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Analysis of Supercritical CO_2 Coiled Tubing Fracturing Technology for Shale Gas Formation

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Abstract: Hydraulic fracturing of shale formations has led to energy boom both in China and abroad. Currently, water is regularly used as fracturing fluid in commercial shale gas and oil production, but it has raised concerns in many aspects such as environment and reservoir protection. Supercritical CO_2, as a non-aqueous fracturing fluid, combined with coiled tubing fracturing technology, can effectively increase shale gas production, shorten operation period, reduce cost, conserve water resources, and minimize environmental impacts. Firstly, the process of supercritical CO_2 fracturing with coiled tubing of shale gas formation was introduced, and the potential advantages of using CO_2 as working fluid in coiled tubing fracturing of shale gas formation were analyzed, including enhanced fracturing and fracture propagation, reduction of flow-blocking, increased desorption of methane adsorbed in organic-rich parts of the shale, and a reduction or elimination of the deep re-injection of flow-back water that has been linked to induced seismicity and other environmental concerns. In addition, shale gas formations may also become a major utilization option for carbon sequestration. Then, the computational fluid dynamics were applied to simulate the flow fields inside cavity of supercritical CO_2 fracturing with coiled tubing, and the pressure boost capability was verified. By comparing the pressure boost effects of water fracturing and supercritical CO_2 fracturing, it could be concluded that supercritical CO_2 fracturing with coiled tubing has stronger pressure boost effect than water fracturing under the same conditions. The research and development status of supercritical CO_2 fracturing equipment and field test were also analyzed. The research results can provide references for the application of supercritical CO_2 fracturing with coiled tubing in shale gas formations and the development of related tools.

Keywords: Shale Gas, Supercritical CO_2, Coiled Tubing, Fracturing, Pressure Boost

1. Introduction

Extracting oil and gas from shale formations often requires hydraulic fracturing to bring commercial production, which increases formation permeability and facilitates gas migration. Water with additives is currently the primary fluid used in commercial shale oil and gas development due to its low cost, easy availability and suitability for fracturing. In recent years, however, the oil industry has become increasingly concerned about the long-term use of water in fracturing. Issues of concern include:(1) High cost of discharge and treatment of contaminated backwater; (2) Availability of water in arid areas; (3) Backwater injection will induce earthquakes; (4) It is possible to pollute fresh water in the stages of injection, oil and gas production and water treatment. These problems have led to the exploration of non-water fracturing fluids including supercritical CO_2 in oil industry [1].

Supercritical CO_2 is a non-water fracturing fluid that can be used for reservoir fracturing. Especially, with the increasingly obvious limitations of conventional fracturing fluids, CO_2 as an energy-enhancing fluid has attracted more attention [2]. Supercritical CO_2 has significant advantages over water, including: enhanced fracturing; miscibility with hydrocarbons can increase the production of hydrocarbons and methane; reduce pressurization requirements on site (depending on the depth of the formation, CO_2 reaching pipeline pressure may require little or no pressurization); enhancing the desorption capacity of methane from organic matter in shale; effectively drive gas from cracks with poor connectivity; reduce or eliminate backflow and injection water. Given future sequestration goals, including capturing large amounts of CO_2 from thermal power plants [3] and the need to store CO_2 away from the atmosphere, shale reservoirs are expected to be an important option for carbon capture, utilization and storage.

This will result in large amounts of CO_2 being used for shale gas production, effectively reducing the amount of water used for fracturing and enabling large-scale CO_2 storage.

Studies have confirmed [4, 5] that when supercritical CO_2 fluid is combined with coiled tubing fracturing technology, supercritical high-speed fluid is used to impact shale under downhole high-temperature and high-pressure conditions, and part of CO_2 entering shale pores can reduce formation fracturing pressure. Under the continuous impact of high-speed fluid, jet pressurization will be formed in the perforation channel. Liquid CO_2 is pumped into the annulus to increase the annulus pressure. When the sum of jet pressurization and annular pressure exceeds the formation fracturing pressure, the formation at the top of the hole is fractured. The high speed jet can drive the annulus fluid into the perforation channel and fracture, so that the fracture can be fully extended. At present, there are few researches on the mechanism of supercritical CO_2 coiled tubing fracturing and high speed jet pressurization in shale gas formation. Therefore, the author analyzes the advantages of supercritical CO_2 coiled tubing fracturing technology in shale gas formation, expounds the potential effectiveness of CO_2 as a substitute for working fluid in shale gas production, simulates the flow field in the hole of supercritical CO_2 coiled tubing fracturing, and compares the jet pressurization effect of hydraulic fracturing. The research and development status of supercritical CO_2 fracturing equipment and field test is analyzed, which can provide a basis for the application of related technologies and the development and optimization of supporting tools.

