Analysis and Evaluation of the Drying Effect in Tight Sandstone Reservoirs

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Abstract: As hydraulic fracturing technology has been widely used in the exploitation of tight gas sandstone reservoirs, the retention of hydraulic fracturing fluid will cause water locking damage to tight gas sandstone reservoirs and it can seriously affect the development of gas reservoirs. Selective injection of drying agents into tight sandstone reservoirs can effectively decrease water saturation and improve gas seepage capacity. Based on the laboratory orthogonal experiments, the injection parameters of drying agents are optimized. Results show that the improvement of gas permeability reaches its best when the concentration of the main drying agent is 1g/L, the injection volume is 4 PV, the injection rate is 0.2 mL/min, the reaction time is 70 min, the reaction temperature is 120 °C, the injection volume of post-positioning fluid is 4 PV, and the reverse displacement time is 90 min. In addition, the higher the irreducible water saturation of the tight core, the greater the increment of gas phase permeability after drying reaction and the higher the degree of water saturation reduction.

1. Introduction
Compared with oil, natural gas has received widespread attention worldwide as a lower-carbon, clean fossil energy. Although renewable energy is the goal of future development, due to its high utilization cost, it cannot completely replace fossil energy in a short time, so natural gas will continue to be an important part of energy consumption in all countries.

Currently, hydraulic fracturing technology has been widely used in the exploitation of tight gas sandstone reservoirs. Water-based fracturing fluid is widely used in the fracturing process, but research shows that only 5% to 50% of the fracturing fluid can successfully flow back after fracturing [1-3]. Even the permeability of tight sandstone is at micro- or nano-scale [4], the remaining liquid can still invade the reservoir by imbibition [5,6]. Consequently, natural gas needs to break through the water invasion area to flow into the fracture network to reach the production well, so water locking prevents the natural gas in the reservoir from flowing into the fracture network. As a result, the production of gas wells declines, so water lock damage cannot be ignored.

If we can find a corresponding method to reduce the water saturation of tight sandstone reservoirs, a large number of pores originally occupied by water film can become gas flowing channels again. The flowing resistance in matrix-micro fracture-hydraulic fracture-wellbore system can be reduces and the recovery of tight gas reservoirs can be enhanced. Our research group imitatively proposed the concept of "drying" of the tight reservoir and developed a drying agent system for tight gas reservoirs. By injecting the developed drying agent into the production well of tight gas reservoir, the formation water near the wellbore can be gasified. Preliminary studies of our research group have found that the drying agent system composed of metal carbide AC, LC and metal alcohol compound CHN in a
certain ratio can consume formation water through chemical reaction and thermal evaporation, thereby achieving the purpose of "reservoir drying". Given that the main pore size distribution range of tight reservoirs is between 40-700 nm [7], while the minimum particle size of the drying agent AC, synergist LC and CHN are in the submicron level. Our research team further studied the effective injection of the drying agents into tight reservoirs and found that the drying agent AC is soluble in supercritical carbon dioxide (SCCO2), so SCCO2 is adopted as a transport agent to bring AC into pores in the tight reservoirs. In addition, SCCO2 will turn into gas after depressurization, meaning it is easy to flow back and will not cause secondary damage to the reservoirs.

Based on the group’s previous research on the drying mechanism of tight reservoirs, the paper carried out a series of core seepage experiments on evaluating the drying effect of tight sandstone reservoirs. The experiment analyzed the water saturation and gas permeability of the sandstone core before and after injection of the drying agents and made a quantitative evaluation on the drying effect. Seven experimental parameters including the drying agent concentration, injection volume, injection speed, reaction time, reaction temperature, overflush fluid injection volume and reverse displacement time were selected from many experimental parameters, and corresponding orthogonal seepage experiments were conducted. Based on the analysis of the influences of different drying agent injection parameters on the drying effect, the optimal injection parameters were determined which would provide a reference for field operation.

