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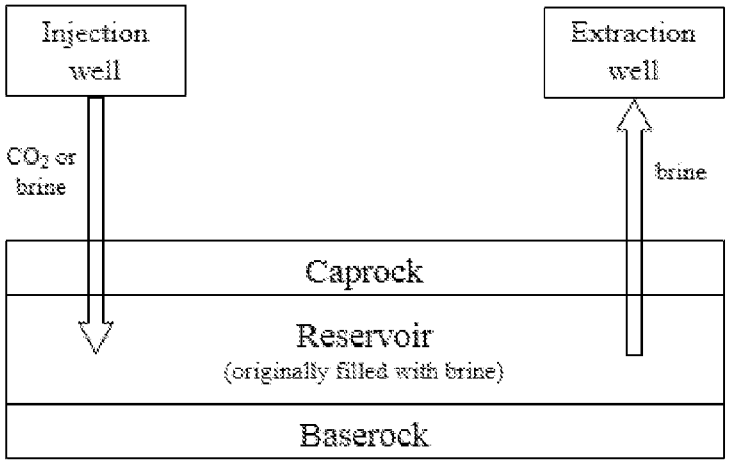

FIG. 5

(57) Abstract: A carbon dioxide storage reservoir, a method for filling the carbon dioxide storage reservoir, a system for filling the carbon dioxide storage reservoir and a program product for filling the carbon dioxide storage reservoir each use a sequential and separate injection of carbon dioxide followed by brine within an injection well, as well as a coordinated extraction of brine from an extraction well separate from the injection well. As a result, a carbon dioxide plume within a subsurface geologic formation within the carbon dioxide storage reservoir is immobilized when a quantity of brine which at least in-part contacts the carbon dioxide plume is quiescent within the subsurface geologic formation within the carbon dioxide storage reservoir.

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EXTRACTION-INJECTION METHOD FOR IMMOBILIZED SUB-SURFACE GEOLOGIC STORAGE OF CARBON DIOXIDE

CROSS-REFERENCE TO RELATED APPLICATION

This application is related to, and derives priority from, United States Provisional Patent Application serial number 61/733,970, filed 6 December 2012 and titled Time-Dependent Injection Method and Apparatus For Geologic Storage of Carbon Dioxide, the contents of which is incorporated herein fully by reference.

STATEMENT OF GOVERNMENT INTEREST

The research that lead to the embodiments as disclosed herein, and the invention as claimed herein, was funded by the United States National Science Foundation under grant number DGE-0966045. The United States Government has rights in any patent that derives from the invention as claimed herein.

BACKGROUND

Field of the Invention

Embodiments relate generally to methods and systems for sequestering carbon dioxide. More particularly, embodiments relate to methods and systems for efficiently sequestering carbon dioxide.

Description of the Related Art

Throughout the last century and continuing into this century, annual anthropogenic atmospheric carbon gas emissions have increased. These increased anthropogenic atmospheric carbon gas emissions in-turn have lead to increased atmospheric carbon gas concentrations which have further in-turn been linked to the evolving global warming trends currently being globally observed. Accordingly, a need exists to sequester atmospheric carbon gases, and in particular atmospheric carbon dioxide gas emitted by various industrial process sources, as a means to control atmospheric carbon gas concentrations and thus in-turn control global warming.

SUMMARY

Embodiments include a carbon dioxide storage reservoir, a method for filling the carbon dioxide storage reservoir, a system for filling the carbon dioxide storage reservoir and a program product for filling the carbon dioxide storage reservoir.

Each of the foregoing carbon dioxide storage reservoir, method for filling the carbon dioxide storage reservoir, system for filling the carbon dioxide storage reservoir and program product for filling the carbon dioxide storage reservoir is predicated on providing the carbon dioxide storage reservoir that includes an artificially introduced carbon dioxide plume at least in-part in contact with a quantity of brine within a subsurface geologic formation having other appropriately defined characteristics. Within the carbon dioxide storage reservoir in accordance with the embodiments the artificially introduced carbon dioxide plume is substantially immobile within the subsurface geologic formation when the quantity of brine is quiescent within the subsurface geologic formation.

The embodiments realize the forgoing immobilization and sequestration effect with respect to the carbon dioxide plume by incorporating a particular sequence and location of brine extraction and brine injection process steps incident to filling the carbon dioxide storage reservoir with the carbon dioxide plume.

According to one embodiment, brine is injected behind a CO_2 plume periodically and with volume ratios large enough to either: (1) fully trap the free-phase CO_2 in a porous rock formation; or (2) completely dissolve the free-phase CO_2 in a quantity of brine.

As is understood by a person skilled in the art, traditional methods of subsurface geologic formation sequestering of CO_2 are anticipated to suffer from a high risk of CO_2 leakage in the event a subsurface geologic formation (i.e., a storage reservoir) becomes compromised. It is believed that such a risk is high since injecting CO_2 into a subsurface geologic formation using traditional methods presumably fails to immobilize the free-phase CO_2 by the end of an injection process cycle. As a result, the free-phase CO_2 will migrate within the subsurface geologic formation under the influences of CO_2 buoyancy. In the event of a caprock failure of the

subsurface geologic formation, mobile free-phase CO_2 would leak from the subsurface geologic formation and rapidly migrate to the terrestrial surface. In the absence of subsurface geologic formation disruption, the free-phase CO_2 plume would spread along the underside of the caprock, leaving in its wake residual pockets of immobilized CO_2. Due to this trailing mass loss, the free-phase CO_2 plume would eventually become immobile as the capillary forces would balance the free-phase CO_2 buoyancy forces. However, this free-phase CO_2 migration and eventual immobilization could take hundreds or even thousands of years. In contrast, prophetic computer based simulations in accordance with the embodiments are believed to provide for immobilization of an entire free-phase CO_2 plume on a time scale equal to an extraction and injection process cycle time, such that at the end of an extraction and injection process cycle an entire free-phase CO_2 plume may be immobilized.

A traditional method for CO_2 injection into a subsurface geologic formation is detailed in FIG. 1(a) and FIG. 1(b). In FIG. 1(a) and FIG. 1(b)i CO_2 is injected as a single plume in a dense free-phase. After the CO_2 injection ends as illustrated in FIG. 1(a) and FIG. 1(b)i, the mobile CO_2 plume migrates within the subsurface geologic formation under the influence of buoyancy forces and will spread along the underside of the caprock leaving immobilized trapped CO_2 in its wake. Under these circumstances, the local brine becomes fully saturated with CO_2, as illustrated in FIG. 1(b)ii. The embodiments call for injecting brine behind the CO_2 plume periodically and with volume ratios large enough to either: (1) fully trap the free-phase CO_2 within porous rock within the subsurface geologic formation, as illustrated in (FIG. 1(c)); or (2) completely dissolve the CO_2 within the quantity of brine, as illustrated in (FIG. 1(d)).

As is illustrated within the gray scale bar legend in FIG. 1, there are four gray scale shades (i.e., dark, medium dark, medium light and light) that correspond with free-phase CO_2, brine without CO_2, trapped free-phase CO_2 and brine with dissolved CO_2, respectively. The trapped free-phase CO_2 is located within the central bow-tie portions of FIG. 1(b)ii, and in the plume portion of FIG. 1(c). The brine with dissolved CO_2 is located within the wing portions of FIG. 1(b)ii and the plume portion of FIG. 1(d).

The embodiments derive from and are expected to mimic prophetic computer based simulations of CO_2 migration determined using computer modeling of a CO_2 subsurface geologic formation storage reservoir that is filled while using an extraction and injection method in accordance with the embodiments, in comparison with solely an injection method.

Within the context of the embodiments as described and the invention as claimed "substantially immobile" with respect to a CO_2 plume within a subsurface geologic formation is intended within the context of additional possible geologic factors as the CO_2 being; (1) quarantined within the pores of a subsurface geologic formation in a free phase having a local saturation equal to or less than the residual saturation of the geologic subsurface formation; or (2) dissolved within a brine solution within the subsurface geologic formation such that any compromise of the caprock will not result in a substantial (i.e., preferably no greater than about 5% of sequestered volume) release of CO_2 dioxide to the atmosphere. Such immobility of a CO_2 plume is, as is understood by a person skilled in the art, measurable via seismology.

Within the context of the embodiments as disclosed and the invention as claimed "quiescent" with respect to a quantity of brine within the subsurface geologic formation is intended as any point in time when there is no introduction or removal of either CO_2 or brine into or from the subsurface geologic formation. "Quiescent" is also intended to include absence of any seismic activity, or any other activity or disruption to the subsurface geologic formation, the brine contained within the subsurface geologic formation and the carbon dioxide plume at least in-part in contact with the quantity of brine within the subsurface geologic formation.

