International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 353

VISUALIZATION OF CO_2 FLOW AND TRANSPORT IN POROUS MEDIA

Sijia Wang, Yongchen Song, Yi Zhang, Yu Liu and Lanlan Jiang*
Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, Dalian University of Technology, Dalian 116024, China
Corresponding Author: lanlan@dlut.edu.cn

ABSTRACT

The implementation of CO_2 capture and sequestration (CCS) in deep saline aquifers can reduce greenhouse gas emissions effectively. The diffusion and dissolution of CO_2 in heterogeneous shallow aquifer is an important area for mass transfer. In order to investigate the effect of gas-water migration in this layer, we carried out experiments at core-scale by using of Magnetic Resonance Imaging (MRI) and pore-scale by using of microfluidic chip. This study place emphasis on CO_2 migration process, including displacement interface change and dissolution regular in several pores. CO_2 saturation is quantitative analyzed respectively at two scale. The continuous phenomenon of drainage-dissolution-drainage process at pore scale was found, which cannot observable at pore scale. The dissolution of CO_2 in limited number pores is observed with qualitative description. The fact proves that the combination of multiple scales can give more comprehensive analysis. These studies can give some implications for the long-term safety of CCS in some degree.

Keywords: two-phase flow, microfluidic chip, MRI, CO_2 migration

NONMENCLATURE

Abbreviations	
CCS	CO_2 capture and sequestration
MRI	Magnetic Resonance Imaging
PV	Pore Volume
Ca	Capillary number

1. INTRODUCTION

The complex flow of groundwater exists in deep saline aquifer during the process of CO_2 storage. Injected CO_2 displace water in the form of seepage and accompanying local binding phenomenon[1, 2]. The bound CO_2 dissolved and stabilized in pore space by convection or diffusion, then reacts with the formation water to solidify the mineralized substance. The two-phase percolation characteristics in porous media affect the micro-distribution of gas and water, the direction of capillary force in the throat, the proportion of CO_2 in the pores of the reservoir, the CO_2/water transport path, the occurrence way of binding gas in the pores and so on, which affect the storage efficiency and final destination of CO_2 ultimately[3-5]. The safety of CCS depends on the regular of interfacial migration of two-phase fluid in some way. However, there still lack of visualization studies on the combination of reservoir scale (10 cm-100 m) and pore scale (10 nm-10 cm) about this topic[6, 7].

Chomsurin[8] et al used homogeneous and heterogeneous etched micromodel to analyze nonaqueous phase liquid dissolution, tetrachloroethylene was used to simulate groundwater pollutants. They found that the mass flux holds constant when the average mass transfer length scale remains constant, which have no relationship with micromodel geometry. Kuo[9] et al studied the effects of velocity of CO_2 and heterogeneity on CO_2/brine displacement process by numerical simulation. The results showed that the dependence of CO_2 saturation distribution on the flow rate is large with high degree of heterogeneity. But the interaction of pore structure characteristics may relate to CO_2 saturation strongly. Previous works have been carried out using optical method at pore scale[10, 11], and with CT images in columns packed with porous media[7, 12]. Optical method has good resolutions (< 1μm), but it is limited to 2D images. MRI or CT technology can analyze the fluid flow at 3D scale quantitatively, but it has to be admitted that MRI or CT images will take long time and the resolution is rough relatively [13, 14].

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).

In this study, the flow pattern of CO_2/water in porous media was studied under two scales, the main work as followings: (i) for core scale, two phase interfaces during drainage process was visualized and CO_2 saturation distribution was calculated. This study can provide information for CO_2 storage safety in reservoir scale; (ii) for pore scale, we mainly concentrate on CO_2/water transport regular after the completion of drainage and reveal microscopic phenomena which difficult to observe at other scales, drainage-dissolution-drainage process was found in this scale.

2. EXPERIMENTAL MATERIAL AND METHODS

2.1 Equipment for Core scale measurement

Fig. 1 shows the experimental setup under core scale. MRI system is performed to visualize drainage process at 6MPa/25℃. Glass beads (BZ02+06 with 1:1 mass ratio) is used as heterogeneous porous media on this experiment which have similar wettability to etched glass model. Three ISCO pumps are used for gas injection, liquid injection and back pressure respectively. The oil bath filled with fluorine oil controls the temperature of the whole system. The time interval of MRI images is set to 2 min 8 s. The field of view (FOV) is 30 mm X 30 mm, the pore volume (PV) is about 0.7 in this area. There is no signal for CO_2 and strong signal for water in MRI images.