2. Supercritical CO_2 Coiled Tubing Fracturing Process for Shale Gas Formation

This process includes supercritical CO_2 abrasive perforation and supercritical CO_2 fracturing [5], as shown in Figure 1. Adequate CO_2 gas source should be prepared before operation, and refrigeration device should be placed for the air source storage tank to ensure that the gas entering the sand mixing truck is in liquid state. Under the condition of formation pressure and temperature, CO_2 will reach the supercritical state (temperature over 31.1°C, pressure over 7.38 MPa). In the process of fracturing, the pressure of CO_2 fluid in the fracturing interval is higher and it is easier to reach supercritical state.

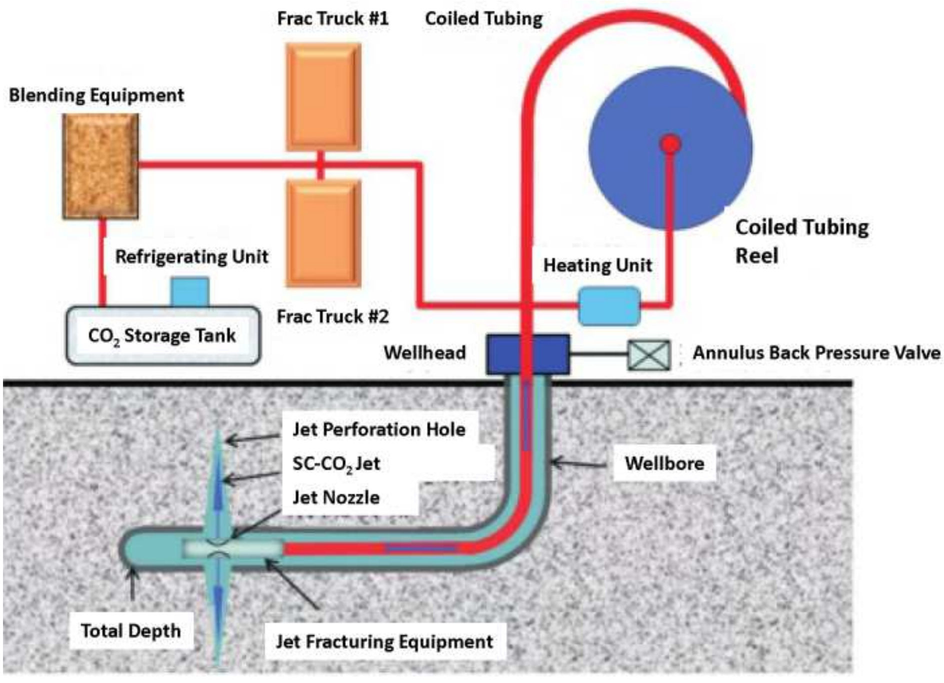

Figure 1. *Schematic diagram of SC-CO_2 fracturing with coiled tubing of shale gas formation.*

2.1. Supercritical CO_2 Abrasive Perforation

The frac truck pumps a mixture of CO_2 and abrasive through coiled tubing into the wellbore. In the process of CO_2 descending in the wellbore, the temperature and pressure will gradually increase until it enters the supercritical state. Supercritical CO_2 reaches the injection fracturing tool and is sprayed to form supercritical CO_2 abrasive jet, which shoots through casing and shale formation and forms perforation holes.

2.2. Supercritical CO_2 Fracturing

After circulating the well, supercritical CO_2 is pumped simultaneously into the coiled tubing and annulus. Due to the pressurization of supercritical CO_2 jet, the stagnation pressure in perforation hole is obviously higher than the annulus pressure. At the same time, supercritical CO_2 has strong diffusion ability and will penetrate into formation pores and micro-cracks under high pressure, further reducing formation fracturing pressure. Eventually, the pressure in the hole is greater than the formation fracturing pressure, causing the fracture to extend. The proppant is then mixed with liquid CO_2 using a sand mixer, and the proppant enters the fracture with the CO_2.

