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CO_2 Plume Migration with Gravitational, Viscous, and Capillary Forces in Saline Aquifers

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ABSTRACT

When injecting CO_2 in saline aquifers, in order to investigate realistic flow, this study proposes a dimensionless group in the form of combination of Capillary number and Bond number to consider three forces of gravitational, viscous and capillary forces, simultaneously. Using of each dimensionless group individually is insufficient to obtain a satisfactory correlation with flow behavior of injected CO_2. With the proposed dimensionless group, the universal profile of CO_2 saturation was obtained in describing CO_2 flow behaviors for CO_2 injection rate, CO_2-water interfacial tension, and density difference between CO_2 and water. Thus, more realistic CO_2 flow behavior was analyzed.

KEY WORDS: CO_2 sequestration; saline aquifers; CO_2 flow behavior; Capillary number; Bond number; dimensionless group.

INTRODUCTION

Geological sequestration of CO_2 is one of the practical technologies for mitigating anthropogenic CO_2 in atmosphere which is caused by the use of fossil fuels. Among the geological formations for CO_2 sequestration, saline aquifers are considered as a promising option because saline aquifers have larger storage capacity of CO_2 than other formations and accessibility from CO_2 sources. In terms of storage safety, saline aquifers are more effective storage sites since structural, residual, solubility and mineralization trapping mechanisms by physical and geochemical interactions of CO_2-water-rock occur actively than depleted oil and gas reservoirs including mainly structural trap.

When two immiscible fluids flow in porous media, viscous force quantified by mobility ratio and gravitational force by density difference of the fluids are important factors affecting flow regimes which mean behaviors of fluids flow. In order to analyze and describe the fluids flow, dimensionless groups defined by using the viscous and gravitational forces have been studied. Crane et al. (1963) classified flow regimes based on range of the dimensionless groups defined as viscous to gravity ratio and estimated sweep efficiency of oil by water flooding in porous media. One of virtues for using the dimensionless groups is that they allow scaling from field conditions to the laboratory conditions, so that the flow regimes analyzed in the laboratory are similar to those in the field. The other is that using dimensionless groups reduces the number of parameters affecting immiscible fluids displacement in porous media to be studied effectively. Majority of previous studies investigated the effect of dimensionless groups on oil recovery performance during gravity drainage process (Kulkarni and Rao, 2006; Wood et al., 2008; Jadhawar and Sarma, 2008, Rostami et al., 2010). They mainly investigated the effects of viscous force affected by rate of gas or CO_2 flooding and gravitational force by upward and downward direction of injection, and density change by oil components. In an aspect of CO_2 storage, plume shape of injected CO_2 and ratio of trapping mechanisms were analyzed under the various CO_2 injection rate condition using Gravity number which is the ratio of viscous force to gravitational force of CO_2-water system (Ide et al., 2007). Kuo et al. (2010) conducted experiments and simulation studies to investigate the effect of gravity and viscous force by changing CO_2 injection rate on flow behavior of injected CO_2 in saline aquifers using Capillary number and Gravity number in homogeneous and heterogeneous systems. However, most of previous studies investigated effect of viscous and gravitational forces independently using dimensionless groups defined by ratio of two forces. Furthermore most of them considered capillary force as constant, and it means characteristics of CO_2 and water, and interaction of the fluids could not be fully analyzed.

In this study, we attempt to consider three forces of gravitational, viscous, and capillary forces, simultaneously, with the proposed dimensionless group to examine more realistic flow behavior of CO_2, when CO_2 is injected in saline aquifers. By the analysis of the acquired each trapping mechanism from flow behavior as flow regimes, optimum CO_2 injection scheme can be designed for maximizing the solubility and residual trappings as stable mechanisms. Mineralization trapping mechanism is neglected in this study due to its slow process for CO_2 sequestration.

