Thermodynamics of Multiphase Flow in Unconventional Liquids-Rich Reservoirs

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Problem Statement

Classical Thermodynamics

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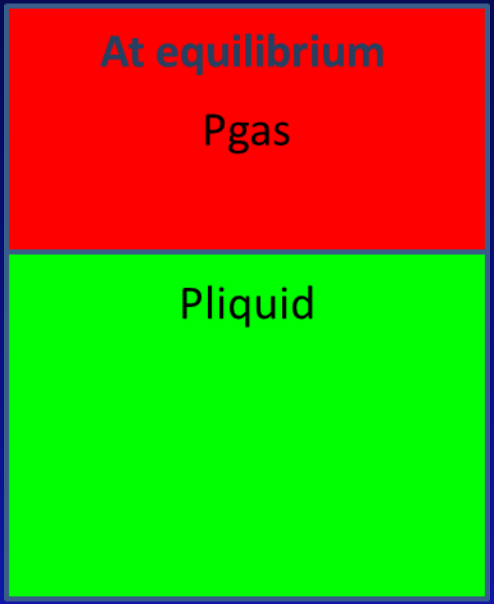
- Industry norm is to use EOS or PVT tables
- PVT behavior from PVT cells ignoring
  - capillary pressure
  - surface forces

Problem Statement

Classical Thermodynamics

Gas phase appears at bubble-point pressure

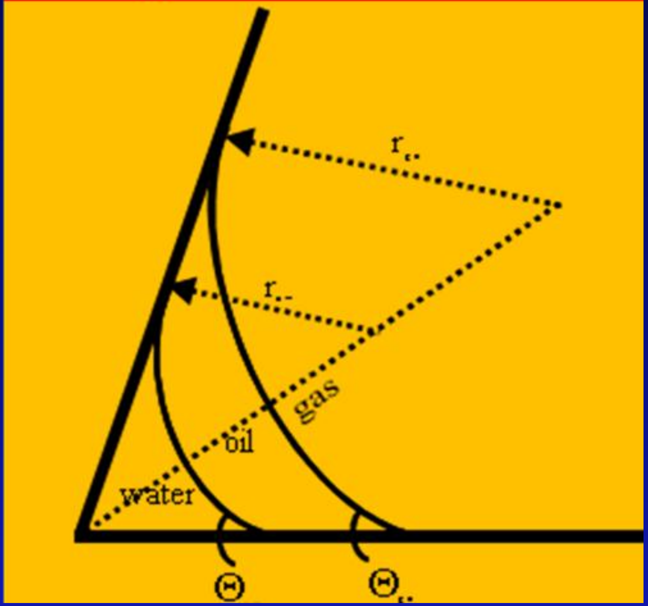


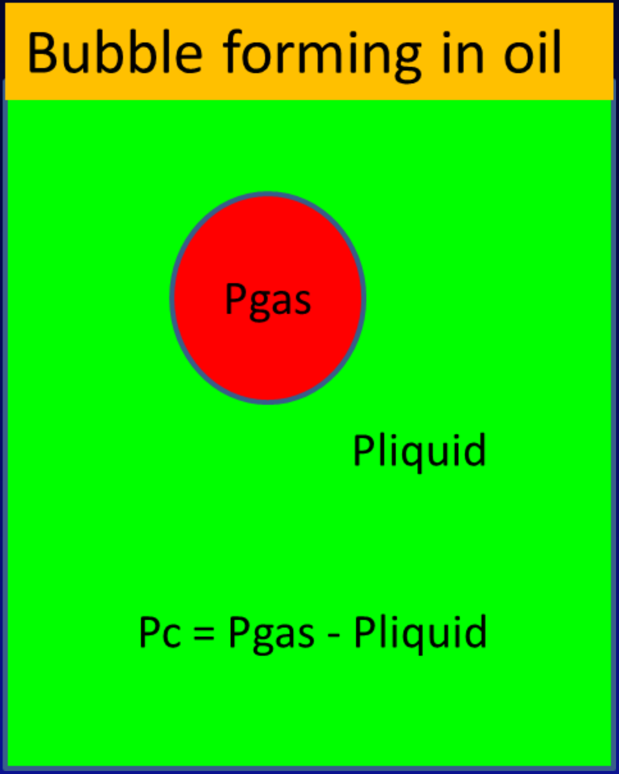
Problem Statement

Confined Environment

The interfaces are curved

Fluids located at the crevices of the pore





Bubble forming in oil

Pgas

Pliquid

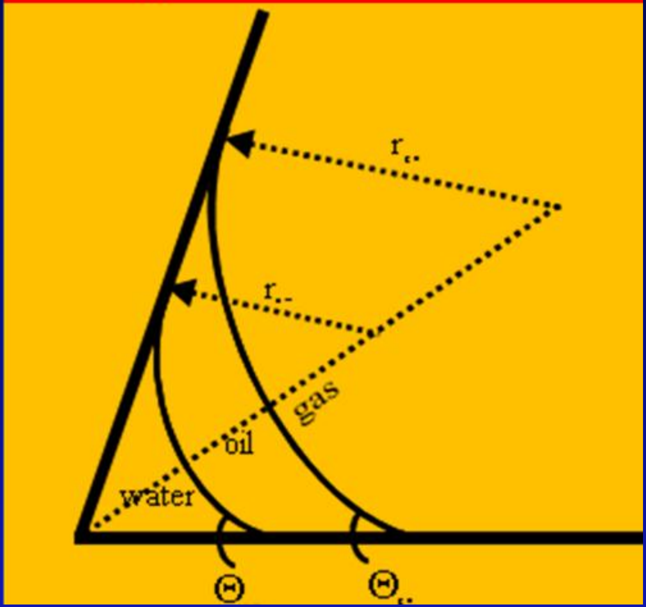
Pc = Pgas - Pliquid

Problem Statement

Confined Environment

Capillary forces, surface forces should not be neglected

Fluids located at the crevices of the pore

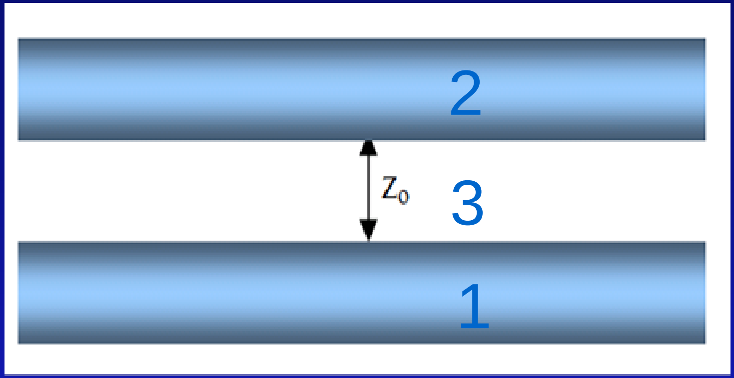


Problem Statement

Capillary Pressure (Laplace Equation)

$$P_g - P_L = \frac{2\sigma}{r}$$

Addition of surface forces



$$P_G - P_L = \frac{2\sigma}{R} + \Pi$$

$$\Pi = -\frac{A_{132}}{6\pi z_o^3}$$

Problem Statement

Confined Environment

- Extra energy cost due to these forces should be included in phase behavior calculations
- Small pores – impact can be significant

Approach

Phase Equilibrium is reached at different liquid and gas pressures

Altered VLE

Altered bubble point pressure

Approach

In this study the impact of confinement manifests itself as:

- reduction (suppression) of the saturation pressure
- changes in the gas composition at the bubble point
- extension of the Bo curve

Approach

PR EOS was used for solution

EOS parameters for the fluid samples were determined through regression to lab measurements

