Modelling of microbial clogging in the subsurface

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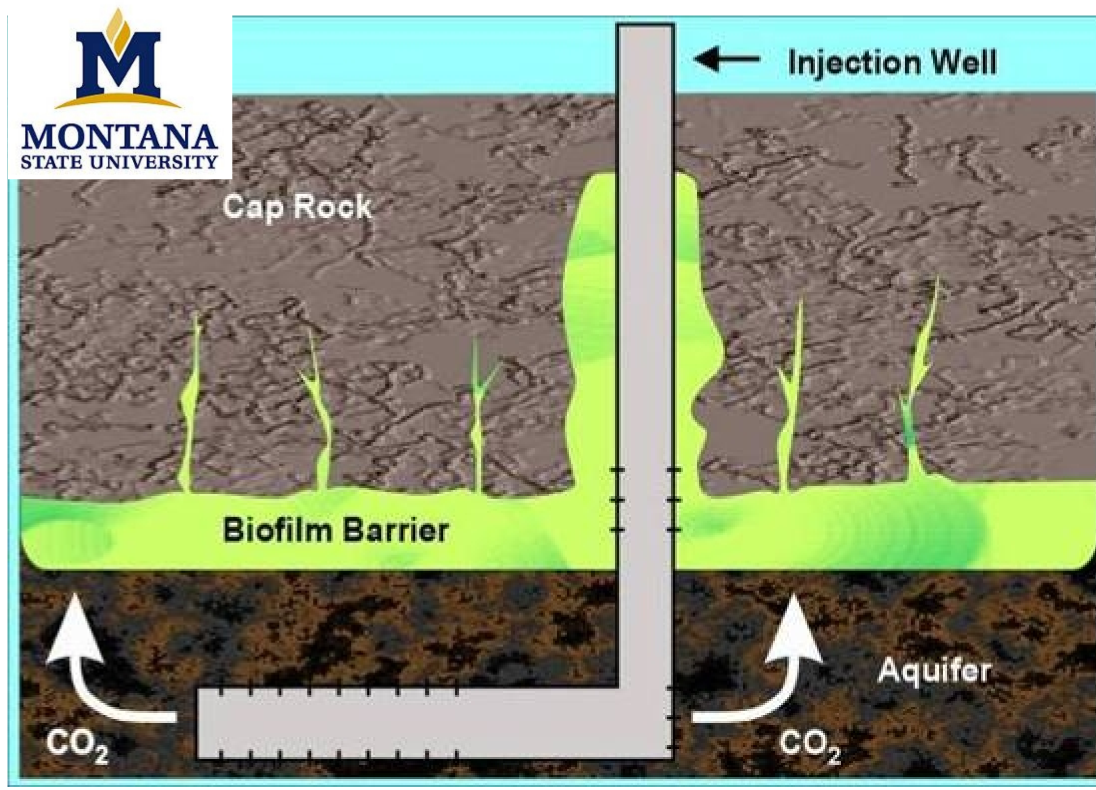
Biobarriers and CO_2 Storage

- CO_2 leakage mitigation using biofilms as hydraulic barriers.
- Plugging of fractures in injection well vicinity.
- Protection of well cement against corrosion.



