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Impairment mechanism of thickened supercritical carbon dioxide fracturing fluid in tight sandstone gas reservoirs

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ABSTRACT

Non-aqueous supercritical CO_2 ($scCO_2$) fracturing stimulation techniques have acquired much attention in the development of tight gas reservoirs recently. However, few researches have devoted to the impact of $scCO_2$ fracturing fluid on permeability and relevant mechanisms. In this study, phase behaviors of thickener polydimethylsiloxane (PDMS) and co-solvent kerosene in $scCO_2$ were studied. The regained permeability investigations reveal that the low filtrated volumes of $scCO_2$ fracturing fluid have instant and major deterioration of sandstone permeability. The regained permeability ratio reaches the equilibrium with the further increase of filtrated volumes. The compositions of $scCO_2$ fracturing fluid also have impact on the regained permeability. Another regained permeability tests demonstrate that slick-water causes more permeability damage to lower-permeable samples, while $scCO_2$ fracturing fluid causes more permeability damage to higher-permeable samples. The relevant mechanisms are proposed. XRD in clay swelling tests detects the existence of the clay minerals in the tight sands and eliminates the potential of clay swelling effect of $scCO_2$ fracturing fluid. Our investigations indicate the operational feasibility of $scCO_2$ fracturing fluid in tight gas reservoirs and the addition of high content of co-solvent should be avoided as to maintain the low permeability damage to gas reservoirs.

1. Introduction

CO_2 has played versatile roles in enhanced oil recovery (EOR), such as CO_2 miscible flooding and CO_2 foam flooding, due to its unique properties, including nontoxic, inexpensive, volatile, nonflammable, readily available in large quantities. It also has an easily accessible critical temperature (31.1 °C) and pressure (7.38 MPa) [1,2]. Since the first publication of CO_2 fracturing stimulation in 1982 [3], there have been hundreds of treatments in Canada, demonstrating the operational feasibility and effectiveness of CO_2 fracturing stimulations [4–8]. In this process, CO_2 can be injected in liquid, dense, or supercritical states, but mostly in supercritical state under normal reservoir conditions. Supercritical CO_2 ($scCO_2$) fracturing fluid, as one of non-aqueous fracturing techniques, has attracted considerable attention [9,10]. However, its effectiveness as a fracturing fluid has been doubted since its first application, due to the low viscosity (0.04–0.10 mPa·s) of CO_2 under reservoir conditions. Many studies have been conducted over the past decades in search for methods to increase the viscosity of $scCO_2$ [11–16]. Polydimethylsiloxane has been identified as an effective thickener for $scCO_2$ with the presence of toluene by Bae and Irani in 1993 and the viscosity of $scCO_2$ was increased from 0.04 mPa·s to 1.2 mPa·s at the polydimethylsiloxane concentration of 4.0% [14].

For a hydraulic fracturing fluid, chemicals, like guar gum or gels, are always employed to reduce the filtration of fracturing fluid and improve its proppant-carrying ability. However, these additives, along with liquid blockage and water sensitivity, can damage the reservoirs seriously [17–19]. The impairment mechanism is rarely studied. In the past, many studies have been conducted to shed light on the impact of conventional fracturing fluids on the matrix of reservoirs. The presence of invading liquid can transfer the petrophysical properties of matrix near fractures and damage the conductivity of the matrix near wellbore through various mechanisms. Such damages, including fracturing face damage, relative permeability hysteresis and water blockage, have been identified to pose a considerable impact on gas production [20–22]. The presence of the trapped water intensifies the formation blockages, resulting in a reduction in relative permeability to gas in the invaded zone [23]. Other problems related to fracturing fluid leak-off is clay swelling. Clay dispersion can also hinder gas permeability due to fracturing fluid invasion in a clay-rich formation [17]. Spontaneous imbibition accounts for a significant impact on the retention of water-based

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fracturing fluids in the matrix near the induced fracture [24]. However, few studies of these categories have been conducted to investigate the impact of $scCO_2$ fracturing fluid on tight sandstones after filtration during tight gas fracturing process. Because of this, some mechanisms related to $scCO_2$ fracturing fluid on tight sandstones remain unclear.

In this study, a novel $scCO_2$ fracturing fluid was prepared using polymeric thickener polydimethylsiloxane (PDMS), co-solvent kerosene and $scCO_2$. Cloud points of PDMS, kerosene and $scCO_2$ ternary systems were measured. A series of regained permeability tests of tight sandstones were conducted to study the impact of fluid compositions and filtrated volumes on regained permeability. After that, a suitable formula as well as slick-water were selected to study the impact of sandstone permeability on regained permeability. Combined with XRD investigation, the permeability damage mechanisms of clay swelling caused by $scCO_2$ fracturing fluid on tight sandstones are proposed.

