Spatio-temporal modelling of filter cake formation in membrane bioreactors

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Survey on technical issues hampering MBR

http://www.thembrsite.com/
Fouling models show lack of knowledge


<table>
<thead>
<tr>
<th>Reference</th>
<th>Resistances in series decomposition</th>
<th>Partial resistance models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broeckmann et al., 2006</td>
<td>$R = R_m + R_c + R_p + R_{ct}$</td>
<td>$R_m$: Darcy’s law&lt;br&gt;$R_c$: Broeckmann et al. (2006)&lt;br&gt;$R_p$: Broeckmann et al. (2006)&lt;br&gt;$R_{ct}$: Wintgens et al. (2003)</td>
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<td>Busch et al., 2007a</td>
<td>$R = R_m + R_c + R_p + R_b$</td>
<td>$R_m$: Darcy’s law&lt;br&gt;$R_c$: Broeckmann et al. (2006)&lt;br&gt;$R_p$: Broeckmann et al. (2006)&lt;br&gt;$R_b$: Busch et al. (2007a)</td>
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<td>Drews et al., 2009</td>
<td>$R = R_m + R_c + R_{in} + R_{com} + R_{ct}$</td>
<td>$R_m$: Darcy’s law&lt;br&gt;$R_{in}$: Chudacek and Fane (1984); Elmaleh and Ghaffor, 1996&lt;br&gt;$R_{com}$, $R_{ct}$: Hermia (1982)</td>
</tr>
<tr>
<td>Khan et al., 2009</td>
<td>$R = R_m + R_c + R_f$</td>
<td>$R_m$: Darcy’s law (clean water)&lt;br&gt;$R_c$: Darcy’s law (at end of filtration)&lt;br&gt;$R_f$: Darcy’s law (after cake layer removal)</td>
</tr>
<tr>
<td>Ludwig et al., 2011</td>
<td>$R = R_m + R_c + R_f$</td>
<td>$R_m$: not mentioned&lt;br&gt;$R_c$: Ludwig et al. (2011)&lt;br&gt;$R_f$: Geissler et al. (2005)</td>
</tr>
</tbody>
</table>
TMP jump hypotheses illustrate knowledge gap

- inhomogeneous fouling (area loss) model
- inhomogeneous fouling (pore loss) model
- critical suction pressure
- percolation theory
- ...


Spatio-temporal modelling

Computational Fluid Dynamics (CFD)

Agent/Individual Based Model (ABM/IBM)
Force balance: Maxey-Riley equation

\[ F_{\text{lift}} \quad \text{Lift force} \\
F_{\text{am}} \quad \text{Added mass force} \\
F_{\text{drag}} \quad \text{Drag force} \\
F_{g} \quad \text{Gravitational force} \\
F_{\text{arch}} \quad \text{Archimedes force} \\
F_{\text{hist}} \quad \text{History force} \\
F_{p} \quad \text{Pressure force} \\

\text{Partially implicit}
Adhesion model

\[ p = e^{\uparrow} - k \cdot U \downarrow p \]
Bottom-up approach means assumptions

» Particles are uniform, rigid, perfect spheres
» No particle interactions in bulk phase
» Steady-state hydrodynamics
Case study: tubular membrane

» Pentair X-flow
  › Diameter = 8 mm
  › Length = 30 cm
  › Cross-flow = 0.01 m.s\(^{-1}\)
  › Flux = 36 LMH
  › MLSS = 10 g.L\(^{-1}\)
  › \(\Delta t = 10^{-4}\) s
  › \(d_p = 50\) µm
Case study: fluid flow

Velocity X-direction (m/s)

Velocity Y-direction (m/s)
Case study: particle motion
Direct observation of fouling

Direct observation of fouling layer formed by alginate/bentonite particle solution on microfiltration hollow fiber

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Influence of “stickyness” by scenario analysis

Mean cake thickness

Cake thickness [m]

$t$ [s]

CF $1 \text{ m/s}$
Influence of particle size by scenario analysis

Mean cake thickness

Cake thickness [m]

CF 1 m/s
Hypothesis of cut-off diameter confirmed


<table>
<thead>
<tr>
<th>$D_p$</th>
<th>50 µm</th>
<th>$D_p$</th>
<th>10 µm</th>
</tr>
</thead>
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<tr>
<td>CF</td>
<td>0.1 m/s</td>
<td>CF</td>
<td>0.1 m/s</td>
</tr>
<tr>
<td>Flux</td>
<td>$10^{-5}$ m/s (36 LMH)</td>
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Calibration and validation?

» Chromatic white light sensor (CWS)
MBR sludge: filaments & sludge flocs
MBR sludge: large sample
Conclusions

» Literature lacks consensus on fouling mechanisms
» Bottom-up modelling approach to build knowledge
» Adhesion probability by momentum influences results
» MLSS and flux similarly increase mean cake thickness
» Cake layer thickness most sensitive to particle diameter
» Confirmation of cut-off diameter hypothesis as upper bound to particle’s fouling potential
What’s up next?

» Particle size distributions
» Force balance on particles in cake
» Dynamic continuous phase
» Contact model for bulk collisions
» Modelling of membrane pores
model-based analysis and optimization of bioprocesses

Kinetic model
Modelling of process dynamics

Impact of spatial heterogeneity on process kinetics

Impact of distributed versus lumped kinetics

Computational Fluid Dynamics (CFD)
Modelling hydrodynamics

Population Balance Model (PBM)
Modelling of distributed population properties

Impact of flow properties on distributed property of a population
model-based analysis and optimization of bioprocesses

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\[ m \downarrow p \frac{d}{dt} \mathbf{U}_p(t) = \]

\[ -3 \pi \eta \downarrow p (\mathbf{U}_r - \frac{1}{24} \downarrow p^2 \nabla^2 \mathbf{U}_c) \]

\[ + (m \downarrow p - V \downarrow p \rho \downarrow f) g \]

**Drag force**

\[ - \frac{1}{2} V \downarrow p \rho \downarrow f \left( \frac{d \mathbf{U}_r}{dt} - \frac{1}{40} \downarrow p^2 \frac{d}{dt} (\nabla^2 \mathbf{U}_c) \right) \]

**Gravity and Archimedes force**

\[ - V \downarrow p \nabla p \]

\[ - \frac{3}{2} \sqrt{\pi} \eta \downarrow f \downarrow p^2 \int_0^t d(t) (\mathbf{U}_r(t) - \frac{1}{24} \downarrow p^2 \nabla^2 \mathbf{U}_c) \]

\[ \left( \tau \right) / dt / \sqrt{t - \tau} \ dt \]

**Added mass force**

**Pressure force**

\[ - 1.615 \rho \downarrow f \downarrow p^2 \left( \mathbf{U}_r - \frac{1}{24} \downarrow p^2 \nabla^2 \mathbf{U}_c \right) \sqrt{v |\kappa|} \ sgn(\kappa) \]

**History force**

**Lift force**
MBR sludge: large sample
Influence of parameters by scenario analysis

Mean cake thickness

- 45μm
- 50μm
- 55μm

Cake thickness [m]

CF 1 m/s