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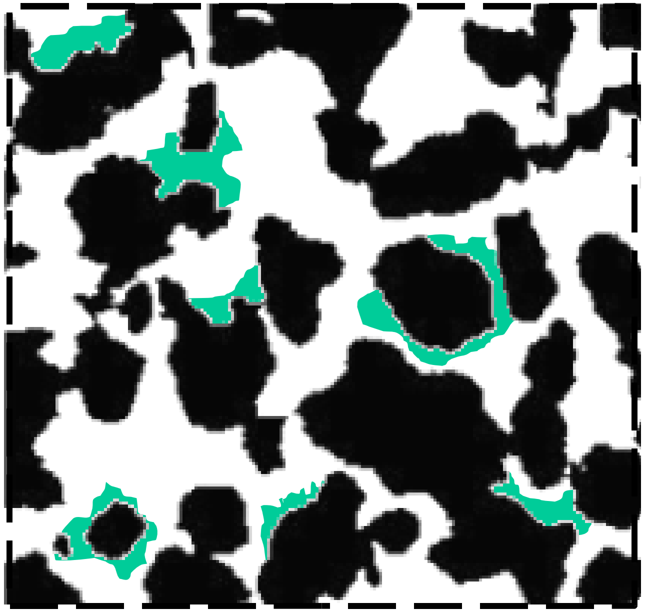
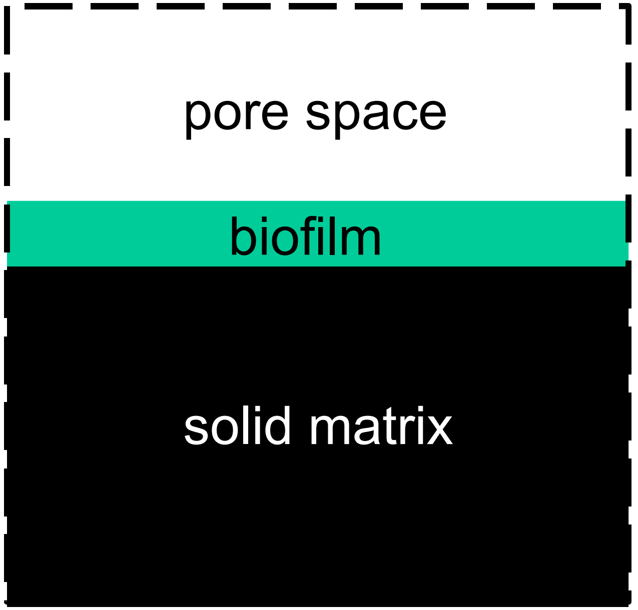
Outline

- Motivation
- Mathematical description
  - one-phase flow with biomass accumulation
- Model testing
- Outlook

Scale





$$\phi_w, \phi_f, M, K$$

Processes

- Transport
  - of microbial cells with bulk fluid
- Attachment
  - of microbial cells to solid surface
- Reproduction and decay
  - of floating and attached microbial cells (growth)
- Detachment
  - due to shear stress and nutrient depletion within biofilm
- Clogging
  - of porous medium due to biomass accumulation

Transport

Bacteria in water

$$J^b_{adv} = C^b_w \mathbf{v}_w$$

$$J^b_{disp} = -D^b_{pm} \nabla C^b_w$$

Substrate in water

$$J^s_{adv} = C^s_w \mathbf{v}_w$$

$$J^s_{disp} = -D^s_{pm} \nabla C^s_w$$

Velocity of water (Darcy)

$$\mathbf{v}_w = -\frac{1}{\mu_w} \mathbf{K}\left(\phi_f\right) \cdot \left(\nabla p - \rho_w \mathbf{g}\right)$$

Attachment (Deposition)

Attachment rate	$R_a = k_a \phi_w C_w^b$
Attachment coefficient *(Collector Filtration Theory)*	$k_a = \frac{3}{2} \frac{(1-\phi_w)}{d_g \phi_w} v_w \alpha \eta_0$
Collector contact efficiency	$\eta_0 = f(d_b, d_g, \phi_w, \mathbf{v}_w, T \ldots)$

Tufenkji & Elimelech, *Environ. Sci. Technol. 2004*

$$k_a = c_1 \phi_f + c_2$$

Taylor & Jaffé, *Water Resour. Res. 1990*

Growth and Decay

Growth rate
Biomass in water

$$Gr^b = (\mu - b) C_w^b \phi_w$$

Growth rate
Biomass in biofilm

$$Gr^f = \mu M L_f \rho_f - b \phi_f \rho_f$$

Growth coefficient

$$\mu = Yk \frac{C_w^s}{K_s + C_w^s}$$

Decay coefficient

$$b \quad \ldots \quad \text{const.}$$

Detachment

Detachment rate $$R_d = R_d^{\tau} + R_d^{\mu}$$

due to shear stress $$R_d^{\tau} = k_d^{\tau} \rho_f \phi_f$$

due to substrate utilisation $$R_d^{\mu} = k_d^{\mu} \mu M L_f^2$$

$$k_d^{\tau} = f(\tau^{0.58})$$

Rittmann, *Biotech. & Bioeng. 1981*

$$k_d^{\mu} = 63 - 454 \text{ cm}^{-1}$$

Peyton & Charaklis, *Biotech. & Bioeng. 1993*

Clogging

$$K/K_0 \quad = \quad (\phi_w/\phi_0)^{19/6}$$

Clement, T.P., Hooker, B.S. and Skeen, R.S. *Ground Water 1996*

$$K/K_0 \quad = \quad a\left(\frac{\phi_w/\phi_0 - \phi_{(K=0)}}{1-\phi_{(K=0)}}\right)^3 + (1-a)\left(\frac{\phi_w/\phi_0 - \phi_{(K=0)}}{1-\phi_{(K=0)}}\right)^2$$