A particular carbon dioxide storage reservoir in accordance with the embodiments includes a subsurface geologic formation and an artificially introduced carbon dioxide plume at least in part contacting a quantity of brine. Both the artificially introduced carbon dioxide plume and the quantity of brine are located within the subsurface geologic formation. Furthermore, the artificially introduced carbon dioxide plume is substantially immobile within the subsurface geologic formation when the quantity of brine is quiescent within the subsurface geologic formation.

Another particular carbon dioxide storage reservoir in accordance with the embodiments includes a subsurface geologic formation including: (1) a carbon dioxide impervious caprock formation; (2) a brine impervious baserock formation separated from and beneath the carbon dioxide impervious cap rock formation; (3) a carbon dioxide porous intermediate rock formation interposed between the carbon dioxide impervious caprock formation and the brine impervious baserock formation; and (4) a quantity of brine at least partially filling the carbon dioxide porous intermediate rock formation. The reservoir further includes: (1) an injection well reaching the carbon dioxide porous intermediate rock formation and being adapted for sequentially and separately injecting carbon dioxide and brine; and (2) an extraction well reaching the quantity of brine.

A particular method for filling a carbon dioxide storage reservoir in accordance with the embodiments includes providing an injection well and an extraction well reaching a subsurface geologic formation. The subsurface geologic formation includes: (1) a carbon dioxide impervious caprock formation; (2) a brine impervious baserock formation separated from and beneath the carbon dioxide impervious caprock formation; (3) a carbon dioxide porous intermediate rock formation interposed between the carbon dioxide impervious caprock formation and the brine impervious baserock formation; and (4) a quantity of brine at least partially filling the carbon dioxide porous intermediate rock formation. Furthermore, the method provides that the injection well extends to the carbon dioxide porous intermediate rock formation and the extraction well extends to the quantity of brine. The method provides for injecting a quantity of injected carbon dioxide at the injection well and extracting a quantity of extracted brine at the extraction well, and then finally injecting a quantity of injected brine at the injection well. Injecting the carbon dioxide and the brine at the injection well may repeat sequentially.

A particular system for filling a carbon dioxide storage reservoir in accordance with the embodiments includes an injection well that reaches a subsurface geologic formation and is adapted for sequential and separate injection of carbon dioxide and brine. The system further includes an extraction well reaching the same subsurface geologic formation. The subsurface geologic formation includes: (1) a carbon dioxide impervious caprock formation; (2) a brine impervious baserock formation separated from and beneath the carbon dioxide impervious

caprock formation; and (3) a carbon dioxide porous intermediate rock formation interposed between the carbon dioxide impervious caprock formation and the brine impervious baserock formation. Furthermore, the subsurface geologic formation includes a quantity of brine at least partially filling the carbon dioxide porous intermediate rock formation. Finally, the injection well extends to the carbon dioxide porous intermediate rock formation and the extraction well extends to the quantity of brine.

A particular computer program product for filling a carbon dioxide storage reservoir comprises a medium containing non-transitory computer-readable instructions for filling a carbon dioxide storage reservoir that, when executed by at least one processor, causes the processor to perform steps, in accordance with the embodiments includes: (1) instructing an injection well, reaching a subsurface geologic formation, to sequentially and separately inject carbon dioxide and brine into a subsurface geologic formation. The medium also includes instructions for instructing an extraction well, reaching a subsurface geologic formation, to extract brine. The subsurface geologic formation includes: (1) a carbon dioxide impervious caprock formation; (2) a brine impervious baserock formation separated from and beneath the carbon dioxide impervious caprock formation; and (3) a carbon dioxide porous intermediate rock formation interposed between the carbon dioxide impervious caprock formation and the brine impervious baserock formation. Furthermore, the subsurface geologic formation includes a quantity of brine at least partially filling the carbon dioxide porous intermediate rock formation. Finally, the injection well extends to the carbon dioxide porous intermediate rock formation and the extraction well extends to the quantity of brine.

BRIEF DESCRIPTION OF THE DRAWINGS

The objects, features and advantages of the embodiments are understood within the context of the detailed description of the non-limiting embodiments, as set forth below. The detailed description of the non-limiting embodiments is understood within the context of the accompanying drawings, that form a material part of this disclosure, wherein:

FIG. 1 shows schematic plan-view and cross-sectional diagrams illustrating: (a-b) conventional methods of injecting CO_2 into a subsurface geologic formation; and (c-d) presently embodied methods of injecting CO_2 into the subsurface geologic formation.

FIG. 2 shows a graph of representative relative permeability curves for injecting CO_2 into a subsurface geologic formation.

FIG. 3 shows a diagram illustrating the results of a simulation of CO_2 sequestration within a subsurface geologic formation in accordance with the embodiments. The diagram shows CO_2 saturation value throughout the subsurface geologic formation after a 4^{th} injection cycle. Each injection cycle consisted of injecting CO_2 into the subsurface geologic formation (from the left hand side of the domain) for 3 days, followed by injecting brine for 8.14 days. After the 4^{th} cycle, the saturation was 0.3 almost everywhere with the exception of the very front of the CO_2, where spreading had occurred. It is believed this was simply an artifact of the way in which the computer simulation solved this complicated flow problem.

FIG. 4a, FIG. 4b, FIG. 4c and FIG. 4d show a series of screen shots from the computer modeling simulation of the dissolution strategy in accordance with the embodiments. The screen shots were taken after the first injection of CO_2 was complete, and then brine was being injected. The well is located at the left boundary of the screen, causing the fluids to convect towards the right. The color map identifies the location and density of the free-phase CO_2 (red (i.e., top of gray-scale bar) = most dense gas, blue (i.e., bottom of gray scale bar) = no gas phase present). As brine was injected, the CO_2 was dissolved into the brine. The last image is at the end of the first brine injection. The original CO_2 is nearly completely dissolved. This process is repeated 4 times over the course of 1 year.

FIG. 5 shows a block diagram of a system in accordance with the embodiments.

DETAILED DESCRIPTION OF THE NON-LIMITING EMBODIMENTS

I. GENERAL CONSIDERATIONS

Embodiments include a carbon dioxide storage reservoir, a method for filling the carbon dioxide storage reservoir, a system for filling the carbon dioxide storage reservoir and a program product for filling the carbon dioxide storage reservoir.

Each of the foregoing carbon dioxide storage reservoir, method for filling the carbon dioxide storage reservoir, system for filling the carbon dioxide storage reservoir and program product for filling the carbon dioxide storage reservoir is predicated on providing the carbon dioxide storage reservoir that includes an artificially introduced carbon dioxide plume at least in-part in contact with a quantity of brine within a subsurface geologic formation having other appropriately defined characteristics. Within the carbon dioxide storage reservoir in accordance with the embodiments the artificially introduced carbon dioxide plume is substantially immobile within the subsurface geologic formation when the quantity of brine is quiescent within the subsurface geologic formation.

The embodiments realize the forgoing immobilization and sequestration effect with respect to the carbon dioxide plume by incorporating a particular sequence and location of brine extraction and brine injection process steps incident to filling the carbon dioxide storage reservoir with the carbon dioxide plume.

The embodiments are computer simulated prophetic embodiments determined using computer modeling of a carbon dioxide storage reservoir. The computer modeling employed otherwise generally standard computer software intended for multiphase flow modeling purposes in accordance with the embodiments. The computer model is capable of solving coupled nonlinear partial differential equations, which arise from the derivation of mass conservation within the reservoir. Solving these types of coupled-dynamic problems are standard for subsurface modeling programs as well as any general multiphase physics simulator.

According to one embodiment, the subsurface geologic formation includes a ceiling (caprock) that is impervious to CO_2, and a floor (baserock) that is impervious to brine. Furthermore the subsurface geologic formation could include a CO_2 porous intermediate rock formation such that a CO_2 plume could become trapped in the pores of the CO_2 porous intermediate rock formation.

The subsurface geologic formation is not limited to certain types or composition of rock, so long as it displays the necessary characteristics listed above. The subsurface geologic formation may also include a quantity of brine that either exists in the subsurface geologic formation prior to a CO_2 plume injection, or has been injected into the subsurface geologic formation after a CO_2 plume injection.

