A Novel “Soundless Cracking Agent Fracturing” for Shale Gas Reservoir Stimulation

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Abstract—In the hydraulic fracturing process of brittle shale, stress conducting effect of rock matrix is one of the key factors to form a complex fracture network. According to this theory, the experimental study on a novel “Soundless Cracking Agent (SCA) fracturing” was initially carried out. Fracture propagation law on the multistage and simultaneous SCA fracturing of horizontal wells was explored. The fracture morphology was observed for the first time by high-energy CT scanning. The results show that SCA can create fractures by generating huge radial compressing stress and circumferential tensile stress. All weakly consolidated natural fractures and beddings could develop into fracture propagating paths along arbitrary angle. Much flaking debris is also created to prevent fractures from closing and further improves fracture conductivity. For the multistage fracturing, the induced stress caused by the former fractures will reduce the horizontal stress difference, so that for the latter fractures, it is easier to deviate from the preferred fracture plane. The simultaneous fracturing could create high-density fracture zones between two wellbores by fracture interactions between the corresponding segments of the wellbores. The excellent performance of SCA fracturing in laboratory shows great potential and vast development prospects in shale gas reservoir stimulation.

Index Terms—Fracturing, horizontal wells, shale gas, soundless cracking agent.

I. INTRODUCTION

Shale gas refers in particular to an unconventional natural gas hosted in shale reservoir. It is mainly located in the dark mud shale or high carbon mud shale, and takes adsorption or free states as the main modes of existence, and is an important new energy sources [1]-[3]. Shale gas reservoirs generally show the physical properties of low porosity and low permeability. The gas flow resistance is much greater than conventional natural gas, resulting in the greater exploitation difficulty and lower recovery efficiency. Economic output of shale gas requires the use of horizontal wells and the large-scale hydraulic fracturing techniques. Under the action of pressure lowered by drilling well and completion well, the shale gas in fracture system flows to the production wellbore and the shale gas in matrix system desorbs from the matrix surface. Under the action of concentration difference, shale gas diffuses from the matrix system to the fracture system.

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Under the action of flow potential, shale gas flows to the production wellbore through the fracture system. For U.S. Devonian shale gas reservoirs, the 90 percent of industrial gas needs the hydraulic fracturing to increase the fractures space and connectivity, so that more adsorption gas desorbs and gathers towards the fractures. Therefore, the greater the fracture volume is manufactured, the greater the shale gas production will be.

Hydraulic fracturing based on stimulated reservoir volume (SRV) is the first-choice technique to achieve commercial development of shale reservoirs [1]-[3]. During fracturing, the natural fractures reopen and the brittle rocks develop shear sliding, forming a network of fractures (artificial ones and natural ones) inter-connected to each other. Compared to conventional sandstone reservoirs, it causes the transition from simple planar fracture morphology to massive fracture zone, thus greatly increasing the volume of stimulated fractures. SRV provides fracture network channel of gas flowing easily for shale gas play with low porosity and low permeability, thereby increasing the initial production and ultimate recovery of shale play. The key factors affecting the morphology of post-fracturing network include horizontal in-situ stress difference, rock brittleness and natural fracture system (sedimentary bedding) [4]-[9]. In addition, the morphology of fracture network can also be affected by the fracturing operation parameters (volume of fracturing fluid, flow rate, spacing between fracturing segments [10], [11]) and fracturing techniques (horizontal well multistage fracturing, synchronous fracturing, zipper fracturing and refracturing [12]).

Lots of experimental studies under triaxial loading show that shale rock has its own unique physical and mechanical properties [13], [14]. Under the action of relatively low horizontal stress, the developed natural fracture system and the brittleness characteristic of rocks themselves cause most areas of shale reservoirs to undergo large-scale shear or tensile fracture opening under the effect of stress conducting of rock matrix before the arrival of fluids, thus forming fracture zones [3], [15], [16]. The volume of the fracture "opened" by the infiltration of non-fluid accounts for a large proportion in the total volume transformed, which is one of the key factors for the forming of complex fracture network. Guo [17] *et al.*, developed a new method for evaluating shales' ability to form fracture networks by fracturing, namely, the evaluation method of full-diameter cores fracturing with soundless cracking agent (SCA). In the experiment, under the stress conducting effect, the fracture-developed hard and brittle shale produce complex fracture network driven by the huge expansion force of SCA.