Approach

Since P_l and P_g are not equal,

VLE was solved for two pressures for the two phases

K value definition is modified and K_c definition is used

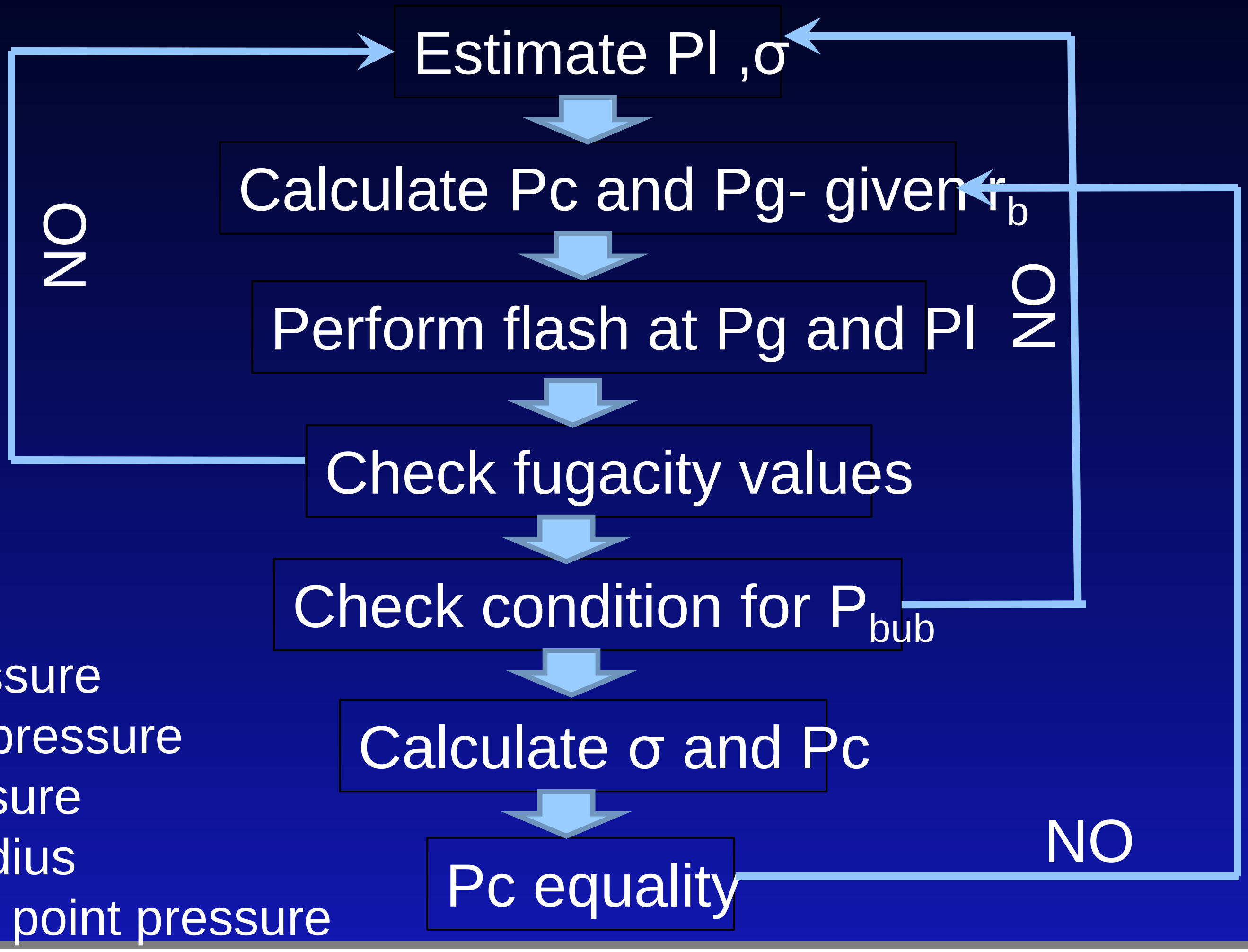
Approach

$$\mathrm{K_{ci}} = \mathrm{K_i}\,\frac{p_l}{p_g}$$

where

$$K_i = \frac{\left[\frac{f_i^L}{x_i P_l}\right]}{\left[\frac{f_i^v}{y_i P_g}\right]} = \frac{\emptyset_i^L}{\emptyset_i^v}$$

Approach



Estimate Pl ,σ

Calculate Pc and Pg- given r_b

Perform flash at Pg and Pl

Check fugacity values

Check condition for P_{bub}

Calculate σ and Pc

Pc equality

NO

NO

NO

Pl:liquid pressure
Pc:capillary pressure
Pg:gas pressure
rb:bubble radius
Pbub:bubble point pressure

Results/Status

Application to three samples from unconventional reservoirs

Sample 1: Monterey
Sample 2: Bakken
Sample 3: Eagle Ford

Results/Status

Impact of Surface Forces

$$P_G - P_L = \frac{2\sigma}{R} + \Pi$$

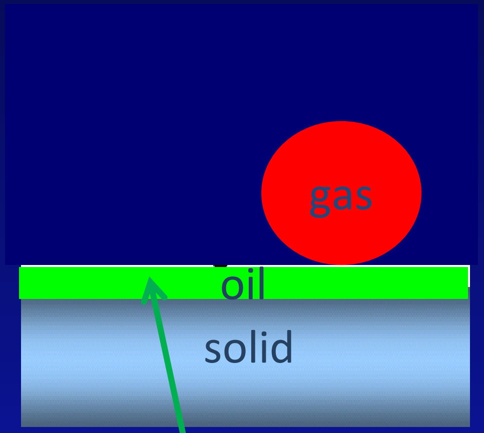
$$\Pi = -\frac{A_{132}}{6\pi z_o^3}$$

Hamaker constant (A) is a function of refractive indexes and dielectric constants of the fluids and the surfaces involved