According to another embodiment, or within the same embodiment, the subsurface geologic formation may include an injection well that reaches the porous intermediate rock formation, and may also include an extraction well that reaches the quantity of brine. The injection well may be used to inject a particular quantity of CO_2 followed by at least one more quantity of brine. The ratio of brine to CO_2 is discussed in depth below. Further, the injection well may be used to inject multiple CO_2 plumes and multiple quantities of brine in sequential layers. The extraction well may reach down into the quantity of brine to extract the brine in order to provide the brine for the injection well. The extraction well may extract the brine concurrent with the injection of the CO_2 plume, after the injection of the CO_2 plume, or it may extract the brine prior to injection of the CO_2 plume and store the brine until the brine is to be injected. In an alternative embodiment, the quantity of brine may be artificially created.

According to another embodiment, the injection well and/or the extraction well may be driven by a program product. The program product may consist of any software, hardware or firmware, sufficient for instructing an injection well to sequentially inject CO_2 and brine into a subsurface geologic formation reservoir. Further, the program product may consist of any software, hardware or firmware known in the art, to extract brine from a subsurface geologic formation by operation of an extraction well in coordination with an injection well. Program products for at least directing injection of CO_2 are well known in the art within the context of traditional methods for CO_2 injection. These products could be adapted to direct the injection wells to sequentially and separately inject CO_2 and then brine in accordance with the strategies and mechanisms to immobilize CO_2 plumes within subsurface geologic formations in accordance with the embodiments. Among other parameters, the program products would direct the flow rates and monitor the pressure necessary to operate the wells.

Using the methods discussed above in accordance with the embodiments, immobilization of an injected CO_2 plume within a subsurface geologic formation is expected to occur much more rapidly than traditional methods. For example, the following results were simulated in accordance with the detailed description below to sequester CO_2 from a 1 GW power plant for 1 year, comparing those results with traditional method of sequestration. The results are provided in Table 1.

Table 1

Injection Strategy	State of CO_2 at end of injection	γ (Vol. brine:Vol. CO_2) required for strategy			Radial Extent of CO_2 at the end of injection [km]		
		Best	Worst	Avg.	Best	Worst	Avg.
Traditional	Mobile	N/A	N/A	N/A	1.6	2.4	1.7
This Work Trapping	Immobile, free-phase	1.26	9	2.06	2.3	6.9	2.8
This Work Dissolving	Immobile, dissolved	7.9	26.7	17.5	6.1	7.9	6.8

Thus, from a review of the data contained in Table 1, it is clear that an immobilized free-phase trapping of CO_2 within a quantity of brine within a subsurface geologic formation requires only on average about 2 to about 3 times a volume of CO_2 for the quantity of brine. In contrast, an immobilized dissolution of CO_2 within a quantity of brine within a subsurface geologic formation requires on average about 9 to about 25 times a volume of CO_2 for the quantity of brine.

Particular times for injection of particular quantities of CO_2 or particular quantities of brine are also not listed in Table 1, but generally such timescales are anticipated to be in the range from about 3 to about 30 days for injection of CO_2. As indicated below, a time for injection of brine will vary dramatically depending upon a particular immobilization strategy intended, in conjunction with a particular density of CO_2. As well, injection temperatures and injection pressures are also not listed in Table I, but an injection temperature is from about 35 to about 50 degrees centigrade and an injection pressure is generally from about 1400 to about 3000 psi.

II. NOMENCLATURE AND DEFINITIONS

In the following detailed description, all parameters, subscripts, and superscripts may be understood to be defined as listed in the following Table 2, Table 3 and Table 4.

Table 2

Parameters		
Parameter	Definition	Unit
A	cross sectional area of reservoir	[m^2]
C_i	concentration of species i	[$kg \cdot m^{-3}$] = [kg species i · m^{-3} solution]
D	$C_{aq,sat}/\rho_c$	[-] = [m^3 CO_2 · m^{-3} brine]
f	k_w:k_c	[-]
h	mass transfer coefficient	[s^{-1}]
H	reservoir height	[m]
γ	brine volume: CO_2 volume	[-]
κ	intrinsic domain permeability	[m^2]
k_i	relative permeability of phase i	[-]
L	Length of domain where CO_2 is present	[m]
N	number of fluid injections	[-]
η	CO_2 viscosity:brine viscosity	[-]
μ_i	dynamic viscosity of phase i	[Pa·s]
ϕ	porosity of reservoir	[-] = [m^3 void space · m^{-3} domain]
ρ_i	density of phase i in free phase	[kg m^{-3}]
ψ	brine density:CO_2 density	[-]
S_i	saturation of phase i	[-] = [m^3 phase i · m^{-3} void space]
u_{di}	Darcy velocity of phase i	[$m \cdot s^{-1}$] = [m^3 phase i · m^{-2} domain · s^{-1}]
V_i	volume of phase i	[m^3]
v	characteristic velocity	[$m \cdot s^{-1}$]
w	shock wave velocity	[$m \cdot s^{-1}$]

Table 3

Subscripts	
Subscript	Definition
aq	CO_2 which is dissolved in brine
b	brine phase
c	CO_2 free-phase
n	nondimensional parameter
-	value behind a shock
+	value ahead of a shock

Table 4

Superscripts	
Superscript	Definition
+	maximum saturation value

-	minimum saturation value

III. EQUATIONS AND ANALYTIC SOLUTION IN THE ABSENCE OF DISSOLUTION

A. Defining the Governing Equations

In order to define the governing equations, the following assumptions were made about the subsurface geologic formation: (1) permeability is isotropic; (2) pressure gradients in the vertical direction are negligible compared with pressure gradients in the horizontal direction; and (3) capillary pressures are negligible in the nonwetting phase. Under these assumptions, a total flow rate leaving an injection well and entering a subsurface geologic formation was defined as the sum of the CO_2 flow rate and the brine flow rate, and was simply expressed as:

$$Q_{total} = A * u_{dc} + A * u_{db} = -\kappa A \frac{\partial P}{\partial x}\left[\frac{k_c}{\mu_c} + \frac{k_b}{\mu_b}\right] \quad \text{Eq. 1}$$

Eq. 1 was used to solve for the pressure gradient given by:

$$\frac{\partial P}{\partial x} = \frac{-Q_{tot}}{A\kappa}\left[\frac{k_c}{\mu_c} + \frac{k_b}{\mu_b}\right]^{-1} \quad \text{Eq. 2}$$

The velocity of the CO_2 phase was written using Darcy's Law. Since, the pressure gradient in the CO_2 phase was assumed to be equal to the pressure gradient in the water phase, Eq. 2 was substituted into Eq. 3.

$$u_{dc} = -\kappa \frac{k_c}{\mu_c}\frac{\partial P}{\partial x} = \frac{-\kappa k_c}{\mu_c} * \frac{-Q_{tot}}{A\kappa}\left[\frac{k_c}{\mu_c} + \frac{k_b}{\mu_b}\right]^{-1} \quad \text{Eq. 3}$$

The CO_2 velocity was then nondimensionalized by dividing both sides of Eq. 3 by Q_{tot}/A. Simplifying this new equation yielded equation 4a. From Eq. 1, it was also shown that the nondimensional velocity of the brine phase can be written as Eq. 4b.

$$u_{ndc} = \frac{1}{1+\eta f} \quad \text{Eq. 4a}$$

$$u_{ndb} = 1 - \frac{1}{1+\eta f} \qquad \text{Eq. 4b}$$

In Eq. 4a and Eq. 4b, η and f are defined in Eq. 5a and Eq. 5b, respectively.

$$\eta = \frac{\mu_o}{\mu_b} \qquad \text{Eq. 5a}$$

$$f = \frac{k_b}{k_o} \qquad \text{Eq. 5b}$$

B. Solving Using the Method of Characteristics

One may turn now to a different governing equation for this same problem: conservation of mass using the definition of saturation to keep track of each phase. The density of each phase was assumed to be constant and the each fluid phase was assumed to be incompressible. These assumptions are consistent with the assumptions made above. Under these assumptions, the conservation of mass for phase i was written as:

$$\frac{\partial S_i}{\partial t} + \frac{\partial}{\partial x}[u_{di}] = 0 \qquad \text{Eq. 6}$$

The second term on the left hand side of Eq. 6 is the saturation convection. The velocity (u_{di}) is the Darcy velocity for whichever phase is being considered, and, is generally an implicit function of saturation due to the relative permeability term. Therefore using the chain rule, Eq. 6 is written as Eq. 7. Eq. 7 is more convenient because this partial differential equation now has the form necessary to solve by the method of characteristics.

$$\frac{\partial S_i}{\partial t} + \left[\frac{\partial u_i}{\partial S_i}\right]\frac{\partial S_i}{\partial x} = 0 \qquad \text{Eq. 7}$$