SCA is a kind of grey powder. It consists of calcium oxides,

silicon dioxide, ferric oxide and little other ingredients. When the SCA mixed with appropriate water and poured into the pre-drilled holes, it will start to expand after an hour, the expansive power is increasing as time goes on. SCA has great intensity of expansion (30-120MPa). Its response time can be regulated according to actual needs. It has other advantages as easy control of shape, easy cutting, safe and simple operation and good sensitivity to temperature. As long as the constraint continues to exist, the cracking agent has the ability for continuous production or reserving a certain degree of expansion pressure, thus constantly enlarging or generating new fractures. Furthermore, except that only an extremely small amount of water is needed for mud production, the fracturing method using SCA has a simple process, without the need of downhole tools and causing no harm for the reservoir. These features are extremely important for water-starved operation in mountainous areas with complex terrain.

This study aims to explore the feasibility of "fracturing method using SCA" in the development of shale gas reservoirs and find out the propagating rules of fracture network under the effect of stress conducting effect of rock matrix in shale [15], [18], [19]. A large-size true triaxial fracturing simulation test using SCA was conducted. It was the first attempt of multi-stage fracturing and simultaneous fracturing for horizontal wells [12] that are unachievable in hydraulic fracturing physical simulation test [20]-[27] and it is also the first application of large high-energy IPT4106D linear accelerator non-destructive inspection system in carrying out high-energy CT scanning [25]-[28]. Meanwhile, the micro-fractures inside the post-frac rock cores were observed in order to explore the expansion rule of fractures in shale under the effect of stress conducting.

II. EXPERIMENTS

A. Test Apparatus and Specimen Processing

Experiment apparatuses included the large-size true triaxial hydraulic fracturing simulation system (Fig. 1(a)) [25] and the large-scale "IPT4106D" non-destructive testing system (6MeV) based on linear accelerator (Fig. 1(b)) [29]. The latter provided high-energy computed tomography (CT) scanning and digital radiography (DR) scanning for large-size work pieces. CT scanning and DR scanning can provide tomographic images and integral perspective views of specimens, respectively.

Specimens were collected from Sichuan shale outcrops in China, belonging from the No.5 layer of the Triassic Xujiahe Formation in Sichuan Basin. During sampling, the weathered rock layer was removed. The well-preserved fresh shale outcrops were obtained, and then they were processed into 30cm×30cm×30cm cubes. Meanwhile, the outer surfaces of the shale were sealed by using adhesive tape or epoxy resin glue, to avoid the opening of bedding fractures due to prolonged exposure to the air. A penetrative hole with a diameter of 3 cm and a length of 30 cm was drilled in the test piece along the horizontal or vertical direction of the bedding plane with different test programs and was cleaned up by alcohol. In order to simulate staged fracturing, core columns

were prepared into segmented cylinders with a length of 3.75 cm and a diameter of 30 mm. Four segmented cylinders were used to form three 5-cm-long filling segments of SCA in the 30-cm-long hole (Fig. 1(c)). In the simulation of simultaneous fracturing of horizontal well, two drilled holes were located in the middle part and distributed at an equal interval of 8 cm (Fig. 1(c)).

The shale mineral analysis showed that the average contents of carbonate, quartz and clay were 13.1%, 41.3% and 39.9%, respectively. Rock mechanics test showed that the average Young's modulus of shale coring along the direction parallel to bedding was 17.2GPa and Poisson's ratio was 0.175. However, the average Young's modulus of shale core along the direction vertical to bedding was 12.3GPa and Poisson's ratio was 0.190. The tensile strengths of shale cores from horizontal and vertical bedding were 1.35 and 3.85MPa, respectively, while the uniaxial compressive strengths were 48.21MPa and 48.92MPa, respectively. As shown by the brittleness index calculated by Young's modulus-Poisson's ratio method [9] and the ratio of uniaxial compressive strength to tensile strength [30], the brittleness of the shale core is high.

Fig. 1. Test apparatus and specimen processing: (a) large-size true triaxial simulation system (b) large-scale "IPT4106D" non-destructive testing system (6MeV) based on linear accelerator (c) processing of experimental specimens.

B. Experiment Design

The main purpose of studying the influencing factors in the fracturing simulation using SCA is to observe the influence of stress. In order to observe the expansion of fracture more conveniently, the principal horizontal stress should be set as 0MPa, which means there is no need to install test rack roof. The research separately carried out the fracturing simulation test, horizontal well staged fracturing simulation test ($\sigma_v:\sigma_H:\sigma_h=9:6:0$ and $6:3:0$ MPa) and horizontal well

simultaneous fracturing simulation test ($\sigma_v:\sigma_H:\sigma_h=6:3:0\text{MPa}$), σ_v , σ_H and σ_h is, the overburden stress, the maximum horizontal in-situ stress and the minimum horizontal in-situ stress, respectively.

