Experimental Study on the CO₂ Fracturing Mechanism

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ABSTRACT
The amount of CO₂ being used as fracturing fluid has been more than 30,000 tons at Changqing oilfield in 2022, which above several times over the sum of the last five years. A serials of experiments and experimental analyses devoted to the CO₂ fracturing mechanism were conducted in order to provide some advices for the CO₂ fracturing treatment design and improve the well performance. An experimental analysis of the CO₂-core leakoff experiments was made which compares the leakoff characteristics under the liquid and gas phase of CO₂. The plot for the square-root time vs. leakoff rate be got. Two sets of CO₂ fracturing physical simulation experiments on the cores of 762 × 762 × 914.4 mm were carried out, which compares the fracture's geometry and size with the slick water's experimental results. The mechanism of rock breakdown pressure's decrease with CO₂ fluid is researched based on the Elasticity mechanics and the Fracture Mechanics theory. The results show that CO₂ has a very high leakoff rate within the core which leads to a lower breakdown pressure value and a smaller fracture size and an excellent capacity for complicating the rock's fractures than the conventional fracturing fluid.

Keywords: CCUS, CO₂, CO₂ fracturing, CO₂ leakoff, leakoff experiment, fracturing simulation

1. INTRODUCTION
More and more CO₂ being used as fracturing fluid in oilfield in recent years. The amount of CO₂ being used as fracturing fluid has been more than 30,000 tons at Changqing oilfield in 2022, which above several times over the sum of the last five years. An enhancement for the fracturing fluid's flow back after the treatment has been recognized that the CO₂ fracturing saved a lot of times and reduced the cost spent on the uplift when the fracturing fluid could not flow back independently.

In addition to the uplift, the people have been concerning on the stimulation performance. There are two important issues need to be figured out: What about the fracture's geometry and size fractured with the CO₂ fracturing fluid? What's difference between CO₂ fracturing fluid and the conventional?

In order to address these issues and give some advices to the fracturing design job.

The paper illustrated the studies result from the core leak off experiments and the core fracturing physical simulation experiments and the analyses based on the Elasticity Mechanics and the Fracture Mechanics theory.

2. THE FRACTURING PHYSICAL SIMULATION EXPERIMENTS
2.1 Specimen
A natural sand stone and an artificial cement specimen were used as the rock specimens in this study. The natural sand stone, which was quarried from Chang6 formation located in Shaanxi province of China, has no any cracks or fissure obviously, and it mainly consist of quartz, orthoclase and clay. The artificial cement was made of the cement of G-grade used for the well cementing process and within which two artificial bedding planes paralleled to the minimum horizontal stress were prefixed.
The size of specimen was 762 × 762 × 914.4mm, and the hole with the diameter of 25.4mm was bored.

2.2 Experimental system

Fig. 1 shows the schematic diagram for the experimental system. The experimental system mainly consists of the true triaxial compression machine, the supplying system of the CO$_2$ fluids, and the measuring system. Fig. 2 shows the rock specimen set in the true triaxial compression machine. Three compression stresses were applied to the specimen using three hydraulic rams of the true triaxial compression machine. The super CO$_2$ was used as the fracturing fluid and was injected into the borehole of the specimen.

![Diagram](image)

Fig. 1. The Diagram for the Physical Simulation Hydraulic Fracturing System

The CO$_2$ gas was supplied from the gas storage tank and was pumped into the wellbore by a cylinder pump. The temperature of the CO$_2$ was controlled and conditioned through an unit of heating/cooling system outside of the flow lines.

2.3 Experimental conditions

Table 1 shows the experimental conditions for the CO$_2$ fracturing experiments. We first used supercritical CO$_2$ as the fracturing fluid. The flow rate were 1.2L/min and 0.24-0.48L/min. Then, we used red slick water with the viscosity of 5 mpa.s as the pumping fluid to colored the fracture walls. The colored specimens were cut with a rope saw, and the cut surfaces were scanned by the image scanner. We traced the fractures from the scanned images, and calculated the sizes of the fractures by a software. The traced images were arranged to the cubic form to clarify the fracture shapes obtained for each condition.

