Effect of wall shear rate on wall flux of bacteria

S. Skali Lami, Y. Abe, G. Francius and J.C Block

UNIVERSITÉ DE LORRAINE

Industrial partners

COST FP1005 "Fibre Suspension Flow Modelling" - ERCOFTAC SIG43 "Fibre suspension flows".
Coimbra – March 2013

Introduction

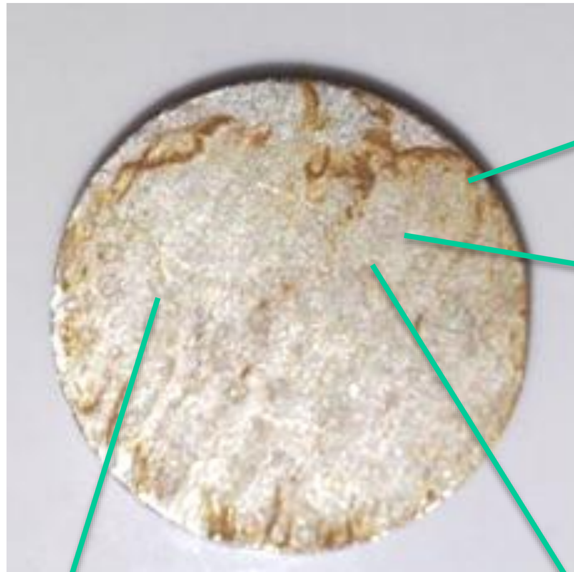
- Bacteria in drinking water : migration to the wall -> biofim ?
- Formation mechanisms of biofilm ? How to investigate?
- Test sections
- Transport equations
- Results
- Bacteria adhesion at the wall (cohesion of biofilm)
- Cleaning the surface colonized by biofilm
- Conclusions

Bacteria and deposits = Biofilm

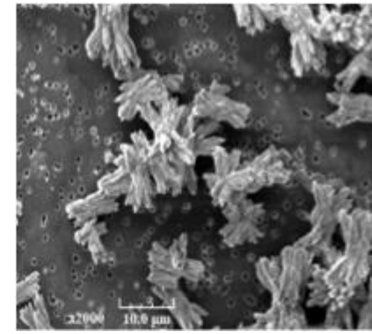
Drinking water bacteria

and

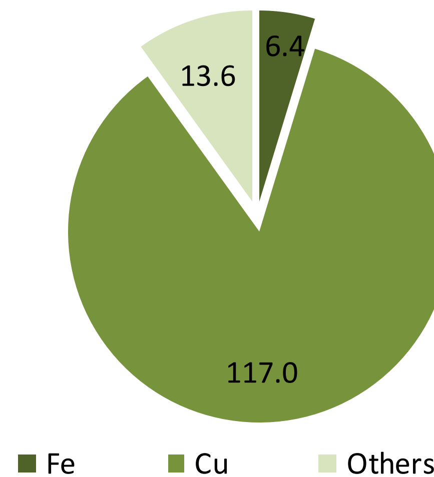
deposits



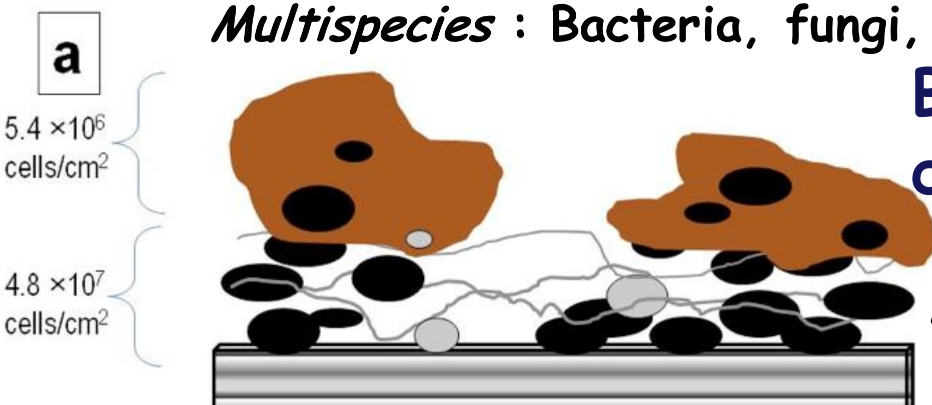
Carbonates



Metals (µg/cm²)



Multispecies : Bacteria, fungi, …



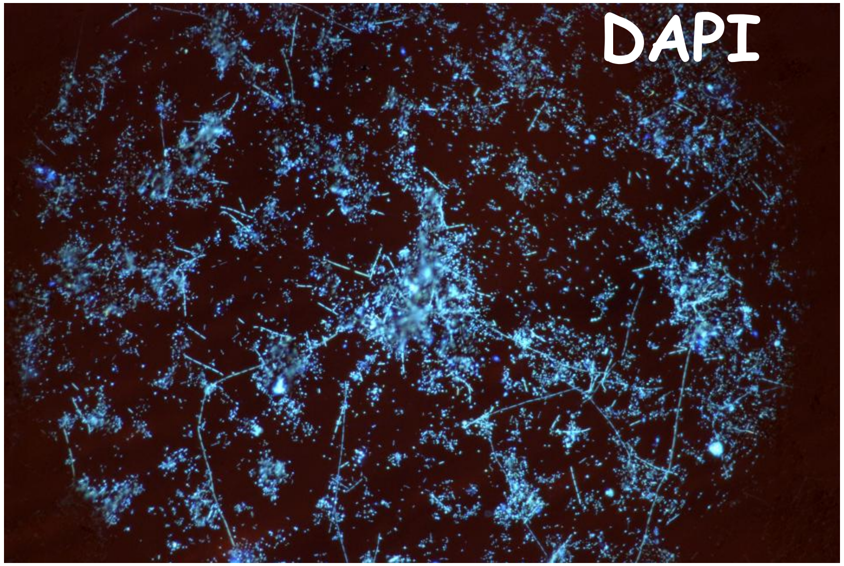
Brown deposits

Bacteria

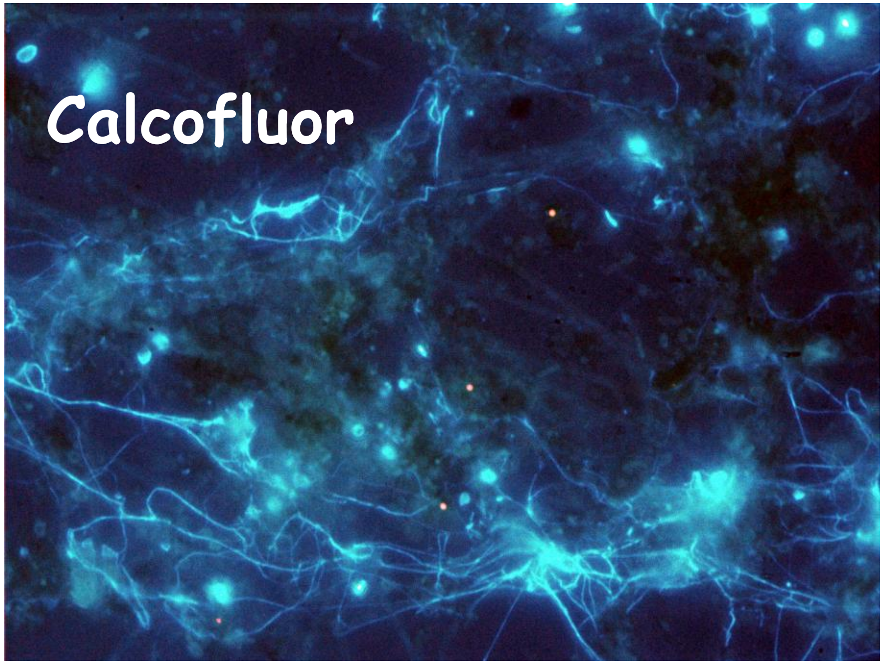
Organic matter :

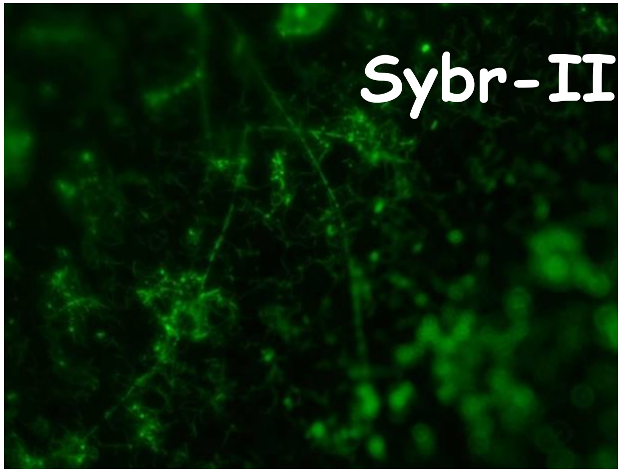
20 to 100 µg TOC/cm²

Drinking water biofilms (4 months old)

