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Experimental study on fracture initiation and propagation in shale using supercritical carbon dioxide fracturing

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HIGHLIGHTS

- SC-CO_2 fracturing experiments with shale were conducted for the first time.
- AE tests, DR and CT scans were used to observe fracture morphology.
- The fracture initiation and propagation of SC-CO_2 fracturing was compared with hydraulic fracturing.
- Multiple factors influencing propagation were studied.

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ABSTRACT

Supercritical carbon dioxide (SC-CO_2) fracturing is a promising technology for developing shale gas because it can effectively solve problems related to shale swelling and lack of water resources. This work conducted simulation experiments on SC-CO_2 fracturing in shale for the first time. Compared with hydraulic fracturing, using SC-CO_2 as the fracturing fluid reduces the pressure needed to initiate fractures by more than 50%. This reduction is due to the increased percolation and pore pressure effects of using SC-CO_2. Acoustic emission tests were used to monitor the progress of fracturing in shale and high-energy CT scanning documented fracture morphology. CT scanning shows that SC-CO_2-induced fractures are irregular multiple cracks. These numerous crooked cracks are more likely to induce secondary fractures in shale and to connect with natural fracture and bedding to form complex fracture networks than those formed by hydraulic fracturing. The volume of rock fractured by SC-CO_2 is several times that fractured by hydraulic fracturing and the surfaces of the fractures opened by SC-CO_2 are more complex and rugged. SC-CO_2 fracturing can achieve better fracture networks for reservoir stimulation in shale than in sandstone, and the degree of bedding development has a great influence on the complexity of the SC-CO_2 induced fractures. Namely, using SC-CO_2 as fracturing fluid can increase fracture conductivity and hence achieve increased shale gas production. This study also determined how fractures propagate under different horizontal stress regimes.

1. Introduction

Shale gas, an important supplement to conventional energy resources, has been paid considerable attention in recent years [1,2]. China has shale gas resource of 3.16×10^{13} m^3 and has the great potential for developing shale gas in the world [3,4]. Horizontal drilling and multistage hydraulic fracturing are the main technologies used to increase commercial shale gas production in North America [2,5–7]. However, most shale reservoirs in China have high clay contents and low or ultra-low permeability [7,8]. Using hydraulic fracturing in China will cause swelling clays to obstruct gas channels. It will be difficult to increase gas production from reservoirs with low permeability because of low injectivity and poor sweep efficiency in the fracture network [9,10]. In addition, most shale reservoirs with good prospects for development in China are located in water-deficient areas. Attempts to employ large-scale reservoir fracturing programs in these areas would be faced with serious water supply and pollution problems [5,9]. Middleton et al. [5] have put forward a non-aqueous method for fracturing shale using supercritical carbon dioxide (SC-CO_2) as a

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fracturing fluid. This proposal received much attention from commercial enterprises and researchers from all over the world [8,10,11]. Supercritical carbon dioxide is a fluid with low viscosity like a gas and high density like a liquid [11], and it has many potential advantages as a fracturing fluid [5]. Among those advantages are increasing regained permeability, avoiding problems with swelling clays, and enhancing desorption of CH_4 from the organic present in the shale [1,12,13]. Enhanced desorption occurs because CO_2 has a greater adsorption capacity than does CH_4 so it replaces the methane and thereby increases gas production and recovery [13]. At the same time, the use of CO_2 fits global environmental policies and has benefits in terms of controlling a greenhouse gas. If SC-CO_2 is an effective fracturing fluid, shale could become major hosts for geological carbon storage [14].

Because the SC-CO_2 fracturing method had just put forward, research on it is still in its infancy. Verdon et al. [15] carried out fracturing experiments using both CO_2 and an aqueous fluid to stimulate reservoirs. Their results showed that CO_2 fracturing can achieve effect of hydraulic fracturing with the same injection pressure and injection rate. Water and SC-CO_2 have completely different physical properties and these differences cause them to behave differently as fracturing fluids. Ishida et al. [16] conducted an experimental study with SC-CO_2 and liquid CO_2 fracturing granite and compared with hydraulic fracturing. Their study indicates that the breakdown pressures needed for SC-CO_2 and liquid CO_2 fracturing were smaller than those needed for hydraulic fracturing. To date there have been just a few published reports on fracture propagation and fracture network geometry of SC-CO_2-fractured shales. Fracture propagation mechanisms and the morphology of fracture networks are very important for evaluating fracturing [17] and determining the feasibility of SC-CO_2 fracturing technology.

