Equation-of-State Approach to Model Relative Permeability Including Hysteresis and Wettability Alteration

Saeid Khorsandi[2], **Liwei Li**[1], **Russell T. Johns**[1,2]

1- John and Willie Leone Family Department of Energy and Mineral Engineering, Penn State University, University Park, PA
2- EMS Energy Institute, Penn State University, University Park, PA

1 BACKGROUND

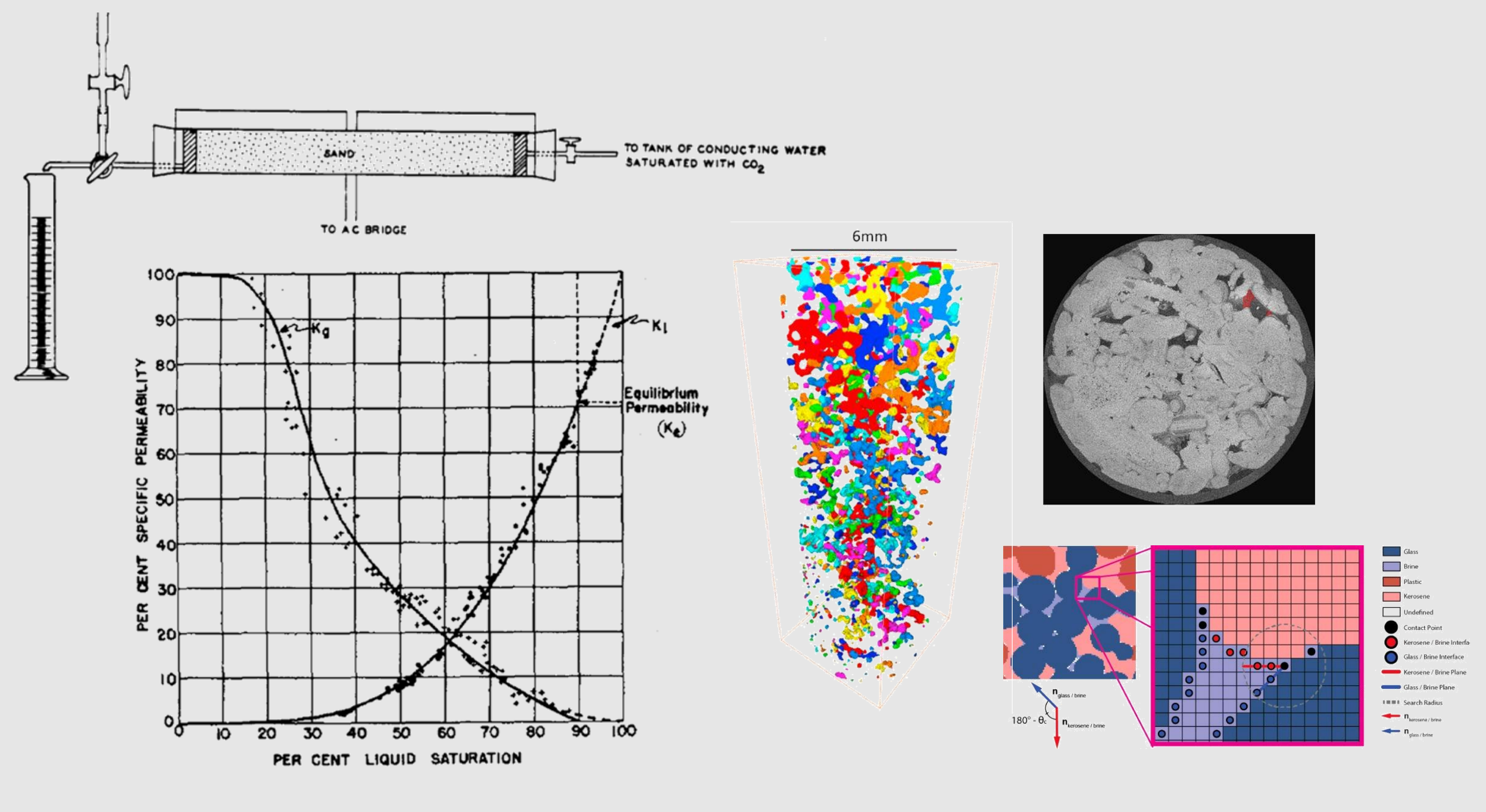


Figure 1: (left) Wyckoff and Botset (1936) experimental apparatus and results for first measured two-phase relative permeabilities. (right) In-situ measurement of trapped phase distribution and contact angle using CT-scanning (Andrew et al. 2013, Klise et al. 2015).