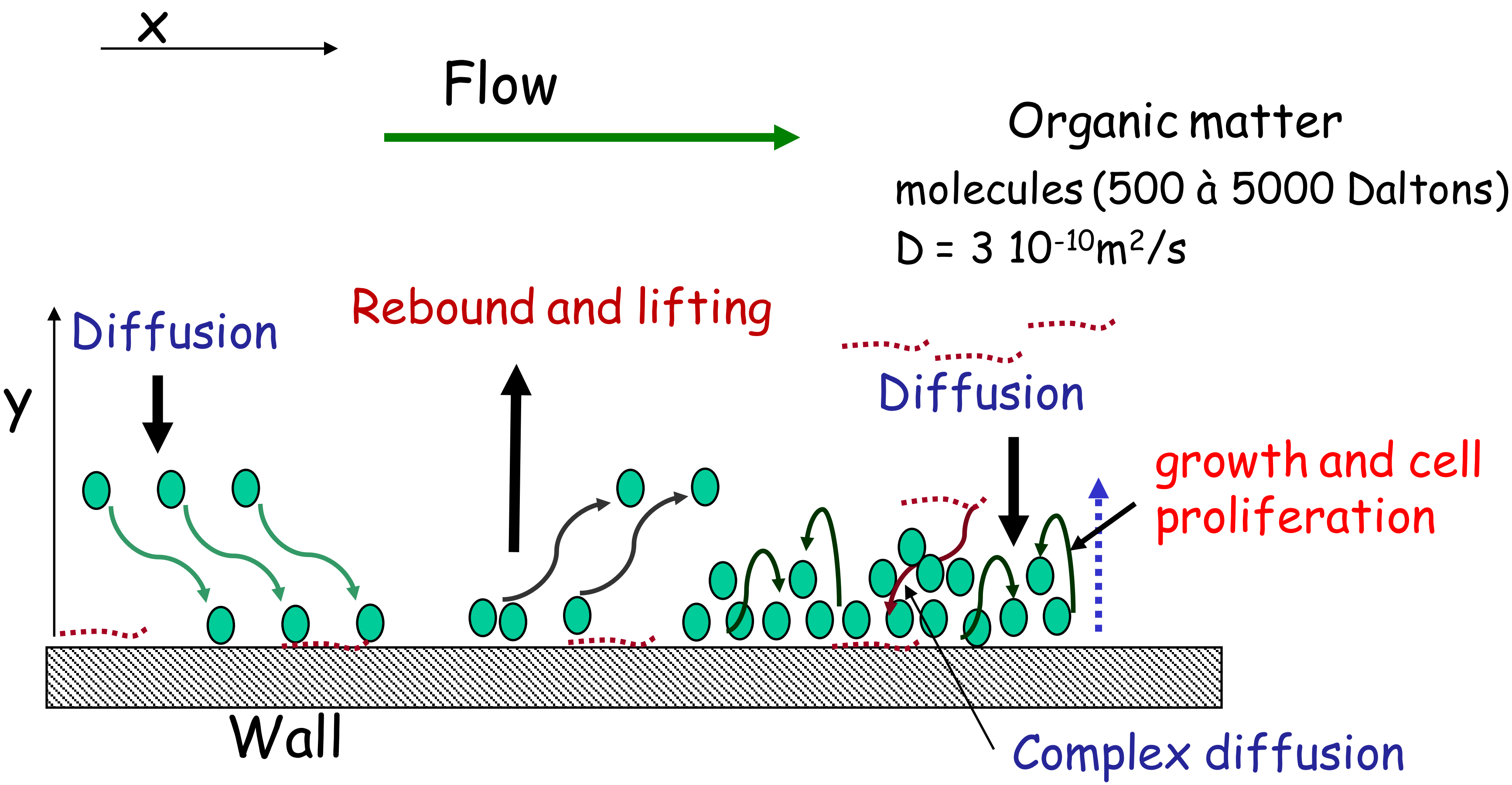


Amoeba





Wall activities



Phenomenological variables – mass transfer

Bacteria

$$D \approx 3\,10^{-13}\, m^2/s$$

Close the wall

$$Pe = \frac{\gamma d^2}{D}$$

$$10\, s^{-1} < \gamma < 10^3\, s^{-1}$$

$$33 < Pe < 340$$

$$D = \frac{kT}{6\pi\mu R}$$

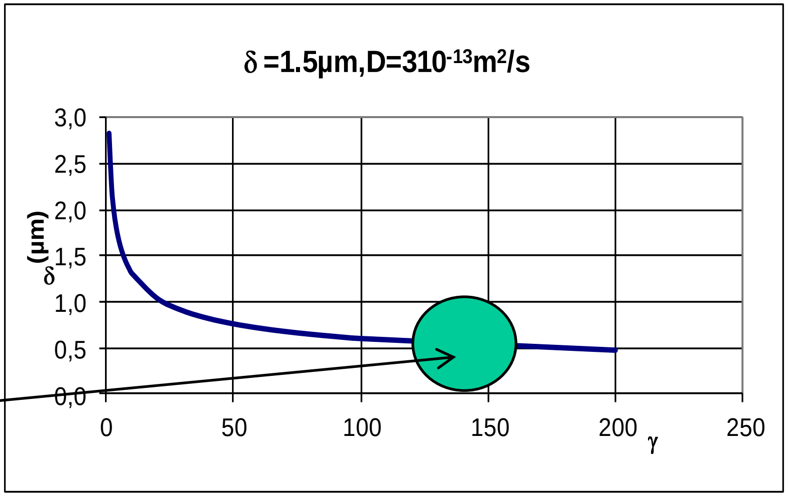
Virus

$$D \approx 1.4\,10^{-11}\, m^2/s$$

$$0.0007 < Pe < 0.07$$

Diffusion boundary layer

$$\delta^* = \delta\sqrt{\frac{\gamma}{\nu}} = 3.68\sqrt{\frac{D}{\nu}}Pe^{\frac{1}{6}}$$



Bacteria

Transport equation

$$\vec{J} = C\vec{V} - D\vec{\nabla}C$$

$$\frac{\partial C}{\partial t} + div\,\vec{J} = 0 \quad \Rightarrow \quad \frac{\partial C}{\partial t} + \vec{V}\left(\vec{\nabla}C\right) = D\,\Delta C$$

$$\frac{\partial C}{\partial t} + \vec{V}\left(\vec{\nabla}C\right) = D\,\Delta C \begin{cases} C = 0 \quad for\, y = 0 \;(active wall) \\ C = C_0 \quad for\ y \to \infty \;(bulk) \\ \left.\dfrac{dC}{dy}\right|_{y=0} \quad for\ y = 0 \;(Inert\, wall) \end{cases}$$

Transport equation

In permanent regime

$$y\gamma \frac{\delta C}{\delta x} - \frac{y^2}{2}\frac{d\gamma}{dx}\frac{dC}{dy} = D\frac{d^2 C}{dy^2}$$

$$\frac{C}{C_o} = \frac{1}{\Gamma(4/3)}\int_0^{\eta} \exp(-\xi^3)\, d\xi \quad \text{avec} \quad \eta = y\sqrt{\gamma}\left[9D\int_0^x \sqrt{\gamma}\, dx\right]^{\frac{1}{3}}$$

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

Transport equation

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

Coefficient characterizing wall surface

Coefficient characterizing colonized surface

Probability of effective shocks

$$\beta = \frac{A_f}{A_o}$$

$$A = \alpha_1 A_0 - \alpha_2 A_f$$

Wall flux

$$\Phi = \frac{d\left(N_f v_0\right)}{dt} = 0.807\, C_0 \frac{A_f}{A_0} A_0 \left(\alpha_1 - \alpha_2 \frac{A_f}{A_0} \right) \left(\frac{\gamma D^2}{d_0} \right)^{1/3}$$

Transport equation

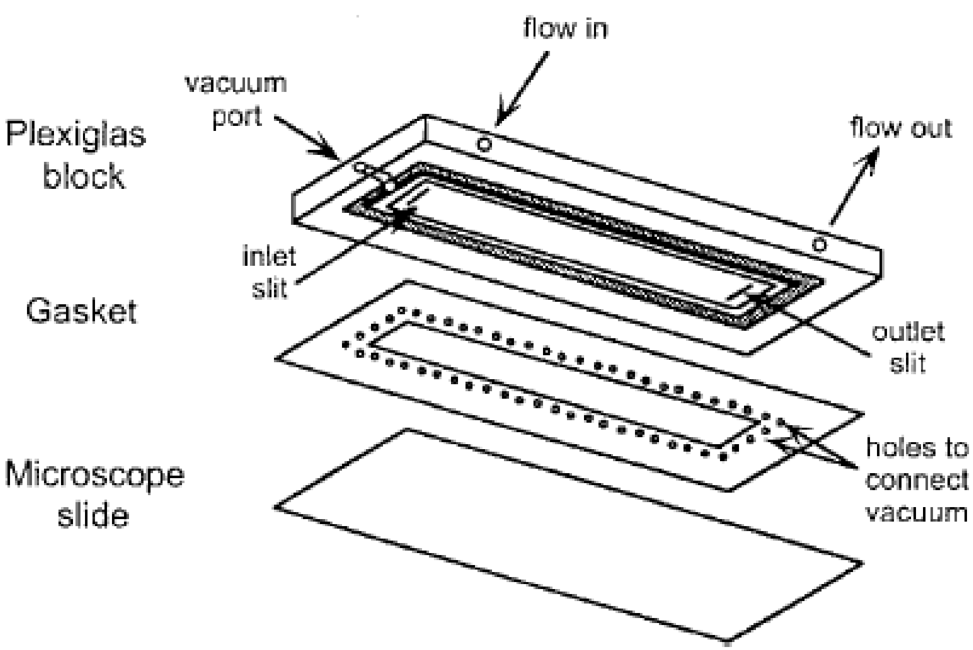
The number of bacteria/unit surface (N*) deposited is related to an adimensional time t*

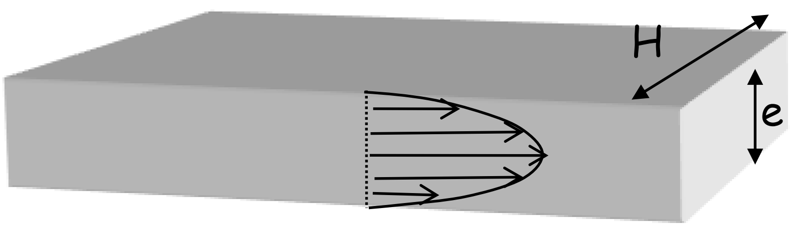
$$t^* = \left(\frac{\gamma D^2}{d_0} \right)^{1/3} t$$

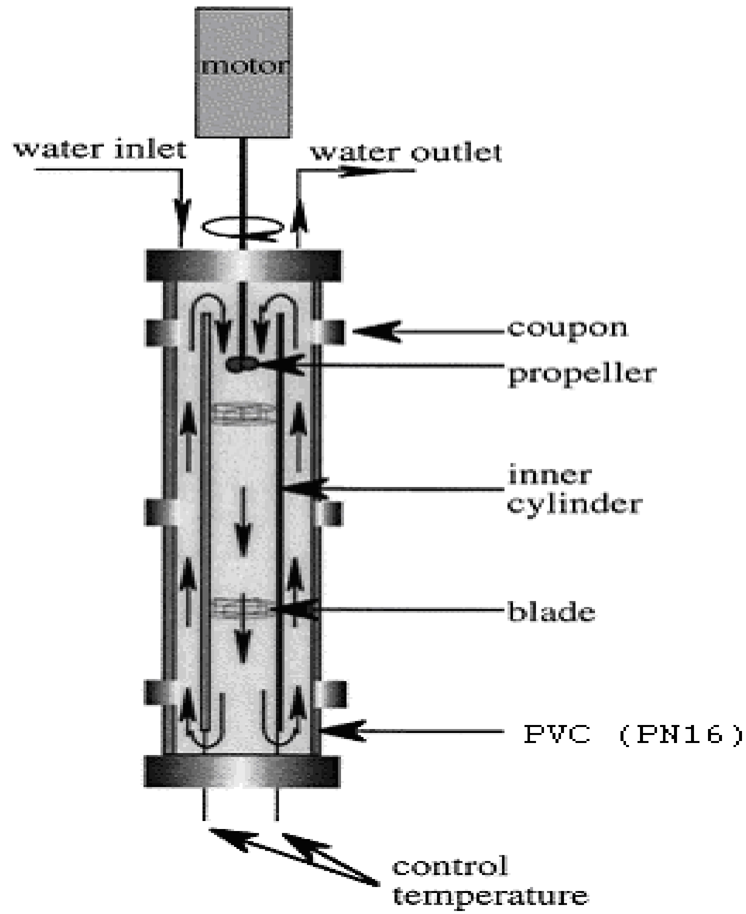
$$N^* = \frac{1}{\dfrac{\alpha_2 \; s_0}{\alpha_1} + s \, exp\left[-0.807 \dfrac{\alpha_1 \, s_0 \; C_o}{v_0} t^* \right]}$$

- Characterize the saturation
- Characterize the initial state of the wall
- Characterize the accumulation kinetic

