Effect of wall shear rate on wall flux of bacteria

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Industrial partners

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Introduction

• Bacteria in drinking water: migration to the wall -> biofilm?
• Formation mechanisms of biofilm? How to investigate?
• Test sections
• Transport equations
• Results
• Bacteria adhesion at the wall (cohesion of biofilm)
• Cleaning the surface colonized by biofilm
• Conclusions
Bacteria and deposits = Biofilm

Drinking water bacteria and deposits

**Multispecies**: Bacteria, fungi, ...

- **Brown deposits**
- **Bacteria**

- **Organic matter**: 20 to 100 µg TOC/cm²

- **Metals (µg/cm²)**:
  - Fe: 13.6
  - Cu: 6.4
  - Others: 117.0

**Carbonates**

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Drinking water biofilms (4 months old)

DAPI

Amoeba

Calcofluor

Sybr-II

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Organic matter molecules (500 à 5000 Daltons)

$D = 3 \times 10^{-10} \text{m}^2/\text{s}$

Wall activities

- Diffusion
- Rebound and lifting
- Diffusion

growth and cell proliferation

Complex diffusion
Phenomenological variables - mass transfer

Bacteria

Close the wall

\[ Pe = \frac{\gamma d^2}{D} \]

\[ D \approx 310^{-13} \text{ m}^2 / \text{s} \]

\[ 10 \text{ s}^{-1} < \gamma < 10^3 \text{ s}^{-1} \]

\[ 33 < Pe < 340 \]

Virus

\[ D \approx 1.410^{-11} \text{ m}^2 / \text{s} \]

\[ 0.0007 < Pe < 0.07 \]

Diffusion boundary layer

\[ \delta^* = \delta \left( \frac{\gamma}{\nu} \right) = 3.68 \sqrt{\frac{D}{\nu}} Pe^{\frac{1}{6}} \]

\[ \delta = 1.5 \mu \text{m}, D = 310^{-13} \text{ m}^2 / \text{s} \]
Transport equation

\[ \vec{J} = C \vec{V} - D \vec{\nabla} C \]

\[ \frac{\partial C}{\partial t} + \text{div} \, \vec{J} = 0 \quad \Rightarrow \quad \frac{\partial C}{\partial t} + \vec{V} \cdot \vec{\nabla} C = D \Delta C \]

\[ \frac{\partial C}{\partial t} + \vec{V} \cdot \vec{\nabla} C = D \Delta C \]

\[ \begin{cases} 
C = 0 \quad \text{for } y = 0 \text{ (active wall)} \\
C = C_0 \quad \text{for } y \to \infty \text{ (bulk)} \\
\frac{dC}{dy} \bigg|_{y=0} \quad \text{for } y = 0 \text{ (Inert wall)}
\end{cases} \]
Transport equation

In permanent regime

\[ y \gamma \frac{\partial C}{\partial x} - \frac{y^2}{2} \frac{d \gamma}{dx} \frac{dC}{dy} = D \frac{d^2 C}{dy^2} \]

\[ \frac{C}{C_0} = \frac{1}{\Gamma(4/3)} \int_{0}^{\eta} \exp(-\xi^3) d\xi \quad \text{avec} \quad \eta = y \sqrt{\gamma} \left[ 9D \int_{0}^{x} \sqrt{\gamma} \, dx \right]^{1/3} \]

\[ \Phi = \int_{y=0} D \frac{dC}{dy} \, dA = \frac{3}{2} \frac{C_0 D L}{\Gamma(4/3)} \frac{1/3}{9^{1/3}} \left[ \frac{\gamma d_0^2}{D} \right]^{1/3} = 0.807 \; C_0 A_0 \left( \frac{\gamma D^2}{d_0} \right)^{1/3} \]
Transport equation

\[ \Phi = 0.807 \, C_0 A \left( \frac{\gamma D^2}{d_0} \right)^{1/3} \]

Wall flux

\[ \Phi = \frac{d \left( \nu_f v_0 \right)}{dt} = 0.807 \, C_0 \frac{A_f}{A_0} \alpha_1 \left( 1 - \frac{A_f}{A_0} \right) \left( \frac{\gamma D^2}{d_0} \right)^{1/3} \]

Coefficient characterizing wall surface

Coefficient characterizing colonized surface

Probability of effective shocks

\[ \beta = \frac{A_f}{A_0} \]
Transport equation

The number of bacteria/unit surface ($N^*$) deposited is related to an adimensional time $t^*$

$$t^* = \left( \frac{\gamma D^2}{d_0} \right)^{1/3} t$$

$$N^* = \frac{\alpha_2 s_0}{\alpha_1} + s \exp \left[ -0.807 \frac{\alpha_1 s_0 C_0}{v_0} t^* \right]$$

Characterize the saturation

Characterize the initial state of the wall

Characterize the accumulation kinetic
Test sections

- Plexiglas block
- Gasket
- Microscope slide

Diagram showing flow in and out, vacuum port, inlet slit, outlet slit, holes to connect vacuum, water inlet, water outlet, coupon, propeller, inner cylinder, blade, PVC (PN16), and control temperature.
Test sections

Cylinder Inner cylinder Coupon Divergent 3 cm

Outer cylinder

Divergent

Test sections

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Test sections

Biofilms 2 months old at 4 wall shear rates

Increasing the wall shear rate led to a space organization of bacteria deposition.
Test sections

Grazing by Amoeba

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Test sections

- **Outer cylinder**
- **Inner cylinder**
- **Case of null Wall shear rate**
- **No bacteria on the wall of outer cylinder**
Conclusions on wall flux

Bacteria in drinking water: migration to the wall -> biofilm?

