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Plugging mechanism of fibers and particulates in hydraulic fracture

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ABSTRACT

Degradable fibers and particulates are the typical diverting agents which can temporarily plug the preexisting hydraulic fractures and redirect the treating fluid to the under-stimulated area. However, it is still unclear how the plugging is initiated and formed in the hydraulic fracture. In this paper, a large-scale visualized experimental system is built based on the similarity criterion to observe the dynamic plugging performance of fibers and particulates in a mimicked hydraulic fracture. Through a series of comparative experiments, it is found that the plugging process starts from the attachment of fibers on fracture bottoms, roofs and faces, then the attached fibers keep capturing the flowing particulates to form scattered plugged zones, finally one flow channel is formed and gradually narrowed until it is plugged completely. Results indicate that the fibers initiate the plugging process, while the particulates accelerate the following plugging process and withstand the pressure difference by acting as the skeleton of the plugged zone. It is suggested that particulates need to be injected into the hydraulic fracture with fibers at least 50 seconds after the injection of fibers, and the ratio between fibers and particulates is recommended to be 1:1. As the fracture width increases, the plugging rate is reduced accordingly. Adding big particulates whose diameters are 60%–80% of the fracture width can improve the plugging effect significantly.

1. Introduction

Success of a stimulation treatment often depends on complete coverage of all zones. To accomplish complete coverage, placement aids are used to divert treating fluid from one zone to another (Van Domelen, 2017). Among all the diversion technologies, applying diverters is regarded as a more promising approach because of its convenience and availability (Allison et al., 2011; Reddy and Cortez, 2013). The key idea of this technology is pumping diverters during the treatment to create a temporary blockage within the active fracture networks, which results in differential pressure increase and redirects the treatment to under-stimulated area (Potapenko et al., 2009), and ultimately enhances the stimulated volume and the fracture complexity (Wang et al., 2015a). Moreover, effective and efficient plugging of previously-formed fractures can also reduce the operation cost and limit the potential formation damage caused by the fracturing fluid (Liang et al., 2017a, b).

Diverters are normally composed of biodegradable fibers and particulates, which can plug previously-formed fractures during fracturing operation and degrade spontaneously at the formation temperature (Solares et al., 2008; Liang et al., 2018). Potapenko et al. (2009) performed a series of plugging experiments using slurry containing fibers and particles, and found the parameters impacting the plugging ability in the fracture, which are rheology of the base fluid, concentration of fibers and particulates, injection rate, volume of the diverting slurry and fracture geometry. Kefi et al. (2010) evaluated the plugging effect of fibers, coarse particulates and fine particulates in the slots whose width ranging from 1 mm to 6 mm, and found the lower concentration limit of each component to form plugging. Kang et al. (2014) analyzed the synergic plugging effect by the combination of rigid granules, deformable particles and fibers. It was believed that rigid granules have stronger crush strength and could resist the closure pressure, the resilient particles could fill the pores in the sealing zone and magnify the dimensionless contact stress because of their strong deformation ability, and the fiber materials could improve the stability of the plugging zone due to their large aspect ratio. Cortez-Montalvo et al. (2015) proposed a broadband plugging technique using a mixture of coarse, medium and fine particulates, among which coarse granules can bridge the opening fractures, medium and fine particles can fill the plugged zone to reduce its permeability. For far field where the width of fracture is between

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0.04 and 0.08 in, there is no need to add large size granules; for near field where the width of fracture is around 0.2 in, coarse particulates must be added to form an effective plug.

Successful cases in the literature have reported that fibers and particulates can plug hydraulic fractures under certain conditions (Wang et al., 2015b; Xue et al., 2015; Gomaa et al., 2016); however, it is still unclear how the plugging is initiated and formed in hydraulic fracture. Thus, a visualized experimental platform is needed to directly observe the forming process of plugged zones and elucidate the roles fibers and particulates play during the plugging process, then provide instructions for using diverting agents in the field operation. Liu (2006) developed an experimental apparatus that can visualize the sand bed evolution process in a fracture. In this apparatus, two pieces of glass were placed in parallel to mimic a fracture, and cameras were applied to record the evolution process of sand bed in the fracture. However, as the evolution speed of plugged zones is tremendously higher than that of sand bed within a fracture, conventional cameras used in Liu's experiments are inadequate for plugging experiments due to their relatively slow shooting speed.