Using the method of characteristics, the partial differential equation in equation 7 was converted into a coupled set of ordinary differential equations, written in Eq. 8a and Eq. 8b. Eq. 8a shows that the rate of change in saturation with respect to time is zero, provided that an observer of the

saturation function moves along the function with a velocity (v_i) given by Eq. 8b. In other words, along a characteristic, the saturation is constant.

$$\frac{dS_c}{dt} = 0 \qquad \text{Eq. 8a}$$

$$\frac{dx}{dt} = v_i = \frac{\partial u_t}{\partial S_c} \qquad \text{Eq. 8b}$$

The characteristic velocity (v_i) can also be nondimensionalized by dividing each side by Q_{tot}/A. The results were substituted from Eq. 4a, Eq. 5a and Eq. 5b to write Eq. 9, which is the nondimensional characteristic velocity for the CO_2 phase.

$$v_{nc} = \frac{du_{nc}}{df}\frac{df}{dS_c} \qquad \text{Eq. 9}$$

Finally, Eq. 9 was used to evaluate du_{nc}/df in Eq. 4. Doing so yields the following result:

$$v_{nc} = \frac{-\eta}{(1+\eta f)^2}\frac{df}{dS_c} \qquad \text{Eq. 10}$$

Eq. 10 is the generalized nondimensional form of the characteristic velocity for the CO_2 phase. As defined above, this characteristic velocity is the velocity required to observe a control volume which has a constant saturation value. However, Eq. 10 cannot be evaluated without knowing the relative permeability function, $f(S_c)$. If this function were known, it could be substituted into Eq. 10 and the characteristic velocities would be completely defined.

C. Defining Relative Permeability of CO_2 and H_2O in the Subsurface Geologic Formation

Relative permeability curves exist for a variety of fluid combinations and rock types. There is no general equation that can be derived for these curves; they all must be empirically determined and then fit with a suitable function. However, the relative permeability curves tend to look like FIG. 2.

For purposes of this analysis, the relative permeability curves were approximated by linear functions of S_c defined in Eq. 11a and Eq. 11b, where the S_c^+ and S_c^- are the residual saturations of brine and CO_2, respectively.

$$k_c(S_c) = \frac{S_c - S_c^-}{S_c^+ - S_c^-} \quad \text{Eq. 11a}$$

$$k_b(S_c) = \frac{S_c^+ - S_c}{S_c^+ - S_c^-} \quad \text{Eq. 11b}$$

The nondimensional governing equations with and without knowing the functional form for the relative permeabilities of each phase are summarized in Table 5

Table 5

	f is unknown	f is known k_c and k_w are linear functions of S_c
Solution to dS/dt = 0	$S_c(t) = S_c$	$S_c(t) = S_c$
Nondimensional characteristic velocity (v_{nc})	$\frac{-\eta}{(1+\eta f)^2}\frac{df}{dS_c}$	$\frac{(S_c^+ - S_c^-)\eta}{(-S_c + S_c^- - \eta S_c^+ + \eta S_c)^2}$

IV. MACROSCALE PUMPING CONSIDERATIONS

As discussed previously, one embodiment of a method of filling a carbon dioxide storage reservoir in the form of a subsurface geologic formation includes periodically injecting brine behind the CO_2 in a free-phase CO_2 plume in an effort to immobilize the CO_2 in the free-phase plume in the subsurface geologic formation, concurrent with the injection. This immobilization can be accomplished by at least two separate mechanisms: *trapping* and *dissolution*. Each mechanism requires different ratios of brine to CO_2, and, consequently, a different reservoir volume.

Aspects of the first mechanism, *trapping*, are shown in FIG. 1(c). CO_2 is immobilized in the pore spaces of a porous rock formation within a subsurface geologic formation at low volume

fractions when surrounded by and compressed by brine. In a sense, the compressing brine "smears" the free-phase CO_2 out over a larger subsurface geologic formation area. The volume ratio required for a first cycle is given by Eq. 12. After the first cycle, a slightly different volume ratio is required, and is defined by Eq. 13. The difference between the two equations derives from the observation that during the first injection of CO_2, the CO_2 is penetrating undisturbed brine. Within all following injections of CO_2, the injected CO_2 is entering a zone which already contains CO_2.

$$\gamma^T = \left[\frac{1-S_c^-}{S_c^- + (1-S_c^-)D} - \frac{1-S_c^+}{S_c^+ + (1-S_c^+)D}\right] \xrightarrow{\lim D \to 0} \left[\frac{1}{S_c^-} - \frac{1}{S_c^+}\right] \quad \text{Eq. 12}$$

$$\gamma^T = \left[\frac{1-S_c^-}{S_c^- + (1-S_c^-)D}\right] \xrightarrow{\lim D \to 0} \left[\frac{1}{S_c^-} - 1\right] \quad \text{Eq. 13}$$

When dissolution is neglected, the extent of CO_2 presence after "*N*" injection cycles in a simple 2D domain is then given by equation 14, and for the radially symmetric 3D domain is then given by equation 15.

$$L_N^T = \frac{NV_c}{A\phi S_c^-} \quad \text{Eq. 14}$$

$$R_N^T = \left[\frac{NV_c}{\pi H \phi S_c^-}\right]^{1/2} \quad \text{Eq. 15}$$

The second mechanism, *dissolution*, requires all of the free-phase CO_2 within the mobile CO_2 plume to be dissolved into the available quantity of brine. Similar to the trapping strategy, volume ratios required for the first cycle and all following cycles are given by Eq. 16 and Eq. 17, respectively. The extent of the CO_2 presence in the reservoir for 2D and 3D domains are given by Eq. 18 and Eq. 19, respectively, for the option of complete dissolution.

$$\gamma^D = \left[\frac{1}{D} - \frac{1-S_c^*}{S_c^+ + (1-S_c^+)D}\right] \quad \text{Eq. 16}$$

$$\gamma^D = \frac{1}{D} \quad \text{Eq. 17}$$

$$L_N^T = \frac{NV_c}{A\phi D} \quad \text{Eq. 18}$$

$$R_N^T = \left[\frac{NV_c}{\pi H\phi D}\right]^{1/2} \quad \text{Eq. 19}$$

By taking advantage of a capillary trapping mechanism for free-phase CO_2 immobilization and/or a dissolution mechanism for free-phase CO_2 immobilization, it is anticipated within the context of the prophetic computer simulations in accordance with the embodiments that the free-phase CO_2 will be completely immobilized at the end of the last brine injection.

V. SUMMARY OF RESULTS AND COMPARISON TO COMMERCIAL SOFTWARE

A. Analytic Predictions

The preceding analysis and equations are valid for any variation of the periodic injection strategy as currently embodied or contemplated to be embodied. However, in order to compare results, the representative values listed in Table 6 were used for macroscale pumping estimates, and some assumptions were made about the mass of CO_2 being sequestered. Table 1 compares some of the key results of the present embodiments in comparison with a traditional single injection strategy. For all of the cases analyzed, all of the CO_2 emissions from a 1 GW coal-fired power plant operating for 1 year had to be sequestered in a carbon dioxide storage reservoir of 10 meter height.

Table 6

Property	Value	Property	Value
K	1 x 10^{-13}	μ_c	1 x 10^{-4}
Φ	0.15	μ_b	1 x 10^{-3}
H	10	S_c^-	0.1 - 0.4
$C_{aq,sat}$	30 – 50	S_c^+	0.8 - 0.9
ρ_c	395 – 800		
ρ_b	1010		

As indicated above, Table 1 shows a summary of results comparing the dissolution and trapping mechanisms of the embodiments to the traditional strategy when sequestering all of the CO_2

emissions from the 1 GW coal-fired power plant for 1 year. The best/worst case values were found by minimizing/maximizing the 4 parameters provided whose value is listed as a range in Table 6. This procedure was done independently for the volume ratio results and for the radial extent results, which is to say that the "best" value for volume ratio does not correspond to the same input parameters as the "best" value for radial extent. However, all the values in the "avg." columns used the same input parameters (Caq,sat = 40, $\rho_c = 700$, $S_c^- = 0.3$, $S_c^+ = 0.9$). Table 7 shows a pilot-scale simulation of the present embodiment compared to the traditional injection strategy at the end of the last fluid injection (at the 12 day mark for the traditional strategy, at the 44.46 day mark for the trapping strategy, and at the 360 day mark for the dissolving strategy).