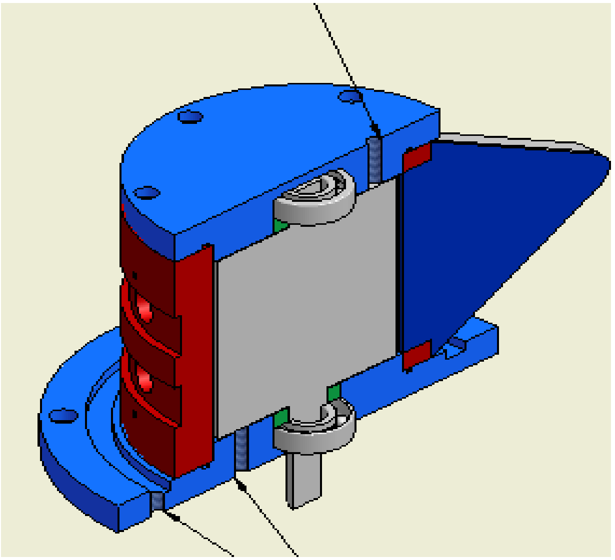
Test sections

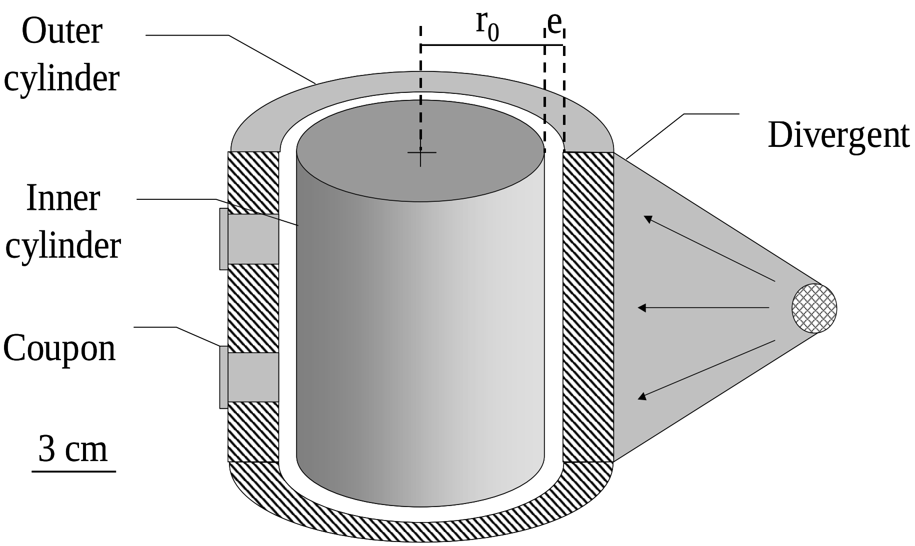


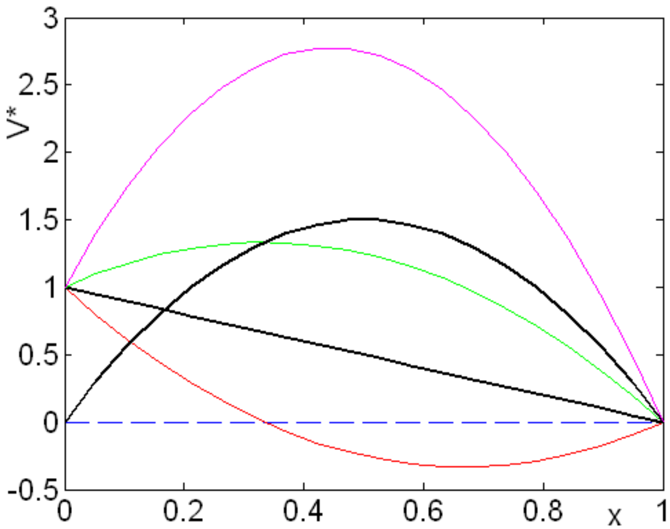


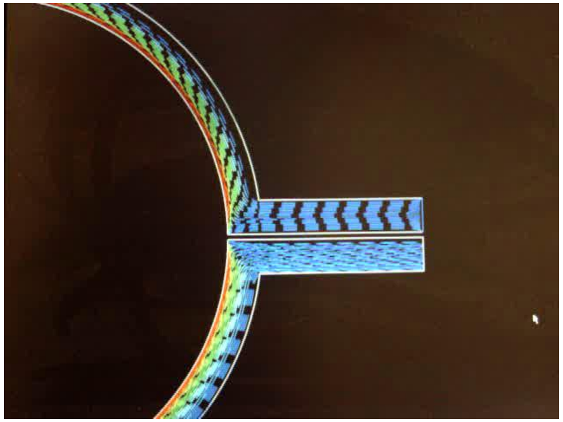


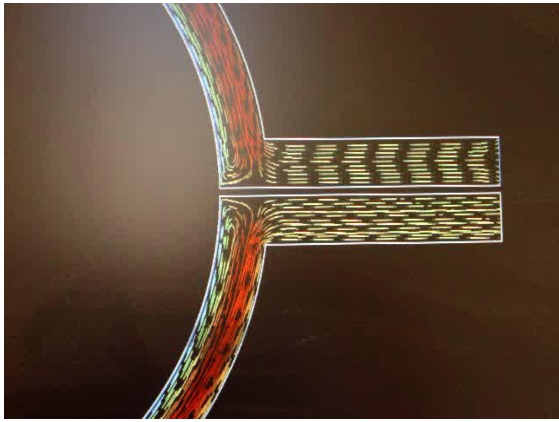
Test sections



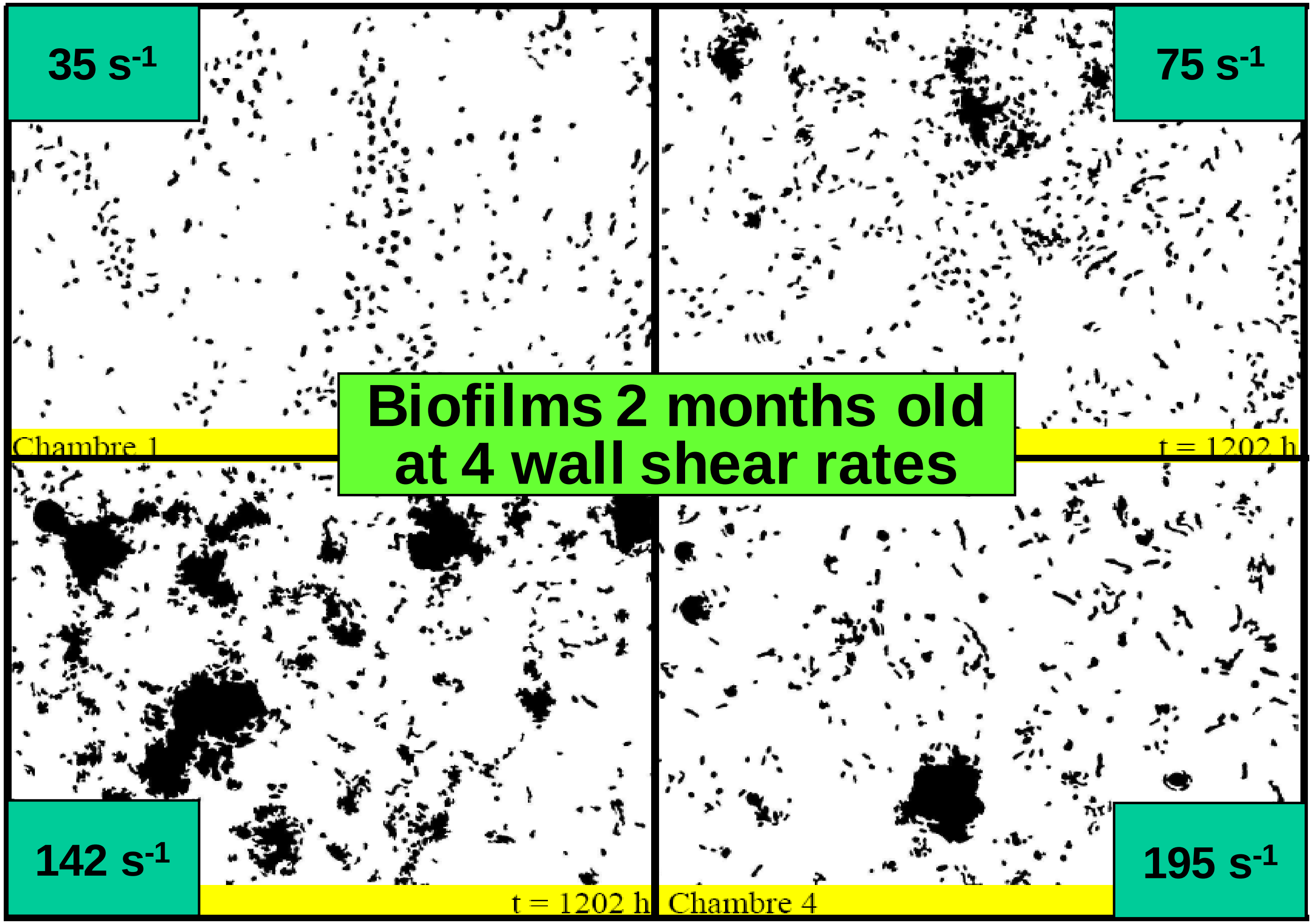






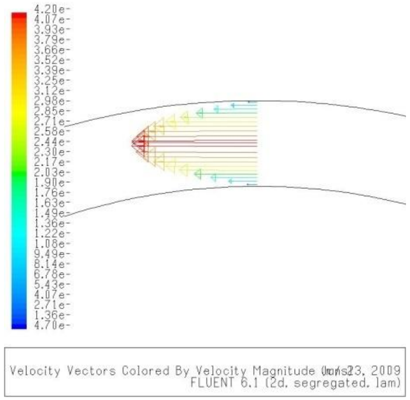


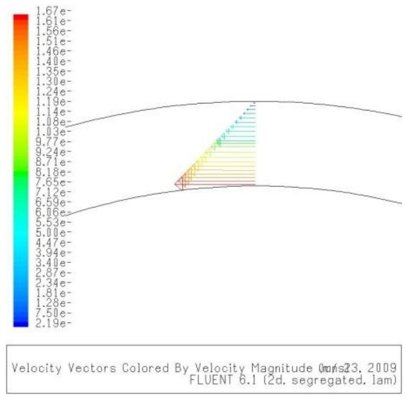
Test sections



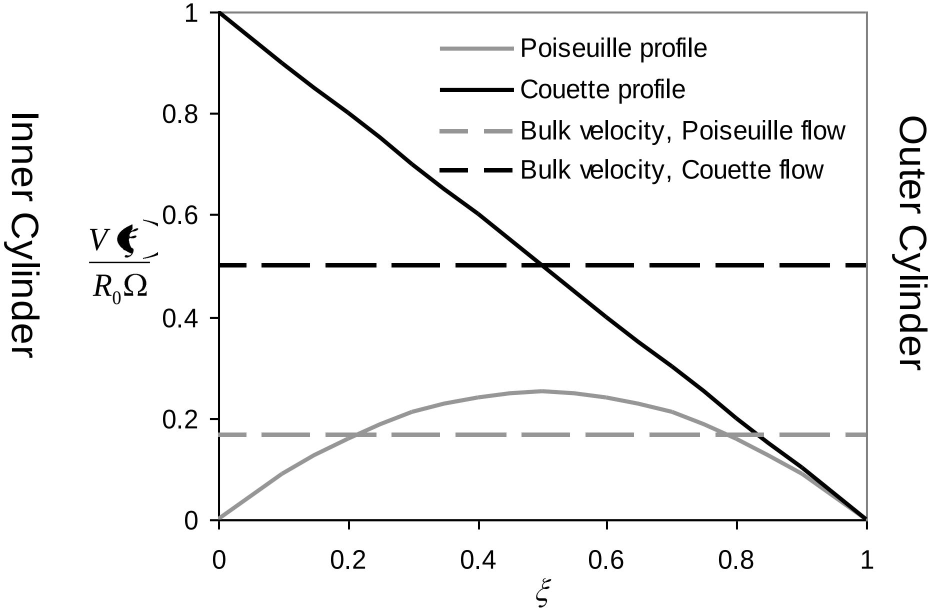
Increasing the wall shear rate led to a space organization of bacteria deposition

