UNCONVENTIONAL RESERVOIR ENGINEERING PROJECT
Colorado School of Mines

UREP

CSM

Summary and Background

PHASE BEHAVIOR IN NANOPOROUS MEDIA

- UREP Research Tasks on Phase Behavior
- Status of Tasks (with more details on T4 and T5)
- Vision for Integration
- Publications

UREP research tasks on phase behavior

PROJECT 1 Flow and Transport of Hydrocarbon Fluids in Nano-Porous Reservoirs	Phase 3 Tasks	
	1. Understand trends in field data	Have not received any data to date
	2. Dew-point measurements in nanofluidic chips and comparison with models	Asm Kamrruzaman (PhD) *Measurement of condensation in nanofluidics* (Tasks 2–3)
	3. Effect of temperature on experiments	
	4. Core measurements	Keerthana Krishnan (MS) *Capillary condensation in Niobrara*
	5. Upscaling experimental results	Ran Gao (visiting student) *Three-phase equilibrium models*
	6. Molecular simulations	Yakup Coskuner (MS)

Research tasks on phase behavior (T2 & T3)

T2 – Sponsored by DOE STTR – Kaia Corp.

- Phase behavior of C_3 in nanofluidics
- Comparison with Kelvin equation (had difficulties in matching)
- Measure pressure change in the vicinity of phase change

T3 – Asm Kamrruzaman

- Repeat previous C_3 experiments
- Design pressure / temperature enclosures
- Conduct nanofluidic experiments at different temperatures
- Experiments with mixtures and compare with model

Green = Completed; Yellow = Current; White = Planned

Research tasks on phase behavior (T4)

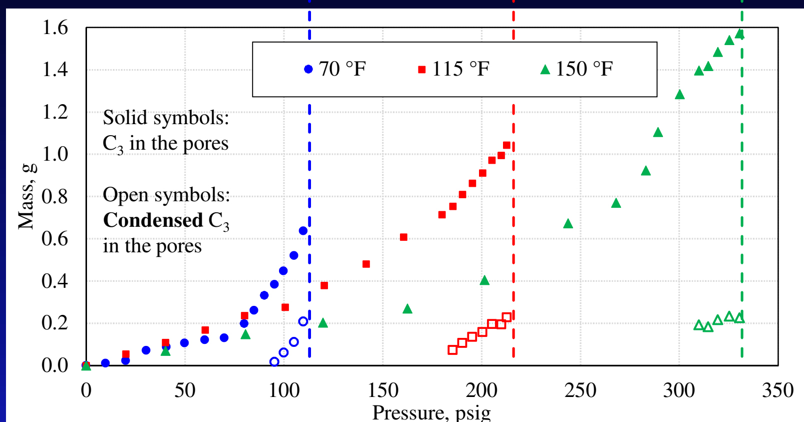
T4 – Keerthana Krishnan

- Capillary condensation of C_3 in Niobrara
- Capillary condensation of C_3 in synthetic nanopores
- Other rocks
- Other gas or gas mixtures
- Effect of water
- Effect of crushing
- Compare with upscaled models (T5 – core level)

Research tasks on phase behavior (T4)

T4 – Main results

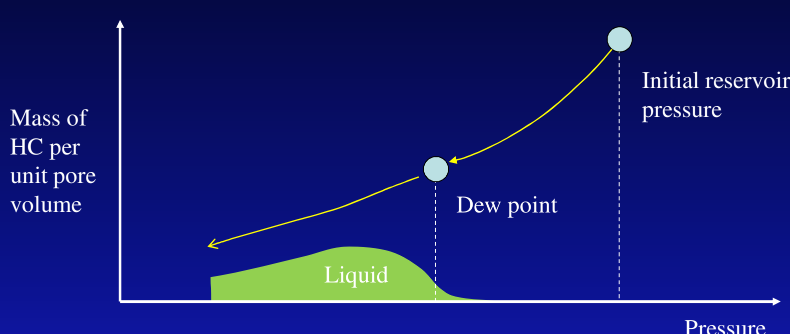
Capillary condensation of C_3 in Niobrara



Research tasks on phase behavior (T4)

Plan for T4

Experimentation and model for HC in place that accounts for the effect of capillary condensation for condensate reservoirs



Research tasks on phase behavior (T5)

T5

Vapor-liquid phase behavior in a <u>single pore</u>

Vapor-liquid phase behavior in <u>multiple pores</u> (pore size distribution)

General multi-phase (≥ 3) equilibrium
- Model constructed and validated using data from literature
- CO_2-oil-water and C_2-oil-water phase behavior measured
- Writing papers …

Vapor-liquid-adsorption phase behavior

Upscale to the *<u>core</u>* level, considering equilibrium among pores of different sizes but no variation in pressure and temperature

Coz-Sim

Upscale to the *<u>reservoir</u>* level, considering pressure variations due to flow, and explain and predict field data (T1)

T5 – Main results

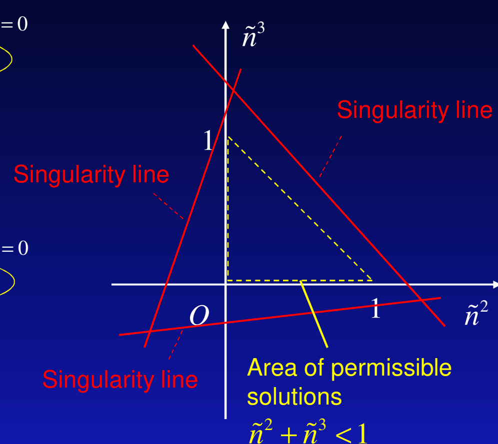
3-Phase equilibrium equations (Rachford-Rice)

$$\sum_{i=1}^{n_c}\frac{(1-K_i^{12})z_i}{K_i^{12}+\left(1-K_i^{12}\right)\tilde{n}^2-K_i^{12}\left(1-\frac{1}{K_i^{13}}\right)\tilde{n}^3}=0$$

