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Relative Permeability Properties of the CO_2/Brine System in Saline Aquifers: An Experimental Study

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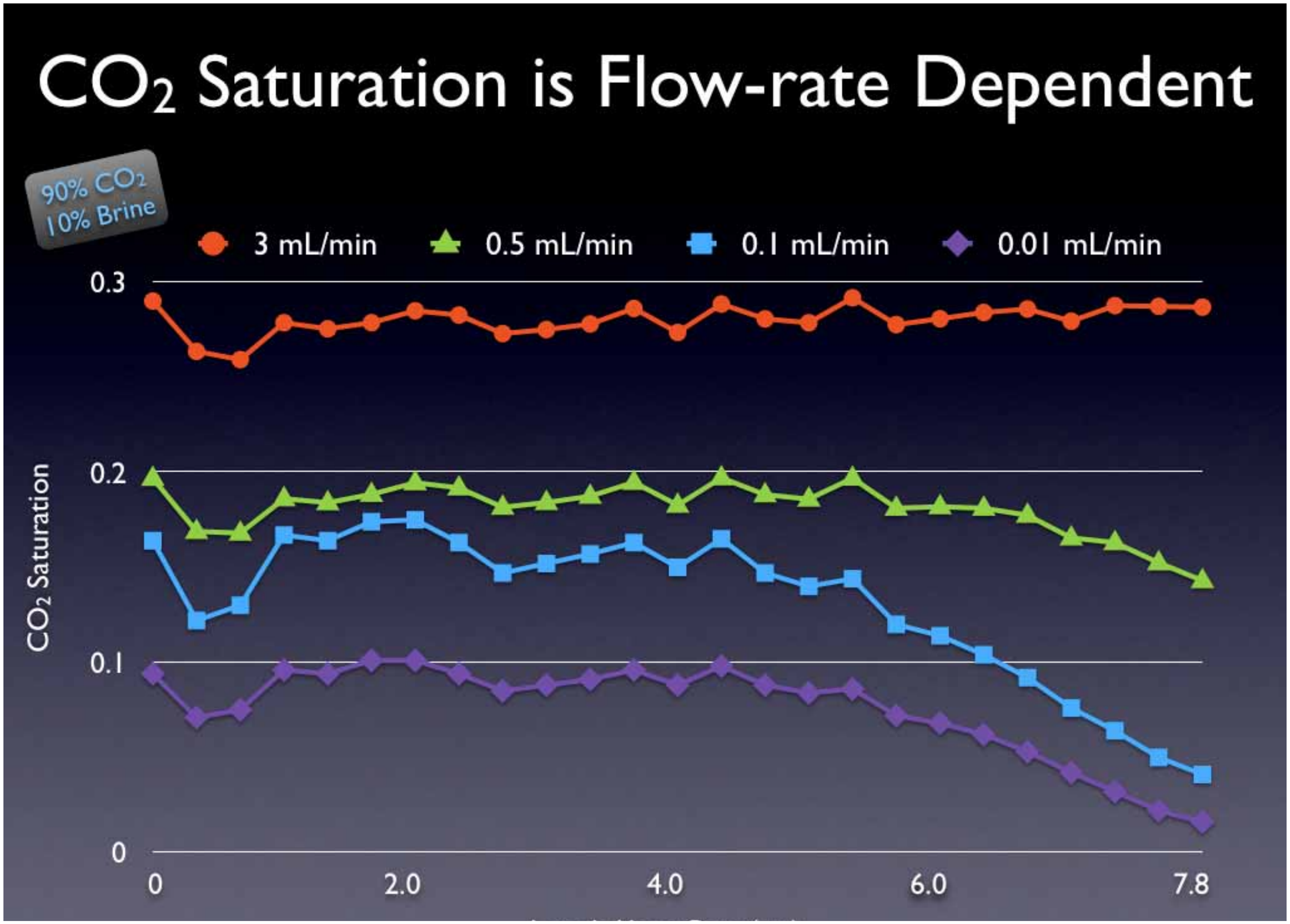
- OVERVIEW -

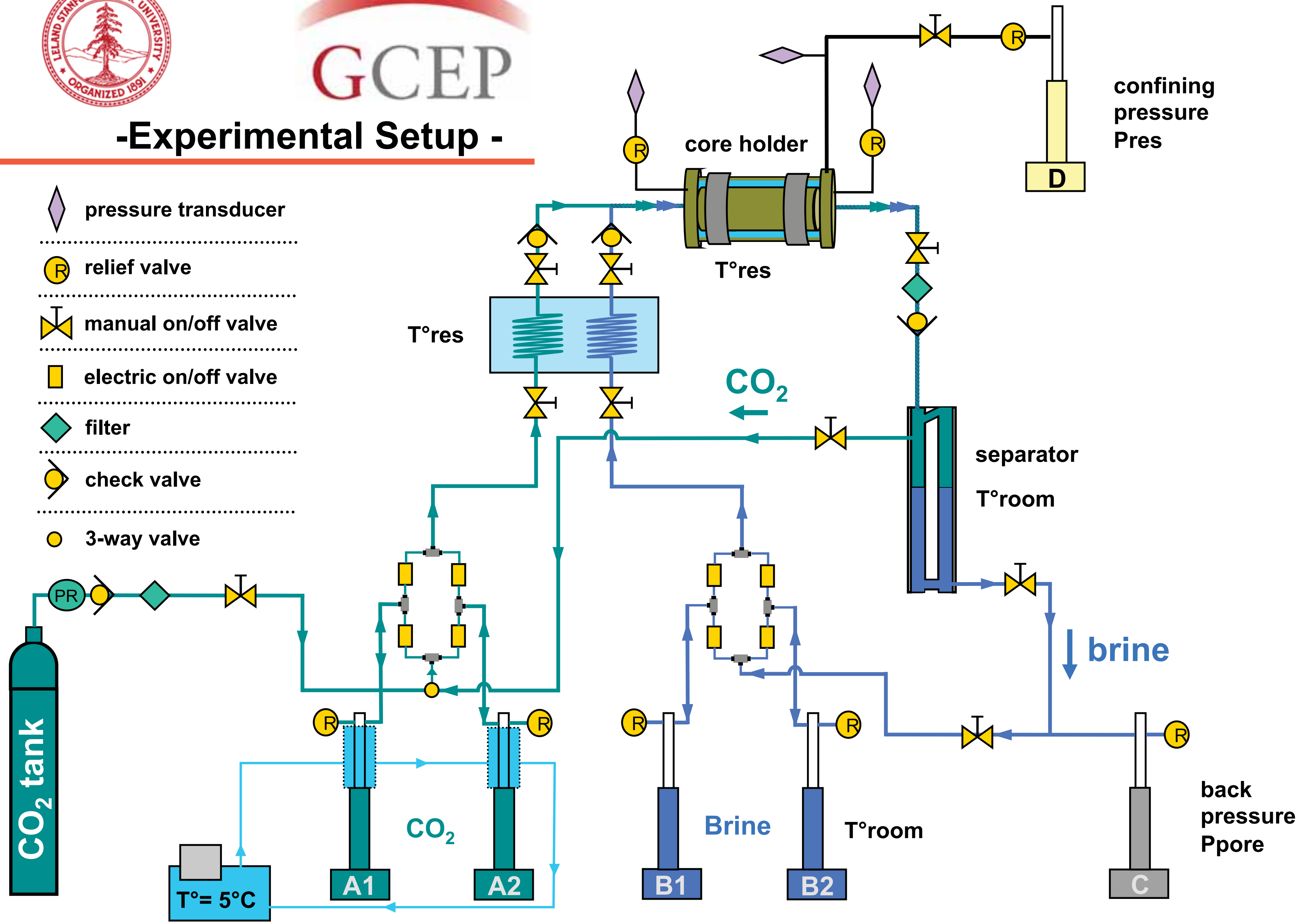
-Motivations
-Experimental Setup
-Core characterization
-2-phase flow : experimental conditions/procedure
-Results
-Conclusions