Problem definition

- Commercial compositional simulators apply correlations or empirical relations requiring phase labeling.
- Phase labeling is discontinuous for complex miscible or near-miscible displacements with multiple hydrocarbon phases. Resulting discontinuities in relative permeability cause simulation inaccuracies and instabilities.
- Phase relative permeabilities should capture effects of hysteresis, fluid composition variations and rock wettability alteration.

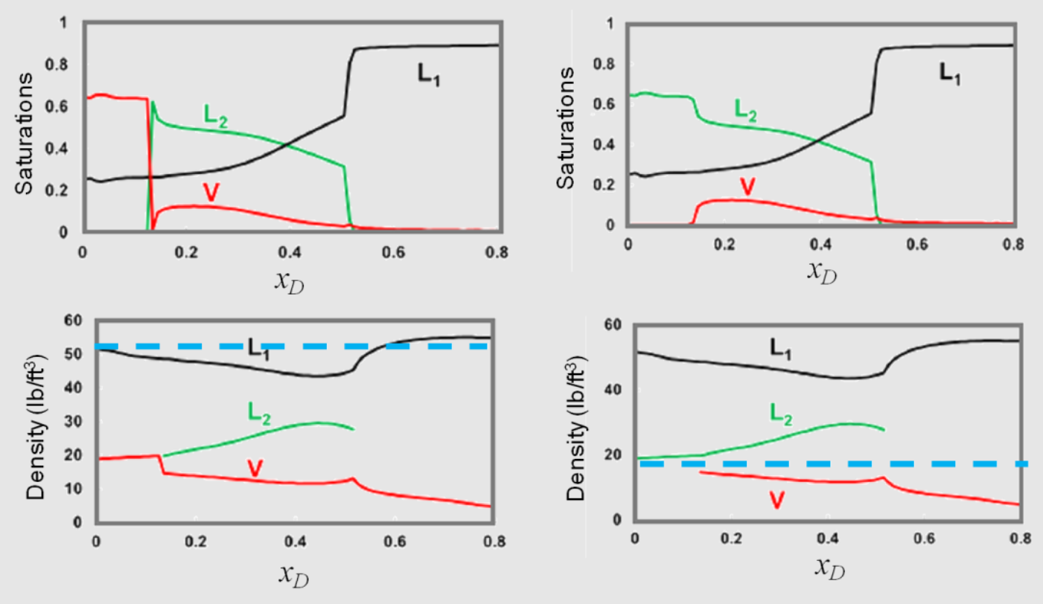


Figure 2: Phase labeling based on density thresholds causes significant differences in the simulation results. The dashed line represents the threshold phase density for each case.

Objectives

- Develop an equation-of-state (EoS) to model robustly and continuously the relative permeability as functions of phase saturations and distributions, fluid compositions, rock surface properties, and rock structure.

$$dk_r = \underbrace{\frac{\partial k_r}{\partial S}dS + \frac{\partial k_r}{\partial \hat{\chi}}d\hat{\chi}}_{\text{Phase distribution}} + \overbrace{\frac{\partial k_r}{\partial I}}^{\text{Wettability}}dI + \underbrace{\frac{\partial k_r}{\partial N_{Ca}}dN_{Ca}}_{\text{Capillary number}} + \overbrace{\frac{\partial k_r}{\partial \lambda}}^{\text{Rock structure}}d\lambda$$

- Eliminate all phase labeling.
- Phase distribution and connectivity is handled through the Euler characteristic with a new method of normalization.
- The new model reduces to the same form as conventional relative permeability models and can be tuned to typical experimental data.
- The new model offers the potential for incorporating results from CT-scans and pore-network models to field scale simulations.
- The model is applicable to all flow in porous media processes, but is especially important for low salinity polymer, surfactant, miscible gas and water-alternating-gas flooding.

