China Australia Geological Storage of CO_2
中澳二氧化碳地质封存

Task1： Site Selection Method and Criteria of CO_2 Geological Storage

Research on Trapping Mechanism and the Assessment Method of the Regional CO_2 Storage Capacity

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Tsinghua's Tasks in CAGS

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- **Project 1:Site Selection Method and Criteria of CO_2 Geological Storage**
  - Task 2: Research on the characterization of dynamic behaviour and the assessment of the CO_2 storage capacity
- **Project 3:The Studies on Environmental Impact and Risk Management of CO_2 Storage**
  - Task: Risk modeling

CO_2 Storage Capacity Pyramid

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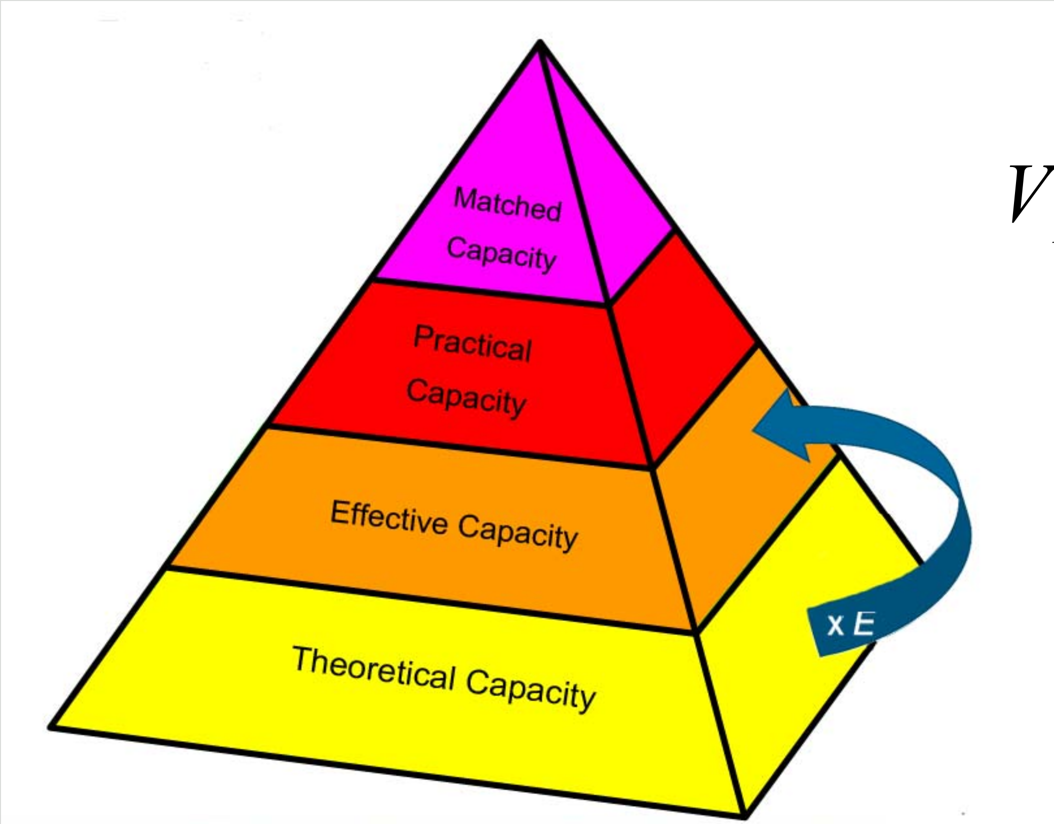
E: Storage efficiency factor



$$V_E = A \cdot h \cdot \phi \cdot E$$

Parameters related to *E* factor

- ***Trapping Mechanisms***
  - Pressure and Temperature
  - S_{wirr}: Irreducible Water Saturation
  - S_{rco^2}: Residual CO_2 Saturation
  - Relative Permeability
- Stratum Properties

  . Structure, Porosity, Rock characters
- Geochemistry

Different models of *E* factor have been developed, with the result that *E* varies from 1% to 20%.

Research Work

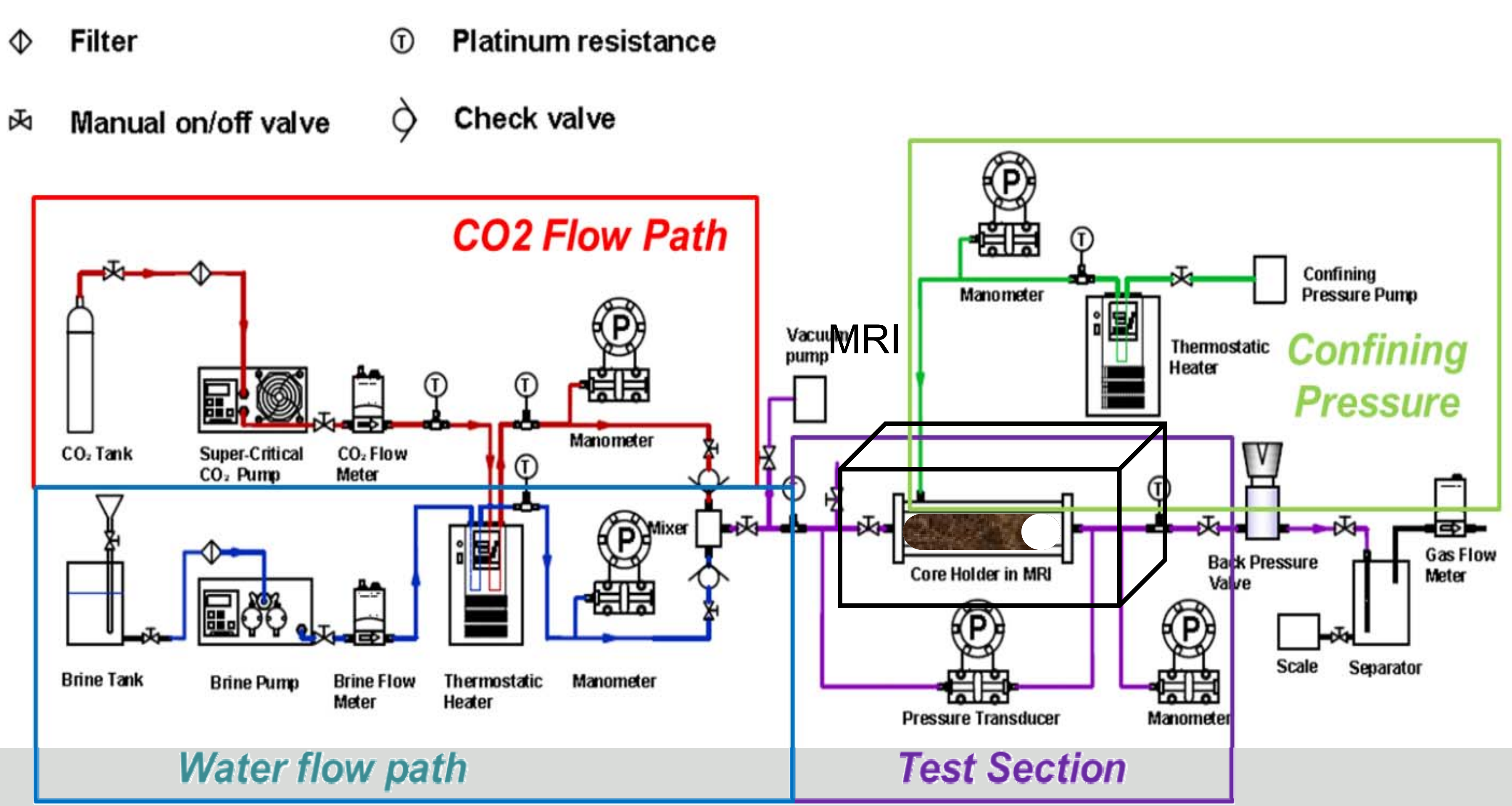
- **Study on CO2 migration and trapping mechanism during CO2 geological storage**
  - ***Physical trapping:*** Visualization experimental investigations of supercritical CO_2 injected into porous media
  - ***Physical trapping:*** Pore scale numerical simulation of supercritical CO_2 injecting into porous media containing water
  - ***Chemical trapping:*** Field scale simulation on the effect of reactive surface area on CO_2 mineral trapping

- **Study on the assessment method on CO2 geological storage capacity, especially the effective factor, E.**
  - Identify the influence factors on E factor and do the preliminary research on E factor value
  - Case study: Build the assessment method to link the lab's experiments results to the field capacity assessment

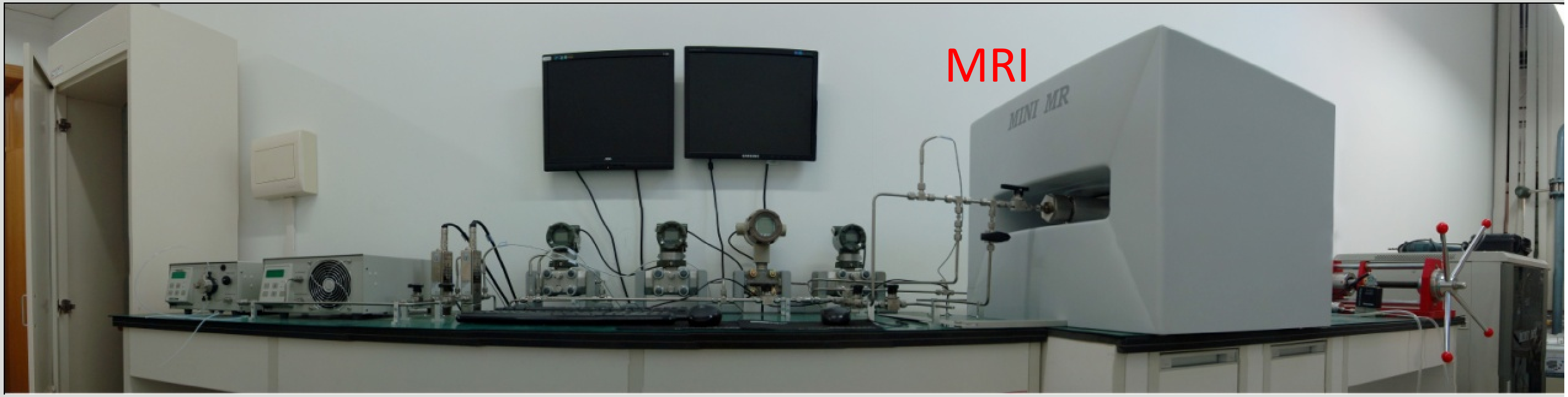
1. Experiment – a) Description

- Core flooding experience, steady state
- CO_2 water mixture flowing inside a rock core
- Visualization method: Magnetic Resonance System (MRI)
- Measurements:
  - Water saturation
  - Pressure drop
  - Relative permeability curves

