CCUS and Low Carbon Fuels

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Study of ultrafine bubble (UFB) technology to enhance CO_2 geological sequestration by high-concentration CO_2 water

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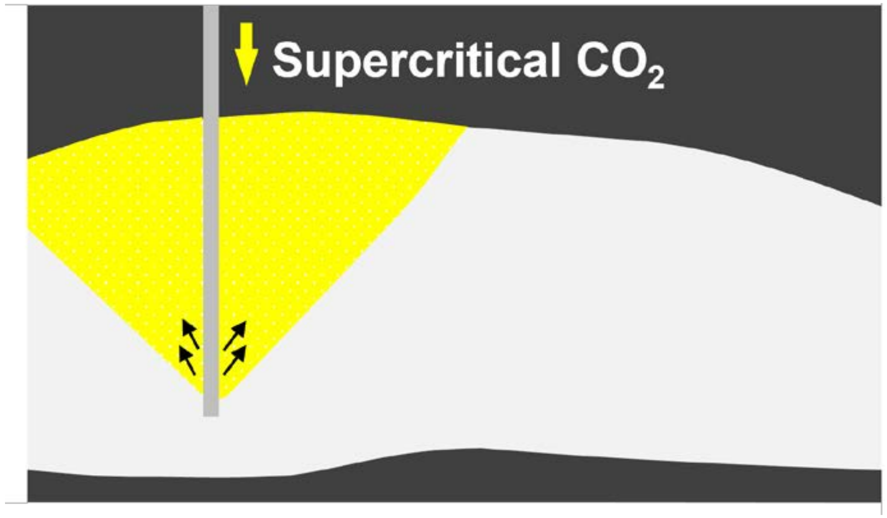
Risks of geological CO_2 sequestration

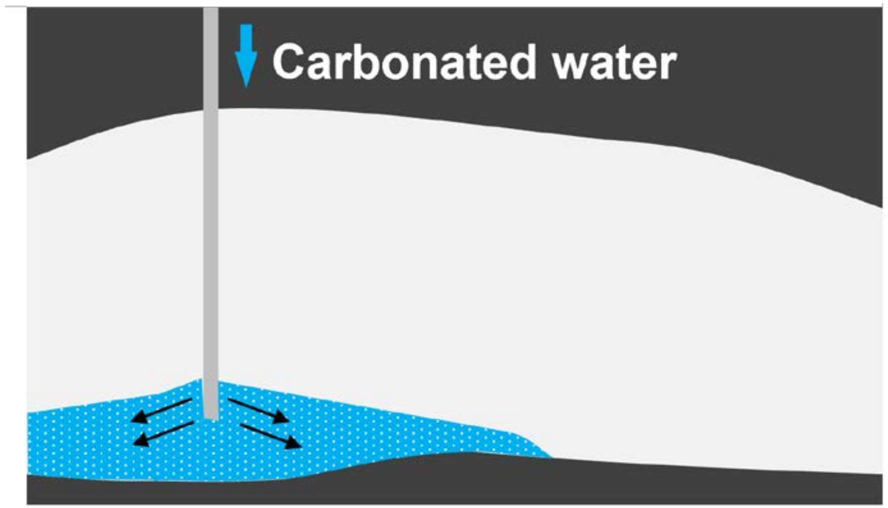
- Supercritical CO_2 injection
  - Upward migration
  - Decreasing sweep efficiency

  ⇨ Risks of **leakage** and **insufficient pore space utilization**



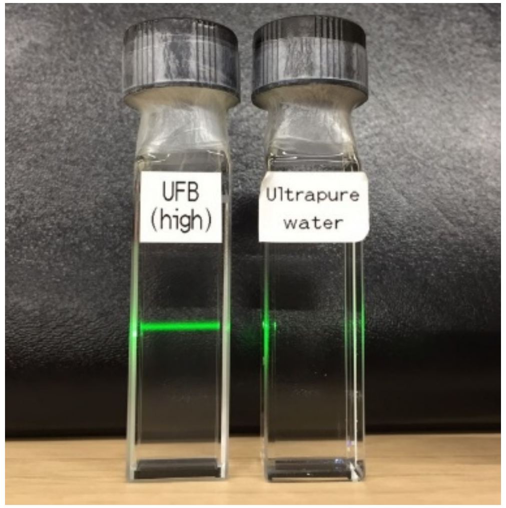
- Carbonated water injection
  - No free-CO_2 phase
  - Downward migration

  ⇨ Enhancement of the storage security
  - but… **CO_2 content per unit volume is little**.



What is UFB ?

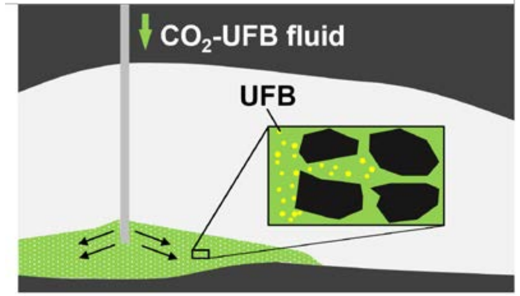
- Diameter: less than 1 µm
- **Long-term stability**



Ultrafine bubbles (left) and pure water (right)

Potentials of CO_2-UFB

- CO_2 supersaturation of water
  - 50 % more CO_2 content than the saturation at 10 MPaA[1] without additives
  - ⇨ Possibility of enhancing CO_2 mineralization
  - ⇨ Possibility of increasing CO_2 content with additives
- Reduction of the upward migration
  - Weak buoyancy of UFBs
- Sweeping into narrow pores
  - Suppression of capillary effect
- CO_2 storage over a wide area
  - Reduction of the differences in mobility between CO_2 and in-situ fluids



[1] Wang et al., 2023. Aqueous Nanobubble Dispersion of CO_2 at Pressures Up To 208 bara. Energy & Fuels 37 (24): 19726–19737.

Objectives

✓ Stability of UFBs is crucial in designing CO_2-UFB injection systems.

✓ Lack of knowledge: Characteristics of UFBs under high pressure conditions

⇨ **Investigation of the feasibility of the CO_2-UFB injection systems**

Laboratory test

- Measurements of UFB stabilities under high pressure
- Five additives are used.