Considerable research on hydraulic fracture propagation mechanism in oil and gas reservoirs has been carried out [18–22]. It is generally believed that horizontal ground stress difference is the major factor influencing fracture propagation [18,19]. In addition, fracture propagation is related to sedimentary rock brittleness, elastic modulus, fracture toughness, pre-existing natural fracture systems, and rheological behavior of the fracturing fluid [20–24]. In the reservoirs with natural fractures and beddings development, when the propagation of hydraulic fracture intersects with natural fracture, the hydraulic fracture will bifurcate and change direction to form a nonplanar and multistranded fracture network [22,25]. Multiple hydraulic fracture propagation phenomena are observed in the laboratory experiments of hydraulic fracturing in shale because of its natural fracture and bedding [22,25,26]. Moreover, the fracturing fluid of low viscosity is more likely to connect with natural fracture due to its high percolation and make shear sliding in brittle rock to form complex crossed fracture networks with many secondary branches, while viscous fracturing fluid tends to generate thick and planar fractures with few branches [27]. The formation of complex networks can enlarge the stimulated reservoir volume, make the fluid in matrix infiltrate along the shortest distance, and reduce the driving pressure difference required for oil and gas flow [28]. In extremely low-permeability reservoirs such as shale, fracture-pattern complexity can lead to the increase of total production and ultimate recovery [26].

Research on the complexity of fractures by SC-CO_2 fracturing in shale is essential for the development of SC-CO_2 fracturing technology in shale reservoirs, and the results will provide guide for designing shale fracturing programs and aid in shale fracture network morphology control. Laboratory hydraulic fracturing experiments on coal, sandstone, and shale have been carried out by many researchers to investigate fracture initiation and propagation under different conditions [6,22,29,30]. Experiments to simulate SC-CO_2 fracturing in shale are intuitive and effective means to study crack propagation.

The aim of this paper is to investigate the differences and similarities of fracture propagation by SC-CO_2 fracturing and hydraulic fracturing. SC-CO_2 fracturing and hydraulic fracturing experiments were conducted on both shale and sandstone specimens. The fractures in the specimens were monitored by acoustic emissions (AE) during the experiments. The experiments explored the influence of fracturing fluid composition, bedding features, and horizontal stress differences on fracture propagation and morphology of the fracture network. After the experiment was run, nondestructive high-energy computed tomography (CT) and digital radiography (DR) scanning were carried out to observe the morphology of fracture networks.

2. Experiments

2.1. Test apparatus and sample preparation

A diagram of the system used for the fracturing experiment is shown in Fig. 1. Laboratory equipment used for the experiments included a triaxial loading system using three hydraulic jacks, a thermotank, a carbon dioxide plunger pump, a CO_2 heating unit and a temperature pressure data collection device. The fracture detection devices included an AE system, a large-scale nondestructive CT scanning system (9 MeV), and a DR scanning system. The plunger pump was an ISCO syringe pump (model 260D, Teledyne, Thousand Oaks, CA, USA) with a maximum pressure of 51.7 MPa and a maximum flow of 107 ml min^{-1} and can be used for either CO_2 or distilled water. The pressure data collection used a pressure transducer with a range of 0–34.5 MPa and an accuracy of 7 kPa. A temperature transducer with a range of 0–200 °C and an accuracy of 0.1 °C was used to detect the inlet temperature of CO_2 injected into the specimens.

Samples of shale were collected from outcrops of the Lower Silurian Longmaxi Formation in the Sichuan basin, China. Shale mineralogy is about 3.8% plagioclase, 11.7% calcite, 40.2% quartz, and 15.1% clay minerals, belonging to brittle rock [31]. The shale samples were wet cut into 200 mm × 200 mm × 200 mm cubes and naturally air-dried. A hole 15 mm in diameter and 110 mm in length was drilled at the center of each cube. The holes were oriented perpendicular to bedding planes and designed to simulate a drill hole. A special glue was used to seal the upper portion of the hole 90 mm leaving an open hole length 20 mm.

2.2. Experiment design

According to data from a shale gas well in the Sichuan basin, the maximum horizontal principal stress in the Longmaxi Formation is 40.51–56.48 MPa, the minimum principal stress is 30.06–32.51 MPa, and the horizontal stress difference coefficients range from 0.24 to 0.74. Where the burial depth of shale reservoirs is more than 1000 m, the injected CO_2 will be a supercritical fluid under reservoir conditions but a liquid when used in shallower reservoirs [16]. The experiments were conducted under different horizontal stress conditions and were designed to test shale and sandstone fracture propagation using water, liquid CO_2 (L-CO_2), and SC-CO_2 as fracturing media. The conditions under which the experiments were run are shown in Table 1. Considering the inhomogeneity of shale specimens, experiments under experimental conditions 1#, 2#, and 3# were repeated three times to investigate the initiation pressure using three different fracturing fluids.

2.3. Experimental procedures

The physical properties of SC-CO_2 are very sensitive to changes in temperature [32]; thus the temperature of SC-CO_2 and the specimen