Microscopic Diversion Techniques
LPS or CDG

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09:20 – 10:00

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Agenda

- Colloid Dispersion Gels (early experience)
- New concept, LPS mechanisms
- Results
- Some answer to key questions

CDG experience

Colloid Dispersion Gel (CDG)

Simplified:

- **A solution of colloid size polymer particles dispersed in water**
- **Partially hydrolyzed polyacrylamide (HPAM) at low concentration crosslinked with Al (III)**
- **Crosslinker: Aluminum Citrate (AlCit)**
- **The ratio of HPAM/AlCit: 10:1 – 40:1**

Colloid Dispersion Gels
Short history of field experience

Efficiency of Colloidal Dispersion Gels for EOR (Mack and Smith, 1994)

- Review of 29 field projects
- 19 were evaluated as successful with incremental oil recoveries ranging from 1.3 to 18.2%.
- Nearly all reported field trials involve heterogeneous reservoirs and relatively fresh injection water.
- *CDG* injection increases oil recovery by in-depth mobility control or **sweep improvement**
- Similar results are reported later by Chang et al. (2006) based on experiences from a field pilot of *CDG* technology in the Daqing Oil Field in China.

Mechanisms

"Classical" CDG injection claims increased oil recovery by sweep improvement

- Laboratory core floods have so far not been able to explain why these systems should give a large improvement of field waterflood performance
- Viscosity increase (or change in water/oil mobility ratio) is limited
- Questionable transport properties of classical CDG particles > 10 microns

Mechanisms of classical CDG

While the CDG field projects involved injection into watered-out reservoirs

- the laboratory tests reported < year 2000 have to our knowledge been performed on water saturated cores only

- Several laboratory core floods indicate significant <u>retention</u> of colloidal dispersion gels in the first part of the cores, with no evidence of *CDG* propagation through the cores to give in-depth permeability reduction (Seright, 1994; Rangathan et al., 1994; Lu and Song, 2000; Wang et al. 2006).

- While Smith et al. (2000) provide <u>no direct verification of *CDG* propagation</u> through cores, gel propagation was inferred from visual evaluation of effluent samples.

- Injection water salinity is said to be limited to less than 30 000 mg/g total dissolved solids, however, the authors offer no physico-chemical explanation as to why such a salinity limit should exist.

CDG/LPS mechanisms

LPS (Linked Polymer Solutions)

- Polymer injection in Chinese oil field
  - New interest in weak polymer gel systems from the success in Chinese oil fields
- CDG procedure in China: Very low concentrations and low injection rates
- Results: Positive field results in heterogeneous high-permeable reservoirs with unfavorable water-oil mobility ratio
- Current study: Can this process be used to improve waterflooding of North Sea oil reservoirs?

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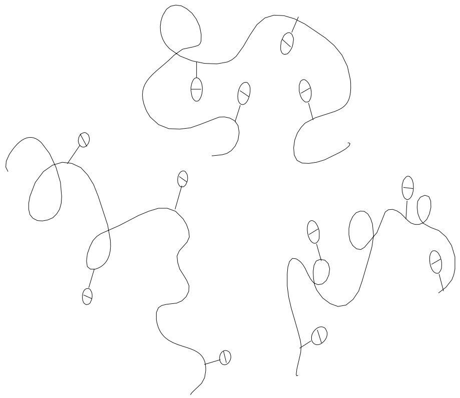
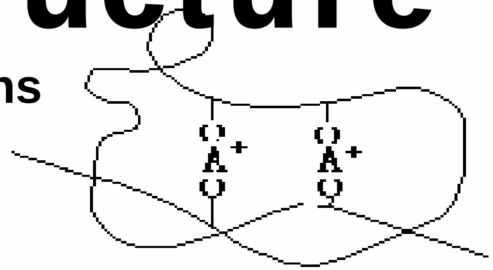
Aggregate Structure



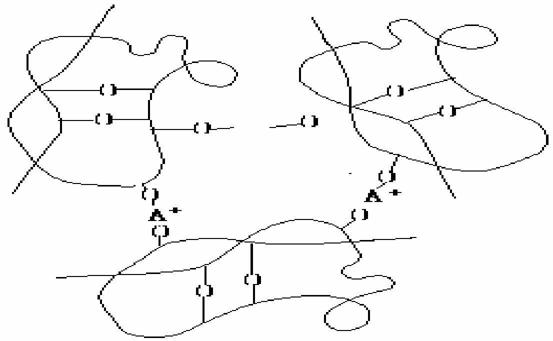
Free HPAM polymer

*Intra*chain interactions

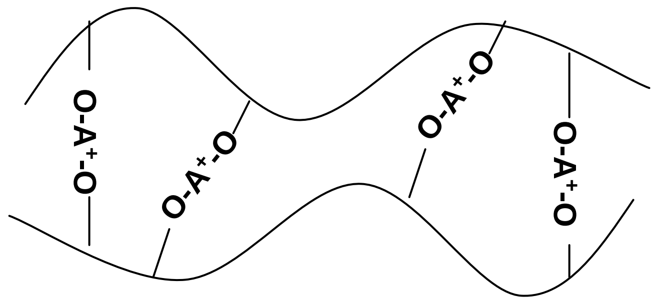


*Intra*chain interactions AND

*Inter*chain interactions



*Inter*chain aggregation to large aggregate → GEL



- **CDG/LPS should be dominated by *intra*molecular interactions**

- **Factors expected to influence the balance between *intra*- and *inter*molecular interactions include:**
  - **HPAM hydrolysis degree; higher hydrolysis degree may promote *inter*molecular interactions**
  - **Concentration of crosslinking metal ion; higher concentration likely promotes *inter*molecular interactions**