C. Experiment Procedure

Along the direction of vertical deposition bedding is overburden pressure and the minimum horizontal stress in the vertical direction is 0MPa. Before filling SCA in the shaft, overburden pressure and maximal stress should be exerted successively. After the exertion of stress, water and SCA are mixed evenly at the ratio of 1:3. Then the filling of mixed slurry and segmented cylinders in the shaft was completed within 20 minutes, or the filling liquidity and expansion effect would severely decline, so the filling must be compact. After the test lasted 24 hours, SCA was basically completed. After the core was torn down from the test shelf, the photos of the appearance of post-frac samples were collected and then the samples were sealed with tapes to prevent damage on the structure of fractures. Lastly, large high-energy IPT4106D linear accelerator non-destructive inspection system was used to carry out high-energy physical CT scanning. As for the completely ruptured rock cores that are no longer an integral whole after the test, the observation of internal fractures does not need CT scanning, and rocks can be directly ruptured for photographing.

III. EXPERIMENT RESULTS AND ANALYSIS

A. Fracturing Simulation Test under the Condition of No Confining Pressure

When the rock core has no three-dimensional confining pressure, if the shaft is parallel to the bedding plane (Fig. 2(a)), in the simulation of horizontal well fracturing, after the expansion of SCA, the fracture basically expands along the bedding fractures (Fig. 2(b)) and the time for rupture is four hours after the filling, suggesting that with low intensity of bedding fractures, crack initiation is highly possible for bedding fractures. Meanwhile, due to the fragility of the shale, a large number of clastic particles will be produced after fracturing.

When the shaft is vertical to the bedding plane (Fig. 3(a)), in the simulation of vertical well fracturing, crack initiation takes place in roughly six hours before the filling, as shown in Fig. 3(b). Due to the relatively complex progress of fracture, four fractures appear in the initial stage, one of which evolves into two branching fractures after extending some distance. 10 hours later, the rock core will completely rupture (Fig. 3(c)). Seen from the internal plane of fracture shown in Fig. 3(d), the rupture planes are relatively smooth bedding planes and natural fracture planes already opened before the fracturing, so fractures extends along the bedding plane with low cementing strength and natural fracture planes. Since there is a high degree of rupture inside the rock core, the complexity of the emerging fractures is much higher than the surface of the test piece. Furthermore, the experiment also found that in the process of fracture propagation, if weak cementing planes vertical to the expansion surface appear (e.g. Natural fractures), the fractures may change its direction to progress

along the expanding path with an angle of 90° , just as marked by the dotted line in the Figure. As no triaxial stress was exerted on rocks in this test, the fractures were mostly open fractures.

Fig. 2. Wellbore filled by SCA parallel to the bedding plane (0MPa).

Fig. 3. Wellbore filled by SCA perpendicular to the bedding plane (0MPa).

B. Staged Fracturing Simulation for Horizontal Wells with SCA

This test was separately carried out on different triaxial stresses, with a result of $\sigma_v:\sigma_H:\sigma_h=6:3:0\text{MPa}$ and $9:6:0\text{MPa}$, respectively.

Fig. 4. Fracture propagation map on rock surface of horizontal well staged fracturing by SCA.

Under two stress levels, according to the rule in crack initiation and propagation of horizontal wells under hydraulic fracturing, the fractures are mostly likely to expand along the direction of the horizontal maximum stress, forming transverse fractures vertical to shaft. During the test process, although it is impossible to observe the internal fracture initiation and expansion, due to the fact that no stress is exerted along the shaft direction, the crack initiation and expansion forms of the fracture along the shaft direction, the direction of minimum stress. Fig. 4 shows the expansion forms of the fracture at different instants of time when the stress difference is 3MPa. In the process increase of swelling pressure by SCA, although the overburden pressure is 6 MPa, the maximum horizontal stress is 3 MPa, but due to the low cementing strength on some sediment bedding planes, crack initiation can still appear along the sediment bedding planes (Fig. 4(a)). Later, affected by stress difference, the fracture begins to expand along the direction roughly vertical to the maximum horizontal stress (Fig. 4(b)). Therefore, in the expansion process of vertical cracks, under the influence of uniformity of shale, the fracture mainly expands along such fragile paths such as natural fracture, so the expansion path of fractures is highly tortuous and complex (Fig. 4(c)). After the fractures along the direction appropriately vertical to stress expands to the boundary, and if the SCA continues to add pressure, some crack initiation will appear on some sediment bedding fractures.

