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Liquid foam in porous media

Context: oil extraction and soil depollution
Liquid foam in porous media

**Context:** oil extraction and soil depollution

It is usual to describe the flows of both gas and liquid phases in terms of relative permeability ($k_{rel} = k_{SW}/k_{S_W=1}$) in function of liquid saturation $S_w$.

![Diagram showing liquid foam injection, soil particle, bubble, increase of gas fraction, and reduction of liquid permeability.](image)

Bernard and al. 1965

- **Liquid saturation $S_w$:**
- **Relative permeability**
- **Increase of the gas fraction**
- **Reduction of the liquid permeability**
**Liquid foam in porous media**

**Context:** oil extraction and soil depollution

It is usual to describe the flows of both gas and liquid phases in terms of relative permeability \( k_{rel} = k_{SW}/k_{SW=1} \) in function of liquid saturation \( S_W \).

The liquid permeability is the same in the presence or in the absence of foam lamellae.

*Bernard and al. 1965*

*Eftekhar and al. 2017*
Objective: to develop a model experiment to explore $S_w < 20\%$, the effects of surfactant and bubble size.

Context: oil extraction and soil depollution

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Eftekhari and al. 2017

 Bernard and al. 1965
Liquid foam and permeability of bulk foam

Structure of bulk foam

- Bubbles
- Films
- Plateau borders (liquid channels)
- Vertex
Liquid foam and permeability of bulk foam

Structure of bulk foam

Plateau borders
(liquid channels)
Liquid foam and permeability of bulk foam

Structure of bulk foam

Plateau borders (liquid channels)
Liquid foam and permeability of bulk foam

Structure of bulk foam

Plateau borders (liquid channels)

Two different surfactants:

- Alkyl Polyglucosides (APG): derived from glucose
- Saponin: present in different seeds or plants

Dimensionless permeability

Liquid fraction

(liquid volume/foam volume)
Foam production and filling of a granular packing

- Monodisperse bubbles
  - $D_b$: 0.3-2 mm

- T junction where the bubbles are formed
  - $N_2$ (Gas flow controller) $\rightarrow$ $Q_g$ $\rightarrow$ $Q_l$ $\rightarrow$ Foaming Solution $\rightarrow$ Syringe-pump

- Discharged foam
- Foam column
- Granular column

- Foam with target liquid saturation $S_w$
- Glass beads ($D_p$), $D_p$: 1-8 mm
- Foam (bubble size $D_b$), $D_b$: 0.3-2 mm
- $S_w$: 3-20%

- Bubbles with target size $D_b$

Hydraulic properties of foam-filled granular packing

**Measurement of liquid permeability:**

Darcy permeability $k_D$ measured with the falling-head test

\[
\frac{z}{z_0} = \exp\left(-\frac{S}{S_t} \frac{k_D \rho g}{H} t\right)
\]

Continuous line: fitted to the experimental points by tuning $k_D$. 
Hydraulic properties of foam-filled granular packing

**Measurement of liquid permeability:**

Darcy permeability $k_D$ measured with the falling-head test

$$\frac{z}{z_0} = \exp\left(-\frac{S}{S_t} \frac{k_D \rho g}{\mu} H t \right)$$

Continuous line: fitted to the experimental points by tuning $k_D$.

Permeability of the confined foam: $k_f = k_D/p$

$p$: porosity of the granular media
Hydraulic properties of foam-filled granular packing

Changing $D_p$ for constant $D_b$ value:

Mobile interfaces

(AGP)

Non mobile interfaces

(saponin)

$$\tilde{k}_f = \frac{k_f}{D_b^2}$$
Hydraulic properties of foam-filled granular packing

Changing $D_p$ for constant $D_b$ value:

$\tilde{k}_f = \frac{k_f}{D_b^2}$

Mobile interfaces

$S_w$ vs $D_b/D_p$

Non mobile interfaces

$S_w$ vs $D_b/D_p$

Changing both $D_b$ and $D_p$ for constant $r$ value:

$r = \frac{D_b}{D_p}$

$\tilde{k}_f = \frac{k_f}{D_b^2}$

$r = 0.4$ (APG)
Hydraulic properties of foam-filled granular packing

Changing $D_p$ for constant $D_b$ value:

$$\tilde{k}_f = \frac{k_f}{D_b^2}$$

Mobile interfaces (APG)

Control parameters for each surfactant:

$$r = \frac{D_b}{D_p}$$

Changing both $D_b$ and $D_p$ for constant $r$ value:

$$\tilde{k}_f = \frac{k_f}{D_b^2}$$

Non mobile interfaces (saponin)

$$r = 0.4 \text{ (APG)}$$

$D_b - D_p$

$\tilde{k}_f$
Hydraulic properties of foam-filled granular packing

Evolution of the permeability according to the size ratio $r$:

$$\frac{\bar{k_f}(S_w, r)}{k_{f0}(S_w)}$$
Hydraulic properties of foam-filled granular packing

Evolution of the permeability according to the size ratio $r$:

$$\frac{\tilde{k}_f(S_w, r)}{k_{f0}(S_w)}$$

$r < 0.25$

- Geometric effect on the permeability
- No dependence of interfacial mobility
Hydraulic properties of foam-filled granular packing

Evolution of the permeability according to the size ratio $r$:

- $r < 0.25$  
  - Geometric effect on the permeability
  - No dependence of interfacial mobility

- $r > 0.25$  
  - Coupling between the interfacial mobility and the geometry of the confined foam
Hydraulic properties of foam-filled granular packing

Evolution of the permeability according to the size ratio $r$:

$$\frac{\bar{k}_f(S_w, r)}{k_{f0}(S_w)}$$

- $r < 0.25$ • Geometric effect on the permeability
  - No dependence of interfacial mobility

- $r > 0.25$ • Coupling between the interfacial mobility and the geometry of the confined foam
Hydraulic properties of foam-filled granular packing

What about geometry of bubbles while $r$ is changing?