2 METHODOLOGY

Topology of fluid in porous media

$$\chi = \beta_0 - \beta_1$$

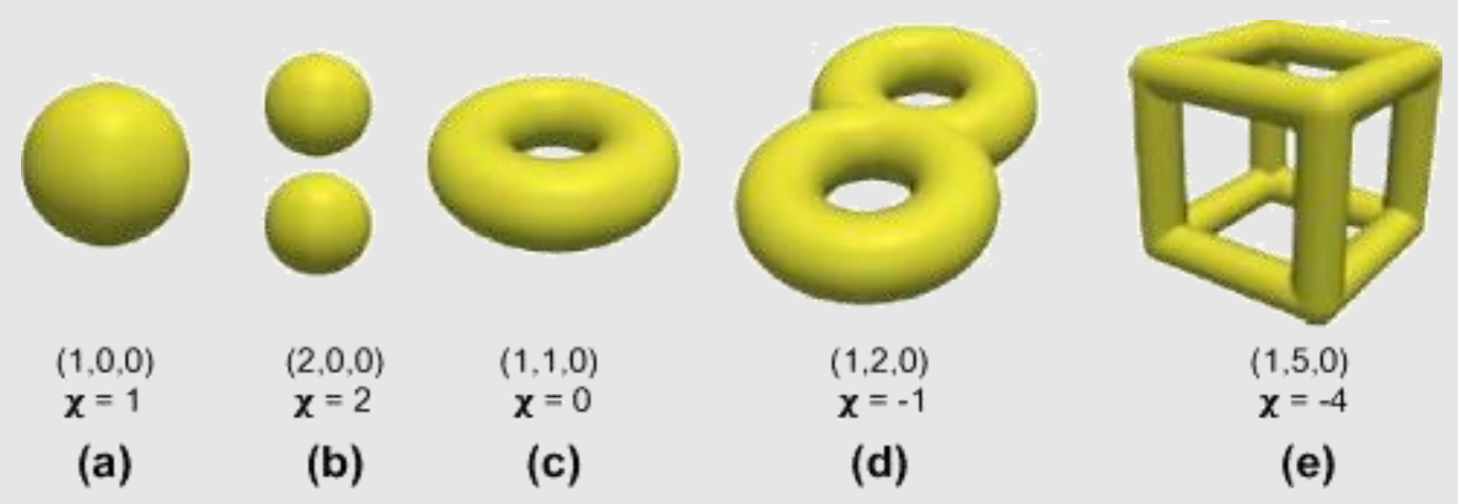


Figure 3: Euler characteristic number examples.

Normalized Euler characteristic: is only a function of ganglion topology and independent of saturation and measurement scale.

