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EXPERIMENTAL AND VISUAL ANALYSIS OF NATURAL CONVECTION DUE TO CO_2 DISSOLUTION UNDER RESERVOIR CONDITIONS

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ABSTRACT

Dissolution of CO_2 into brine forms a mixture that is denser than the ambient brine. The density gradient causes gravitational instability and triggers convective fingers, which is a favorable process for CO_2 sequestration in saline aquifers. A series experiments of density driven natural convection due to CO_2 dissolution were conducted in a transparent vertical Hele Shaw cell under different conditions. A spectrophotometric method for measuring the concentration of dissolved CO_2 using an acid-base color indicator. The visualization of CO_2 dissolving into brine process demonstrated that the onset time of fingers occurrence was too short to captured. Our results showed that higher pressure and temperature can promote the fingers growth; Brine salinity increase inhibits fingers growth, thus decreasing the concentration of the dissolved CO_2.

Keywords: CO_2 sequestration, visualization, natural convection, Hele-Shaw, density driven

1. INTRODUCTION

Carbon dioxide (CO_2) capture and sequestration (CCS) is one of the viable techniques to mitigate greenhouse gases in the atmosphere[1, 2]. CO_2 storage in saline aquifers have the highest potential global capacity for long-term CO_2 storage[3]. When CO_2 injected into saline formations, it reaches supercriticality, the positive buoyancy of $scCO_2$(supercritical CO_2) relative to the ambient brine causes the CO_2 rises beneath an impermeable cap rock[4]. CO_2 dissolution and diffusion in the brine increases its density, CO_2-dissolved brine is 0.1% to 1% dense compared to native brine, depending on pressure, temperature, and salinity[5]. The density difference leads to gravitational instability and results in convective mixing between CO_2-dissolved brine and native brine, which could significantly enhance the CO_2 dissolution rate[6, 7].

Many studies have been reported in this area to investigate the natural convection driven by density difference[8]. The numerical simulation of the natural convection process is complicated by the coupling of multi-dimensional with uncertainties geological parameters. Despite recent improvements in reservoir simulation technology have made by researchers, it is still difficult to accurately predict and quantify analyze the convective mixing process of CO_2 dissolution in saline aquifers [9, 10].

The subsurface geological conditions are not readily simulated in laboratory, so scholars' interest in experimental investigation for natural convection is growing. Hele Shaw cell is the preferred experimental device for visualization of dissolution process, and it usually used to study convective instability. The common optical techniques for Hele Shaw cell include schlieren method[11], interference method[12] and Indicator

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discoloration method[13]. Another experimental setup is pressure-volume temperature (PVT) equipment, it usually consists of a cylindrical cell used to measure mass transfer and dynamic dissolution rate due to natural convection between CO_2 and brine[14, 15].

2. EXPERIMENTAL SECTION

2.1 Apparatus

The experimental configuration is shown in Fig. 1. The images were captured using an MV-E800M image processing charge-coupled device (CCD) camera (Microvision Digital Image Technology Co., Ltd). It was placed in a camera bellows accompanied by a monochromatic light filter and a uniform light source as a backlight. The camera was directly connected to a computer to facilitate advanced image processing.

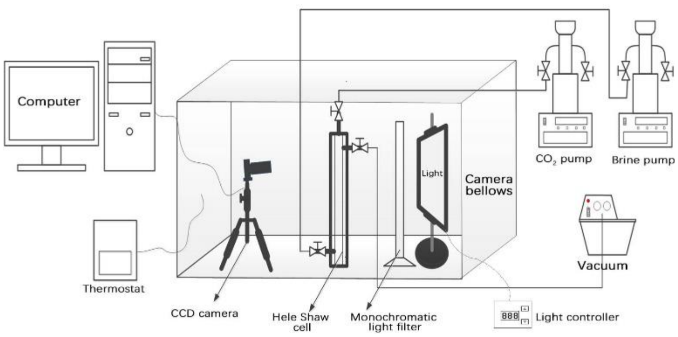

Fig 1 Schematic diagram of CO_2/brine convective mixing experiment

Natural convection experiments were conducted in a high-pressure Hele Shaw cell (Fig. 2). The Hele Shaw cell is equipped with two flat glass windows, which are maintained together vertically in a gravity field and separated by a spacer with a thickness of l = 1.0 mm. The maximum allowable pressure and temperature of the high-pressure cell is 15 MPa and 80 ℃.