- MOTIVATIONS -



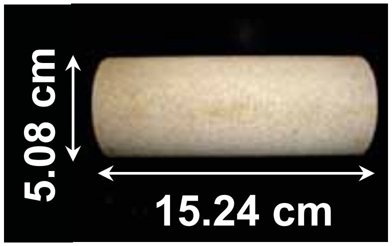
Distance along the core (cm)

-Experimental Setup -

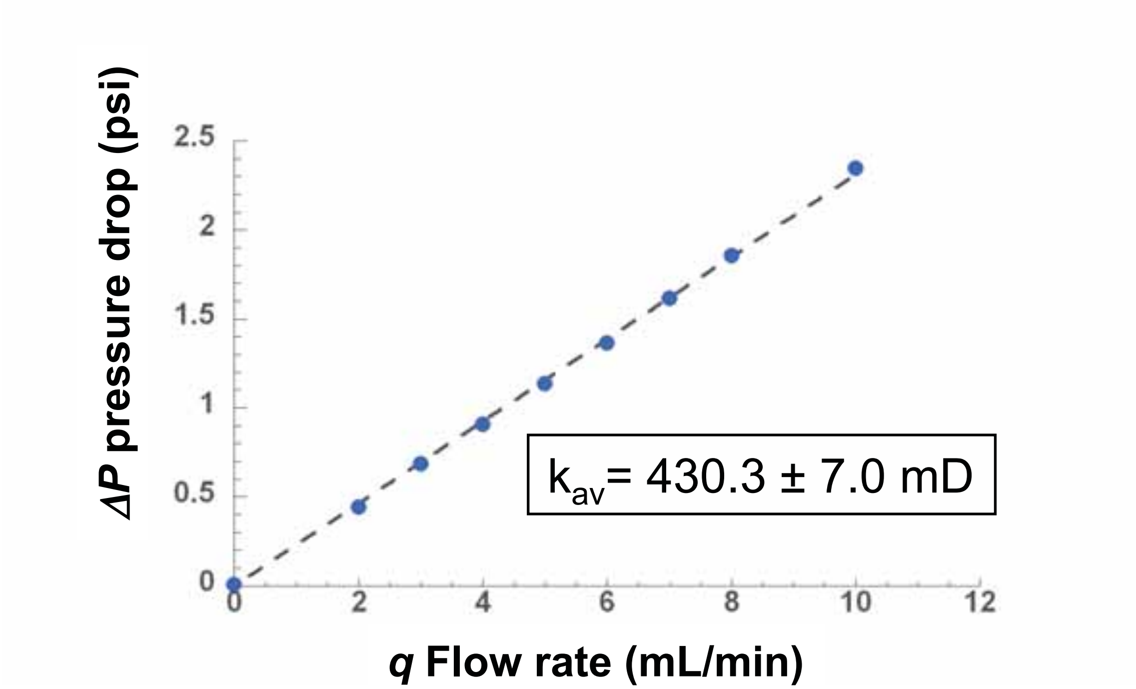


– Core characterization – Absolute Permeability

- Sample = Berea Sandstone



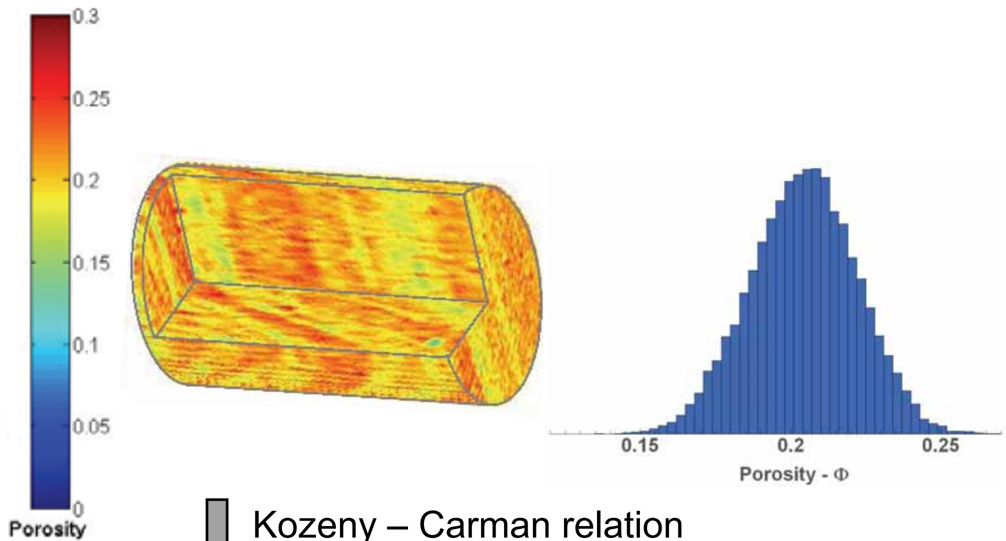
- Absolute permeability:
  - Injection of brine (10 000 ppm NaCl ≈ 10 g/L)
    T°= 50°C , P_{pore} = 12.4 MPa
  - Measure ***ΔP*** as a function of the Flow Rate ***q***



$$\Delta P = \frac{1}{k}\underbrace{\frac{L\mu}{A}}_{\text{known coefficient}}\, q$$