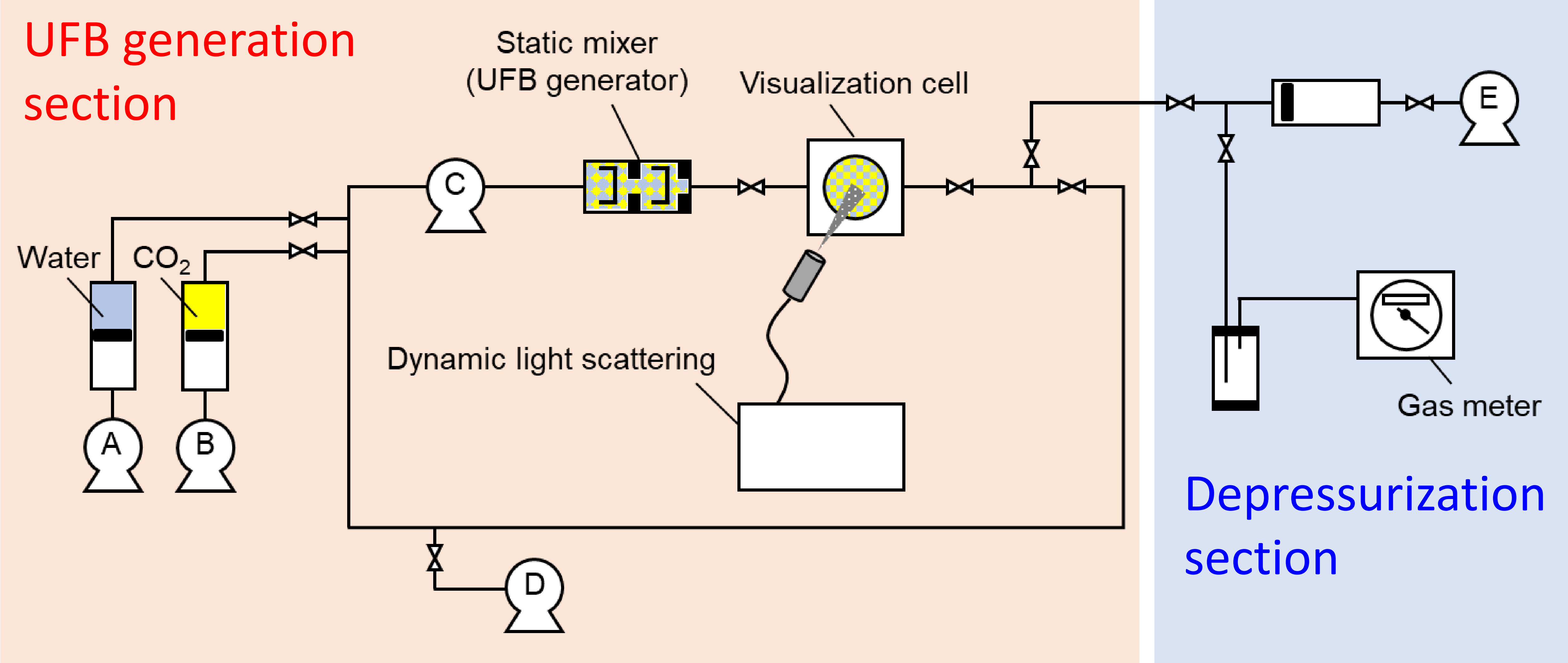
Simulation study

- Examination of effective injection strategies

Laboratory test

- Stability of the CO_2-UFB under high pressure
- CO_2 content in water supersaturated by CO_2-UFB

Laboratory test - Experimental setup



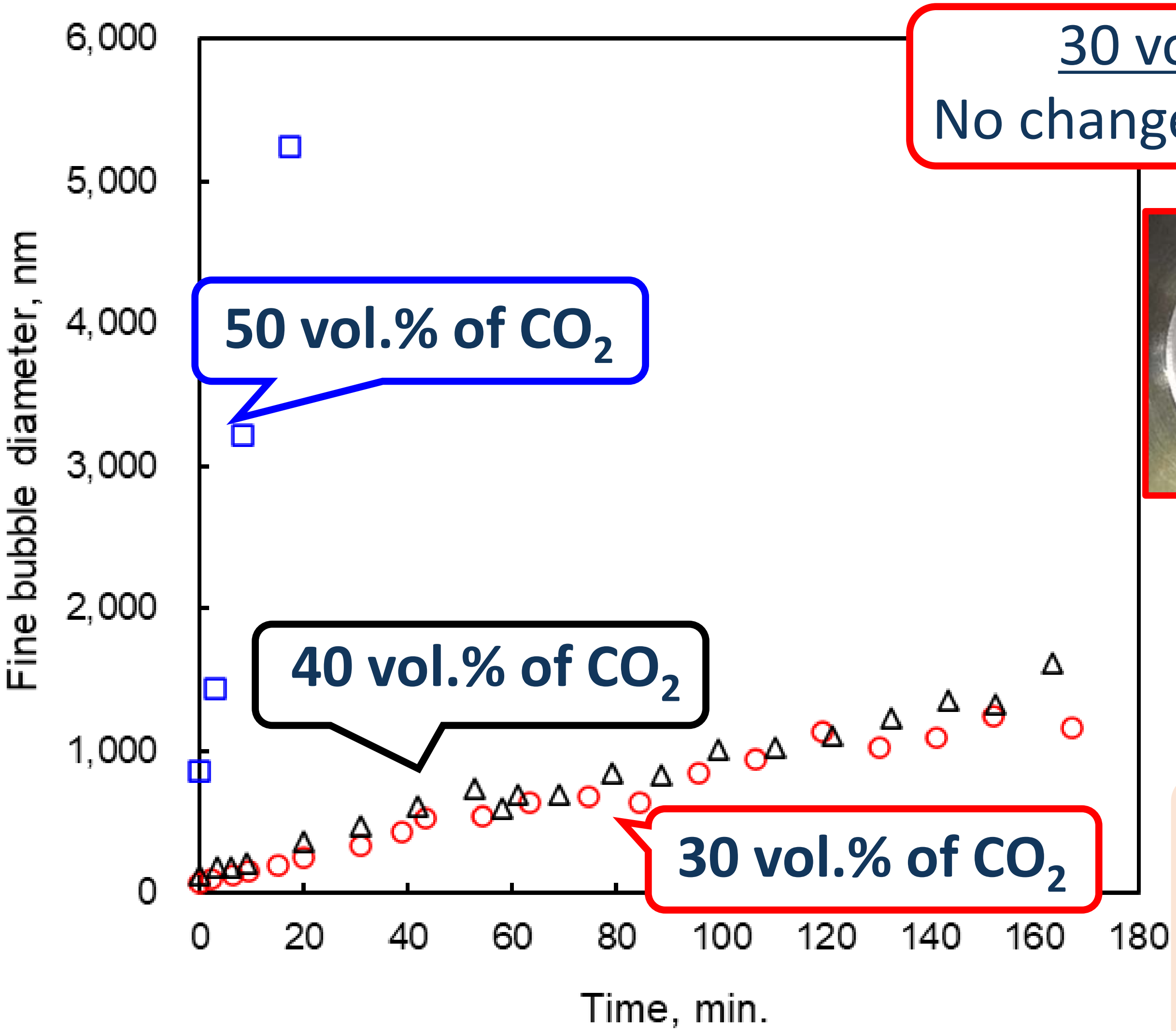
Laboratory test - Additives

Additive	Concentration	Note
Trisiloxane	1 wt.%	
Calcium carbonate particle	1 wt.%	20 nm particle size
Oleic acid	100 vol.ppm	
Ethanol	5 wt.%	
Saponin	0.1 wt.%	

- ✓ Not hazardous substances
- ✓ Easy to handle under high pressure conditions
- ✓ Reasonable concentrations (Cost effectiveness)

