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Research Summary

Experimental Study and Modeling of the Effect of Pore Size Distribution on Phase Behavior in Nanopores

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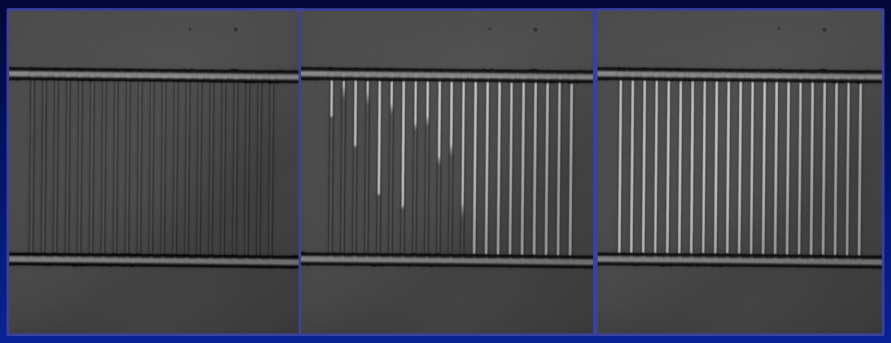
Presentation outline

- Recapitulation of last report
- Motivation and objective
- Depressurization of a light oil (Eagle Ford)
- Depressurization of a retrograde gas (Synthetic)
- Conclusion

Recapitulation: Evaporation of n-pentane

Evaporation of nC5 in micro- & nanochannels at ~20℃ (68˚F).



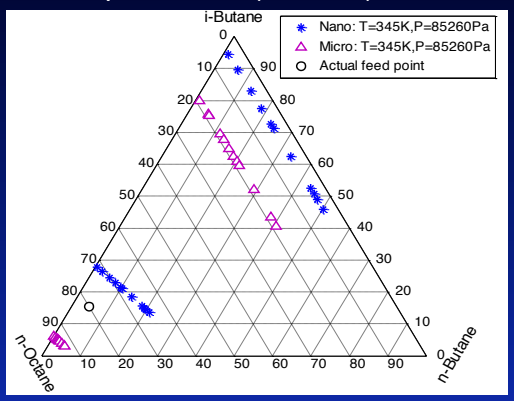
Nanochannels Filled with Liquid | Partially vaporized | Completely vaporized.

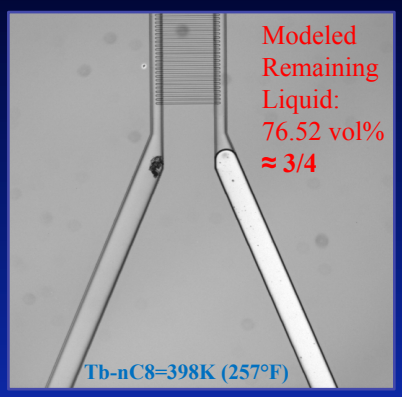
3 consecutive images taken at 0.05 s interval. $Tb_{pentane}$ = 36℃ (97˚F).

N-Pentane in microchannels evaporated first, and then nanochannels; Evaporation in both micro- and nanochannels is very rapid.

Recapitulation: Evaporation of a ternary mixture

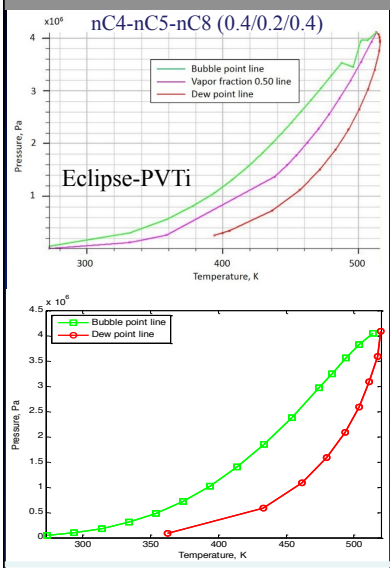
Experimental condition: nC4 (0.155), iC4 (0.045), nC8 (0.80), 12.4 psia, 345K (161.3°F)



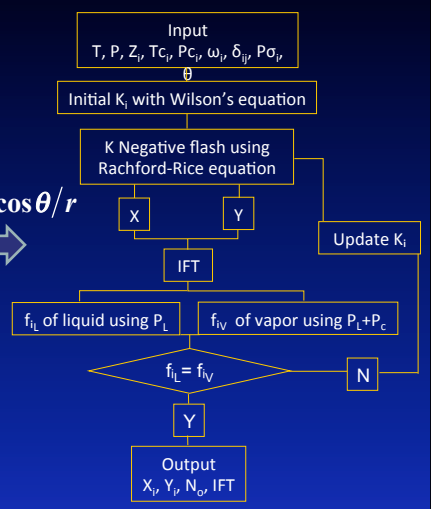


Evaporation first took place in big channel, then slowed down and stopped. Remaining liquid became heavier after light components left.