NB! **Divalent ions such as Ca2+ present in seawater may also contribute to both *inter*- and *intra*molecular interactions**

Chemistry of the CDG/LPS

Prefer intramolecular interactions (internal binding)

One polymer molecule stronger coiled due to Al ions

Nano size particles can be formed

Slow exchange of Al – ligand from citrate to polymer

Subtle change of physical properties but very important

Coiled Polymer → CDG (nano size) → CDG (conventional) → GEL

Polymer concentration
Al concentration
Al / Polymer ratio
Brine salinity

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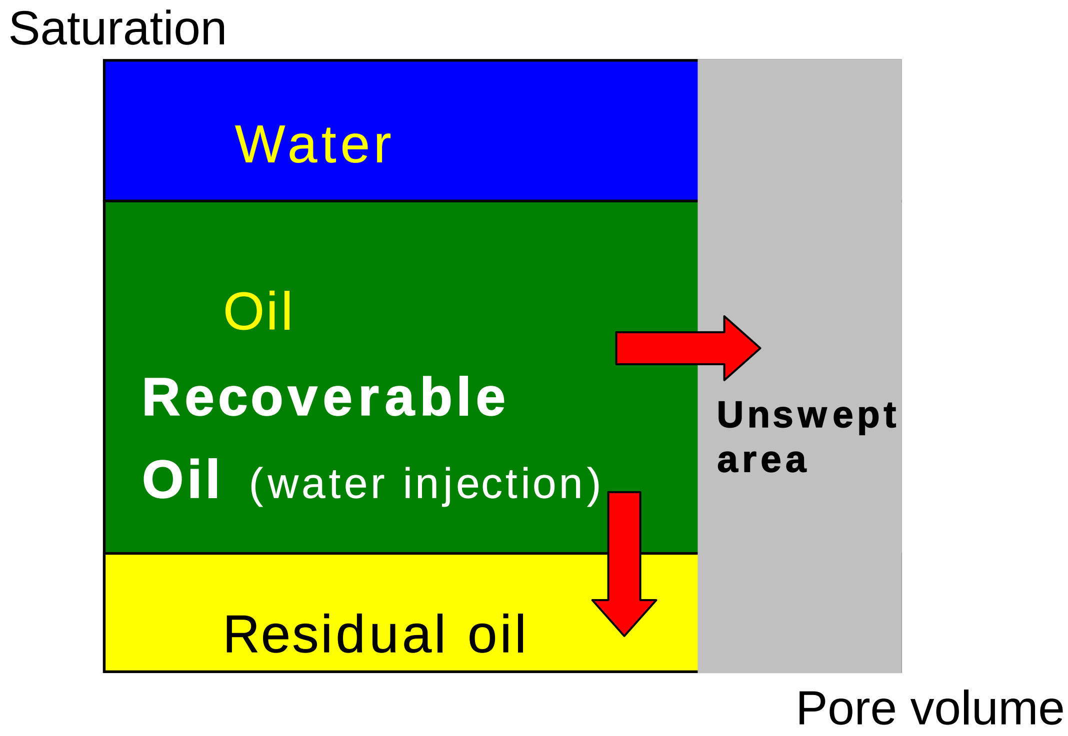
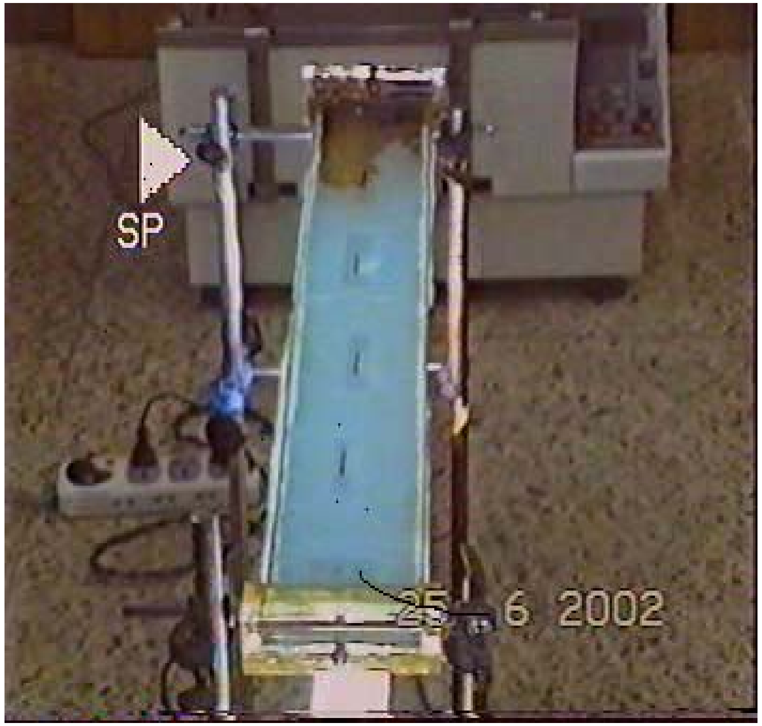
Recent research at CIPR