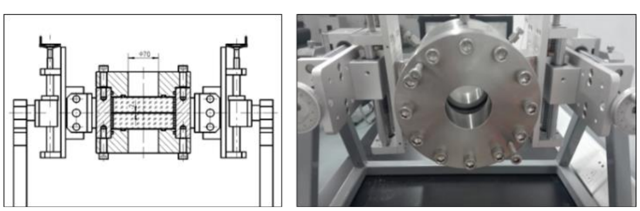
Fig 2 High-pressure Hele Shaw cell.

The experimental temperature was controlled by a temperature controller (Autolise AT72AAS4R), it can maintain a stable temperature point from 25 ℃ to 80 ℃. Two syringe pumps (ISCO 260D, Teledyne Technologies Inc.,) were used for brine and CO_2 injection, respectively. The digital signals of the temperature, injection flow rate, and injection pressure were monitored using the computer.

2.2 Material and method

CO_2 with a specified purity of 99.99% (instrument grade) was supplied by Dalian Date Gas Co., LTD.. The brine samples used in the experiments was prepared by bromocresol green, distilled water and pure NaCl crystal. Bromocresol green was used as acid-base color indicator, its concentration 2.4×10^{-4} mol/L. Table 1 shows the summary of the density driven natural convection experiments condition. The spectrophotometric method for measuring dissolved CO_2 in brine was described in detail in a previous article[16].

Tab 1 Schematic diagram of density driven natural convection experiment

Temperature(℃)	Pressure(MPa)	Salinity(g/L)
33	9	10
38	10	20
43	11	30

2.3 Procedures

Experiments were conducted according to the following procedure. First, the Hele Shaw cell was filled with colored brine to the experimental pressure, and the temperature controller was used to control the temperature. Second, the CCD camera recorded images without interruption. Third, CO_2 was introduced through the top of the high-pressure cell using a tube connected to a CO_2 pump that was operated at constant pressure to ensure that the CO_2 mixed with the brine. Fourth, images were captured until the gray value remained constant, which indicated that natural convection was complete and the system had equilibrated. Lastly, pressure was released from the system, and the high-pressure cell was cleaned for the next experiment. The steps mentioned above were repeated, and new experiments were started.

3. RESULTS AND DISCUSSION

3.1 Fingering morphology in natural convection

A region of interest (ROI) in the images was selected to analyze the convective mixing process. Each ROI was 50 mm high, and 49 mm wide. The convective fingers images of the density-driven natural convection in Hele Shaw cell were shown in Fig. 3. The dark means the brine without dissolved CO_2 (native brine); the gray means CO_2-dissolved brine, and the bright means CO_2.

The rate of CO_2 dissolution is high under in-situ pressure, the density difference between native brine and CO_2-dissolved brine formed in a short time. The instability was triggered because the denser CO_2-dissolved brine was located above the less dense native brine. Natural convection onset time was much shorter than the CCD camera shooting interval(1s), therefore, we cannot obtain the specific onset time.

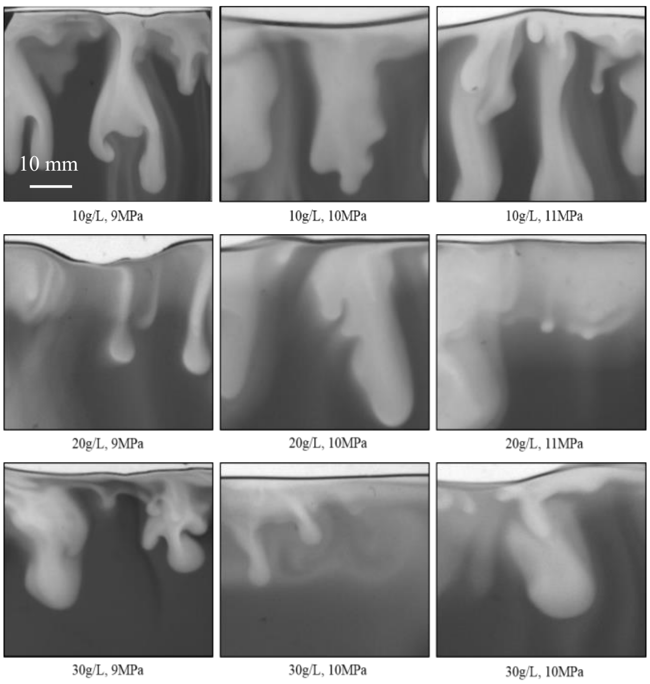

Fig.3 Convective fingers images of the density-driven natural convection experiments at 10th sec and 38°C

Compared with the CO_2/brine convective mixing experiments under atmosphere pressure[17], the fingers width increased and the fingers number decreased. The migration rate of the fingers is fast that can reach 5mm/s, fingers propagation period last 12-15 sec on average, it hit the bottom of the ROI quickly.