Table 7

	Parameter	Traditional Injection Strategy	Our Trapping Strategy	Our Dissolving Strategy
Simulation Inputs	Fluid Injection Rate [kg/s]	5	5	5
	Total Time Spent Injecting CO_2 [days]	12	12	12
	Total Time Spent Injecting Brine [days]	0	32.56	348
Simulation Results at the end of injection	γ (Vol. brine:Vol. CO_2)	0	2.36	25.25
	mobile fraction of CO_2	93.97 %	1.38 %	0.00 %
	immobile fraction of CO_2 (free-phase)	0.07 %	78.46 %	0.01 %
	immobile fraction of CO_2 (dissolved)	5.96 %	20.16 %	99.99 %

FIG. 4a, FIG. 4b, FIG. 4c and FIG. 4d show the simulation of the present embodiment, which were taken after the first injection of CO_2 was complete, and brine was injected. Each figure represents a progression of dissolution of the CO_2 into the brine. FIG. 4a represents the dissolution directly after the injection of brine, with each intermediate figure representing further dissolution until FIG. 4d represents the end of the first brine injection. The well is located at the left boundary of each figure, causing the fluids to convect towards the right. The color map identifies the location and density of the free-phase CO_2 (red = most dense gas and highest on gray scale, blue = no gas phase present and lowest on gray scale). As brine is injected, the CO_2 dissolves into the brine. The original CO_2 is nearly completely dissolved. This process is repeated 4 times over the course of 1 year.

As shown in FIG. 5, and according to another embodiment, an embodiment may comprise comprise a system having an injection well adapted for sequential injection of brine and CO_2, and an extraction well for the extraction of brine. The injection well may be any injection well known in the art, as is commonly used to inject CO_2 into subsurface geologic formations, so long as the well is adapted or otherwise configured to inject at least one injection of CO_2, and to inject at least one injection of brine. The extraction well is any extraction well known in the art suitable for the extraction of brine from a subsurface geologic formation. As previously stated, the extraction of brine may occur prior to, during, or after the beginning of injection of CO_2. The extracted brine may be extracted from the same subsurface geologic formation or a separate formation. Furthermore, as previously stated, the subsurface geologic formation may comprise a carbon dioxide impervious caprock formation, a brine impervious baserock formation, and a carbon dioxide porous intermediate rock formation. The system may be further adapted to inject ratios of CO_2 and brine suited for trapping the CO_2 in the porous intermediate rock formation as described in the embodiments and calculations above, or may be adapted to inject ratios of CO_2 and brine suited for the dissolution of CO_2 within the brine as described in the embodiments and calculations above. In yet an alternative embodiment, the system may be adapted for injecting a ratio of CO_2 and brine which is calculated to take advantage of both the trapping and dissolution mechanisms.

All references, including publications, patent applications, and patents cited herein are hereby incorporated by reference in their entireties to the extent allowed, and as if each reference was individually and specifically indicated to be incorporated by reference and was set forth in its entirety herein.

The use of the terms "a" and "an" and "the" and similar referents in the context of describing the invention (especially in the context of the following claims) is to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. The terms "comprising," "having," "including," and "containing" are to be construed as open-ended terms (i.e., meaning "including, but not limited to,") unless otherwise noted. The term “connected” is to be construed as partly or wholly contained within, attached to, or joined together, even if there is something intervening.

The recitation of ranges of values herein is merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it was individually recited herein.

All methods described herein may be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., "such as") provided herein, is intended merely to better illuminate embodiments of the invention and does not impose a limitation on the scope of the invention unless otherwise claimed.

No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the invention.

It will be apparent to those skilled in the art that various modifications and variations can be made to the present invention without departing from the spirit and scope of the invention. There is no intention to limit the invention to the specific form or forms disclosed, but on the contrary, the intention is to cover all modifications, alternative constructions, and equivalents falling within the spirit and scope of the invention, as defined in the appended claims. Thus, it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.

CLAIMS

What is claimed is:

1. A carbon dioxide storage reservoir comprising:

a subsurface geologic formation; and

an artificially introduced carbon dioxide plume at least in part contacting a quantity of brine, each located within the subsurface geologic formation, wherein the artificially introduced carbon dioxide plume is substantially immobile within the subsurface geologic formation when the quantity of brine is quiescent within the subsurface geologic formation.

2. The carbon dioxide storage reservoir of claim 1 wherein the subsurface geologic formation comprises:

a carbon dioxide impervious cap rock formation;

a brine impervious base rock formation separated from and beneath the carbon dioxide impervious cap rock formation;

a carbon dioxide porous intermediate rock formation interposed between the carbon dioxide impervious cap rock formation and the brine impervious base rock formation; and

a quantity of brine at least partially filling the carbon dioxide porous intermediate rock formation.

3. The carbon dioxide storage reservoir of claim 2 wherein the carbon dioxide storage reservoir further comprises:

an injection well reaching the carbon dioxide porous intermediate rock formation; and

an extraction well reaching the quantity of brine.

4. A carbon dioxide storage reservoir comprising:

a subsurface geologic formation including a quantity of brine;

an injection well reaching the subsurface geologic formation and adapted to sequentially and separately inject carbon dioxide and brine into the subsurface geologic formation; and

an extraction well reaching the quantity of brine.

5. A carbon dioxide storage reservoir comprising:

a subsurface geologic formation including:

a carbon dioxide impervious cap rock formation;

a brine impervious base rock formation separated from and beneath the carbon dioxide impervious cap rock formation;

a carbon dioxide porous intermediate rock formation interposed between the carbon dioxide impervious cap rock formation and the brine impervious base rock formation; and

a quantity of brine at least partially filling the carbon dioxide porous intermediate rock formation;

an injection well reaching the carbon dioxide porous intermediate rock formation and being adapted for sequentially and separately injecting carbon dioxide and brine; and

an extraction well reaching the quantity of brine.

6. A method for filling a carbon dioxide storage reservoir comprising:

providing an injection well and an extraction well reaching a subsurface geologic formation;

injecting a quantity of injected carbon dioxide at the injection well and extracting a quantity of extracted brine at the extraction well; and then

injecting a quantity of injected brine at the injection well.

7. A method for filling a carbon dioxide storage reservoir comprising:

providing an injection well and an extraction well reaching a subsurface geologic formation, the subsurface geologic formation including:

a carbon dioxide impervious cap rock formation;

a brine impervious base rock formation separated from and beneath the carbon dioxide impervious cap rock formation;

a carbon dioxide porous intermediate rock formation interposed between the carbon dioxide impervious cap rock formation and the brine impervious base rock formation; and

a quantity of brine at least partially filling the carbon dioxide porous intermediate rock formation; wherein the injection well extends to the carbon dioxide porous intermediate rock formation and the extraction well extends to the quantity of brine;

injecting a quantity of injected carbon dioxide at the injection well and extracting a quantity of extracted brine at the extraction well; and then

injecting a quantity of injected brine at the injection well.

8. The method of claim 7 wherein the quantity of injected carbon dioxide is injected before extracting the quantity of extracted brine.

9. The method of claim 7 wherein the quantity of injected carbon dioxide is injected simultaneous with extracting the quantity of extracted brine.

10. The method of claim 7 wherein the quantity of injected carbon dioxide is injected after extracting the quantity of extracted brine.

11. The method of claim 7 wherein:

a volume ratio of a volume of injected brine to a volume of injected carbon dioxide is from about 2:1 to about 3:1; and

the method uses a trapping assumption when filling the carbon dioxide storage reservoir.

12. The method of claim 11 wherein a volume ratio of extracted brine to a volume of injected brine is about 1:1.

13. The method of claim 7 wherein:

a volume ratio of a volume of injected brine to a volume of injected carbon dioxide is from about 9:1 to about 25:1; and

the method uses a dissolution assumption when filling the carbon dioxide storage reservoir.

14. The method of claim 11 wherein a volume ratio of extracted brine to a volume of injected brine is about 1:1.

15. A method for filling a carbon dioxide storage reservoir comprising:

providing an injection well and an extraction well reaching a subsurface geologic formation, the subsurface geologic formation including:

a carbon dioxide impervious cap rock formation;

a brine impervious base rock formation separated from and beneath the carbon dioxide impervious cap rock formation;

a carbon dioxide porous intermediate rock formation interposed between the carbon dioxide impervious cap rock formation and the brine impervious base rock formation; and

a quantity of brine at least partially filling the carbon dioxide porous intermediate rock formation, wherein the injection well extends to the carbon dioxide porous intermediate rock formation and the extraction well extends to the quantity of brine;

injecting a quantity of injected carbon dioxide at the injection well and extracting a quantity of extracted brine at the extraction well; and then

injecting a quantity of injected brine at the injection well, wherein a volume ratio of a volume of injected brine to a volume of injected carbon dioxide is from about 2:1 to about 3:1; and

the method uses a trapping assumption when filling the carbon dioxide storage reservoir.