MODEL DESCRIPTION

CO_2 plume migration was analyzed using GEM-GHG which is a compositional simulator developed by Computer Modeling Group. The simulation model of two-dimensional vertical cross-sectional system was created to consider gravitational, viscous, and capillary forces. The system is for CO_2 storage with closed boundaries on three sides and one open boundary on the right side for constant pressure boundary condition which makes no pressure effect by CO_2 injection well and favorable CO_2 flow condition. Aquifer size is assumed to 1,000 m in width and 250 m in height. Considering 1,200 m in depth, initial pressure and temperature are set by 11.7 MPa and 50 ℃, respectively. Degree of heterogeneity within the aquifer permeability is described by Dykstra-Parsons coefficient, and value of 0.5 for this coefficient is assumed which represents intermediate heterogeneity. Range of aquifer permeability is in 10~90 md and average permeability is 50 md for a heterogeneous system (Fig. 1). In order to take heterogeneity into account in capillary pressure at each grid, Leverett J-function is applied in this model. The aquifer porosity is 0.2 and the properties and initial conditions of the aquifer are shown in Table 1. One vertical well was installed and CO_2 was injected into the left side of system. Completion for injection well in whole of the aquifer pay thickness was implemented to analyze buoyancy and viscous flows of injected CO_2. CO_2 injection period is set by the time that CO_2 injected into the left side of system flows through the right side of the aquifer. During the migration of CO_2 the types of CO_2 plume were analyzed with variations of CO_2 injection rate and density difference between CO_2 and water. CO_2 sequestration was monitored after 100 years of CO_2 injection which is the running time of simulation.

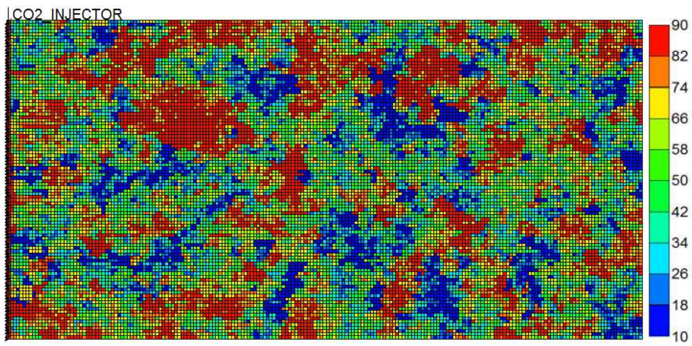

Fig. 1. Permeability distribution of system

Table 1. Properties of simulation model

Parameters	Value
Number of grid	200 * 100 cells
Aquifer size	1,000 * 250 m^2
Aquifer depth	1,200 m
Aquifer temperature	50 ℃
Aquifer pressure	11.7 MPa
Aquifer porosity	0.2
Aquifer permeability	10~90 md (mean 50 md)

To analyze the behaviors of CO_2 flow and sequestration with the conditions of CO_2 injection, CO_2 injection rate for analyzing viscous force and CO_2-water density difference for analyzing gravitational force were applied for the system. The density difference of CO_2-water is resulted from changing brine salinity in aquifer. For capillary force between CO_2 and water, interfacial tension of CO_2-water was considered as the range in following table. These physical and operational simulation parameters and values are summarized in Table 2. Interval of flow rate is 5,000 m^3/day and injection time of each case are 9.8, 6.4, 5.0, 4.1, 3.5, and 3.2 years, respectively.

Table 2. Simulation parameters

Parameters	Value
CO_2 flow rate	5,000~30,000 m^3/day
Density difference	0.4~0.8 g/cm^3
Interfacial tension	0.1~1 dyne/cm

RESULTS AND DISCUSSION

Considering two phase flow of CO_2 and water when CO_2 is injected into a saline aquifer, relationship of Capillary number (N_{Ca}) and Bond number (N_{Bo}) is derived for dimensionless capillary pressure term defined as a function of saturation (Dawson and Roberts, 1997). From this derivation, a new dimensionless groups is defined as a linear combination of Capillary number and Bond number (N_{gvc}).

$$N_{gvc} = \frac{N_{Ca}}{k_{r(CO_2)}} + N_{Bo} \tag{1}$$

It is assumed that CO_2 is displacing fluid, and water in saline aquifer is displaced fluid, and relative permeability of CO_2 (k_r) in Equation (1) is defined as a value at residual water saturation. From the linear combination of Capillary number and Bond number, we analyzed the effects of CO_2 injection rate, CO_2-water density difference, and interfacial tension of CO_2-water system through investigating saturation distribution of injected CO_2. The results for Capillary number, Bond number, and linear combination of those dimensionless group were investigated respectively, using CO_2 saturation distribution for analyzing plume shape of injected CO_2. Relationship of each dimensionless group with average saturation of the system, and ratio of trapping mechanisms with each dimensionless group are investigated for analyzing condition of storage safety.