Laboratory test - UFB under the high pressure

Additive	Trisiloxane
Pressure	8 MPaA
Temperature	288.15 K



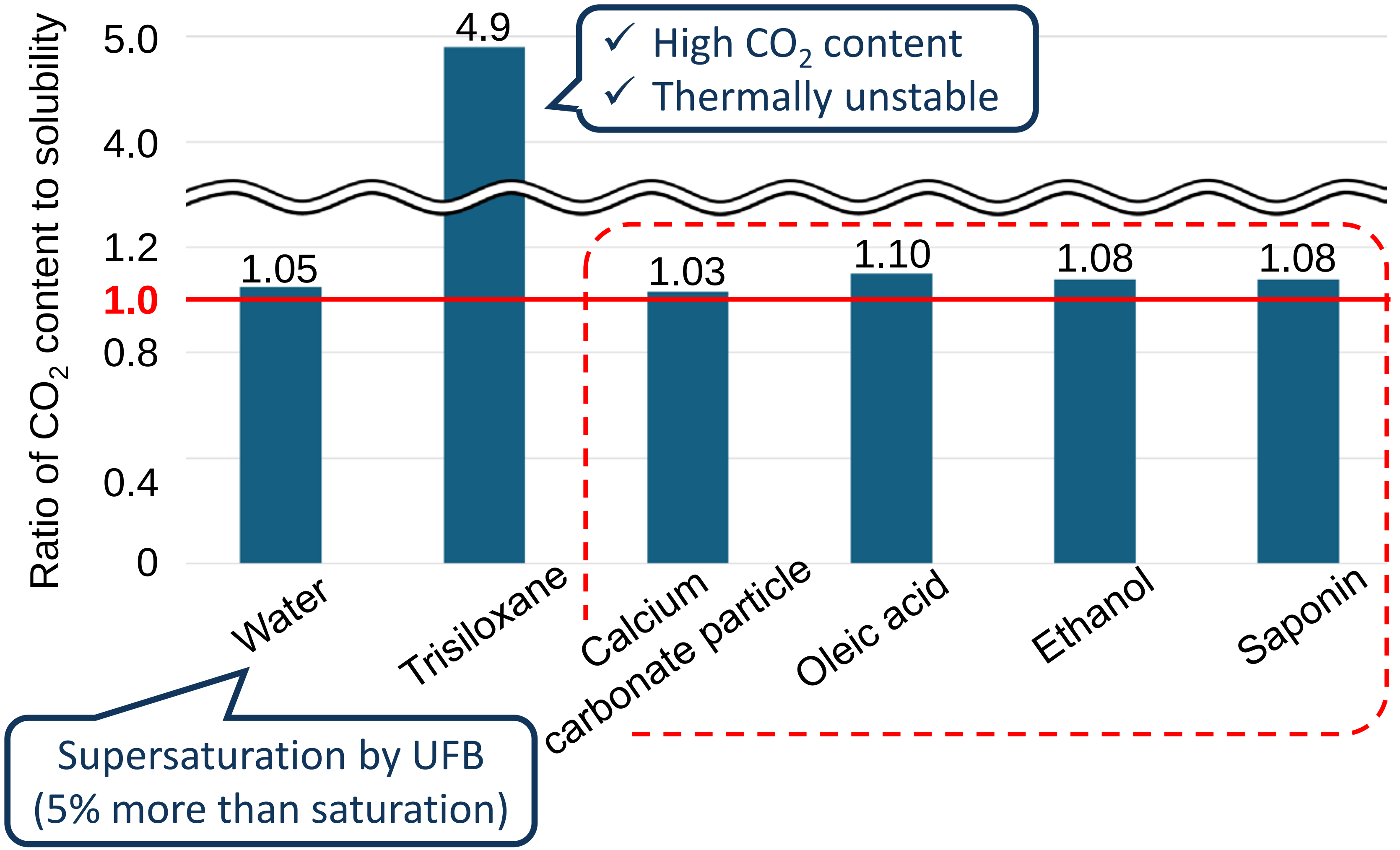
30 vol.% of CO_2
No change in appearance

50 vol.% of CO_2 Growth and buoyancy-driven rise of the bubbles

✓ 30-40 vol.% of CO_2 can be dispersed in water as UFBs.

⇨ Duration: approximately 120min.

Laboratory test - Effect of additives on CO_2 content



Pressure	8 MPaA
Temperature	288.15 K

✓ CO_2 content is increased by these additives.
(max. 10 % higher than saturation)

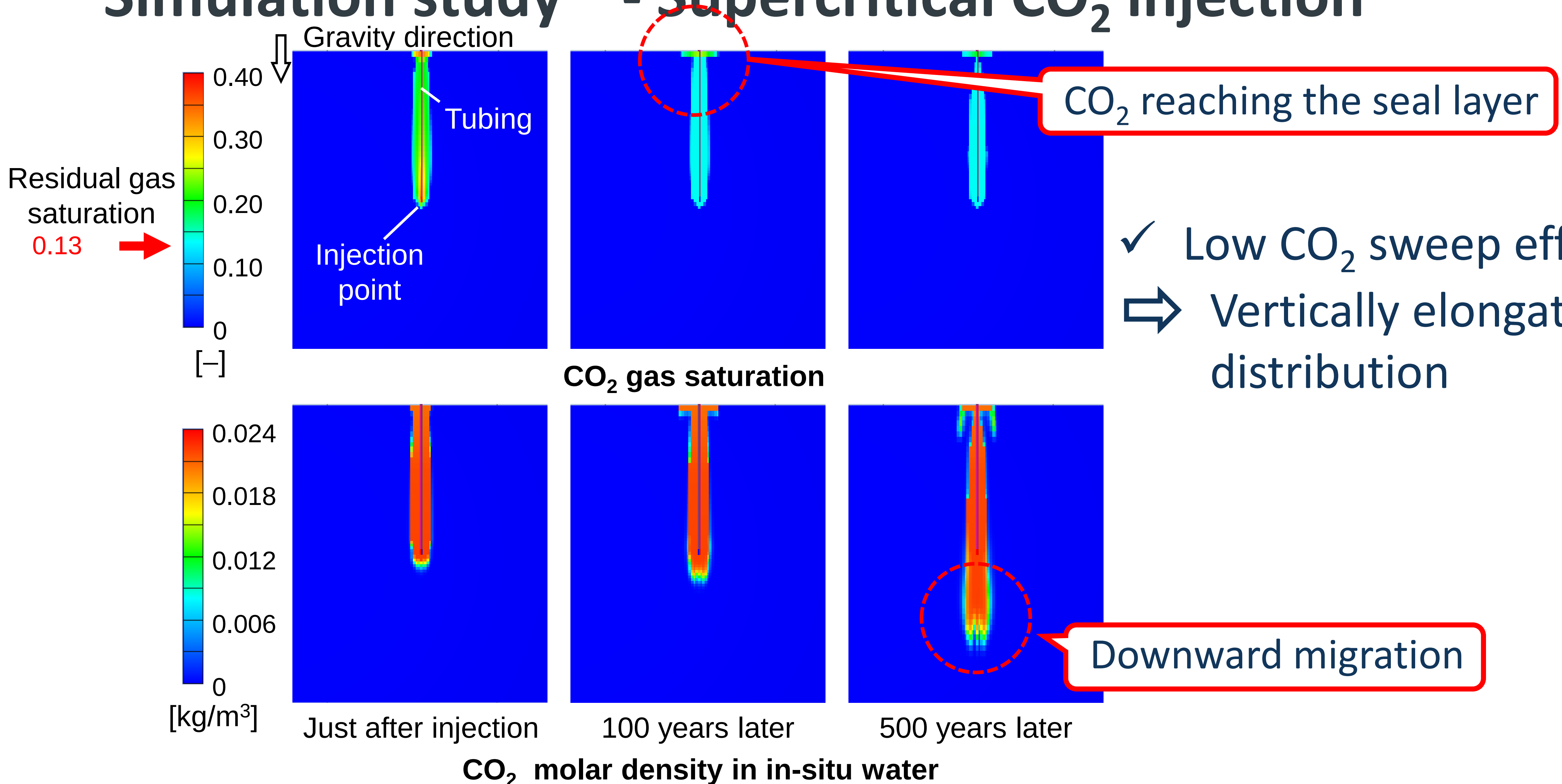
✓ Slight supersaturation by CO_2-UFB has a possibility of a long duration[1].

[1] Wang et al., 2023. Aqueous Nanobubble Dispersion of CO_2 at Pressures Up To 208 bara. Energy & Fuels 37 (24): 19726–19737.