3. Advantages of Supercritical CO_2 Coiled Tubing Fracturing Technology

CO_2 can significantly increase shale gas production and reduce environmental damage through a variety of physical mechanisms. For example: (1) miscibility of CO_2 and hydrocarbons significantly reduces flow resistance in micropores; (2) Iso-enthalpy expansion can induce additional fracture propagation; (3) The characteristics of supercritical CO_2 can effectively play the technical advantages of coiled tubing fracturing and supercritical CO_2 jet; (4) Adsorbed methane at organic-rich locations in shale formations can be desorbed with CO_2; (5) CO_2-based fracturing modifications provide the industry with options for CO_2 sequestration, including the fracturing stage (mainly because CO_2 preferentially replaces methane adsorption), and CO_2 sequestration by injecting CO_2 into depleted reservoirs after production [6].

4. Analysis of Jet Pressurization Mechanism

4.1. Model

Shale formation pores formed by supercritical CO_2 fracturing are in spindle shape [7], and the flow region includes nozzle inlet, annulus and formation pores, as shown in Figure 2.

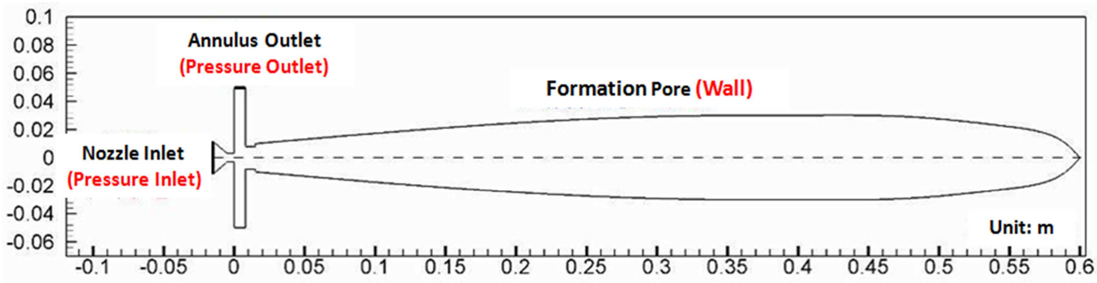

Figure 2. *Geometry model of flow field.*

In supercritical CO_2 coiled tubing injection fracturing, the supercritical fluid is injected from the nozzle into the annulus and the pore successively. The flow field and flow boundary in the hole are approximately axisymmetric, so a two-dimensional numerical simulation scheme is adopted. Gambit software was used to divide the computational domain into structured grid model, and local grid mesh density was increased in the straight section of nozzle with large pressure gradient variation to improve the computational accuracy.

Parameter Settings: nozzle diameter 6 mm, casing hole diameter 12 mm, nozzle pressure drop 20 MPa, annulus pressure 25 MPa, fluid temperature 350 K.

Boundary conditions: the nozzle inlet is the pressure inlet boundary, the annulus outlet is the pressure outlet boundary, and the other boundaries are the non-slip wall boundary.

Calculation process: Supercritical CO_2 jet belongs to high-speed compressible flow. Therefore, the coupling solver [8], which is more advantageous for solving this problem, can calculate the pressure field, temperature field and supercritical CO_2 physical parameters coupling, and accurately simulate the flow field in the supercritical CO_2 coiled tubing fracturing tunnel.

4.2. Simulation Results

4.2.1. Jet Pressurization Mechanism

Fluent software is used to simulate the velocity of supercritical CO_2 jet (Figure 3) and pressure distribution cloud diagram (Figure 4). It can be seen that after the high-pressure supercritical CO_2 fluid is accelerated at the nozzle, the pressure drops rapidly, and the velocity at the nozzle exit reaches 226.5m/s, and there is an isokinetic core of jet flow. The flow line in the isokinetic core is basically parallel to the axis, and the velocity and pressure on the jet axis are basically constant.

