Characterizing sub-core hysteretic relative permeability and capillary pressure for accurate imbibition coreflood modeling

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November 26, 2022

Abstract

Using x-ray tomography in corefiooding experiments allows to characterize the sub-core, mm-scale, multiphase flow properties such as permeability, porosity, relative permeability and capillary pressure. This has been studied previously for CO2-brine drainage experiments and a procedure has been developed for sub-core property estimation, showing that their implementation in numerical models leads to accurate predictions of experimental measurements, such as core saturation distribution. Much less work has been conducted regarding CO2-brine imbibition modeling. In this work we characterize hysteretic sub-core properties using experimental data of CO2-brine imbibition coreflooding conducted on two core samples. We adopt the approach of [1] for sub-core capillary pressure modeling and that of [2] for relative permeability modeling, however, we find that these are not sufficient for accurate modeling of saturation distribution within the core. We improve the models by considering a unique turning point and Land trapping coefficient for each mm-scale grid block in our model and also by calculating new imbibition characteristic relative permeability curves based on a procedure developed in [3]. Results show improvements in matching experimental data. [1] R. Pini, and S.M. Benson. "Capillary pressure heterogeneity and hysteresis for the supercritical CO2/water system in a sandstone." Advances in Water Resources 108 (2017): 277-292. [2] O. Dury, U. Fischer, and R. Schulin. "A comparison of relative nonwetting-phase permeability models." Water Resources Research 35.5 (1999): 1481-1493. [3] E. Anto-Darkwah, S.M. Benson, and A. Rabinovich. "An improved procedure for sub-core property characterization using data from multiple coreflooding experiments." International Journal of Greenhouse Gas Control 105 (2021): 103226.

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AGU FALL MEETING
New Orleans, LA & Online Everywhere
13–17 December 2021

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Summary

- Drainage and imbibition corefIooding experiments were conducted on two core samples along with X-ray CT imaging resulting in detailed sub-core saturation distributions.
- Previous work estimated drainage relative permeability (k_r), capillary pressure (P_c) and 3D permeability distribution (k).
- In this work we characterize hysteretic sub-core k_r and P_c in order to accurately model imbibition coreflooding.
- We first adopt the methods of Pini and Benson (2017) for sub-core capillary pressure modeling and that of Dury et al. (1999) for relative permeability modeling, however, we find that these are not sufficient for accurate modeling of core saturation distribution.
- The models are improved using unique Land trapping coefficients for each mm-scale grid block in our model and also by calculating new imbibition characteristic relative permeability curves based on a procedure developed in Anto-Darkwah et al. (2020).
- Results show improvements in matching experimental data.

Experimental Data

- Corefloods were conducted at the Benson Lab in Stanford Univ.
- For drainage, P_c^D is obtained by MICP and fitted by:

$$P_c^D(S_w) = P_e \cdot (\tilde{S}_w)^{-1/\lambda}, \quad \tilde{S}_w = (S_w - S_{wi})/(1-S_{wi}), \quad \tilde{S}_{w,m} = 1-\tilde{S}_{nw,m}$$

- Imbibition P_c^I is modeled by: $P_c^I(S_w) = P_{c,i}\cdot(\tilde{S}_{w,m}^{-1/\lambda} - 1)$

$$\tilde{S}_{nw,m} = \frac{1}{2}\left[(\tilde{S}_{nw}-\tilde{S}_{nw,r}) + \sqrt{(\tilde{S}_{nw}-\tilde{S}_{nw,r})^2 + \frac{4}{C_L}(\tilde{S}_{nw}-\tilde{S}_{nw,r})}\right], \quad C_L = \frac{1}{\langle S_{nw,r}\rangle} - \frac{1}{\langle S_{nw,i}\rangle}$$