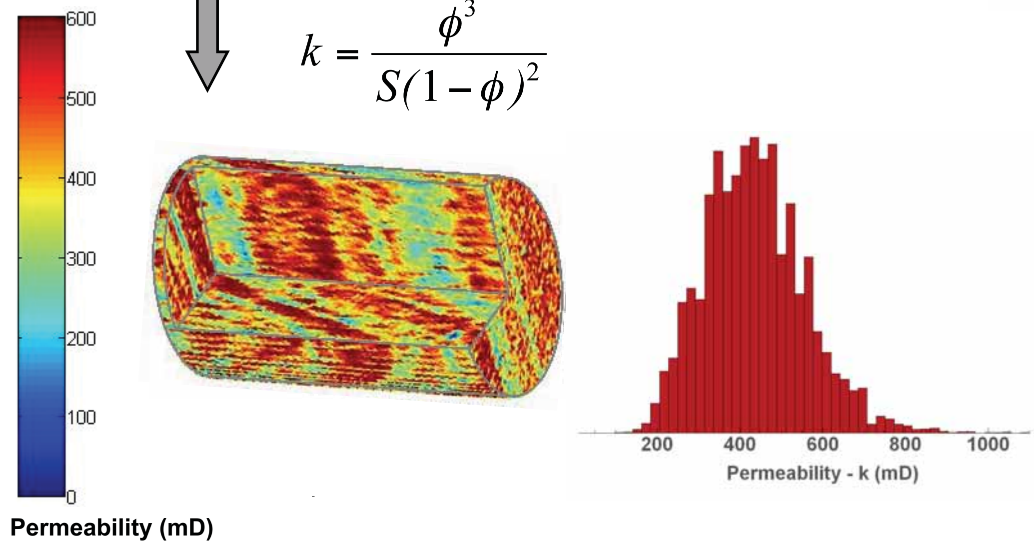
$A = 40.53\ \mathrm{cm}^2$
$L = 15.24\ \mathrm{cm}$
$\mu = 0.54\ \mathrm{cp}$

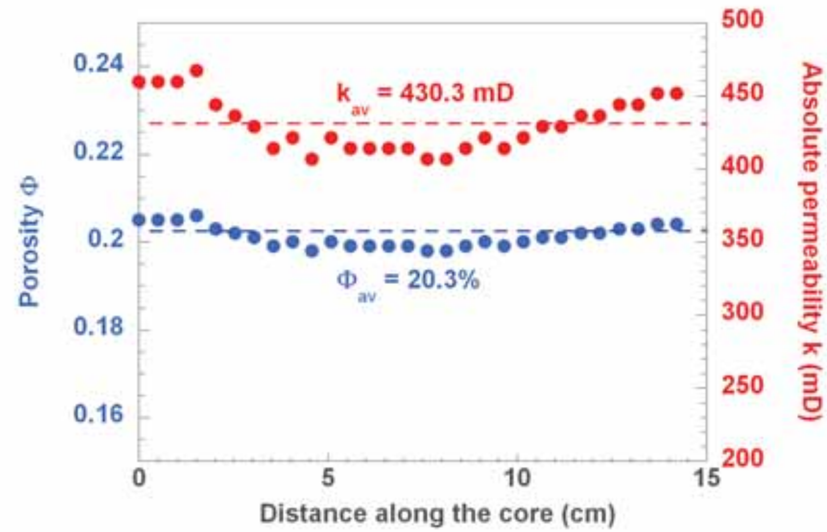
– Core characterization –
Porosity, Permeability



Kozeny – Carman relation

$$k = \frac{\phi^3}{S(1-\phi)^2}$$





Porosity and permeability have important spatial variations due to the pore-scale structure of the rock sample.

The slice-averaged values are relatively constant along the core.

– 2-phase flow experiments – Experimental conditions

- Co-injection of supercritical CO_2 and brine at *reservoir conditions*:

T° = 50°C
P_{pore} = 12.4 MPa

→ corresponds to a depth of 1700 m
(for ∇ T°=0.3°C/100m and ∇ P=820 kPa/100m)

- Physical properties of CO_2 and brine at reservoir conditions:

CO_2 saturated brine	**CO_2**
Liquid μ = 0.558 cP d = 0.990 g/cm³	**Supercritical** μ = 0.046 cP d = 0.28 g/cm³

Viscosity ratio $\nu = \mu_{brine} / \mu_{CO2} = 12.1$

Density ratio $d_{brine} / d_{CO2} = 3.5$

Bond number ~ 0.2

Capillary number ~ $[2.10^{-6} - 10^{-5}]$

– 2-phase flow experiments – Experimental procedure

- At a given total Flow Rate $FR(CO_2) + FR(brine)$:
  - the core is initially saturated with brine
  - CO_2 and brine are injected at a *given fractional flow*

$$f_{brine} = \frac{FR(brine)}{FR(CO_2) + FR(brine)}$$

$$f_{CO_2} = \frac{FR(CO_2)}{FR(CO_2) + FR(brine)}$$

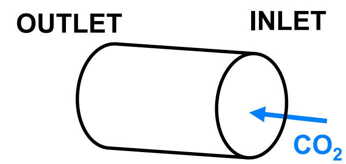
  - wait until steady state is reached (HOW LONG?)
    → stabilization of pressure drop and saturation

  - measure ΔP, saturation

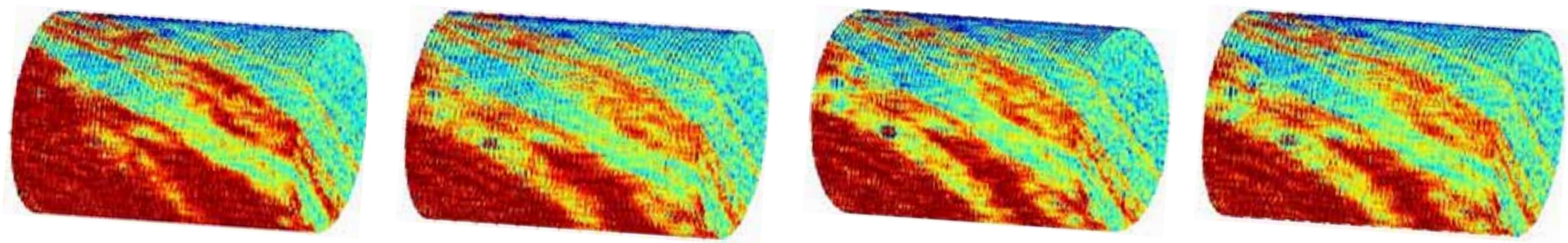
  -increase the proportion of CO_2 ($f_{CO_2} \nearrow$)