In this paper, a visualized slot-flow system with high speed cameral was established to observe the dynamic plugging performance of fibers and particulates in a mimicked fracture. Based on the experimental results, the synergic plugging mechanism by fibers and particulates in the hydraulic fracture was analyzed.

2. Methodology

2.1. Materials

Degradable fibers and particulates are the widely-used diverters in the field (Zhou et al., 2017). A mixture of them are tested in this study to reveal the plugging mechanism in the hydraulic fracture (see Fig. 1). This type of diverter is a copolymer of lactic acid with glycolic acid, whose specific gravity is around 1.2. The diverter is insoluble in water and oil, and can self-degrade at the formation temperature. In this study, the chosen fibers have an average length of 6 mm and an average diameter of 8 μm (with the Aspect Ratio of 750), while the chosen particulates have an average diameter of 1 mm or 3 mm. To increase the diverter carrying capacity, 0.2% mass concentration of guar solution was used as the typical fracturing fluid.

2.2. Equipment

A visualized slot-flow experimental system was established as shown in Fig. 2. Fibers and particulates can be mixed with fracturing fluid at a certain concentration in the stirred tank to form a slurry. The slurry is injected into a mimicked wellbore by a progressive-cavity pump, and then it enters a transparent fracture (Frac.1 or Frac.2) through the perforations. The dynamic plugging performance in the fracture is captured by the high-speed camera. The effluent slurry flows into the recovery tank, where the diverters are filtered out for subsequent experiments. Relief valves are installed to ensure the safety. The pressure in the fracture increases with the plugging process, if the pressure exceeds the pre-set value (0.1 MPa), the relief valves will activate automatically to release pressure, indicating the fracture is plugged completely in the experiments. The electromagnetic flowmeters and pressure sensors are installed at the inlet and outlet of the fracture to record the flow rate and pressure.

Fig. 1. Diverters used in the experiments (top: particulates, below: fibers).

Fig. 3 shows the practical photo of the experimental system. The volume of the stirred tank is $3\,m^3$ and the maximum pump rate is $10\,m^3/h$. Two pieces of transparent plexiglass plates are placed in parallel to mimic a hydraulic fracture (Frac.1 and Frac.2). The length of the fracture is 4 m, the height of Frac.1 and Frac.2 are 0.3 m and 0.5 m, while the width of Frac.1 and Frac.2 are 3 mm and 5 mm separately. The inner diameter of the mimicked wellbore is 7 cm, the diameter of each perforation is 1 cm, and the distance between each perforation is 10 cm. The high-speed camera has 1280 × 800 image resolution, 3250 frames/sec full-frame shooting speed, 1 microsecond minimum exposure time, and 8 GB storage space.

After the dynamic plugging experiments, plugged zones formed in the fracture are taken out, left to dry for 24 h and scanned by the CT device (see Fig. 4). The CT device is produced by the GE Company and has a cell pixel of 200 μm × 200 μm, which can show the inner structure of the plugged zones clearly.

2.3. Design of parameters

Because of low diverter density, high fluid viscosity, and high flow rate in the fracture, the viscous force is dominant over the gravity in this case. So the settlement effect can be neglected, and the Reynolds number should be selected as the similarity criterion to design the experimental parameters. The Reynolds number Re in the fracture is defined as:

$$\mathrm{Re} = \frac{\rho u R}{\mu} \tag{1}$$

where ρ is the fluid density, u is the average flow velocity in the fracture, μ is the fluid viscosity, and R is the hydraulic radius of the fracture defined as:

$$R = \frac{Hd}{2(H+d)} \tag{2}$$

where H and d are the height and width of the fracture separately.

Considering a typical field case during hydraulic fracturing operations: the flow rate in the fracture is $2\,m^3/min$, the fracture height is 20 m, and the fracture width is regarded as 3–5 mm. To simulate this field case in the slot-flow system, based on the equations (1) and (2), the pumping rate in the experimental system should be set to around $1.9\,m^3/h$ to make sure the Reynolds number in the mimicked fracture is equal to that in the real hydraulic fracture. So the flow rate of $1.9\,m^3/h$ was used in the present experiments to represent the field conditions.

Frac.1 (3 mm wide) and Frac.2 (5 mm wide) were used to mimic the narrow and wide hydraulic fractures separately. According to the field experience, the mass concentration of the diverters ranges from 0 to 1.5%, so 7 groups of typical experiments were performed with parameters as detailed in Table 1.