The fracture distribution after the release of pressure is shown in Fig. 5 and the rock core almost completely ruptures (Fig. 5(a)), developing wide fractures. At the same time, according to Fig. 5(b) and (d), there are obvious transverse fractures (dotted line diagram) and three major fractures have emerged on three filling sections, the traverse fractures intersected with bedding fractures. Fig. 5(c) shows complex fracture expansion path on plane 3.

Fig. 5. Fracture propagation morphology of horizontal well staged fracturing by SCA.

When there is $\sigma_v:\sigma_H:\sigma_h=6:3:0$ MPa, post-frac rock core fractures can be observed with high-energy CT scanning. Fig. 6(a) and (b) are the perspective drawing for the core of the shale along the shaft direction. The red line has marked

corresponding scan position in the Figure. On the traverse line in (a) and (b), the scan from the principal plane to the inside correspond to the scanning imaging from the bottom to the top in (1) and (2), respectively. According to the perspective drawing, there is obvious initiation of two bedding fractures and there are also several long vertical fractures roughly vertical to the direction of maximum principal stress. Fig. 6(1) is the scan parallel to the bedding plane. Two transverse fractures, along with other two vertical ones near the shaft, have emerged in the three fracturing segments. Obvious large fracture zones have appeared in the middle fracturing segments which were formed by vulnerable rocks. The No.2 scanning image vertical to the bedding direction shows two principal transverse fractures and three obvious bedding fractures in the same position. Furthermore, the initiation of multiple long bedding fractures can be observed, the volume size of the fractures higher than the parallel bedding direction. Therefore, the intertwining of transverse fractures and bedding fractures (natural fractures) have produced plentiful "quadrangular fragments to form complex fracture networks. Compared with the rock cores with a horizontal stress difference of 3MPa, when the difference rises to 6MPa, seen from the appearance of post-frac rock cores, the fracture density has somewhat reduced, but it is still possible to form large-scale complex fracture volume.

The fractures formed only by being compressed by SCA expansion under the effect of stress conducting has complicated expansion path and both the bedding plane with weak cementing plane and natural fractures can be developed into the expansion path of the fractures and expand along any angle. Therefore, the intertwining of transverse fractures, bedding fractures and vertical fractures has jointly created complicated fracture volume.

Fig. 6. CT scanning image of horizontal well staged fracturing by SCA.

C. Simulation of Simultaneous Fracturing for Horizontal Wells Using SCA

In order to explore the contribution of simultaneous fracturing to volume of fractures, SCA is used to fill the two shafts to carry out the simulation test for simultaneous fracturing, with a triaxial stress of $\sigma_v:\sigma_H:\sigma_h=6:3:0$ MPa. The

space between shafts is 8 cm. Fig. 7 is the scan results along the direction of post-frac horizontal bedding. According to the perspective drawing in Fig. 7(a), simultaneous fracturing has formed a fracture network of greater density. No. 1 scanning image shows three apparent sections made up of five through transverse fractures and two vertical fractures along the shaft direction. In the lower area in the Figure has emerged multiple short transverse fractures intersected with vertical fractures. No. 2 shows transverse fractures with even greater density between shafts. Moreover, all of the shafts have ruptured, the fracture zone marked by the black area shown on the right side. Compared with Fig. 6(1), the fractures show much higher density. No. 3 scanning image shows two fracturing segments comprising six transverse fractures. Meanwhile, a large number of tiny micro-fractures are distributed there.

Fig. 8 shows the scanning image vertical to the bedding plane. On the three bedding planes, three apparent sections of transverse fractures can be observed, similar in shape to the hydraulic fracturing on the horizontal well segment. As in Fig. 6(2), due to the bedding development of the shale and low cementing strength of the bedding plane, a large number of bedding fractures intertwine with transverse fractures after the fracturing, resulting in mass of quadrangular fracture zones. Moreover, large quantities of fragments have peeled off on the fracture surface formed in the post-frac shale. As a result, the fractures cannot be closed, which has greatly improved the flow conductivity of the fractures. Fig. 9 is the stereogram combining two CT scanning images. It can be seen from different angles that high-density and complex fracture networks have formed after the fracturing, which has proved that shale reservoirs have the potential for volumetric fracturing. The induced stress produced by the initiation of the fractures on the adjacent fracturing segments for each shaft has reduced the influence exerted by the maximum and minimum horizontal stress. Similarly, the fracture initiation of the corresponding fracturing segments of two shafts has reduced the effect of the difference between overburden pressure and maximum horizontal stress, jointly causing the change of the stress field. Relatively small stress difference makes it much easier for the fracture to reorient. In the process of rock expansion, some tip-adjacent areas are in the tension zone, making two adjacent fractures inter-attract and expand on the edge but repel each other in the middle. In addition, shearing strength peaks near the fracture end to prevent the interconnection of the fracture to form separate fractures, which can orient toward each other. If they are very close with each, the fractures may be cut off, just as shown by the dotted line in Fig. 7(2).