We analyzed the results of Capillary number which is the ratio of viscous force for displacing fluid to capillary force. Viscous force by CO_2 injection rate, and capillary force by interfacial tension of CO_2-water were investigated on migration of injected CO_2 and trapping mechanisms using Capillary number. The result of distribution of CO_2 saturation with CO_2 injection rate is shown in Fig. 2. At the reservoir condition for CO_2 sequestration in this study, density of supercritical phase CO_2 is lower than water in saline aquifer. Although vertical to horizontal permeability ratio in this model is value of 0.1, and it is assumed that completion of injection well is for full pay thickness of the system, CO_2-water density difference makes buoyancy effect. As CO_2 injection rate decreases, the buoyancy force occurs dominantly. When CO_2 injection rate increases, injected CO_2 migrates more far from the injection well through horizontal flow by viscous force. Because the CO_2 injection period is assumed as the time that CO_2 injected into the injection well in left side of system flows through the right side, and CO_2 mainly migrates through flow paths built in early time of CO_2 injection, displacement of CO_2 to water occurs more favorably when CO_2 injection rate is high.

Distribution of CO_2 saturation at 100 years of monitoring period with capillary force by the change of interfacial tension of CO_2-water is shown in Fig. 3. We set various interfacial tensions at initial reservoir condition. Interfacial tension of CO_2-water does not affect plume shape of injected CO_2, as shown in Fig. 3, and only makes effect on displacing water by CO_2 in narrow and heterogeneous flow paths. Thus interfacial tension of CO_2-water is a factor affecting the ratio of trapping mechanisms by changing contact area of injected CO_2 with brine.

All the take the results of CO_2 injection rate and interfacial tension of CO_2-water together, average CO_2 saturation of system with Capillary number is shown in Fig. 4, and percent of each trapping mechanism with Capillary number is summarized in Table 3. As Capillary number increases, average CO_2 saturation of system increases. It can be interpreted as high CO_2 saturated condition is favorable for displacement of CO_2 to water and injected CO_2 more contacts with water. For this reason the amount of CO_2 trapped by residual gas trapping mechanism increases. However, the portion of CO_2 trapped by structural trapping mechanism is also increases due to high CO_2 injection rate. Thus the amount of CO_2 trapped by solubility trapping mechanism relatively decreases. Furthermore if condition of density difference between CO_2 and water changes, displacing force of CO_2 to water also changes so, trend of average CO_2 saturation with Capillary number varies as shown in Fig. 4. It can be interpreted as Capillary number is not sufficient to explain flow behavior, and it is needed to be analyzed with the effect of density difference.