3. Results and discussions

3.1. Dynamic plugging performance

Experiment Group 1 was performed to observe the dynamic plugging performance in the fracture. According to field experience, the typical mass concentrations of the fibers and particulates are 1%

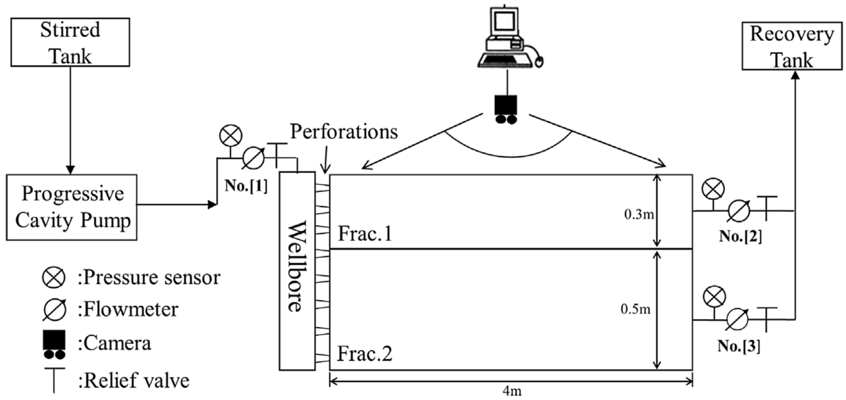

Fig. 2. Flow diagram of the experimental system.

Fig. 3. The visualized slot-flow experimental system.

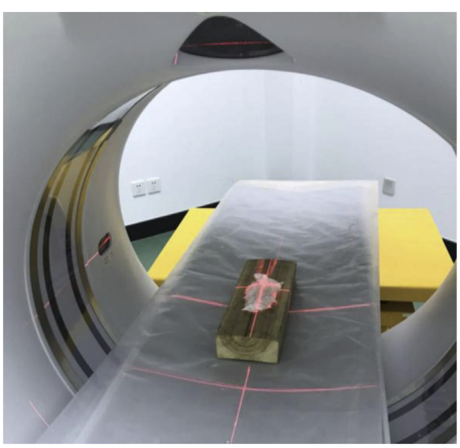

Fig. 4. CT device.

Table 1
Fracture width and diverter concentration in different groups of experiments.

Experiment Group No.	Fracture Width (mm)	Fiber Concentration	1 mm Particulates Concentration	3 mm Particulates Concentration
1	3	1%	1%	0
2	3	0	1%	0
3	3	1%	0	0
4	3	1.5%	0.5%	0
5	3	0.5%	1.5%	0
6	5	1%	1%	0
7	5	1%	1%	0.25%

separately. The slurry containing fibers and particulates was injected into Frac.1 (3 mm wide) while Frac.2 (5 mm wide) was closed. The initial pumping rate was 1.9 m^3/h and the total pump power was kept constant. In order to eliminate the entrance and the outlet effects in the fracture (Liu, 2006), the observation area starts at 1 m away from the inlet and ends at 2 m away from the inlet.

The pressure (from Gauge No. [1]) and flow rate (from Gauge No. [2]) during the plugging process are shown in Fig. 5. According to the dynamic plugging performance, the whole plugging process could be described in four stages (Fig. 5):

3.1.1. Stage 1 (0–43 s)

After entering Frac.1, fibers first attached on both faces at the top and bottom of the fracture to form plugged zones (as shown in Fig. 6). The plugged zones expanded gradually but no particulates were found in the plugged zones at this time. The pressure and flow rate in the fracture nearly kept constant, which indicated that no effective plugging was formed in this stage.

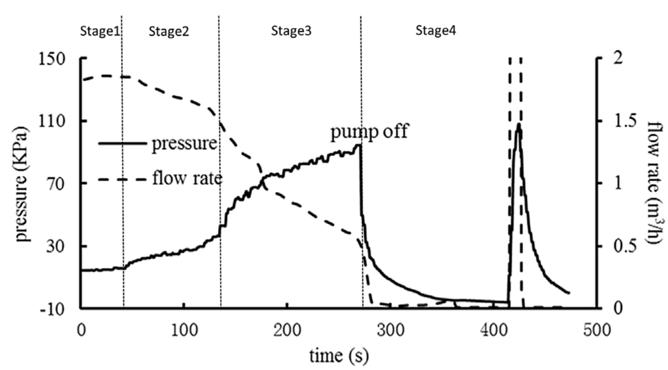

Fig. 5. Pressure and flow rate in the fracture during plugging process.