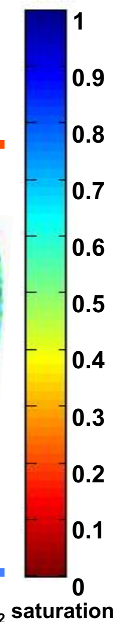
- Run the same procedure at different total flow rates: 2.6, 1.2 and 0.5 mL/min

Injection of 100% CO_2 @ 2mL/min

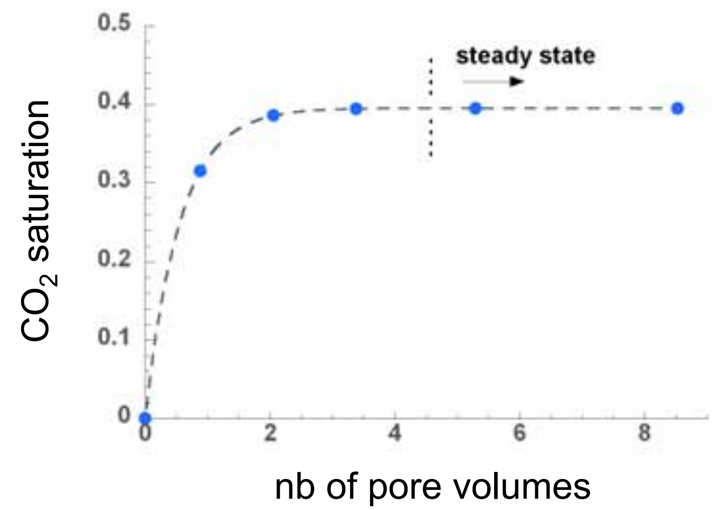


# pore volumes	0.88	2.06	3.38	5.29



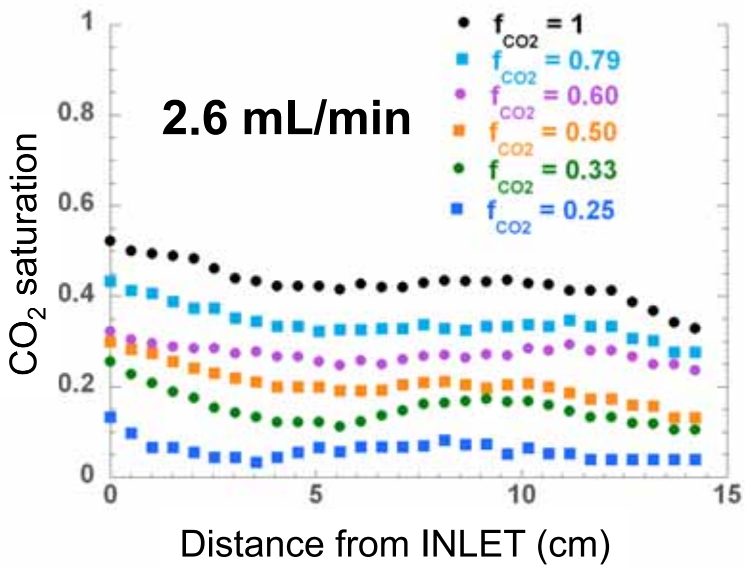


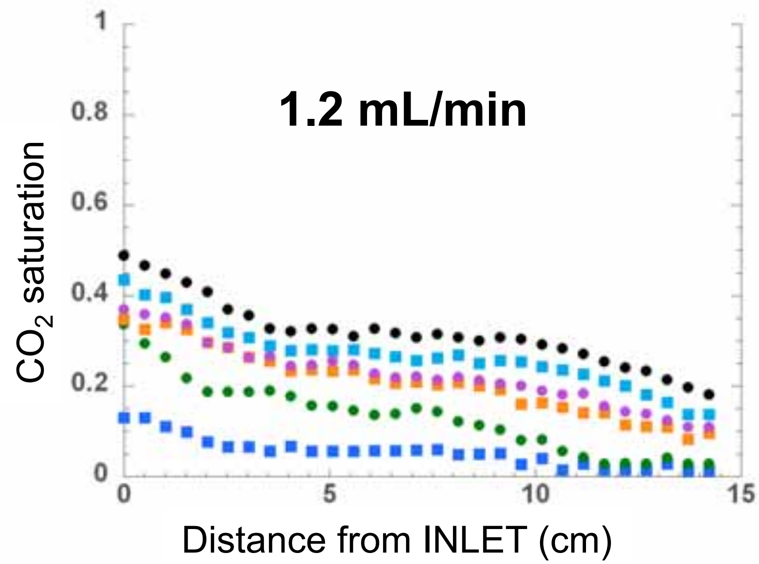
S_{CO_2}	0.315	0.387	0.394	0.395

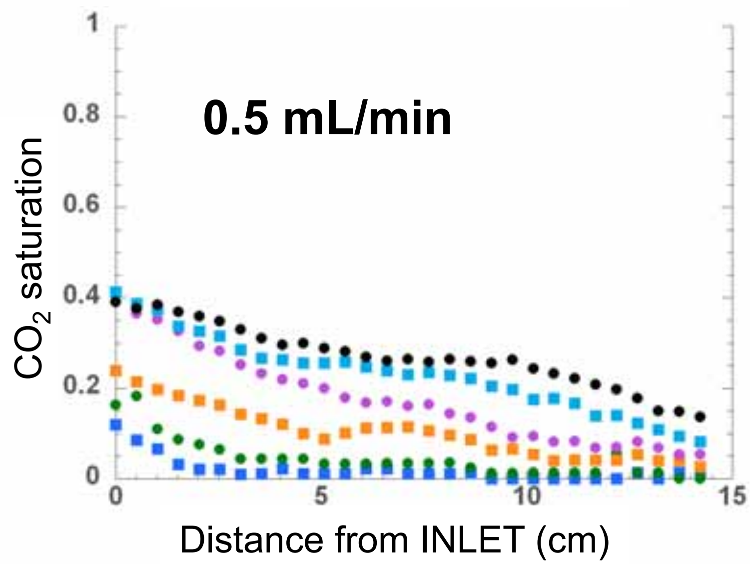


- The steady state is reached after ~ 5 pore volumes
- To be sure to always reach steady state DP and S_{CO_2} are measured after having injected 8-10 pore volumes of fluid.

