension calculation method and fracture closure calculation method. The discretization method is shown in Figure 1, using a Cartesian coordinate system, and the length and width dimensions of each discrete grid are $\triangle x$, $\triangle y$, respectively. The calculation starts from a known solution at time $t$. The solution includes the location of the fracture front intersecting the grid, the width of each cell center within the fracture, and the fluid pressure$^{[19-22]}$. 
In the nonlinear solver for elastohydrodynamic, an iterative solution algorithm with an immobile point scheme is used. The width and pressure increment of all cell centroids within the fracture footprint is used as the main unknowns to solve for the fracture extension footprint. The fracture front is constructed in each cell using a segmented linear approximation and is represented by the level set function. The model is computed iteratively in a fully implicit manner to obtain the new location of the fracture at the end of each time step. The solution process is completed using the solver at the given fracture front location, and then the solution at the fracture front location is combined with the estimated value of the cell width behind the fracture front for the next iterative solution calculation. The solutions for the fracture width increment and fracture tip pressure values are then obtained, and convergence is reached when the subsequent estimates of the solved solutions are below a given tolerance.

Fracture closure simulations are modeled by contact conditions on the grid. In the ILSA algorithm, the fracture tip is described as two states, propagation and stagnation, so that the fracture tip can only move forward and not backward, but the fracture can be closed in the stagnation state. The fracture close when the width of the fracture tip is less than a certain value, at which point we can assume that the fracture tip has "retreated". And the fracture breaking in the model is based on the magnitude of the local fracture strength factor and the fracture toughness at the tip of the fracture. The fracture stagnates when the local fracture strength factor \( K_I < K_{IC} \), and the fracture extends forward under the opposite condition.

3. Cuttings re-injection fracture extension simulation
In this section, a homogeneous formation with 120m in length and 120m in height was established using the simulator described in the previous section. Then, the extension simulation of induced fractures during cuttings re-injection was carried out to study the fracture extension under different formation parameters and construction parameters.

3.1. Fracture extension simulation under different in-situ stress models

The parameters of the model were set as Young's modulus of 35 GPa, Poisson's ratio of 0.4, leakage coefficient of $1 \times 10^{-5}$, re-injection fluid viscosity of 10 mpa.s, re-injection rate of 0.05 m$^3$/s, and injection time of 1 hour. The minimum in-situ stress was set to 5MPa, 10MPa, 15MPa and 20MPa respectively in the model. The simulation results are shown in Figure 2 and Figure 3. It can be observed that the fracture started from the origin and extends steadily with a circular final fracture profile when re-injection was carried out in a homogeneous and unsegregated formation. As shown in Figure 2, the height and width of the fracture were almost independent of the minimum in-situ stress variation. Therefore, the fracture opened as soon as the pressure inside the fracture was greater than the minimum horizontal in-situ stress under homogeneous stratigraphic conditions, and then the fracture extended steadily with continuous fluid injection, which is also confirmed in Figure 3. In addition, the pressure of fracture opening gradually increased with the increase of minimum in-situ stress under the same construction conditions. It maintained a higher pressure inside the fracture during the forward propagation.

![Figure 2. Fracture profile and fracture width under different minimum in-situ stress](image)

![Figure 3. Fracture profile and fracture pressure under different minimum in-situ stress](image)