2. Mechanism of reservoir drying

The drying agent system is a composite composed of metal carbide AC, metal organic compound CHN and metal carbonized complex LC (called "ALCN") [9]. The main drying agent AC can react with formation water at normal temperature and pressure to form ethanol-soluble hydroxide and gaseous methane; synergist LC is insoluble in ethanol, and can react with formation water at normal temperature and pressure to form ethanol-soluble hydroxide, gaseous acetylene and ammonia; CHN is soluble in ethanol without reaction and can react with water to form strong alkaline hydroxide and ethanol. The reaction equations of AC, LC, CHN and formation water are as follows:

\[
AC(s) + H_2O(l) \rightarrow AOH(s) + CH_4(g) \quad (1)
\]
\[
LC(s) + H_2O(l) \rightarrow LOH(s) + C_2H_2(g) + CN(l) \quad (2)
\]
\[
CHN(s) + H_2O(l) \rightarrow NOH(aq) + C_2H_2OH(l) \quad (3)
\]

Thermochemical calculations show that the reaction between drying agent and water is an exothermic reaction, which can cause part of the water to evaporate at high temperature and change from liquid phase to gas phase, so that the total volume of water consumed during the drying process is composed of two parts [10].

![Figure 1. Schematic diagram of theoretical water consumption of the drying agent system](image-url)
3. Rock samples and drying agents
The experimental sandstone samples are outcrop cores taken from a tight gas sandstone reservoir in China. The salinity of the simulated formation water used in the experiment is 80,000 mg/ L. The drying agents used in the seepage experiments mainly include AC powder as the main agent, synergist LC, CHN, absolute ethanol, sodium chloride, carbon dioxide and deionized water.

4. Evaluation of drying effect based on seepage experiments
The experimental apparatus used to simulate drying process in porous media is shown in Figure 2. It is mainly composed of a drying agent dissolving and injection section, a seepage flowing section, a heating and pressurizing section and a metering collection section. The drying agent dissolving and injection section is used for injecting drying agent dissolved in SCCO₂ into the sandstone core sample. The seepage flowing section is used to simulate drying process in the rock sample. The heating and pressurizing device is used to provide simulated pressure and temperature. The metering collection section is used to measure gas flowing rate as well as inlet and outlet pressures. The cores used in the experiment are all tight sandstone cores with a length of 5 cm, a diameter of 2.5 cm, and a porosity less than 10%.

The laboratory seepage flowing experiments were conducted under the Oil and Gas Industry Standard SY/T 5358-2010 of the People’s Republic of China. The first step of the experiment is to clean and dry the core samples, and measure the basic parameters of the samples (including geometric parameters, dry weight, and gas permeability). Secondly, use a vacuum pressurization device to saturate the core with simulated formation water and measure the weight of the saturated core to calculate the core porosity. Thirdly, load the saturated core into a high-pressure core holder, displace the core with nitrogen to irreducible water state and measure corresponding water saturation and effective gas phase permeability. In the fourth step, inject the prepared drying agent suspension (100ml ethanol+1.27 wt.%AC+2.53wt.% CHN+2.53wt.%LC) and CO₂ gas into the intermediate vessel, and the vessel is pressurized and heated to supercritical state of CO₂. Then use a double-cylinder constant pressure and constant speed pump to inject a certain amount of drying agents dissolved in SCCO₂ into the core at a constant speed. The core is heated to the experimental reaction temperature, and the inlet and outlet valves of the core holder are closed to maintain constant temperature and pressure, so that the drying agent can fully react with formation water in the rock sample. After the reaction is over, inject ethanol as overflush liquid into the core and wait 30 minutes for their reaction. Finally reversely displace the core with high-pressure nitrogen at a constant pressure of 3MPa, and measure the permeability and water saturation of the core after the displacement.

Figure 2. Schematic diagram of experiment device for evaluating drying effect in tight rock samples.