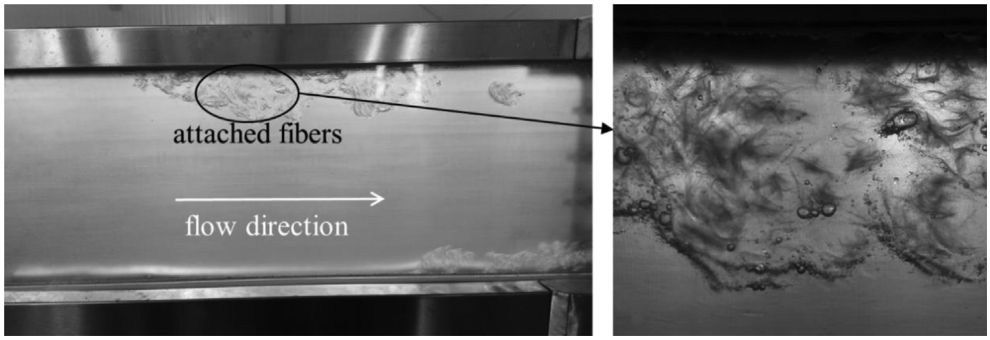

Fig. 6. Attached fibers on the fracture faces (Stage 1).

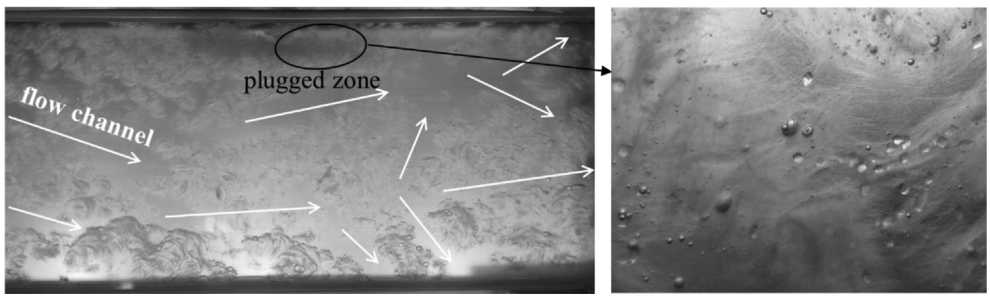

Fig. 7. Scattered plugged zones in the fracture (Stage 2).

3.1.2. Stage 2 (43 s-134 s)

In this stage, scattered plugged zones were formed in the fracture to divide the mainstream into a number of tributaries (as shown in Fig. 7). At the same time, particulates started to appear in the plugged zones. Because particulates were only found in the fiber-attached zones, the particulates could be regarded to be captured by the attached fibers. The pressure increased and the flow rate decreased gradually in the fracture, which indicated that effective plugging began to form in this stage. It is notable that the generation, deformation, and disappearance of different plugged zones occurred simultaneously in the fracture, causing continuous pressure fluctuation in this stage.

3.1.3. Stage 3 (134 s-267 s)

The scattered plugged zones kept expanding, forcing the flow channel to adjust continuously. When one main channel was formed in the fracture (as Fig. 8 shown), the plugging process was considered to enter the Stage 3. In this stage, the main flow channel was narrowed constantly until it was plugged completely. The pressure increased acceleratively until the relief valve was activated, then the pump was turned off. The flow rate decreased correspondingly at the same time.

3.1.4. Stage 4 (after 267 s)

In this stage, the fracture was considered to be plugged completely (as shown in Fig. 9). After the pump was turned off, negative pressure appeared in the fracture. That is because the pressure in the fracture released suddenly and a "breathing" effect was generated associated with the recovery of the glass expansion. When the pump was turned on again, a pressure jump occurred immediately, indicating that a stable plugging had been formed in the fracture.

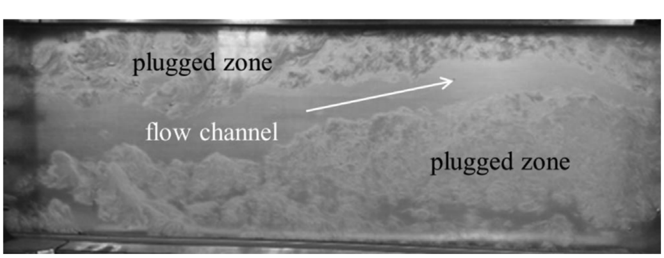

Fig. 8. Merged plugged zones and the main flow channel (Stage 3).

