Scientific and Social Research, 2024, Volume 6, Issue 2
https://ojs.bbwpublisher.com/index.php/SSR

Research Status and Prospect of Liquid Carbon Dioxide Fracturing Technology

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Abstract: Liquid carbon dioxide fracturing technology has emerged as a novel unconventional method of retrieving oil and gas resources. As carbon dioxide is used as the fracturing fluid, it reduces the dependence on water resources and environmental pollution. The low viscosity and high diffusion properties of liquid carbon dioxide allow it to penetrate rocks more effectively, improving the efficiency of oil and gas extraction. In addition, the technology has potential carbon dioxide sequestration benefits that could help mitigate climate change. However, liquid carbon dioxide fracturing technology still faces challenges in terms of cost, technology maturity, and environmental impact. At present, academia and industry are actively engaged in research to improve the feasibility and economics of this technology, with the goal of providing new solutions for the sustainable development of energy in the future. This paper focuses on the research status and prospect of liquid carbon dioxide fracturing technology.

Keywords: Liquid carbon dioxide; Fracturing technology; Current status and prospect

Online publication: February 28, 2024

1. Introduction

The biggest advantage of liquid carbon dioxide fracturing over traditional water-based fracturing is its environmental friendliness and efficiency. Carbon dioxide as a fracturing medium not only reduces water consumption and pollution but also utilizes carbon dioxide stored underground, thereby reducing greenhouse gas emissions.

Liquid carbon dioxide infusion can reduce the risk of underground gas explosions by injecting liquid carbon dioxide into the air mining domain because liquid carbon dioxide has a high degree of infiltrability, which can drive the gas out of the coal seams, thus reducing the possibility of gas explosions [1]. However, although this technology shows great potential and advantages, there are still many problems in its practical application. Looking to the future, the development of this technology will inevitably be influenced by a variety of factors such as energy policy, market demand, and technological advances, thus placing greater demands on researchers and industrial practitioners.

2. Research status of liquid carbon dioxide fracturing technology

2.1. Carbon dioxide dry fracturing

Carbon dioxide dry fracturing technology, as an emerging method for oil and gas field extraction, uses pure liquid carbon dioxide instead of traditional water-based fracturing fluids. The development of this technology has benefited from advances in the research and development of thickeners and proppants. Domestic and foreign scholars have developed fluoropolymers, polysiloxanes, polyesters, and other types of thickeners (**Table 1**), which play a key role in increasing the viscosity of liquid carbon dioxide. Innovations in proppant, such as the new self-suspended low-density proppant with an apparent density of 0.95–1.05g/cm³ mark a major breakthrough in carbon dioxide dry fracturing technology. This new proppant combined with liquid carbon dioxide creates an effective dry fracturing process. In the application of prolonged shale gas reservoirs, this technology has successfully realized sand ratios of up to 10%. However, carbon dioxide dry fracturing technology still faces several challenges in terms of scaling up its application. The low viscosity of liquid carbon dioxide results in poor sand-carrying capacity, limiting the scale of construction. An effective viscosity-increasing technology is yet to be developed. Since 2013, although more than 10 wells have been built, the sand ratio is still less than 15%, indicating that the scale of reservoir modification is severely limited.

Table 1. Carbon dioxide thickener research status

Type	Thickener	Dosage (%)	Cosolvent	Effect (times)
Fluoropolymers	[1,6-Bis(1,3-diperfluorooctanoic acid propyl-2-ureido)]hexane	2	/	39
	P(HFDA0.0.28-co-MM0.72), P(HFDA0.26-co-EAL0.74)	5	/	51, 87
	P(HFDA0.49-co-VAc0.51)	5	/	62
Polysiloxane	Aminopropyltriethoxysilane copolymerized with methyltriethoxysilane	3	/	5.7
	Polydimethylsiloxane	5	10% toluene	40
	Hyperbranched siloxane	1	/	19.3
Polyesters	Benzoyl-vinyl acetate cool copolymer	1-2	/	40–80%
	Four-armed polyvinyl acetate (PVAc)	1	5% ethanol	31–35%

2.2. Carbon dioxide foam fracturing technology

Natural gas hydrate films can be grown at the interface between liquid carbon dioxide and water and sodium dodecyl sulfate solutions [2]. Carbon dioxide foam fracturing is an emerging method for oil and gas field extraction that utilizes carbon dioxide foam as a fracturing medium to increase fracturing efficiency and reduce environmental impact (**Table 2**). In recent years, the direction of research has gradually shifted from traditional high-viscosity foam systems to polymer-free foam systems and nanoparticle-enhanced foam systems. The development of polymer-free carbon dioxide foam fracturing fluid systems is a key area for the advancement of this technology. For example, a polymer-free carbon dioxide foam fracturing fluid system formulated with 0.5% α-olefin sulfonate + 0.5% betaine performed close to conventional polymer-stabilized foam systems under high-temperature, high-pressure, and high-shear conditions. This polymer-free foam system is environmentally friendly and cost-effective. The incorporation of nanoparticles further enhances the stability of the carbon dioxide foam. The addition of SiO_2 nanoparticles to α-olefin sulfonate solutions significantly improves the stability of carbon dioxide foams, although the half-life of the foam decreases with increasing temperature. A study found that SiO_2 nanoparticles could enhance the interfacial viscoelastic modulus and foam stability of succinate sulfonate foam systems at high temperatures and pressure. When the foam mass fraction was 50–93%, 0.5% SiO_2 nanoparticles increased the foam viscosity by 2.2–4.8 times [3] A researcher proposed that liquid carbon dioxide can be used as an additive in concrete and cementitious paste to positively improve its properties and microstructure [4].