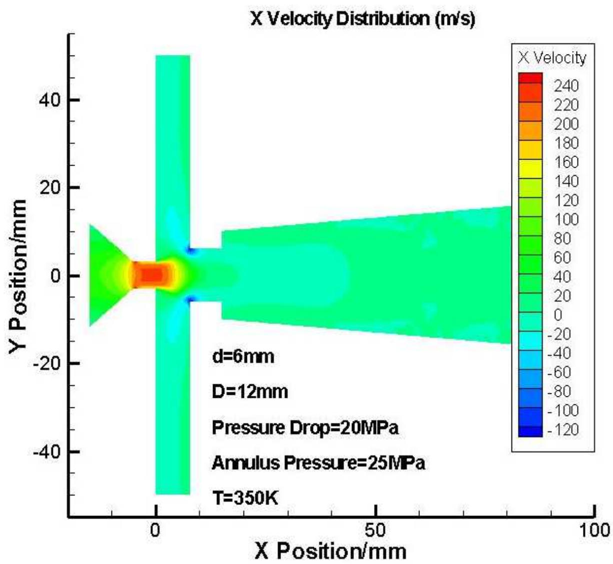

Figure 3. *Cloud atlas of velocity distribution in X direction of CO_2 jet.*

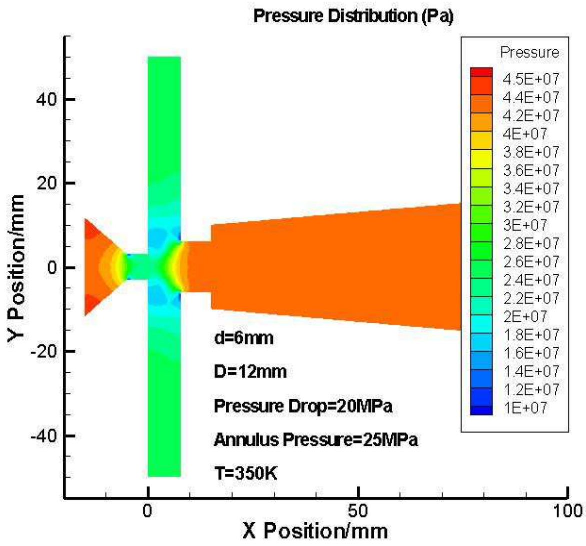

Figure 4. *Cloud atlas of pressure distribution of CO_2 jet.*

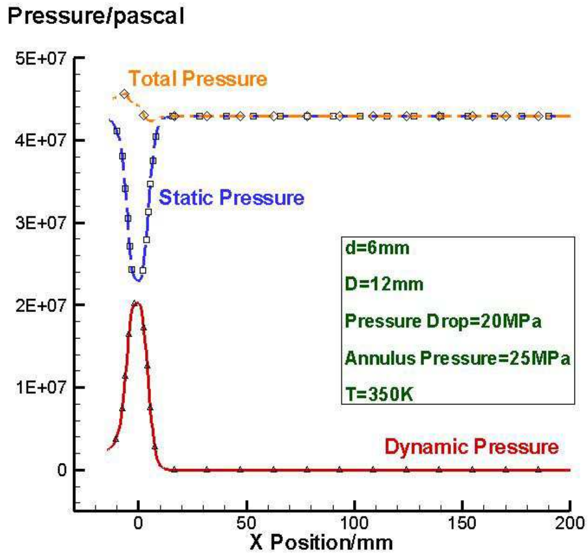

Figure 5. *Distribution of pressure along cavity axis.*

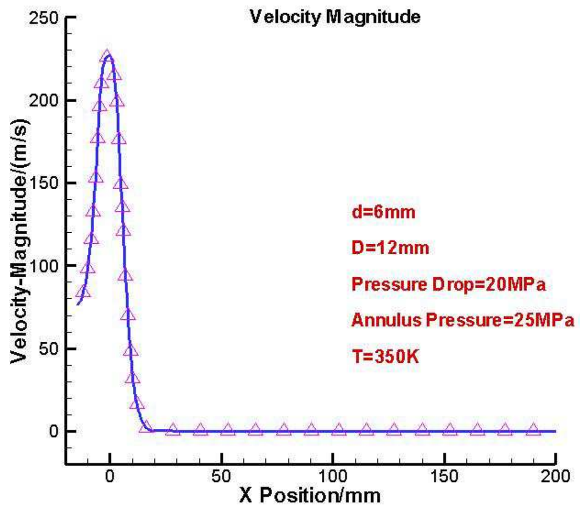

Figure 6. *Distribution of velocity along cavity axis.*

The distribution of total pressure, static pressure, dynamic pressure and velocity along the axis of the hole in supercritical CO_2 coiled tubing fracturing process is studied. The total pressure is directly proportional to the mechanical energy of the fluid and is the sum of static pressure and dynamic pressure. The static pressure is directly proportional to the pressure energy of the fluid, which is the pressure generated by the irregular movement of the fluid molecules. The dynamic pressure is proportional to the kinetic energy of the fluid and is the pressure generated by the fluid flow ($\frac{1}{2}\rho v^2$). As shown in Figure 5 and Figure 6, when the supercritical CO_2 fluid passes through the nozzle and annulus, the static pressure drops sharply from 42.5 MPa to 22.9 MPa, while the dynamic pressure increases rapidly to 20.2 MPa and the flow rate of CO_2 increases rapidly to 226.5 m/s, which is the result of the fluid pressure energy being transformed into kinetic energy. When the supercritical CO_2 high-speed jet enters the casing hole, the static pressure rises, while the dynamic pressure and velocity begin to decline, which is the result of the fluid kinetic energy being transformed into pressure energy. Finally, when the CO_2 fluid stagnates in the channel, the static pressure curve coincides with the total pressure curve because the dynamic pressure drops to 0, and the value is the stagnating pressure (42.9 MPa), 17.9 MPa higher than the annulus pressure (25 MPa), that is, the jet pressurization value is 17.9 MPa. It can be seen that supercritical CO_2 fracturing has a significant jet pressurization effect, which can open the formation under the condition that the annulus pressure is lower than the formation fracture pressure.