$$\hat{\chi} = \frac{\dfrac{\chi}{S} - \chi_{max}}{\chi_{100\%} - \chi_{max}}$$

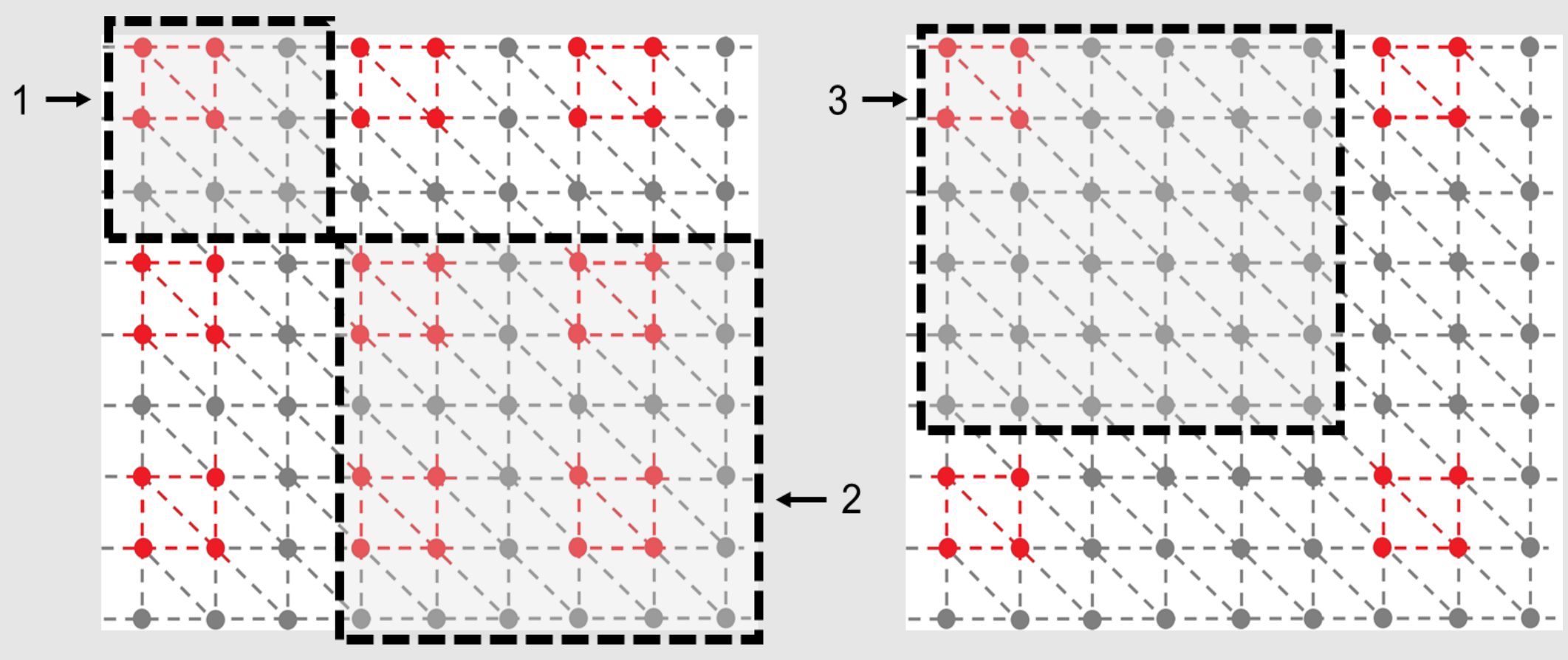


Figure 4: Ganglion distribution across the micromodel. Normalized Euler characteristics remain the same values for both cases.

State functions and thermodynamic process

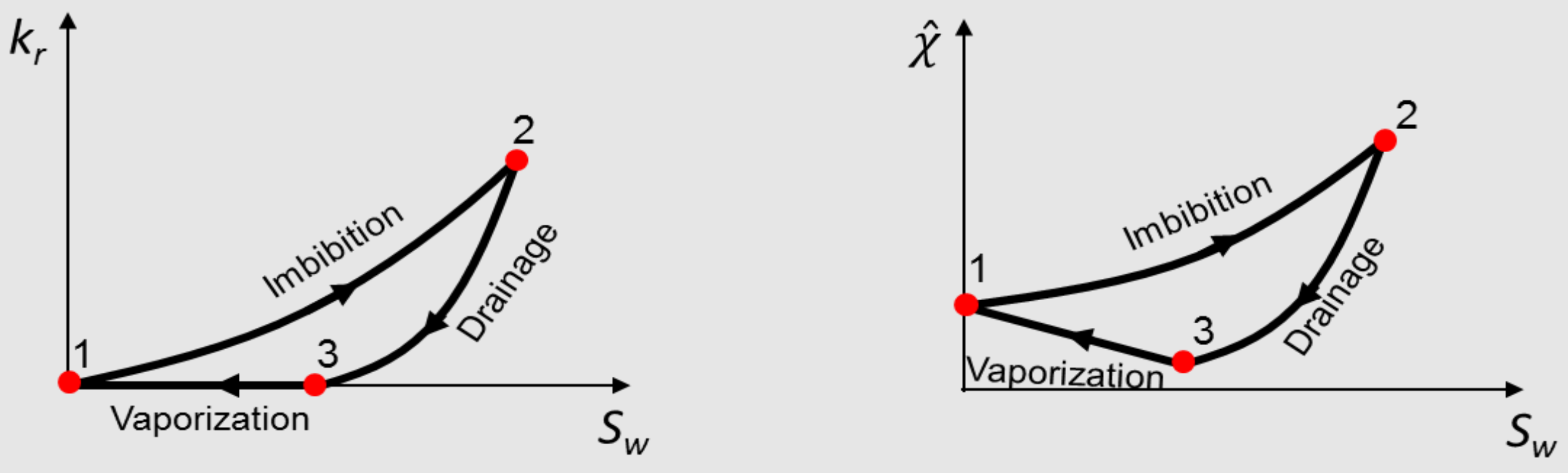


Figure 5: Schematic representation in a water-alternating-gas cycle.

