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Shear induced detachment of microorganisms attached to a plane wall

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Introduction

•Contamination of food industry equipment surfaces to prevent foodborne illnesses

•Bacteria/material interaction dynamics

•Coupling experiments / CFD

- AFM
- Parallel-plate flow chamber assays
- Numerical simulation

➡ *Quantify interaction forces considering bacterial properties*

Methods

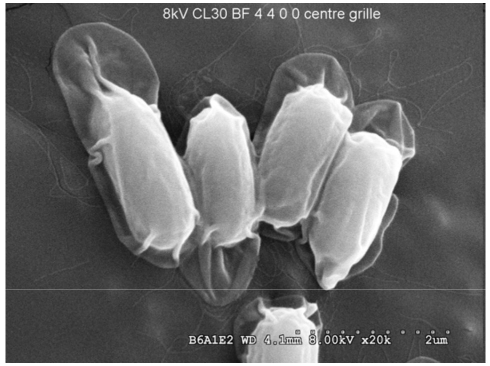
Microorganism modelling :

•Rigid obstacle embedded into the substrate

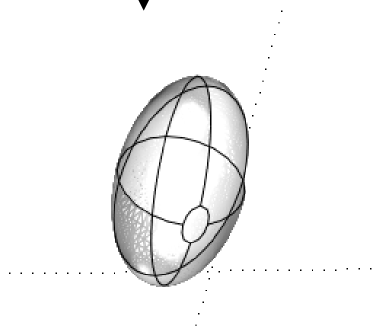
•Approach a realistic shape for several strains

•**Isolated** microorganism

•Heterogeneity



authors : Faille/Lequette - institute : INRA



LISBP

Methods

Flow modelling :

- Stokes flow
- Laminar sublayer

Experiments in parallel plate flow chamber

Particulate Reynolds number

$$Re_p = \frac{u(r_p) r_p}{\nu} = \frac{r_p^2 \tau_w}{\nu \mu} \in [10^{-5}, 10^{-3}]$$

Wall shear stress

$$\tau_w = \frac{3 \mu Q}{4 h^2 l},$$

Flow chamber dimensions :

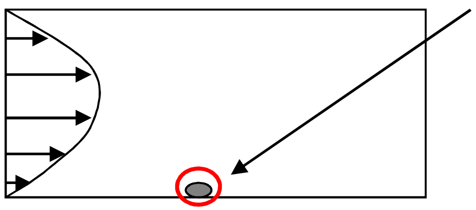
h : 200 µm

b: 1200 µm

Cell dimension

r_p~1 µm

ρ=1000 kg.m^{-3} , η=10^{-3} Pa.s



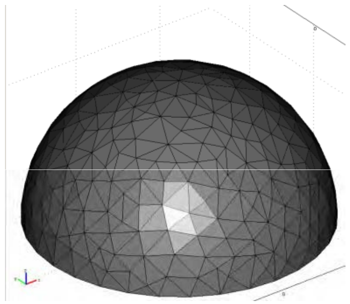
Domain reduction

CFD model – Domain parameters

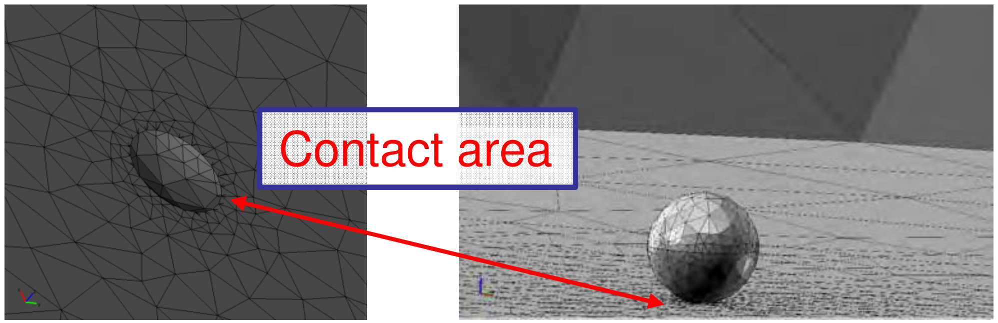
•3D Laminar Navier-Stokes application mode