In the conversion between dynamic pressure and static pressure, it can be seen that the total pressure drops significantly near the nozzle, which indicates that mechanical energy loss occurs due to the work done by overcoming friction in the flow of supercritical CO_2 fluid. Therefore, the amount of work done by the CO_2 fluid to overcome the friction in the flow will affect the stagnation pressure, that is, the smaller the work done by the fluid to overcome the friction, the greater the stagnation pressure, and the better the pressurization effect of the jet.

4.2.2. Comparison with the Pressurization Effect of Coiled Tubing Hydraulic Fracturing Jet

In order to verify the pressurization effect of supercritical CO_2 coiled tubing fracturing, the author simulated the flow field in the process of supercritical CO_2 coiled tubing fracturing and hydraulic fracturing under the same parameters, and compared the pressurization effect of the two. Figure 7 compares the in-hole pressurization values for the two frac methods at six different nozzle pressure drops. It can be seen that under the same pressure drop, the in-hole pressurization value of supercritical CO_2 coiled tubing fracturing is generally higher than that of hydraulic fracturing. For example, when the nozzle pressure drop is 20 MPa, the pressurization value of supercritical CO2 jet fracturing is 17.9 MPa, which is 2.4 MPa higher than that of water jet under the same condition. It can be seen that supercritical CO_2 coiled tubing fracturing has stronger in-hole pressurization effect than hydraulic fracturing under the same conditions.

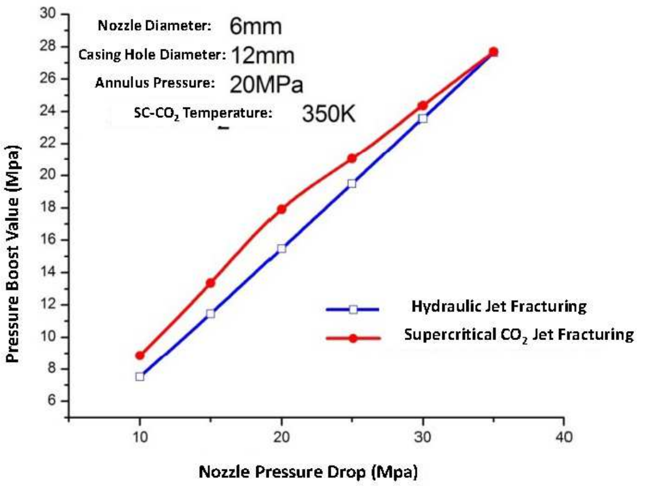

Figure 7. *Boost pressure comparison between SC-CO_2 fracturing and water fracturing with coiled tubing.*

5. Supercritical CO_2 Fracturing Equipment

Supercritical CO_2 coiled tubing fracturing requires approximately the same equipment as CO_2 coiled tubing dry fracturing. The field operation experience indicates that equipment overpressure, sand blocking and difficult sand concentration control are common problems in CO_2 fracturing operation [9], resulting in the difficulty for conventional fracturing equipment to adapt to supercritical CO_2 fracturing, and higher requirements for pressurization and sand mixing equipment and technology are put forward.