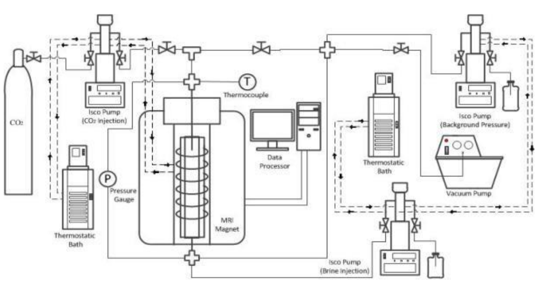

Fig 1 Experimental system diagram of core-scale

2.2 Equipment for Pore scale measurement

The process of CO_2-water drainage at pore scale is studied by microfluidic chip at a wide range of pressure (1-7 MPa) and 25℃. Fig. 2 shows the 3D overall structure picture of microfluidic chip sample. The chip is composed of a high-pressure glass model and a high-pressure connector which can withstand 10 MPa inside. This micromodel composing of inlet, porous media area and outlet, it is formed by two 2 mm glass sheets bonded at high temperature. As shown in Fig.2 (b)-(c), the single channel width of the entrance is 200 μm, and the interior of the porous media is mainly composed of three types of channels: 110 μm, 85 μm and 63 μm, respectively. A typical channel on the chip have a width of 110 μm and a length of 100 μm. Micro-scale experimental system mainly including injection pump, back pressure pump, micromodel and microscope. The process of CO_2-water drainage is observed in this heterogeneous porous media.

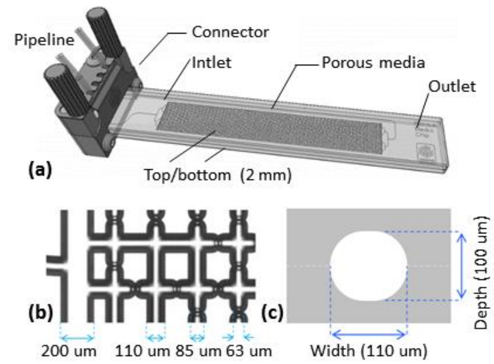

Fig 2 Microfluidic chip sample. (a) 3D overall structure picture; (b) size of local pores and throats;(c) a typical channel profile on the chip.

3. RESULTS AND DISCUSSION

3.1 Behavior of CO_2 migration at two scales

Fig 3 shows the CO_2 drainage process and MRI mean intensity value during injection process. Three MRI images present the state before the CO_2 enters sample (saturated with water completely), CO_2 displacing water and end of the CO_2 drainage respectively. Viscous fingering is observed clearly due to large viscosity ratio between two fluids. MRI mean intensity value begin to decrease when CO_2 enter the FOV, but there is no significant change more than 25 PV. Small amount of residual water remains in the pores and cannot be displaced completely. Although the drainage process has no significant change in the end, the migration of residual CO_2 bubbles and the dissolution of CO_2 in pores will be involved over a longer period of time. The

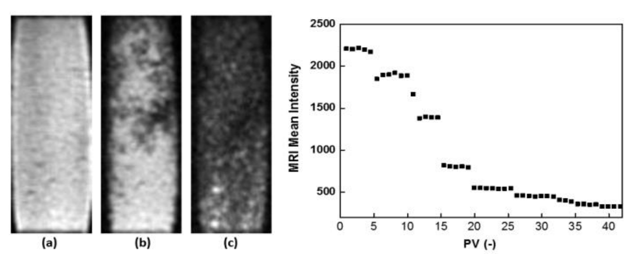

Fig 3 CO_2 drainage process at core scale (left; Ca=4.35×10^{-8}); MRI mean intensity varies with injection CO_2 volume.

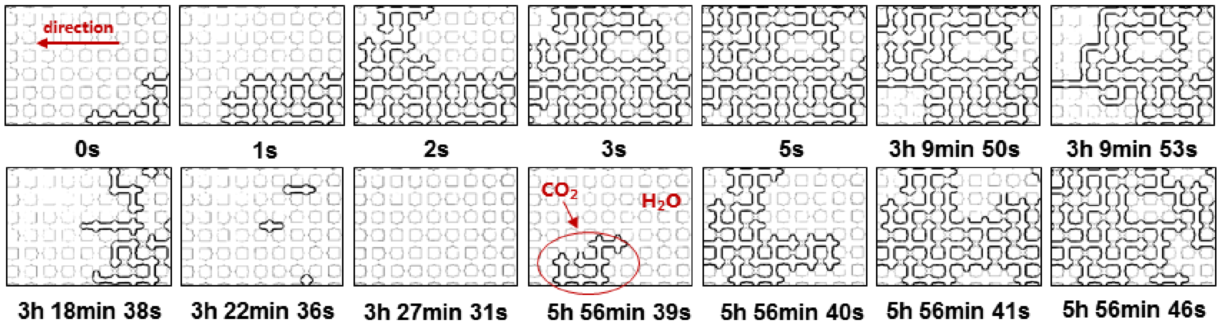

Fig 4 CO_2 drainage process at pore scale (Ca=5.3×10^{-7}). The area bounded by black line represents CO_2. The porous region was saturated with water completely in the initial.

