Multi-scale Discussions on Natural Gas Storage and Transport in Nanoporous Material

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Multi-scale Pore Network

core plug

SEM Evidence of Nano-porosity

4 nm

1 μm
Question 1

Considerations for Gas Storage Capacity

- Reference pore volume, $V_{p0}$

- Adjustments to this pore volume necessary under reservoir conditions:
  - Pore-compressibility effect
  - Adsorption layer effect

![Diagram showing pore pressure and pore volume relationship](diagram)

$V_{p0} = 0.3914$ cm$^3$

$C_p = 5.42 \times 10^{-6}$ psi$^{-1}$

$G_{sl} = 0.1962$ cm$^3$

$P_L = 1800$ psi

$\rho_{ads,max} = 0.025$ mole/cm$^3$

Kang et al. (2011) SPEJ 16:4
MC Simulation of Fluid Adsorption

4nm, 3,000 psi (20.7MPa) pore pressure and 176°F (80°C) temperature

\[ \rho^*_\text{CH}_4 \times (1000^\circ\text{A}^{-3}) \]

VMD visualization of methane-ethane mixture in slit-pore

Free fluid

Adsorbed fluid

Ambrose et al. (2011) SPE Journal 17:1
Adsorption in SWCNT

Structured density profile across the tube under thermodynamic equilibrium conditions:

Rahmani and Akkutlu, 2013, SPE-164099
Phase Diagrams of Methane, Butane and Octane under Confinement

Methane

Butane

Octane

Akkutlu and Rahmani, 2015, URTeC-2151854
IFT of Methane in Nano-channel

From the local stress tensor, pressures are calculated considering both kinetic and internal (inter- and intra-molecular) contributions:

\[
\gamma = \frac{1}{N_0} \int_0^{L_z} \left[ p_N(z) - p_T(z) \right] dz = \frac{1}{N_0} \int_0^{L_z} \left[ p_{zz}(z) - \frac{p_{xx}(z) + p_{yy}(z)}{2} \right] dz
\]

http://dx.doi.org/10.1080/00268976.2015.1037369

Value of IFT is 6.65 mN/m across the V-L interface. This value is 45% smaller than that of the bulk IFT.
Fluid Transport in SWCNT

- Driving force generated using piston-like arrangement, controlling source and sink volumes to emulate pressure gradient
- Transport properties measured through the tube, e.g. velocity profile, to infer the effects of free and adsorbed phases on the overall transport

Riewchotisakul and Akkutlu, 2015. SPE-175107
Fluid Density and Velocity Profiles: Low Pressure

Average Pressure = 250 psi, \( \Delta P = 5-10 \) psi
Fluid Density and Velocity Profiles: High Pressure

Average pressure: 1,687 psi
Δp = 50 psi
Mass Transport Enhancement Ratio

\[ R_{me} = \left( \frac{2r^2_{tube}r^2_{ads} - r^4_{ads}}{r^4_{tube}} \right) + 8\mu C_{sv} \left[ \frac{r^2_{ads}}{r^4_{tube}} + \frac{\rho_{ads}}{\rho_{bulk}} \frac{r^2_{tube} - r^2_{ads}}{r^4_{tube}} \right] \]
Methane Mass Flux Profile across the Diameter of 5 nm Tube

Adsorbed phase transport contribute a large portion of the total mass flux
Bundle of Capillaries Approach

Nanoporous material permeability correction for the capillaries

\[ k_a = k \sum [f(r_{tube}) \cdot R_{me}] \]

where \( f(r_{tube}) = \) organic pore size distribution (fraction)

A flow cutoff of 2 nm applied

\[ [f(r_{tube}) \cdot R_{me}] = 1.573 \]

\( k_a = 1.573 \) k

57.3% enhancement in permeability

Question 4
Effect of Adding a Heavier Component

Feng and Akkutlu 2015, SPE-177005

- Density, g/cm³
- Normalized steaming velocity

Distance to the center of capillary, nm

- Pure CH₄, smooth
- 90% CH₄, smooth
- 10% C₄H₁₀, smooth
- 10% C₄H₁₀, smooth
Effect of Changing Wall Morphology

Feng and Akkutlu 2015, SPE-177005

- Effect of changing $a$, $b$ values (the length of the trench/bump, or the frequency of the defects)
Permeability Model

Wasaki and Akkutlu, 2015, SPEJ December issue

$$k_{gas} = k_m + \mu D c_g + \mu D_s \frac{G_{sL} \rho_{grain} B_g}{\varepsilon_{ks}} \frac{p_L}{(p + p_L)^2}$$

$$k_m = k_o \left(1 - \left(\frac{p_{conf} - \alpha p}{p_1}\right)^m\right)^3$$

Molecular transport effects of organic nanopores

Geomechanical effect of inorganic pores only
Coupled Fracture-Matrix Simulation I: The impact of Dynamic Matrix Permeability

Wasaki and Akkutlu, 2015, SPEJ December issue

Constant permeability

13% more
Coupled Fracture-Matrix Simulation II: The impact of Limited Fracture Conductivity

Wasaki and Akkutlu, 2015, SPE 175033

**Question 6**

Because of relatively high pressure near the fracture, molecular transport effects become less influential on production.
Surfactant: dodecylhepta(oxy-ethylene)ether \( (C_{12}E_7) \) contains one hydrophobic tail of 12 alkyl groups, and one hydrophilic head of 7 ethylene oxide groups and 1 terminal OH group

Oil: d-limonene (terpene solvent)
Questions!

- Can we develop advanced laboratory techniques targeting unconventional resources petrophysics?
- How accurately can we make the assessment of our resources?
- Is there multi-phase flow based on the classical concepts of displacement?
- How can we scale up transport processes so that we can better predict production?
- Do we need upscaling? How about multi-scale approaches?
- How well do we understand fracture-matrix coupling?
- How to improve the qualities of hydraulic fracture?
References


References, con’t

- Feng, F., and Akkutlu, I.Y., 2015. Flow of Hydrocarbons in Nanocapillary: A Non-Equilibrium Molecular Dynamics Study. SPE-177005, paper to be presented at the SPE Asia Pacific Unconventional Resources and Exhibition held in Brisbane, Australia, November 9-11.