In supercritical CO_2 fracturing operation, CO_2 in sand mixing truck needs to keep liquid state under certain pressure and temperature, and proppant needs to be added continuously under such pressure environment. Therefore, conventional sand mixing equipment cannot meet the requirements of operation, and sealed sand mixing equipment that can be pressurized and insulated must be used. In the early stage of CO_2 sand fracturing operation, due to the limitation of technical parameters of sand mixing equipment, the amount of sand added was limited, which significantly affected the productivity improvement. In the first China's field test of CO_2 dry sand fracturing conducted in Sulige Gas Field, the volume of sand mixing equipment used was 10 m^3, the working pressure was 2.5 MPa, the maximum sand transport rate was only 0.5 m^3/min, and the final sand amount was only 2.8 m^3 [10]. Jilin Oilfield and Changqing Oilfield have made many design improvements and filed tests on CO_2 special closed sand mixing equipment [11, 12]. Taking the enclosed sand mixing equipment currently used in Changqing Sulige Gas Field as an example, the maximum volume is 20 m^3, the working pressure can reach 3.5 MPa, the sand transport rate is increased to 1.0 m^3/min, and the maximum amount of sand in field operation is 20 m^3, which further improves the performance. However, considering the amount of sand commonly used in volume fracturing, the current closed sand mixing equipment still cannot meet the needs of large-scale fracturing operations. In addition, in order to pump CO_2 smoothly into the well, surface equipment (such as surface manifolds, high-pressure pumps, etc.) needs to be cooled to prevent CO_2 gasification from affecting pump efficiency. At this point, low temperature liquid CO_2 circulating cooling is needed, usually consuming 40~60 m^3 liquid CO_2, which not only causes waste, but also has certain impact on the environment. In addition, the matched pump set and surface manifolds special cooling devices need to be developed.

6. Field Test of Supercritical CO_2 Fracturing

Supercritical CO_2 fracturing is a new anhydrous fracturing technology after CO_2 dry fracturing. This technology can more accurately describe the phase state of CO_2 acting on the reservoir, and the design of construction technical parameters is more in line with the characteristics of supercritical CO_2. At present, this technology is still in the basic research stage, with only a small number of field tests, all of which are concentrated in China [13, 14].

In May and June 2017, Shaanxin Yanchang Petroleum (Group) Co. conducted a field test of supercritical CO_2 fracturing in each vertical well in a block in Yan'an, mainly verifying the feasibility of supercritical CO_2 fracturing. The fracturing depth of the first well was 2940 m. Conventional hydraulic jet was used for window cutting, and supercritical CO_2 fluid was replaced for fracturing. A total of 386 m^3 liquid CO_2 was injected through tubing and casing. The friction resistance and wellbore temperature profile of supercritical CO_2 along the process were tested in the field, and its sand carrying performance was tested. Field tests show that compared with traditional hydraulic fracturing, supercritical CO_2 fracturing has higher friction resistance, which is mainly reflected in the process of nozzle injection. Under the condition of 8-hole 6.5 mm nozzle with flow rate of 2.7 m^3/min, the friction resistance of slick water jet nozzle is 19.3 MPa, while that of supercritical CO_2 jet nozzle is as high as 27 MPa, resulting in frequent overpressure of ground equipment in the operation. In addition, under the field conditions, the underground CO_2 temperature is higher than the critical temperature, which can meet the temperature conditions required by supercritical CO_2. The sand carrying performance test used low density ceramsite, volume density of 1.45 g/cm^3, sand carrying liquid ceramsite volume fraction is about 3%. Due to the low density and viscosity of supercritical CO_2, frequent sand plugging at fracture ends resulted in overpressure at the wellhead. Later, conventional fracturing fluid was used to carry sand. In addition, microseismic fracture monitoring results show that fracture initiation signals of supercritical CO_2 fracturing show radial dense and uniform distribution in all directions around the wellbore, compared with conventional hydraulic fracturing fracture initiation signals only distribute along the direction of maximum horizontal principal stress (Figure 8). It is further confirmed that supercritical CO_2 fracturing can effectively breakthrough the limitation of stress factors on fracture morphology, which is conducive to the formation of complex fracture networks.