Literature values of oil, gas and dolomite were used in calculations

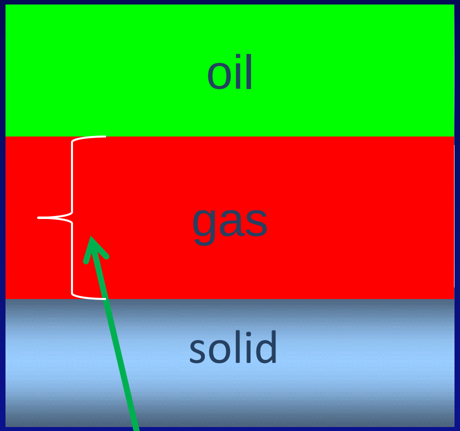
Impact of Surface Forces

Particle close to a surface



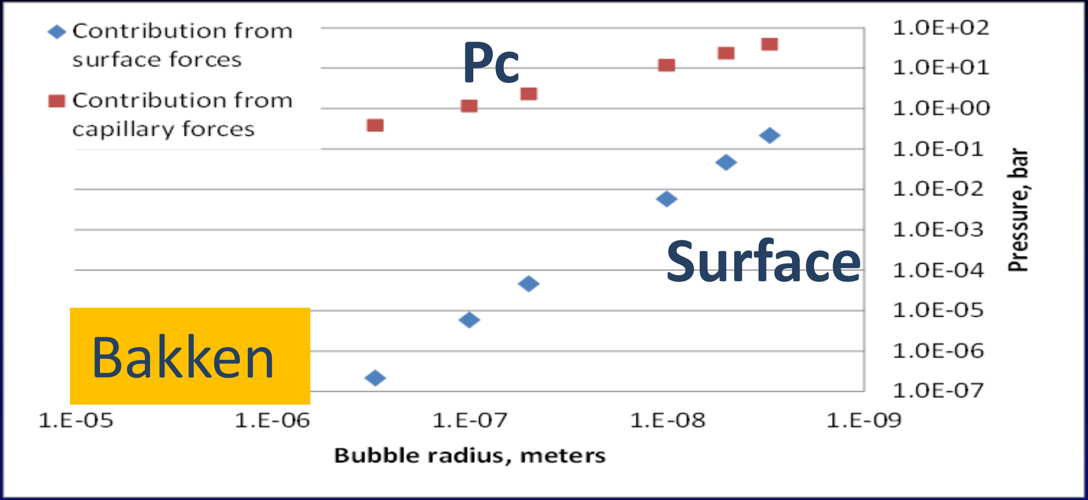
separation dist. = 4°A

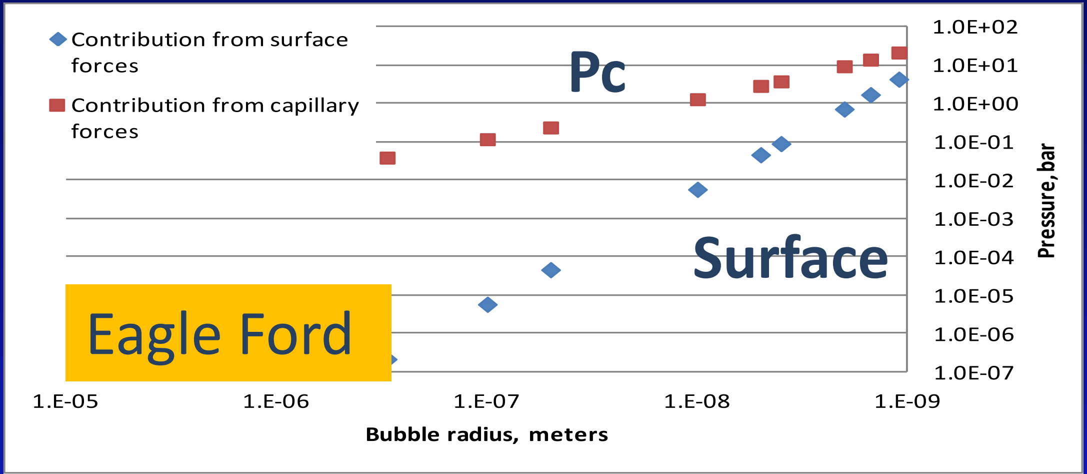
Slit pore geometry



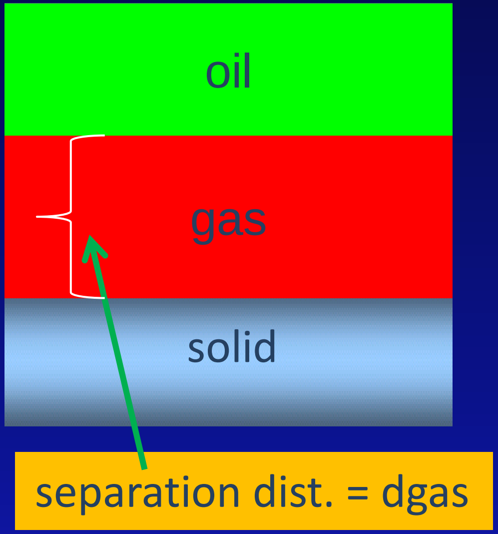
separation dist. = dgas