1. Experiments – a) Description



Experimental system



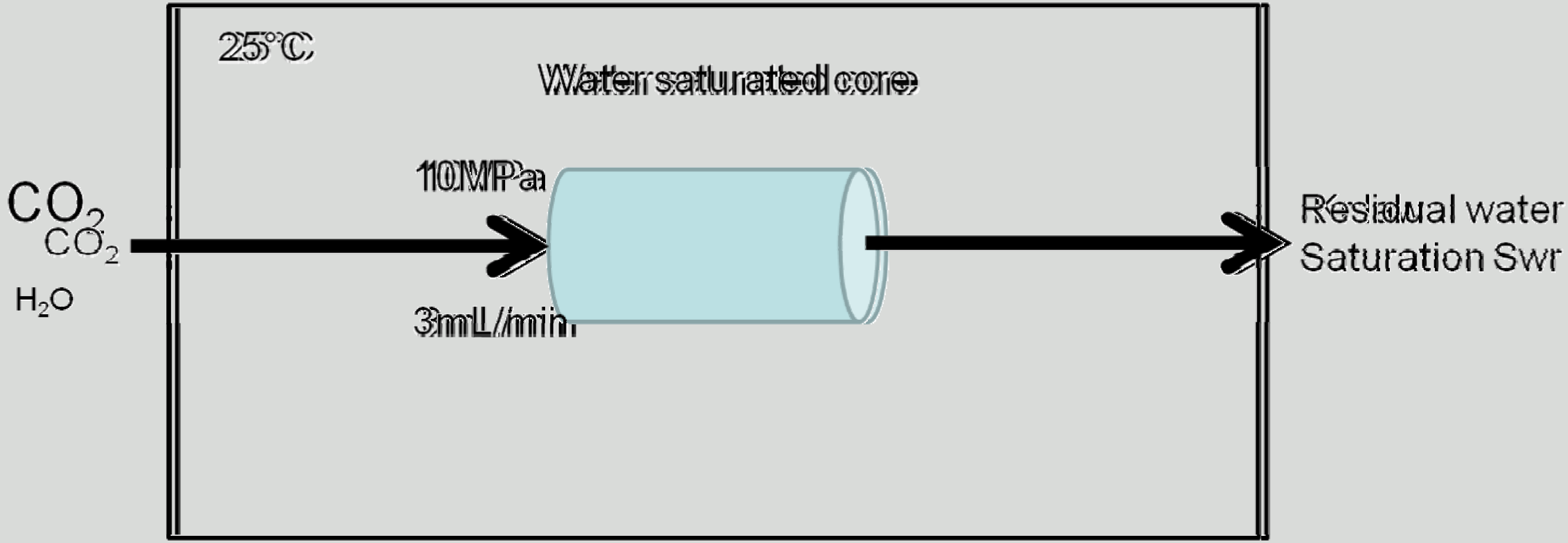
MRI visualization experimental system of supercritical CO_2 migration in porous media under CO2 geological storage conditions

Berea sandstone Sintered glass beads

1.2 Core scale experiments

- **Porosity measurement:**
  - **Mercury Injection： Φ=22.10%**
  - **NMR： Φ=22.02%**

Difference:0.81%。



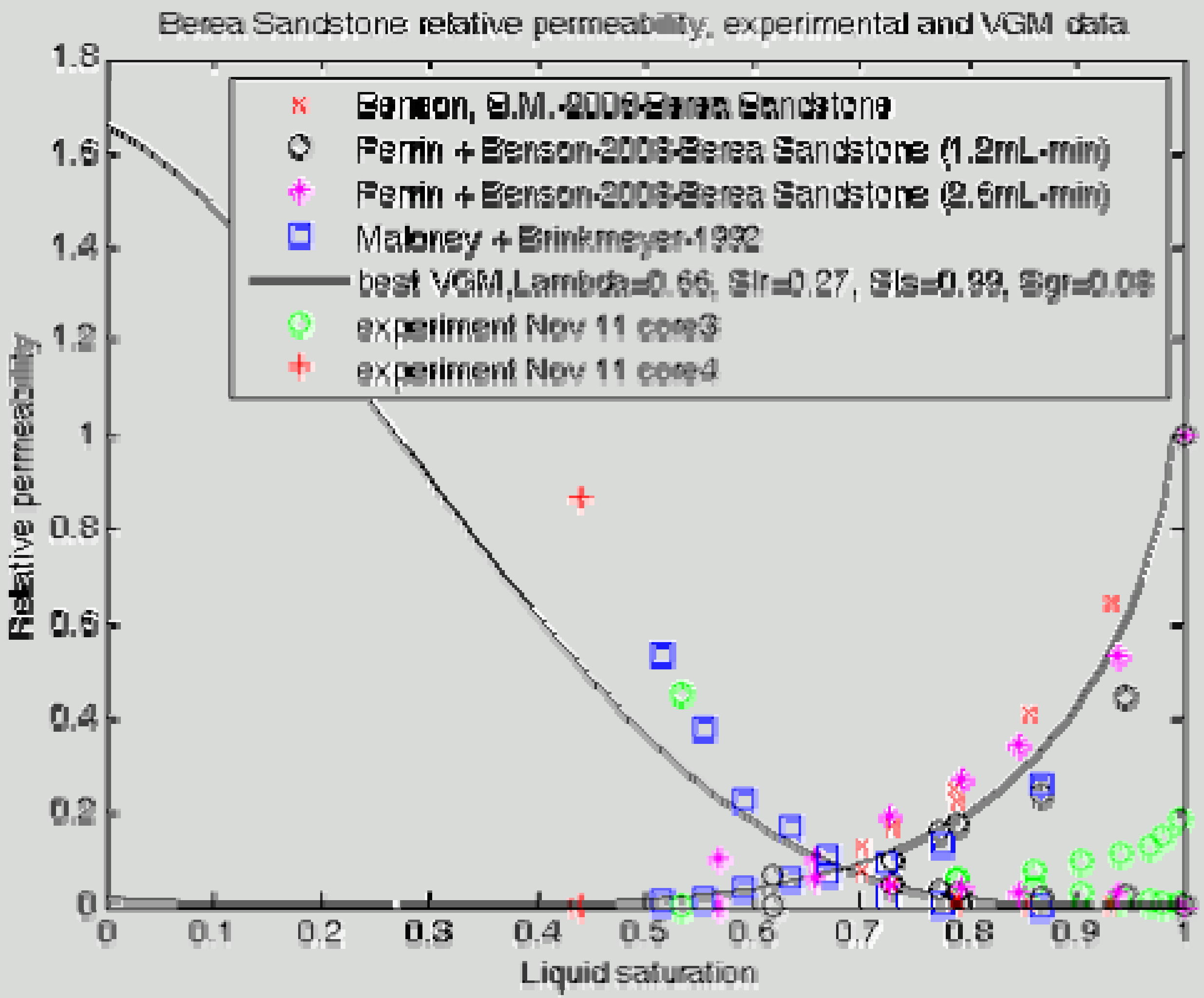
Imbibition process

- 4 cases

	Core	Temperature	Inlet pressure	Total injection flow rate
Experience 1	Core #3	47°C	**10MPa**	3mL/min
Experience 2	Core #3	47°C	**8MPa**	3mL/min
Experience 3	Core #4	25°C	10MPa	**2mL/min**
Experience 4	Core #4	25°C	10MPa	**3mL/min**

Kr + comparison

Van Genuchten Mualem law



$$K_{rl} = \sqrt{S^*}\{1-[1-(S^*)^{1/\lambda}]^{\lambda}\}^2$$

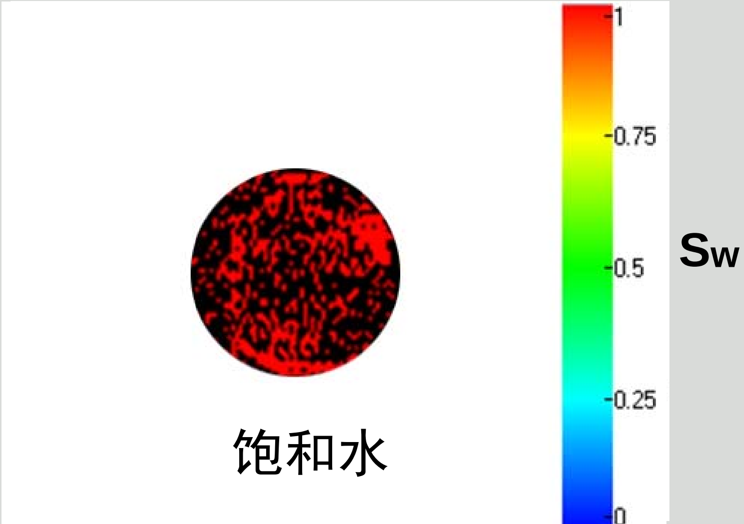
$$K_{rg} = (1-\hat{S})^2(1-\hat{S}^2)$$

$$S^* = \frac{(S_l - S_{lr})}{(S_{ls} - S_{lr})}$$

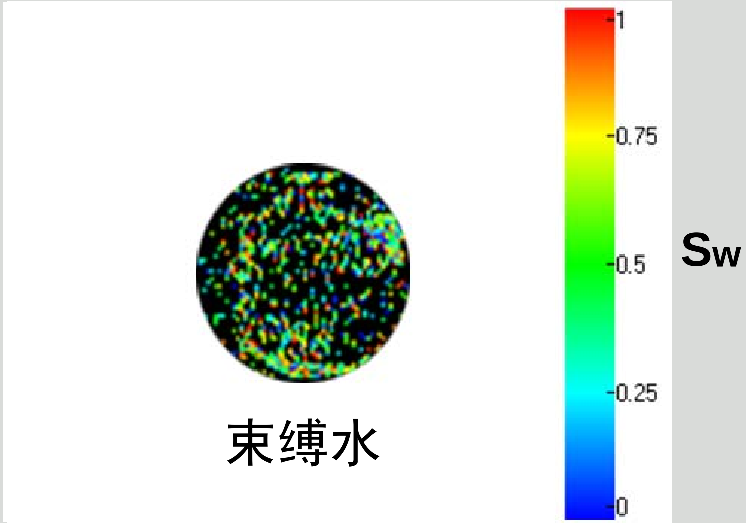
$$\hat{S} = \frac{(S_l - S_{lr})}{(1 - S_{lr} - S_{gr})}$$