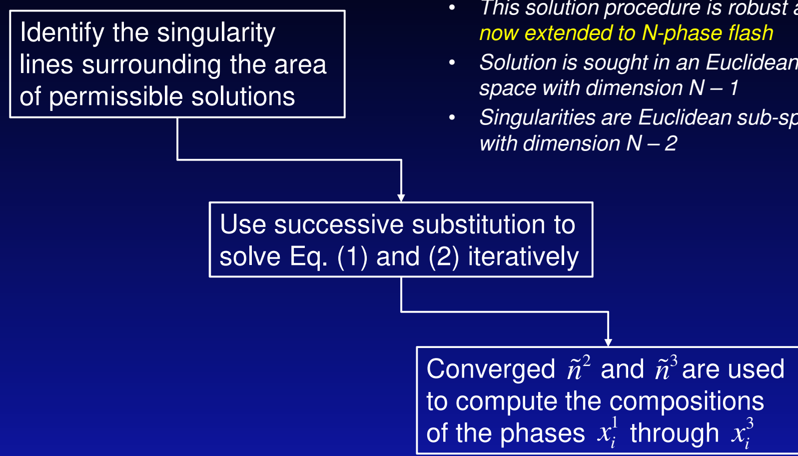
Condition that the denominator = 0 gives a set of lines on which ① → ± ∞

$$\sum_{i=1}^{n_c}\frac{(1-K_i^{13})z_i}{K_i^{13}+\left(1-K_i^{13}\right)\tilde{n}^3-K_i^{13}\left(1-\frac{1}{K_i^{12}}\right)\tilde{n}^2}=0$$

Eq. ② also has a set of singularity lines

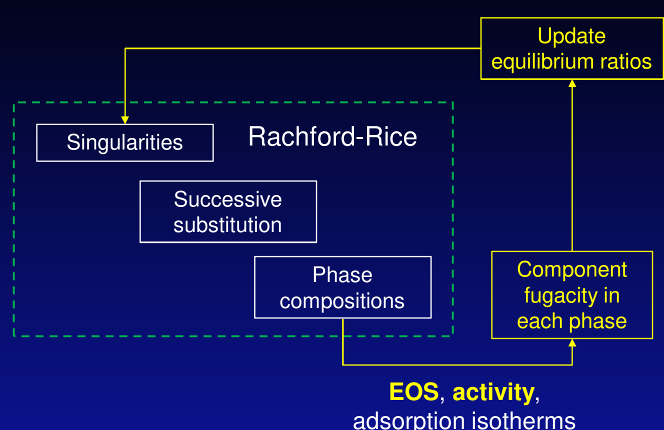


Solution procedure of multiphase equilibrium



- *This solution procedure is robust and is now extended to N-phase flash*
- *Solution is sought in an Euclidean space with dimension N – 1*
- *Singularities are Euclidean sub-spaces with dimension N – 2*

Incorporation of fugacity models



Work completed

- EOS and activity models have been implemented
- Gas-oil phase behavior with water can now be done

3-Phase PVT measurements for verification

Gas: CO_2, C_2H_6
Liquid: Niobrara Oil, DI water
Temperature = 215 F

Fluids	Bubble point
90% oil + 10% CO_2	336 psig
90% oil + 10% C_2H_6	146 psig
0.2*(0.9*oil + 0.1*CO_2) + 0.8*water	182 psig
0.2*(0.9*oil + 0.1*C_2H_6) + 0.8*water	165 psig

- C_2H_6 is easier to dissolve in oil than CO_2
- Water affects phase behavior of gas-oil systems
- CO_2-oil system was affected more than C_2H_6-oil system

Research tasks on phase behavior (T6 & T1)

T6

Characterize bulk phase behavior of a pure substance
Characterize confined phase behavior of a pure substance
Characterize confined phase behavior of mixtures
Compare with model (T5 - pore) and experiments (T2 and T3)

T1

Acquire and analyze field data
Use Coz-Sim to simulate field cases and compare (T5 – reservoir)

Green = Completed; Yellow = Current; White = Planned

Phase behavior in nanopores – integration

- Molecular simulations
  - Molecular scale
  - Inter-molecular interactions

  T6

- Fluid property models
  - Density correlations
  - Phase transitions
  - Equilibrium across many pores

  T5

- Reservoir engineering tools
  - Reserve estimation
  - Understand decline
  - Reservoir simulation

  T1

- Nanofluidic experiments
  - Pore scale
  - Direct observations

  T2, T3

- Core experiments
  - Verification of predictions

  T4

Phase behavior in nanopores – publications

T1
- Firingioglu et al. SPE 166459, 2013

T2 & T3
- Parsa et al. SPE 175118, 2015

T4
- Larson et al. *Measurement Sci. Tech.* (2017), 28:065902
- Cho et al. on capillary condensation in Niobrara – under preparation

T5
- Firingioglu et al. SPE 159869, 2012
- Teklu et al. *SPE Res. Eval. Eng.* (2014), 17:396
- Wang et al. *SPE J.* (2016), 21:1981
- Gao and Yin on modeling of multi-phase equilibrium – under preparation
- Gao et al. on PVT of gas-oil-water phase equilibrium – under preparation

T6
- Coskuner et al. SPE 187163, 2017