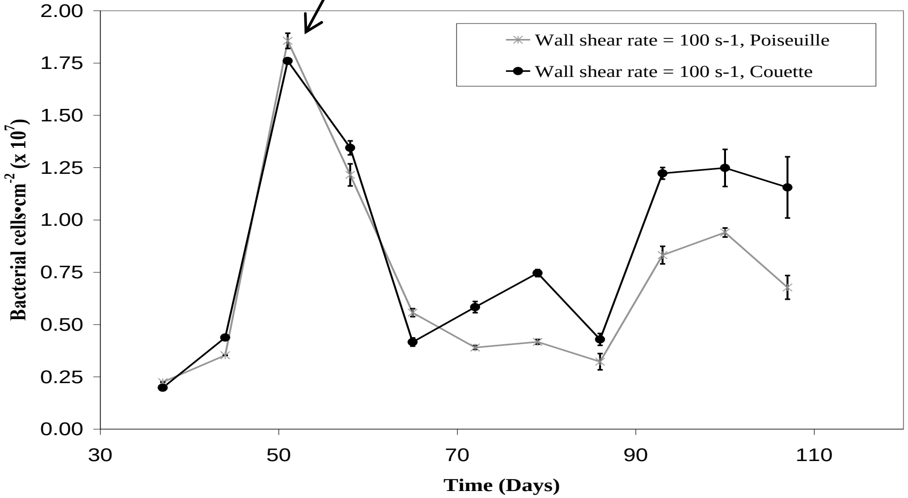
Test sections





Grazing by Amoeba



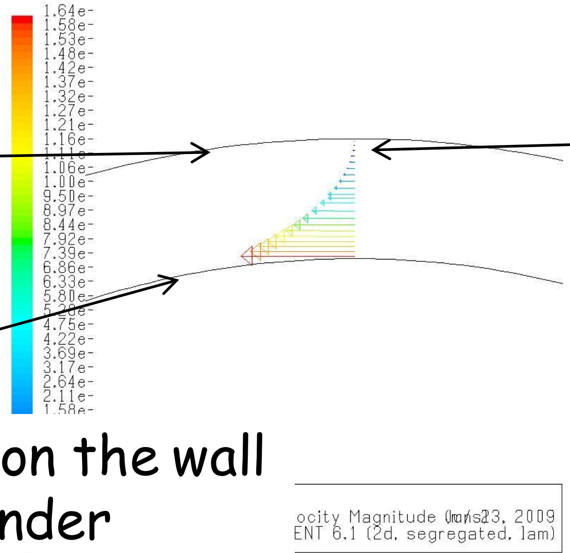


Test sections

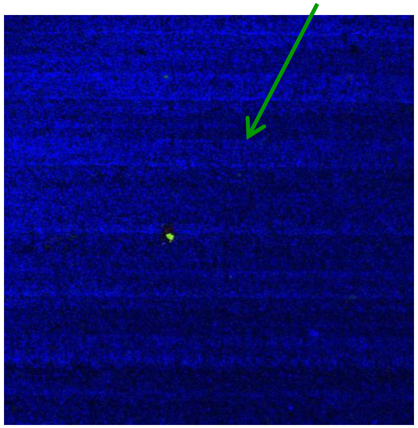
Outer cylinder

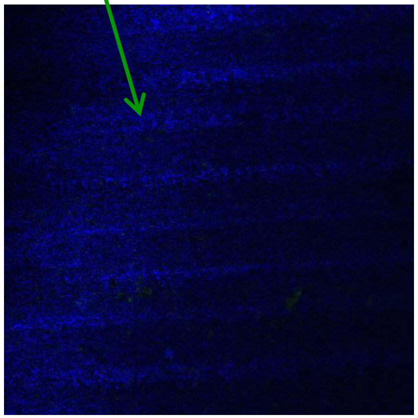
Inner cylinder

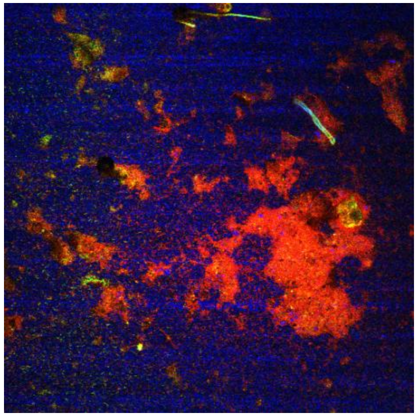
Case of null Wall shear rate

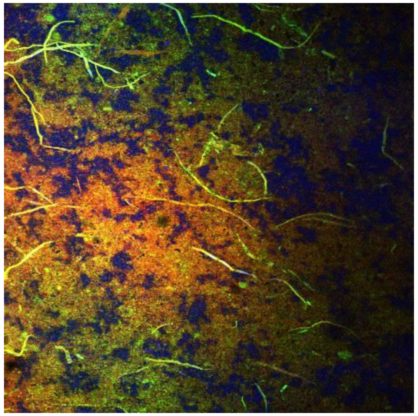


No bacteria on the wall of outer cylinder









Conclusions on wall flux

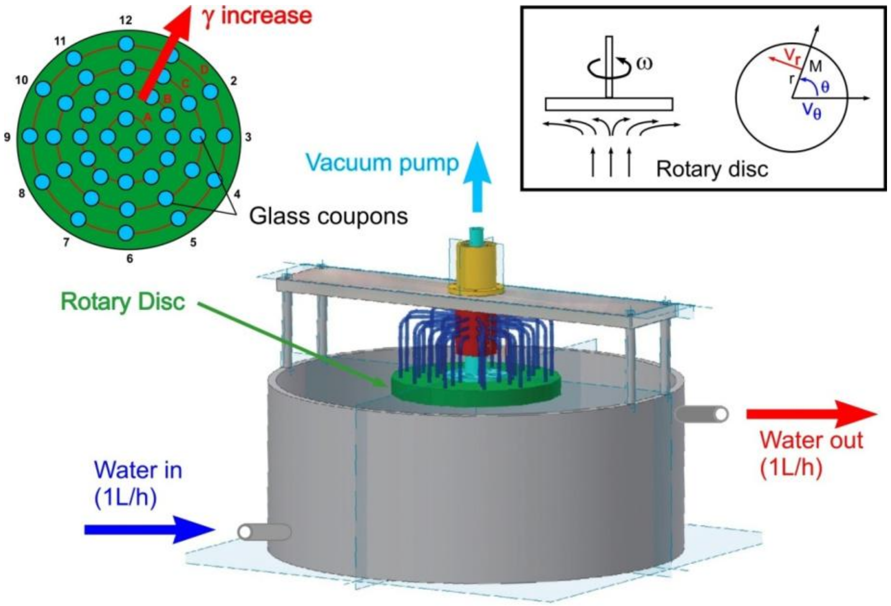
Bacteria in drinking water : migration to the wall -> biofim ?

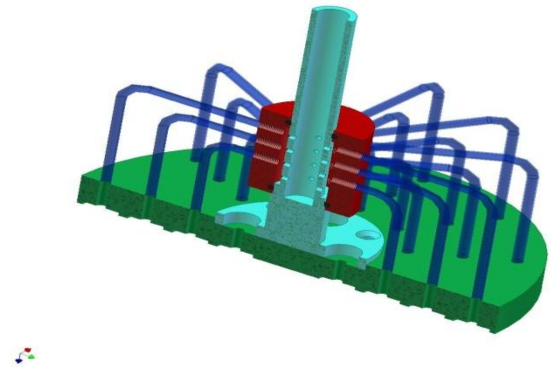
No wall shear rate -> no bacteria on the wall

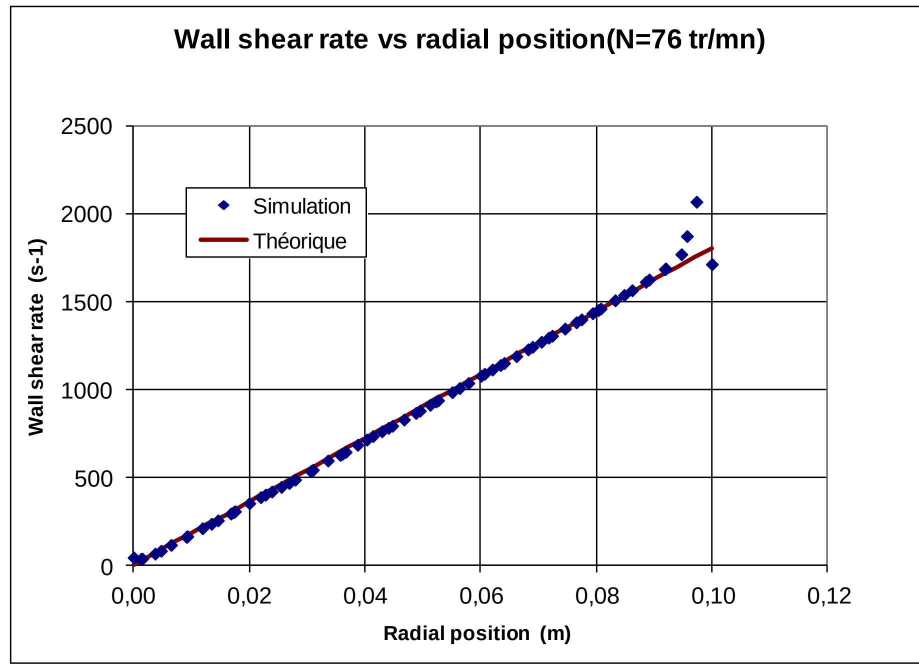
Even if the Peclet number is high -> Convection –diffusion works

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

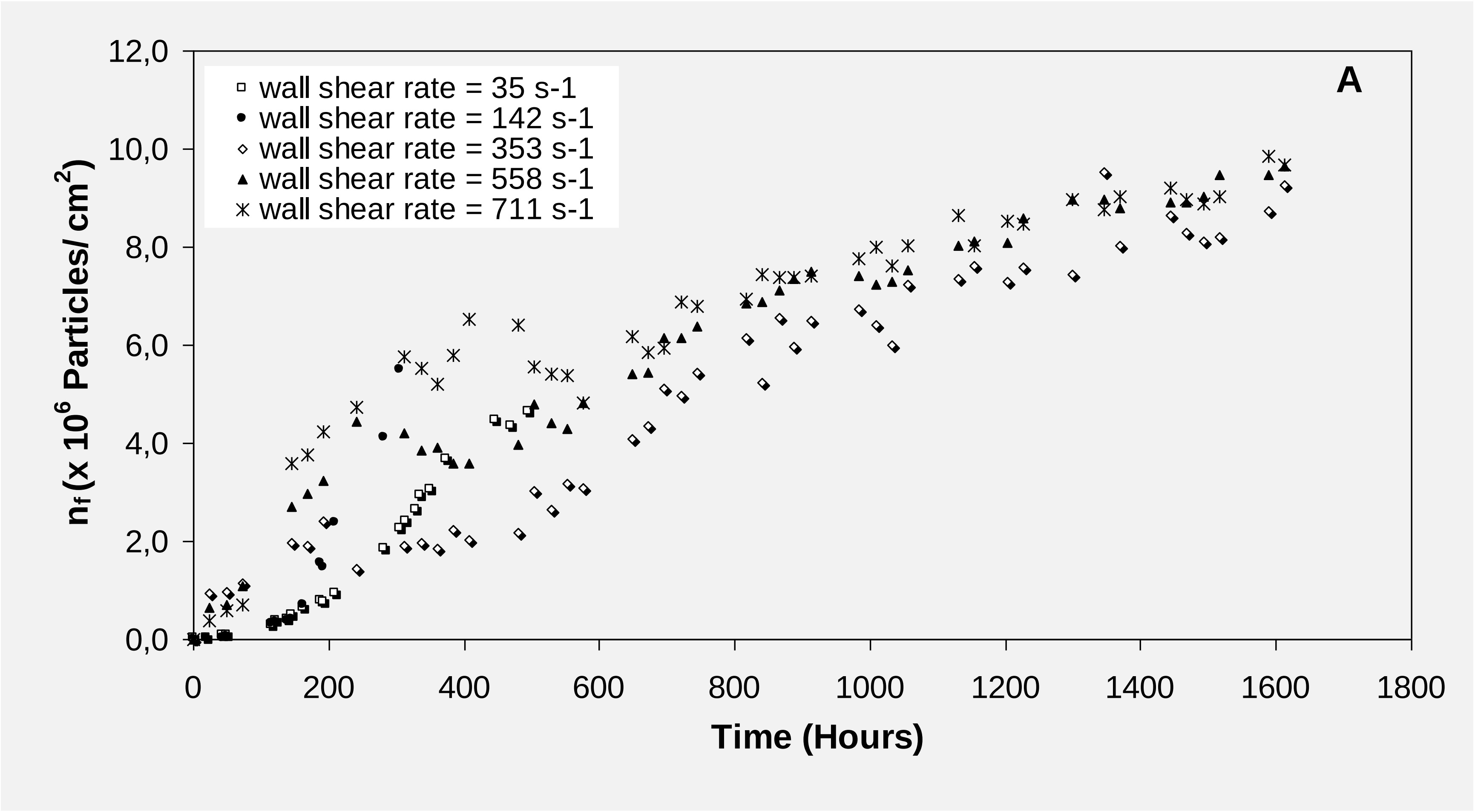
Test sections (Rotating disc)