D. Advantages and Development Prospect of the Fracturing Method Using SCA

The fracturing method using SCA enjoys the following advantages: 1) The technology is simple and safe without any need for downhole tools, and all that is required is to drill the shaft and prepare the mud to fill the shaft; 2) It can realize self-pressurizing and the response time can be adjusted according to actual needs, not requiring extra fracturing bump truck. With the extension of time, the expansion force of SCA continues to increase until the formation is crushed. 3) It is

water-saving, and only an extremely small amount of water is needed to prepare the mud, without any need for the tens of thousands of cubic meters of water used in the fracturing the shale reservoir. 4) It is low-cost, for the fracturing materials, ground equipment and downhole tools are not required, which has greatly reduced the construction cost. 5) It can control the shape easily and realize staged fracturing and the filling of any shapes.

Fig. 7. CT scanning image parallel to sedimentary bedding of simul-fracs.

Fig. 8. CT scanning image perpendicular to sedimentary bedding of simul-fracs.

The reason why this means can be used in the development of unconventional gas reservoir such as in the development of shale gas or tight gas, is that gas reservoir development has very low demand for the flow conductivity of fractures. Due to the shear dislocation and the migration and filling of clastic particles, it is well-qualified in the aspect of fracture conductivity. Therefore, this development means is highly effective.

Besides, it can be noted that the development effect of this method depends mainly upon the geological conditions of the reservoir. In the fragile shale reservoirs, if the horizontal stress difference is relatively low (less than 9MPa), the natural

fracture system (including sediment bedding) will be more developed and the transformational effect of the reservoir will be much better.

Fig. 9. CT scanning comprehensive images of horizontal well simultaneous fracturing by SCA.

Unlike hydraulic fracturing, the fracturing method using SCA based on stress conducting effect is not caused by non-fluid pressure, making it unable to realize fluid-solid interaction, and the length and number of the fractures formed are also smaller compared with hydraulic fracturing, but due to the fact that this method has simple construction process and low cost, the shortcomings can be made up for by means of drilling multiple holes. For example, the fracturing method of cluster wells or fish bones multilateral wells using SCA can fully take advantage of the interference mechanism between holes and fractures to effectively increase the volume of reservoir reform by SCA rupturing.

The advantages of the fracturing method using SCA seem especially advantageous for the construction in water-starved mountainous areas with complicated terrain. If we need to further develop the products in which the expansion pressure is even higher and the expanded SCA columns have high permeability, this technology will promise better and broader application.

IV. CONCLUSION

This research has for the first time started the experiment and exploration of a new-type fracturing method for shale reservoir using SCA. The rule of expansion of fracture networks in large-size true triaxial horizontal wells on shale outcrops under staged fracturing and simultaneous fracturing are studied. In addition, the large-scale high-energy linear accelerator non-destructive detection system was used for the first time to carry out high-energy CT scanning on post-frac large-size rock cores. The conclusions are as follows:

- 1) The results of staged fracturing of horizontal well using SCA showed that when expansion and extrusion (without liquid) were performed to produce fractures in the core of the shale, the fractures had a complex propagation path. The weakly cemented bedding planes and natural fractures all had the potential to develop into propagation paths. These paths could extend along any directions. The interweaving of transverse fractures, bedding fractures and natural fractures gave rise to a large amount of "quadrangular" fragments, leading to complex volume

of fractures under fracturing. Therefore, under the action of stress conduction by substrate, staged fracturing using SCA can also produce high-density fracture volume.

- 2) Simultaneous fracturing for horizontal well using SCA produced higher fracture density than single-well fracturing. The initiation of adjacent segments of each wellbore would cause induced stress, thus lowering the influence of difference between maximal and minimal horizontal stress. Moreover, the initiation of the corresponding fracturing segments of two wellbores would reduce the influence of the difference between the pressure exerted by overlying stratum and the maximal horizontal stress. As a result, the stress field was modified; the horizontal stress difference was reduced, and hence the fractures could change direction more easily.
- 3) The fracturing technique using SCA is easy and safe to operate, the cost is lower, and only a trace amount of water is needed. The type is easy to control with the fracturing method using SCA, so this technique is very suitable for mountainous areas with water deficiency, complex terrain and small area. By multi-borehole method, the volume of reservoir reconstruction can be effectively increased for the fracturing method using SCA.

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