Challenges in two phase flow A petroleum tainted perspective

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Who am I?

- Theoretical physics background (PhD 1987 – Post Doc 1987-1992) Mainly work on phase behavior of systems a lattice, including Monte Carlo simulations.
- 25 years of experience in research related to petroleum reservoirs

18 years at Statoil research center in Trondheim.

- Shared Earth Modelling
- Data integration across scales
- Conditioning of models on dynamic data
- Uncertainty quantification, and decisions under uncertainty
- A lifetime studying **the science of ignorance**:

$$p(\lambda) \propto e^{-H(\lambda)}$$

What will I talk about??

- Two phase flow at **low rates** in the sub surface (Water flooding of oil reservoirs).
- Why the oil industry sees **no need** to replace current macroscopic theories.
- That the industry might **miss opportunities** in doing so.
- Which **problem areas** alternative theories should address in order to be of interest.

The generalized Darcy law A theory in need of replacement ??

$$\boldsymbol{q}_{\alpha} = -\frac{kk_{r\alpha}(S)}{\mu_{\alpha}} \left(\nabla p_{\alpha} - \boldsymbol{g}\rho_{\alpha}\right)$$
$$p_{\alpha} - p_{\beta} = P_{c\alpha\beta}(S)$$

- Assumes local capillary equilibrium.
 - Sub surface flows are characterized by very low capillary numbers $(N_c = \frac{\mu |q|}{\varphi \sigma} < 10^{-6})$

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- No model for hysteresis 😕
- Problems with counterflow (segregating flow) 💛

Characteristics of sub-surface reservoirs



- Heterogeneous porous medium with poor separation of scales.
- Almost unknown properties and geometry.
- Flow-properties connects to in-situ flow related measurements as **ill-posed inverse problems**.
- The connection between two-phase flow properties measured on core material and actual in-situ properties is **questionable**.
 - Cleaning, wettability "restoration", ...

Enhanced Oil Recovery (EOR)

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(Water based) EOR means **adding substances** to injected water that

- Block (Foams, gels, ...)
- Viscosify (Polymers, ...)

or

- Change surface free energies (Surfactants, salinity, ionic composition, ...)
 New driving forces !!!
 - Surface tension gradients
 - Concentration gradients

Near critical Gas/Oil systems

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Systems with compositional gradients coupled with gradients in interfacial tensions.

- Condensate
- Multiple contact miscibility in gas injection.

In high-pressure gas/oil reservoirs the difference between phases (gas and oil) is more in **composition** than in density.

- A change in total composition is accompanied by
 - Component exchange
 - Change in interfacial tension

Models based on pore size distribution



The parameters $k_{r\alpha}(S)$ and $P_{c\alpha\beta}(S)$ in the generalized Darcy law are traditionally understood in terms models where the determining factor is the **pore size distribution**.

- Wetting fluid fills small pores
- Non-wetting fluid fills large pores

Wetting is understood in terms of **interface free energies**, σ :

$$w = \frac{\sigma_{\alpha r} - \sigma_{\beta r}}{\sigma_{\alpha \beta}} = \cos(\theta_w)$$

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Effect of changing interfacial tension

Adding variation in interface free energies to a pore size distribution based picture:

Complete wetting

$$P_{c} = \sigma_{\alpha\beta} J(S)$$
$$k_{r} = k_{r}(S)$$

Incomplete wetting

$$P_{c} = (\sigma_{\alpha r} - \sigma_{\beta r}) J\left(\frac{\sigma_{\alpha r} - \sigma_{\beta r}}{\sigma_{\alpha \beta}}, S\right)$$
$$k_{r} = k_{r} \left(\frac{\sigma_{\alpha r} - \sigma_{\beta r}}{\sigma_{\alpha \beta}}, S\right)$$

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Desaturation An orthogonal perspective

Capillary number

$$N_c = \frac{\mu |\boldsymbol{q}|}{\varphi \sigma_{\alpha \beta}}$$

• For $N_c > 10^{-4}$ the flow properties depend on capillary number



• Low interfacial tension, $\sigma_{\alpha\beta}$, means higher capillary numbers,

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Adding desaturation to the pore size distribution based picture

- Low interfacial tension, $\sigma_{\alpha\beta}$, means higher capillary numbers,
- Systems with low interfacial tension tend to be completely wetting.

 $P_c \propto \sigma_{\alpha\beta}$ $k_r = k_r \left(\sigma_{\alpha\beta}, S\right)$

Current understanding

Current understanding of the effect of surface active additives is on the macroscopic level **limited to the desaturation picture**, that is the effect of a reduced surface tension on k_r .

- A reduction in σ by a factor of at least 100 is needed to get any effects.
- No new driving forces.
- Effect of additives are analyzed on a **mechanistic** microscopic level.

We should be able to **do better than this** if we had a workable macroscopic theory for two phase flow where the effect of gradients in interface energies and saturations are correctly described.

The sub surface is heterogeneous



• Phase exchange between layers with different permeability due to capillarity,

$$P_c = \sigma_{\alpha\beta} \, \mathbf{J}(x, S)$$

- Is this (counter-current) flow described correctly in the traditional theory?
- Surfactants introduce gradients in interfacial energies. Can the effect of this be adequately described through capillary pressure gradients?

$$\nabla P_c = \mathbf{J}(x, S) \nabla \sigma_{\alpha\beta} + \sigma_{\alpha\beta} \nabla \mathbf{J}(x, S)$$

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Demands on a workable theory

- Thermodynamically consistent
- A small number of macroscopic variables
- A small number of **independently measurable** parameters or constitutive relations
- We must be able to **control** macroscopic variables externally, at least in lab experiments.

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