Table 2. Overview of carbon dioxide foam fracturing technology

Feature	Advantage	Disadvantage	Areas of application	Future development
Environmental friendliness	Reduces dependence on water resources and environmental pollution	The technology is relatively new and its feasibility needs to be further validated	Ecologically sensitive area	Continuous optimization of environmental performance
Efficiency	Improves crack formation efficiency and rejection speed	High requirements for equipment and operating skills	Unconventional oil and gas reservoirs	Improved operational efficiency and reliability
Applicability	Suitable for complex geological conditions	Only applicable to reservoirs with certain properties	Low permeability reservoir	Adaptation to a wider variety of reservoirs
Technical difficulty	Capable of forming more complex crack networks	Difficulty in controlling foam quality	Repeat fracturing wells	Streamlining the technical operation process
Cost	Offers long-term economic benefits	Higher initial investment compared to traditional technologies	Highly water-sensitive reservoirs	Reduced costs and improved economy

2.3. Hybrid carbon dioxide fracturing

The storage efficiency and safety of liquid carbon dioxide can be optimized by adopting different liquefaction methods, which in turn improves the economy and reliability of the whole system [5]. There are two types of carbon dioxide hybrid fracturing techniques: front and mix injection. In front-end energized fracturing, carbon dioxide is used as a front-end fluid to create complex fracture structures. Subsequently, conventional fracturing fluids are used as sand-carrying fluids to expand the reservoir reforming volume and near-well conductivity. The main advantages of this approach are increased reservoir energy, improved return efficiency, and reduced reservoir damage. In-depth theoretical and experimental studies have been carried out on hybrid carbon dioxide fracturing technology. Studies have shown that liquid carbon dioxide leaching can be used for experimental studies on the evolution of organic groups in coal rock[6]. The nature and behavior of liquid carbon dioxide freeze-thaw cracking coal bodies are affected by multiple factors. Carbon dioxide permeates microfractures more readily than water-based fluids and that its low viscosity allows for fracture complexity by increasing the surface area of modified fractures and fracture density[7]. Carbon dioxide has higher unpropped fracture conductivity than slickwater. An experimental study and numerical simulation of the carbon dioxide front-energized fracturing process in tight reservoirs. The results showed that carbon dioxide immersion can form complex fracture structures on the rock surface and significantly increased the permeability of the core. The front-end carbon dioxide-enhanced fracturing process increased production by more than 15% in the first year compared to normal fracturing. For fracturing new wells, it is recommended to use the "fracturing fluid + carbon dioxide + fracturing fluid" method. In contrast, for fracturing old wells, it is recommended to use the "carbon dioxide + fracturing fluid" method. Although the carbon dioxide hybrid fracturing technology is relatively mature and relevant technical specifications have been formed (e.g., DB61/T1189-2018 "Technical Specification for Front-End Carbon Dioxide Hybrid Fracturing") [8], further research on this area is still needed.

3. Prospects of liquid carbon dioxide fracturing

3.1. Yield increase

The properties of liquid carbon dioxide can be used to improve the cracking process of coal bodies and reduce the generation of coal dust in coal mine production. Besides, it also improves the efficiency and safety of coal mine production [9]. The use of solar and wind energy in conjunction with liquid carbon dioxide storage systems could result in a stable power supply [10]. Liquid carbon dioxide fracturing technology, especially supercritical carbon dioxide fracturing, is expected to play an important role in oil and gas extraction in the future. Supercritical carbon dioxide, with its zero surface tension and excellent fluidity, can penetrate microfractures that are difficult to reach with conventional fracturing fluids, thus greatly improving reservoir efficiency and fracture network formation. Due to its ability to flow into tiny spaces in the reservoir, this fracturing technique can effectively retrieve hydrocarbon resources that cannot be obtained using conventional techniques. This technique is particularly valuable in the development of unconventional oil and gas resources such as shale gas, which often have complex fracture networks and low permeability. Supercritical carbon dioxide allows the maximum utilization of existing fracture networks or even the formation of new ones, thus increasing recoverable reserves of hydrocarbons. Studies have shown that supercritical carbon dioxide shows better penetration in less permeable rocks. This implies that supercritical carbon dioxide fracturing may be more effective than conventional water-based fracturing or liquid carbon dioxide fracturing in low-permeability rocks such as shales. In addition, supercritical carbon dioxide can reduce the viscosity of oil and gas, further improving the fluidity and recovery of these resources. Research has shown that the construction of a liquid carbon dioxide energy storage system is technically feasible [11]. However, there are still several technical and economic challenges that need to be overcome to popularize supercritical carbon dioxide fracturing. For example, more efficient and less costly recovery and treatment technologies need to be developed to ensure economic viability. Meanwhile, an in-depth understanding of the flow of supercritical carbon dioxide and fracture formation mechanism under different geological conditions is crucial for optimizing the fracturing design and improving the fracturing effect.

