Key Issues in the Application of Supercritical Carbon Dioxide Fracturing in Unconventional Gas Well

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Abstract. Supercritical carbon dioxide is a promising approach to enhance oil recovery in a greener way compared to conventional fracturing technology. SC-CO\textsubscript{2} fracturing has advantages of the complicated fracture network, low formation pollution, and methane replacement on account of its good performance of permeability, anhydrous fracturing fluid, less chemical additives, and solubility. Technical features and research state of SC-CO\textsubscript{2} fracturing were discussed in this paper. Key issues in the application of SC-CO\textsubscript{2} fracturing was summarized in the following aspects: Flow laws of SC-CO\textsubscript{2} in the wellbore and fracture need to be lucubrated to provide a basis for fracturing design; Interactions between formation rock and SC-CO\textsubscript{2} need to be studied to find the Fracture propagation laws; The proppant-carrying laws need to be explained clearly to form better support effect of the fracture; Effective CO\textsubscript{2} tackifier and ultra-light proppant need to be found to improve the proppant-carrying capacity; SC-CO\textsubscript{2} source and fracturing devices should be further considered to reduce the cost, increase the efficiency ensure production safety of SC-CO\textsubscript{2} fracturing.

1. Introduction
Unconventional resources (including tight gas, shale gas, and coal-bed gas) have already played an important role as the conventional oil and gas resources being exhausted. It is reported that the reserves of global tight gas and shale gas resources are about $665.8 \times 1012$ m$^3$, which is 1.42 times of conventional natural gas resources approximately [1]. Although the abundant reserves of unconventional resources, its characteristics of low porosity, low permeability, and small pore-throat radius make it necessary to develop with the help of fracturing technology [2]. Although hydraulic fracturing could enhance oil recovery effectively, the requirements of the water resources and environmental harm of formation bring a negative effect on the application of technology. Firstly, hydraulic fracturing need to consume 2.3-5.5 million gallons per well approximately [3] which is enormous especially for the wells in water-deficient areas. Secondly, several kinds of chemical additives need to be added into the fracturing fluids which would contaminate formation and environment. Besides, relevant reports indicated that there were some relationships between hydraulic fracturing and triggering earthquakes.
In order to reduce the risk of formation damage and environmental pollution, numerous anhydrous fracturing technologies have been studied, like high energy gas fracturing, CO\textsubscript{2} fracturing, foam fracturing, and LPG fracturing. Supercritical carbon dioxide (SC-CO\textsubscript{2}) fracturing is gradually becoming the main development direction of CO\textsubscript{2} fracturing because of the great characters of environmental protection and resource-saving [4-8]. With better properties of solubility, diffusivity, permeability, flowability, and environmental protection, SC-CO\textsubscript{2} fracturing is regarded as a promising approach to improve EOR in unconventional resources [9-12]. SC-CO\textsubscript{2} fracturing is holding back by the lack of basic research on SC-CO\textsubscript{2} fracturing and exists of some disadvantages although it has been applied in many conditions. Therefore, technical features, strengths, and weaknesses in SC-CO\textsubscript{2} fracturing were studied and the key issues were analyzed in the application of SC-CO\textsubscript{2} fracturing in unconventional oil and gas well which should be drawn more attention in future studies.

2. SC-CO\textsubscript{2} Fracturing

2.1. Technical Features of SC-CO\textsubscript{2} Fracturing
SC-CO\textsubscript{2} fracturing technology is a kind of anhydrous fracturing technology that uses supercritical carbon dioxide (CO\textsubscript{2} above 31.1 °C and 7.38 MPa, shown in figure 1) as the fracturing fluid. Liquid CO\textsubscript{2} was injected into the well with a certain pressure and temperature from the ground powered by the CO\textsubscript{2} pump. CO\textsubscript{2} will reach the supercritical state at some position of the well with the effect of heat transfer. The formation rock would be fractured by SC-CO\textsubscript{2} in a predetermined location, which forms the flow channel from the reservoir to the wellbore. Then proppants with specific fraction will be mixed with SC-CO\textsubscript{2} on the ground and taken to the fracture in the formation rock to prevent the fracture from closure. The physical properties of SC-CO\textsubscript{2} are controlled by temperature and pressure which make many processes transient during fracturing.