Table 1: Euler characteristic evolution functions

$$\frac{d\hat{\chi}}{dt} = \left.\frac{\partial \hat{\chi}}{\partial S}\right|_{Imbibition}\frac{dS}{dt}, \qquad \frac{\partial \hat{\chi}}{\partial S} = f\left(N_{Ca}, I, \lambda, \hat{\chi}, S\right).$$

	$\frac{\partial S}{\partial t} > 0$	$\frac{\partial S}{\partial t} < 0$
$\frac{\partial \hat{\chi}}{\partial S}$	$\alpha_\chi \frac{\hat{\chi}-1}{S-1}$	$\frac{1}{C_\chi(\hat{\chi}S)^{n_\chi}}$

Tuning procedure:

- Simultaneously include hysteresis, capillary desaturation and relative permeability data.
- Fit to CT-scan measurements and/or initial - residual saturation curves

$$\hat{\chi} = (\hat{\chi}_0 - 1)\left(\frac{S-1}{S_0-1}\right)^{\alpha_\chi} + 1 \qquad \hat{\chi} = \left(\frac{n+1}{C(1-n)}\left(\frac{1}{S^{n+1}} - \frac{1}{S_0^{n+1}}\right) + \hat{\chi}_0^{n+1}\right)^{\frac{1}{n+1}}$$

Implementation in reservoir simulator

The IMPECX scheme is developed to estimate flux between grid blocks and update Euler characteristic.

3 RESULTS AND CONCLUSIONS

1 Euler characteristics tuned to micromodel images

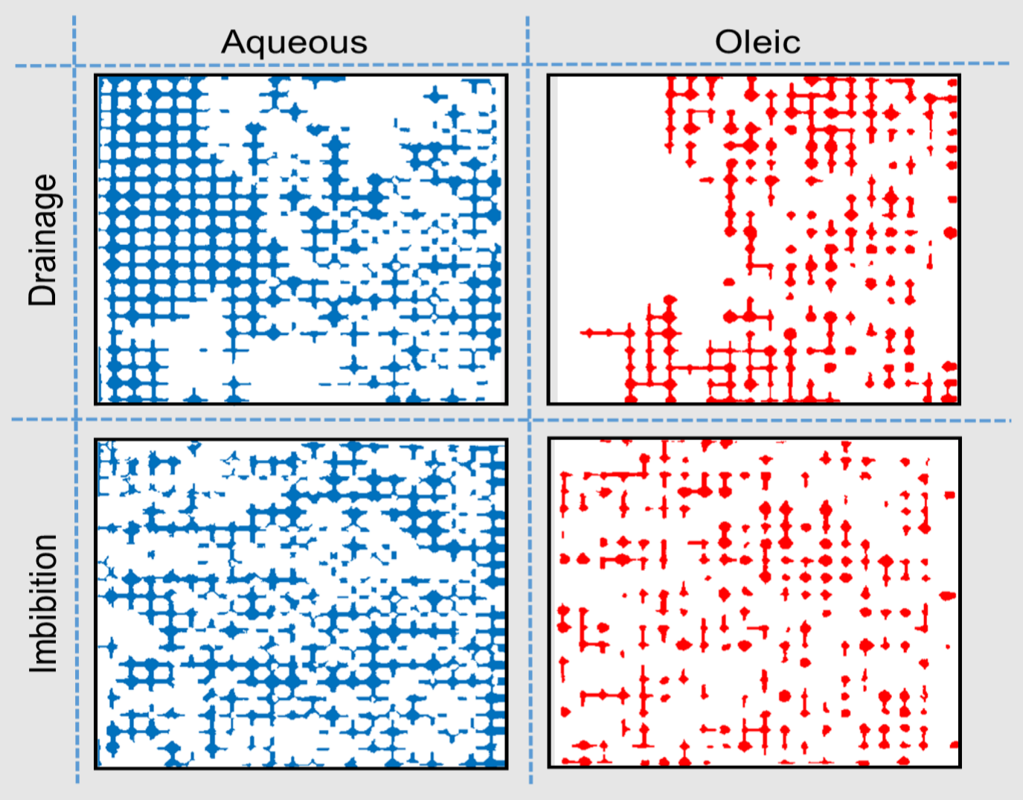
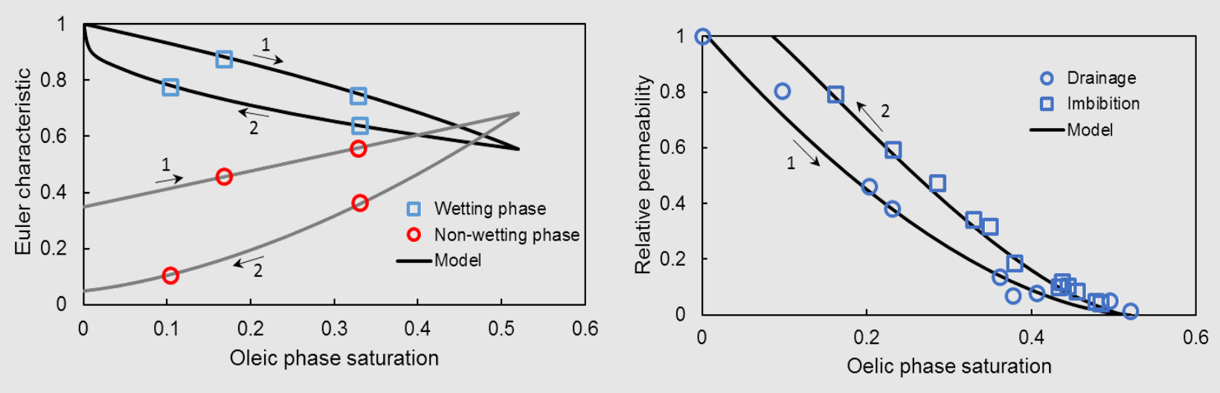