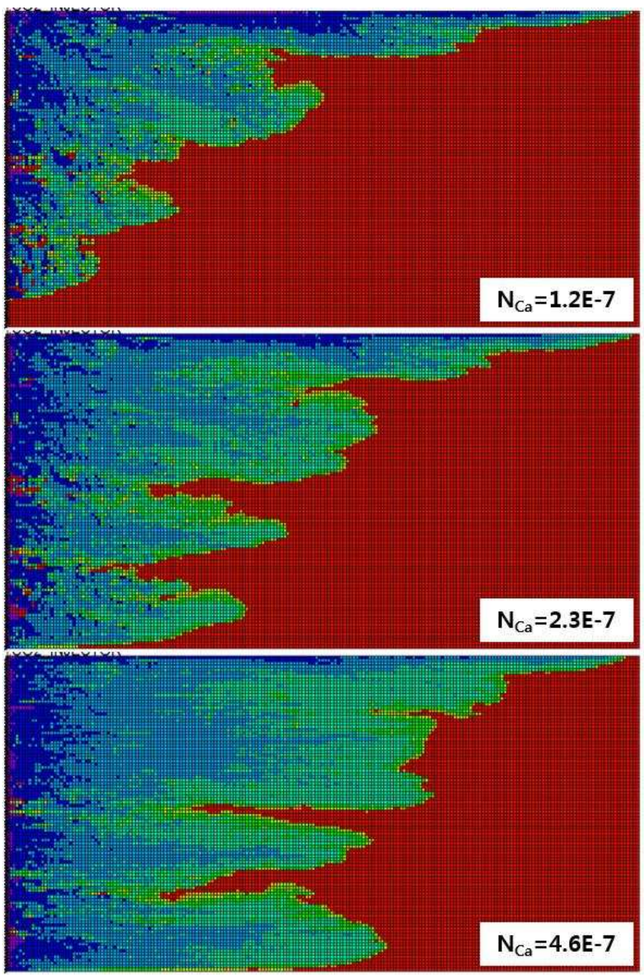

Fig. 2. CO_2 saturation distribution for various CO_2 injection rate

We analyzed the results of Bond number which is the ratio of gravitational force to capillary force between fluids. Gravitational force by density difference of CO_2 and water, and capillary force by interfacial tension of CO_2-water were investigated for migration of injected CO_2 and trap mechanisms using Bond number. The density difference between CO_2 and water is considered by changing salinity of aquifer system. The result of distribution of CO_2 saturation with density difference between CO_2 and water is shown in Fig. 5. The effect of interfacial tension of CO_2 and water on distribution of CO_2 saturation is same with the result of Capillary number.

The results of density difference between CO_2 and water by brine salinity and interfacial tension of CO_2-water are synthesized by average CO_2 saturation of system with Bond number as shown in Fig. 6, and percent of each trap mechanism with Bond number as summarized in Table 4.