![Figure 1. Phase diagram of CO\textsubscript{2}.](image)

Compared to the conventional hydraulic fracturing, SC-CO\textsubscript{2} fracturing has advantages of low formation pollution, more complicated fracture network, and excellent replacement performance of absorbed gas…Specifically, its advantages include the following parts:

- Complicated fracture network. SC-CO\textsubscript{2} has a high diffusion coefficient and low surface tension, which is easy to flow into smaller pores and microfractures. The strength of formation rocks is reduced due to the dissolution of SC-CO\textsubscript{2}, which will make the formation fracture pressure decrease. As a result, the formation rock in which CO\textsubscript{2} enters is more easily to be fractured and complicated fracture network is formed.
- Increase the enhanced oil recovery (EOR). SC-CO\textsubscript{2} have a stronger ability of adsorbability than methane. Methane molecules can be replaced by SC-CO\textsubscript{2} from the surface of the rock on account of the stronger acting forces between SC-CO\textsubscript{2} and the formation rock. The state of methane turns from the adsorbed state to the free state which is beneficial to the increase of EOR.
Low formation pollution. The water lock effect could be avoided in SC-CO₂ fracturing as no water is used in the fracturing. Besides, fewer additives are used in SC-CO₂ compared to hydraulic fracturing, which could prevent the formation from being destroyed.

Increase formation energy. With the variation of pressure and temperature during the fracturing, the volume of CO₂ will increase with the state change. The energy of the formation will be increased with the inflation of CO₂, which is more favorable to gas production.

Sequestration of greenhouse gas. With the aggravation of global warming, it is extremely urgent to find effective ways to deal with greenhouse. The application of SC-CO₂ fracturing could save water and store CO₂ simultaneously, which will be beneficial to improve environmental quality.

However, SC-CO₂ also has some shortcomings that limit the development of this technology.

- Low capacity of proppant-carrying. The density and viscosity of SC-CO₂ are relatively low compared to water. Therefore, SC-CO₂ has a poor transport capacity for proppants which is not conducive to production.
- Corrosive action on fracturing equipment. The fracturing equipment and sealing structure have a risk to be corroded when CO₂ meets water.

2.2. Research State of SC-CO₂ Fracturing
Firstly liquid CO₂ was used as an additive in the fracturing fluid to increase the energy of the oil and gas well in the 1960s [13]. Since then CO₂ has been gradually put into use in the fracturing. Field applications of CO₂ fracturing have been conducted all over the world and achieved good results with the growth of shale gas. Shale gas in Lewis and Devonian was developed with pure liquid CO₂ fracturing [14]. CO₂ fracturing fluid with N₂ as an additive was raised by Mazza [15], which had improved the EOR in many wells of Canada [16]. On-site tests of CO₂ /N₂ foam fracturing techniques were conducted by BJ Company with good performance [17]. Yanchang Petroleum Group of China successfully conducted a field test of SC-CO₂ fracturing in continental shale gas in June 2017 [18]. Numerous studies on SC-CO₂ fracturing have been conducted in recent years, mainly focusing on flow laws of SC-CO₂ in the well and the fracture, the interactions between rocks and SC-CO₂, fracture propagation mechanism, the proppant-carrying laws of SC-CO₂ and the effective tackifiers of SC-CO₂. Although great efforts have been made from these studies, it still has a long way to realize the large-scale application of SC-CO₂ fracturing.