Simulation study

- Effective injection strategies using CO_2-UFB

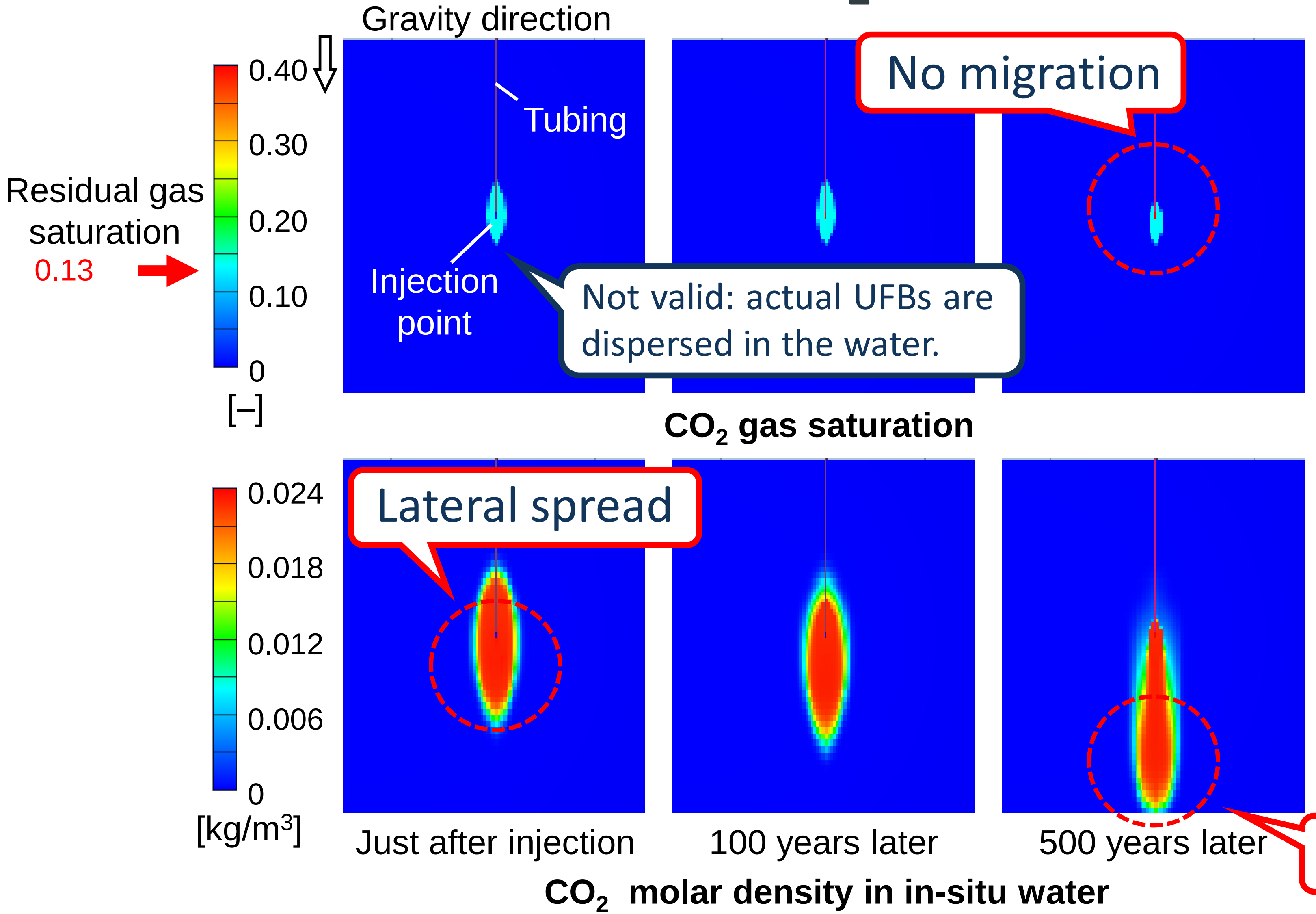
Simulation study - Supercritical CO_2 injection



✓ Low CO_2 sweep efficiency

⇨ Vertically elongated CO_2 distribution

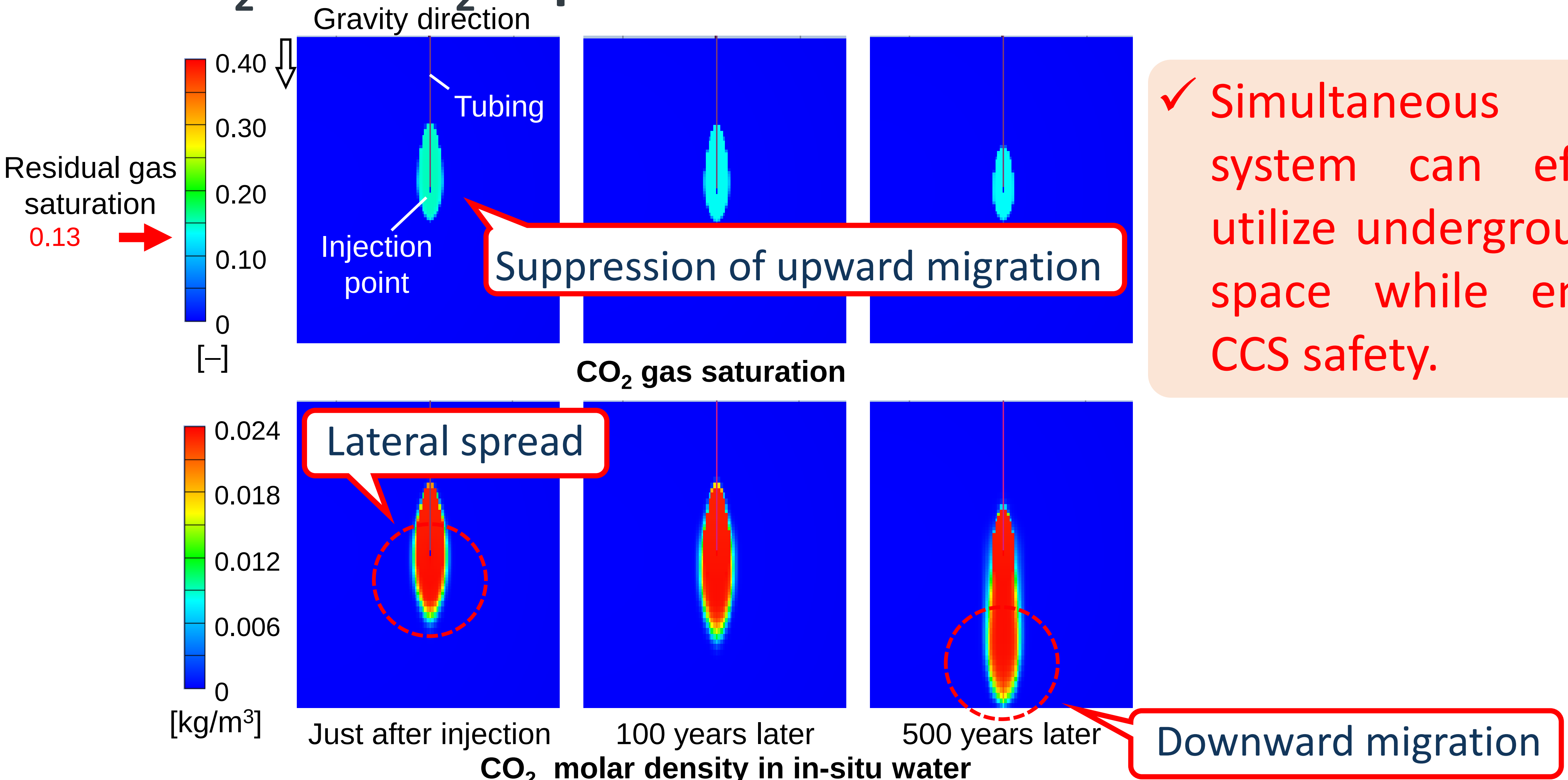
Simulation study - CO_2-supersaturated water injection



✓ Even if UFB stability are lost by external influences, they will be trapped as residual gas.

✓ Lateral spread of CO_2
⇨ CO_2-cosuming by contact between supersaturated water and CO_2-lean water

Simulation study - Simultaneous injection of supercritical CO_2 and CO_2-supersaturated water



✓ Simultaneous injection system can effectively utilize underground pore space while enhancing CCS safety.

Conclusions

1. 30-40 vol.% of CO_2 can be dispersed in water as UFBs and maintained for approximately 120 minutes by using trisiloxane. However, the UFBs at high temperatures become unstable immediately.