Gain insight in the *CDG* mechanisms that may increase the recovery in an already waterflooded reservoir

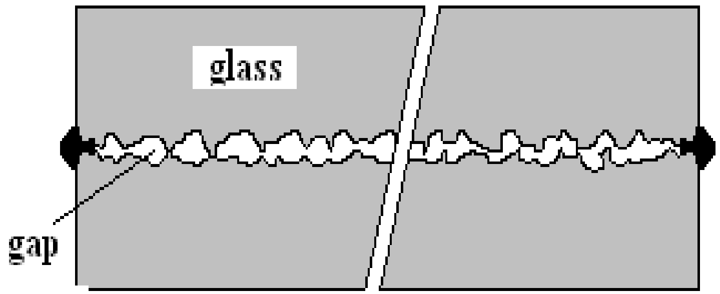
evaluate the applicability of *CDG* to field conditions like North Sea oil reservoirs



LPS flooding in a glass model



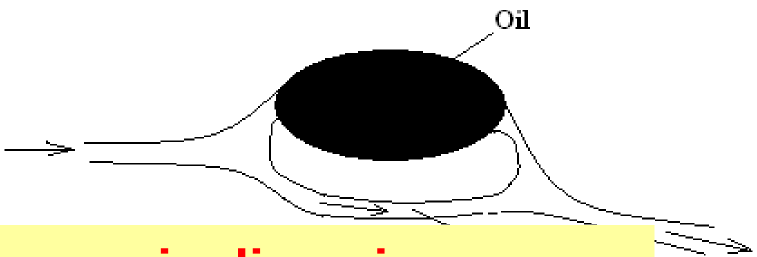
Heterogeneous etched pores on glass plates



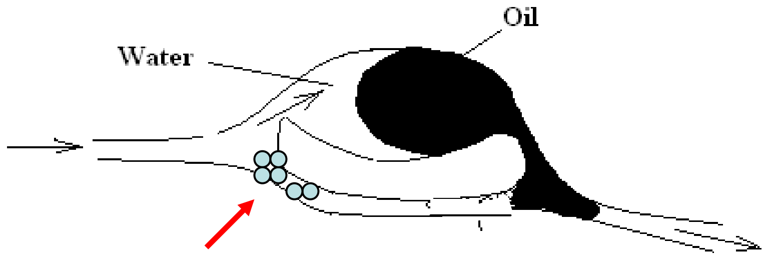
L: 625 mm W: 100 mm Gap: 50-100 μm

Experiments show that water after LPS injection is following new pathways and is mobilising bypassed oil

CDG mechanisms sweep improvement, but also..

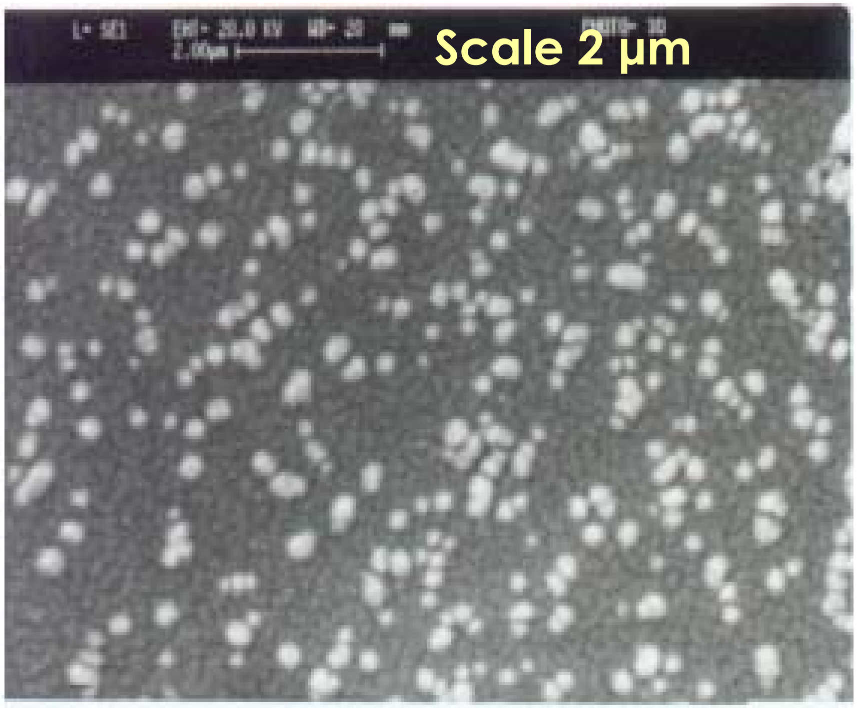


Microscopic diversion



Linked Polymer solutions

SEM photograph of CDG particles



Spherical particles

Typical size 50-100 nm

Pre-generated particles;