Thullner, M., Zeyer, J. and Kinzelbach, W. *Trans. in Porous Media 2001*

$$K/K_0 = F(B)(1-B)^2 + (1-F(B))\, a/(a+B-aB)$$

$$F(B) = exp[-0.5(B/B_c)^2]$$

Vandevivere, P. *Biofouling 1995*

Mass Balance Equations

Biomass in water

$$\frac{\partial}{\partial t}\left(\phi_w C_w^b\right) + \nabla \cdot J_{adv}^b + \nabla \cdot J_{disp}^b - Gr^b - R_d + R_a = 0$$

Biomass in biofilm

$$\frac{\partial}{\partial t}\left(\phi_f \rho_f\right) - Gr^f + R_d - R_a = 0$$

Substrate

$$\frac{\partial}{\partial t}\left(\phi_w C_w^s\right) + \nabla \cdot J_{adv}^b + \nabla \cdot J_{disp}^s + Gr^b/Y + Gr^f/Y = 0$$

Water

$$\frac{\partial}{\partial t}\left(\phi_w \rho_w\right) + \nabla \cdot \left(\rho_w \mathbf{v}_w\right) = 0$$

Supplementary equations

Volume fractions

$$\phi_0 = \phi_w + \phi_f$$

Average biofilm length

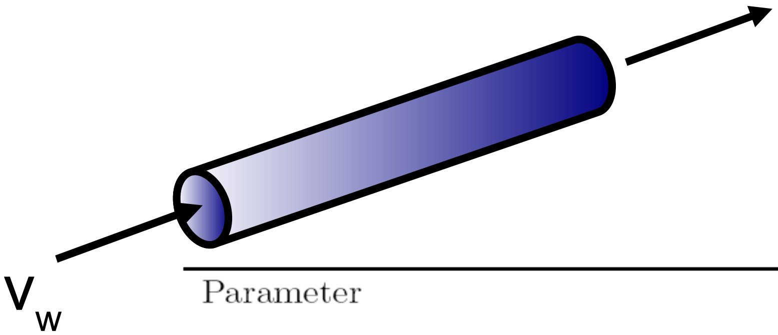
$$\frac{d\phi_f}{dL_f} = M$$

Interfacial area

$$\frac{M}{M_0} = \left(\frac{\phi_w}{\phi_0}\right)^{2/3}$$

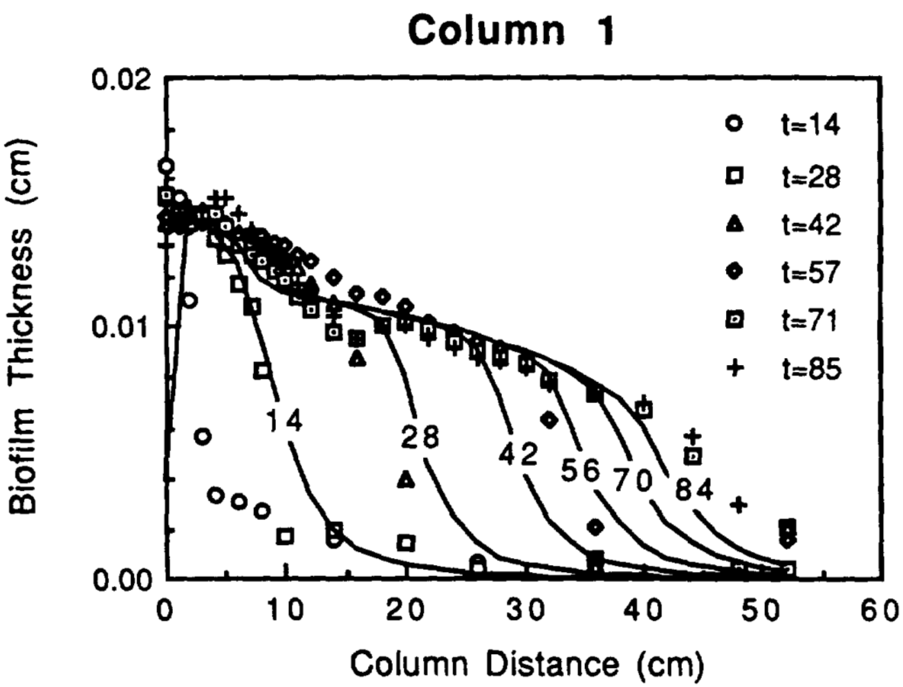
Clement, T.P., Hooker, B.S. and Skeen, R.S. *Ground Water 1996*