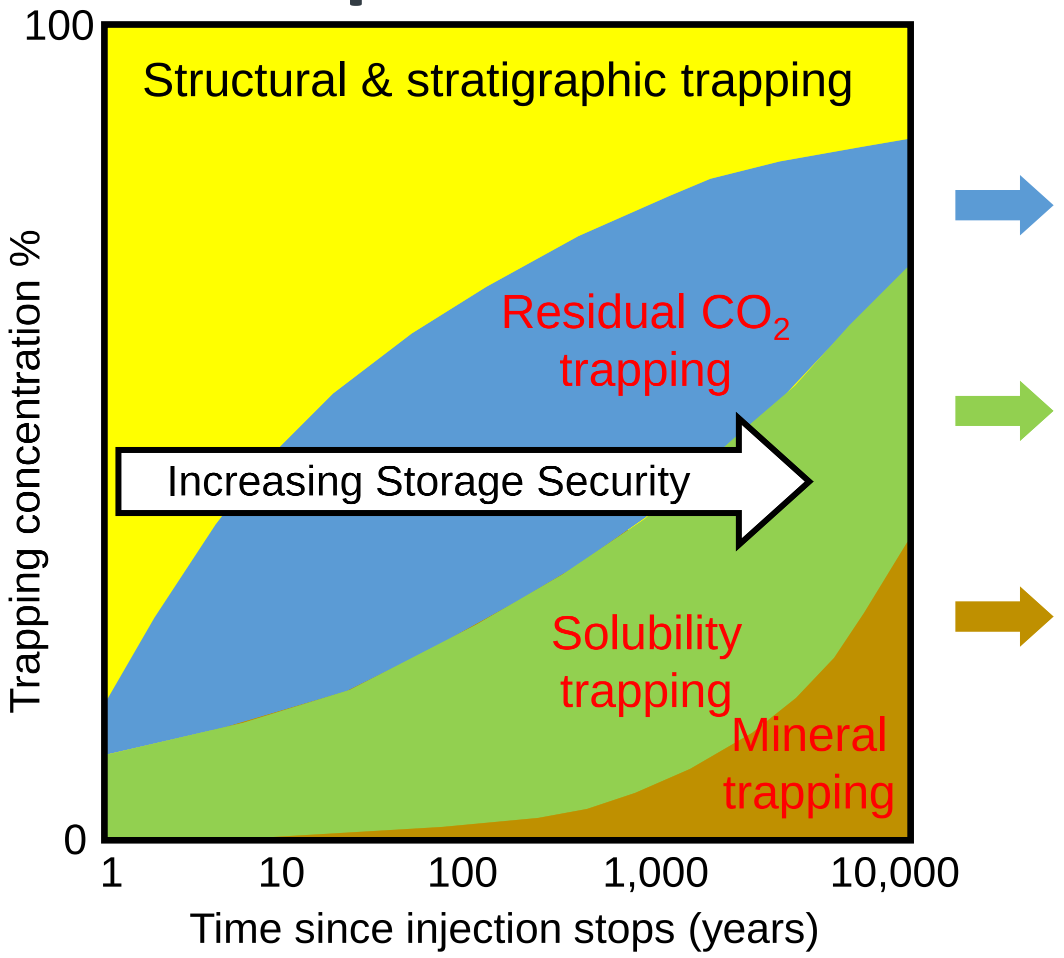
2. The other additives, except for calcium carbonate particles, also have an effect on increasing the CO_2 content in the water. The maximum increase ratio of the CO_2 content in the solubility is 10%.

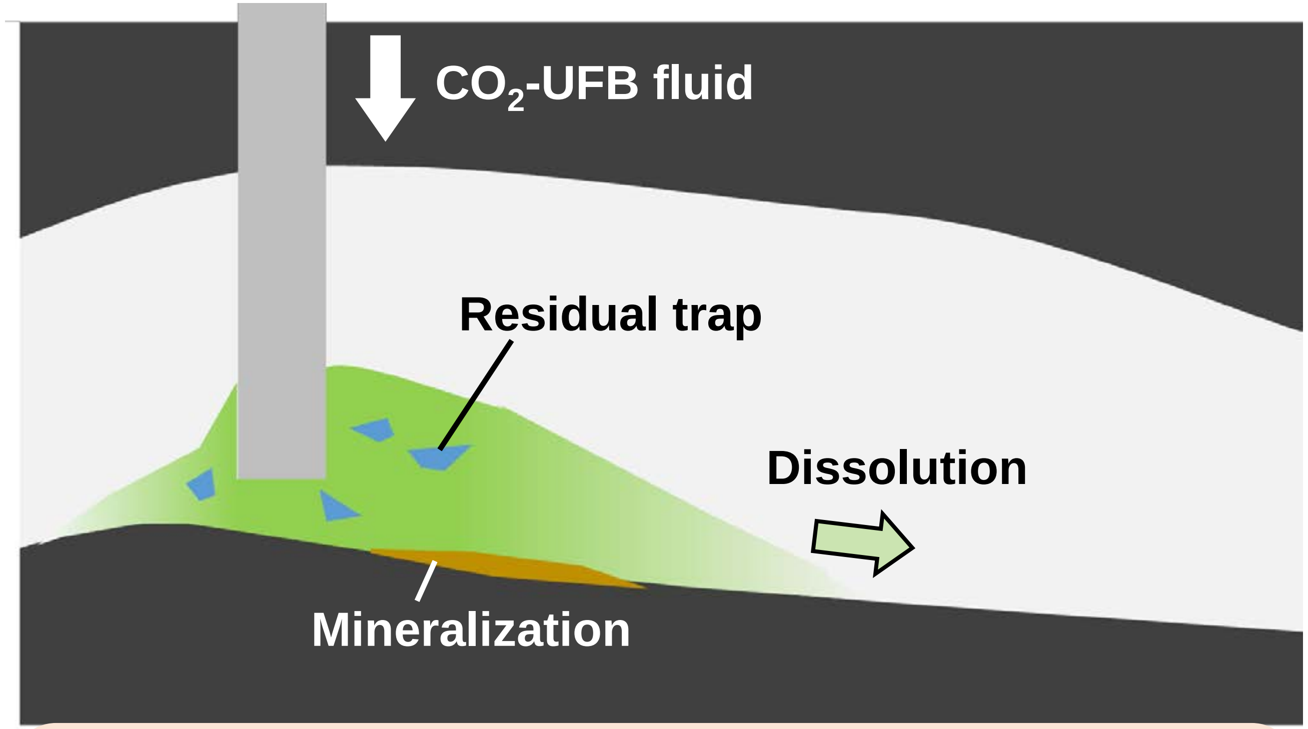
3. Numerical flow simulations have suggested that the CO_2-UFB injection carries minimal risk of CO_2-leakage to the surface and can improve sweep efficiency.

Back up

Concept

[4] Metz et al., 2005. IPCC Special Report on Carbon Dioxide Capture and Storage. Cambridge University Press.