3.2. Construction pressure

The phase transition characteristics of liquid carbon dioxide play an important role in rock fracture and the development of mining and underground engineering [12]. The rock-breaking capacity and mobility of supercritical carbon dioxide, especially in terms of construction pressure, are key to the future development of this technology. Supercritical carbon dioxide can effectively break rocks at lower pressures. For example, supercritical carbon dioxide requires only half or less the pressure of water to break shale rocks. This is particularly important in oil and gas field exploitation as it means that lower construction pressures can be used, thus reducing stresses on the wellbore and formation and construction risks. In addition, the frictional resistance of supercritical carbon dioxide is lower than that of liquid carbon dioxide. This property further reduces energy consumption and costs. The high frictional resistance of conventional dry fracturing with liquid carbon dioxide results in higher energy consumption and construction costs. Supercritical carbon dioxide can achieve higher flow efficiencies with lower pumping energy due to its lower frictional resistance, which is crucial in oil and gas field extraction, especially in the development of deep or low-permeability reservoirs. Despite the significant potential of supercritical carbon dioxide fracturing to reduce construction pressures, its technical and safety challenges are still noteworthy. For example, the temperature and pressure of the fracturing fluid need to be precisely controlled to maintain the supercritical state of the carbon dioxide. The high-pressure and low-temperature of liquid carbon dioxide require special equipment and technology to ensure safe transportation, or else accidents may occur, jeopardizing the lives of the employees and the safety of the mine [13]. In addition, the equipment and materials used should be able to accommodate the properties of supercritical carbon dioxide.

3.3. Key equipment

Research progress on conjugated heat transfer between supercritical carbon dioxide and liquid metals has been discussed in a paper [14]. Additionally, researchers have also reviewed the coupled heat transfer characteristics of supercritical carbon dioxide and liquid lead-bismuth-eutectic in asymmetric compact heat exchange [15].

Improvements in equipment for handling supercritical carbon dioxide involve several key aspects. These include enhancements in sand mixing equipment, which benefit from the higher initial temperature of the supercritical carbon dioxide, reducing the risk of sand freezing in the mixer and allowing for smoother sand feeding and homogeneous mixing. Additionally, precise control of carbon dioxide phase changes is essential for enhancing process efficiency and reliability. Moreover, ensuring high sealing and puncture resistance for fracturing construction equipment is crucial to maintaining safety and effectiveness during operations involving supercritical carbon dioxide. These advancements collectively contribute to the improved handling and utilization of supercritical carbon dioxide in various industrial processes. One of the primary challenges of supercritical carbon dioxide fracturing technology is effectively controlling the phase change of carbon dioxide, particularly in shallow wells where achieving spontaneous phase change within the wellbore is challenging. Efficiently and uniformly heating the carbon dioxide becomes crucial in such scenarios, representing a key aspect in the advancement of this technology. Achieving consistent and controlled phase changes is essential for optimizing the effectiveness and reliability of supercritical carbon dioxide fracturing operations. Precise temperature control is essential to maintain the stability of the supercritical carbon dioxide. In addition, due to the penetrating nature of supercritical carbon dioxide, higher requirements are placed on the sealing and puncture-proof performance of fracturing construction equipment. This requires the development and application of novel materials and technologies to ensure operational safety and reliability in high-pressure and high-temperature environments. In terms of viscosity enhancement, the advanced fatty acid ester thickener developed by the Fracturing and Acidizing Laboratory of China University of Petroleum (Beijing) can effectively improve the viscosity of supercritical carbon dioxide. This breakthrough is important for improving the sand-carrying capacity and fracturing effectiveness of supercritical carbon dioxide. Overall, despite the many challenges in supercritical carbon dioxide fracturing technology, it shows significant potential to improve the efficiency and environmental sustainability of oil and gas field extraction. Future research will focus on improving the design of key equipment, increasing the efficiency of viscosity enhancers, and optimizing phase change control techniques for carbon dioxide. As these technical challenges are overcome, supercritical carbon dioxide fracturing technology is expected to play an even more important role in oil and gas extraction in the future.

4. Conclusion

Liquid carbon dioxide fracturing represents a promising method of oil and gas extraction that is environmentally friendly, efficient, and sustainable. The study of carbon dioxide dissolution processes in liquid methane is crucial for understanding gas exchange and reservoir behavior in natural gas reservoirs [16]. Besides, integrating solar energy with liquid carbon dioxide storage systems in charging stations can provide a sustainable energy supply [17]. Despite some challenges, through continued research and innovation, this technology is expected to make even greater breakthroughs in the future, opening up new possibilities in the field of energy development. Moreover, with the improvement of policies and regulations, liquid carbon dioxide fracturing technology will gradually mature and contribute to the sustainable development of the energy industry.

Disclosure statement

The author declares no conflict of interest.

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