Multifluid flow in oil and gas reservoirs: from invasion percolation to shale gas

Distinguished Lecture in the memory of A.C. Payatakes
Friday 7th of December 2012

Roland Lenormand
Gordon Conference ...
Importance of flow in porous rocks

- Gas/oil reservoirs
- Shale gas
- CO2 sequestration
- Hydrology, water resources, pollution
- Nuclear waste storage (H2 through the confining rock)
Purposes of the pore scale approach

- Pore scale description to explain the very complex mechanisms due to interactions between fluids and solid (capillarity, wettability, geometry ...) → micromodels

- Modeling and compare with experiments → pore scale flow simulators → academic studies

- To replace expensive experiments (Pc curves, relative permeabilities, ...) → commercial activity

- To calculate properties when experiments are not possible → shale gas
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In this presentation

- Not a complete review

- Just a few examples for micromodels and pore-scale simulations

- Available documents from IMF Toulouse, IFP, from Christos and Olga, commercial sites Ingrain and DigitalCore

- Much more laboratories
  - Dullien, Chatsis, Waterloo
  - Morrow
  - Heriot Watt
  - Oslo ....
Basic Flows: drainage-imbibition
Analogic models – Chauveteau
Analogic models – Chauveteau (Toulouse)
Analogic models – Ganoulis (Toulouse) 1974

Same size as Chauveteau

Very interesting results for two-phase flow

Very close to the discovery of percolation theory

(missing pictures from thesis)

Jacques Ganoulis, Professor and Director of the Hydraulics and Environmental Engineering Laboratory, UNESCO Chair, Aristotle University of Thessaloniki, Greece
Resin micromodels Lenormand (Toulouse)

- Following Ganoulis work but with smaller size
- Basic mechanisms
Displacement by a non-wetting fluid (drainage)
Resin Micromodels: Drainage

Role of films on the solid

a)  
b)  
c)
Dynamic pore network simulators

- Dynamic: simulation of the invasion pore after pore, quite slow
- Used for "statistical" studies
  - Percolation for capillary displacement (Wilkinson, Lenormand …)
  - DLA (diffusion limited aggregation) for viscous fingering (Paterson)

R. Lenormand et al. J. Fluid mechanics, 189
Invasion percolation

- Depending on pore size, links between nodes are open or closed.
- For a given pressure (fraction of open pores) the network becomes connected.
Diffusion limited aggregation (DLA)

micromodel  Network simulator  DIA process
Experiments from percolation to DLA
Transitions between flow patterns 1981

Less viscous fluid injected

More viscous fluid injected

Very slow, dominated by capillary effects, don’t depends on viscosity
Displacement by a wetting fluid (imbibition)
Imbibition – Water-wet
Modeling imbibition

FIG. 6 - Different mechanisms for the meniscus displacement.
In a triangular network, increasing flow rate
Imbibition flow by film

- At low flow rate
Effects of wettability

important for oil reservoirs
Mixed wettability

"corners" still water-wet
Pores in contact with oil are oil-wet

Conclusion: need spatial correlation between the oil wet pores
Correction to the static model?

Valvatne and Blunt, Water Resources research 40, 2004
Hydrophobic surfaces (microfluidics)
Neutral wettability

- **Neutral wettability to explain reservoir wettability**
  - Pores filled by water remains water-wet
  - Pores invade by oil have a neutral wettability ($90^\circ$)

- **Not found any simulation with neutral wettability ($90^\circ$)**

- Need for micromodel experiments to determine the rules of pore invasion

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*Figure 5.50. Immiscible displacement in an etched glass capillary under neutral wettability conditions: The contact line is stationary and the meniscus changes its shape (even “turns inside out” if the phase with lighter shading is the displacing fluid) as the displacing fluid advances (Dullien, unpublished work).*