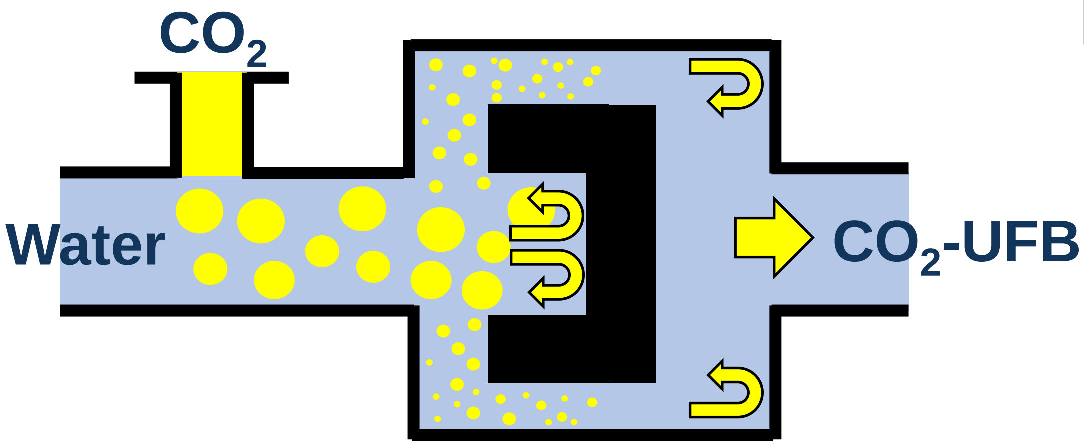




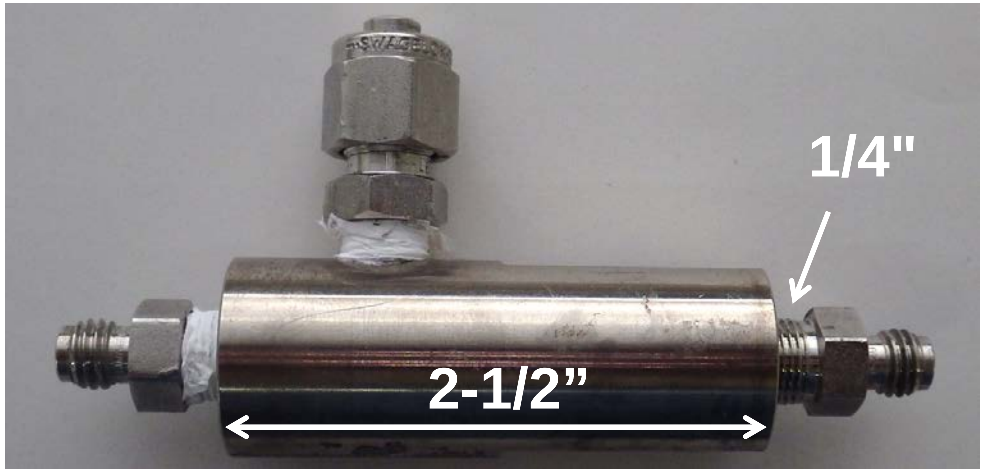
Storage security depends on a combination of physical and geochemical trapping[4]

✓ UFBs can be useful to the CO_2 sequestration through **various trapping mechanisms, depending on their stability**.

Laboratory test - Static mixer type of UFB generation



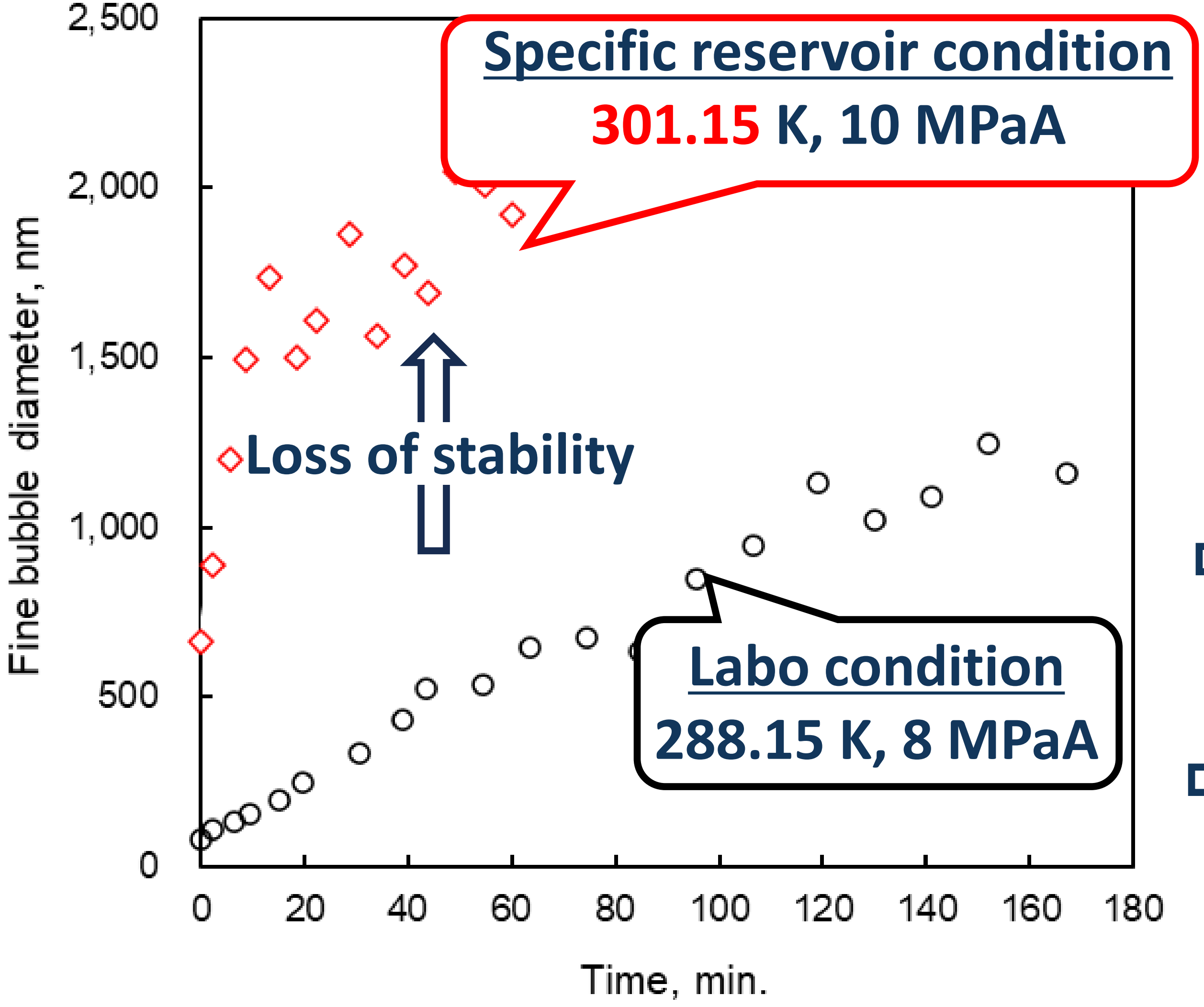
Schematic of static mixer



Labo-scale static mixer

- Structure & UFB generation process
  - Complex flow paths
  - Multiple mixing stages
  - ⇨ Strong shear forces
  - ⇨ UFB generation
- Pros of a static mixer
  - Simple design
  - Small footprint
  - ⇨ Applicability for field-scale operations
    - ✓ High pressure
    - ✓ Large flow rate

Laboratory test - UFB under the reservoir condition



Additive	Trisiloxane
CO_2 content	30 vol.%

✓ Significant reduction in the anti-coalescence effect of surfactants at high temperature

⇨ Installation of cooling system?

High operating const

⇨ **Surfactant which is tailored to resist high temperature** is required.

Simulation study - Numerical conditions

- ✓ It cannot rigorously address the dynamic UFB behavior.
- ✓ but it can predict the migration of CO_2 in the storage reservoir.

Reservoir parameters

Initial reservoir pressure, MPaA	9
Reservoir temperature, K	325
NaCl concentration, wt.%	0.6
Reservoir thickness, m	570
Horizontal permeability, mD	27
Vertical permeability, mD	9
Porosity, %	30

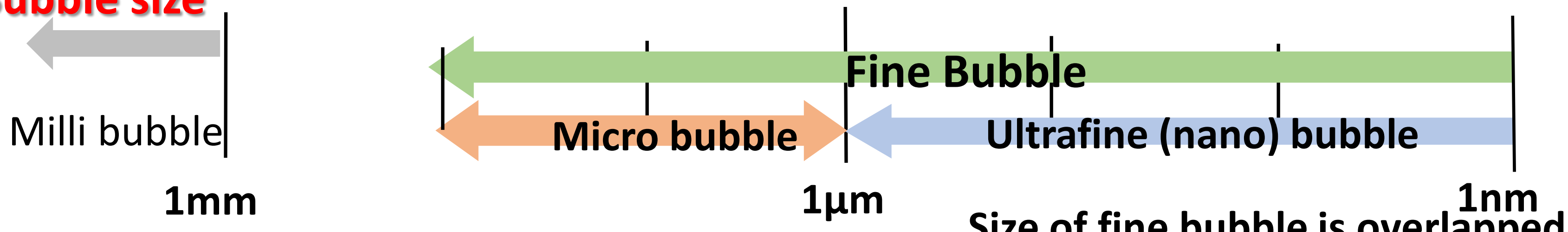
Scenarios

(a) Supercritical CO_2 injection
(b) CO_2-supersaturated water injection
(c) Simultaneous injection of supercritical CO_2 and CO_2-supersaturated water