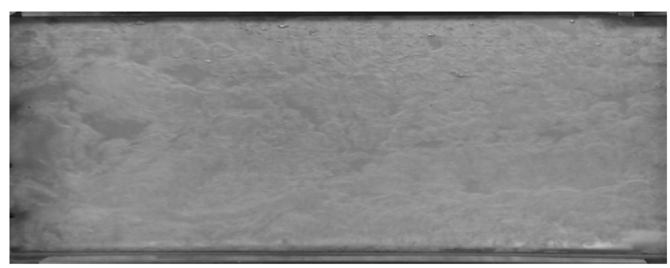

Fig. 9. Complete plugging of the fracture (Stage 4).

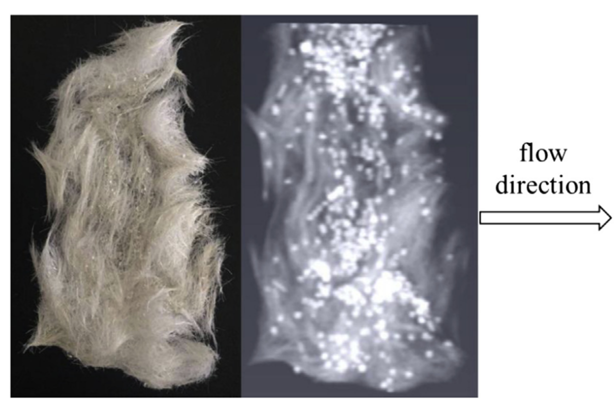

Fig. 10. Sample plugged zone and its inner structure.

After the dynamic plugging experiment, plugged zones were taken out of the fracture, left to dry for 24 h and scanned by the CT device. The inner structure of a sample plugged zone was shown in Fig. 10, it could be seen that particulates distributed in the spaces between fibers and acted as the skeleton of the plugged zone.

It is worth mentioning that, due to the needs of visualization, the

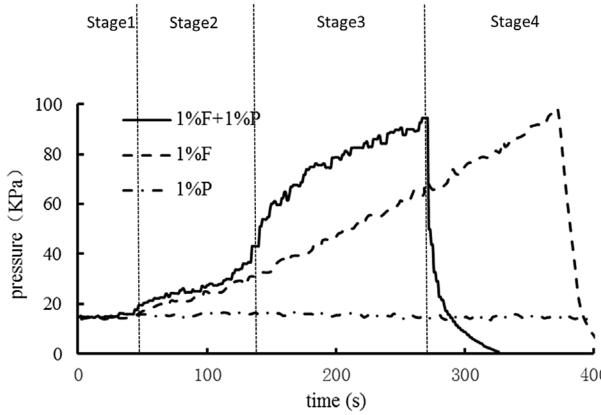

Fig. 11. Pressure in the fracture using fibers (F), particulates (P) and their mixture.

maximum pressure capacity of the present experimental system is 0.1 MPa. This system can be used to observe the plugging forming process because it has nothing to do with the fracture pressure. However, this instrument cannot evaluate the pressure-bearing ability of the plugged zones because of its low pressure capacity. This should be studied by an experimental instrument with a greater pressure capacity, which will be built in the further research.

3.2. Roles of fibers and particulates in plugging process

To further clarify the roles which fibers and particulates played in the plugging process, Experiment Group 2 and 3 were conducted using particulates or fibers only with the same mass concentration as Experiment Group 1. Fig. 11 shows the pressure in the fracture (from Gauge No.[1]) during the plugging process. When only 1 mm-diameter particulates were used, the pressure in the fracture almost kept constant during the whole process of the experiment, indicating that 1 mm-diameter particulates did not bridge and cannot plug the 3 mm-wide smooth fracture. While only fibers were used, the pressure rose gently and reached the pressure limit of 0.1 MPa at about 375 s. As a contrast, when the mixture of fibers and particulates were used in the Experiment Group 1, it took 267 s for the pressure to reach 0.1 MPa.

By comparing the pressure changes in each stage, it was found that particulates do not contribute to the plugging process in Stage 1. For the cases with fibers, scattered plugged zones were formed in Stage 2, causing a gentle increase of pressure. In Stage 3, the pressure in the case of 1% fibers (F) + 1% 1 mm-diameter particulates (P) increased much faster than the case of 1%F. This is mainly because the plugged zones formed by fibers only was relatively loose and difficult to expand in the late stage due to the high flow speed. Particulates could accelerate the growth of plugged zones by filling the space and acting as the skeleton.