Number of bubbles/tetrahedral pore

Tetrahedral arrangement of grains

Foam regime

Graph:

- $r = \frac{D_b}{D_p}$

- Bulk foam

- Number of bubbles/tetrahedral pore

- Tetrahedral arrangement of grains

- $r = 0.16$
Hydraulic properties of foam-filled granular packing

What about geometry of bubbles while \( r \) is changing?

Number of bubbles/tetrahedral pore

![Graph showing the relationship between bulk foam and number of bubbles/tetrahedral pore.]

\[ r = \frac{D_b}{D_p} \]

Tetrahedral arrangement of grains

- Entry of the cavity
- Tetrahedral cavity
- Pore volume
Hydraulic properties of foam-filled granular packing

What about geometry of bubbles while $r$ is changing?

Number of bubbles/tetrahedral pore

- **Foam regime**

$r = \frac{D_b}{D_p}$

Tetrahedral arrangement of grains

Entry of the cavity

Tetrahedral cavity

Pore volume

Liquid bridge

Liquid film

Parietal liquid channel

All the liquid bridges are connected together by parietal plateau borders which ensures liquid permeability at low liquid saturation.
Hydraulic properties of foam-filled granular packing

Permeability ratio of APG and saponin foam in function of $r$: two regimes

- $r \leq 0.25$ : Foam regime
  - Several bubbles (foam)/pore
  - Permeability ratio comparable to unconfined foam
Hydraulic properties of foam-filled granular packing

**Permeability ratio of APG and saponin foam in function of $r$: two regimes**

- $r \leq 0.25$: **Foam regime**
  Several bubbles (foam)/pore
  Permeability ratio comparable to unconfined foam

- $r > 0.25$: **Liquid bridges regime**
  Transition to $\sim 1$ bubble/pore (no more « bulk liquid channels » into pores)
  Permeability is controlled by liquid bridges and their connectivity

The dominant effect of interfacial mobility in these liquid zones remains to be understood in details.
Conclusion - Liquid relative permeability through foam-filled porous media

- Setting up a model experiment of packed glass beads filled with monodisperse foam (highly controlled samples)

- The liquid permeability depends on three parameters:
  - the interfacial mobility (two surfactants: APG and saponin)
  - the bubble-to-grain size ratio $r$ between 0.05 and 0.5
  - the liquid saturation $S_w$ below 20%

- When plotting the ratio $\frac{k_f^{APG}}{k_f^{sap}}$, two regimes are revealed as a function of $r$:
  - for $r \leq 0.25$ the permeability ratio is equal to the ratio corresponding to the bulk foams
  - for $r > 0.25$ the permeability ratio is increased by one order of magnitude

- The latter regime involves liquid foam bridges, connected together by liquid channels formed by the foam on the surface of the grains, which ensures finite liquid permeability at low liquid saturation.
Thanks for your attention

Any questions?
Foam production and filling of the granular packing

Control of bubble size: variation of the flow rate of the foaming solution and the gas ($Q_l/Q_g$)

Control of foam liquid fraction: variation of the foam height (h)

Discharged foam

Foam with target liquid fraction

Foil column

Porous column

T junction where the bubbles are formed

Foaming Solution

Syringe-pump

Gas flow controller

$Q_l$

$Q_g$

$q_a$

$D_b$

$\mathcal{E}$

$h (m)$
Hydraulic properties of foam-filled granular packing

Measurement of liquid permeability:

**Darcy method:**
- Inspired by methods for measuring the permeability of porous materials
- Imposed liquid fraction

**Darcy law:**
\[
\frac{Q}{S} = \frac{k_D}{\mu} \frac{\Delta P}{L}
\]

**Flow rate:**
\[
Q = -S_t \frac{dz}{dt}
\]

**Permeability of the confined foam:**
\[
k_f = \frac{k_D}{p}
\]

**Forced drainage method:**
- Inspired by methods for measuring the liquid permeability of foam

**Darcy law:**
\[
\frac{q_i}{S} = \frac{k_f}{\mu} \rho g
\]

**Volume conservation:**
\[
\varepsilon = \varepsilon_0 + \frac{q_i}{S v_f}
\]

- Bubbles are untrapped
- Bubbles are trapped

Column section \(S\)

Front velocity \(v_f\)

Flow rate \(Q\)

Pressure difference \(\Delta P\)

Density \(\rho\)

Viscosity \(\mu\)

Permeability \(k\)

Hydraulic conductivity \(k_f\)

Bubbles are trapped

Bubbles are untrapped