3.2. Fracture extension simulation under different Young's modulus

Young's modulus is a response to the ability of the rock to resist deformation. The higher Young's modulus, the more difficult it is for the formation to deform. The parameters of the model were set as Poisson's ratio of 0.4, leakage coefficient of $1 \times 10^{-5}$, minimum horizontal in-situ stress of 10MPa, re-injection fluid viscosity of 10 mpa.s, re-injection rate of 0.05m$^3$/s and injection time of 1 hour. The models were set with Young's modulus of 10GPa, 20GPa, 30GPa and 40GPa to investigate the effect of Young's modulus on fractures. The simulation results are shown in Figures 4 and Figure5. The height and length of fractures were hardly impacted by the change of Young's modulus, so the final...
height and length of the fractures were almost the same. However, there was a significant change in fracture width and pressure. As shown in Figure 4, the maximum fracture width gradually decreased from 2.5 mm corresponding with 10 GPa to 1.75 mm corresponding with 40 GPa. The formation becomes stronger in resisting deformation as Young's modulus increases, so higher pressures are required for fracture initiation and result in eventual narrower fractures. On the other hand, Figure 5 also demonstrated that higher Young's modulus formations require greater pressure to form fractures. The pressure at the center point of the fracture increased from 18 MPa to 35 MPa with the increase of Young's modulus to overcome the resistance caused by the higher style modulus. Therefore, the fracture width and Young's modulus are negatively correlated and the pressure inside the fracture is positively correlated with Young's modulus under the same construction conditions.

![Figure 4. Fracture profile and fracture width under different Young's modulus](image1)

![Figure 5. Fracture profile and fracture pressure under different Young's modulus](image2)

3.3. Fracture extension simulation under different Poisson's Ratio

Poisson's ratio is a measure of the Poisson effect, the deformation (expansion or contraction) of material in directions perpendicular to the specific direction of loading. The value of Poisson's ratio is the negative of the ratio of transverse strain to axial strain. Poisson's ratio reflects the lateral deformation capacity of the rock.

In the model, Young's modulus of the formation was set as 30 Gpa. And, the leakage coefficient was $1 \times 10^{-5}$, the minimum horizontal stress was 10 MPa, the viscosity of the re-injection fluid was 10 mpa.s, the re-injection rate was 0.05 m$^3$/s, and the re-injection time was 1 hour. Then the Poisson's ratios of the model were set as 0.2, 0.25, 0.3 and 0.35, respectively. The simulation results are shown in Figure 6 and Figure 7. The variation of Poisson's ratio has almost no effect on the length, height and width of the fracture and the pressure inside the fracture. Therefore, Poisson's ratio impacts the deformation of the formation in the vertical direction according to the definition of Poisson's ratio. The vertical deformation of the formation is not considered in the model. Similarly, in the real situation, the vertical deformation of the formation is considered to be zero.
3.4. Fracture extension simulation under different in-situ stress difference value

The impact of formation parameters on fracture extension in uncompartmentalized formations was discussed previously. There are various lithologies in the actual formation, and the minimum horizontal stress varies for different formations. The in-situ stress difference between the formations can effectively control the vertical extension of the fractures as demonstrated by early numerical simulations of hydraulic fracturing and field experience. The thickness of the reinjection layer was set as 12 m in the model, and the rest of the formations were compartments. The formation parameters were set as Young's modulus of 15 GPa, Poisson's ratio of 0.25, leakage coefficient of $1 \times 10^{-5}$, minimum horizontal stress of 8 MPa in the reinjection layer, reinjection fluid viscosity of 10 mPa.s, reinjection rate of 0.05 m$^3$/s, and injection time of 1 hour. Then, the minimum horizontal stress of the compartments was set in the model as 13MPa, 18MPa, 23MPa, 33MPa. The simulation results are shown in Figure 8, Figure 9 and Figure 10. The stress difference had a significant effect on the fracture shape as shown in Figure 8. The fracture was more likely to extend in the re-injection layer with the increasing stress difference. The fracture would be completely confined in the re-injection layer when the stress difference reaches a certain value. In addition, the decrease in fracture height led to an increase in fracture width and fracture pressure due to the constant injection volume, as evidenced by Figures 9 and Figure 10.
3.5. Fracture extension simulation under different viscosity of the injected slurry