Figure 6: Distribution of oleic and aqueous phase in drainage and imbibition processes



	Euler characteristic			
Phase	α_χ	$\hat{\chi}_0$	C_χ	n_χ
Oleic	0.98	0.35	0.38	-0.29
Aqueous	0.47	1.00	1.51	0.49

	Relative permeability			
Phase	α_Φ	C_k	Φ_r	n_k
Oleic	-	-	-	-
Aqueous	-0.41	5.11	0.26	1.51

Figure 7: Tuned Euler characteristic and relative permeability functions.

2 Euler characteristics tuned to hysteresis data

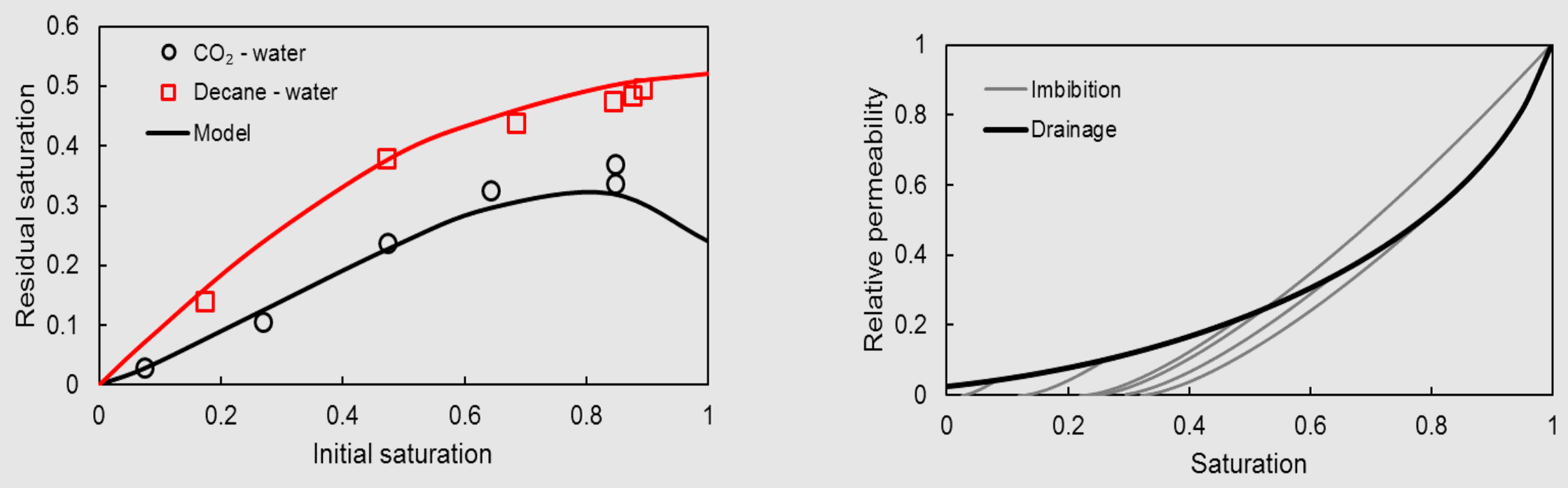


Figure 8: Tuned Euler characteristic and relative permeability functions.