- CO_2 injection rate: 3,340 ton/year (All scenarios)
- Injection period: 60 years (All scenarios)
- Water injection rate:
  - 150 kL/d (Scenario (b))
  - 75 kL/d (Scenario (c))

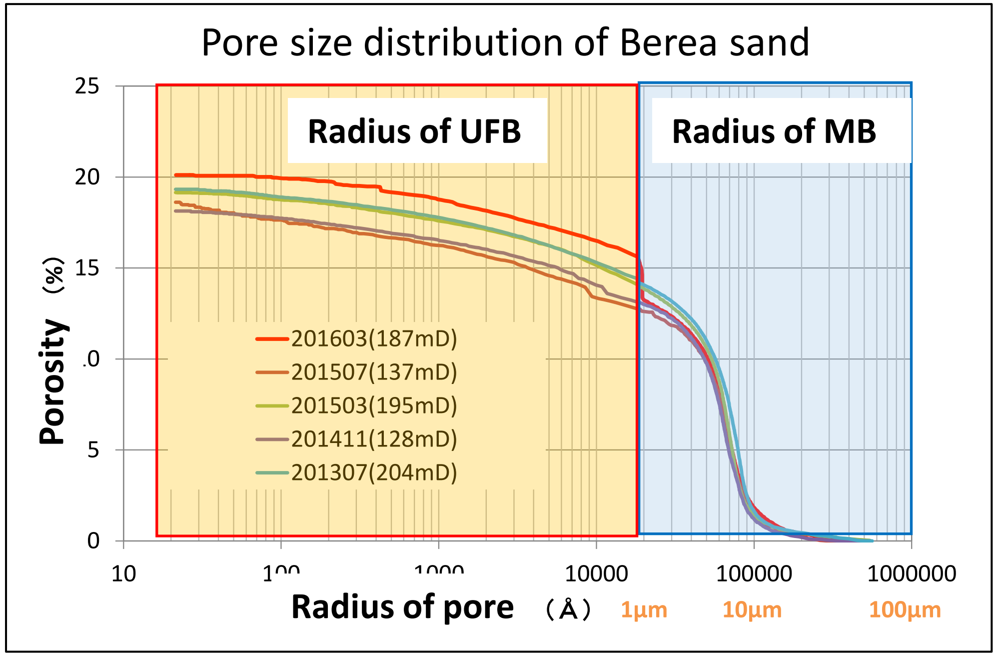
What is UFB?

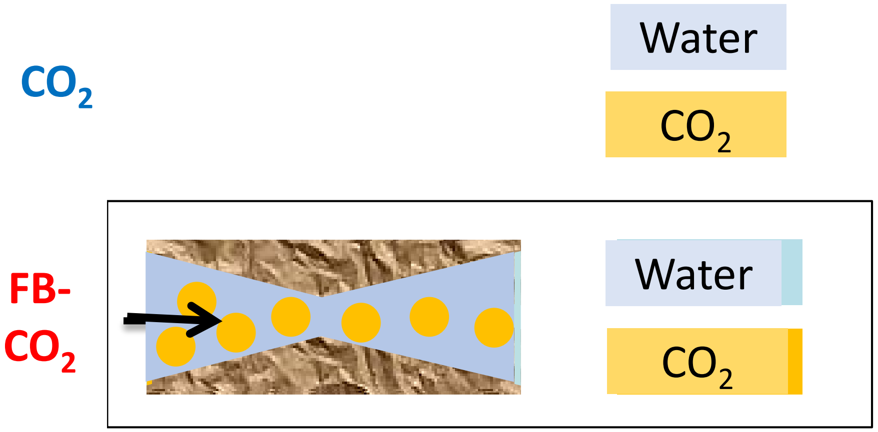
1. Bubble size



Size of fine bubble is overlapped that of pore of Berea sand

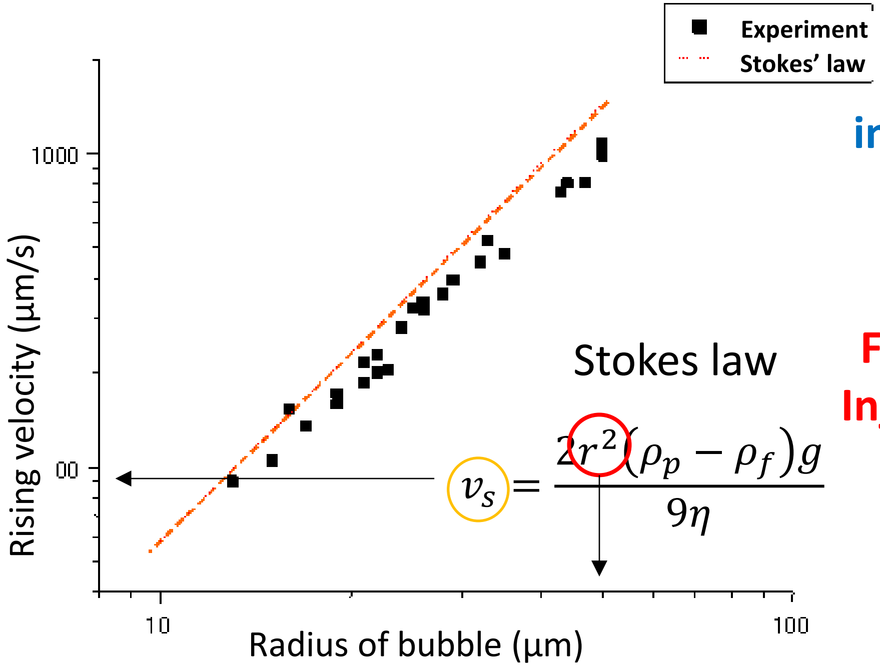
⇒Fine bubble is invaded into a lot of pore spaces of sand stone



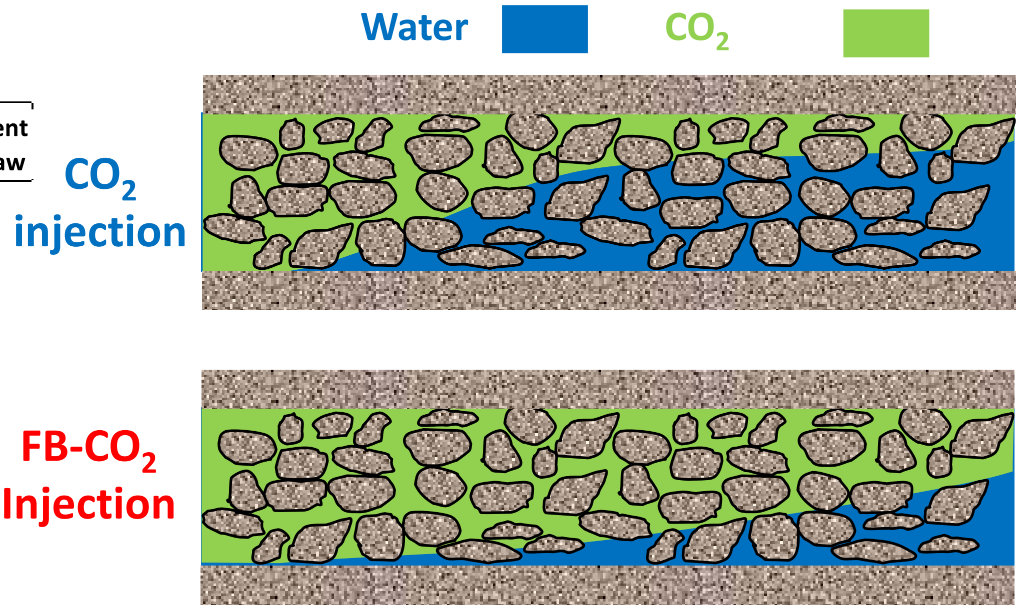


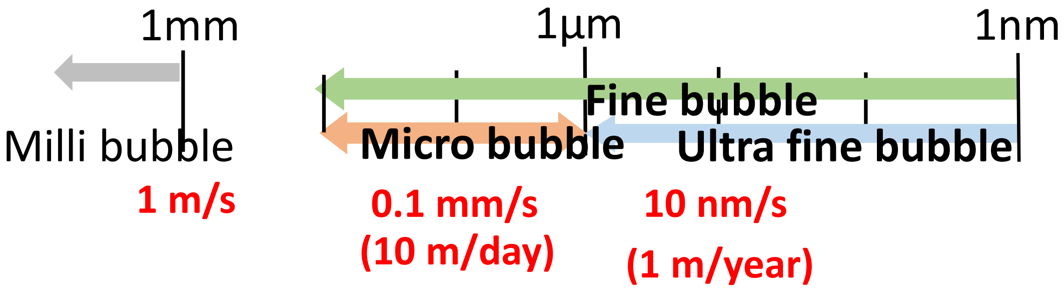
What is UFB?