- Results - CO_2 saturation at different fractional flow



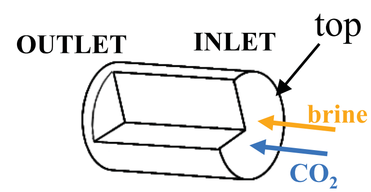


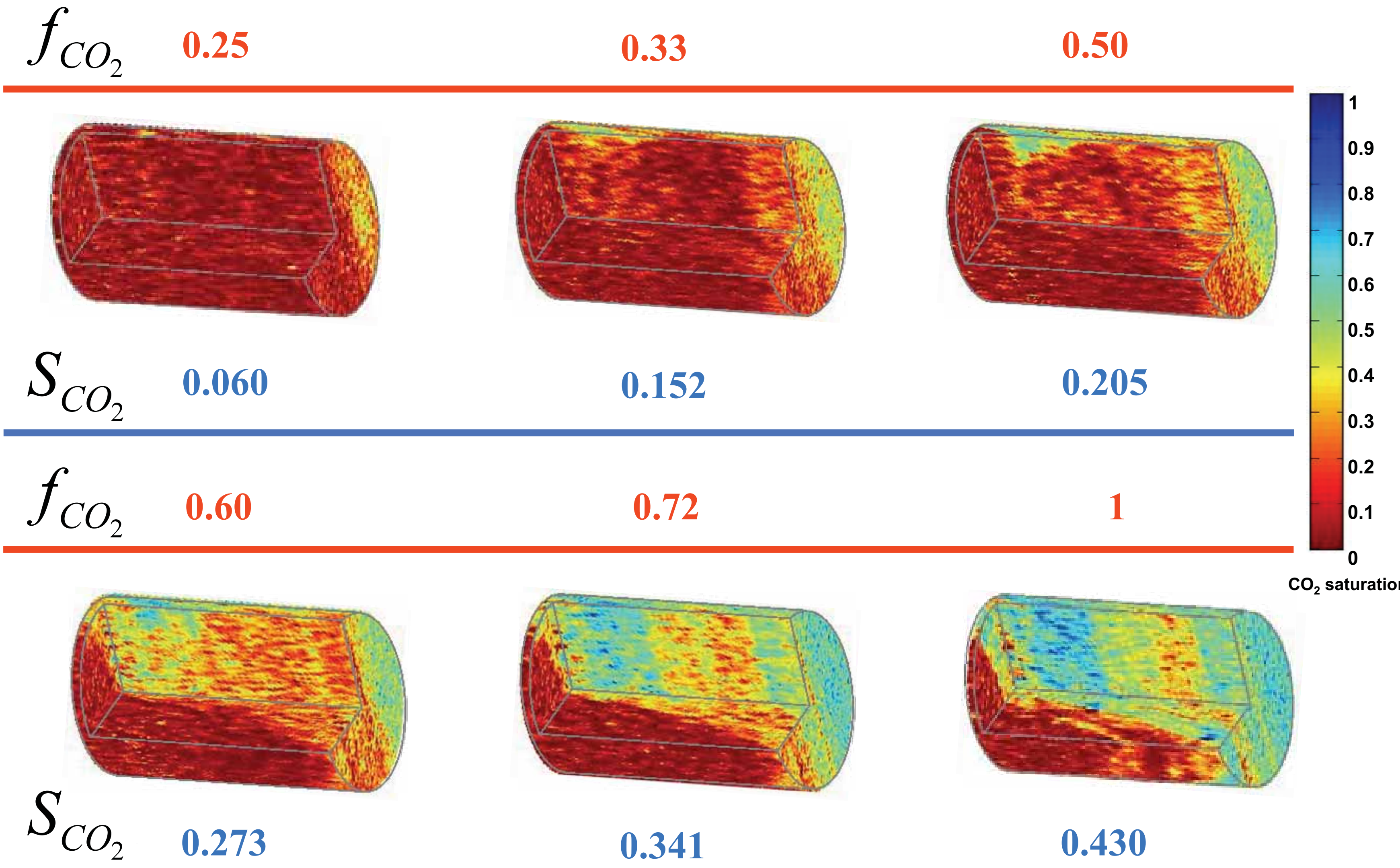


- The higher the proportion of CO_2, the higher the CO_2 saturation.
- Lower values when the flow rate decreases.