1. **Less likely to be adsorbed**
2. **Expect less chromatographic separation**

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Summary from our physical chemistry characterization

- CDG have low viscosities

- High salinity water, like in the North sea, do not seem to alter the particle size

-The cross-linking reaction is relatively fast at 40ºC

- CDG can be prepared from distilled water and from salt solution

- Dialysis tests indicate a very slow dissolution of the cross-linked aggregates

- These results are very favourable for reducing chromatographic separation when transported through porous medium in oil reservoir applications

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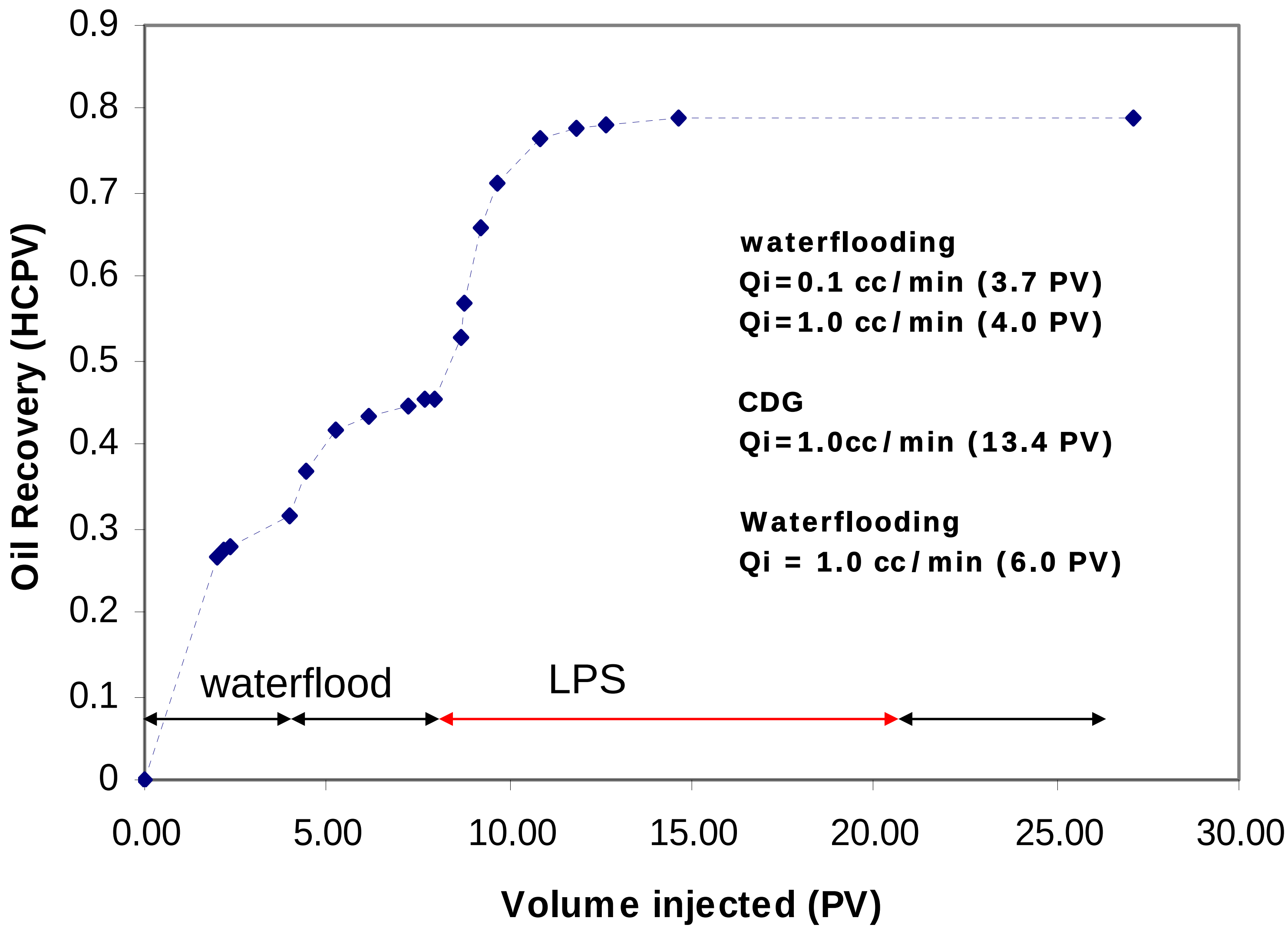
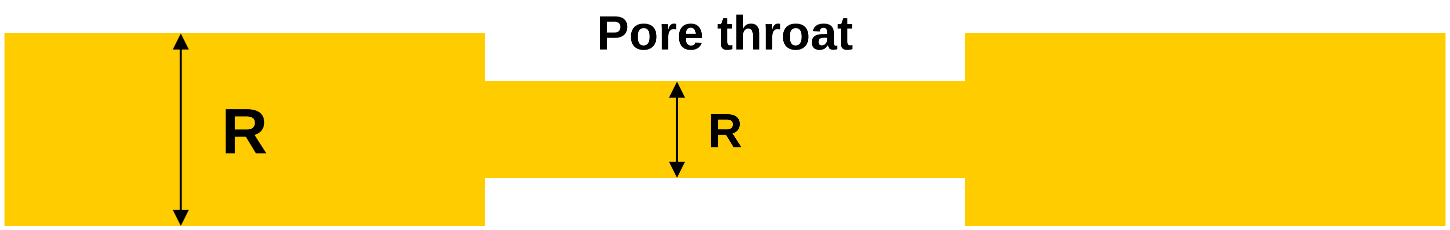
Core flood results
Sandstone reservoir core (fresh core), K=900 mD