Impact of Surface Forces

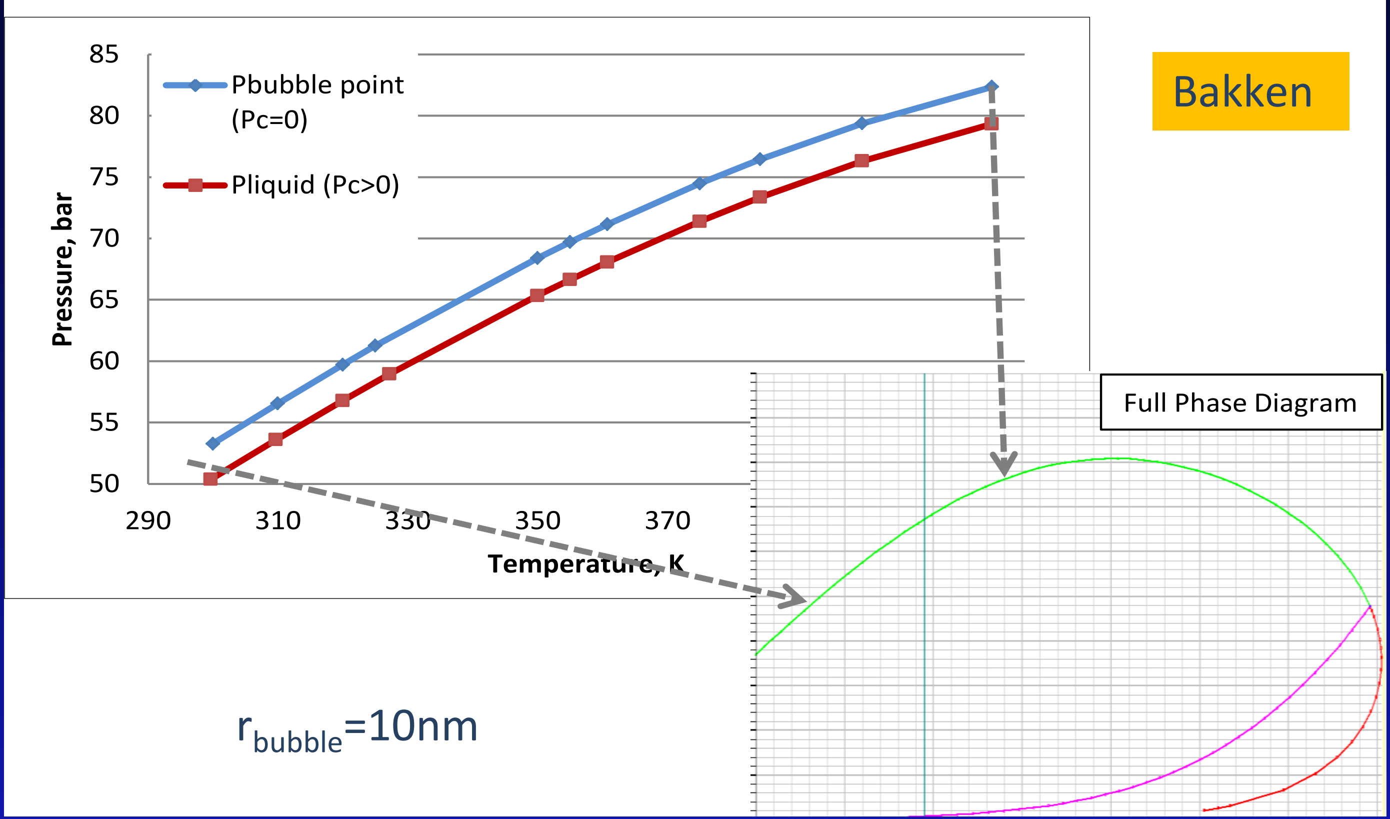




Slit pore geometry



Phase Diagram Shift and Bubble Point Suppression

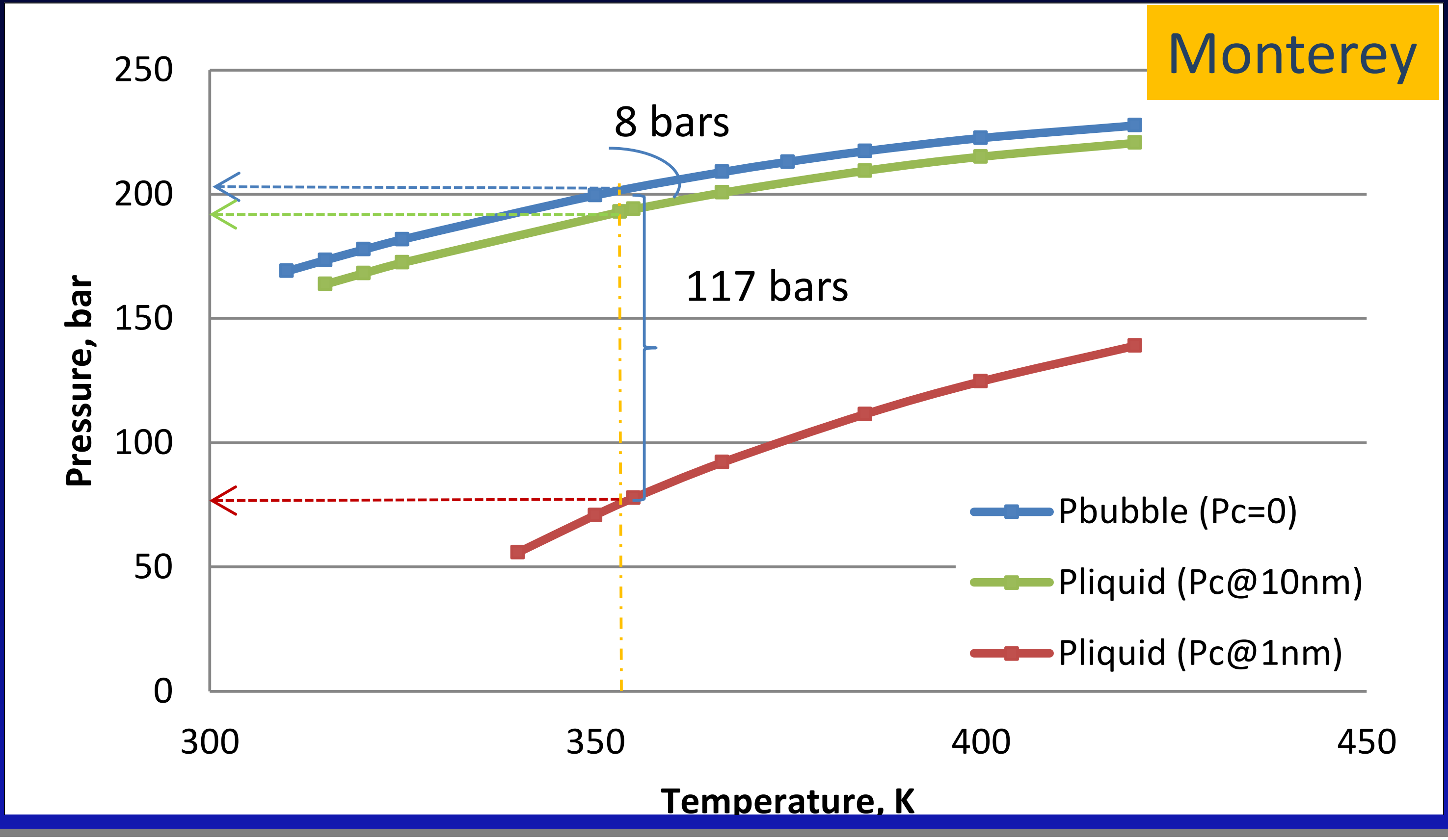


Bakken

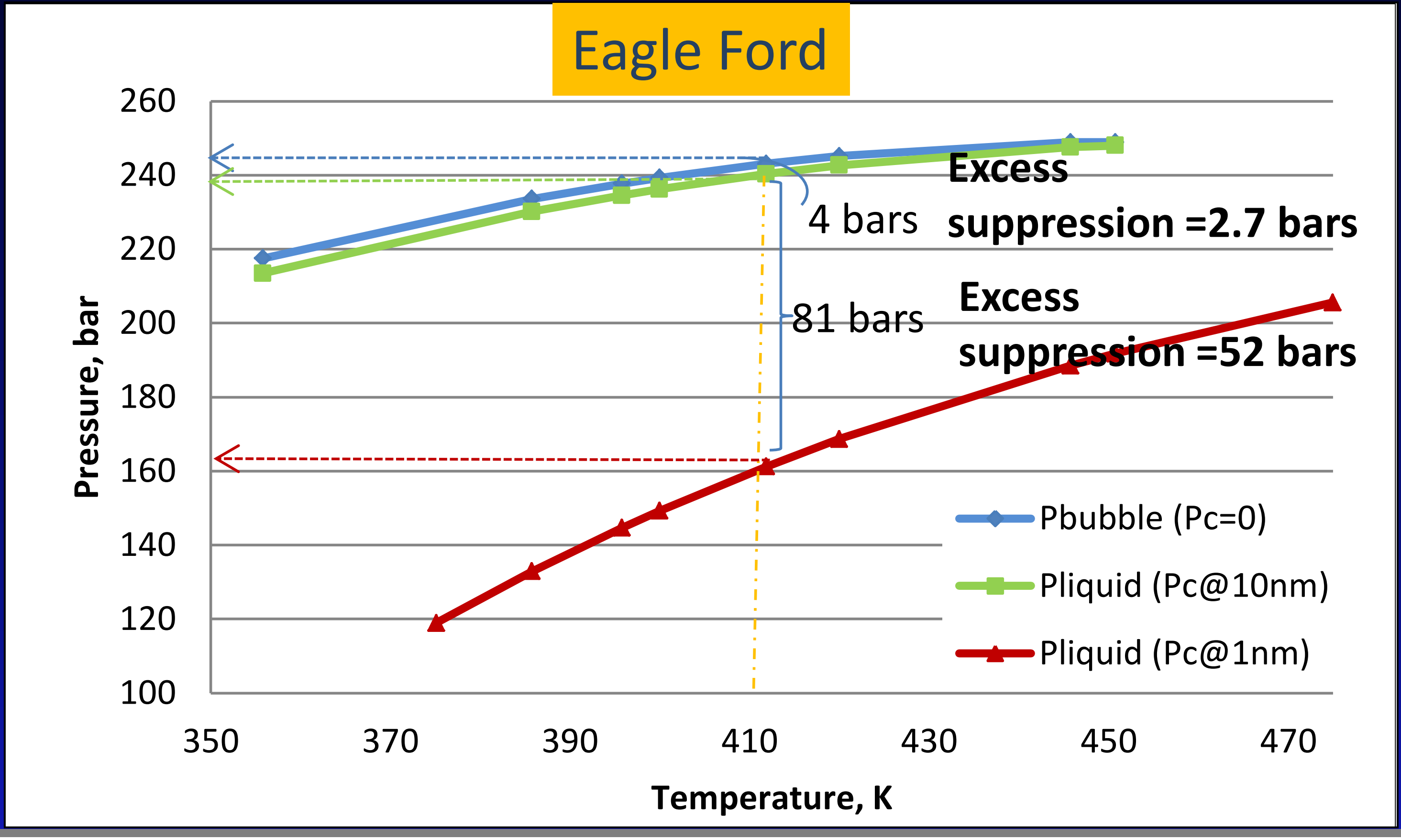
r_{bubble}=10nm

Results/Status

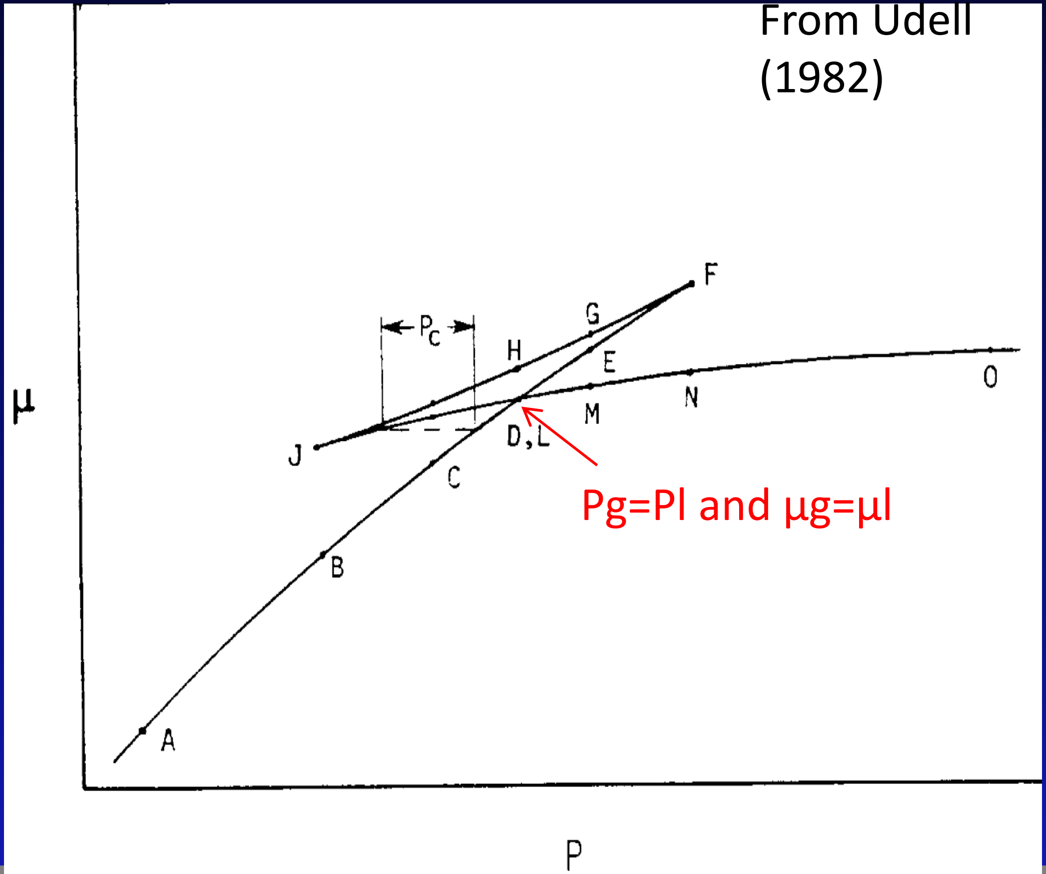
Phase Diagram Shift and Bubble Point Suppression