λ = 0.66
Slr = 0.27
Sls = 0.99
Sgr = 0.08

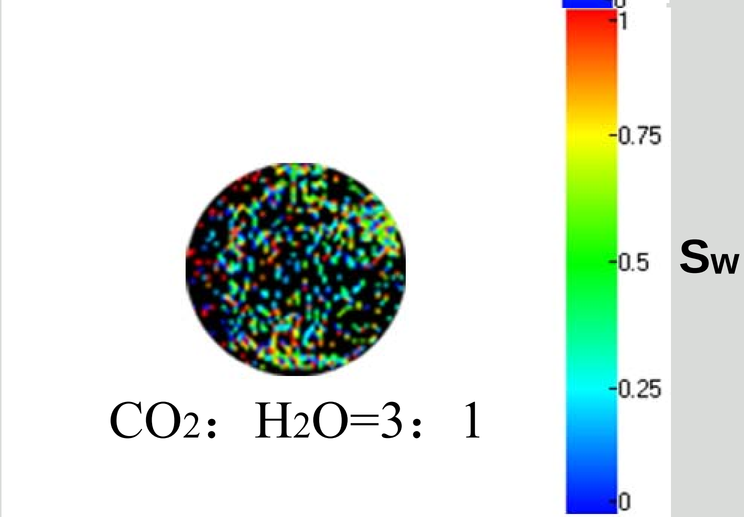
1.3 Images-Rock



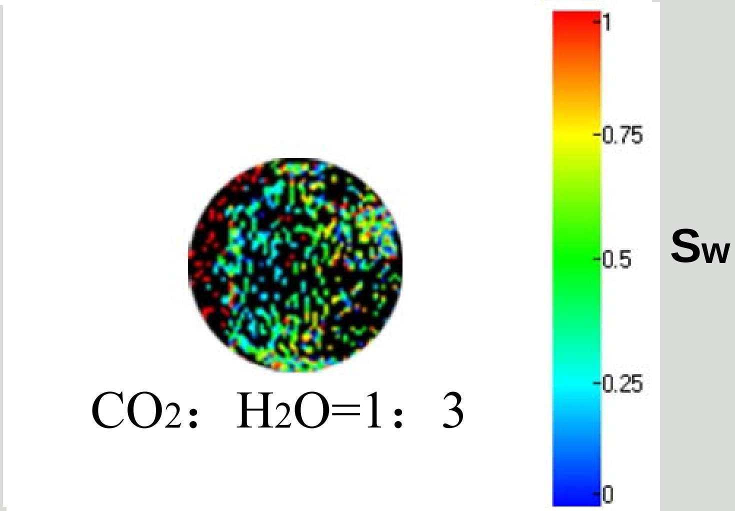
饱和水



束缚水



CO_2：H_2O=3：1



CO_2：H_2O=1：3

Imbibiton--Sintered glass beads

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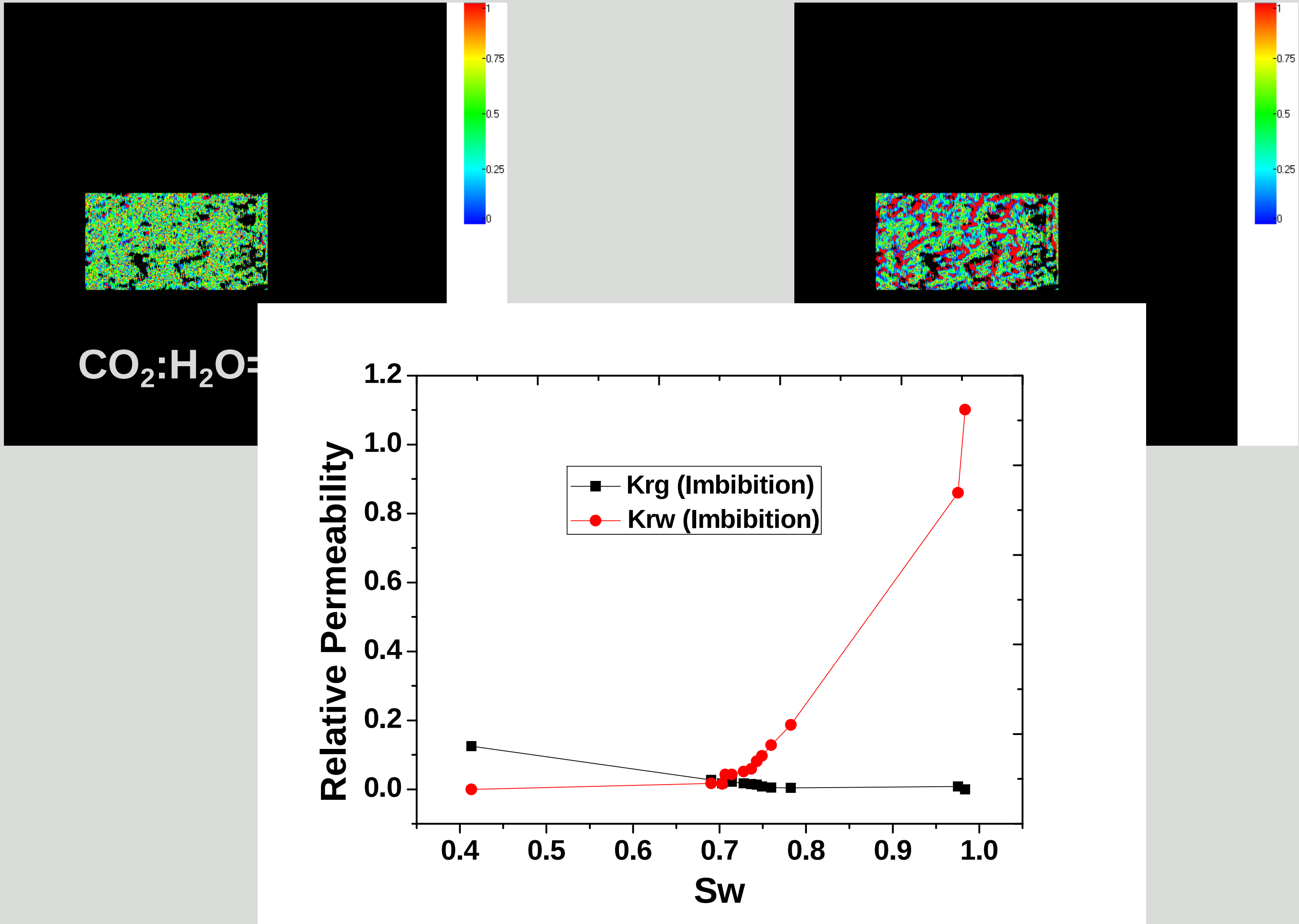
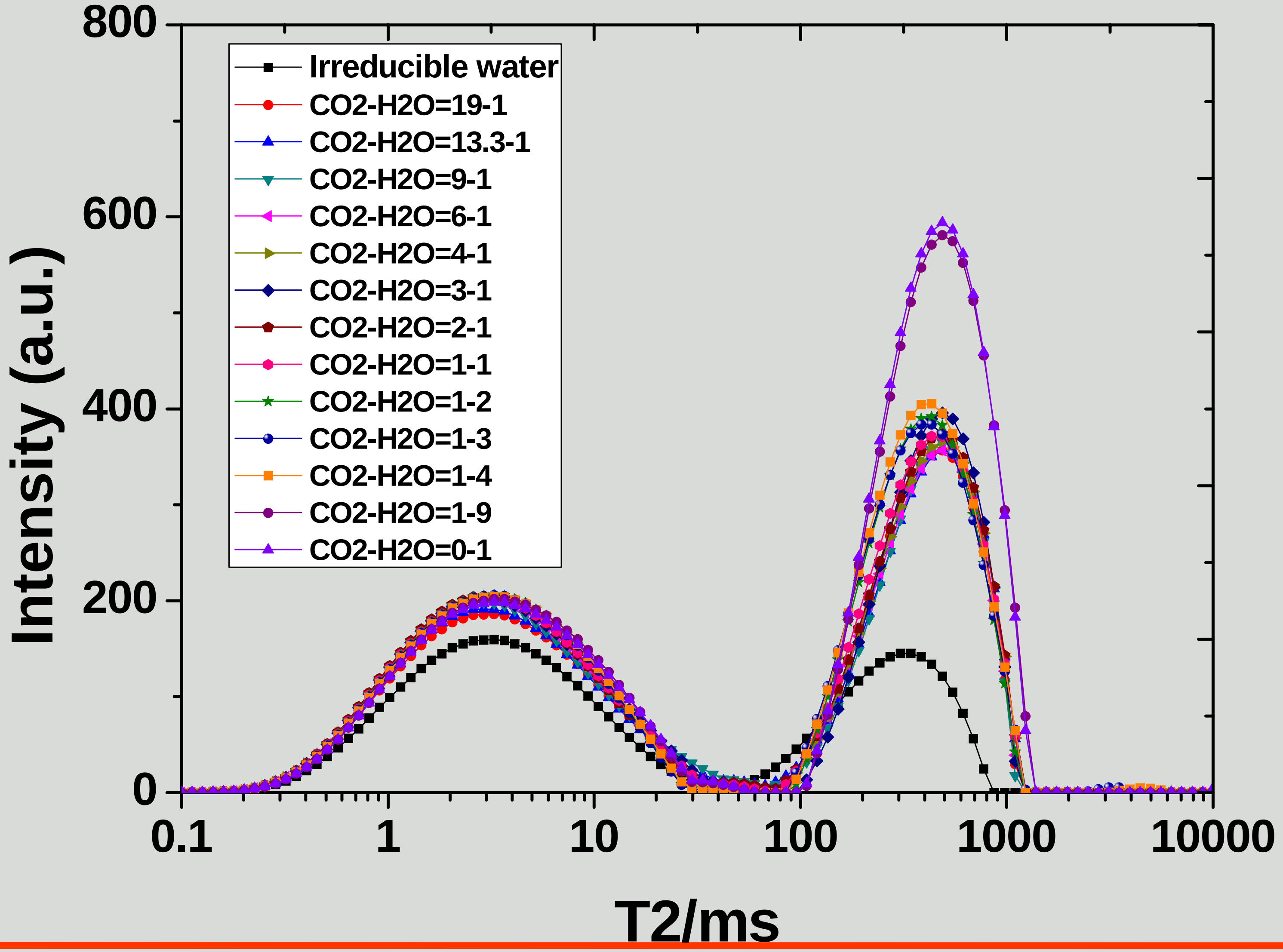