C_L - global land trapping coefficient

P_e , $P_{c,i}$ - drainage and imbibition entry pressures

$\tilde{S}_{nw,i}$, $\tilde{S}_{nw,r}$ - turning point and residual saturations

$$P_{c,i} = P_e \cdot (1-\tilde{S}_{w,i}^{-1/\lambda})^{-1}$$

$$k_{rw} = (\tilde{S}_w)^{n_w}$$

Imbibition

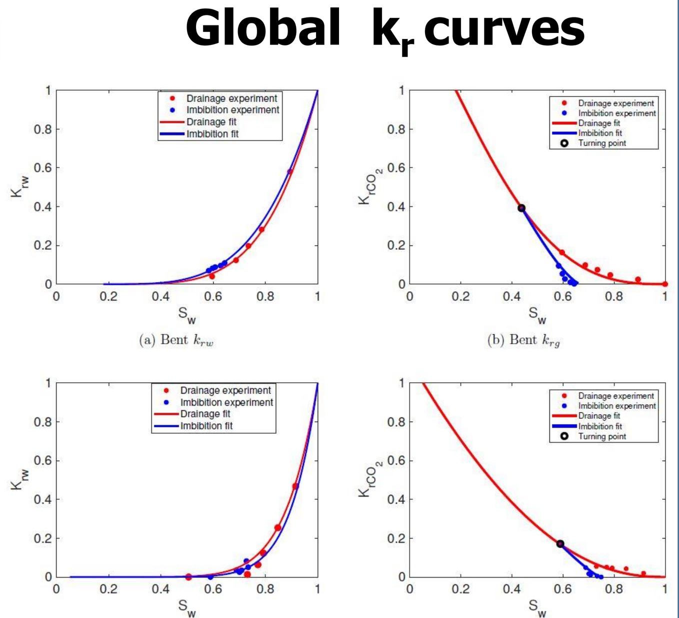
$$k^I_{rco_2} = (1-\bar{S}_w)^C (1-\bar{S}_w^{\,A})^B$$

Drainage

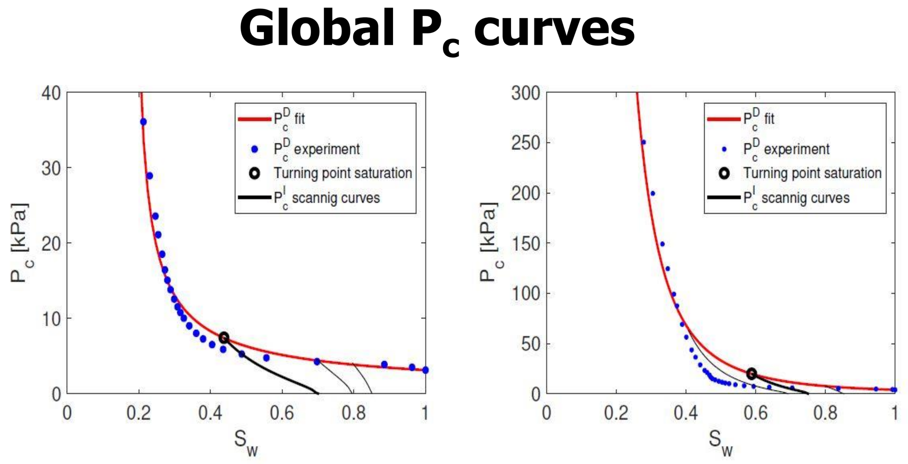
$$k^D_{rco_2} = (1-\hat{S}_w)^C (1-\hat{S}_w^{\,A})^B$$

$$\bar{S}_w = \frac{S_w - S_{wi}}{1-S_{wi} - \frac{S_{nw,i}}{1+C_L S_{nw,i}}}, \quad \hat{S}_w = \frac{S_w - S_{wi}}{1-S_{wi} - \frac{(1-S_w)}{1+C_L(1-S_w)}}$$

Global k_r curves



Global P_c curves



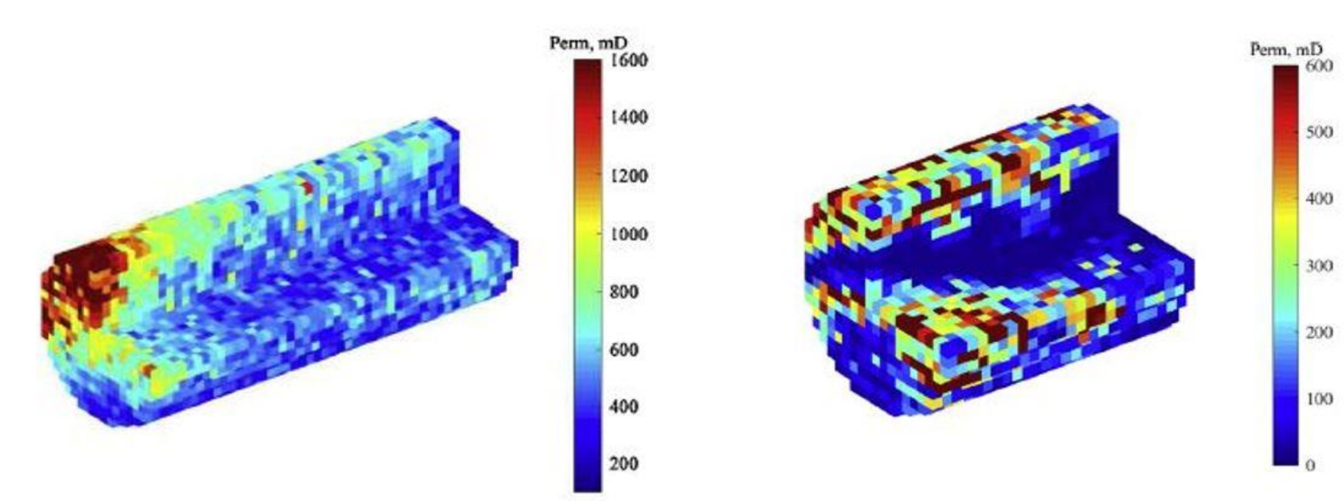
- A, B and C are fitting parameters obtained from simultaneous fitting of $k^D_{rco_2}$, $k^I_{rco_2}$ curves