Construction parameters are also important factors affecting cuttings re-injection induced fracture extension. Viscosity is an important indicator of the injected slurry. High viscosity slurry can carry more cuttings particles, allowing the particles to be suspended in the slurry for a longer period. The model set the thickness of the re-injection layer at 12 m, Young's modulus of the formation at 15GPa, Poisson's ratio at 0.25, the leakage coefficient at $1 \times 10^{-5}$, the minimum horizontal stress of the re-injection layer at 10MPa, the minimum horizontal stress of the compartment at 20MPa, the
re-injection rate at 0.05 m³/s, and the injection time at 1 hour. The fracture propagation was simulated at slurry viscosities of 10 mPas, 20 mPas, 30 mPas and 40 mPas, respectively. The simulation results are shown in Figure 11 and Figure 12. The fracture length decreased and the fracture width increased with the increasing viscosity of the re-injection slurry. The fracture height was almost constant and the pressure inside the fracture increased. Because the increased resistance to flow within the formation caused the fluid to move more difficult in the fracture length direction when the viscosity of the re-injection slurry increased. Then, the pressure inside the fracture increased further leading to an additional fracture width.

3.6. Fracture extension simulation under different Interval time

The biggest difference between cuttings re-injection and hydraulic fracturing is that cuttings re-injection requires intermittent injection. To investigate the effect of interval time on fracture extension, a model was established with a re-injection layer thickness of 12 m, a formation Young's modulus of 15 GPa, Poisson's ratio of 0.25, a leakage coefficient of 1×10⁻⁵, a minimum horizontal ground stress of 10 MPa in the re-injection layer, minimum horizontal stress of 20 MPa in the compartment, a re-injection slurry viscosity of 10 mPas, an injection time of 1 hour, and a total re-injection volume of 180 m³ in all cases. The models with injection intervals of 300s, 600s and 900s were set up respectively, and the simulation results were compared with no interval injection (Figure 14 and Figure 15). For the same injection volume, the fracture length, height, width and internal pressure were reduced by intermittent injection compared to non-intermittent injection. The reason is that continuous injection is similar to hydraulic fracturing construction without a pump stoppage period. On the contrary, cuttings re-injection is intermittent injection. The fluid in the fracture is rapidly filtered out, while the pressure drops and the fracture closes during the pump stopping process. The next injection will open an already existing fracture and the pressure in the fracture will rise again. But, the peak pressure in the fracture at re-injection is less than it at continuous injection because the fracture already exists. Therefore, the intermittent injection will produce a smaller range of induced fractures with the same injection volume. It is worth to be noted that the pressure inside the fracture appeared negative during the simulation at an interval of 900s. The reality represented is that the pressure in the fracture is less than the fluid pressure in the formation. One possible reason is that the
formation pressure rises with fluid injection and the formation becomes saturated in the area near the fracture. During a pump stoppage fluid is filtered out rapidly and the pressure drops. Negative values will occur when the pressure in the fracture decreases below the formation pressure.

**Figure 13.** Fracture profile and fracture width under different Interval time

**Figure 14.** Fracture profile and fracture pressure under different Interval time

4. Conclusions

In this paper, we build a simulator that can simulate cuttings re-injection-induced fractures by secondary development based on the open-source Pyfrac software. The simulator has the advantages of adaptive meshing, fast calculation speed, strong stability and easy convergence. Simulations of cuttings re-injection process induced fractures under different formation parameters and construction parameters were carried out by the constructed simulator, and the following conclusions were obtained by analyzing the simulation results.

The magnitude of the minimum in-situ stress in the formation only has a large effect on the fracture opening pressure and has little effect on the final shape of the fracture.

The fracture width and Young's modulus are negatively correlated, the fracture pressure and Young's modulus are positively correlated, while Young's modulus has almost no effect on the crack height and width.

Poisson's ratio of the formation has very little effect on the induced fractures.

The stress difference between the compartment and re-injection layer is the main factor controlling the fracture height. With the increase of stress difference, the fracture height decreases until it is completely controlled in the re-injection layer, while the pressure inside the fracture and the fracture width increase.

The increase of injected fluid viscosity will lead to the decrease of fracture length and increase of fracture pressure.

Intermittent re-injection will provide time for the fluid in the fracture to filter out while the pressure in the fracture decreases. Therefore, under the same injection volume, compared with continuous injection, the fracture length, width and fracture pressure of intermittent injection are reduced, and the induced fracture ripple area is smaller, which further proves that intermittent re-injection is suitable for cuttings re-injection construction.
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