16. A system for filling a carbon dioxide storage reservoir comprising:

an injection well reaching a subsurface geologic formation and adapted for sequential and separate injection of carbon dioxide and brine;

an extraction well reaching a subsurface geologic formation; and

a computer programmed to effect the sequential and separate injection of carbon dioxide and brine at the injection well and the extraction of brine at the extraction well.

17. The system of claim 16 wherein the subsurface geologic formation comprises:

a carbon dioxide impervious cap rock formation;

a brine impervious base rock formation separated from and beneath the carbon dioxide impervious cap rock formation;

a carbon dioxide porous intermediate rock formation interposed between the carbon dioxide impervious cap rock formation and the brine impervious base rock formation; and

a quantity of brine at least partially filling the carbon dioxide porous intermediate rock formation, wherein the injection well extends to the carbon dioxide porous intermediate rock formation and the extraction well extends to the quantity of brine.

18. A non-transitory computer-readable storage medium having stored thereon instructions for sequentially and separately injecting carbon dioxide and brine into a subsurface geologic formation reservoir that, when executed by at least one processor, causes the processor to perform steps comprising:

instructing an injection well, reaching the subsurface geologic formation, to sequentially and separately inject carbon dioxide and brine into a subsurface geologic formation; and

instructing an extraction well, reaching a subsurface geologic formation, to extract brine from the subsurface geologic formation.

19. The non-transitory computer-readable storage medium of claim 18 wherein the subsurface geologic formation comprises:

a carbon dioxide impervious cap rock formation;

a brine impervious base rock formation separated from and beneath the carbon dioxide impervious cap rock formation;

a carbon dioxide porous intermediate rock formation interposed between the carbon dioxide impervious cap rock formation and the brine impervious base rock formation; and

a quantity of brine at least partially filling the carbon dioxide porous intermediate rock, wherein the injection well extends to the carbon dioxide porous intermediate rock formation and the extraction well extends to the quantity of brine.

20. The medium of claim 19 wherein instructing the extraction well comprises dictating the flow rate of the extraction well.

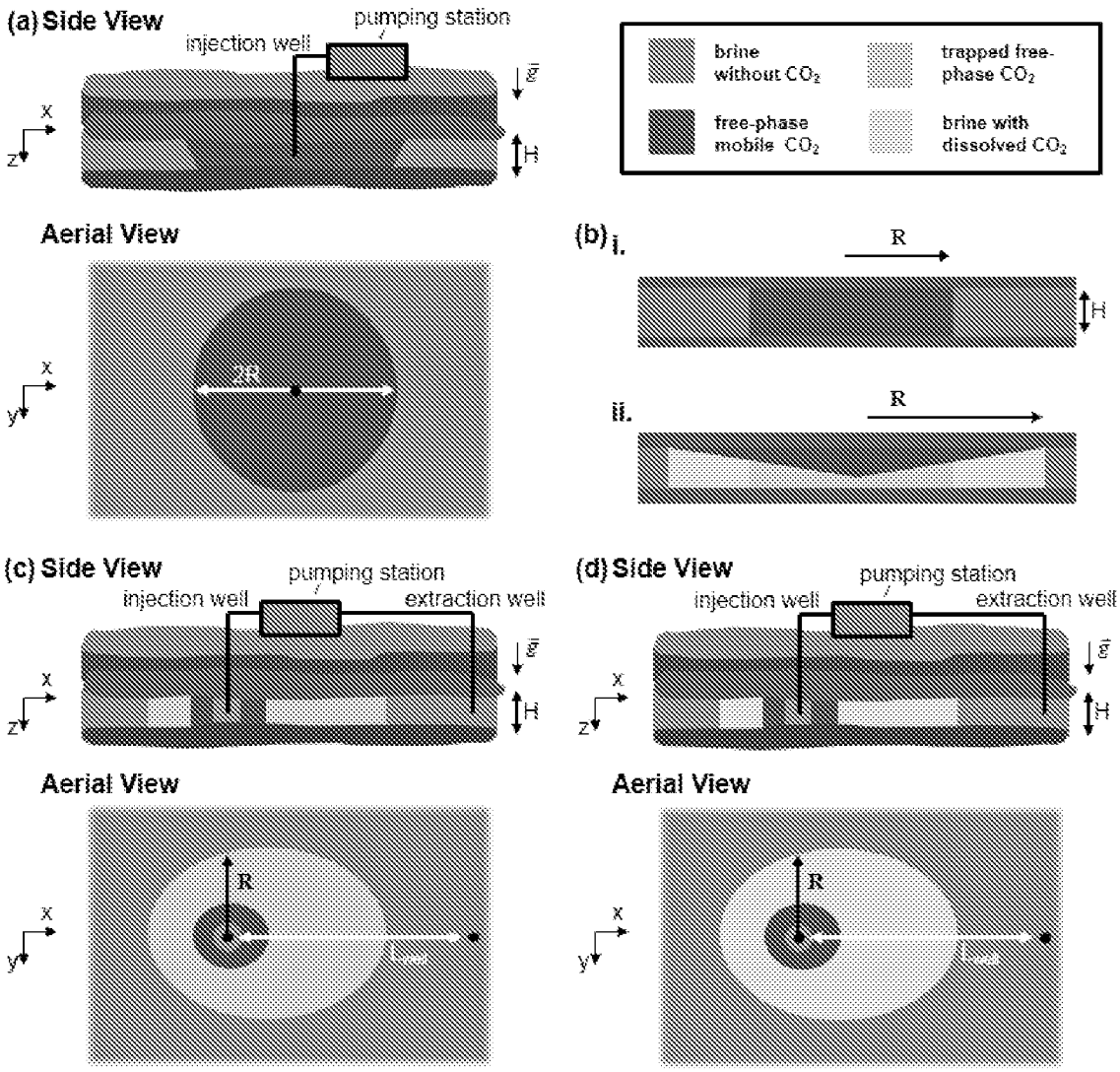
(a) Side View
injection well
pumping station
x
z
H
brine without CO_2
trapped free-phase CO_2
free-phase mobile CO_2
brine with dissolved CO_2
Aerial View
x
y
2R
(b) i.
R
H
ii.
R
(c) Side View
injection well
pumping station
extraction well
x
z
H
Aerial View
x
y
R
(d) Side View
injection well
pumping station
extraction well
x
z
H
Aerial View
x
y
R

FIG. 1

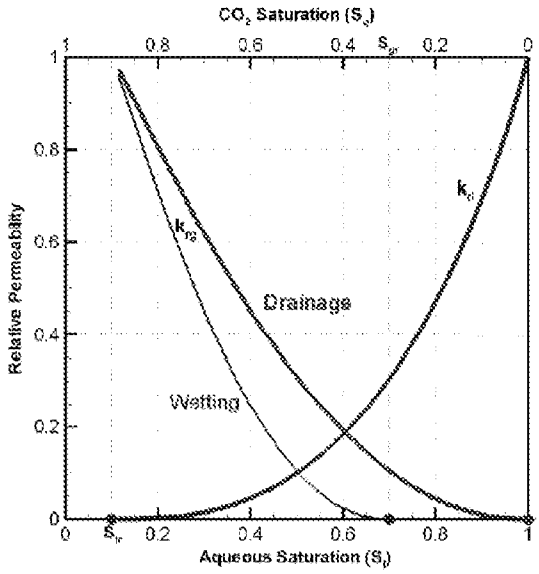
CO2 Saturation (Sg)
1
0.8
0.6
0.4
Sgr
0.2
0
Relative Permeability
0.8
0.6
0.4
0.2
0
krg
krw
Drainage
Wetting
Swr
0.2
0.4
0.6
0.8
1
Aqueous Saturation (Sw)