Why should small particles lead to diversion of flow?

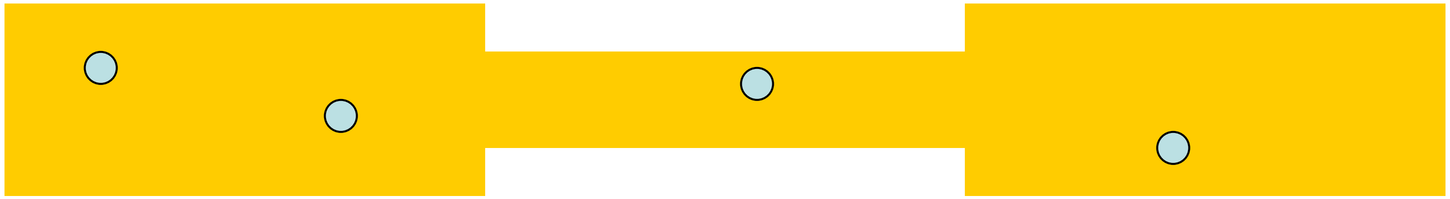
"log-jamming"



Assume a simple capillary tube model

Why should small particles lead to diversion of flow?

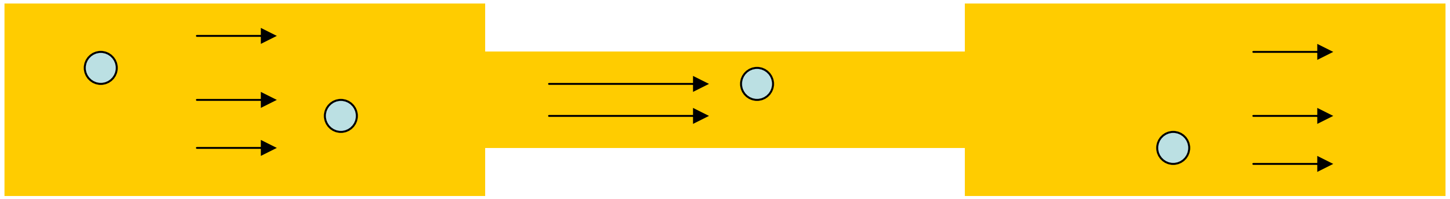
“log-jamming”



Nano size particles dispersed in water

Why should small particles lead to diversion of flow?

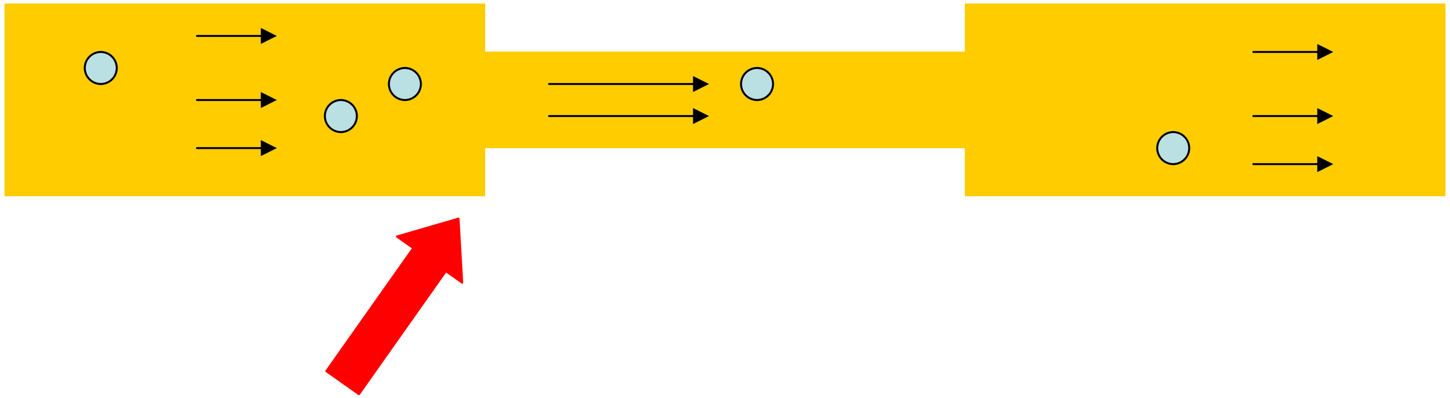
“log-jamming”



Pressure gradient results in different flow rate of the water dependent on pore radius

Why should small particles lead to diversion of flow?