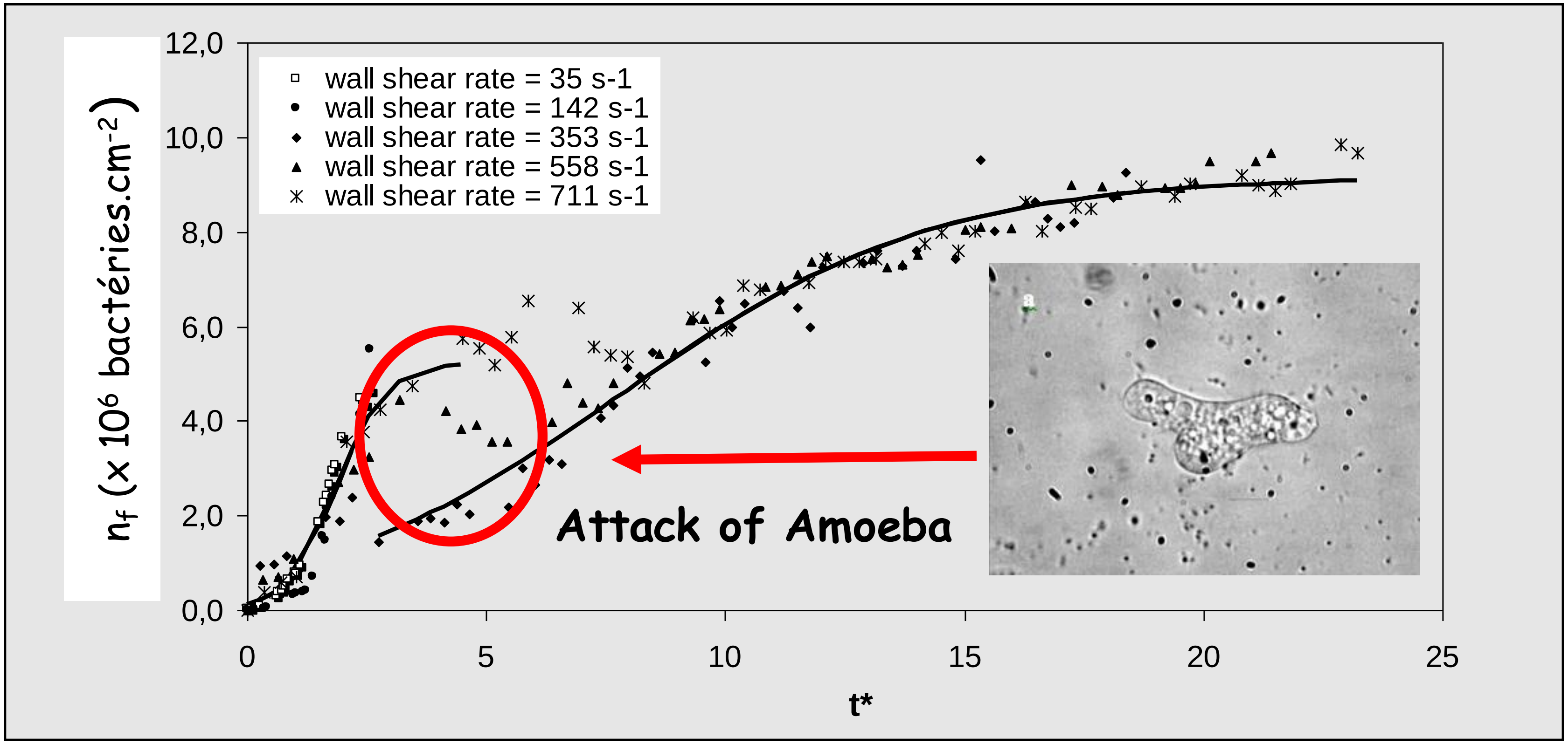


Results



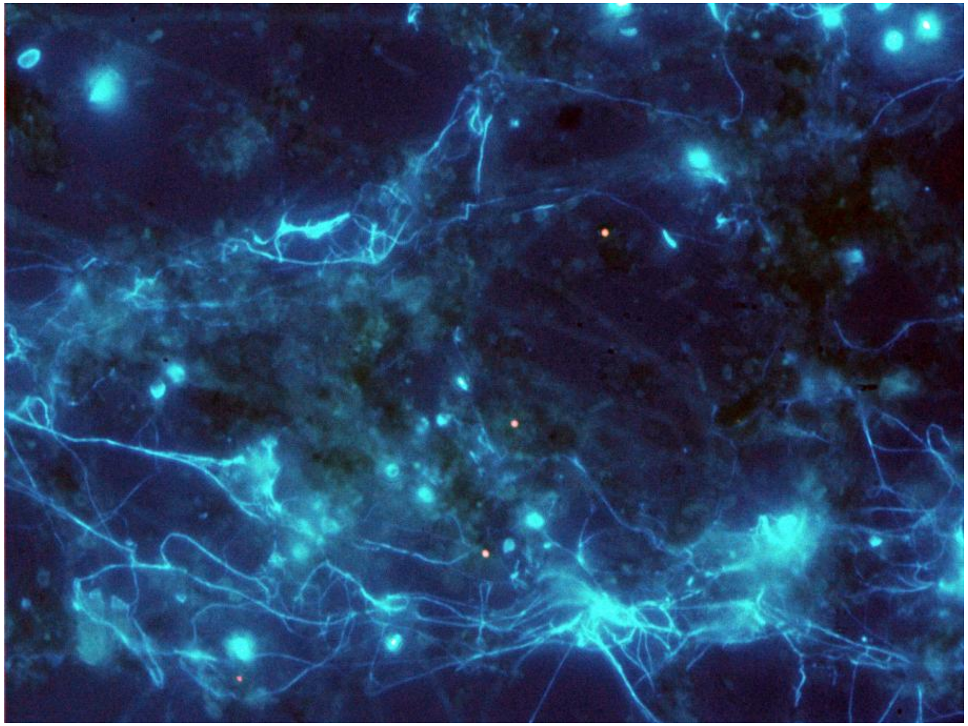
wall shear rate = 35 s-1
wall shear rate = 142 s-1
wall shear rate = 353 s-1
wall shear rate = 558 s-1
wall shear rate = 711 s-1
A
12,0
10,0
8,0
6,0
4,0
2,0
0,0
0
200
400
600
800
1000
1200
1400
1600
1800
n_f (x 10^6 Particles/ cm^2)
Time (Hours)

Results



	Phase 1	Phase 2
alpha 1	1	0,3
alpha 2	30	5
S_0	$8\ 10^{-6}$	$1\ 10^{-6}$

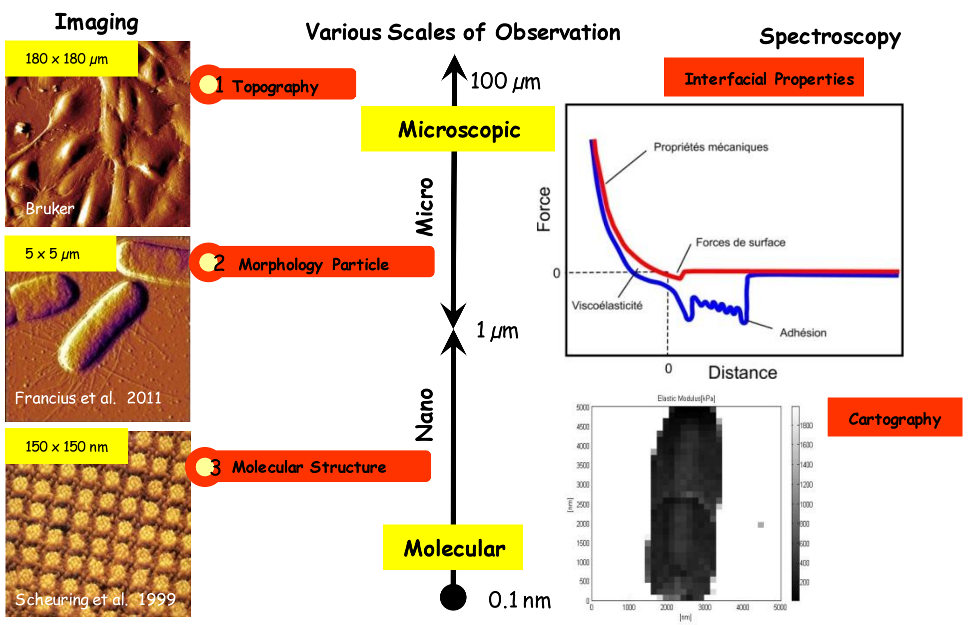
Bacteria adhesion at the wall (cohesion of biofilm)



Measurement technique

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

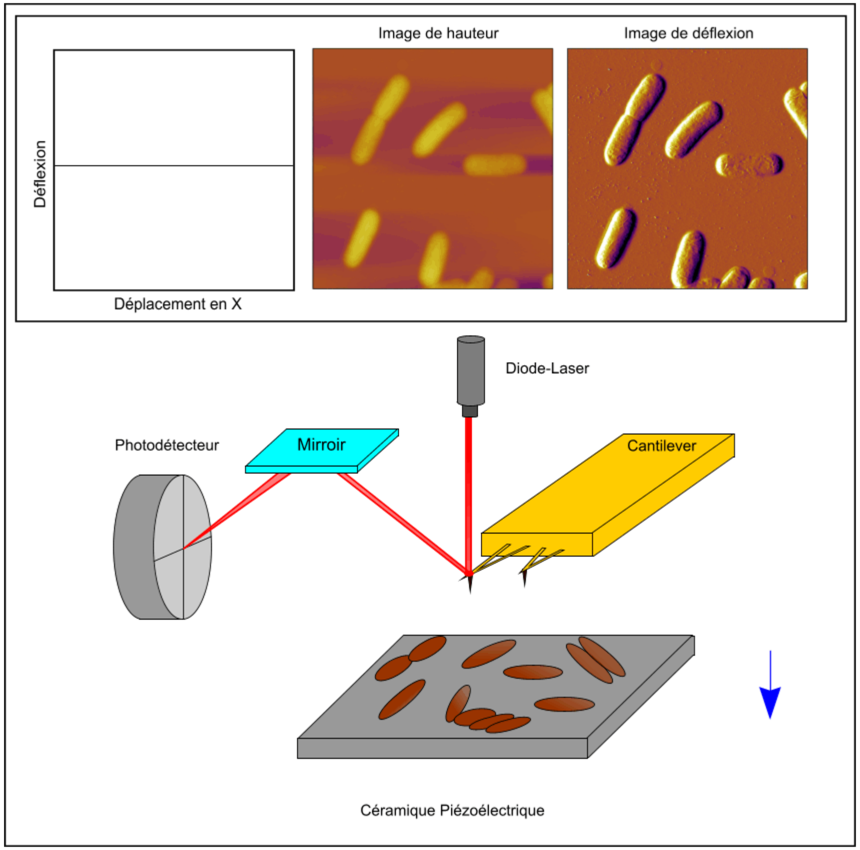
➢ Imaging samples surface in various environments