Since particulates hardly contribute to the plugging process in Stage 1, to reduce the treatment cost without affecting the plugging effect, it is suggested that particulates need to be injected into the hydraulic fracture from the Stage 2, i.e. about 50 s after the injection of fibers. It's worth noting that, the period of 50 s is based on the present experiment, if used in the field operation, this value should be further optimized based on the real fracture geometry and treatment pressure.

It is known that with the increase of diverter concentration, the fracture will be plugged more easily and quickly (Potapenko et al., 2009). However, for a fixed concentration, how the ratio between fibers and particulates influence the plugging effect is still unclear. So, keeping the total diverter concentration as 2%, Experiment Group 4 (1.5%F + 0.5%P) and 5 (0.5%F + 1.5%F) were performed. The pressure in the fracture during the experiments was shown in Fig. 12. Compared with 1% F + 1%P, when 1.5%F + 0.5%P was applied, the pressure rose more quickly in the early stage but more slowly in the later stage, and it

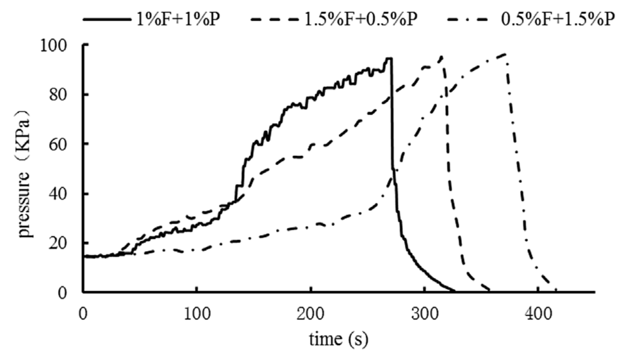

Fig. 12. Pressure in the fracture using different ratios of fibers and particulates.

took about 314 s to plug the fracture; when 0.5%F + 1.5%P was applied, the pressure rose more slowly in the early stage but more quickly in the later stage, and it took about 369 s to plug the pressure. Therefore, it can be concluded that the plugging process starts earlier if adding more fibers, and the plugging process is accelerated more sharply at the later stage if adding more particulates. This is because fibers attach on the fracture faces in the early stage, and capture the flowing particulates to fill the spaces between them in the later stage. Taken together, for the fixed diverter concentration, the ratio between fibers and particulates is recommended as 1:1 to achieve higher plugging rate.

3.3. Plugging mechanism in hydraulic fracture

From the experiments above, the plugging mechanism of fiber and particulate in hydraulic fracture can be depicted by Figs. 13 and 14. Fibers and particulates first enter the fracture with fluid as shown in Figs. 13(a) and 14(a), then some fibers attach on the fracture faces and bridge over the flow path as shown in Figs. 13(b) and 14(b). The attached fibers capture the flowing particulates in the fluids to fill the space between them forming scattered plugged zones in the fracture (see Figs. 13(c) and 14(c)). More and more plugged zones are formed to narrow the flow channel (see Figs. 13(d) and 14(d)) until the fracture is plugged completely. Therefore, the plugging mechanism of fibers and particulates can be summed up as:

(1) Fibers firstly attach on the fracture faces, then capture the flowing particulates to fill the spaces between them forming scattered plugged zones;
(2) One main flow channel is formed after dynamic evolution of scattered plugged zones;
(3) The main flow channel is narrowed continuously until the fracture is plugged completely;
(4) Fibers start the plugging process in the early stage, while particulates accelerate the following plugging process in the later stage and enhance the pressure-bearing capacity by acting as the skeleton of the plugged zone.

3.4. Influence of fracture width on plugging

To investigate the influence of the fracture width on the plugging effect, Experiment Group 6 was performed using Frac.2 (5 mm wide) instead of Frac. 1 (3 mm wide). The same injection flow rate was used as before and the pressure in the fracture (at Gauge No. [1]) is shown in Fig. 15. It was found that 1%F + 1%P could plug 5 mm-wide fracture, but the time used to form plugging was relatively longer than the time used to plug 3 mm-wide fracture. It took 267s when the pressure reached 0.1 MPa in the 3 mm wide fracture, while the time used to reach 0.1 MPa in the 5 mm wide fracture is about 457s.