Phase Diagram Shift and Bubble Point Suppression



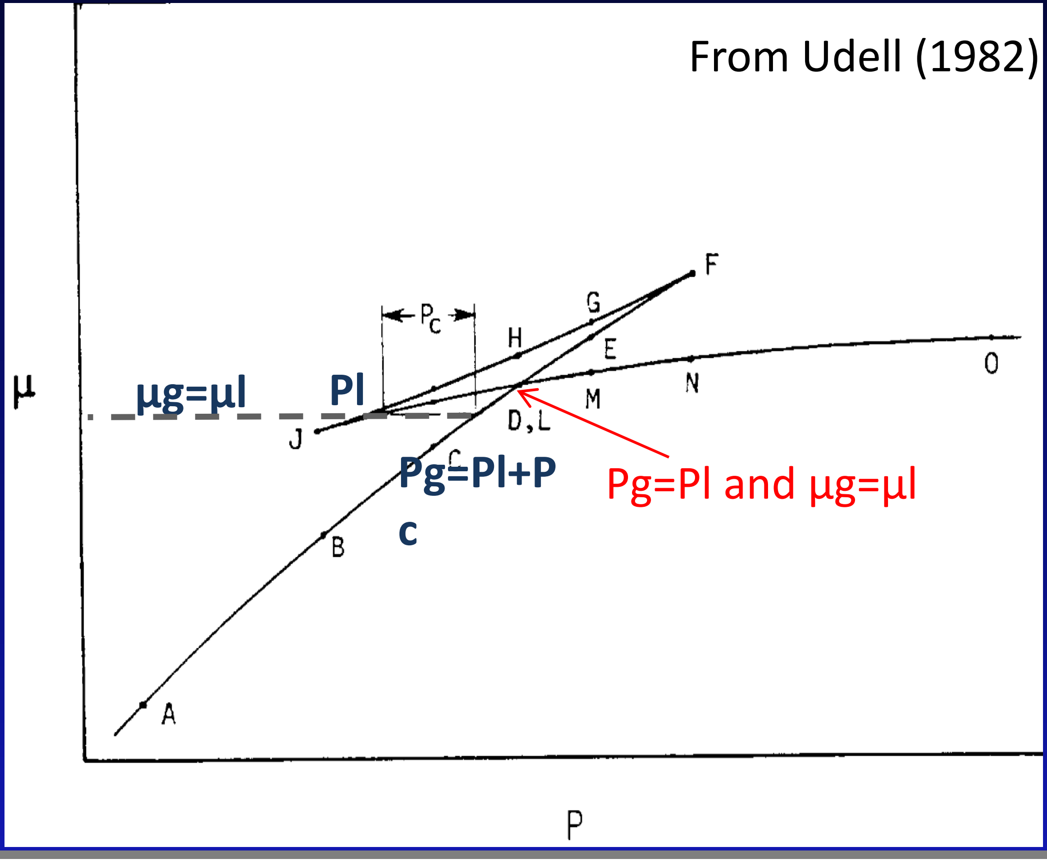
Phase Diagram Shift and Bubble Point Suppression



From Udell (1982)

Pg=Pl and μg=μl

Phase Diagram Shift and Bubble Point Suppression



From Udell (1982)