Experiments by Taylor & Jaffé (1990)



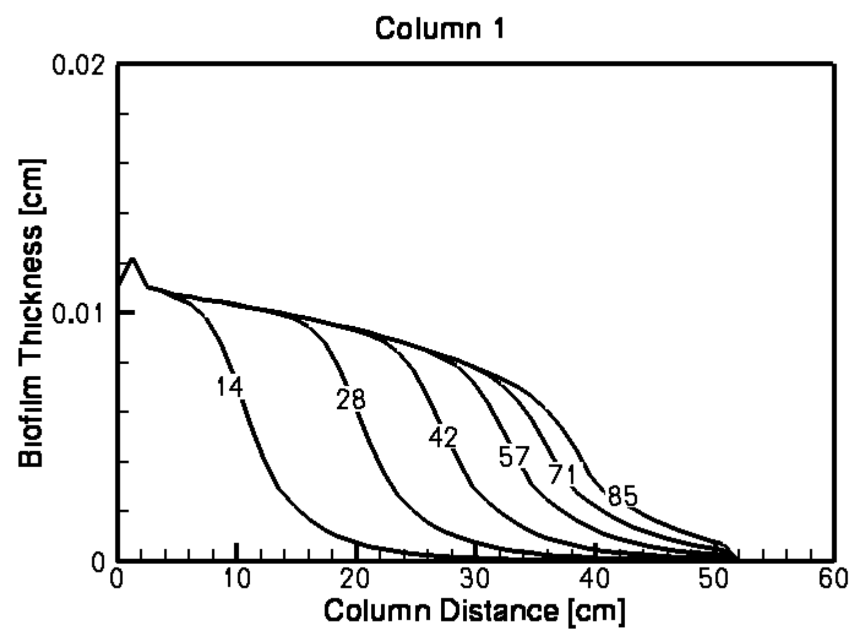
<table>
<tr><th rowspan="2">Parameter</th><th colspan="2">Value</th></tr>
<tr><th>Column 1</th><th>Column 2</th></tr>
<tr><td>Column length</td><td colspan="2">52 cm</td></tr>
<tr><td>Initial specific surface area M_0</td><td colspan="2">$48.5\,\mathrm{cm}^{-1}$</td></tr>
<tr><td>Initial porosity ϕ_0</td><td colspan="2">0.347</td></tr>
<tr><td>Initial permeability K_0</td><td colspan="2">$2.93 \times 10^{-10}\,\mathrm{m}^2$</td></tr>
<tr><td>Water viscosity μ_w</td><td colspan="2">$1.139 \times 10^{-3}\,\mathrm{Pa\cdot\ s}$</td></tr>
<tr><td>Maximum substrate utilisation rate k</td><td colspan="2">$8.912 \times 10^{-5}\,\mathrm{s}^{-1}$</td></tr>
<tr><td>Monod half-maximum rate concentration K_s</td><td colspan="2">$7.99 \times 10^{-4}\,\mathrm{kg/m}^3$</td></tr>
<tr><td>Yield coefficient Y</td><td colspan="2">0.0975</td></tr>
<tr><td>Decay rate b</td><td colspan="2">$3.1829 \times 10^{-7}\,\mathrm{s}^{-1}$</td></tr>
<tr><td>Darcy velocity v_w</td><td>$10.9375 \times 10^{-5}\,\mathrm{m/s}$</td><td>$3.6458 \times 10^{-5}\,\mathrm{m/s}$</td></tr>
<tr><td>Influent substrate concentration</td><td>$7.20 \times 10^{-3}\,\mathrm{kg/m}^3$</td><td>$5.59 \times 10^{-3}\,\mathrm{kg/m}^3$</td></tr>
<tr><td>Biofilm density ρ_f</td><td>$3.0\,\mathrm{kg/m}^3$</td><td>$2.5\,\mathrm{kg/m}^3$</td></tr>
<tr><td colspan="3">Parameters fitted by Taylor and Jaffé (1990)</td></tr>
<tr><td>Constants for attachment coefficient k_c</td><td colspan="2">$c_1 = 6810,\ c_2 = 635$</td></tr>
<tr><td>Coefficient for detachment rate R_s</td><td colspan="2">$f_b = 0.665$</td></tr>
</table>