•Semi-circular domain (orientation)

r_{domain} =30 r_p (Brooks and Tozeren, 1996)



•Embedded cell shape



One mesh for each geometry

Boundary conditions

Inlet and outlet : shear flow

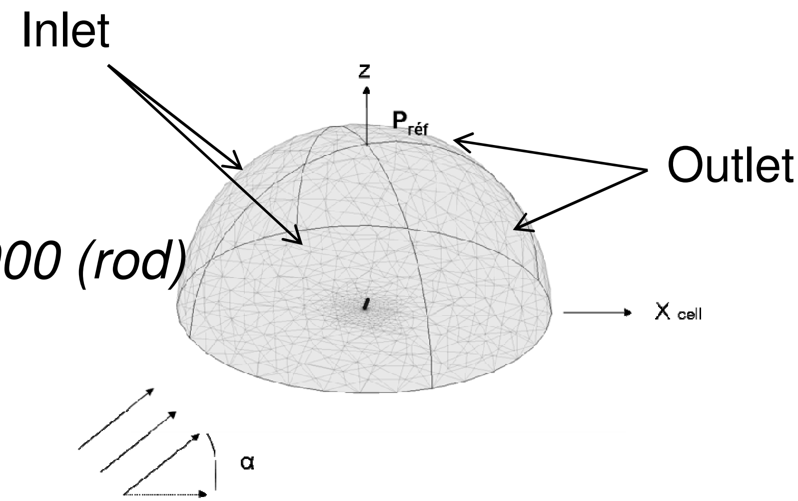
$$u(\gamma,\alpha) = \gamma z(\cos(\alpha)\mathbf{x}_{cell} + \sin(\alpha)\mathbf{y}_{cell})$$

Cell boundaries and bottom plate

No-slip walls

Triangular mesh

12000 DOFs (sphere) – 118000 (rod)



Parameters

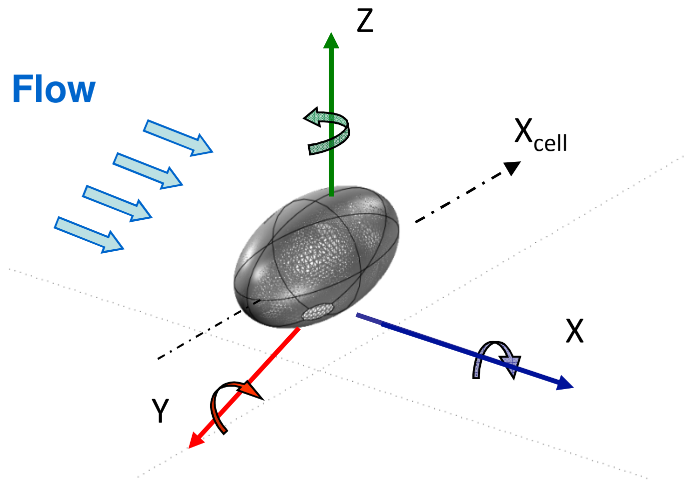
γ : shear rate

α : main flow incidence

Output

Integration of the stresses on the cell boundaries
Calculations are made in the frame of reference of the cell (X_{cell}, Y_{cell}, Z)
Results are shown in the frame of reference of the flow (X,Y, Z)

⇨ Cell motion (sliding, rolling, reorientation) regarding the flow



Validation – Spherical model

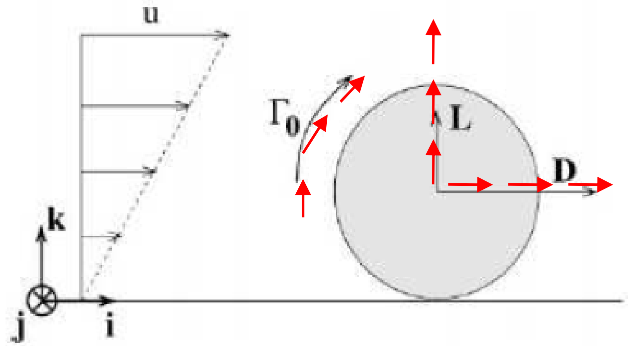
Drag – Torque (O'Neill, 1968)

$$\mathbf{D} = \left[32.0 r_p^2 \tau_w + \mathcal{O}(\mathrm{Re}_p)\right] \mathbf{i},$$

$$\mathbf{\Gamma}_0 = \left[11.9 r_p^3 \tau_w + \mathcal{O}(\mathrm{Re}_p)\right] \mathbf{j}.$$