3. Key Issues in SC-CO₂ Fracturing

3.1. Flow Laws in SC-CO₂ fracturing
The temperature and pressure fields are the basis for other studies like the proppant-capacity, fracture propagation mechanism, and so on. The temperature and pressure field in the wellbore and fracture need to be calculated coupled with the flow of SC-CO₂ and heat and mass transfer with the formation rock [18]. Fracturing parameters like injection pressure, temperature, and displacement could be controlled in order to obtain the CO₂ with a specific state. Many studies calculated the temperature and pressure fields, while the models still need to be further amended. A set of temperature fields in fracture of SC-CO₂ fracturing is shown in figure 2.

3.2. The Interactions between SC-CO₂ and Rocks
The physical and mechanical properties of the formation rock are changed after contacting with SC-CO₂, which will affect the effect of fracturing [19]. Besides, the laws of fracture propagation and fracture network are related to the interaction between SC-CO₂ and rocks. Injection parameters could be controlled to form a better fracture network if the interactions between SC-CO₂ and rocks are clarified clearly.
Figure 2. Numerical simulation on the temperature field in the fracture of SC-CO$_2$ fracturing.

3.3. The Proppant-Carrying Capacity of SC-CO$_2$
Low proppant-carrying capacity hampers the application of SC-CO$_2$ fracturing. Therefore, the issue of proppant-carrying capacity is of great significance to this technology [20]. It is meaningful to find the relationships between the injection parameters and the shape of proppant beds so that the relevant parameter could be optimized to form a better flow channel. The changing process of proppant beds is shown in figure 3.

Figure 3. Changing process of proppant beds in the fracture.

3.4. SC-CO$_2$ Tackifier and Ultra-Light Proppant
CO$_2$ tackifier is regarded as an efficient way to increase the viscosity of SC-CO$_2$ to improve the proppant-carrying capacity [8]. Tackifier should have good solubility in CO$_2$. The more effective tackifier is a fluorine-containing copolymer, which is expensive and will destroy the formation. Therefore, new tackifiers with good environmental protection and viscosity increase performance still need to be explored. Besides, ultra-light proppant with lower density is another research direction to improve the effect of fracturing. Low-density proppant is more easily to be carried to the further position of the fracture, which could support the fracture effectively.

3.5. SC-CO$_2$ Source and Fracturing Devices
Large amounts of CO$_2$ will be used in the fracturing on account of the high leak-off effect. At present, CO$_2$ used in the onsite is mainly relied on the transport by tank truck from industrial factories, which cause an increase in the cost of SC-CO$_2$ fracturing. Some scholars put forward that transport pipes can be built from the industrial factories to the gas production areas, while studies on the economics and feasibility still need to be required. Besides, devices of SC-CO$_2$ fracturing are quite different from that
of hydraulic fracturing as the CO$_2$ will be set up to specified temperature and pressure. And fracturing devices should have good corrosion resistance.

4. Conclusions
SC-CO$_2$ fracturing technology has remarkable advantages in reducing rock fracture initiation pressure, increasing fracture network complexity, increasing EOR, and reducing formation pollution. Good performances have been achieved in the onsite test of SC-CO$_2$ fracturing, which demonstrates the great potential of this technology in unconventional gas wells. Basic research is still not yet sufficient to promote the development of SC-CO$_2$ fracturing although numerous achievements have been obtained in the CO$_2$ flow field, proppant-carrying capacity, and so on. In the long run, SC-CO$_2$ fracturing still need to be studied in the following aspects: Flow laws of SC-CO$_2$ in the wellbore and fracture need to be lucubrated to provide a basis for fracturing design; Interactions between formation rock and SC-CO$_2$ need to be studied to find the Fracture propagation laws; The proppant-carrying laws need to be explained clearly to form better support effect of the fracture; Effective CO$_2$ tackifier and ultra-light proppant need to be found to improve the proppant-carrying capacity; SC-CO$_2$ source and fracturing devices should be further considered to reduce the cost, increase the efficiency ensure production safety of SC-CO$_2$ fracturing.

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