Imbibiton--Sintered glass beads



Research Work

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  - ***Physical trapping:*** Visualization experimental investigations of supercritical CO_2 injected into porous media
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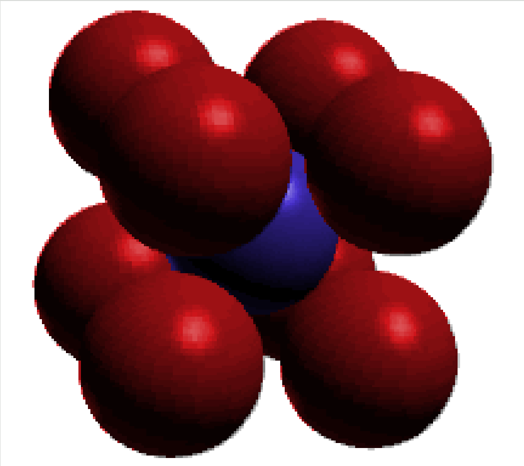
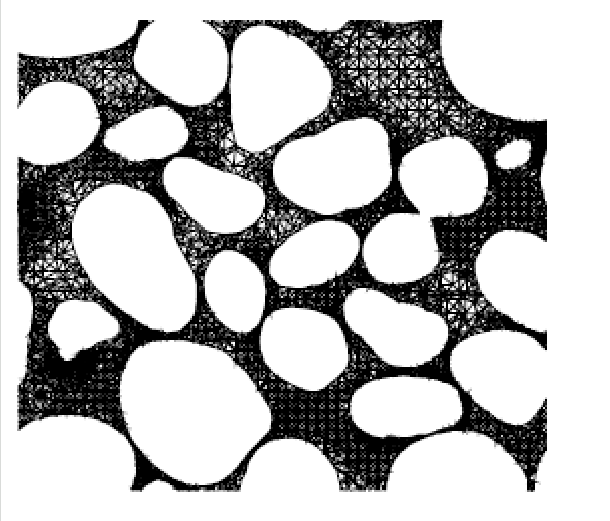
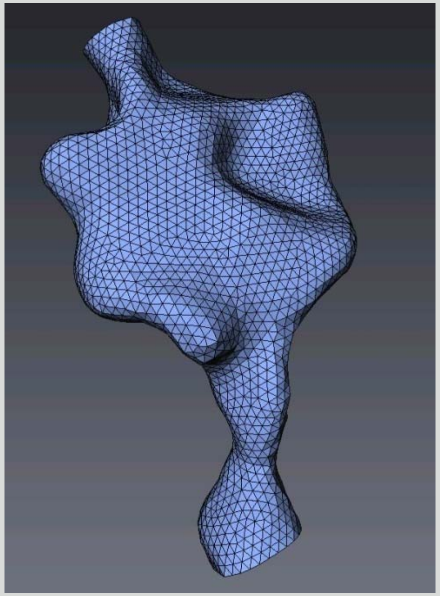
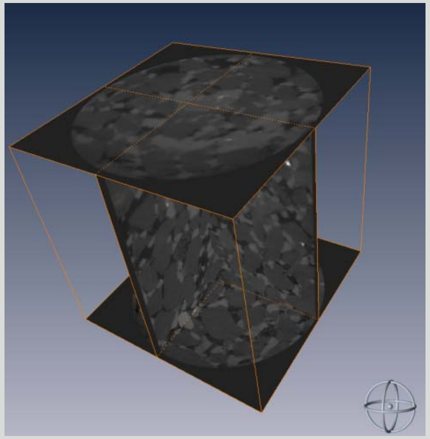
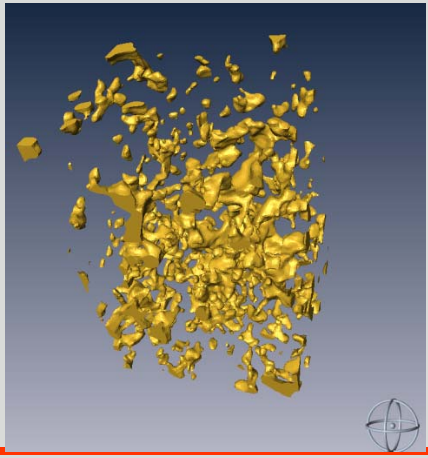
1. 4 Pore scale numerical simulation











Governing Equations

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- Continuity equation:

$$\frac{1}{\rho_{\mathrm{q}}} = \frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{V}_q) = S_{\alpha_q} + \sum_{p=1}^{n} (\dot{m}_{pq} - \dot{m}_{qp})$$

- Momentum equation:

$$\frac{\partial}{\partial t}(\rho \vec{V}) + \nabla \cdot (\rho \vec{V}\vec{V}) = -\nabla \rho + \nabla \cdot [\mu(\nabla \vec{V} + \nabla \vec{V}^T)] + \rho \vec{g} + \vec{F}$$

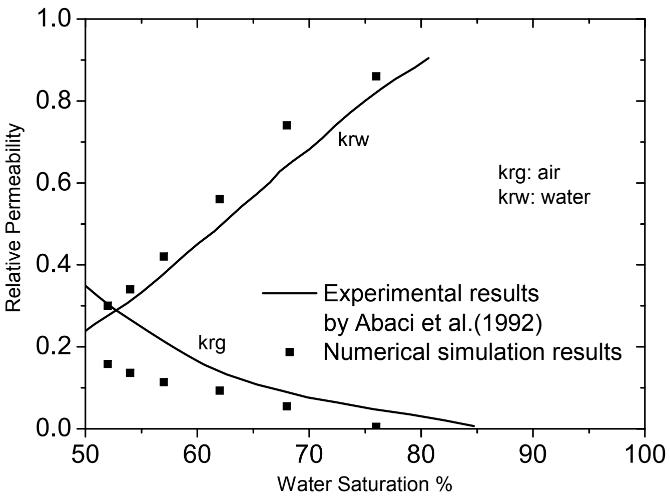
- Capillary pressure equation:

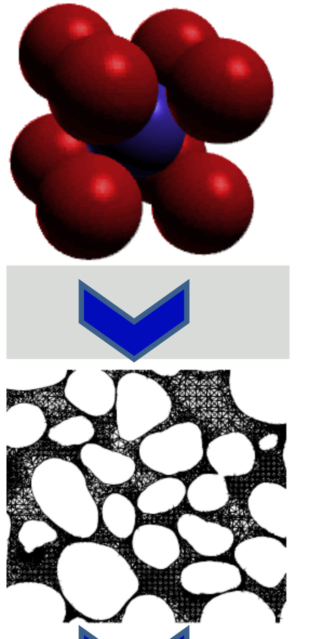
$$P_c = \frac{2\sigma \cos\theta}{r}$$

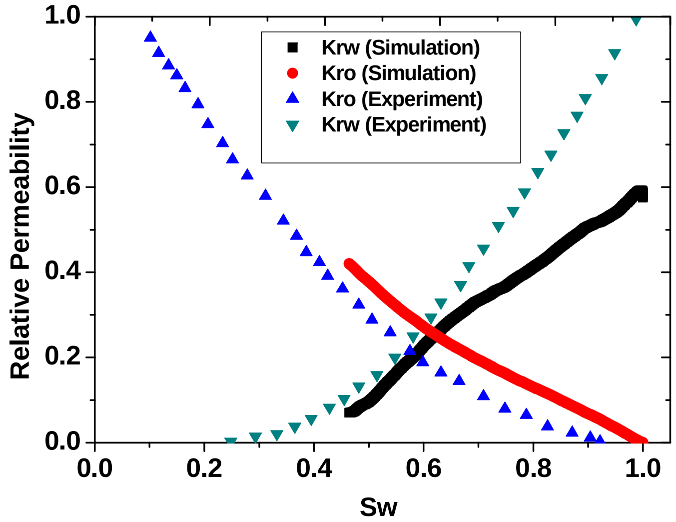
✓The numerical simulation method was provided to simulate the two phase flow in porous media by solving the **Navier-Stokes equation directly**.