- Results -

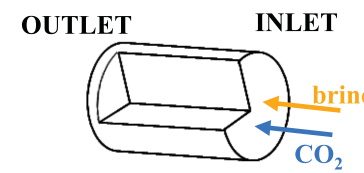
Total flow rate = 2.6 mL/min

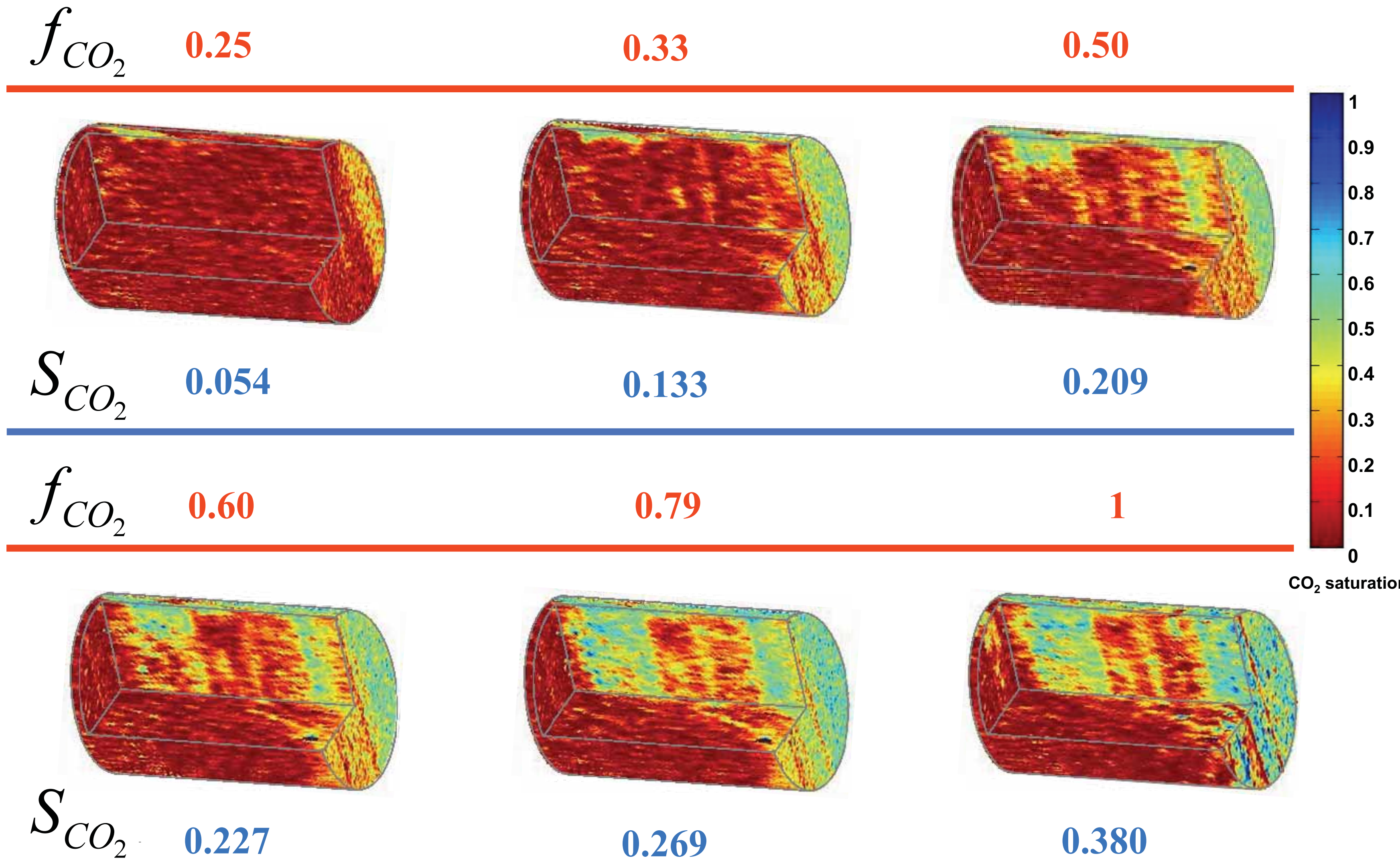




- Results -

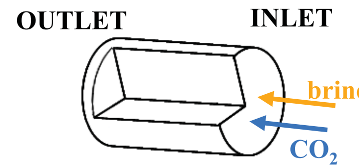
Total flow rate = 1.2 mL/min



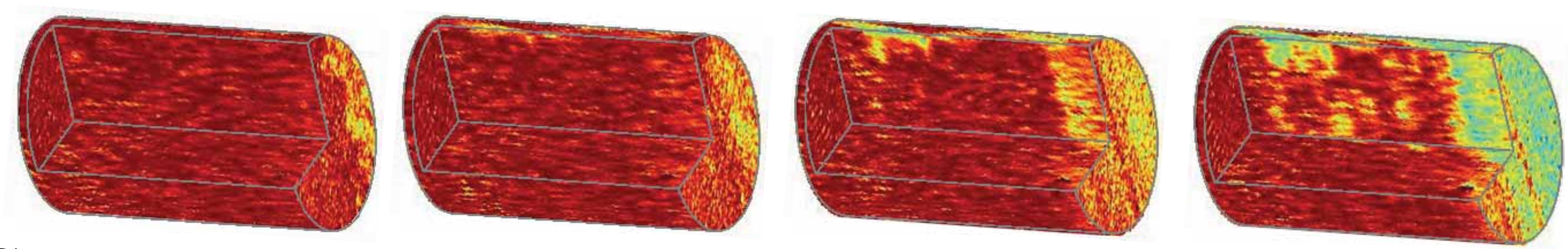


- Results -

Total flow rate = 0.5 mL/min

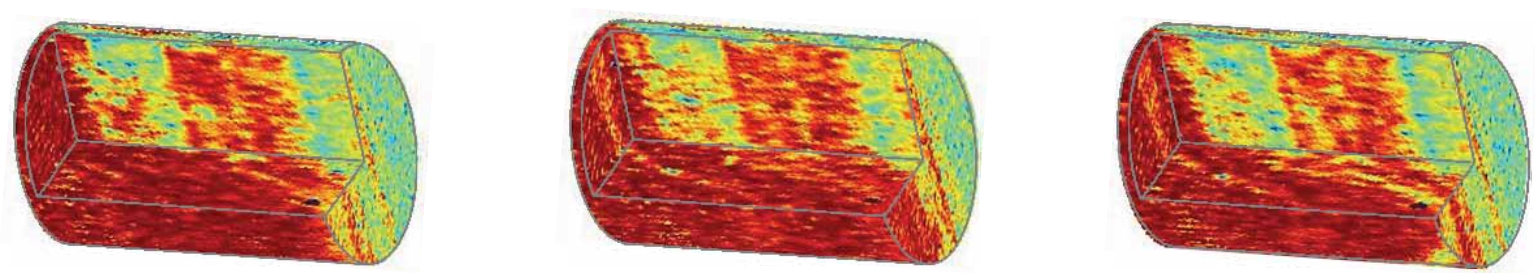


f_{CO_2}	0.16	0.30	0.42	0.60



S_{CO_2}	0.019	0.045	0.105	0.177

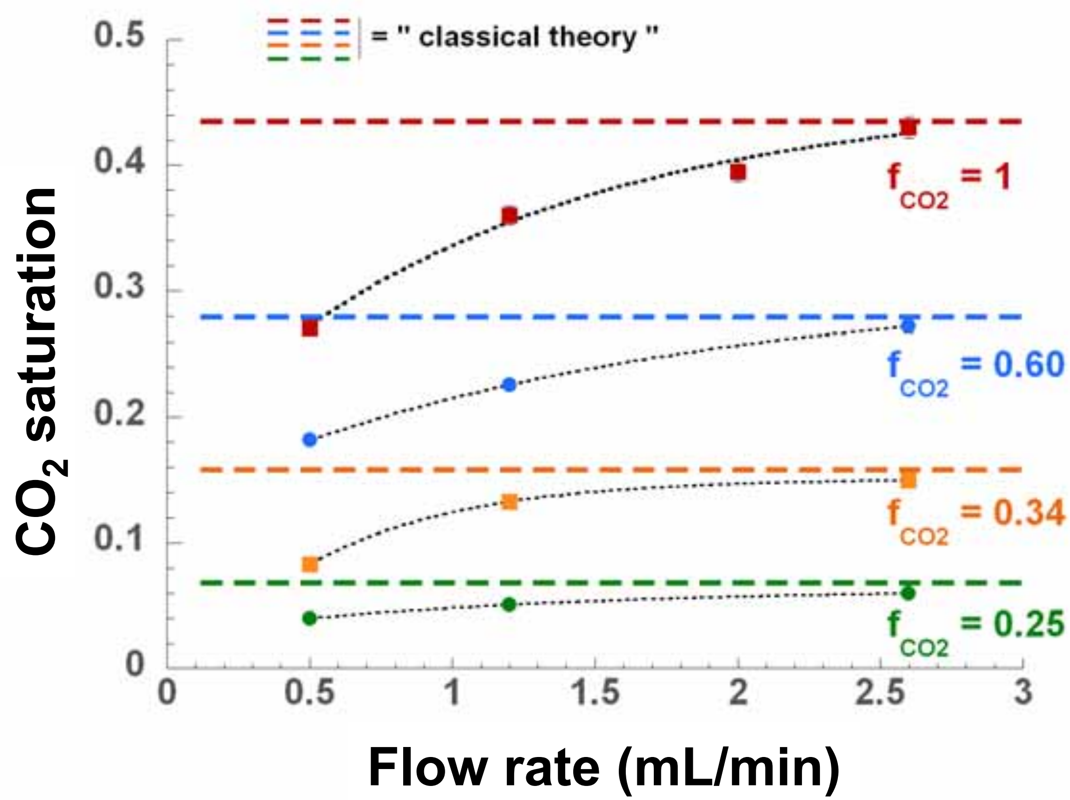
f_{CO_2}	0.74	0.84	1



S_{CO_2}	0.233	0.244	0.271