Column 1: Biofilm thickness

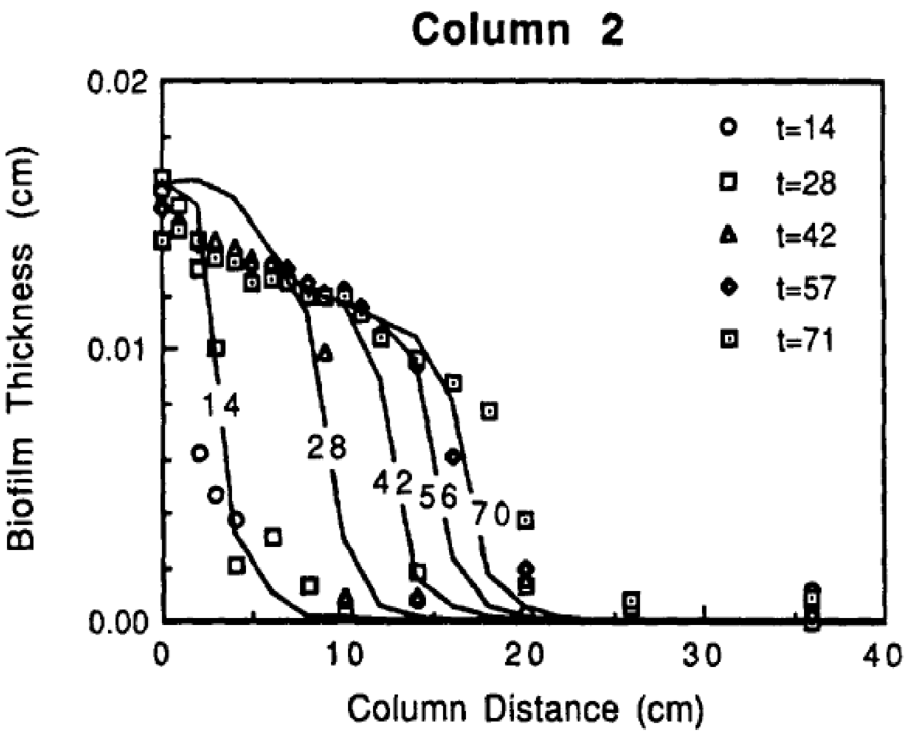


Taylor and Jaffé (1990)

presented model

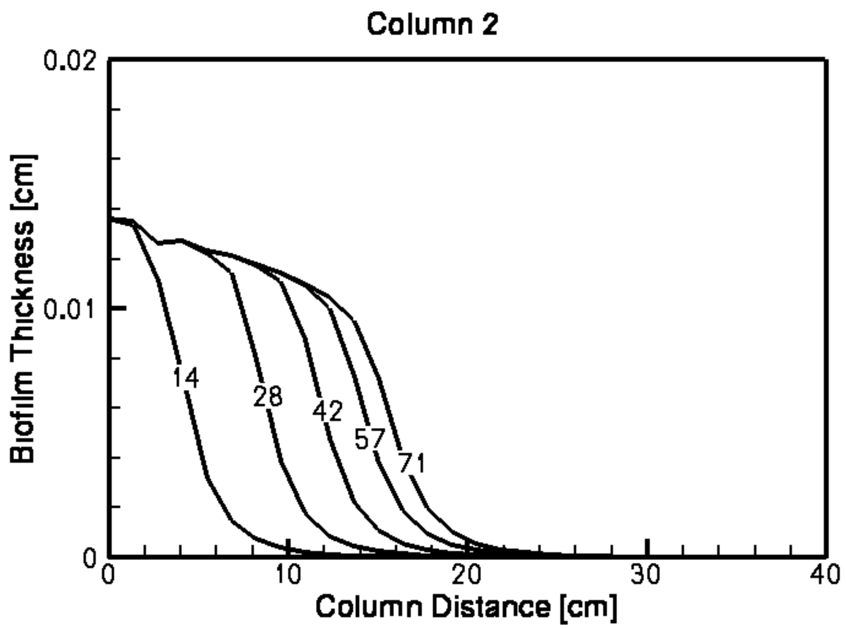


Column 2: Biofilm thickness



Taylor and Jaffé (1990)

presented model



Outlook: Extension to Two-Phase Flow

- Quantification of the
  - influence of the water-gas interface on the transport and deposition of microbial cells.
  - effect of supercritical CO_2 on the biofilm.
  - effect of the biofilm on capillary pressure.
- Code verification with experiments.
- Simulation of CO_2 injection scenarios with biofilm growth.