Lift (Krishnan and Leighton, 1995)

$$\mathbf{L} = 9.257 r_p^2 \tau_w \mathrm{Re}_p \mathbf{k}.$$



Fixed

Radius r_p = 1µm

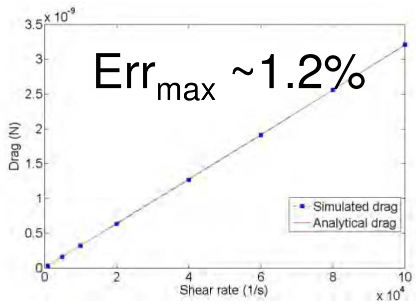
1 parameter

shear rate : $\gamma \in [0, 10^4\ s^{-1}]$

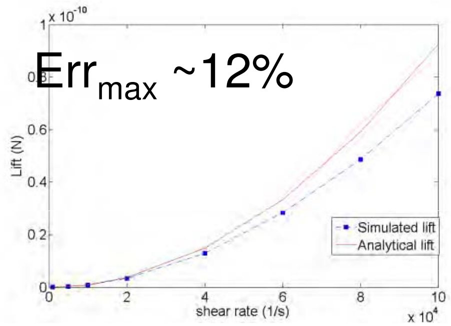
Validation – Spherical model

Results as a function of the shear rate

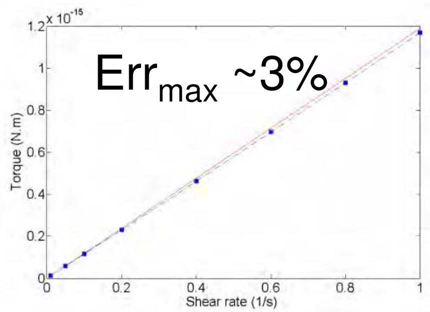
Drag



Lift



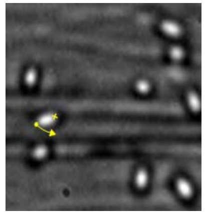
Torque



Good agreement with the theory
Drag prevails
Lift neglected

Spheroidal model

Shape : e.g. Bacillus cereus spore

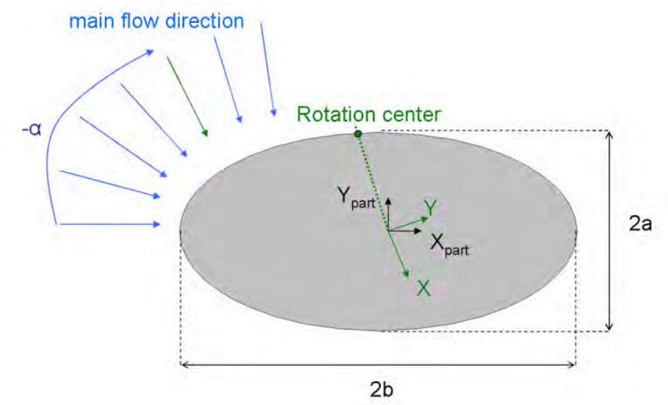