- Results -

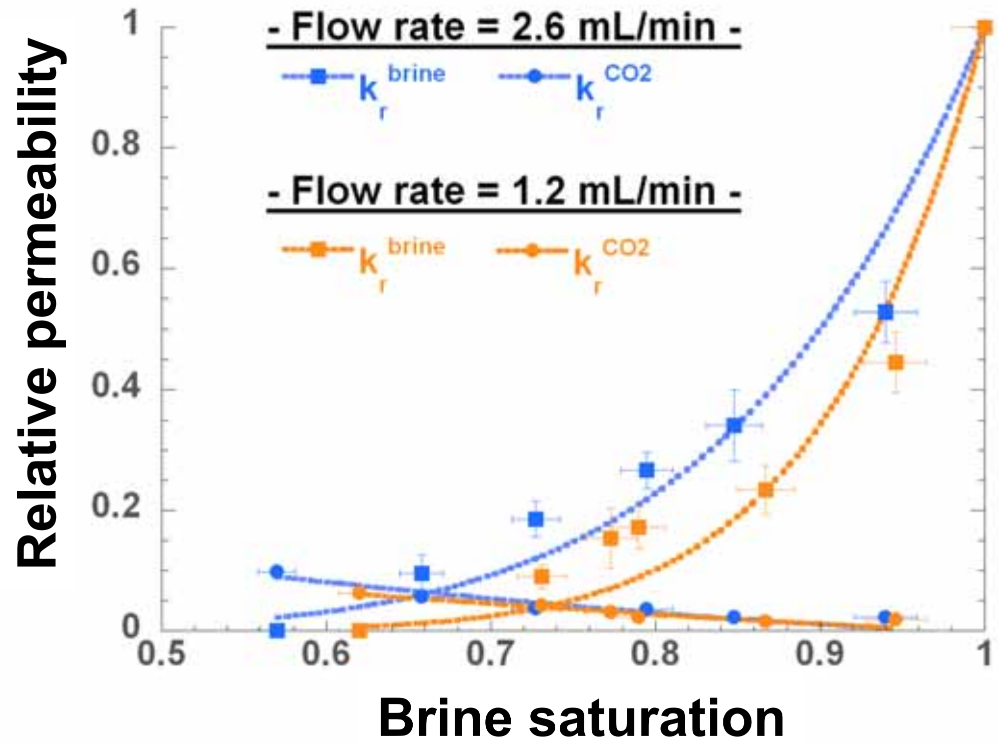
The CO_2 saturation is flow rate dependant



- At any given fractional flow the CO_2 saturation is a function of the flow rate
- The higher the flow rate, the higher the CO_2 saturation
- Results not consistent with classical multi-phase flow theory where saturation – and thus relative permeability – are independent of flow rate

- Results -

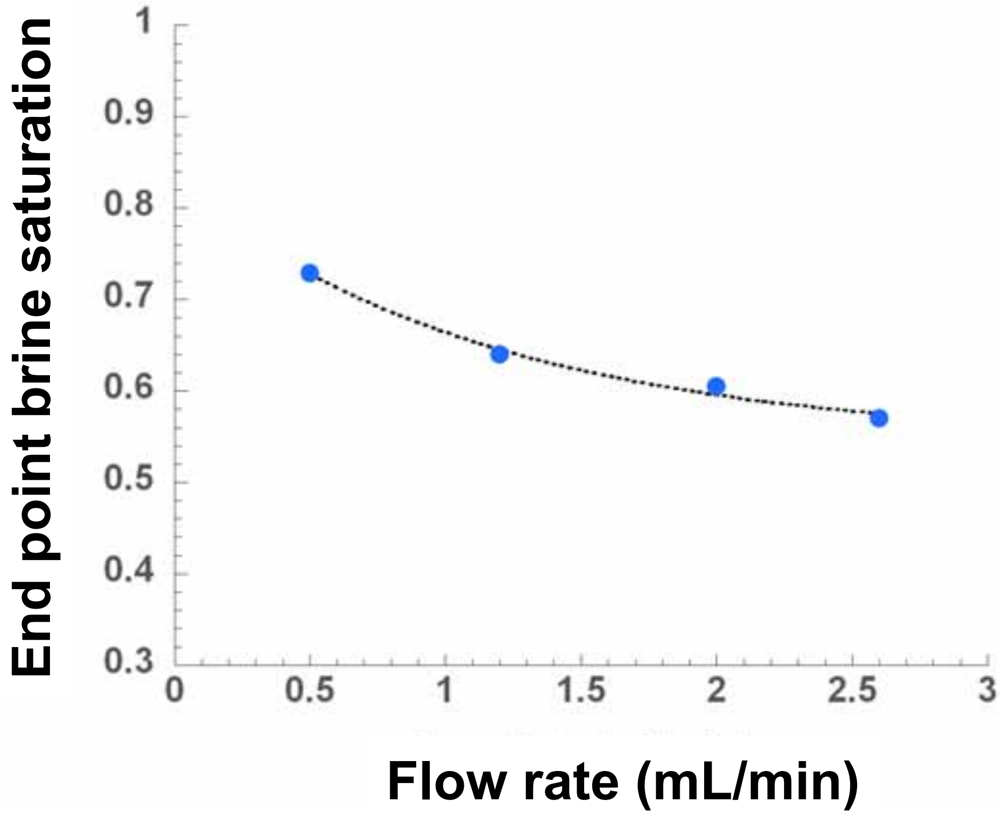
The Relative Permeability curve is flow rate dependant