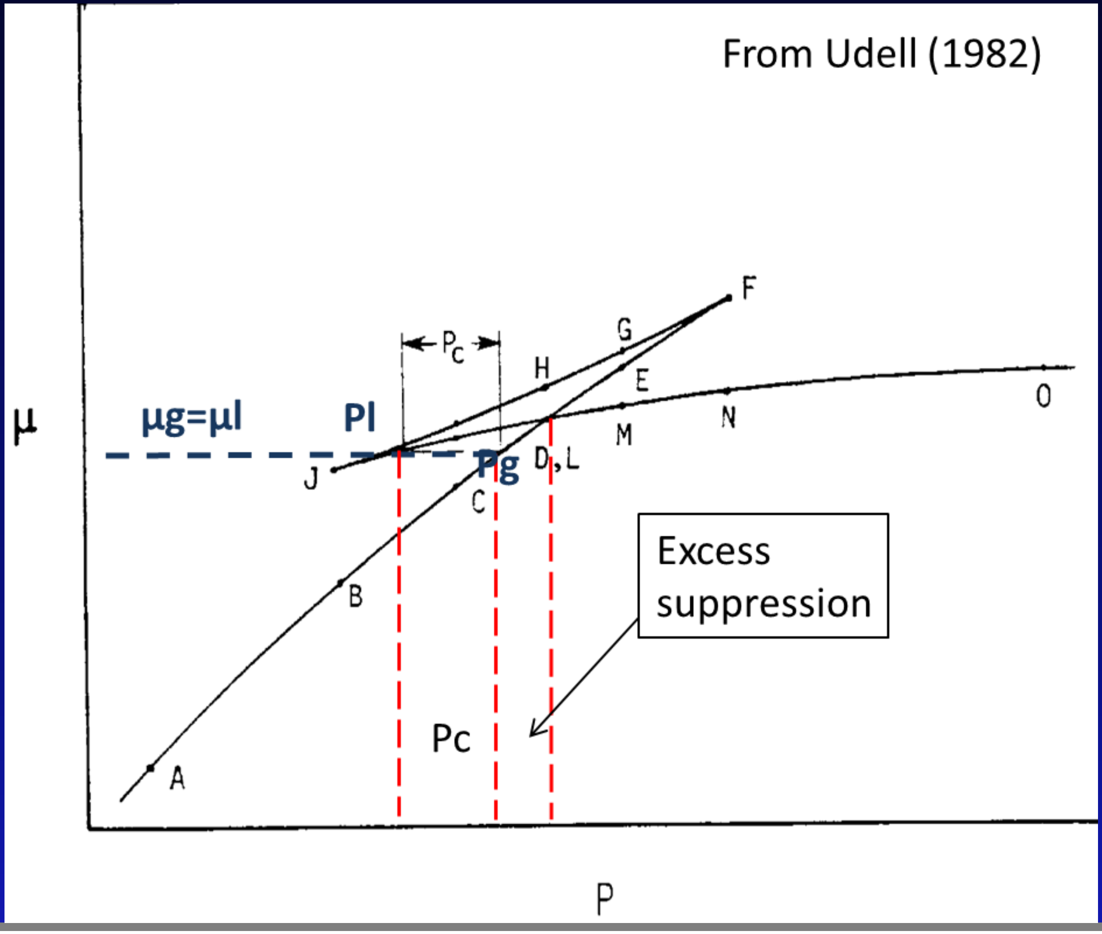
μg=μl

Pl

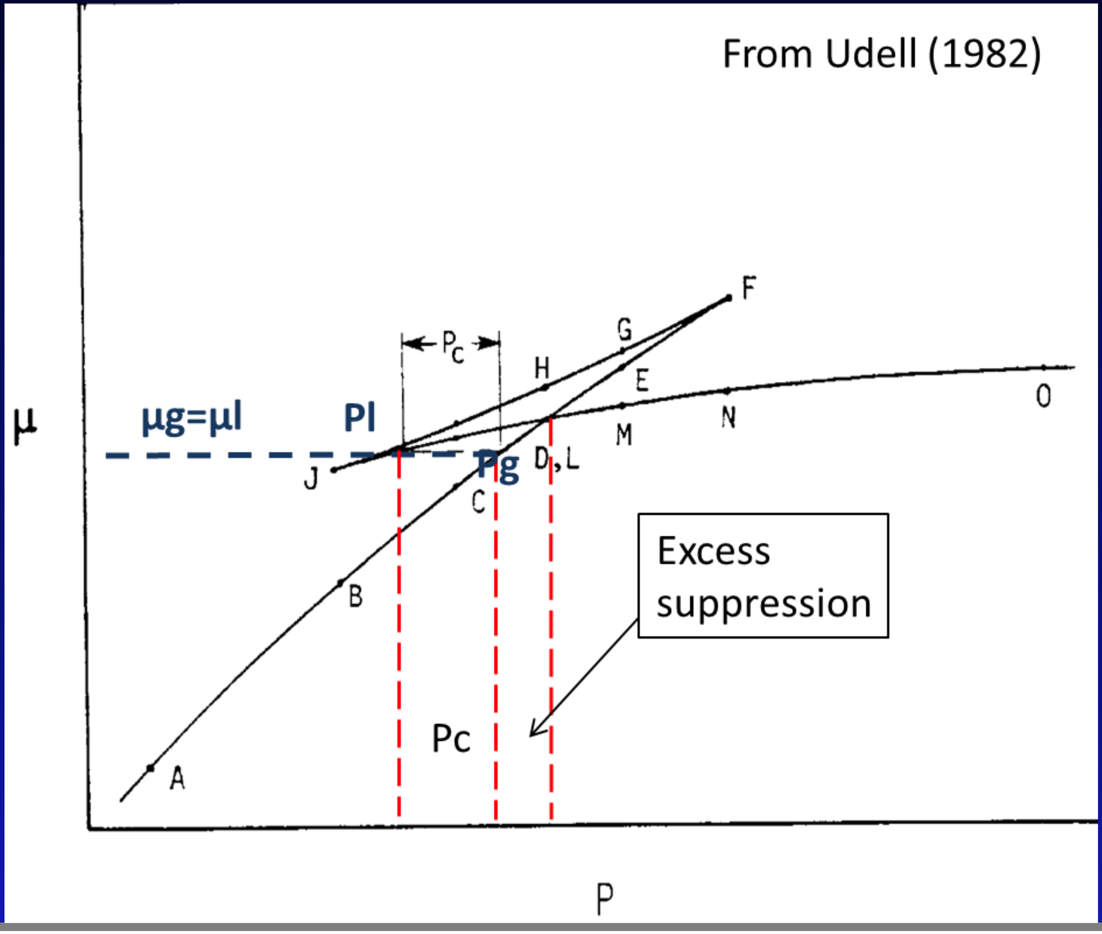
Pg=Pl+Pc

Pg=Pl and μg=μl

Phase Diagram Shift and Bubble Point Suppression



Phase Diagram Shift and Bubble Point Suppression



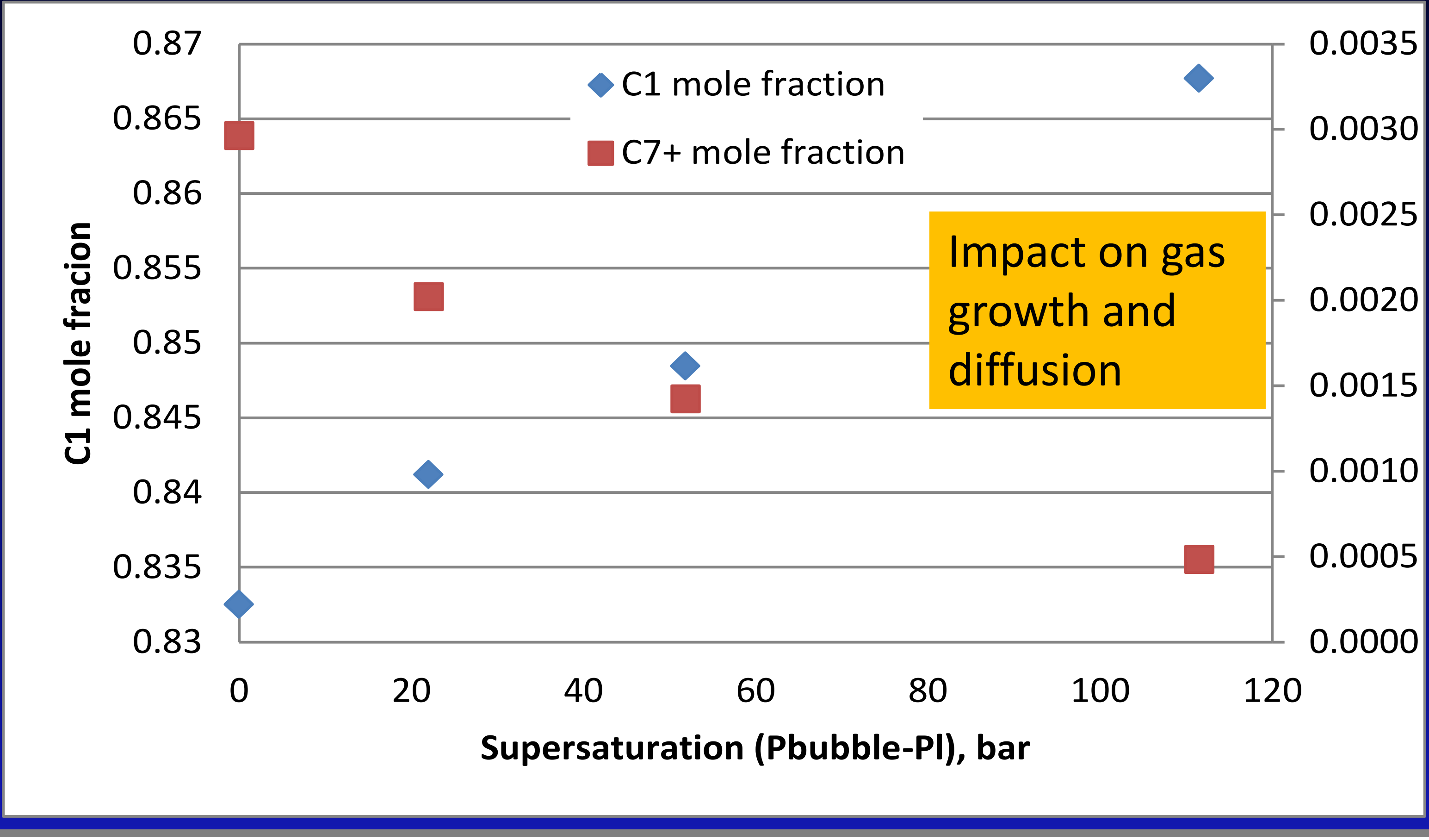
Excess suppression

Gas Composition Change due to Suppression

The gaseous phase contains lighter components as the bubble-point suppression increases.

Results/Status

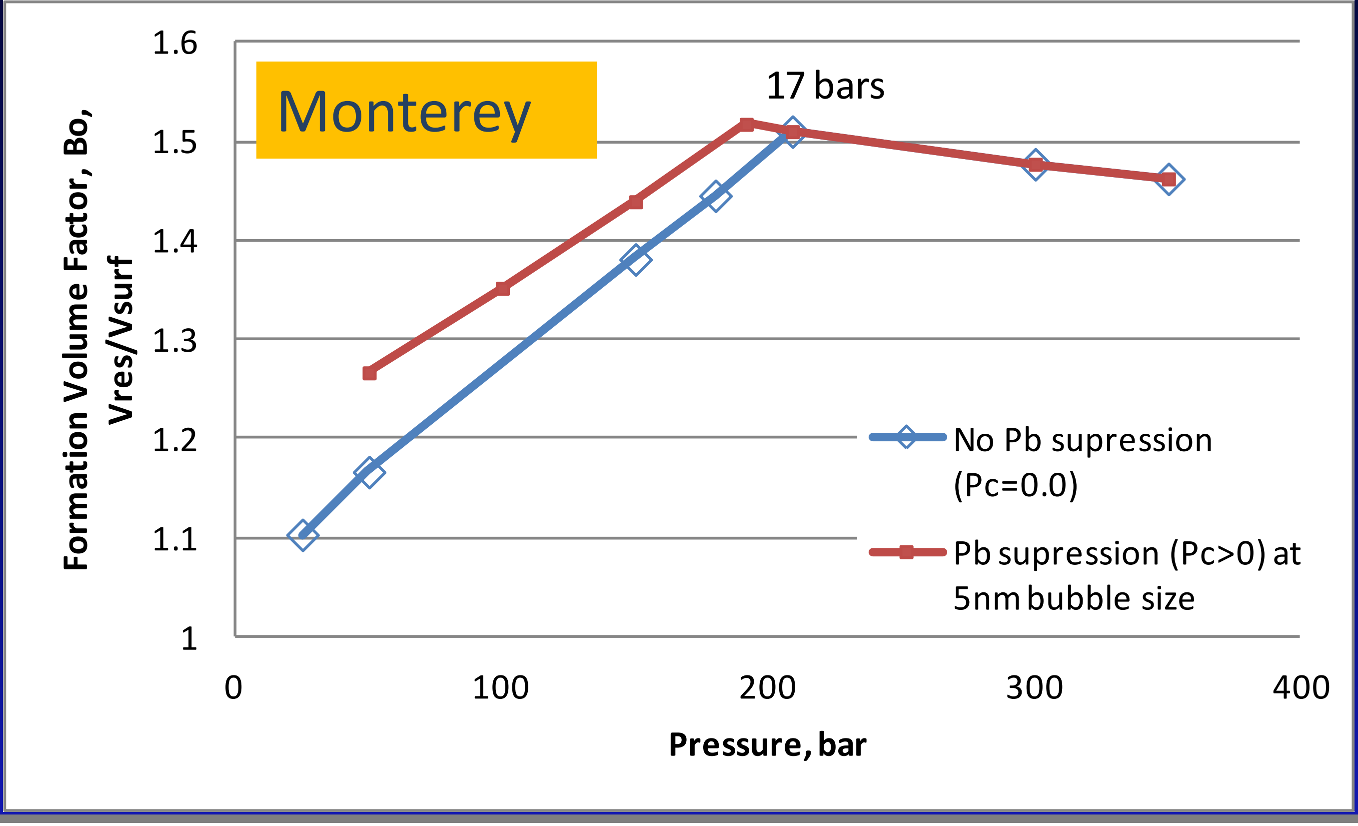
The gaseous phase contains lighter components as the bubble-point suppression increases.