Rock	λ	A	B	C	C_L	n_w	P_e (kPa)	$S_{nw,i}$ (Global)	$S_{nw,r}$ (Global)
Bent	1.35	1.78	0.329	1.06	1.236	3.79	3.14	0.561	0.331
Shezaf	0.35	0.76	0.001	1.19	1.496	9.10	3.89	0.411	0.254

Permeability estimation

- Permeability distributions $k(x,y,z)$ were previously obtained from drainage experiments (Anto-Darkwah et al. 2020)

Bentheimer rock permeability **Shezaf rock permeability**



Sub-core scale imbibition $k^{b,I}_{rco_2}$, $P_c^{b,I}$ curves

- We used the previous equations for $k^I_{rco_2}$, P_c^I however, grid block values: C_L^b, $\tilde{S}^b_{nw,i}$, $\tilde{S}^b_{nw,r}$ are used as opposed to global values
- Grid block land coefficients were calculated as: $C_L^b = \frac{1}{S^b_{nw,r}} - \frac{1}{S^b_{nw,i}}$

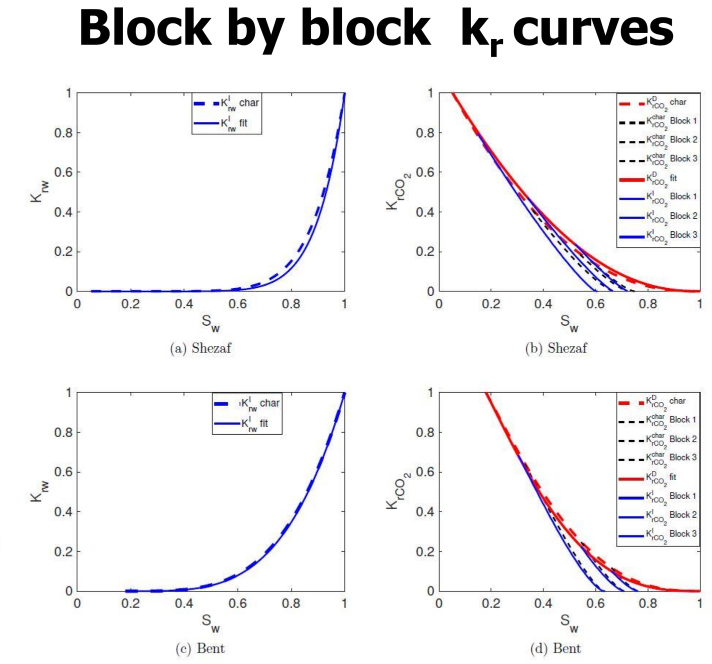
Imbibition characteristic k_{rj}^{char} curves

$k^{I,char}_{rco_2}(\bar{S}_w^{\,b})$ curves changes with each grid block

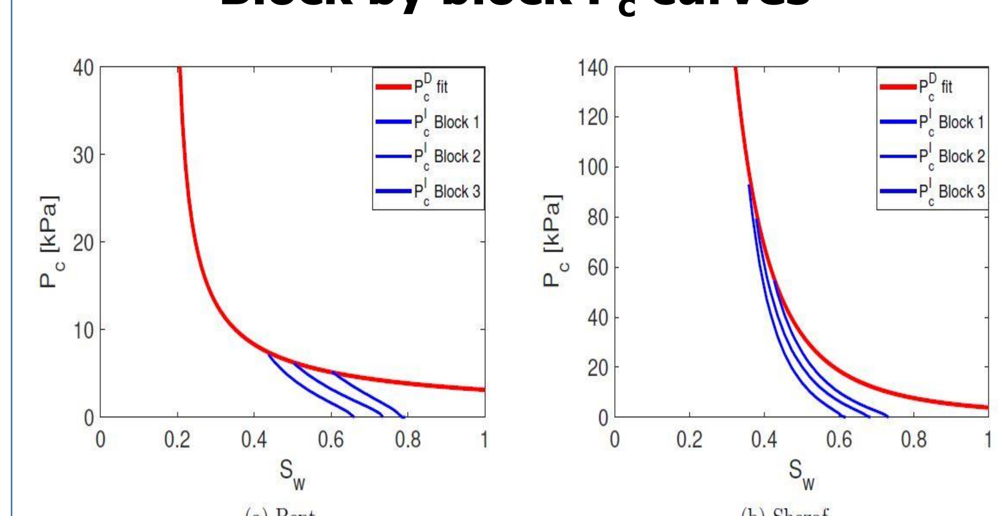
A^{char}, B^{char}, C^{char}, n_w^{char} are optimized so core effective rel perm matches the experimental measured values