Asymetrical shape ⟹ orientation effect

Fixed

shear rate $\gamma=10^4 s^{-1}$

a= 1µm

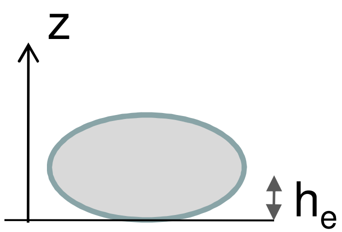


3 parameters

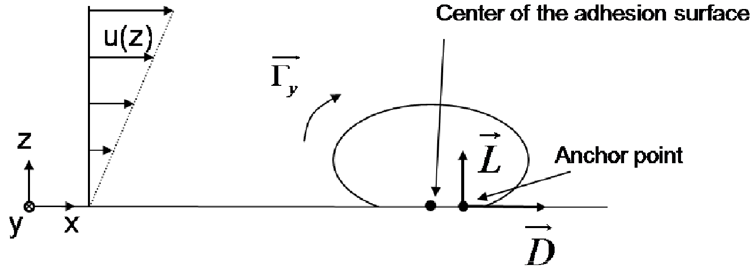
flow incidence : $\alpha \in [0,\pi]$

axes ratio : $b/a \in [1,2]$

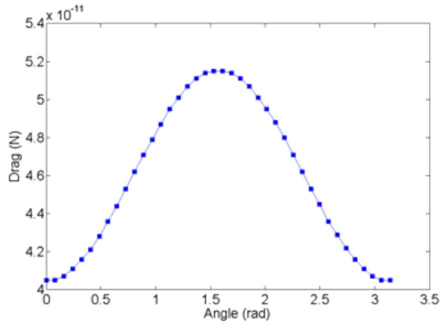
Embedment height : $h_e \in [0.1, 0.9\ \mu m]$ *(cell spreading, protrusions)*



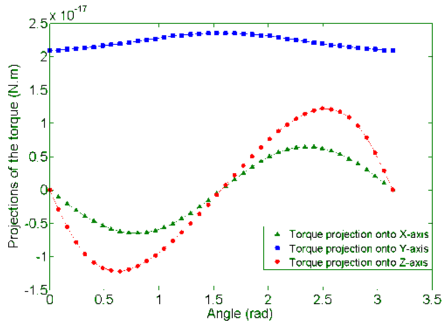
Spheroid model



Drag



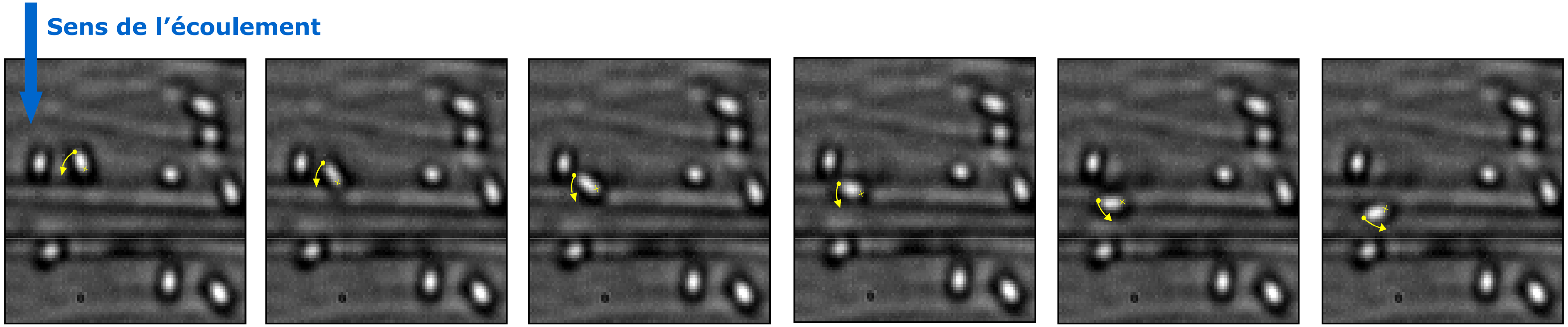
Torque components



The components of the torque have same order of magnitude

Γ_y prevails

Reorientation



Bc 98/4 strain- t_w = 7 Pa (2000 images/s)