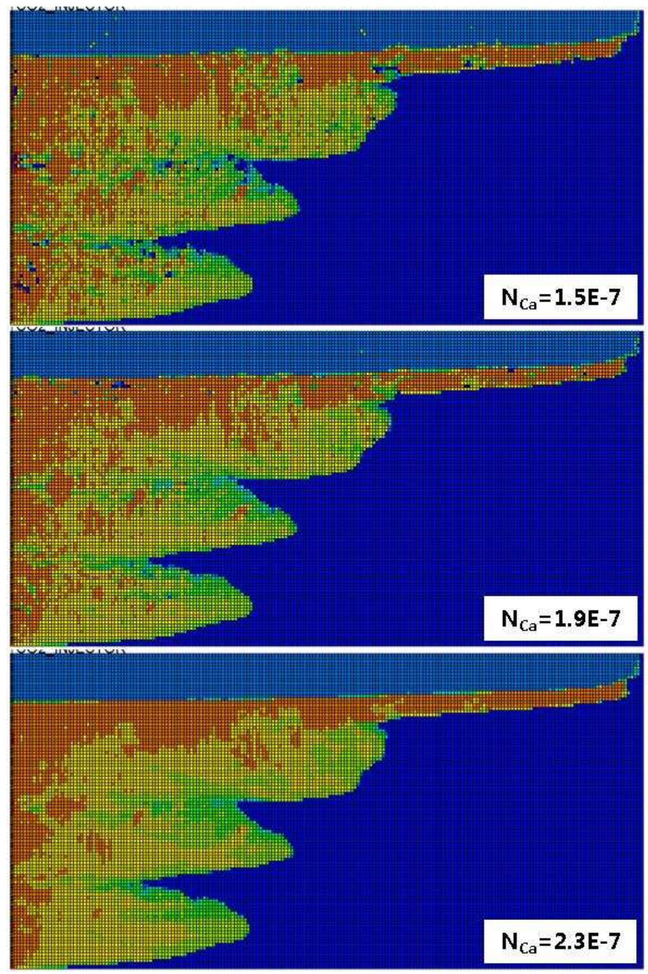

Fig. 3. CO_2 saturation distribution for various CO_2-water interfacial tension

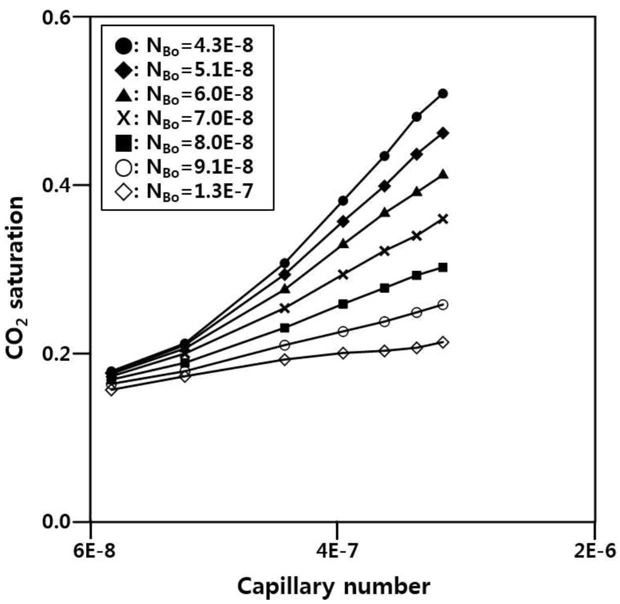

Fig. 4. Average CO_2 saturation with Capillary number

Table 3. The ratio of trap mechanisms with Capillary number

	Capillary number		
	1.2E-7	2.3E-7	4.6E-7
Structural Trapping	24%	26%	30%
Residual Trapping	37%	41%	41%
Solubility Trapping	39%	33%	23%

The average CO_2 saturation of system increases as the Bond number increases. It is expected that the increase in density difference of CO_2 with water, and injecting condition that injection period is assumed to the time injected CO_2 into the left side of system flows through the right side make more dominant buoyant flow. However, change of brine salinity affect not only density difference between CO_2 and water but also CO_2 solubility condition into the water. Thus CO_2 flow behavior as gaseous phase of CO_2 is varied by CO_2 solubility condition. This is why the amount of CO_2 trapped by solubility trapping mechanism decreases, and portion of CO_2 trapped by residual gas trapping mechanism increases due to lower solubility condition and larger contact area of CO_2 with water as brine salinity increases. As shown in Fig. 6, trend of average CO_2 saturation with Bond number varies by CO_2 injection rate. It can be interpreted as Bond number is also not sufficient to explain fluids flow behavior fully, that Bond number does not consider the viscous force effect.

As a result of this study, using each dimensionless group, Capillary number and Bond number, is insufficient to obtain a satisfactory correlation with flow behavior of injected CO_2 into saline aquifers. Thus, linearly combined dimensionless group of Capillary number and Bond number from flow equation of CO_2 and water is needed which combines the effect of all the three forces as shown in Fig. 7. The average CO_2 saturation has universal relationship with derived dimensionless group.

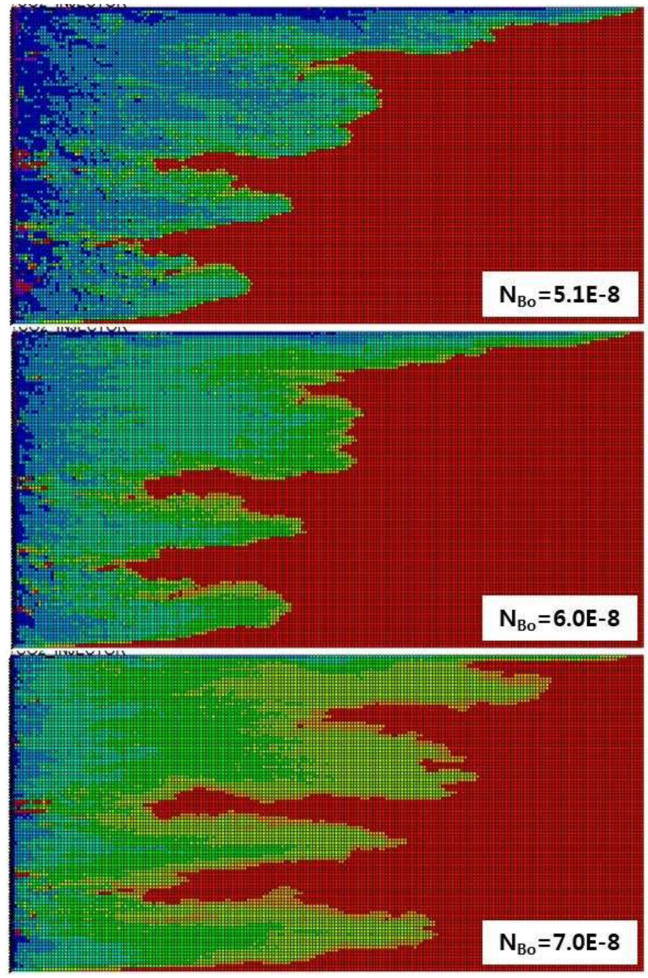

Fig. 5. Distribution of CO_2 saturation with density difference of CO_2 and water