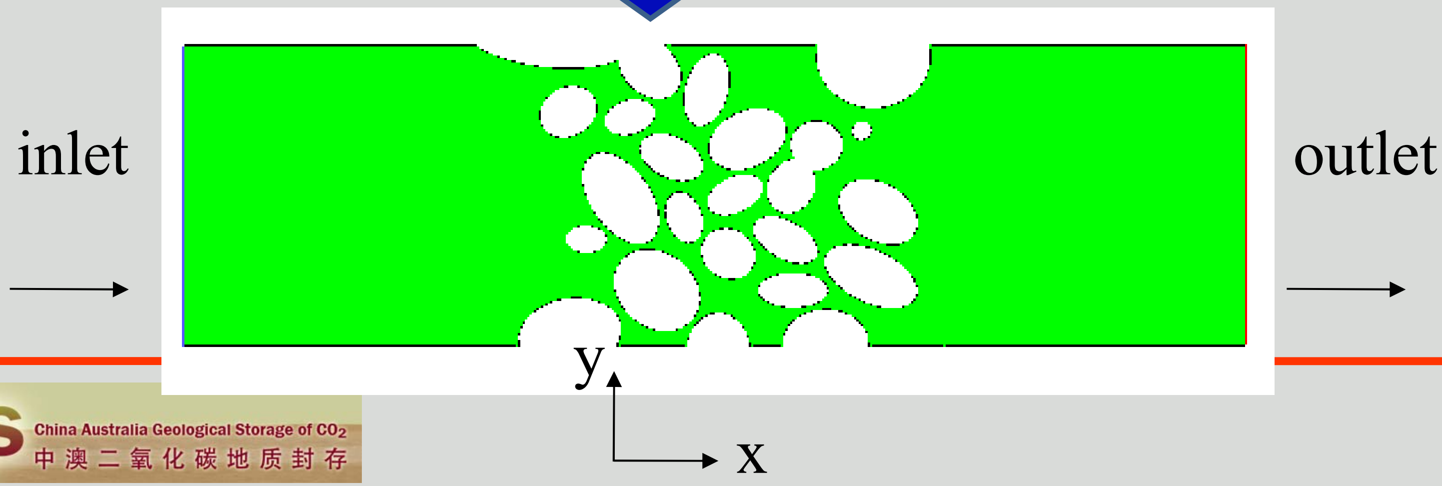
✓The pore scale method can provide the fundamental understanding of the mechanism of trapping and CO_2 behavior after CO_2 injection into the saline aquifer.

Model Validation

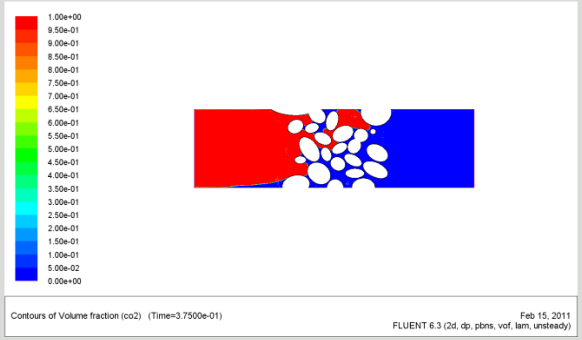


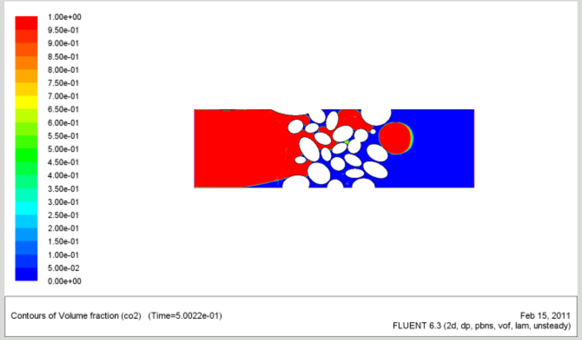


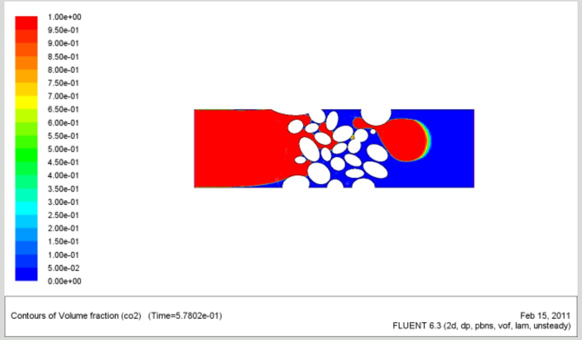




Inlet Velocity Effects

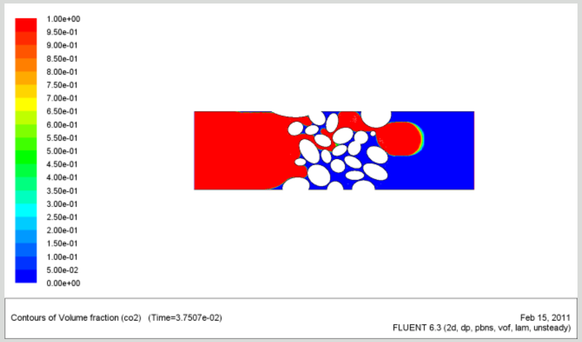


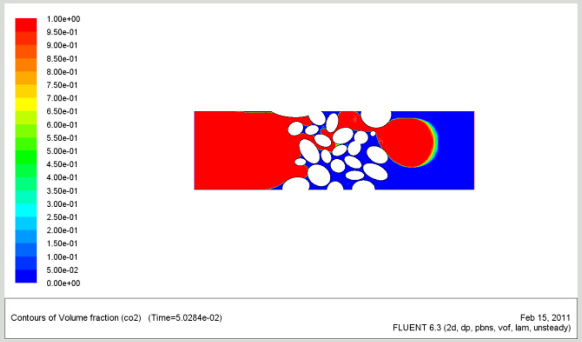


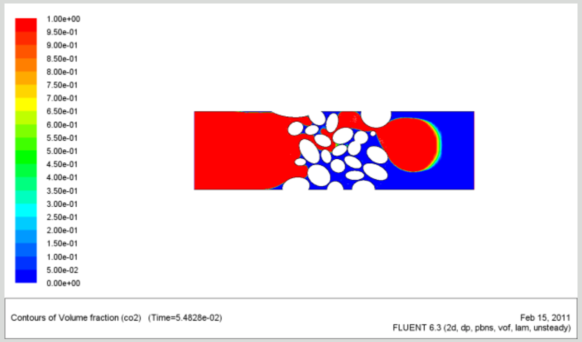


t=0.375 s t=0.5 s t=0.578 s

The water saturation distribution(Inlet velocity=0.001 m/s)







t=0.0375 s t=0.0503 s t=0.0548 s

The water saturation distribution(Inlet velocity=0.01 m/s)

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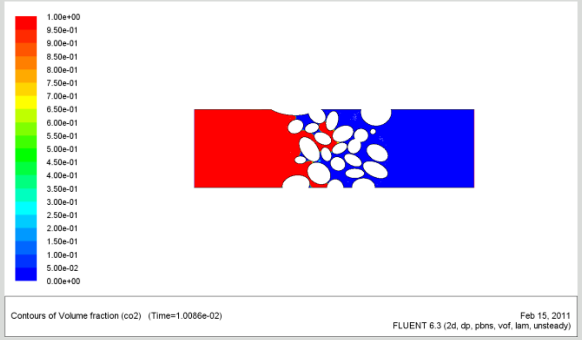
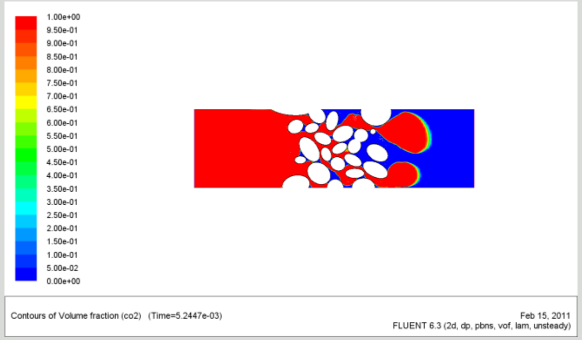
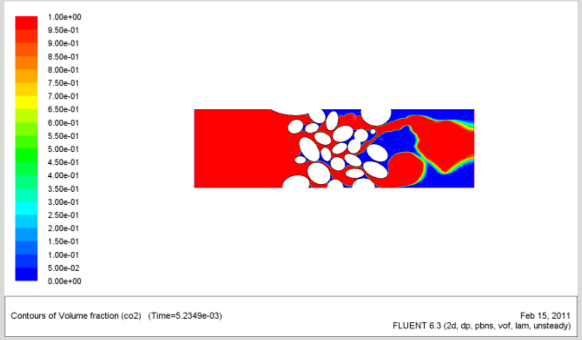
Pressure Difference Effects