2. Material and methods

2.1. Material

CO_2 (99.9% mass purity) used in the experiments was supplied by Tianyuan Gas Co., Ltd. (Qingdao, China). PDMS (99% mass purity) was purchased from Dow Corning Co., Ltd. (Shanghai, China). Kerosene (99.9% mass purity) were provided by Lanzhou refinery Co., Ltd. (Lanzhou, China). Outcrop sandstone cores were purchased from Shengweijiye Technology (Beijing) Co., Ltd. Montmorillonite sample (90% mass purity) was generously donated by Kunyao Technology Development (Guangxi) Co., Ltd. And the slick-water sample was obtained from Orient Baolin Technology Development Co., Ltd. (Beijing, China).

2.2. Phase behaviors of PDMS in $scCO_2$ with co-solvent

The experimental apparatus for phase behaviors is illustrated in Fig. 1, which mainly comprises of a variable-volume visualized PVT cell and a computer for data processing. The PVT cell contains four visualized windows (2 for front viewing and 2 for back lighting), a moving piston with a hand pump, a magnetic stirrer and a motor for stirring. The software collects experimental data from two sensors, including temperature sensor with the accuracy of 0.1 °C and pressure sensor with the accuracy of 0.02 MPa. The experimental process of phase behaviors is described below:

1) Certain amounts of co-solvents and polymers are first added into the PVT cell, and then CO_2 is pumped into the cell at the required temperature (52 °C) and pressure of 10.00 MPa.
2) Then the hand pump is used to compress the mixtures, and the mixtures are fully stirred at a high speed (750 rpm) for 10 min to achieve equilibrium. After dissolution equilibrium is attained, the pressure is reduced at a decrement of 0.10 MPa to determine cloud points of the co-solvent and the polymer in $scCO_2$ and this operation is repeated three times to eliminate random errors.
3) The compressed mixture is discharged through the vent line, and the PVT cell is cleaned with the same co-solvents thoroughly and dried by air.

Before each solubility measurement, the desired mass of polymers and co-solvents are weighed by an analytical balance (PL 403, Mettler Toledo Instruments Co., Ltd.) which has an accuracy of 0.001 g.

2.3. Regained permeability measurements of tight sandstones

Before the regained permeability tests, porosity and permeability of these samples were measured with the helium porosity measuring instrument (PMI-100, Yineng Petrotech Co., Ltd.) and the gas permeability measuring instrument (ULP-613, Yineng Petrotech Co., Ltd.).

Basic parameters of tight sandstone samples used in this study are presented in Table 1. And one sample of this kind was selected to conduct the pore size analysis using a mercury intrusion porosimeter (AutoPore IV 9500, Micromeritics Instrument (USA) Co., Ltd.) which reveals the sandstone sample has a median pore diameter of 42.89 μm and pore size distribution of this sample is presented in Fig. 2.

In the proposed experiments, every sample was exposed to fracturing fluid on one of its sides to trigger filtration and migration into the matrix. A back pressure of 24.00 MPa was imposed on the outlets of the tight sandstones to simulate the reservoir pressure with a back-pressure

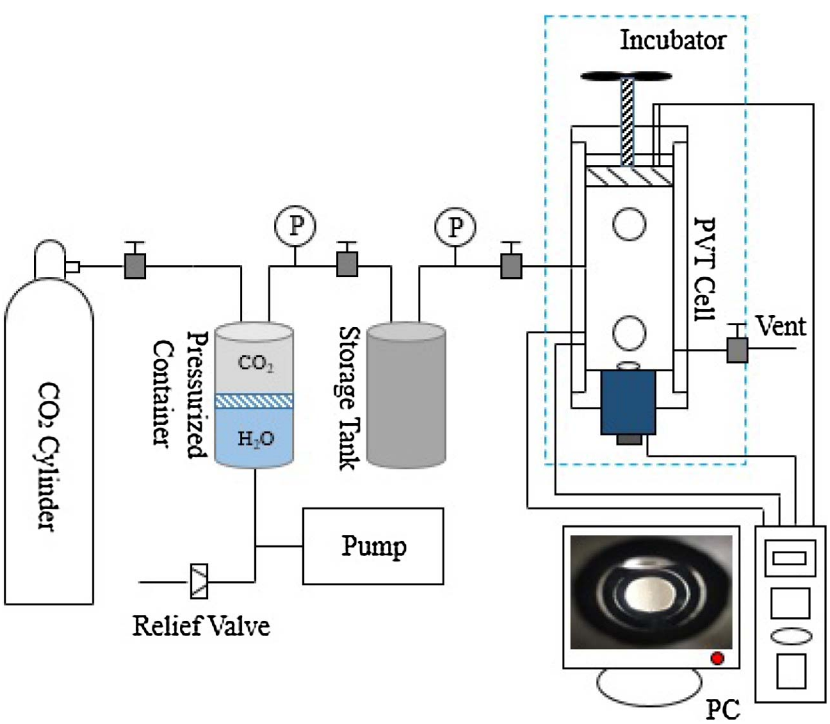

Fig. 1. The experimental apparatus of phase behaviors mainly comprises of CO_2 cylinder, a high-pressure container, a piston pump, a storage tank, a PVT cell, a computer and an incubator.