investigation for pore scale can supplement this deficiency. Fig 4 shows the CO_2 drainage process at pore scale. CO_2 entered from the right edge randomly because only a small area was used in this experiment. We can find that CO_2 can pass through the straight channel easily, but will take more time for variable diameter or narrow channel, this shows that heterogeneity and pore/throat distribution will affect the flow direction to some degree. Lateral flow and reflux also occur during drainage process (1 s-3 s). The change is not significant for a long time after the first displacement, only small amount of CO_2 is observed dissolving in water (5 s-3 h 9 min 50 s). However, a large amounts of CO_2 continue to dissolve in water until all of it disappears (3 h 9 min 50 s-3 h 27 min 31 s). What's interesting is that displacement process re-occurrence with time goes by (5 h 56 min 39 s-5h 56 min 46 s), which can not be observed at core scale.

3.2 CO_2 saturation

The analysis of CO_2 saturation at reservoir scale is important. CO_2 storage efficiency can be evaluated by the core scale analysis, but the local (several pores) saturation analysis can give the unexplained mechanism from core scale.

Fig 5 (a) shows the CO_2 saturation profiles at different times. The distance from top to bottom of the sample is 30 mm, the drainage process starts at the top,

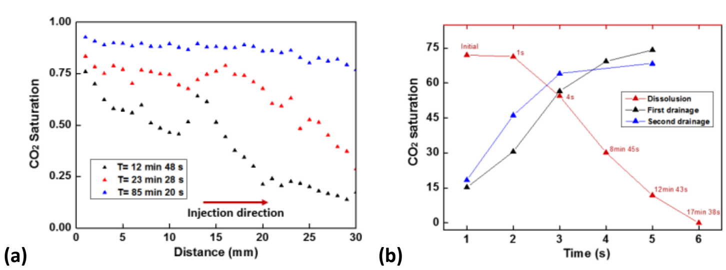

Fig 5 CO_2Saturation distribution. (a) CO_2 saturation profiles at core scale; (b) variation in the CO_2 saturation with time at pore scale

CO_2 saturation is calculated from the signal intensity ratio. We can find that CO_2 saturation decreases with the displacement direction when displacement occurs. CO_2 saturation at the top decreases with time due to the constant scour of CO_2, also, CO_2 saturation at the top is still higher than bottom even a long period of observation. The resolution of the MRI images can not sufficient to analyze the flow in the pores, the saturation analysis of local CO_2 in porous media can be achieved by pore scale. As shown in Fig 5 (b), the change of CO_2 saturation distribution with time is obtained by calculating the area percentage of CO_2 in displacement process. As mentioned of two displacement process in section 3.1, we found that CO_2 saturation both increased with time and have similar degree. The displacement process are quick, whereas the dissolution process is longer after the first displacement. CO_2 saturation decrease with time during dissolution process. It dissolves faster at the beginning (0 s-4 s), may be exist of a relative large pressure difference between the inlet and outlet of chip. But the dissolution time slows down later until dissolution completely (4 s-17 min 38 s).

3.3 *CO_2 dissolution in pores after drainage process*

The existence of dissolving morphology may be affected by heterogeneous structure in porous media. Two kind of CO_2 dissolution morphology after first drainage under 6 MPa is found in this study, as shown in Fig 6. Case A presents a process of a connected water

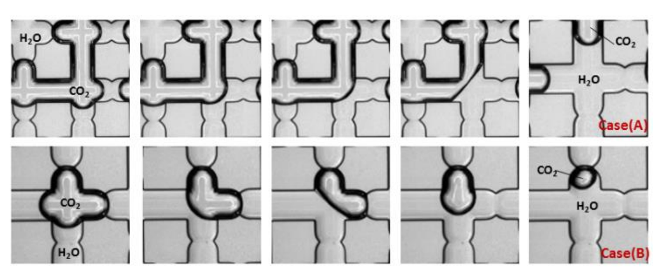

Fig 6 CO_2 dissolution morphology after first drainage under 6MPa.

channel separate into two single CO_2 bubbles after dissolution. At the cross passage, two-phase interface changes from arch to plane shape due to the small pressure difference between the two directions. As time goes by, the connection state changes into a state of separation.Case B presents a process of disappearance of a single CO_2 bubble after dissolution. CO_2 bubble tends to adhere to the wall surface during the process.