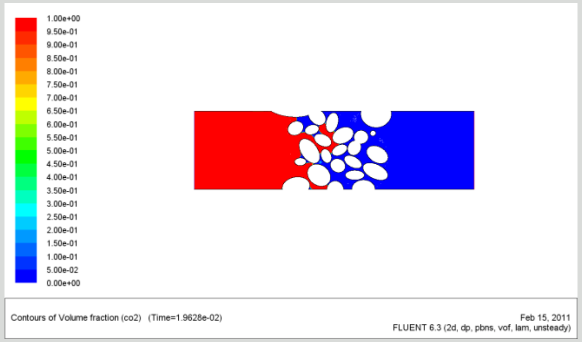
t=0.01 s



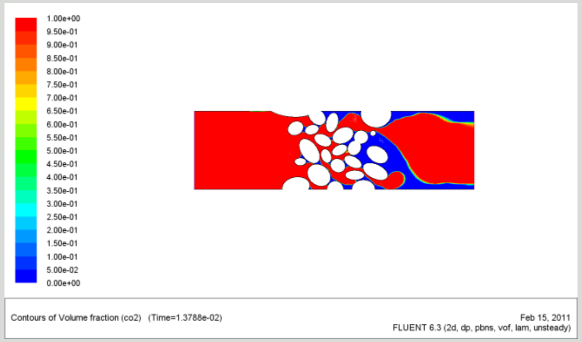
t=0.00524 s



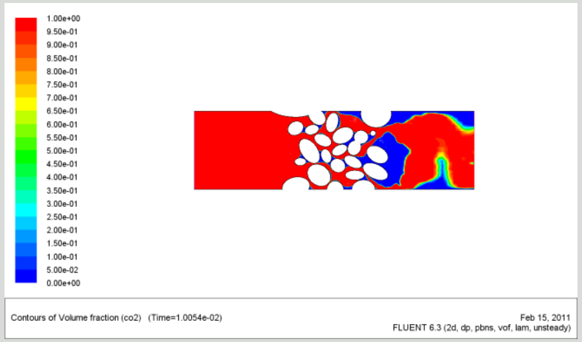
t=0.00523 s



t=0.0196 s



t=0.0138 s



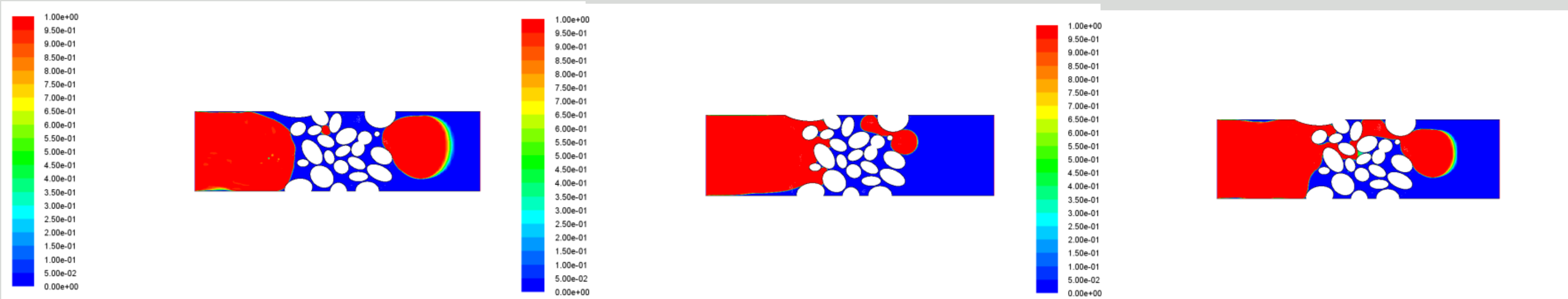
t=0.01 s

进出口压差为5000 Pa

进出口压差为7500 Pa

进出口压差为10000 Pa

Temperature Effects



t =45 ℃ *t* = 60 ℃ *t* = 75 ℃

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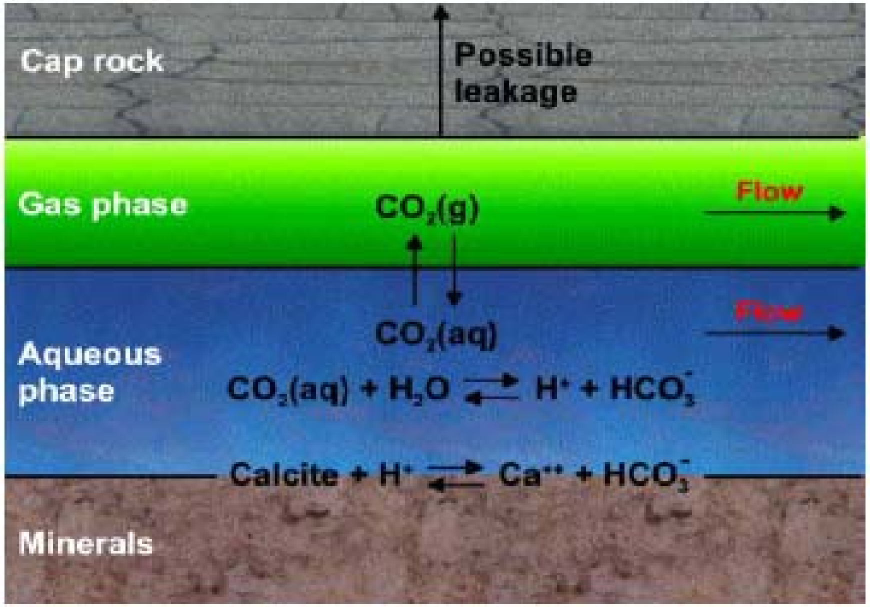
1.6 Effect of reactive surface area on mineral trapping of CO_2

- Field scale simulation using GEM-CMG software to investigate:
  - the effect of relative permeability model on solution trapping of CO_2 and
  - the effect of reactive surface area on mineral trapping of CO_2
- CAGS exchange achievements
  - Exchange student: Mr. Shu Luo, GA, for half year.

Dissolution and Mineral Reactions



$$CO_2(g) \Leftrightarrow CO_2(aq)$$

$$CO_2(aq) + H_2O \Leftrightarrow H^+ + HCO_3^-$$

$$HCO_3^- \Leftrightarrow H^+ + CO_3^{2-}$$

$$H_2O \Leftrightarrow H^+ + OH^-$$

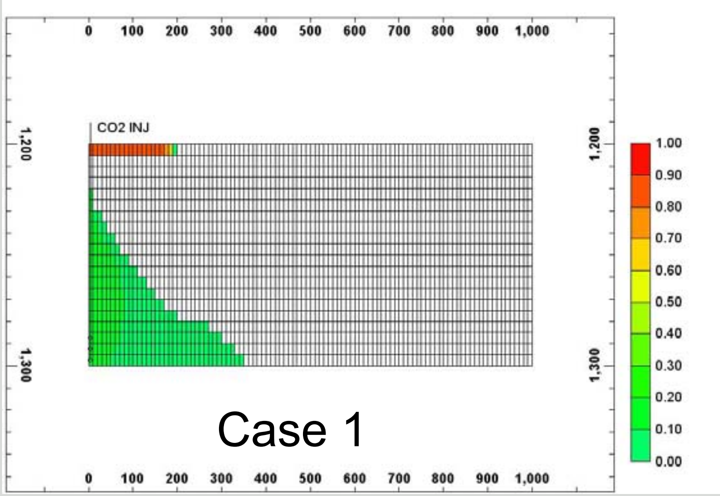
$$Calcite + H^+ \Leftrightarrow Ca^{2+} + HCO_3^-$$

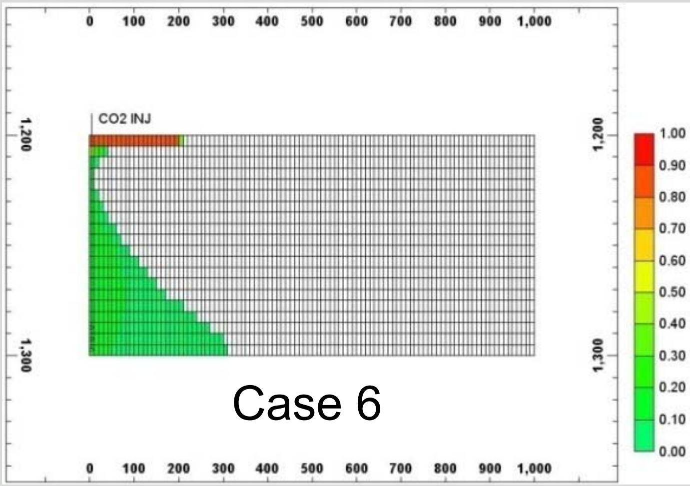
$$Anorthite + 8H^+ \Leftrightarrow Ca^{2+} + 2Al^{3+} + 2SiO_2(aq) + 4H_2O$$

$$Kaolinite + 6H^+ \Leftrightarrow 2Al^{3+} + 2SiO_2(aq) + 5H_2O$$

CMG Training, 2008

	Partical diameter	Free CO_2	Dissolved CO_2	Mineral CO_2	Trapped CO_2
Case1	50	23.22%	33.52%	18.89%	24.37%
Case2	100	25.24%	33.30%	18.55%	22.91%
Case3	200	25.62%	33.04%	18.22%	23.12%
Case4	300	24.97%	33.48%	17.74%	23.81%
Case5	500	25.66%	34.25%	15.66%	24.43%
Case6	800	27.48%	35.50%	11.85%	25.17%





The gas saturation of the interface between the upper and lower parts increases with decreasing anorthite and calcite reactive surface areas.