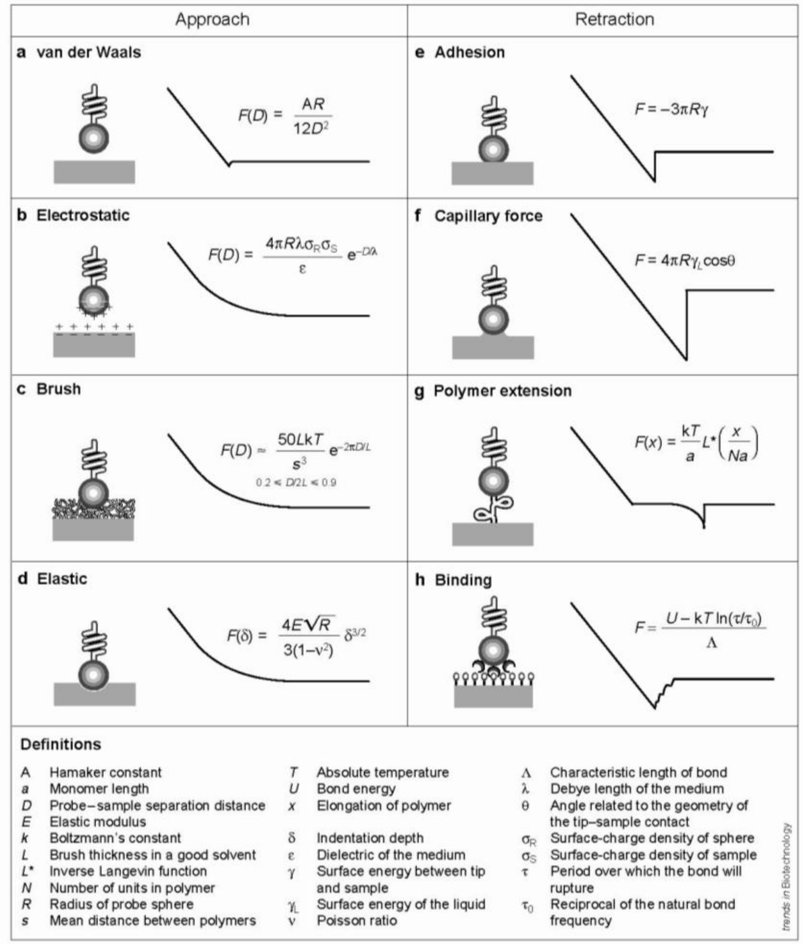


In the last decade ⇒ experiencing boom of AFM in nanosciences and life sciences :

AFM technique

Panorama of measurable forces in AFM



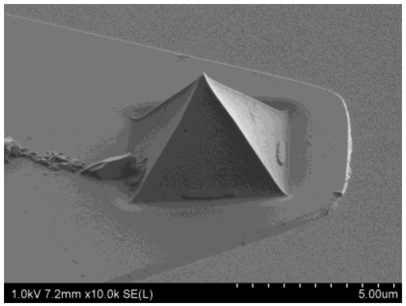


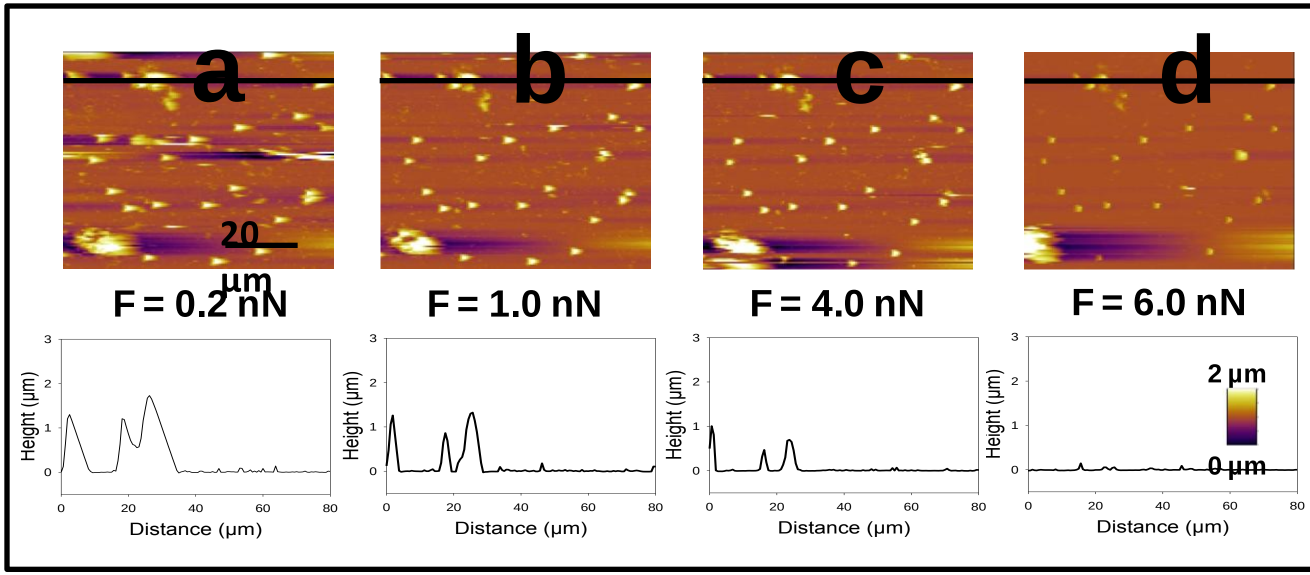
Atomic force spectroscopy :

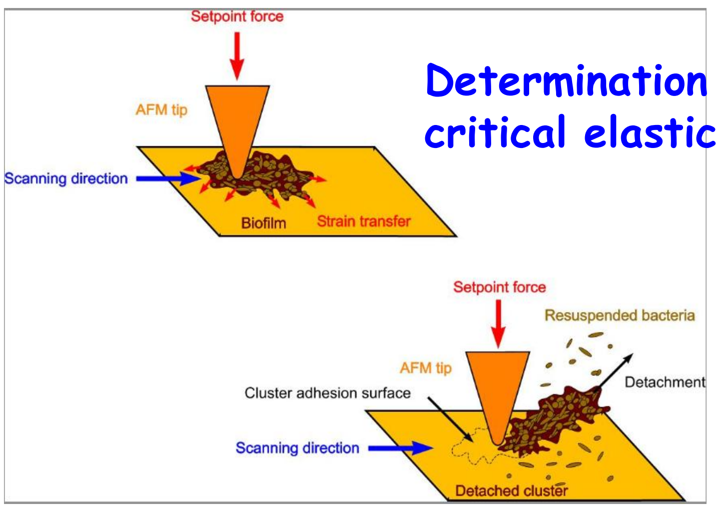
- Combination of imaging and force measurements
- Mapping reconstruction with spatially resolved physical parameter value for each pixel
- Which physico-chemical parameters can be extracted from the AFM force-curves ?

AFM : Cohesion of drinking water biofilm clusters

Scanning surface by AFM (F↗)





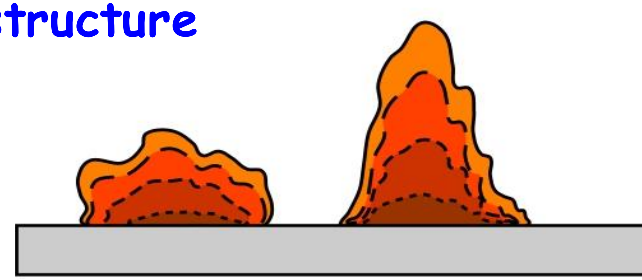


Determination of the critical elastic modulus

Young modulus

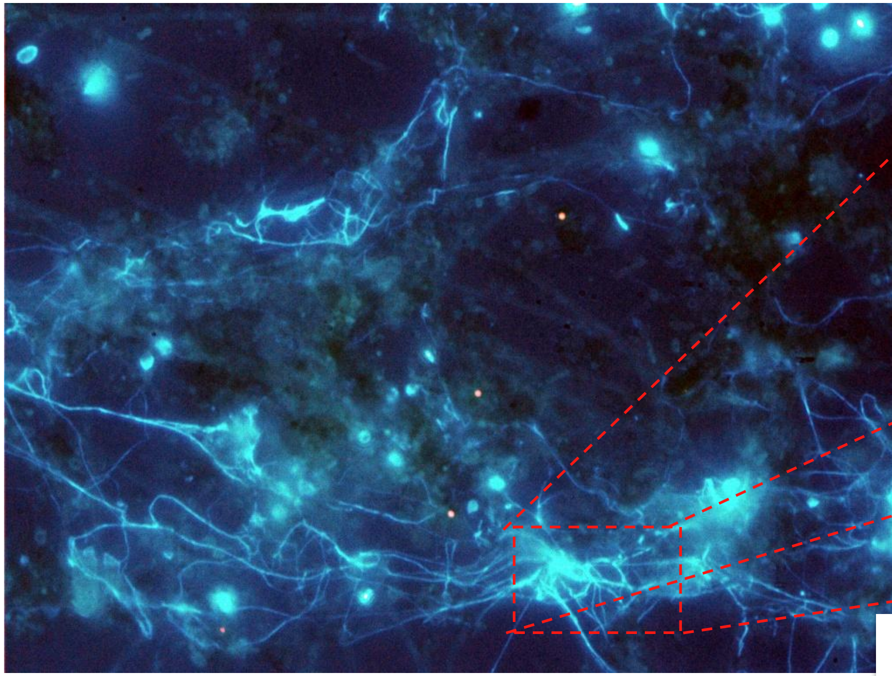
0 MPa — 10 MPa

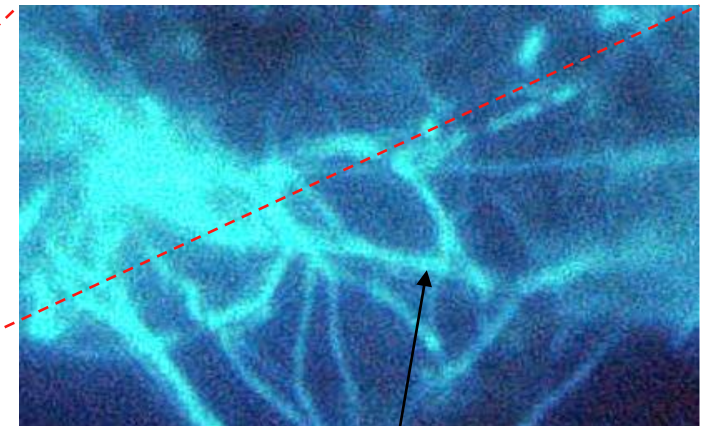
Stratification of the cluster structure

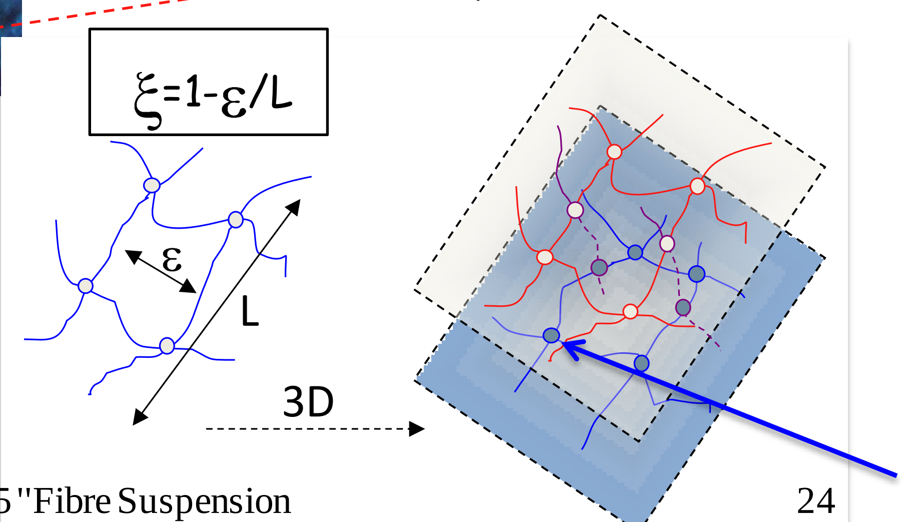


Water drinking biofilm

The rate of entanglement ξ is a factor of cohesion linked to the volume and elasticity of the clusters