“log-jamming”



There will be an acceleration of the water velocity at the pore throat entry

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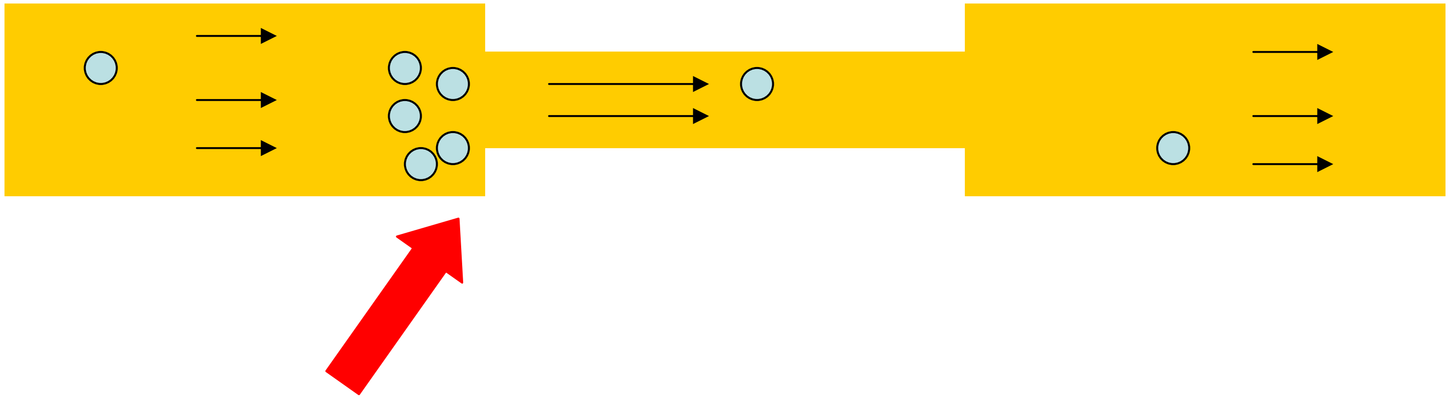
“log-jamming”



There will be an acceleration of the water velocity at the pore throat entry

Due to difference in mass the particles will accelerate slower than the water
Thus, particles will accumulate at the entry of the pore throat
The increase in differential pressure over the pore throat due to particle blocking will increase => diversion of flow paths

Experimental detection of intra-molecular bound CDG/LPS

- Reduced solution viscosity compared to free (relaxed) polymers in solution

- At low polymer concentration change from intra-molecular to intermolecular bindings may not be detectable from solution viscosity measurements

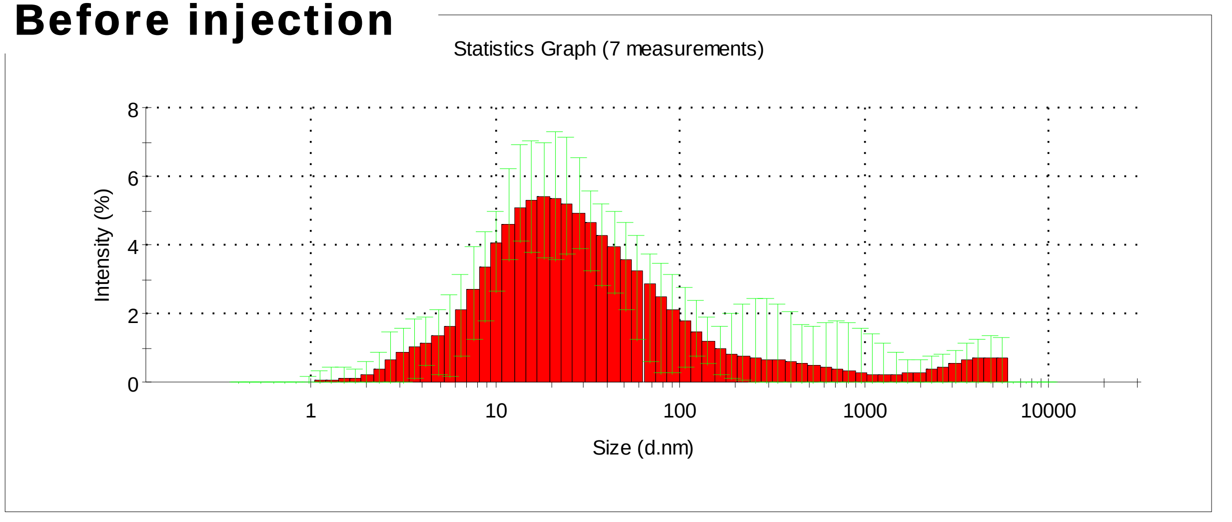
- Filter tests can differentiate intra-molecular from intermolecular binding.