Study of the Trapping mechanism

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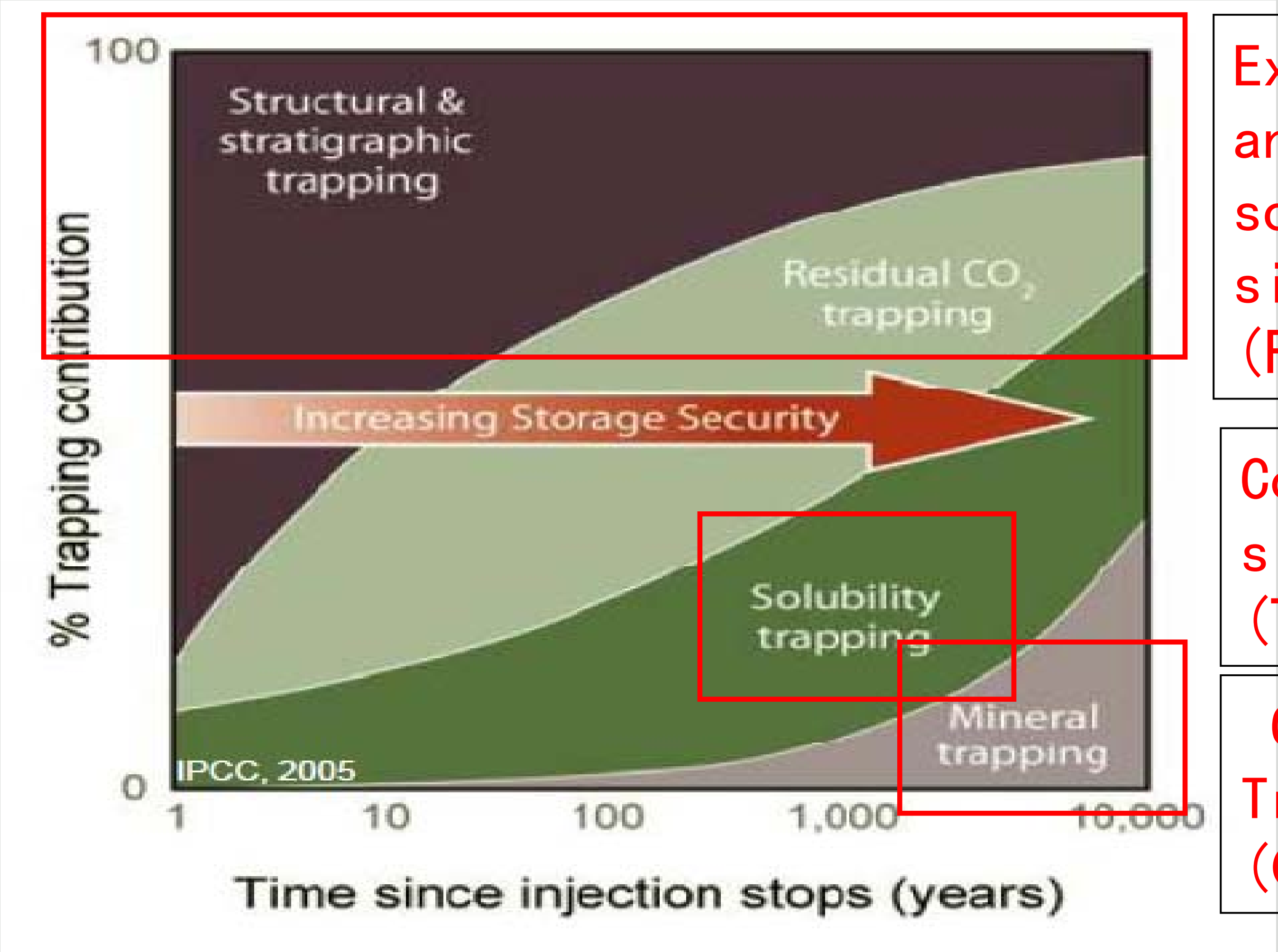

Experiments and Pore scale simulation (Fluent)

Core scale simulation (TOUGH)

Chemical Trapping (GEM-CMG)

Research Work

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The Research Approach

✓To choose a proper model, based on the research of CO_2 displacement mechanisms.

✓To find the key parameters affecting *E*, using AHP method.

✓To develop the calculating methodology of *E*, considering the possible range of the parameters.

✓Do Experimental case study.

Research Approach

✓Choose a proper model, based on the research of CO_2 displacement mechanics.

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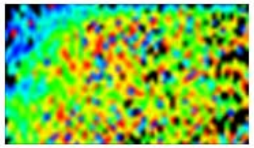
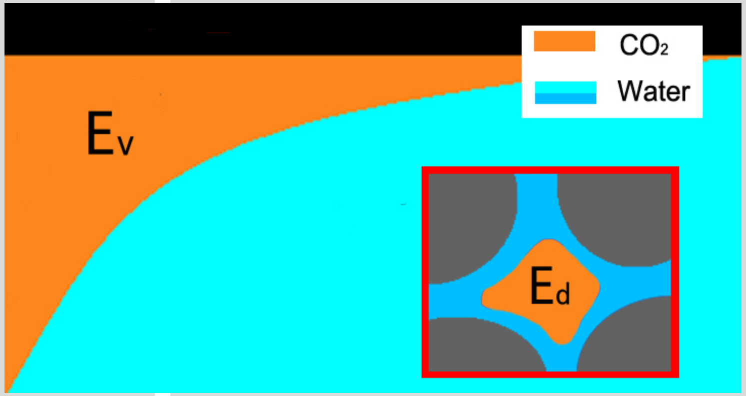
2.1 The model selection





$$V_E = A \cdot h \cdot \phi \cdot E$$

$$E = E_{Geol} \cdot E_v \cdot E_d$$

- E_{geol}, *Geologic efficiency.* E_{Geol}=1, in case of homogenous aquifers. This research focuses on homogenous model for now, therefor cases in which $E_{Geol} \neq 1$ are out of the consideration.
- E_v, *Volumetric displacement efficiency. It represents the fraction of the pore space that is contacted by injection CO_2, affected by gravity in homogenous models.*
- E_d, *Microscopic displacement efficiency. It represents the fraction of CO_2 contacted pores volume that can be replaced by CO_2, related to average residual water saturation*（$1-S_{wave}$）.

Research Approach

✓Choose a proper model, based on the research of CO_2 displacement mechanics.

✓Find the key parameters affecting *E*, using AHP method.

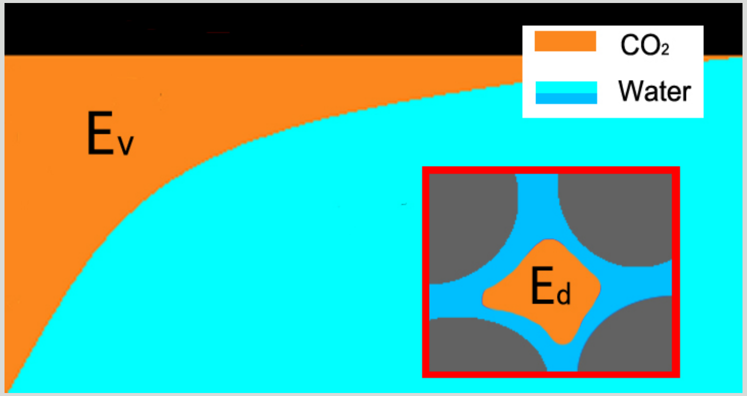
✓Develop the calculating methodology for *E*, considering the possible range of the parameters.

✓Experimental case study.

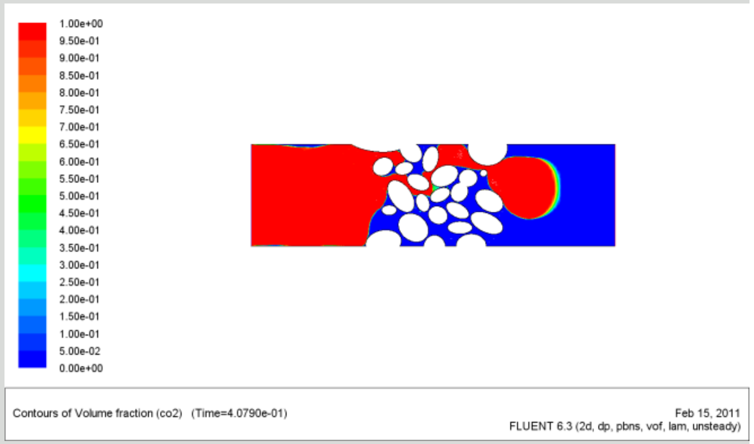
2.2 Key Parameters

- Current status: available parameters are limited from the storage site at the beginning of CCS projects.
- The key parameters are possible to measure and have main effects on the *E* factor.

2.2 Key Parameters



- Structure: curvature（τ）
- Depth（h）
- Land surface temperature（T）
- Temperature gradient（TG）
- Injection rate（G）
- Salinity（S_a）
- Irreducible water saturation（S_{wirr}）
- Relative permeability of CO_2 at S_{wirr}（K_{rCO2}, S_{wirr}）
- Permeability anisotropy（k_v/k_h）



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✓Find the key parameters affecting *E*, using AHP method.

✓Develop the calculating methodology for *E*, considering the possible range of the parameters.

✓Experimental case study.

- Samples:

  simulation results of storage capacity in different conditions

- Methodology:

  Analytic Hierarchy Process (AHP)

Table 2. List of Homogeneous Models

Homogeneous Models	Ref Depth, m	P, MPa	T, °C	S_{wirr}	kr_{CO2} at S_{wirr}	Structure	k_v/k_h	Q, ton/yr
Median – (1 ton/yr) (Median Case)	2338	23.9	75	0.197	0.5265	Flat	0.108	1
Median – (4 tons/yr)	2338	23.9	75	0.197	0.5265	Flat	0.108	4
Median – (2 tons/yr)	2338	23.9	75	0.197	0.5265	Flat	0.108	2
Median – (0.4 ton/yr)	2338	23.9	75	0.197	0.5265	Flat	0.108	0.4
Median – (0.2 ton/yr)	2338	23.9	75	0.197	0.5265	Flat	0.108	0.2
Median – (0.1 ton/yr)	2338	23.9	75	0.197	0.5265	Flat	0.108	0.1
Median – Dome	2338	23.9	75	0.197	0.5265	Dome	0.108	1
Median – Anticline	2338	23.9	75	0.197	0.5265	Anticline	0.108	1
Median – 5° Incline	2338	23.9	75	0.197	0.5265	5° incline	0.108	1
Median – 10° Incline	2338	23.9	75	0.197	0.5265	10° incline	0.108	1
Median – Quarter Dome	2338	23.9	75	0.197	0.5265	1/4 Dome	0.108	1
Median – Half Dome	2338	23.9	75	0.197	0.5265	1/2 Dome	0.108	1
Median – Three-Quarter Dome	2338	23.9	75	0.197	0.5265	3/4 Dome	0.108	1
Shallow – High Temp.	895	9.2	45	0.197	0.5265	Flat	0.108	1
Shallow – Mid Temp.	895	9.2	38	0.197	0.5265	Flat	0.108	1
Shallow – Low Temp.	895	9.2	33	0.197	0.5265	Flat	0.108	1
Median – High Temp.	2338	23.9	92	0.197	0.5265	Flat	0.108	1
Median – Low Temp.	2338	23.9	62	0.197	0.5265	Flat	0.108	1
Deep – High Temp.	3802	38.8	141	0.197	0.5265	Flat	0.108	1
Deep – Mid Temp.	3802	38.8	113	0.197	0.5265	Flat	0.108	1
Deep – Low Temp.	3802	38.8	92	0.197	0.5265	Flat	0.108	1
Median – k_v/k_h 0.01	2338	23.9	75	0.197	0.5265	Flat	0.01	1
Median – k_v/k_h 0.05	2338	23.9	75	0.197	0.5265	Flat	0.05	1
Median – k_v/k_h 0.1	2338	23.9	75	0.197	0.5265	Flat	0.1	1
Median – k_v/k_h 0.25	2338	23.9	75	0.197	0.5265	Flat	0.25	1
Median – k_v/k_h 0.5	2338	23.9	75	0.197	0.5265	Flat	0.5	1
Median – k_v/k_h 1	2338	23.9	75	0.197	0.5265	Flat	1	1
Median – k_v/k_h 2	2338	23.9	75	0.197	0.5265	Flat	2	1
Median – k_v/k_h 4	2338	23.9	75	0.197	0.5265	Flat	4	1
Median – Basal Sandstone	2338	23.9	75	0.294	0.5446	Flat	0.1	1
Median – Calmar	2338	23.9	75	0.638	0.1871	Flat	0.1	1
Median – Cardium 1	2338	23.9	75	0.379	0.2978	Flat	0.1	1
Median – Cardium 2	2338	23.9	75	0.197	0.5265	Flat	0.1	1
Median – Ellerslie	2338	23.9	75	0.659	0.1156	Flat	0.1	1
Median – Viking 2	2338	23.9	75	0.423	0.2638	Flat	0.1	1
Median – Viking 1	2338	23.9	75	0.558	0.3319	Flat	0.1	1