2.4 Results and discussion

2.4.1 Pressure during the fracturing experiments

Figure 3 and figure 4 show the pressures during the fracturing experiments using the CO$_2$ with flow rate of 1.2 L/min and 0.24-0.48 L/min. After the CO$_2$ was supplied, the pressure increased rapidly firstly. Then, the pressure keep constant approximately till the pump was shutdown. Compared the both of pressure curves, it could be seen that the breakdown pressure with the cement specimen was lower and more obvious than the sand stone specimen’s. The reason due to that the treatment pressure of the sand stone specimen was higher than the cement’s is that the pump rate of sand stone was bigger. After the pump rate was shut down, the pressure dropped to approach the minimum stress of the specimens.

![Diagram](image)

Fig. 2. The Diagram for the Specimen and Wellbore and Stresses Loading

<table>
<thead>
<tr>
<th>Fracturing fluid</th>
<th>Specimen</th>
<th>Permeability (mD)</th>
<th>Flow rate (L/min)</th>
<th>CO$_2$ pumping volume (mL)</th>
<th>Stress condition (MPa)</th>
<th>Temperature (℃)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>A natural sand stone (Chang 6)</td>
<td>3.0</td>
<td>1.2</td>
<td>2886</td>
<td>63=10, 62=15, 61=20</td>
<td>41</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>An artificial cement</td>
<td>0.02</td>
<td>0.24-0.48</td>
<td>2884</td>
<td>63=12, 62=15, 61=20</td>
<td>34</td>
</tr>
<tr>
<td>Slick water</td>
<td>A natural sand stone (Chang 6)</td>
<td>3.0</td>
<td>0.015-0.15</td>
<td>1897</td>
<td>63=7, 62=14, 61=21</td>
<td>20</td>
</tr>
</tbody>
</table>
2.4.2 Fractures created by the CO$_2$ fracturing experiments

Fig. 5 shows the perspective views of the fractured specimens. Fig. 5(a), (b) are the perspective views of the fractured specimens pumped with the CO$_2$, while (c) is that obtained with the slick water. It could be seen that the fractures are all the ones of single fracture. The size of the fractures were calculated with an AUTO CADE software that they are 8.14 dm$^2$, 28.34 dm$^2$ and 58.72 dm$^2$, respectively. We found that the fracture's area created by the CO$_2$ is only 13.86% of the slick water's with the same kind of specimen of sand stone. And the fracture's area within the sand stone specimen is 28.7% of the artificial cement specimen's.

2.4.3 Penetration depth of the CO$_2$

It's known that the volume of CO$_2$ pumped and the fracture's area. The penetration depth of CO$_2$ could be calculated that the volume of CO$_2$ lost was penetrated into the specimen. We calculated that the average penetration depth of CO$_2$ within the sand stone specimen is 35.5 mm, the average penetration depth of CO$_2$ within the artificial specimen is 10.2 mm. However, the average penetration depth of slick water within the sand stone specimen is only 3.2 mm.

Main results obtained in this study can be summarized as follows: The fracture's area created by the CO$_2$ is very sensible to the permeability of the specimen. The capability for fracturing of the CO$_2$ is weaker than the slick water very much.

3. ANALYSES ON THE LABORATORY MEASUREMENTS OF LEAKOFF FOR CO$_2$

A paper titled "Field and Laboratory Measurements of Leakoff Parameters for Liquid CO$_2$ and Liquid CO$_2$/N$_2$ Fracturing" was published in 1997. The paper introduced CO$_2$ leakoff experiments on the sandstone cores. The main points what we concerned are summarized as follows:

3.1 Cores used

A paper titled "Field and Laboratory Measurements of Leakoff Parameters for Liquid CO$_2$ and Liquid CO$_2$/N$_2$ Fracturing" was published in 1997. The paper introduced CO$_2$ leakoff experiments on the sandstone cores. The main points what we concerned are summarized as follows:

3.2 Experimental equipment

Liquid CO$_2$ was maintained at 10 MPa in the top of an accumulator in the injection line by means of N2 gas underneath the accumulator piston (Fig. 6). At the beginning, 2 L of liquid CO$_2$ was exposed to the core by opening a valve in the injection line. The injection line included a 30 cm long concentric tubing section with -
20°C to -25°C glycol-water in the annulus) to keep the 
CO₂ temperature at about -20°C as it flowed through 
the pressure vessel wall to the core-holder inlet.