Impact on gas growth and diffusion

Formation Volume Factor

Undersaturated portion of the curve is extended



Formation Volume Factor

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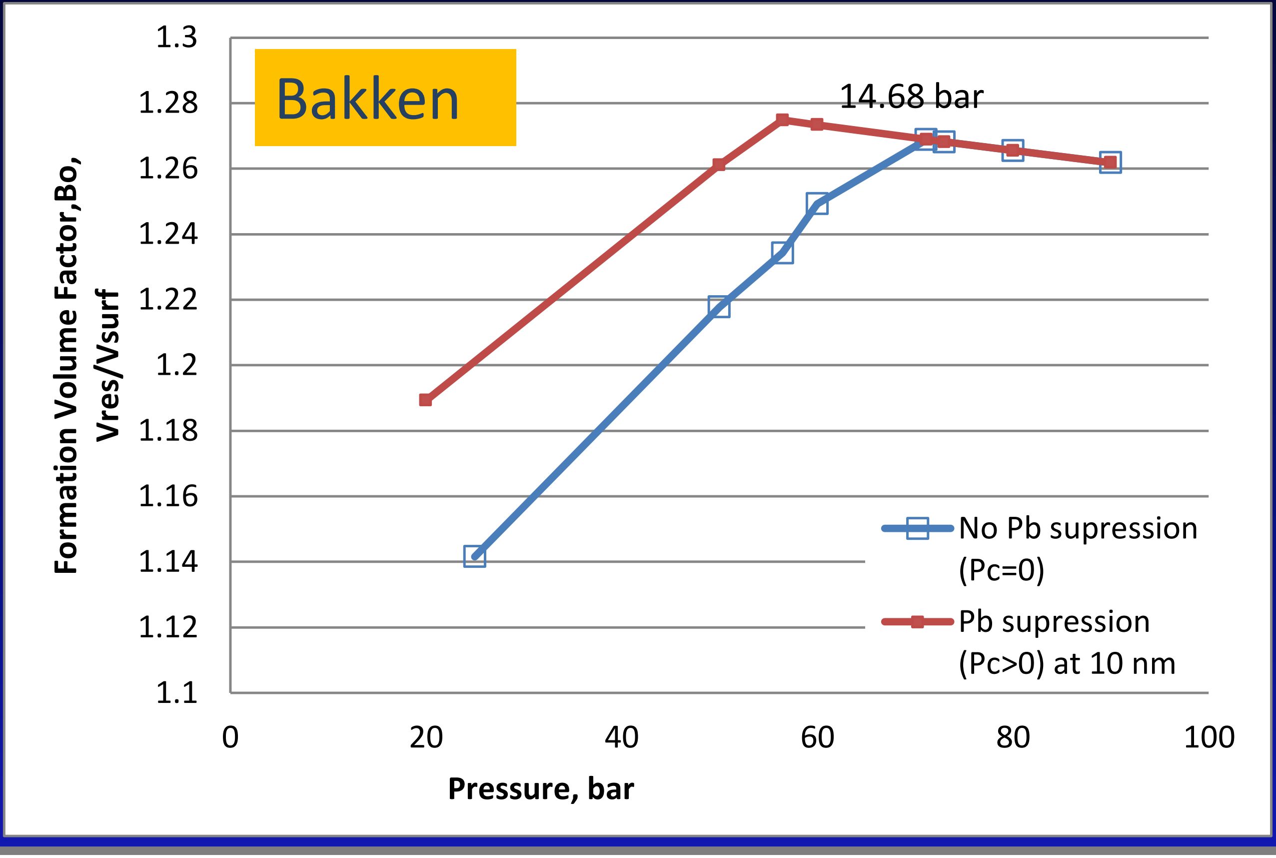


Oil Volume in Equilibrium with the First Gas Bubble
Possible pore sizes…

Common approach is to assume that the gas bubble occupies the entire pore space

$$r_{bubble} = r_{pore}$$

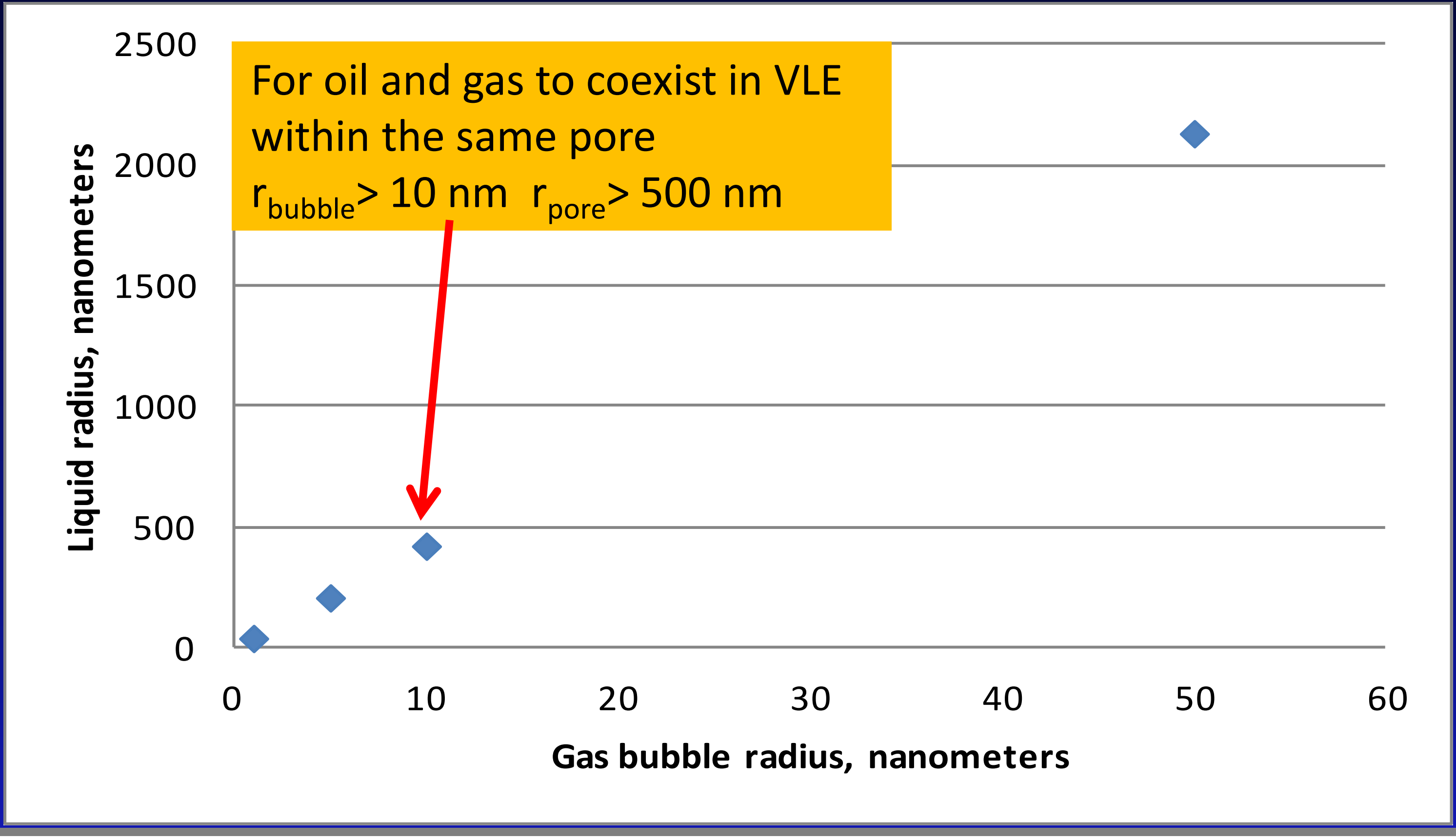
Results/Status

We investigate the gas bubble being in equilibrium with the oil that occupies the rest of the pore

Assumption: At bubble point gas bubble is infinitesimal (mole fraction 10^{-5})

Results/Status

Gas bubble is in equilibrium with the oil that occupies the rest of the pore


For oil and gas to coexist in VLE within the same pore

r_{bubble}> 10 nm r_{pore}> 500 nm

Results/Status

Conclusions

In confinement the bubble-point pressure is suppressed and the excessive suppression amount is a function of the bubble radius and the interfacial tension.

For the particular examples considered in this paper, the contribution of the surface forces was small. However, the trends indicate the possibility of surface forces becoming significant.

Results/Status

Conclusions

The pore size may constraint the gas formation in a confined environment.

Due to suppression equilibrium gas composition will be different .