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2.3 Evaluation Criterion of E

$$E = E_v \cdot E_d$$

Recommend value for E_v

$$E_v = \sum_{i=1}^{9} E_{v,i} \cdot W_{v,i}$$

Score / Key Parameters	0.05-0.10	0.20-0.25	0.30-0.35	0.40-0.45	0.55-0.65	Weight
τ, %	0-20	20-55	55-60	60-75	75-100	0.185
h, m	≤800	≥3500	800-1500	3000-3500	1500-3000	0.13
T,℃	≥20	10-20	5-10	-2-5	≤-2	0.005
TG,℃/m	≥0.033	0.026-0.033	0.024-0.026	0.02-0.024	≤0.02	0.025
S_a, ‰	≥174	60-174	50-60	8-50	≤8	0.01
S_{wirr}	≤0.2	0.2-0.3	0.3-0.5	0.5-0.65	≥0.65	0.18
$K_{rCO2,S_{wirr}}$	≥0.6	0.5-0.6	0.35-0.5	0.2-0.35	≤0.2	0.125
k_v / k_h	≥0.25	0.1-0.25	0.05-0.1	0.01-0.05	≤0.01	0.21
G,ton/yr	≤0.1	0.1-0.3	0.3-0.6	0.6-1	1-2	0.13

2.3 Evaluation Criterion of E $\quad E = E_v \cdot E_d$

Recommend value for E_d $\quad E_d = \sum_{i=1}^{9} E_{d,i} \cdot W_{d,i}$

Score / Key Parameters	0.20-0.35	0.35-0.50	0.50-0.60	0.60-0.70	0.70-0.80	Weight
τ, %	0-20	20-40	40-60	60-80	80-100	0.09
h, m	≤800	≥3500	800-1500	3000-3500	1500-3000	0.03
T,℃	≤-2	-2-5	5-10	10-20	≥20	0.01
TG,℃/m	≤0.02	0.02-0.024	0.024-0.026	0.026-0.033	≥0.033	0.10
S_a, ‰	≥174	60-174	50-60	8-50	≤8	0.005
S_{wirr}	≥0.65	0.50.65	0.35-0.5	0.2-0.35	≤0.2	0.22
$K_{rCO2,S_{wirr}}$	≤0.2	0.2-0.35	0.35-0.5	0.5-0.6	≥0.6	0.17
k_v / k_h	≤0.01	0.01-0.06	0.06-0.08	0.08-0.25	≥0.25	0.225
G,ton/yr	1-2	0.6-1	0.3-0.6	0.1-0.3	≤0.1	0.15

	E_v		E_d		E		
	Simulate	Calculate	Simulate	Calculate	Simulate	Calculate	Error
Median-Flat	0.26	0.2605	0.58	0.5705	0.1508	0.1486	-1.45%
Median-1/4 Dome	0.28	0.2808	0.60	0.5930	0.1680	0.16654	-0.88%
Median-1/2 Dome	0.29	0.2926	0.61	0.6020	0.1769	0.1761	-0.43%
Median-3/4 Dome	0.38	0.3625	0.62	0.6110	0.2356	0.2215	-5.99%
Median-Dome	0.39	0.3718	0.64	0.6245	0.2496	0.2322	-6.98%
Median-Low Temp.	0.23	0.2303	0.52	0.5211	0.1196	0.1201	0.34%
Median-Mid Temp.	0.22	0.2252	0.58	0.5740	0.1276	0.1293	1.30%
Median-High Temp.	0.21	0.2203	0.63	0.5978	0.1323	0.1317	-0.46%
Cardium Sandstone	0.26	0.2603	0.59	0.5891	0.1534	0.1533	-0.04%
Basal Sandstone	0.32	0.2990	0.56	0.5583	0.1792	0.1669	-6.85%
Viking Sandstone	0.50	0.3921	0.31	0.4071	0.1550	0.1596	2.98%
Ellerslie Sandstone	0.56	0.4379	0.28	0.3486	0.1568	0.1527	-2.65%
Wabamun Sandstone	0.45	0.4109	0.38	0.3986	0.1710	0.1638	-4.22%
Median- 0.01	0.48	0.3461	0.35	0.4641	0.1680	0.1606	-4.39%
Median- 0.05	0.32	0.3146	0.48	0.5204	0.1536	0.1637	6.59%
Median- 0.1	0.27	0.2701	0.58	0.5654	0.1566	0.1527	-2.48%
Median- 0.25	0.19	0.2115	0.64	0.5991	0.1216	0.1267	4.20%
Median-0.1ton/yr	0.16	0.1668	0.70	0.6554	0.1120	0.1093	-2.39%
Median-0.2ton/yr	0.18	0.1873	0.67	0.6329	0.1206	0.1185	-1.71%
Median-0.4ton/yr	0.19	0.2003	0.65	0.6179	0.1235	0.1238	0.21%
Median-1ton/yr	0.26	0.2603	0.58	0.5804	0.1508	0.1511	0.18%

Research Approach

✓Choose a proper model, based on the research of CO_2 displacement mechanics.

✓Find the key parameters affecting *E*, using AHP method.

✓Develop the calculating methodology for *E*, considering the possible range of the parameters.

✓Experimental case study.

2.4 Experimental case study

The relevant data for E assessment can be achieved by sample analysis, data collection, injection test, etc.
For this study, we try to use the laboratory experimental data to do the case study.

Case	Depth m	T ℃	Injection rate ton/yr	S_{wirr}	$K_{rCO2,S_{wirr}}$	E_v	E_d	E
1	1000	47	1.5×10^6	0.53	0.45	0.322	0.476	0.153
2	800	47	1.5×10^6	0.53	0.45	0.316	0.475	0.150
3	1000	25	1.0×10^6	0.44	0.86	0.272	0.505	0.137
4	1000	25	1.5×10^6	0.64	0.57	0.318	0.439	0.140

3. Conclusion

- 利用可视化实验和数值模拟方法针对CO_2封存机理研究表明，在二氧化碳深部咸水层中封存的压力下，岩心超临界压力二氧化碳和水相对渗透率随饱和度变化曲线与VGM公式形式符合较好；在超临界压力二氧化碳在含水岩心中流动时，浮升力作用不可忽视
- 提出了800-3500米深度二氧化碳地质封存有效封存系数取值推荐方法，搭建了工程可获得参数与二氧化碳目标储层整场尺度下有效封存系数之间的桥梁，为较为简便和准确预测目标储层的二氧化碳有效容量和场地选址提供了重要参考指标。

4. Paper publication and Exchange activities

- Published 3 papers, indexed by EI. 1 peer review paper (SCI)
- 发表论文3篇，其中EI检索收录3篇，另有1篇已被SCI期刊接收
- Exchange student: Mr. Shu Luo, GA, for half year.博士研究生罗庶赴澳大利亚地质调查局学习半年（2011.03-2011.09）

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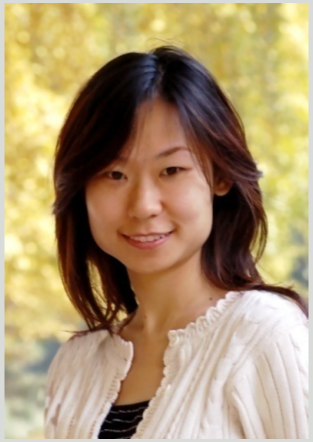
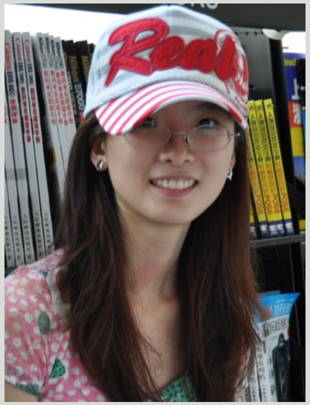
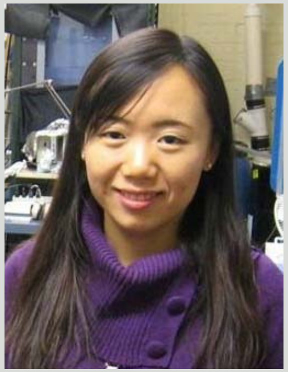


Mr. Feng Luo



Ms. Jin Ma



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Mr. Cheng Gao

Ms. Desiree

Thanks for your attention!

谢谢各位专家！ 请批评指正！