Rock	A^{char}	B^{char}	C^{char}	n_w^{char}
Bent	1.792	0.319	0.992	3.70
Shezaf	0.775	0.049	1.238	7.75

Block by block k_r curves



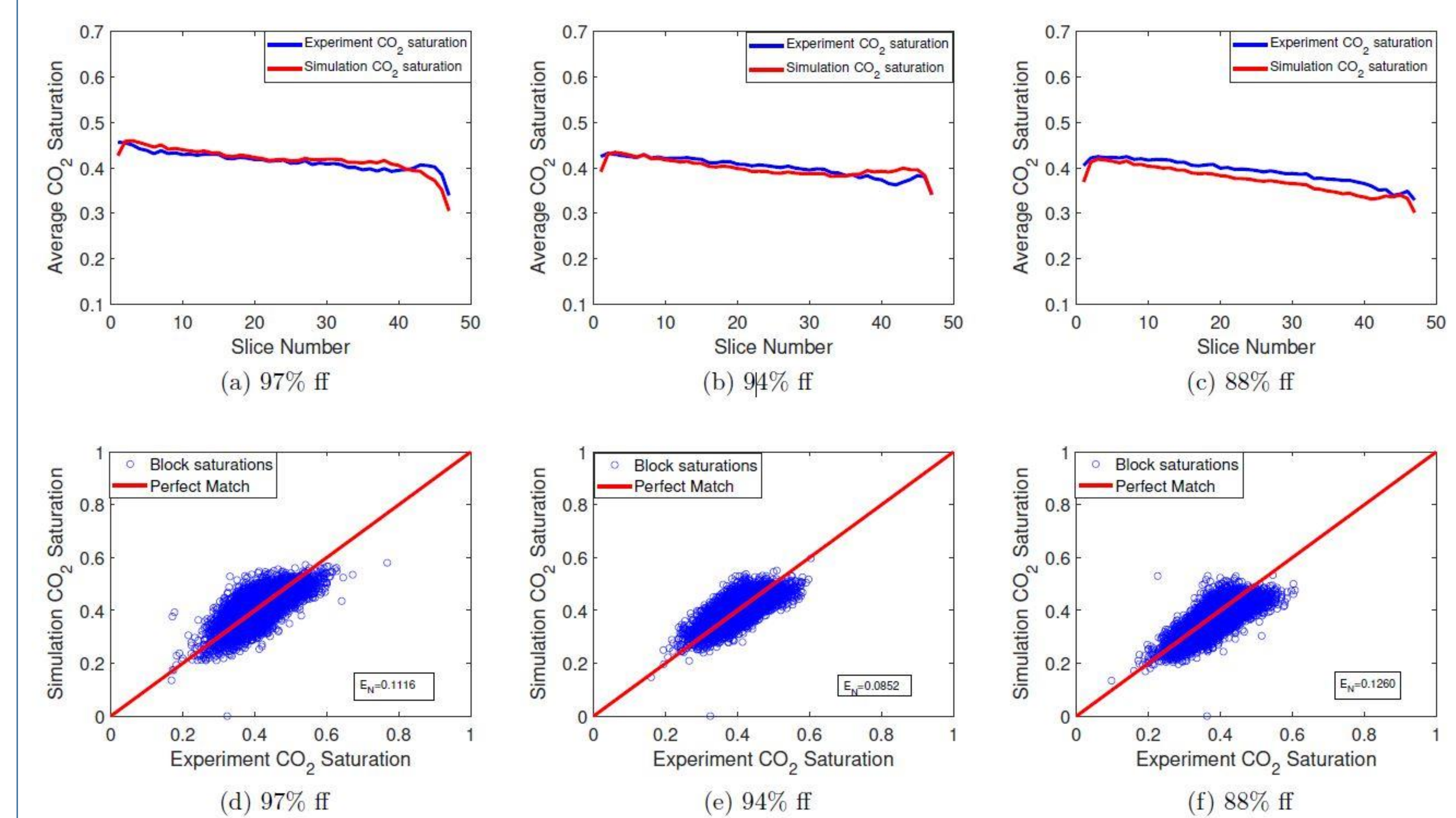
Block by block P_c curves



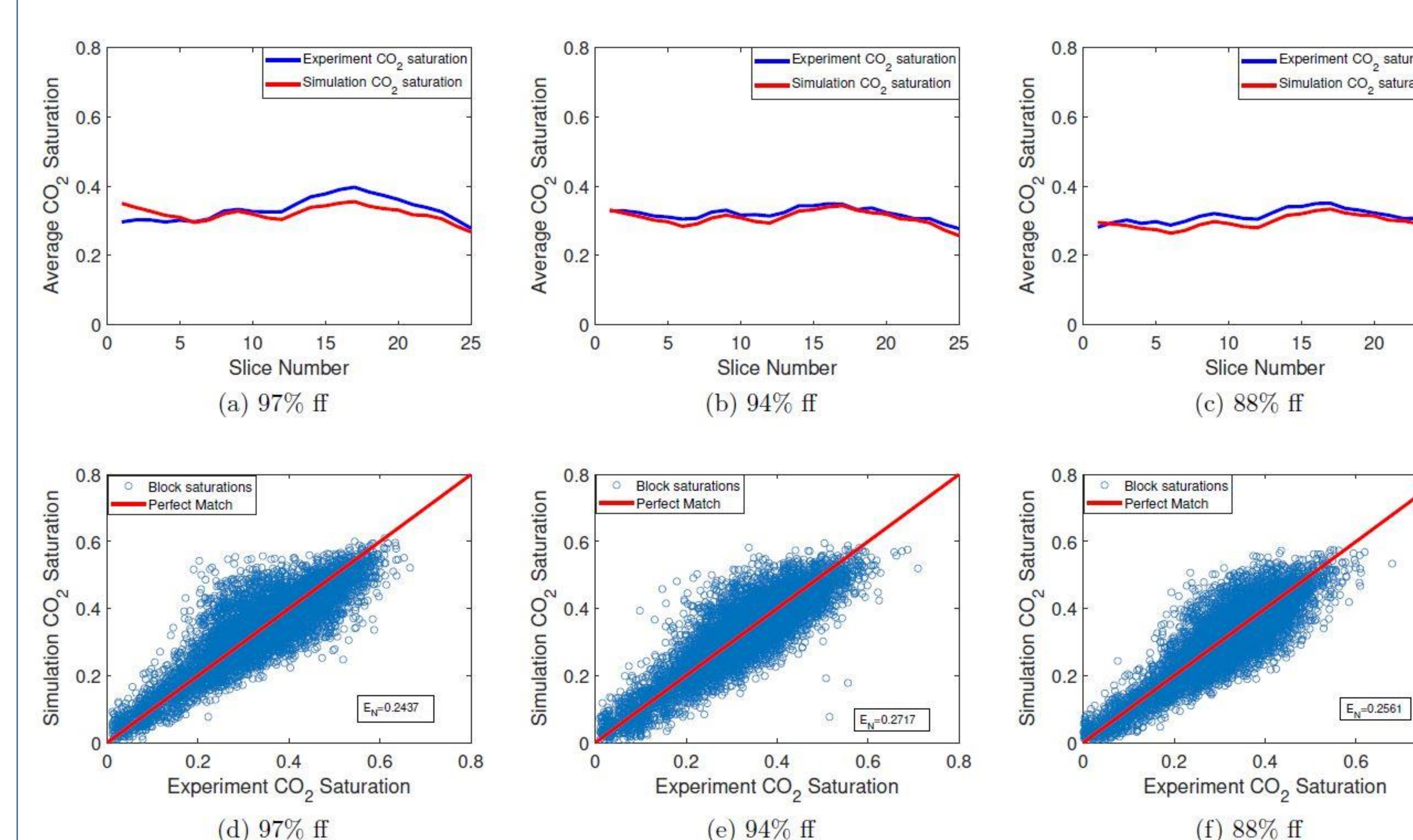
Results

- Flow simulations are conducted with the new sub-core scale $k_{rj}^{I,char}$, $P_c^{I,char}$ as input

Bentheimer saturation comparisons



Shezaf saturation comparisons



Relative permeability comparisons