The average porosity of the core samples is 9.66%, and the average permeability of the dry core sample is 0.099mD. Under irreducible water saturation state, the gas permeabilities of most core
samples are less than 0.1mD, which can be used to simulate the drying process in tight formations. By analyzing the changes of the effective gas permeability and the water saturation after and before the drying reaction, the results show that the injected drying agent can effectively reduce the water saturation of the sample and greatly increase the effective gas permeability. Averagely, the water saturation of the core samples is reduced by 27.50%, and the gas permeability is increased by 171.66% (compared to the irreducible water state).

![Figure 3. gas permeability before and after drying reaction.](image1.png)

![Figure 4. water saturation before and after drying reaction.](image2.png)

Table 1. Experimental data.

| No.  | Dry core sample | Irreducible water state | After drying reaction | \(\Delta K\) (10\(^{-3}\)μm\(^2\)) | \(\Delta Sw\) (%) |
|------|-----------------|-------------------------|-----------------------|-----------------------------------|-----------------|
|      | Porosity (%)    | Permeability (10\(^{-3}\)μm\(^2\)) | Gas permeability (10\(^{-3}\)μm\(^2\)) | Water saturation (%) | Gas permeability (10\(^{-3}\)μm\(^2\)) | Water saturation (%) |
| TS7  | 16.85 | 1.57 | 0.079 | 69.98 | 0.171 | 54.19 | 0.092 | 15.79 |
| TS8  | 15.98 | 1.395 | 0.059 | 71.03 | 0.203 | 51.89 | 0.144 | 19.14 |
| TS13 | 16.02 | 0.275 | 0.012 | 63.86 | 0.055 | 45.99 | 0.043 | 17.87 |
| TS15 | 17.84 | 0.193 | 0.009 | 64.7 | 0.052 | 45.64 | 0.043 | 19.06 |
| TS16 | 17.71 | 0.226 | 0.012 | 60.77 | 0.058 | 43.01 | 0.046 | 17.76 |
| TS17 | 17.69 | 0.255 | 0.011 | 62.6 | 0.056 | 45.08 | 0.045 | 17.52 |
| TS18 | 15.48 | 0.654 | 0.0318 | 59.4 | 0.083 | 40.96 | 0.051 | 18.44 |
| TS19 | 15.82 | 0.602 | 0.033 | 58.21 | 0.077 | 42.82 | 0.044 | 15.39 |

5. Orthogonal experiments and result discussion

Based on the analysis of the drying mechanism of drying agent and the process of drying agents injection, it can be found that the parameters which affect the drying effect mainly include the concentration of the main drying agent, injection volume, injection rate, reaction time, reaction temperature, overflush fluid injection volume and reverse displacement time. By selecting the above seven parameters as control variables (experimental optimal parameters) and applying orthogonal principle, 32 sets of orthogonal experiments were designed. Corresponding experimental parameters are shown in Table 2.
Table 2. Orthogonal experiment design

| Levels | A (Concentration of main drying agent (g/L)) | B (Injection volume (PV)) | C (Injection rate (mL/min)) | D (Reaction time (min)) | E (Reaction temperature (°C)) | F (Injection volume of overflush liquid (PV)) | G (Reverse displacement time (min)) |
|--------|---------------------------------------------|---------------------------|-----------------------------|------------------------|-----------------------------|---------------------------------------------|----------------------------------|
| Level 1 | 1                                           | 1                         | 0.1                         | 30                     | 30                          | 1                                           | 30                               |
| Level 2 | 2                                           | 2                         | 0.2                         | 50                     | 60                          | 2                                           | 60                               |
| Level 3 | 3                                           | 3                         | 0.3                         | 70                     | 90                          | 3                                           | 90                               |
| Level 4 | 4                                           | 4                         | 0.4                         | 90                     | 120                         | 4                                           | 120                              |

Range analysis method is adopted to analyze the results of the orthogonal experiments. If we take the increment of gas permeability as the evaluation index, the optimal injection parameters of drying agent are as follows: the concentration of the main drying agent AC is 1 g/L, the injection volume is 4 PV, the injection rate is 0.2 mL/min, the reaction time is 70 min, the reaction temperature is 120 °C, the injection volume of the post-position liquid is 4 PV, and the reverse displacement time is 90 min.