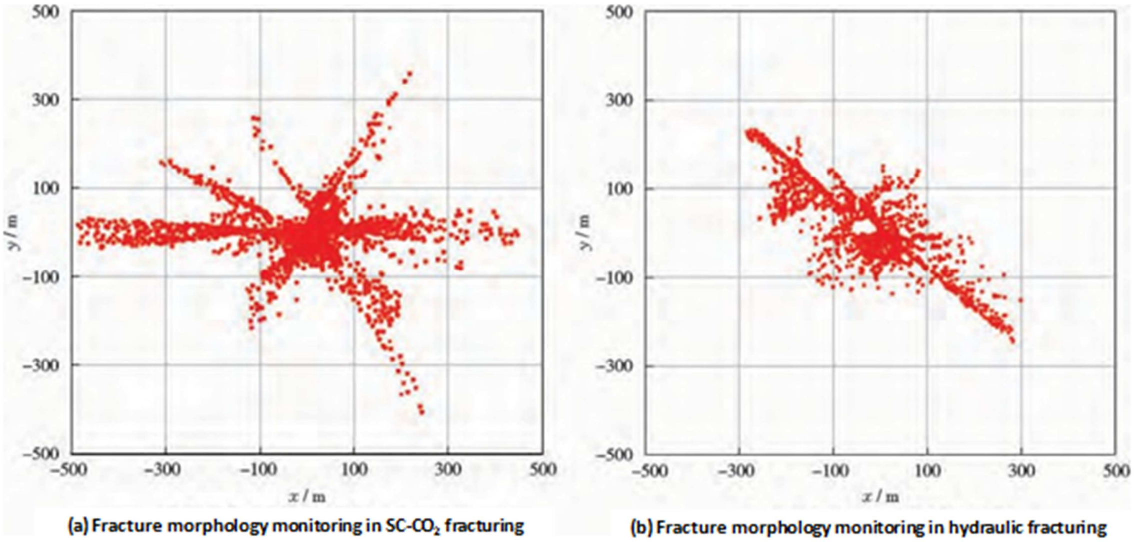

Figure 8. *Comparison chart of micro-seismic crack monitoring data.*

The second test well was also a vertical well, and the test results were basically the same as the first well. Since then, Yanchang Petroleum has carried out field tests on three wells in Yan'an area and achieved good fracturing results.

Although the whole process of supercritical CO_2 fracturing has not been realized in the field tests mentioned above, high stimulation effect has been achieved. Compared to offset wells, the stimulation was more than 40%, providing a significant fracturing advantage. Flowback monitoring data showed that the injected CO_2 was partially sequestered. In addition, the feasibility and development prospects of supercritical CO_2 have also been proved.

7. Conclusion

(1) Supercritical CO_2 can replace water and become the working fluid in shale gas formation fracturing. CO_2 can increase shale gas production through a variety of physical mechanisms, reduce environmental impacts, and hopefully provide CO_2 sequestration during the fracturing phase and after shale gas production.

(2) Supercritical CO_2 coiled tubing fracturing in shale gas formation can give full play to the advantages of supercritical CO_2 fluid characteristics and coiled tubing fracturing technology, and is expected to solve the problems that cannot be solved by conventional hydraulic fracturing technology.

(3) In the process of fracturing, supercritical CO_2 high-speed jet will produce pressurization effect on the perforation channel, so that the formation will be opened under the condition that the casing pressure is lower than the formation fracturing pressure. In addition, supercritical CO_2 coiled tubing fracturing has better jet pressurization effect than hydraulic fracturing under the same conditions.

(4) Compared with water, the properties of supercritical CO_2 are quite different, and conventional fracturing equipment cannot meet the operation requirements, such as sand mixing device, surface circulating cooling equipment, downhole jet fracturing tools, etc. Fracturing opearation also faces many challenges, and it is necessary to develop special surface and downhole equipment combined with the special properties of supercritical CO_2.

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