G. De Genne

ε : coherence length

AFM : Cohesion of clusters in biofilm drinking water

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

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

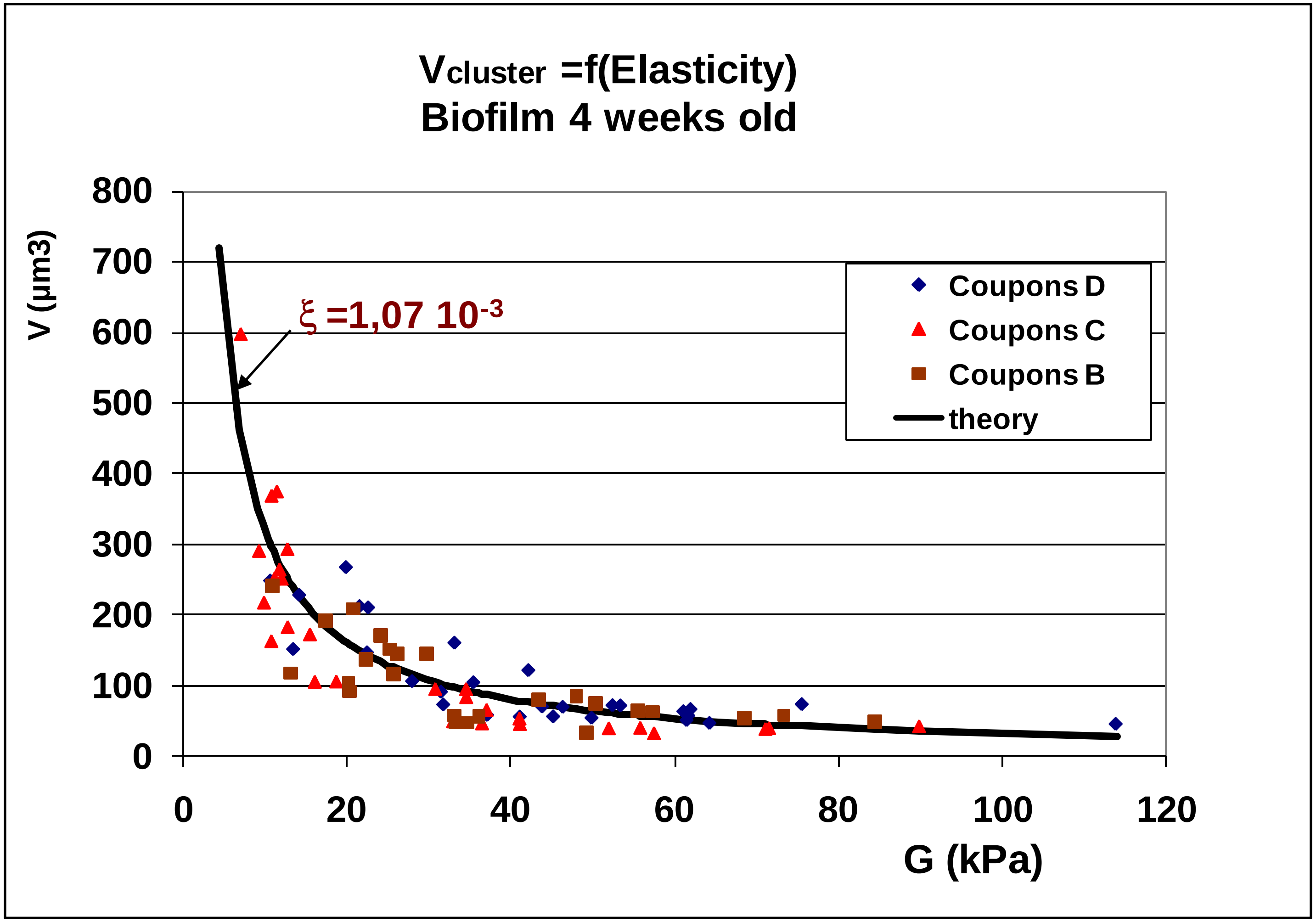
At the limit of cohesion, cluster we can put:

$$G\,\xi^3 V_{cluster} = k_B T \Rightarrow \boxed{V_{cluster} = \frac{k_B T}{\xi^3 G}}$$

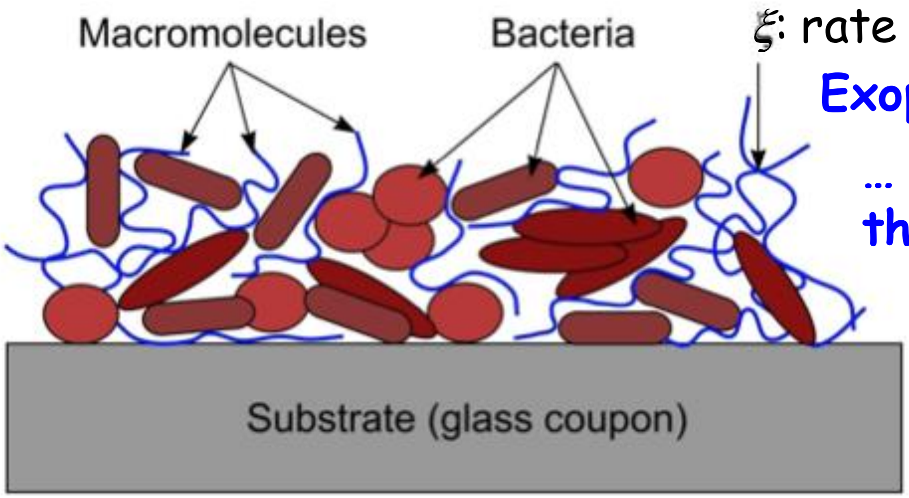
k_B T = 4 10^{-21} m^2 Kg/s^2/ K

$V_{cluster}$ and G given by AFM

AFM : Cohesion of clusters in biofilm drinking water



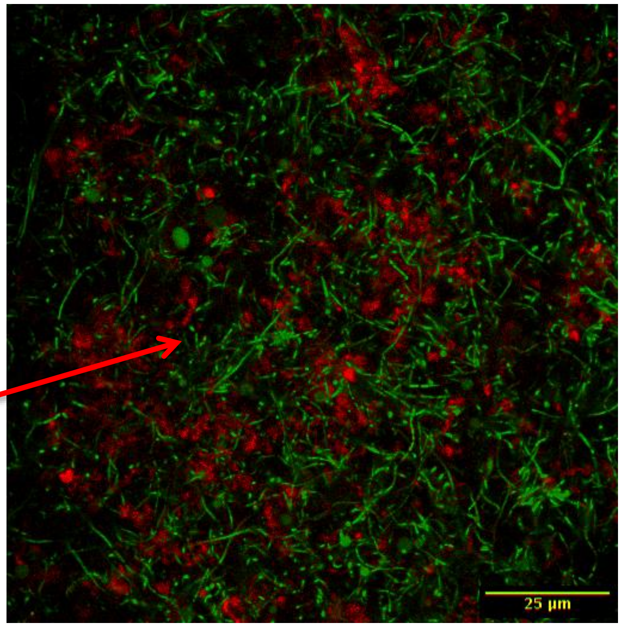
Cohesion of clusters in biofilm drinking water

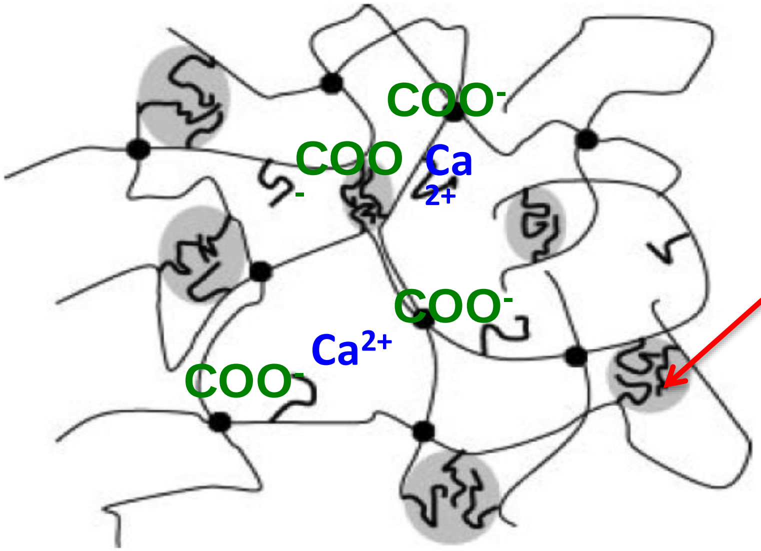


ξ: rate of entanglement

Exopolymers in drinking water biofilms …

… govern the elastic deformation of the clusters





Hydrophobic domains

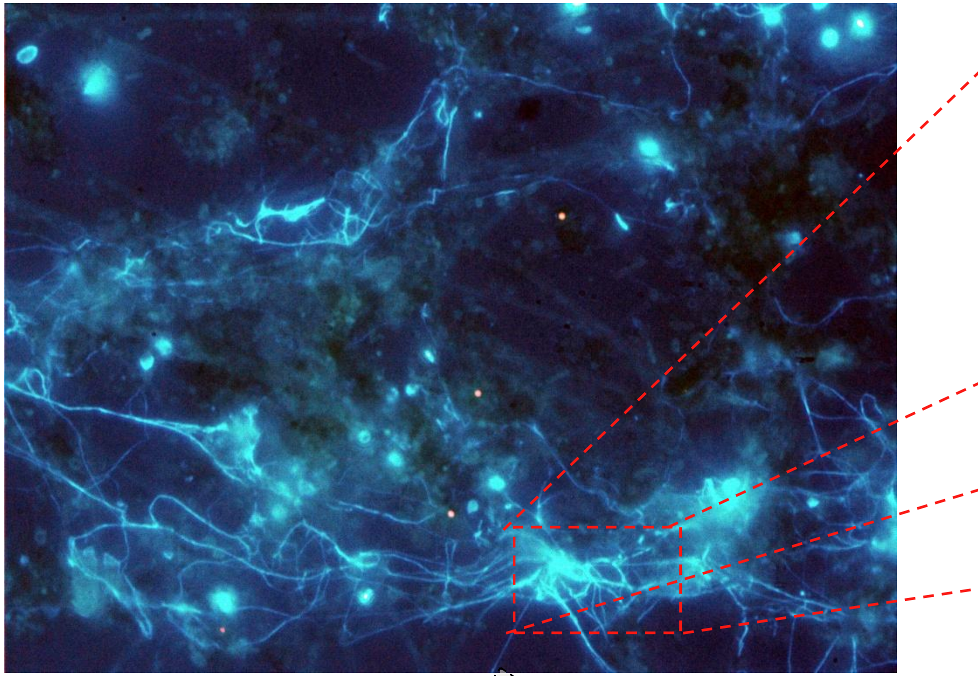
Aldeek *et al., AEM,* 2013

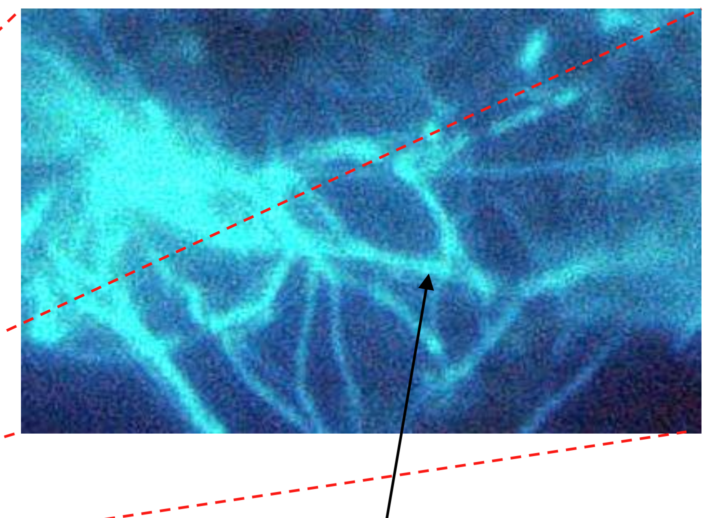
(Biofilm of *Shewanella oneidensis*)

(Miquelard-Garnier *et al.*, 2007)