Recapitulation: Validation of flash calculation



$$p_c = 2IFT\cos\theta / r$$



Sigmund et al., 1973; Brusilovsky, 1992; Shapiro and Stenby 2001

Recapitulation: Summary

When the pressure of an oil-saturated porous medium is reduced

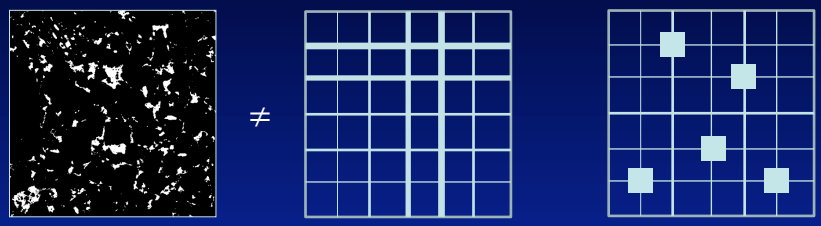
a) Vapor phase first appears in the large pores (pore bodies)

b) Vaporization increases the weight of the remaining liquid phase

Pore size distribution, sequence of vaporization, and the compositional change must be simultaneously considered to predict the state of phases in pores of given sizes.

Motivation and objective

- Existing phase behavior models only use a single pore size, effect of pore size distribution hasn't been investigated.
- Pore connectivity is complex in real rocks.



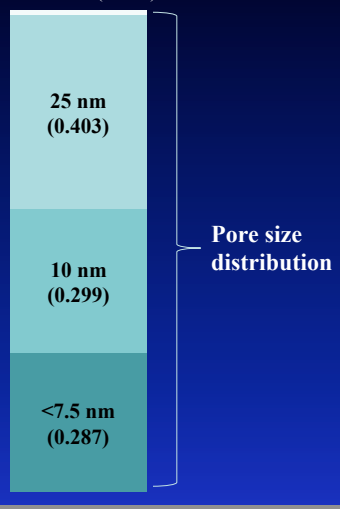
Conceptual model that considers pore connectivity and critical gas saturation (CGS)

Objective:

- Model Differential Expansion (DE) of a light oil with CGS and DE of a retrograde gas in porous media with pore size distributions.

Porous medium and light oil

(Courtesy of Dr. Honarpour.)



Fluid composition – a light oil (Eagle Ford)
Liquid Specific Gravity = 0.551
Liquid Viscosity = 0.103 cp
Solution GOR = 1006 scf/STB

- N_2 0.007
- CO_2 0.023
- C1 0.330
- C2 0.050
- C3 0.053
- iC4 0.060
- nC4 0.067
- iC5 0.070
- nC5 0.080
- nC6 0.110
- C13 0.150

Formation temperature = 189 °F

Pb with no confinement = 1820 psia

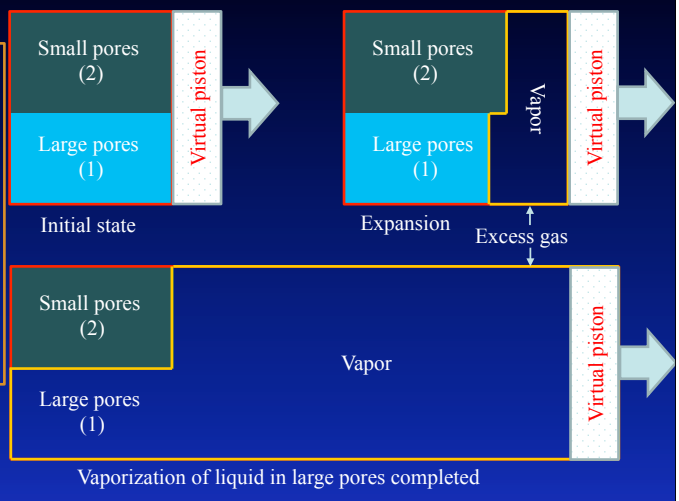
IFT @ Pb = 1.91 mN/m

(Gong et al. 2013)

Constant composition expansion (CCE) of light oil

Assumptions:

- All pores are inter-connected
- All pores have direct access to the outside
- Gas can leave the porous medium
- Liquid remains imbibed
- Contact angle = 45°

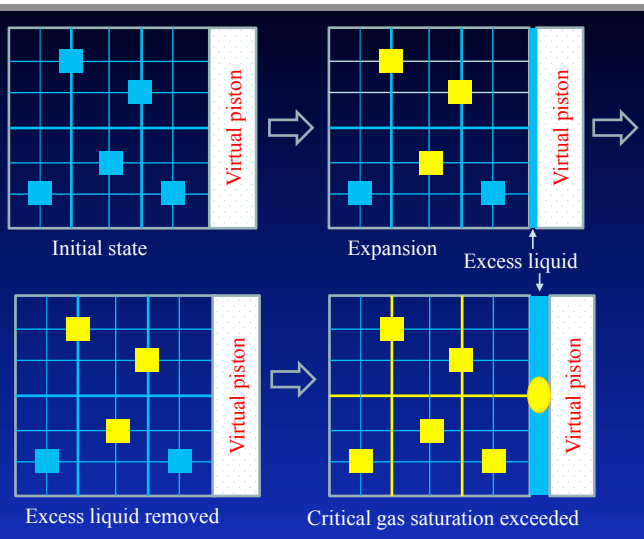


DE of light oil with CGS

Assumptions:

- All pores are inter-connected
- Contact angle = 45°
- Larger pores (pore bodies) are connected to each other and to the outside through smaller pores (pore throats= 10nm)

Yellow: gas; Blue: oil



Firoozabadi et al., 1992; Kamath and Boyer, 1995

DE of light oil with CGS--Results

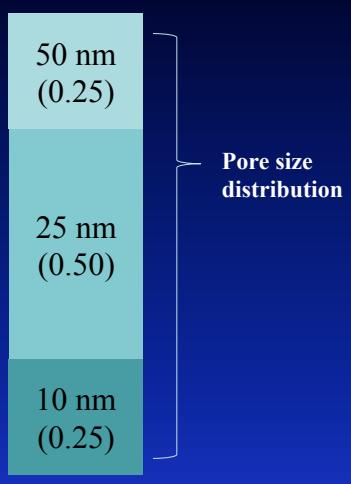
	CCE	DE with CGS
Pressure when liquid in 50nm pores is vaporized (1.1vol%)	**1781 psia**	**1810 psia**
Expansion ratio	**1.018**	**1.007**
Fluid in the excess volume	Gas	Liquid
Liquid specific gravity	0.554	0.552
Liquid viscosity	0.104 cp	0.103 cp
IFT	2.09 mN/m	2.00 mN/m
Pressure when liquid in 25nm pores is vaporized (40.3vol%)	**193 psia**	**1300 psia**
Expansion ratio	**11.37**	**1.295**
Fluid in the excess volume	Gas	Liquid
Liquid specific gravity	0.658	0.580
Liquid viscosity	0.190 cp	0.120 cp
IFT	11.60 mN/m	3.90 mN/m

DE improves liquid properties.

In CCE, liquid in pores <10 nm cannot vaporize because of much heavier composition.

In DE, vapor phase breaks through liquid in pores < 10nm.

Porous medium and retrograde gas



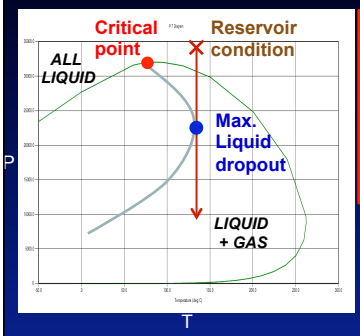
Composition – a model retrograde gas
Gas Specific Gravity = 1.14
Gas Viscosity = 0.0565 cp

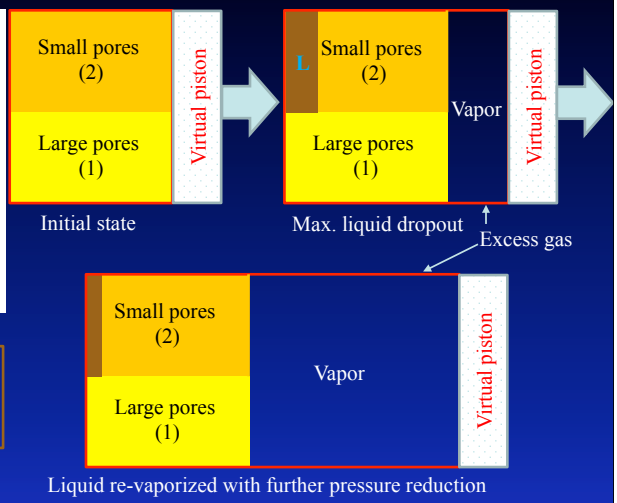
- N_2 0.005
- CO_2 0.023
- C1 0.731
- C2 0.089
- C3 0.036
- iC4 0.007
- nC4 0.012
- iC5 0.006
- nC5 0.007
- nC6 0.011
- C7+ 0.072