FIG. 2

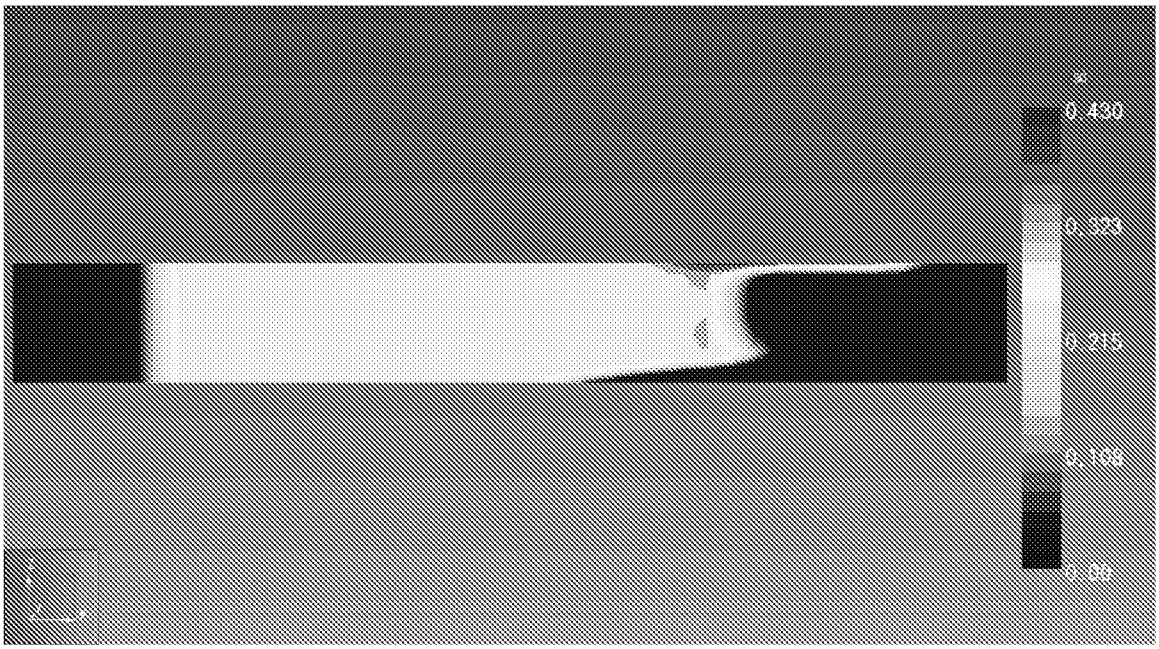
0.430
0.323
0.215
0.108
0.000

FIG. 3

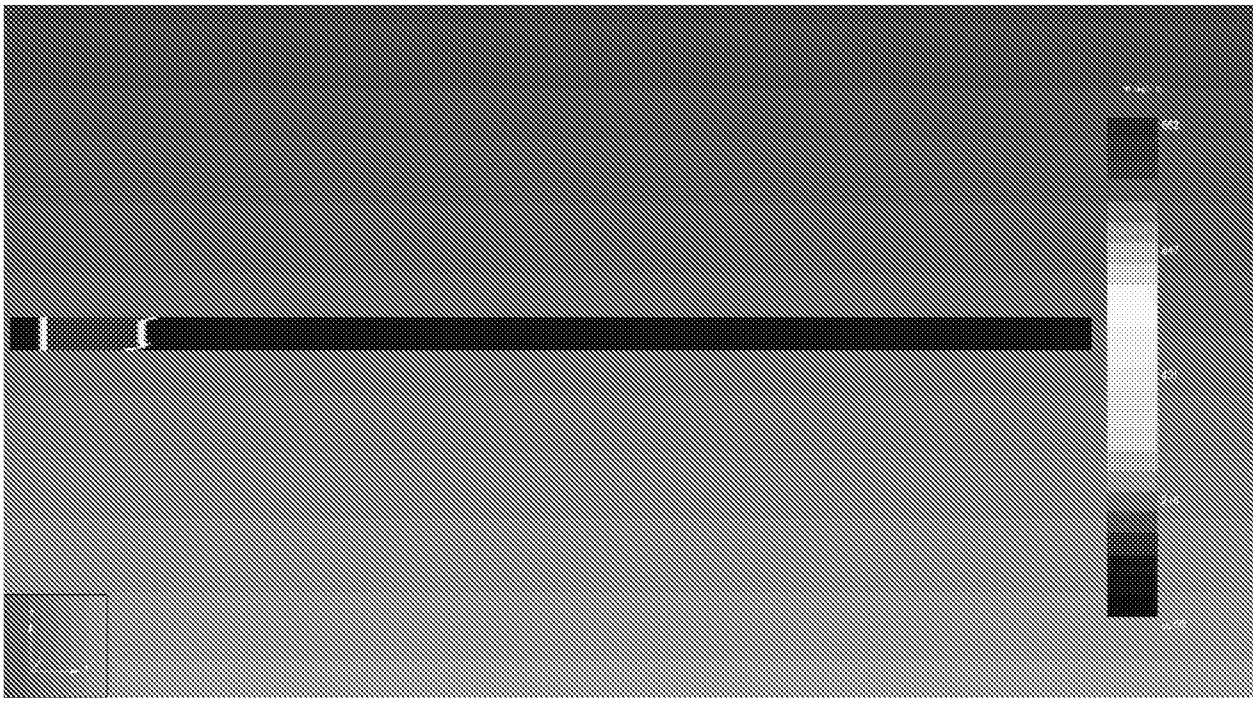

FIG. 4a

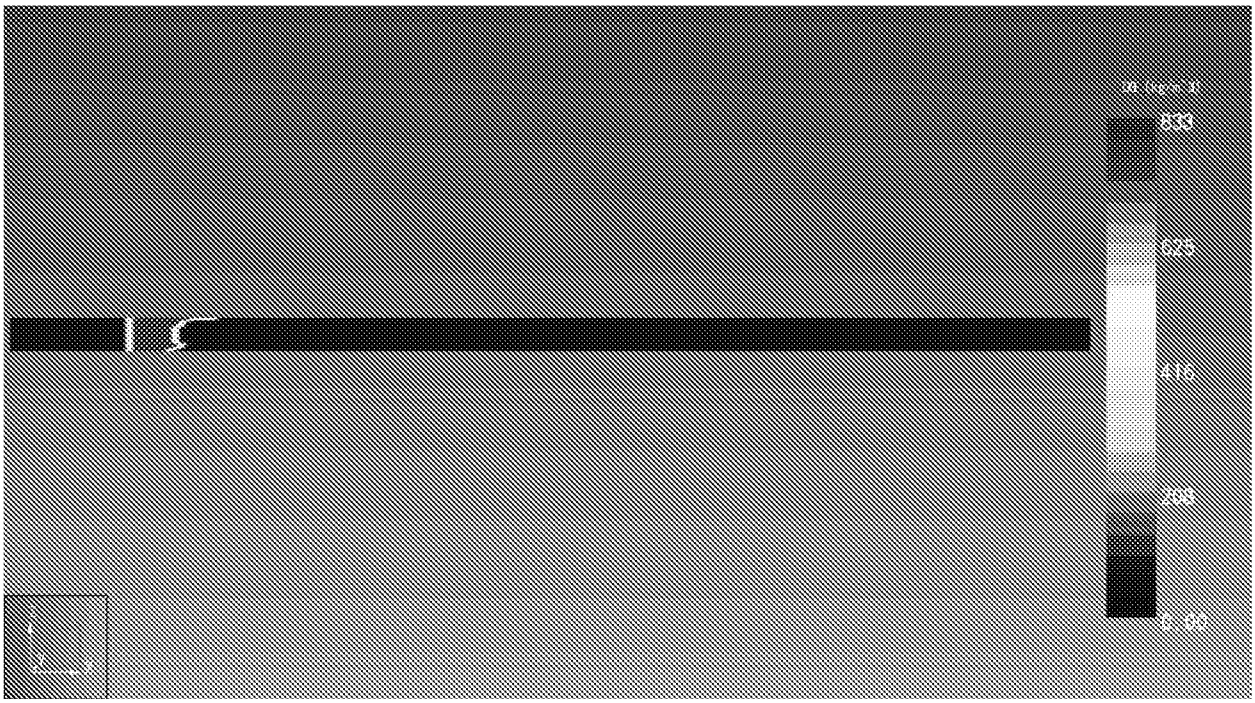

FIG. 4b

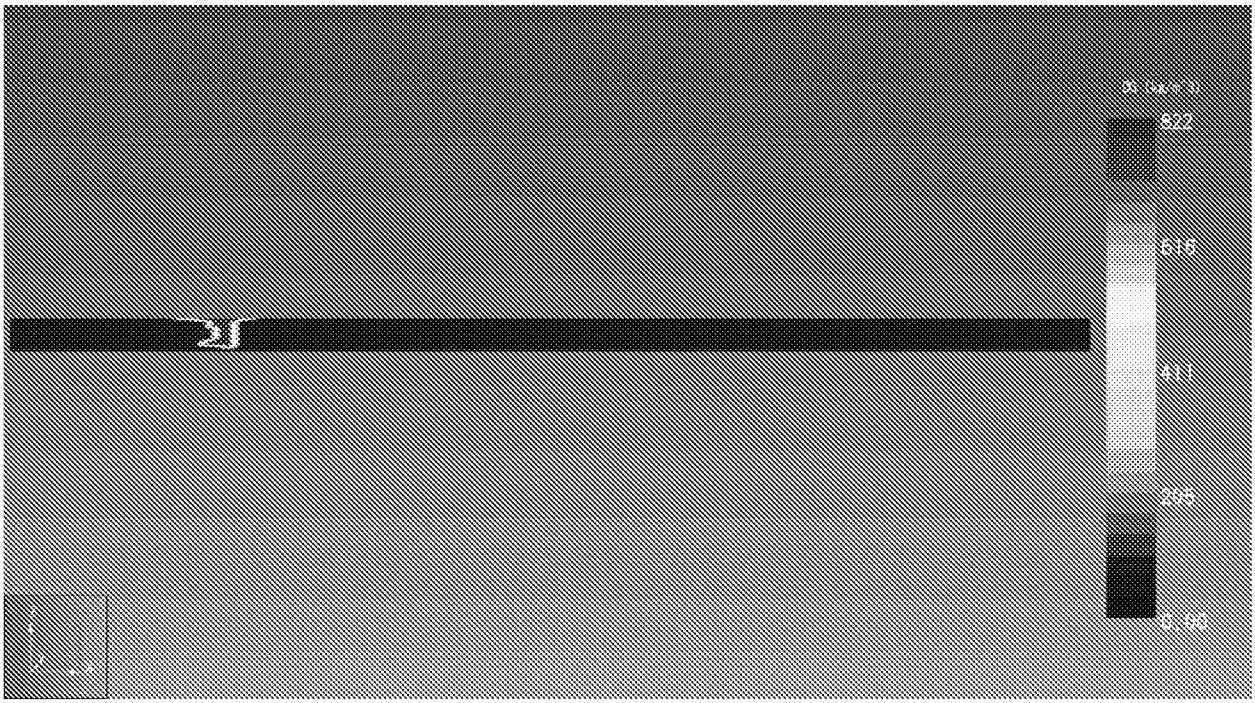

FIG. 4c

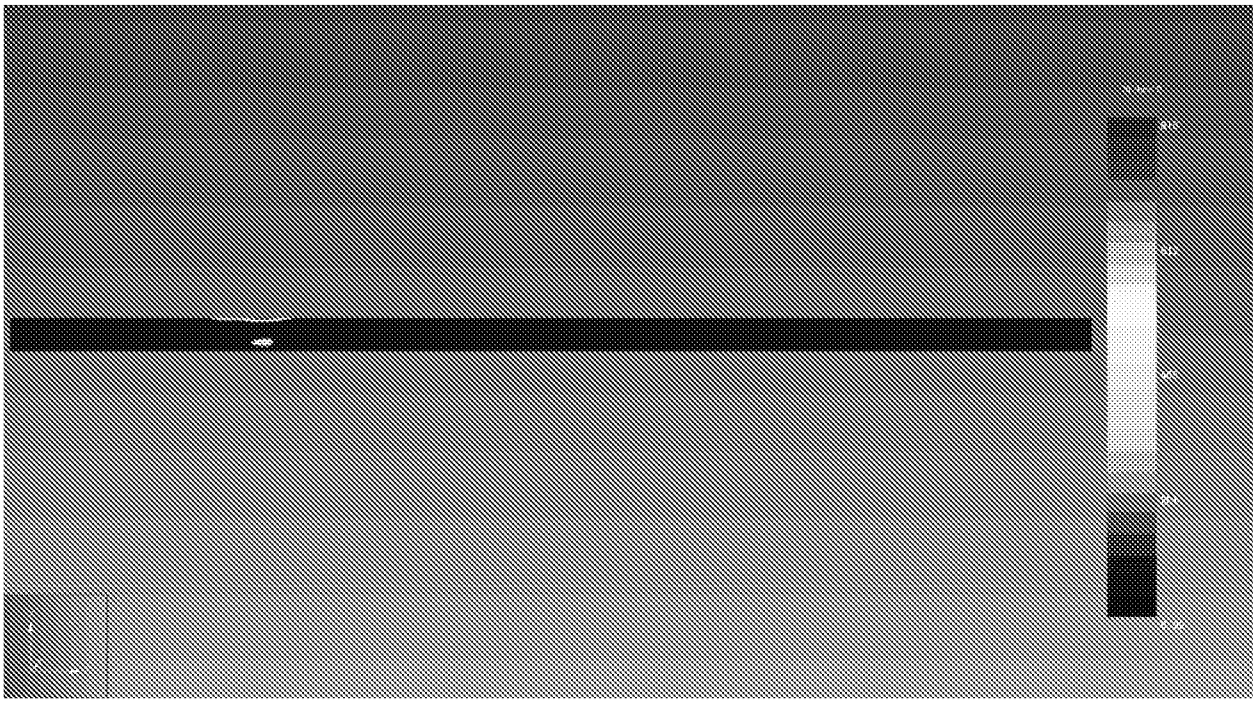

FIG. 4d

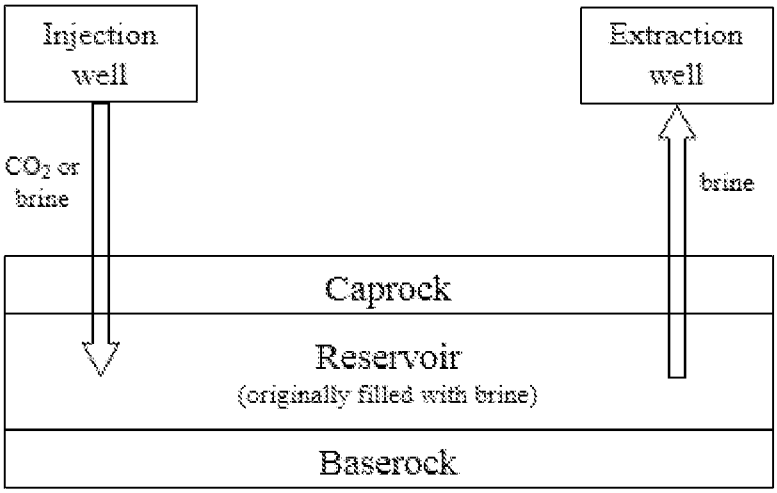
Injection well
Extraction well
CO_2 or brine
brine
Caprock
Reservoir
(originally filled with brine)
Baserock

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2013/073079

A. CLASSIFICATION OF SUBJECT MATTER

B65G 5/00(2006.01)i, F17C 13/00(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B65G 5/00; C01B 31/20; E21B 43/24; F03G 7/00; B01J 19/00; E21B 41/00; F17C 13/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & keywords: carbon dioxide, extraction, injection, immobilized, subsurface, deologic, storage, reservoir, brine, rock, computer, and medium

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 2011-031154 A (NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE & TECHNOLOGY) 17 February 2011 See paragraphs [0012]-[0014] and figure 2.	1,4,6,16,18
Y		2-3,5,7-15,17,19-20
Y	US 8316955 B2 (SAAR et al.) 27 November 2012 See column 7, lines 33-60, column 8, lines 28-31, column 10, lines 46-54, and figure 1.	2-3,5,7-15,17,19-20