If the decrease of water saturation is taken as the evaluation index, the optimal injection parameters of drying agent are as follows: the concentration of the main drying agent AC is 3 g/L, the injection volume is 3 PV, the injection rate is 0.4 mL/min, the reaction time is 90 min, the reaction temperature is 90 °C, the injection volume of the post-position liquid is 4 PV, and the reverse displacement time is 30 min.

It can also be concluded from the range analysis that when the increment of gas permeability is used as the evaluation index, the concentration of the main drying agent and reaction temperature’s impacts on the drying effect are the most significant. When the decrement of water saturation is used as the evaluation index, the concentration of the main drying agent, the reaction time and the injection rate’s impacts on the permeability of the core after drying reaction are the most significant.

Variance analysis method is also adopted to analyze the significant degree of those parameters’ impacts on drying effect. Results show that the concentration of the main drying agent, injection rate and reaction temperature’s impacts on drying effect are significant, and that reaction temperature’s impact is the most significant (analysis results are shown in Tables 3 and 4).

Table 3. Variance analysis of the orthogonal experiments—permeability as the evaluation index

| Parameters | Sum of squares of deviation | DOF | Mean square | F | Sig. | Significance |
|------------|-----------------------------|-----|-------------|---|------|--------------|
| A          | 0.410                       | 3   | 0.137       | 3.495 | 0.029 | *            |
| B          | 0.028                       | 3   | 0.009       | 0.174 | 0.913 |              |

Figure 5. The increment of permeability is used as the evaluation index.

Figure 6. The decrement the water saturation is used as the evaluation index.

Variance analysis method is also adopted to analyze the significant degree of those parameters’ impacts on drying effect. Results show that the concentration of the main drying agent, injection rate and reaction temperature’s impacts on drying effect are significant, and that reaction temperature’s impact is the most significant (analysis results are shown in Tables 3 and 4).
Table 4. Variance analysis of the orthogonal experiments——water saturation as the evaluation index

| Parameters | Sum of squares of deviation | DOF | Mean square | F    | Sig. | Significance |
|------------|-----------------------------|-----|-------------|------|------|--------------|
| A          | 0.153                       | 3   | 0.051       | 2.742| 0.062| *            |
| B          | 0.028                       | 3   | 0.009       | 0.403| 0.752|              |
| C          | 0.148                       | 3   | 0.049       | 2.627| 0.070| *            |
| D          | 0.029                       | 3   | 0.010       | 0.418| 0.741|              |
| E          | 0.278                       | 3   | 0.093       | 6.539| 0.002| *            |
| F          | 0.020                       | 3   | 0.007       | 0.280| 0.840|              |
| G          | 0.009                       | 3   | 0.003       | 0.121| 0.947|              |

P=0.05 * refers to significant

6. Conclusion
(1) Supercritical carbon dioxide (SCCO₂) can effectively dissolve the main drying agent AC, thus can transport more drying agents into micro pores in tight sandstone reservoirs. Laboratory experiments show that the proposed drying agent system can significantly reduce the water saturation as well as improve the gas permeability of the core samples.

(2) Range analysis of the orthogonal experiments shows that when permeability is used as the evaluation index, the optimal combination is that the concentration of the main drying agent AC is 1 g/L, the injection volume is 4 PV, the injection rate is 0.2 mL/min, the reaction time is 70 min, the reaction temperature is 120 °C, the injection volume of the post-position liquid injection is 4 PV, and the reverse displacement time is 90 min. The concentration of the drying agent has the greatest influence on the drying effect, followed by the reaction temperature. The reverse displacement time, the injection volume of the overflush liquid and the injection rate of the drying agent also have a certain influence, but the injection volume of the drying agent and the reaction time have the least influence.

(3) Variance analysis of the orthogonal experiments shows that the concentration of the main drying agent, the injection rate and reaction temperature have the most significant influence on the decrement of water saturation and the increment of gas permeability.

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