Thermocouples were placed every 5 cm along the 
core starting at the core inlet and ending at the core 
outlet. The thermocouples were along the central axis of 
the core, and were inserted from the side of the core.

A dry gas meter was to used to measure the rate at 
which gas exited the core.

### 3.3 Experimental procedure

There were two sets of leakoff experiments: the 
first set using two dry cores and the second using two 
cores flooded with saline solution.

In the first set of experiments (Frac1 and Frac2) 
the core’s permeability was 120mD.

In the second set of experiments (Frac3 and Frac4) 
the core was flooded with 4300PPM saline solution 
first. CH₄ was then injected to displace excess saline 
solution from the core until a constant pressure drop 
was obtained. The total length of the CH₄ injection 
period was 2.87h. Following this procedure, the gas 
phase effective permeability was 6-8mD, and the water 
saturation was 49%. The core was exposed to the liquid 
CO₂ for 5 minutes and then the injection valve was 
closed.

Core temperatures and pressures were recorded 
every 1.5 seconds. Cumulative gas production was 
recorded every 15 seconds for the first 10 minutes and 
subsequently, every 30 seconds.

### 3.4 Discussion of results

The first two leakoff experiments (Frac1 and Frac2) 
involved exposing a 100% CH₄ saturated core to liquid 
CO₂ at 10MPa. The core was at pressure of 1MPa 
initially. In these two experiments, a high flow rate was 
obtained due to the high permeability (120mD). 
Essentially all of the 500 std L of the CO₂ in the 
injection accumulator passed through the core in the 
first 1.5 minutes that’s equivalent to a leakoff rate of 
260,000 std L/m²/min.

In runs experiments of Frac3 and Frac4, the Berea 
sandstone core had a low gas phase permeability due to 
the presence of saline solution (4300PPM). For these 
runs, the produced gas rate after the initial 1.5 minutes 
was in the range of 900-1,800 std L/m²/min.

In runs experiments of Frac3 and Frac4, the 
temperature at the inlet of the cores in experiments of 
Frac3 and Frac4 was 4°C and -9°C and the pressure 
drop was 9.2 MPa and 3.3 MPa respectively. The CO₂ 
was during the transition range between the gas phase 
and liquid phase in Frac3. However, the CO₂ was under 
the liquid phase in Frac4.

Main results obtained in this study can be 
summarized as follows: The leakoff rate of CO₂ was very 
high especially within the cores with high 
permeability. Most of the pressure drop is in the part of 
the core where CO₂ vaporization occurs. It means that 
the vaporization for CO₂ could reduce the rate of leakoff 
of CO₂.

### 4. MECHANICS ANALYSES BASED ON THE 
ELASTICITY MECHANICS AND FRACTURE 
MECHANICS

The concentration of stress near the wellbore is 
known widely which shows the stress is higher where 
the distance is closer to the wellbore. Tab.3 shows the 
stress values located in the different distance to the 
wellbore in an specific simple plane stress model based 
on the Elasticity Mechanics theory. This explain why 
the breakdown pressure of CO₂ fluid is lower than the 
conventional fracturing fluids which come from the high 
penetration depth for CO₂.

In the Fracture Mechanics theory, the crack tip’s 
stress intensity factor is the function of the length of the 
crack(KI=6(πa)0.5). This explain the CO₂ fluid achieved
more depth in the crack could create more complicated fracture nets compared to the conventional fluids.

5. CONCLUSIONS
In this study, the CO₂ fracturing experiments were conducted on 762 × 762 × 914.4mm sandstone and artificial cement specimens, the CO₂ core leakoff experiments were carried out on Ø3.8cm*30.48cm sandstone cores. Main results obtained in this study could be summarized as follows: CO₂ fracturing fluid has a very high leakoff rate with which the fractures’ area was smaller prominently than the slick water’s. Most of the pressure drop is in the part of the core where CO₂ vaporization occurs. The leakoff rate is controlled by the rate at which liquid and gaseous CO₂ can flow through the formation. CO₂ with high leakoff rate is better in lowering the rock breakup pressures and complicating the fracture net.

DECLARATION OF INTEREST STATEMENT
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

REFERENCE