2. Low buoyancy



$$v_s = \frac{2r^2(\rho_p - \rho_f)g}{9\eta}$$



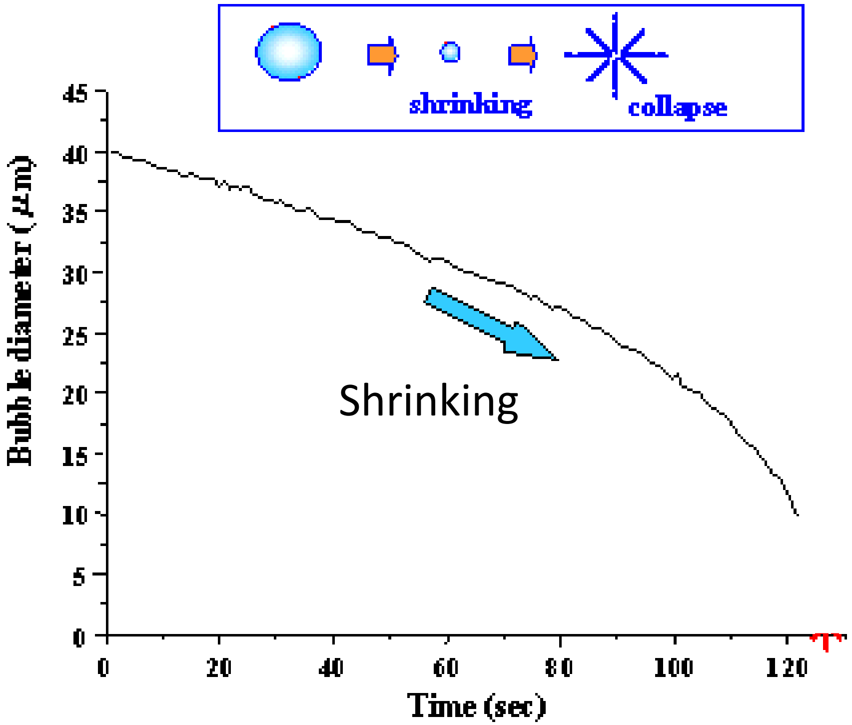


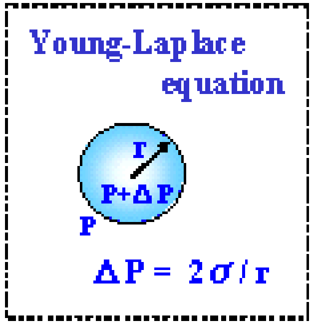
- **Rising velocity (buoyancy) of a bubble is proportional to the square of the bubble diameter.**

⇒ Fine bubble will reduce the effect of gravity override caused by the density difference between CO_2 and reservoir fluid

What is UFB?

3. High solubility to reservoir fluid





Diameter μm	ΔP kg/cm2
10	0.3
1	3
0.1	30

Young-Laplace equation

$$p_A = P + \Delta P = P + \frac{2\sigma}{r}$$

Henry's Law

$$[A] = kp_A$$

$$Solubitily: [A]$$

Specific surface area

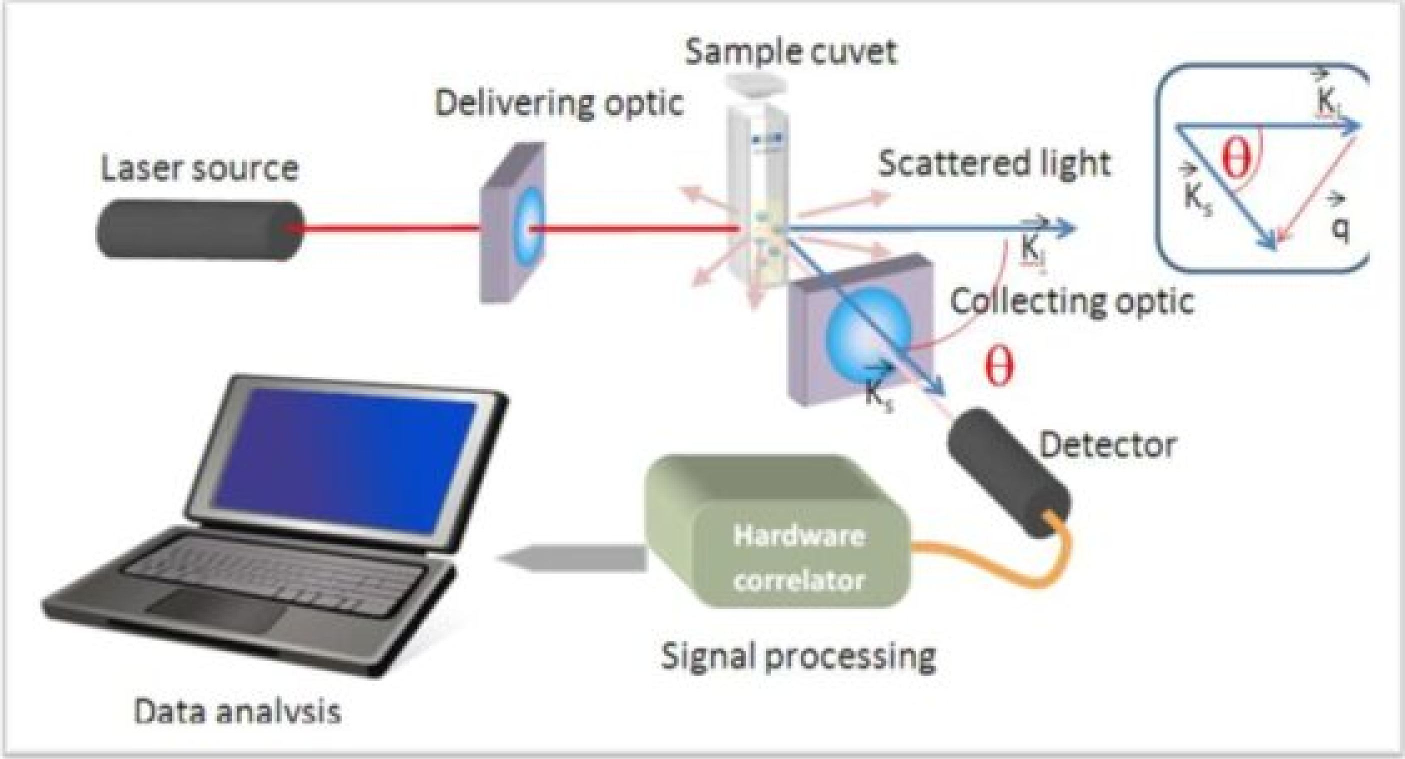
$$a_i = \frac{3\alpha}{r}$$

・**Internal pressure of fine bubble is higher than that of general bubbles according to the Young-Laplace equation.**

・**Increase of internal pressure increases the solubility according to Henry's law.**

⇒ FIne bubble will enhance dissolution in geological fluids

Laboratory test - Detecting UFB with Dynamic Light Scattering (DLS) system[3]



・Estimate the size distribution of UFB from captured intensity fluctuation of scattered light by Brownian motion of UFB.

[3] https://www.sanyo-si.com/learn/report/dls-dynamic-light-scattering-feature/