Evaluation of CDG properties

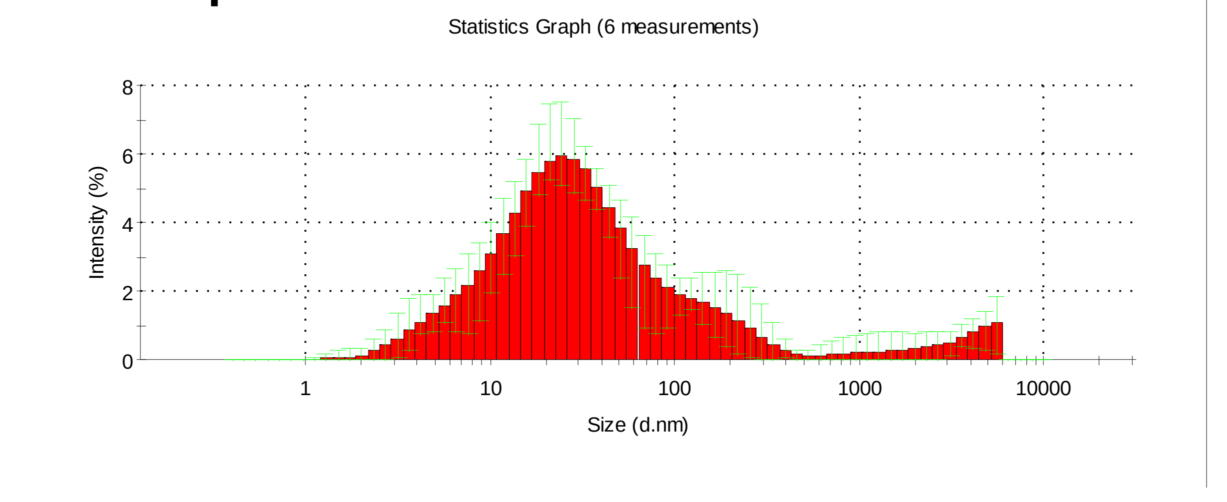
Do CDG progress through the core? YES

Measurement of particle size distribution

Before injection



Effluent production from the core



Summary of remaining oil saturations at different stages of the flooding experiments fro composites A-E						
Core	K_w [mD]	S_{wi}	S_{orw1} (0.1 ml/min)	S_{orw2} (1 ml/min)	S_{orCDG}	**% reduction in S_{or} after *CDG***
A	**900**	**0.06**	**0.64**	**0.51**	**0.20**	**61**
B	**500**	**0.18**	**0.38**	**0.30**	**0.17**	**42**
C	**300**	**0.24**	**0.40**	**0.32**	**0.19**	**41**
D	**0.15**	**0.21**	**0.31**	**0.25**	**0.20**	**22**
E	**0.10**	**0.21**	**0.38**	**0.33**	**0.26**	**19**

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Is the oil recovery due to polymer injection (polymer flooding)?

Capillary number increase says NO

Viscoelastic behavior may give some oil recovery, but less if any at all

LPS modelling

Mechanistic Pore-Scale Network Modeling

Core scale modelling

Mechanisms

- Flow diversion as a result of blocking of some pores
- Polymer mechanism
  - Viscosity effect

$$\mu_p = \mu_w \left[1 + \left(AP_1 C_P + AP_2 C_P{}^2 + AP_3 C_P{}^3\right)\right]$$

  - Adsorption
    - Permeability reduction
    - Removal of polymer from bulk solution
  - Blocking effect
    - Straining
    - Log-jamming

Coupling two network types

- Semi static network
  - Capillary forces are dominant
  - Drainage and imbibition process
- Dynamic network
  - LPS model

Approach

- Run standard pressure step on a two-phase invasion percolation network model
- Start with primary drainage and then imbibition until pre-specified residual oil saturation
- Identify water phase backbone
- Run LPS model as a dynamic model and calculate blocking bond, changes in local pressure and the new pressure field of the network
- Use the local pressures to see if any oil displacement occurs