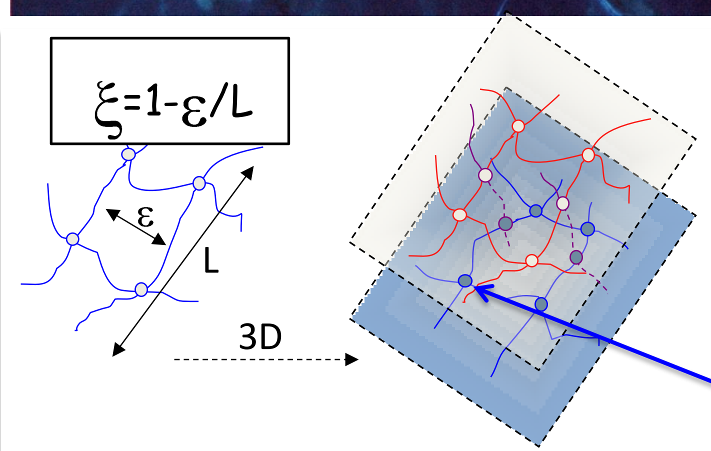
Number of entanglement points $10^9/mm^3$

The rate of entanglement ξ is a factor of cohesion linked to the volume and elasticity of the clusters





$$V_{cluster} = \frac{k_B T}{x^3 G}$$



Drinking water biofilms behave like a viscoelastic solid

$\xi = 10^{-4}$ to 10^{-3}

Number of entanglement points 10^8 to 10^9/mm^3

Cleaning the surface colonized by biofilm hydrodynamic shear stress vs cluster volume

Mean shear stress in volume of cluster V: $\sigma_{ij} = \frac{1}{V}\sum_{1}^{n}\left(\int_{A_0 - A_1} \sigma_{ik}\, x_j\, n_k\, dA + \int_{A_1} \sigma_{ik}^{b}\, x_j\, n_k\, dA \right)$

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

$$\sigma_{ij}^{f} = \mu \frac{d\alpha}{dt} = \mu\gamma \quad et \quad \sigma_{ij}^{b} = G\alpha$$

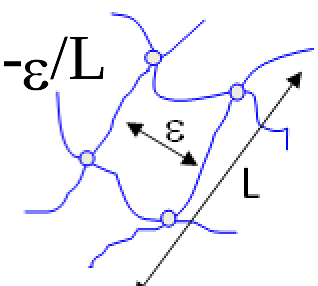
$$\tau = \mu C (1-\xi)\frac{d\alpha}{dt} + G C \xi \alpha$$

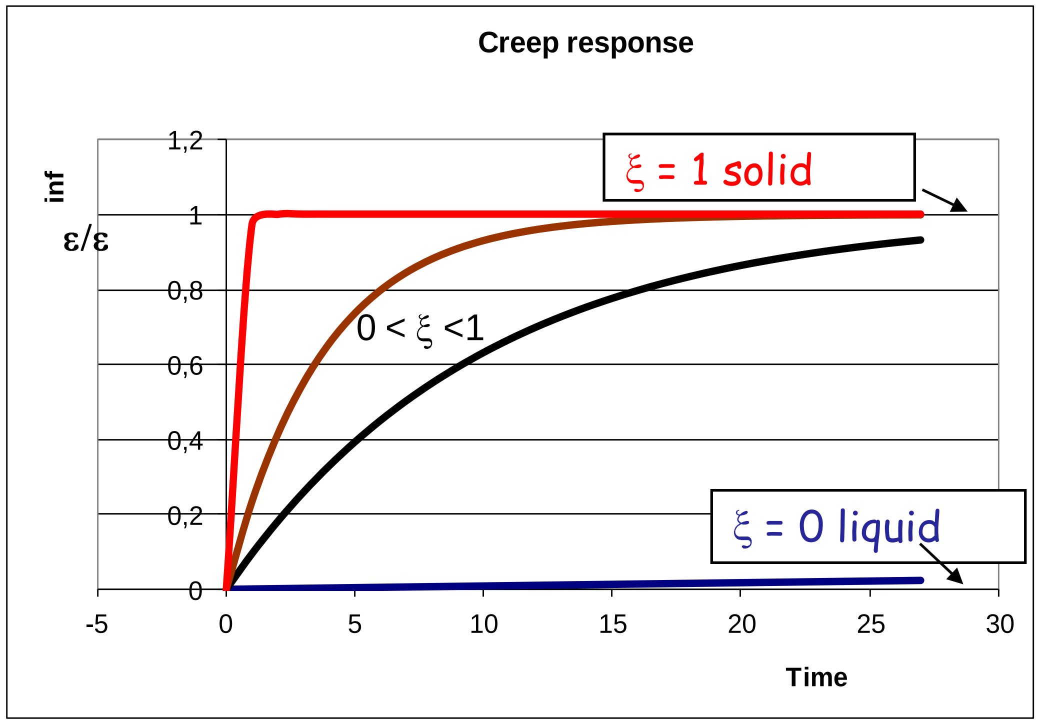
Creep function

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

with $\theta = \frac{\mu(1-\xi)}{G\xi}$

$\xi = 1 - \varepsilon / L$





Cleaning the surface colonized by biofilm hydrodynamic shear stress vs cluster volume

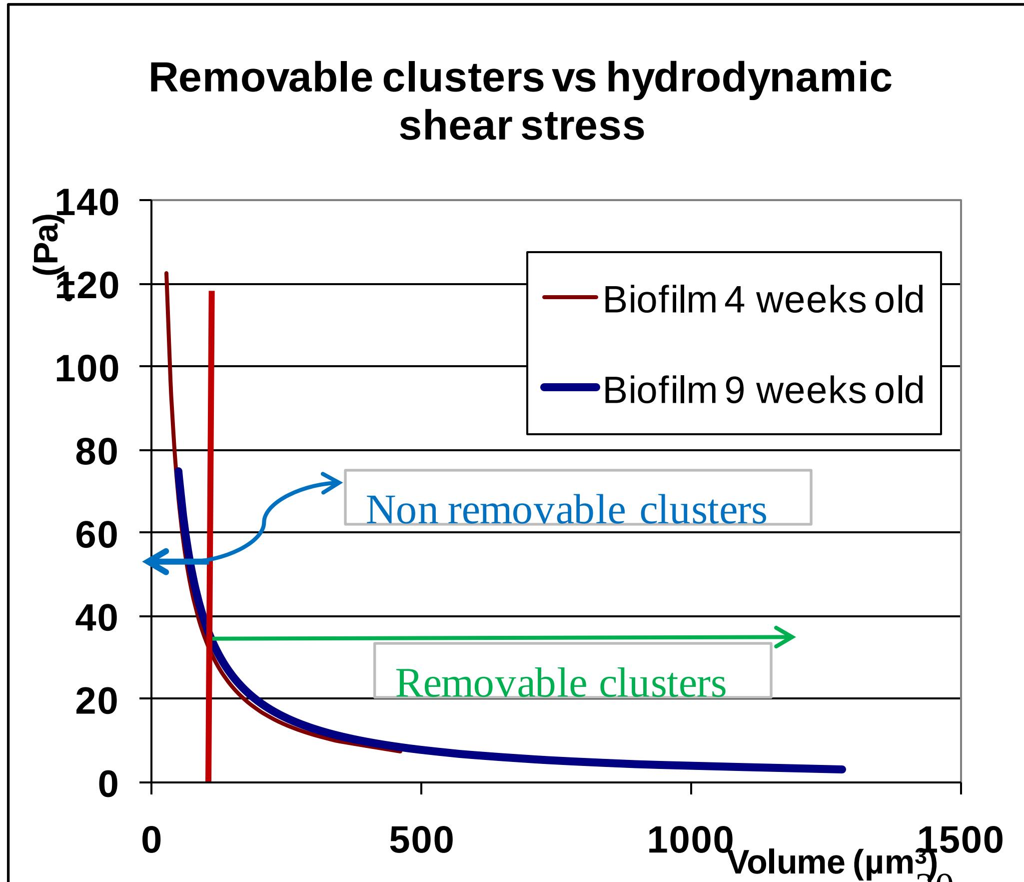
Elastic limit before removing clusters:

$$\mu \frac{d\alpha}{dt} C(1-\xi) = \mu \gamma C(1-\xi) = G C \xi \alpha_{\max}$$

Strain rate α_{max} = 100%:

$$\tau_{hyd} = \mu \gamma = \frac{G\xi}{1-\xi}$$

City network drinking water distribution τ< 30 Pa



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 $<100\mu m^3$ non removable
- Perspective : diffusion of nutrients on biofilm - population balance (growth, mortality and partial detachment)

THANK YOU FOR YOUR ATTENTION

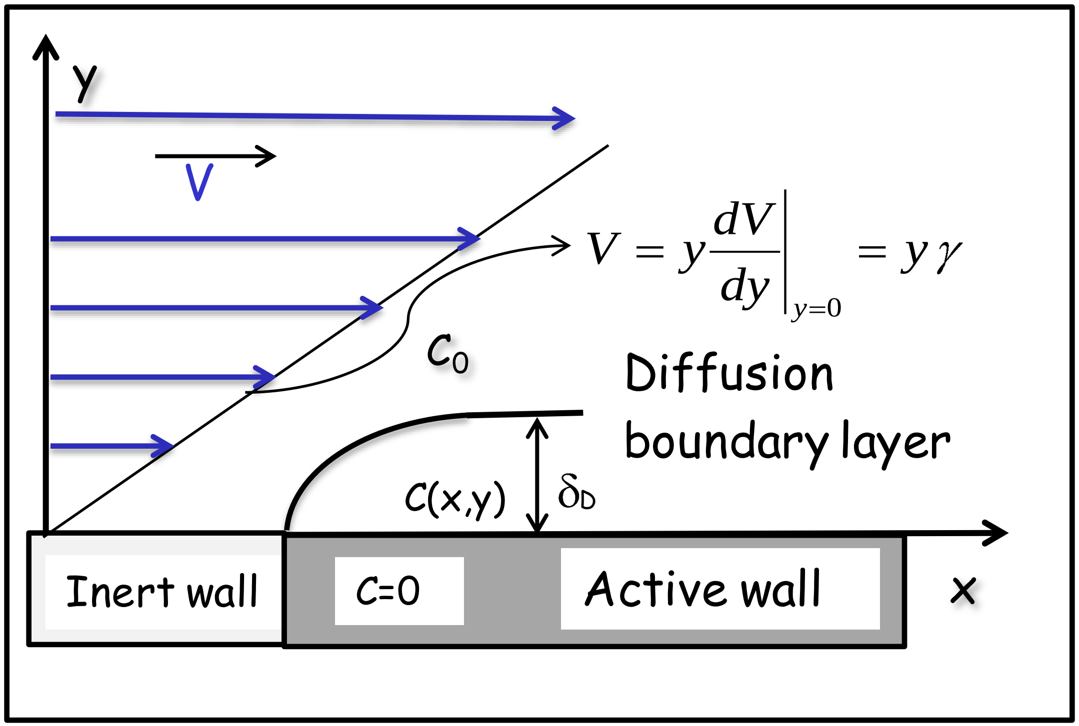
- Tony Paris, Salaheddine Skali-Lami, Jean-Claude Block **(2007)** : ***Effect of Wall Shear Rate on Biofilm Deposition and Grazing in Drinking Water Flow Chambers***. Biotechnology and Bioengineering, V. 97, issue. 6: 1550_1561.

- Paris T., Skali-Lami S., and Block J.C. **(2009)** : ***Probing young drinking water biofilms with hard and soft particles. Water Research***, v. 43, issue 1: 117 – 126

- El Khatib R., Lartiges B., Mustin C., Skali-Lami S. **(2011)** : ***Hydrodynamic control of wastewater biofilm organization***. *La Houille Blanche*, Issue 5: 29 – 33.

- Abe Y., Polyakov P., Skali-Lami S., and Francius G. **(2011)** : ***Elasticity and physico-chemical properties during drinking water biofilms formation***. *Biofouling*, v. 27(7): 739 – 750.

- Abe Y., Skali-Lami S., Block J.C., and Francius G. **(2012) :** ***Cohesiveness and hydrodynamic properties of young drinking water biofilms***. *Water Research*, 46: 1155 – 1166.


y
V
$V = y\frac{dV}{dy}\Big|_{y=0} = y\gamma$
C_0
Diffusion
boundary layer
C(x,y)
δ_D
Inert wall
C=0
Active wall
x