It can be observed from Fig 3 that the fingers growth velocity increase with the pressure and decrease with increased salinity. However, the pressure and salinity variation impact on fingers growth is relatively weak, because the changing gradient of pressure and salinity is too small.

3.2 Concentration of dissolved CO_2

The concentration of dissolved CO_2 during the density driven natural convection process was measured by the spectrophotometric method[16]. The gray value variation of images was used to determine the dissolved CO_2 concentration. The end of the convective mixing corresponds to the fingers become blurred and the gray value remained constant. Figure 4 shows the measured dissolved CO_2 concentration for the CO_2/brine convective mixing experiment.

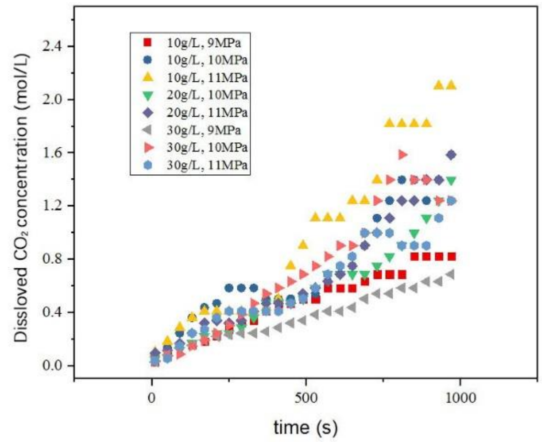

Fig 4 Average value of dissolved CO_2 concentration for different conditions

At the initial stage of experiments, the dissolved CO_2 concentration of 10 g/L, 11MPa (yellow triangle) was highest than others, and the 30 g/L, 9 MPa (gray triangle) was the lowest. It means that pressure increase can promote CO_2 dissolution into brine, while salinity increase can inhibit it. For the first 15 second of the finger's propagation period (Fig 5), we focused on the effect of temperature on CO_2 concentration. Although temperature increase reduces the solubility of CO_2, the absolute solubility of CO_2 in brine is much higher than the experiments conducted under atmospheric pressure. The temperature increase leads to the greater mass transfer coefficient and the lower viscosity, therefore, the higher the temperature, the faster fingers migration rate and the higher the CO_2 concentration.

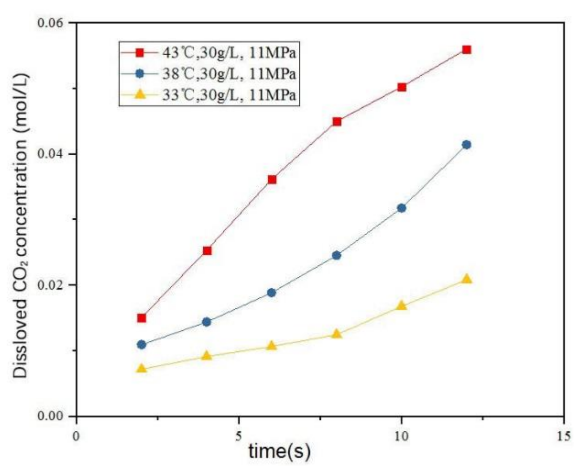

Fig 5 Effects of temperature on the increasing rate of dissolved CO_2 concentration

4. CONCLUSION

The setup in this study can carried out visual quantitative analysis of CO_2/brine density driven natural convection under reservoir condition. The influence of pressure, salinity and temperature change on the natural convection process have also been analyzed. The increase in pressure and temperature could improve the dissolved CO_2 concentration, while the increase in salinity could reduce it. Based on calculations, we concluded that the instability of density driven natural convection results in a faster increase in dissolved CO_2 concentrations. The proposal of using spectrophotometric method to measure the concentration of dissolved CO_2 has a guiding significance for the quantitative study of natural convection in the CO_2 dissolution process in the future.

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