Occurs for asymetrical cells

Reduction of the stresses exerted by the shear flow

May happen while sliding – rotation around an anchor point

Rod model

Shape : e.g. Escherischia coli

Fixed

shear rate : $\gamma = 10^4 s^{-1}$

a= 1µm

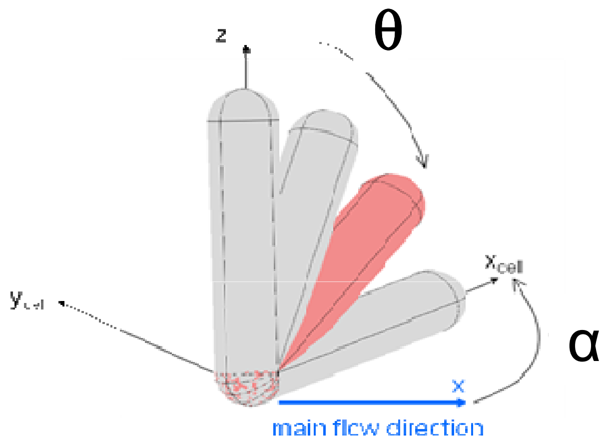
Rod length: 1.5 µm

Radius : 0.25 µm

2 parameters

flow incidence : $\alpha \in [0,\pi]$

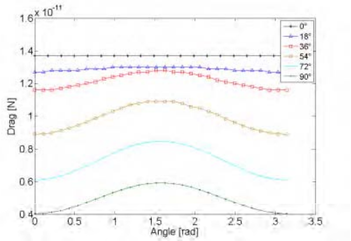
cell inclination : $\theta \in [0, \pi]$



Rod model

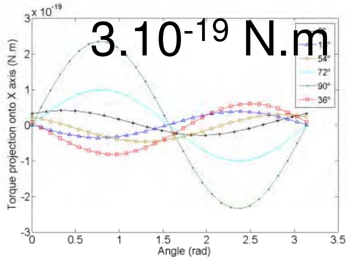
Results as a function of the incidence α for several inclinations θ

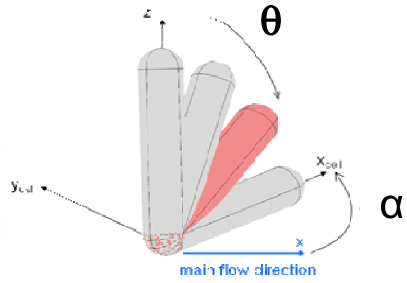
Drag



Torque projection onto X-axis

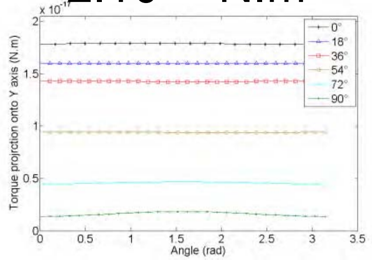
3.10^{-19} N.m





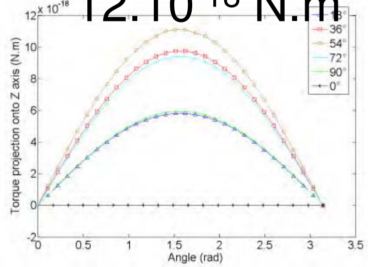
Torque projection onto Y-axis

2.10^{-17} N.m



Torque projection onto Z-axis

12.10^{-18} N.m



Strong variations with the inclination

Remaining cells are those lying on the substrate and oriented in the main flow direction

Reorientation

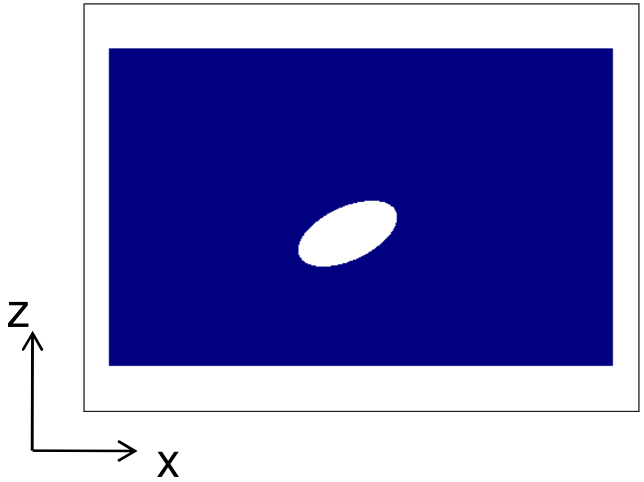
E. coli strain- t_w = 22 – 24 - 26 Pa

Conclusion

•First approach to the simulation of the detachment of various shaped microorganisms
(Boulbene et al., submitted)
•Competition between sliding, rolling and reorientation

Prospects

•Transient simulation
•Fluid-structure interaction with deforming mesh
•Population model
Parameterized geometries



Acknowledgments

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THANK YOU!