According to the field experience, adding some big particulates (whose diameter is 60%–80% of the fracture width) could markedly

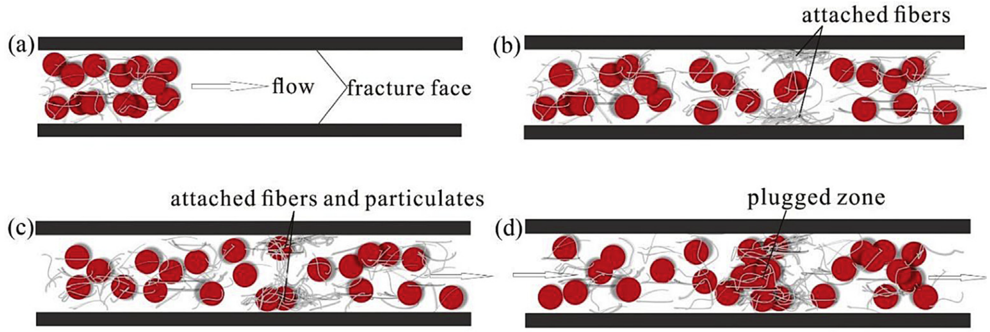

Fig. 13. Sketch map of the plugging process (top view).

accelerate the plugging process. In order to evaluate this effect, Experiment Group 7 was performed in the 5 mm-wide fracture using 1% fibers + 1% 1 mm-diameter particulates + 0.25% big particulates (with the diameter of 3–4 mm). The pressure curve in Fig. 15 shows that at the first 100 s the pressure was almost the same as the case without big particulates, but after 100 s the pressure rose much more quickly than the case without big particulates. That demonstrates again that at the early stage of plugging, fibers were the key factor to affect the plugging rate, while in the later stage particulates were the key factor to determine the plugging rate. Adding 0.25% of the big particulates could accelerate the plugging process significantly.

To make clear the influential mechanism of the big particulates on the plugging effect, plugged zones were taken out of the fracture after the experiment, and scanned by the CT device. Fig. 16 shows a sample plugged zone and its inner structure obtained by the plain CT scan. It could be found that big particulates mainly assembled near the front edge of the plugged zone and formed a column, behind which fibers and small particulates gathered. Similar structures were also found in other pieces of plugged zones. Extrapolating from the inner structure of the plugged zones, after fibers are attached on the fracture faces, big particulates are first captured and arrayed in a column spontaneously. This column can enhance the strength of the plugged zones and make small particulates easier to capture, causing the plugging process to be accelerated accordingly.

In summary, by a series of experiments, the plugging mechanism of fibers and particulates in hydraulic fracture is revealed, including how the plugging is formed, what the roles fibers and particulates play in the plugging process, and the influence of fracture width on plugging effect. Moreover, based on the experimental results, three suggestions are made for the hydraulic fracturing operation in the field: (1) Particulates should be injected into the fracture with fibers at least 50s after the injection of fibers; (2) The ratio between fibers and particulates is recommended to be 1:1 for the fixed diverter concentration; (3) Adding 0.25% of the big particulates whose diameter is 60%–80% of fracture width could improve the plugging effect greatly. However, because of the limitation of the instrument, only two fracture widths and one flow rate were adopted in the experiment. This caused the quantitative relationship between the flow velocity, fracture width and plugging effect not to be established. Nevertheless, this is out of the scope of this study, and can be lines of future research.

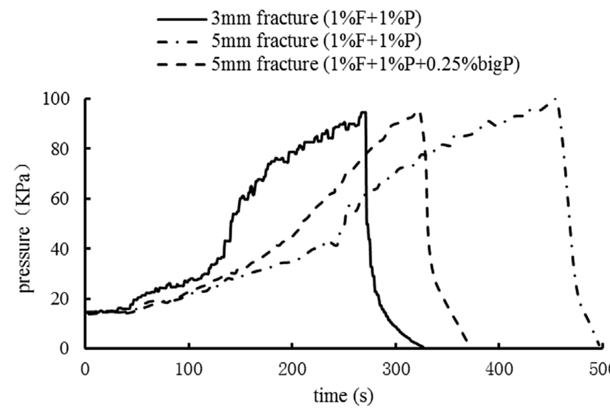

Fig. 15. Pressure in the fractures with the width of 3 mm and 5 mm during plugging process.