Table 2: Tuned parameters for case2.

	Euler characteristic				Relative permeability			
Experiment	α_χ	$\hat{\chi}_0$	C_χ	n_χ	α_Φ	C_k	Φ_r	n_k
CO_2 - water	1.18	0.30	1.47	1.25	2.56	0.11	0.30	2.00
Decane - water	0.43	0.30	1.52	0.39	2.56	0.11	0.30	2.00

3 Two-phase three-component miscible flood

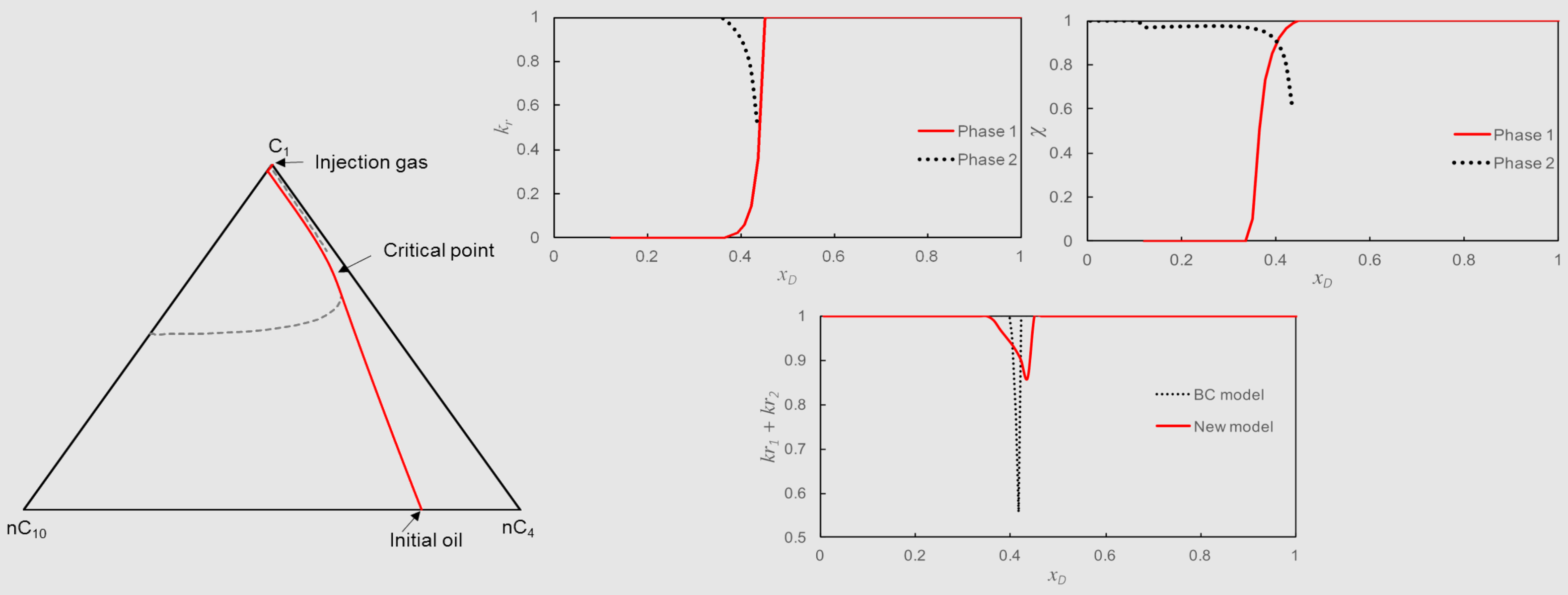


Figure 9: One-dimensional simulations: new EoS model avoids the unphysical discontinuities of conventional relative permeability models.

Conclusions

We developed a framework for modeling relative permeabilities as a function the phase state in porous media, where effects of wettability, hysteresis, and compositional variations are incorporated.

- Phase relative permeabilities are independent of labeling and saturation paths.
- Impact of phase compositions on relative permeabilities was implemented by modelling phase wettability and interfacial tensions compositionally.
- Hysteresis effects on relative permeability model were added by defining the phase distributions and phase connectivity.
- The model only requires a few tuning parameters.

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