LPS modelling

Mechanistic Pore-Scale Network Modeling

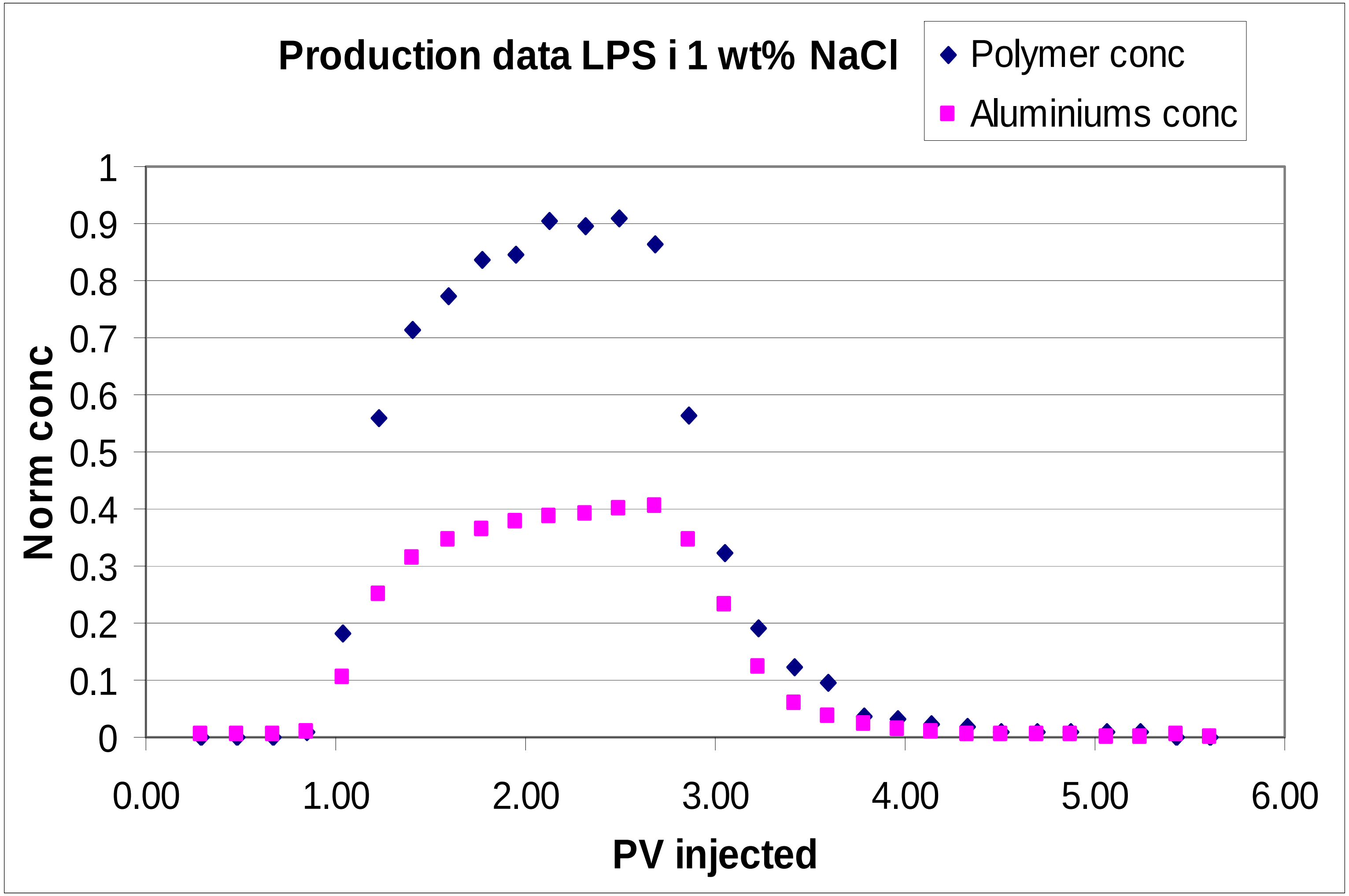
Core scale modelling

Answer: YES we can

Adsorption / retention
Chromatographic separation

Adsorption values
Polymer = 32.3 µg/g
Al = 4.1 µg/g

No detectable chromatographic separation
Equilibrium ratio P/AL = 540ppm / 12ppm



Adsorption /retention

Polymer adsorption is lower for LPS than for polymer solution

Al adsorption is similar in all experiments

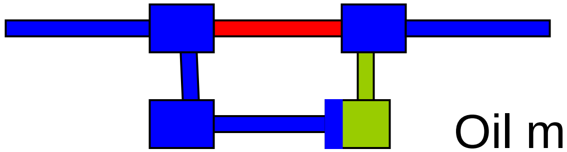
Ratio of Polymer/Al during dynamic flow

540ppm / 12ppm

Conclusions

- The standard capillary number relationship for microscopic displacement is not able to explain oil production by LPS, and most likely not for low-sal either

- Microscopic diversion is a plausible explanation for oil mobilization both as one of several possible mechanisms in losal and may be the dominant mechanism for LPS



Oil mobilization

Summary and conclusions

- ***CDG* injection gives increased recovery from core material from different North Sea reservoir formations that has been waterflooded to residual oil saturation**

- **Our hypothesis is that the additional oil recovery is mainly due to increased microscopic diversion, caused by blocking of pores/ pore throats by polymer particles**

- **The nano-size polymer particle system may induce both microscopic and macroscopic (sweep) diversion on the field scale**

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