For a confined fluid, the undersaturated portion of B_o must be extended to lower pressure values.

Results/Status

Future Work

Verify the impact of confined phase behavior on flow

Develop a **reservoir simulator** that incorporates the findings

Results/Status

Future Work

- Black Oil Application
  - PVT tables
  - Pc

Results/Status

Future Work

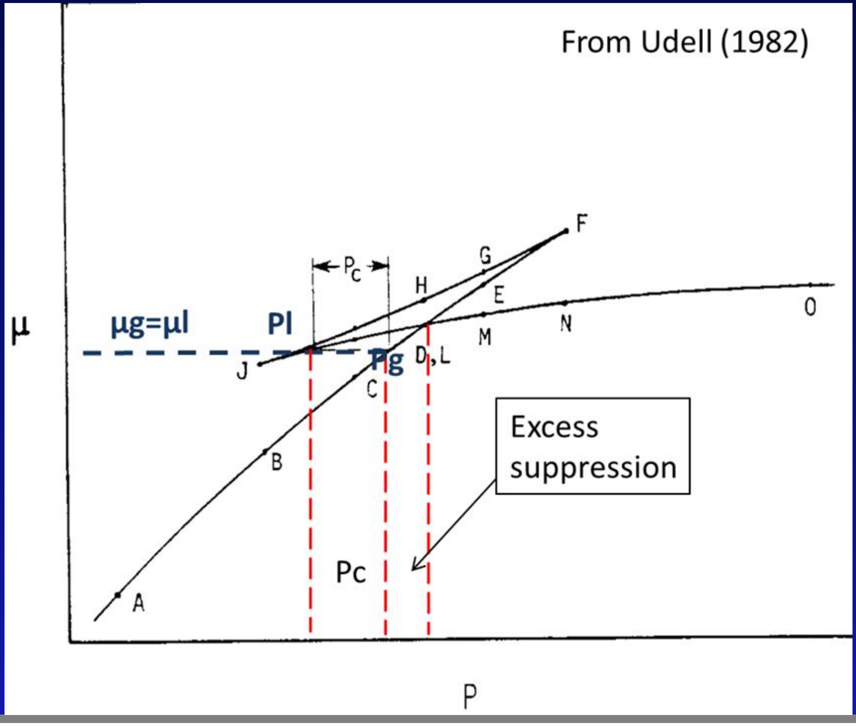
Unconventional simulator should address

PVT property evaluation at different pressures for oil and gas

Future Work

Unconventional simulator should address

Excess suppression



From Udell (1982)

Excess suppression

Future Work

Excess suppression needs to be correlated and input into the simulator

If data is not available it can be handled as a history matching parameter

It may be calculated as a function of bulk Psat (composition @ bulk Psat) and the bubble radius

Results/Status

Future Work

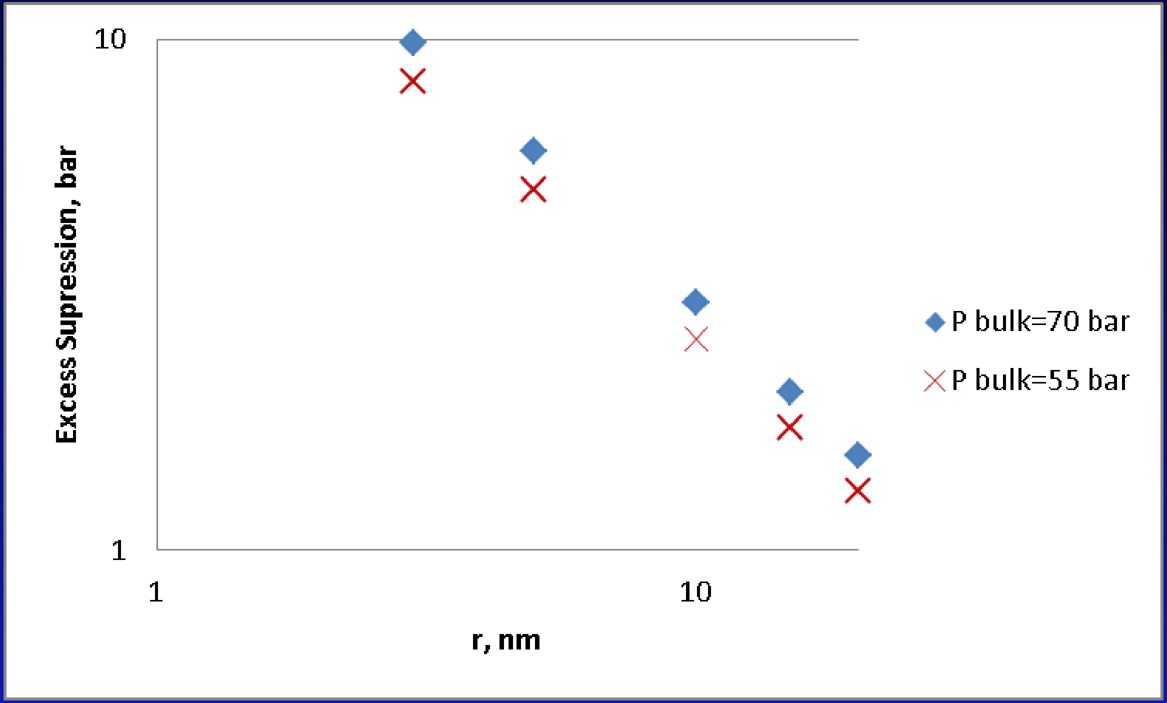
The suppression values increase with the decreasing radius (more confinement)

Trends are consistent with bulk pressure within a sample but different for different samples

Future Work

Example Trend – low GOR, low pressure

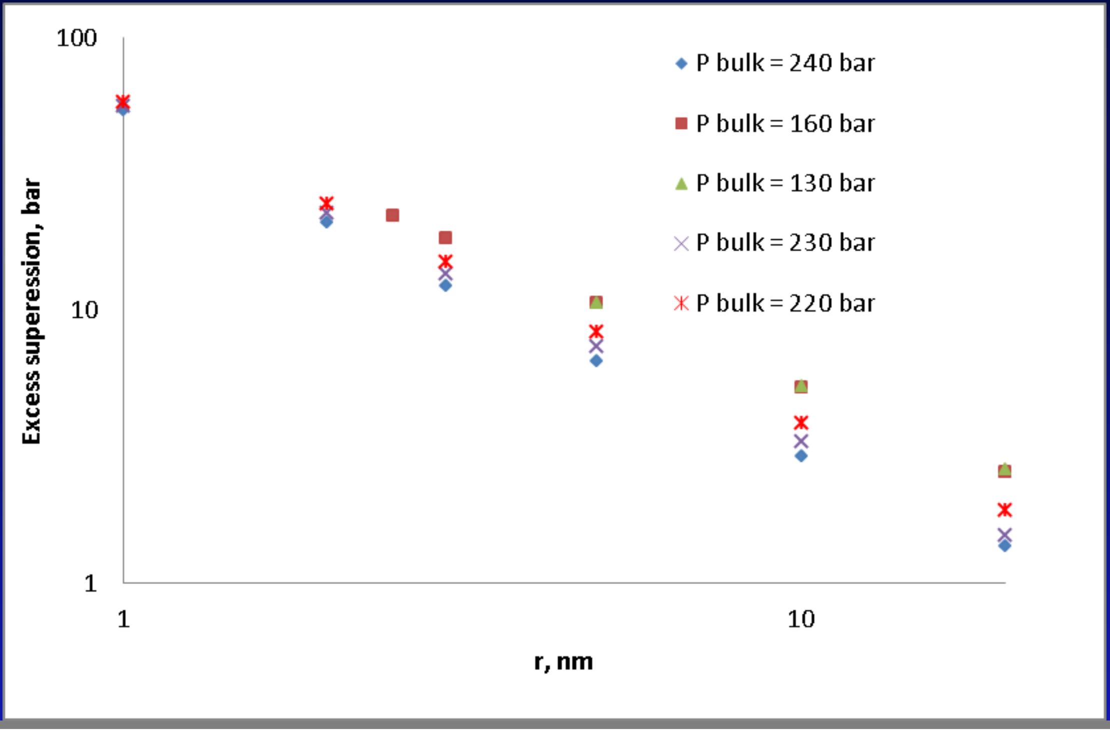
Excess suppression decreases with decreasing pressure



Future Work

Example Trend – high GOR, high pressure

Excess suppression increases with decreasing pressure



Results/Status

Future Work

Chet Ozgen will explain how to incorporate these findings into a reservoir simulator

Results/Status

Thank you!