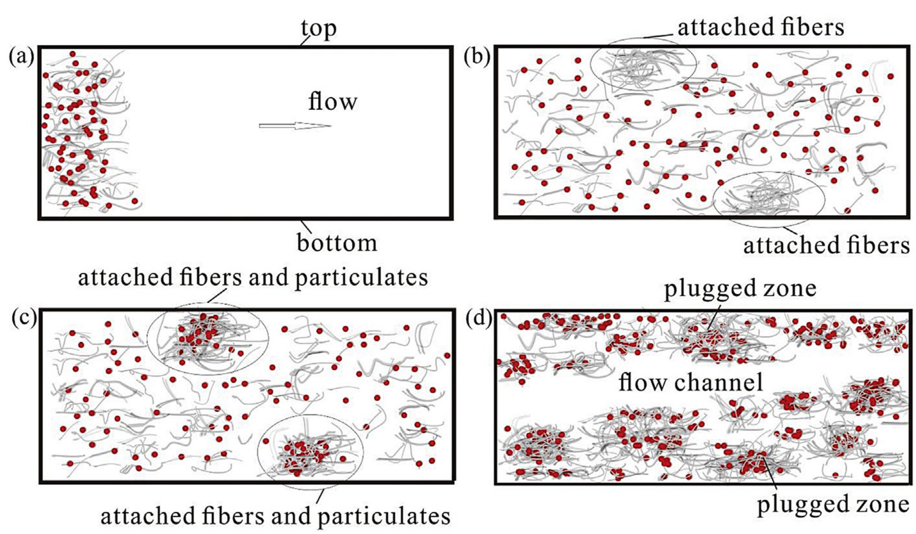

Fig. 14. Sketch map of the plugging process (side view).

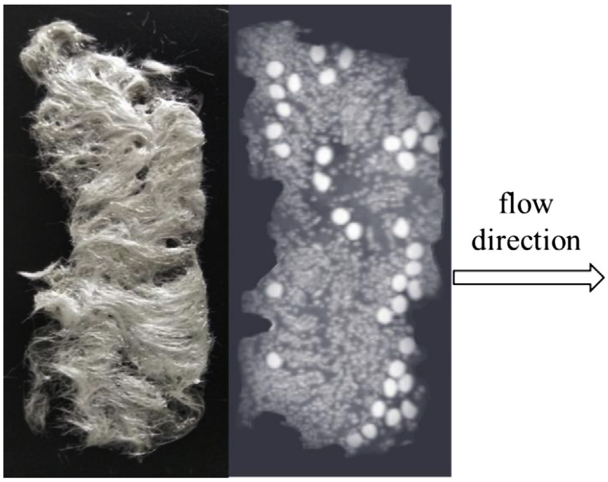

Fig. 16. Plugged zone and its inner structure obtained by the plain CT scan.

4. Conclusions

The plugging mechanism of fibers and particulates in hydraulic fracture was revealed in this paper. The following conclusions could be drawn from the experimental results:

(1) The plugging process can be described in four stages: in stage 1, fibers attach on the bottom, roof and faces of the fracture; in stage 2, the attached fibers capture the flowing particulates to fill the spaces between them, forming scattered plugged zones; in stage 3, a main flow channel is formed and narrowed continuously; in stage 4, the fracture is plugged completely. After the plugging process, particulates are well distributed in the plugged zones to act as the skeleton.
(2) The 3 mm-wide smooth fracture cannot be plugged if using 1% 1 mm-diameter particulates only. While using 1% fiber only, the 3 mm-wide fracture can be plugged but the plugging rate is relatively slow. It indicates that the plugging starts from the attachment of fibers on the fracture face, and particulates can accelerate the following plugging process during the later stage.
(3) For a fixed concentration of diverter, more fibers lead to earlier start of plugging while more particulates lead to a greater plugging acceleration. It is suggested that particulates are injected into the fracture with fibers 50s after the injection of fibers. 1% fiber + 1% particulates is a better composition compared with 1.5% fiber + 0.5% particulates and 0.5% fiber + 1.5% particulates. The ratio between fibers and particulates is recommended as 1:1.
(4) As the facture width increases, the plugging rate becomes lower accordingly. Adding 0.25% of the big particulates whose diameter is 60%–80% of fracture width could improve the plugging effect greatly. That is mainly because big particulates are first captured by fibers and form a column at the front edge of the plugged zone. The column could accelerate the plugging process and help withstand the pressure difference.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.petrol.2019.01.084.

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