For future researches, detailed analysis combined with two scales under same capillary number will be carried out according to reservoir parameters. Miscible drainage process will be carried out and give more qualitative and quantitative analysis.

4. CONCLUSIONS

In this paper, we have observed drainage process in a CCS reservoir by use of two scales. The results show that viscous fingering occurs during drainage, lateral flow and reflux of CO_2 appears in local pores. CO_2 is easier to pass through the connective channels and blocking appears in reducing channel. At pore scale, dissolution and secondary drainage process occur when the first drainage completely. CO_2 saturation has a gradient along the injection direction, CO_2 saturation decreases significantly at the beginning and then decreases slightly in local pores during dissolution. The quantitation analysis of core scale combined with the mechainism of pore scale provides better explanations for the safety of CCS in reservoir conditions.

ACKNOWLEDGEMENT

This study was supported by the National Key Research and Development Program of China (Grant No. 2016YFB0600804), and the National Natural Science Foundation of China (51706154, and 51576032). It was also supported by the Fundamental Research Funds for the Central Universities (Grant No. DUT18RC (3)032).

REFERENCE

[1] H. J. Herzog, "Peer Reviewed: What Future for Carbon Capture and Sequestration?," Environmental Science & Technology, vol. 35, pp. 148A-153A, 2001.
[2] P. Folger, "Carbon Capture and Sequestration (CCS): A Primer," in National Congress for Environmental Studies, 2008.
[3] Jiang L, Yu M, Ying T, et al. Displacement and Dissolution Characteristics of CO_2/Brine System in Unconsolidated Porous Media[J]. Transport in Porous Media, 2018, 122(5):1-15.
[4] J. M. Nordbotten, M. A. Celia, and S. Bachu, "Injection and storage of CO_2 in deep saline aquifers: Analytical solution for CO_2 plume evolution during injection," Transport in Porous Media, vol. 58, pp. 339-360, Mar 2005.
[5] P. J. Mickler, C. Yang, B. R. Scanlon, R. Reedy, and J. Lu, "Potential impacts of CO_2 leakage on groundwater chemistry from laboratory batch experiments and field push-pull tests," Environmental Science & Technology, vol. 47, pp. 10694-10702, 2013.
[6] H. Geistlinger and I. Ataei-Dadavi, "Influence of the heterogeneous wettability on capillary trapping in glass-beads monolayers: Comparison between experiments and the invasion percolation theory," Journal of Colloid & Interface Science, vol. 459, pp. 230-240, 2015.
[7] J.-Q. Shi, Z. Xue, and S. Durucan, "Supercritical CO_2 core flooding and imbibition in Tako sandstone-Influence of sub-core scale heterogeneity," International Journal of Greenhouse Gas Control, vol. 5, pp. 75-87, Jan 2011.
[8] C. Chomsurin and C. J. Werth, "Analysis of pore-scale nonaqueous phase liquid dissolution in etched silicon pore networks," Water Resources Research, vol. 39, Sep 24 2003.
[9] C. W. Kuo, J. C. Perrin, and S. M. Benson, "Simulation studies of effect of flow rate and small scale heterogeneity on multiphase flow of CO_2 and brine," Energy Procedia, vol. 4, pp. 4516-4523, 2009.
[10] Y. Liu, P. Lv, Y. Liu, L. Jiang, S. Tetsuya, Y. Song, et al., "CO_2/water two-phase flow in a two-dimensional micromodel of heterogeneous pores and throats," RSC Advances, vol. 6, pp. 73897-73905, 2016.
[11] G. R. Jerauld and S. J. Salter, "The effect of pore-structure on hysteresis in relative permeability and capillary pressure: Pore-level modeling," Transport in Porous Media, vol. 5, pp. 103-151, 1990.
[12] J.-C. Perrin and S. Benson, "An Experimental Study on the Influence of Sub-Core Scale Heterogeneities on CO_2 Distribution in Reservoir Rocks," Transport in Porous Media, vol. 82, pp. 93-109, Mar 2010.
[13] P. Lv, Y. Liu, Z. Wang, S. Liu, L. Jiang, J. Chen, et al., "In Situ Local Contact Angle Measurement in a CO_2-Brine-Sand System Using Microfocused X-ray CT," Langmuir, vol. 33, pp. 3358-3366, Apr 11 2017.
[14] P. Lv, Y. Liu, J. Chen, L. Jiang, B. Wu, S. Liu, et al., "Pore-scale investigation of effects of heterogeneity on CO_2 geological storage using stratified sand packs," Greenhouse Gases-Science and Technology, vol. 7, pp. 972-987, Dec 2017.