A	CN 101190743 A (INSTITUTE OF ROCK AND SOIL MECHANICS, CHINESE ACADEMY OF SCIENCES) 4 June 2008 See page 5, line 13 - page 6, line 9 and figures 1.1-1.3.	1-20
A	WO 2012-041926 A2 (STATOIL ASA) 5 April 2012 See abstract, page 1, lines 22-32, and figure 2.	1-20
A	US 2011-0013986 A1 (ZEBROWSKI, DANIEL R.) 20 January 2011 See paragraphs [0017],[0019] and figure 1.	1-20

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 February 2014 (27.02.2014)	**04 March 2014 (04.03.2014)**

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/US2013/073079

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
JP 2011-031154 A	17/02/2011	None	
US 8316955 B2	27/11/2012	AU 2010-223059 A1	22/09/2011
		CA 2753393 A1	16/09/2010
		CA 2753393 C	03/09/2013
		EP 2406562 A2	18/01/2012
		EP 2406562 A4	04/12/2013
		US 2012-001429 A1	05/01/2012
		US 2013-062890 A1	14/03/2013
		WO 2010-104599 A2	16/09/2010
		WO 2010-104599 A3	27/01/2011
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		WO 2009-071001 A1	11/06/2009
WO 2012-041926 A2	05/04/2012	AU 2011-310560 A1	18/04/2013
		CA 2812470 A1	05/04/2012
		EP 2622174 A2	07/08/2013
		NO 20101350 A	30/03/2012
		US 2013-259575 A1	03/10/2013
		WO 2012-041926 A3	28/03/2013
US 2011-0013986 A1	20/01/2011	US 8496060 B2	30/07/2013