Table 4. The ratio of trap mechanisms with Bond number

	Bond number		
	5.1E-8	6.0E-8	7.0E-8
Structural Trapping	26%	29%	33%
Residual Trapping	41%	44%	47%
Solubility Trapping	33%	27%	21%

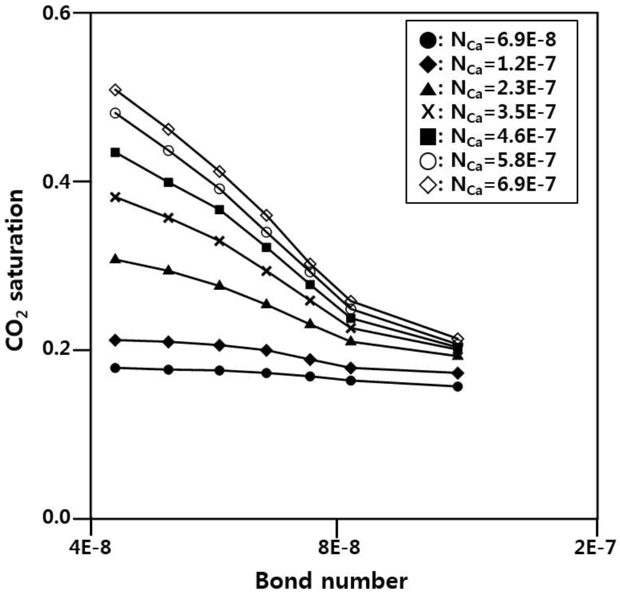

Fig. 6. Average CO_2 saturation with Bond number

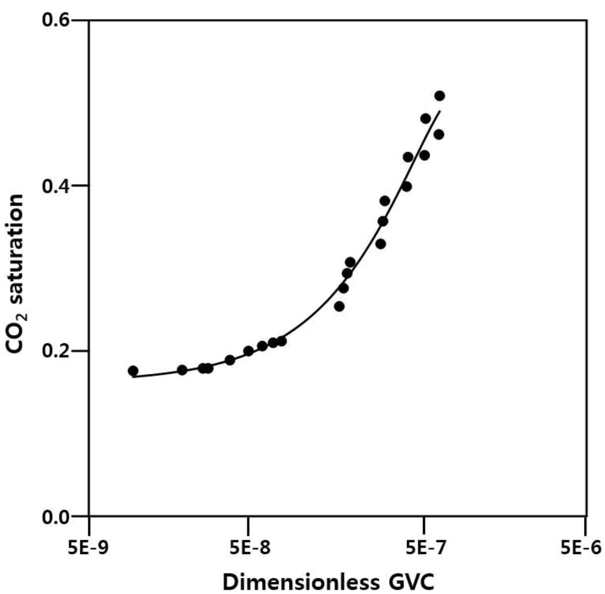

Fig. 7. Average CO_2 saturation with derived dimensionless group, Dimensionless GVC.

CONCLUSIONS

Numerical simulations were conducted to investigate the effect of viscous, gravitational, and capillary forces between CO_2 and water on behavior of injected CO_2 in saline aquifers for CO_2 sequestration. By using the linearly combined dimensionless group of Capillary number and Bond number, physical and operational parameters were analyzed for CO_2 plume and trap mechanisms. From the simulation result in this study, using of each dimensionless group alone is insufficient to obtain a satisfactory correlation with flow behavior of injected CO_2 into saline aquifers. With the proposed dimensionless group, we could consider two variables of density differences and CO_2 injection rates simultaneously, that is, three forces considering at the same time, more realistic CO_2 flow behavior would be analyzed.

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