Formation temperature = 221 °F

Pd with no confinement = 5584 psia

CCE of retrograde gas with capillary pressure





Assumptions are the same as those for CCE of light oil except:

- Contact angle = 60°

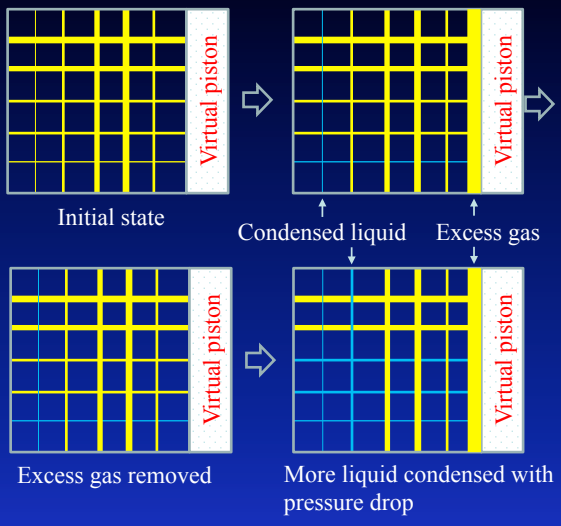
DE of retrograde gas with gas liberation

Assumptions:

- **All pores are inter-connected and have access to the outside**
- **Gas can leave the porous medium, liquid remains imbibed**
- **Contact angle = 60°**

Yellow: gas;

Blue: condensate



DE of retrograde gas with gas liberation--Results

	CCE	DE with gas liberation
Pressure when 10nm pores are filled with liquid	**5440 psia**	**5440 psia**
Expansion ratio	**1.013**	**1.013**
Gas specific gravity / viscosity	1.06 / 0.050 cp	1.06 / 0.050 cp
Liquid specific gravity / viscosity	0.447 / 0.065 cp	0.447 / 0.065 cp
IFT	0.001 mN/m	0.001 mN/m
Pressure when liquid saturation reaches maximum	**4630 psia**	**4702 psia**
Expansion ratio	**1.117**	**1.091**
Maximum liquid saturation	**32.55%**	**32.23%**
Gas specific gravity / viscosity	0.88 / 0.034 cp	0.89 / 0.035 cp
Liquid specific gravity / viscosity	0.519 / 0.090 cp	0.514 / 0.088 cp
IFT	0.112 mN/m	0.093 mN/m

No difference here.

Removal of gas slightly reduced maximum liquid saturation, liquid gravity/viscosity and IFT.

DE of retrograde gas with gas liberation--Results

	CCE	Differential Expansion
Pressure when liquid in 25nm pores is re-vaporized	**2022 psia**	**2022 psia**
Expansion ratio	**2.22**	**2.00**
Gas specific gravity / viscosity	0.73 / 0.017 cp	0.73 / 0.017 cp
Liquid specific gravity / viscosity	0.630 / 0.162 cp	0.630 / 0.162 cp
IFT	3.66 mN/m	3.66 mN/m

- **Whether gas is removed or not makes little difference in the subsequent revaporization.**
- **When the pressure is reduced to ~2000 psia, the liquid-gas contrast becomes similar to the previously studied light oil situation.**
- **Liquid in < 10nm pores will be difficult to re-vaporize by further expansion.**

Conclusions

- Nanofluidics experiments showed that, vaporization follows the sequence dictated by pore size distribution, and the composition of remaining fluid changes as the vaporization proceeds, which was predicted by the modified flash calculation.
- For light oil, critical gas saturation & pore connectivity have significant effect on the point of phase transition in pores of different sizes.
- For retrograde gas, capillary pressure does not play a significant role due to the very low IFT (for our particular pore size distribution)
- Considering the composition change during depressurization, for both reservoir fluids, the smallest pores will probably always be filled with liquid.

Acknowledgement

Thank you all UREP sponsors!