- Same general trend
- Global shift between the two curves
- The lower the flow rate, the lower the relative permeability

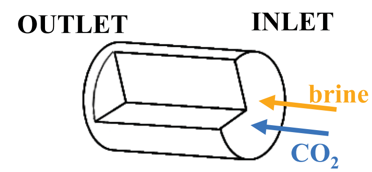
- Results -

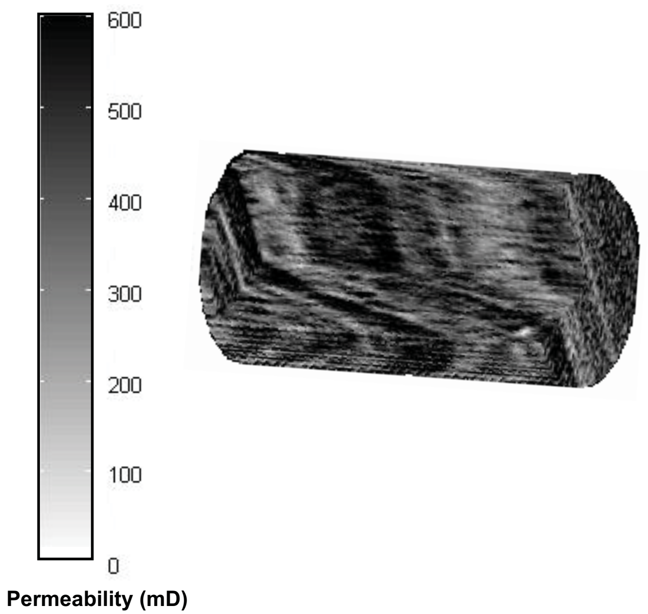
The end-point brine saturation is flow rate dependant



- Strong variations of the end point brine saturation
- Unusually high values
- Asymptotic value for high flow rates

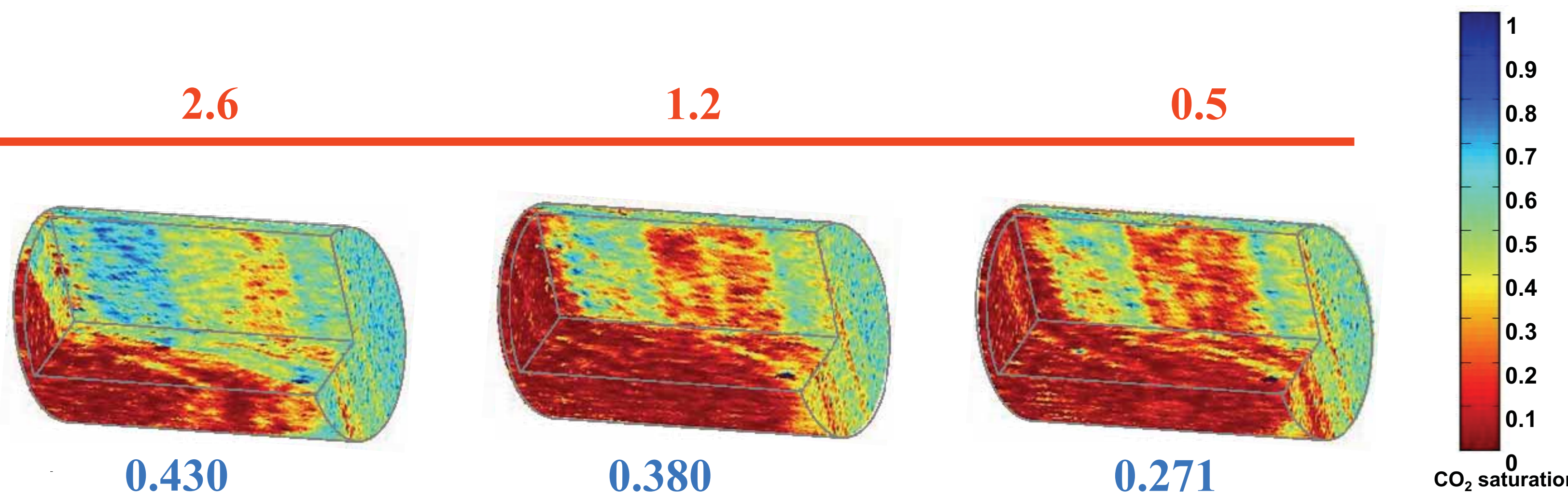
- Results -
Link Permeability - Saturation??





- High permeability paths correspond to high CO_2 saturation close to inlet
- Elsewhere the correlation Permeability – Saturation is poor due to non connected high permeability pathways

Flow rate (mL/min)	2.6	1.2	0.5



S_{CO_2}	0.430	0.380	0.271

- CONCLUSIONS -

- We built a new core flooding experimental setup
- The setup allows us to continuously inject CO_2 and Brine at reservoir conditions

- CONCLUSIONS (2) -

- The first experiments confirm the predicted dependence of CO_2 saturations
- The spatial variations of the permeability (heterogeneities of the pore structure) play a fundamental role in the distribution of CO_2

- CONCLUSIONS (3) -

- Numerical simulations are needed to better understand these observations
- Sub-core scale permeability maps are needed as input in the simulations

- FUTURE WORK -

- More experiments to confirm and more precisely describe the flow rate effect.
- Experimental investigation of imbibitions, relative permeability hysteresis and capillary trapping
- Image the displacement front
- Measure of the relative permeability curve on “real samples” (e.g Otway project, Australia)

- AKNOWLEDGMENTS -

- Sally Benson
- Global Climate and Energy Project at Stanford
- Organizing committee of the CCS conference