No wall shear rate -> no bacteria on the wall
Even if the Peclet number is high -> Convection – diffusion works

\[ N^* = \frac{1}{\frac{\alpha_2 s_0}{\alpha_1} + s \exp \left[ -0.807 \frac{\alpha_1 s_0 C_o}{v_0} t^* \right]} \]
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Results

![Graph showing results](image)

- \( n_f (x 10^6 \text{ Particles/cm}^2) \)
- Wall shear rate = 35 s\(^{-1}\)
- Wall shear rate = 142 s\(^{-1}\)
- Wall shear rate = 353 s\(^{-1}\)
- Wall shear rate = 558 s\(^{-1}\)
- Wall shear rate = 711 s\(^{-1}\)
Results

<table>
<thead>
<tr>
<th></th>
<th>Phase 1</th>
<th>Phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>alpha 1</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>alpha 2</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>$S_0$</td>
<td>$8 \times 10^{-6}$</td>
<td>$1 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

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Bacteria adhesion at the wall (cohesion of biofilm)
Measurement technique

AFM ⇒ an application of the scanning tunneling microscope (STM):

- Imaging samples surface in various environments

In the last decade ⇒ experiencing boom of AFM in nanosciences and life sciences:

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AFM technique

Panorama of measurable forces in AFM

Atomic force spectroscopy:
- Combination of imaging and force measurements
- Mapping reconstruction with spatially resolved physical parameter value for each pixel
- Which physico-chemical parameters can be extracted from the AFM force-curves?
AFM: Cohesion of drinking water biofilm clusters

Scanning surface by AFM ($F^\uparrow$)

Determination of the critical elastic modulus

Young modulus
0 MPa 10 MPa

Stratification of the cluster structure

Water drinking biofilm

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The rate of entanglement $\xi$ is a factor of cohesion linked to the volume and elasticity of the clusters.

$G. \text{De Genne}$

$\varepsilon$ : coherence length

$\xi = 1 - \varepsilon / L$

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AFM : Cohesion of clusters in biofilm drinking water

\[ W_{elas} \approx G L^3 \approx G \xi d^3 \approx G \xi^3 V_{cluster} \quad \text{avec} \quad \begin{cases} G : \text{Shear modulus elasticity} \\ \xi : \text{rate of entanglement in cluster} \\ V_{cluster} : \text{volume of cluster} \end{cases} \]

\[ W_{elas} = k_B T \quad \text{avec} \quad \begin{cases} k_B = 1.38 \times 10^{-23} \text{ m}^2 \text{ kg/s}^2 / \text{K} \quad \text{Bolzmann constante} \\ T : \text{absolute temperature} \end{cases} \]

At the limit of cohesion, cluster we can put:

\[ G \xi^3 V_{cluster} = k_B T \implies V_{cluster} = \frac{k_B T}{\xi^3 G} \quad k_B T = 4 \times 10^{-24} \text{ m}^2 \text{ Kg/s}^2 / \text{K} \]

\[ V_{cluster} \text{ and } G \text{ given by AFM} \]
AFM: Cohesion of clusters in biofilm drinking water

$V_{\text{cluster}} = f(\text{Elasticity})$

Biofilm 4 weeks old

$\xi = 1.07 \times 10^{-3}$
Cohesion of clusters in biofilm drinking water

Exopolymers in drinking water biofilms ... ... govern the elastic deformation of the clusters

Hydrophobic domains

Number of entanglement points $10^9$/mm$^3$

Aldeek et al., AEM, 2013
(Biofilm of Shewanella oneidensis)

(Miquelard-Garnier et al., 2007)

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The rate of entanglement $\xi$ is a factor of cohesion linked to the volume and elasticity of the clusters.

Drinking water biofilms behave like a viscoelastic solid.

Number of entanglement points $10^8$ to $10^9$/mm$^3$
Mean shear stress in volume of cluster V:

\[
\sigma_{ij} = \sigma_{ij}^f C (1 - \xi) + \sigma_{ij}^b C \xi
\]

\[
\tau = \mu C (1 - \xi) \frac{d\alpha}{dt} + GC \xi \alpha
\]

**Creep function**

\[
f(t) = \frac{1}{G \xi} \left(1 - e^{-\frac{t}{\theta}}\right)
\]

with \( \theta = \frac{\mu}{G \xi} \)

\[
\xi = 1 - \frac{\epsilon}{L}
\]
Cleaning the surface colonized by biofilm
hydrodynamic shear stress vs cluster volume

Elastic limit before removing clusters:
\[ \mu \frac{d\alpha}{dt} C (1 - \xi) = \mu \gamma C (1 - \xi) = G C \xi \alpha_{\text{max}} \]

Strain rate \( \alpha_{\text{max}} = 100\%: \)
\[ \tau_{\text{hyd}} = \mu \gamma = \frac{G \xi}{1 - \xi} \]

City network drinking water distribution \( \tau < 30 \text{ Pa} \)

Removable clusters vs hydrodynamic shear stress

- Red line: Biofilm 4 weeks old
- Blue line: Biofilm 9 weeks old

Non removable clusters
Removable clusters

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Conclusions

• Biofilm formation – convective diffusion
• Strong adhesion at the wall (AFM measurements)
• Cleaning the surface colonized by biofilm with only hydrodynamic shear stress → volume clusters <100µm³ not removable
• Perspective: diffusion of nutrients on biofilm - population balance (growth, mortality and partial detachment)
THANK YOU FOR YOUR ATTENTION


\[ V = \left. y \frac{dV}{dy} \right|_{y=0} = y \gamma \]

**Diffusion boundary layer**

- Inert wall
- Active wall

\[ C(x,y) \]

\[ C=0 \]

\[ \delta_b \]