FAL Dullien's book
Other studies
3-phase flow - spreading

From Richard Dawe, Heriot-Watt
3-phase flow - Effect of wettability

Catherine Laroche IFP
- oil in red
- Starts at irreducible water saturation

Water-wet

Oil-wet stripe // flow
Role of surfactants

- P. Hammond and E. Unsal (TIPM 2012)
- Associated with micromodel observations
Flow lines follow randomness in fluid velocity
Flow with trapped gas

Saturated with red fluid, displaced by white and then by blue
Increase of dispersion coefficient
Effect of viscosity for miscible flow

$$M = \frac{\mu_{\text{displaced}}}{\mu_{\text{injected}}}$$

M = 10

M = 1

M = 0.1
Viscous fingering (miscible)

Between two smooth plates (Hele-Shaw cell)

Micromodel with regular square network
Determination of Flow properties
- capillary pressure
- relative permeabilities
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Three-dimensional images of pores

- Image of the pore using X-Ray micro-scanner (micron scale)
- More recently using synchrotron (much faster acquisition)
- SEM ion beam for nanoscale (FIB tomography: image and erodes a few nanometers and then new image) → shales
- Transformed into an irregular pore network
- Or use the real pore geometry

![Figure 2](image.png)

Figure 2. (a) Three-dimensional image of a sandstone along with (b) a topologically equivalent network representation [Bakke and Oman, 1997].
Numerical rock
Ingrain Shales

http://www.ingrainrocks.com/
Flow simulation in the real pore space

More recent simulations use lattice Boltzmann method instead of Stokes differential equations

- As been observed (Rothman) then demonstrated (Frish, Pomeau) than particle collisions on a lattice with specific collision rules can reproduce viscous flow (lattice gas automata)

- Like a random walk on a lattice reproduce a diffusion equation

- Too much noise with LGA, discrete collision rules replaced by a continuous probability \(\rightarrow\) lattice Boltzmann

- Extended for two-phase flows

- Much more faster for complex geometry

- Can handle interactions with solid walls and interfacial properties

- But not always very well calibrated
Lattice Boltzman simulations

- Example, comparison with micromodels (Christos)
- Leads to discontinuous flow, like observed
- Published good agreement between DRP (digital Rock Physics) and laboratory experiments
Simulations instead of real experiments?

- **Sorbie Skauge 2011 - SCA2011-29**
  - Indeed, one of our conclusions on pore scale modeling in mixed wet systems is that we *cannot* predict two-phase functions reliably in “blind” tests

- **Paper SCA 01 (2012)**
  - Independently of the methodology, “genuine prediction” of multi-phase flow properties will remain not credible until important progress is achieved in the area of wettability characterization

- **Paper SCA 03 (2012)**
  - The comparisons between relative permeability curves derived from DRP and experimental steady state tests provide an assessment on the validity of the DRP based tests. (DRP=Digital Rock Physics)

- **At least, need to provide "wettability" data from laboratory**
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Experimental difficulties with shales

- Very small permeabilities, below nanoDarcy
- Possible gas permeability with special equipment
- Possible mercury injection
- Impossible to perform Capillary Pressure with oil or water
- Impossible to perform relative permeabilities

(FIB tomography from Ingrain)
Relative permeability for shales

http://www.ingrainrocks.com/
Conclusion

- Recent work confirms A.C. Payatakes' approach:
  - Observe at the pore scale
  - Model pore scale structure and displacement mechanisms
  - Measure multiphase flow macroscopic properties at the relevant scale

- Confirms important results
  - Role of pore geometry: convergent-divergent pore shape
  - Role of flow by film
  - Discontinuous flow in contradiction with two-phase Darcy’s law

- Improvements for reservoir wettability models will need to follow the same approach with micromodel experiments
Aknowlegement

- Christos Tsakiroglou for the movies on micromodels and slides
- Olga Vizika for discussions and slides
- Ingrain and Numerical Rocks for pore level flow simulations
- Cesar Zarcone for photos of micromodels