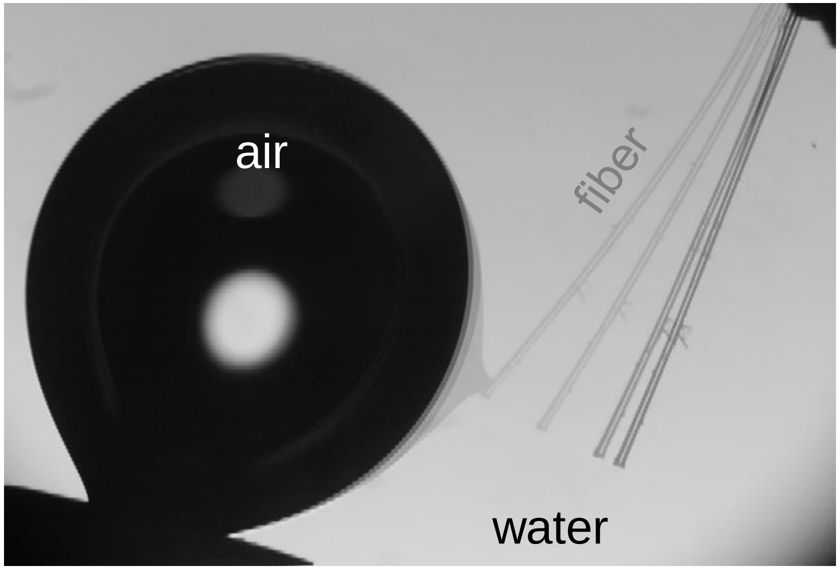
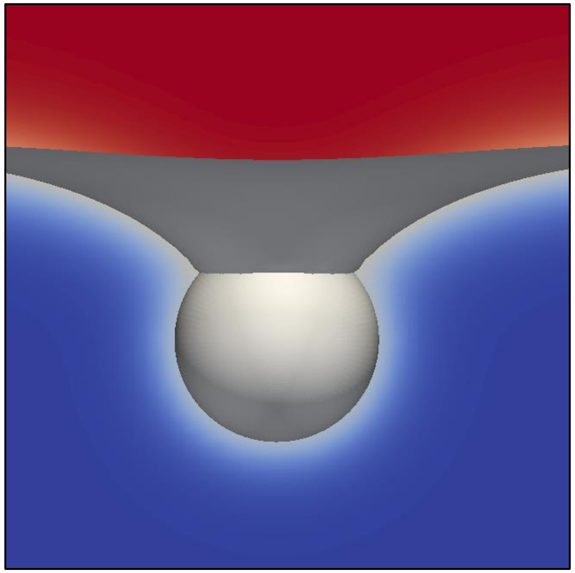
Direct numerical simulation of a flexible fiber interacting with a fluidic interface



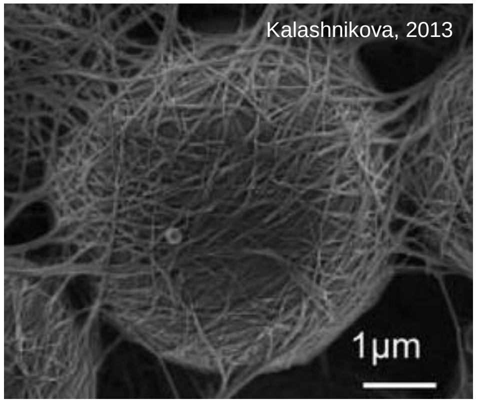


Gregory Lecrivain

Helmholtz-Zentrum Dresden-Rossendorf
Institut für Fluiddynamik
Germany

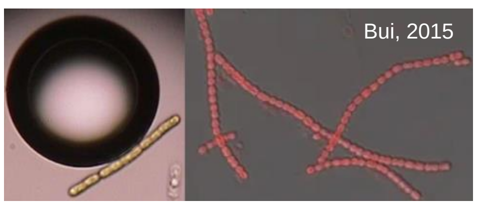
Industrial applications

1 µm
10 µm



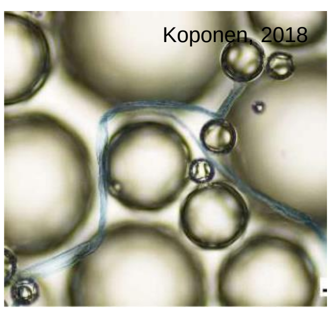
Water-in-oil drops stabilized by cellulose fibers

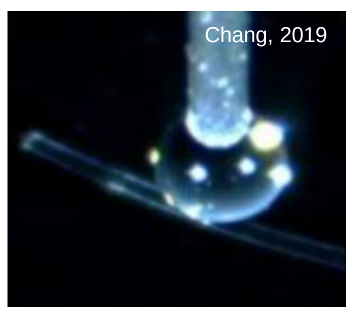
10 µm
100 µm



Recovery of filamentous algae by rising vapor drops

0.1 mm
1 mm





Fiber-laden slurries and foams

Fabrication of microelectronics

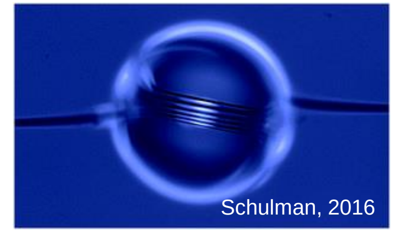
DRESDEN concept HZDR

Elasto-capillary length L_{ec}

Stiffness — Radius

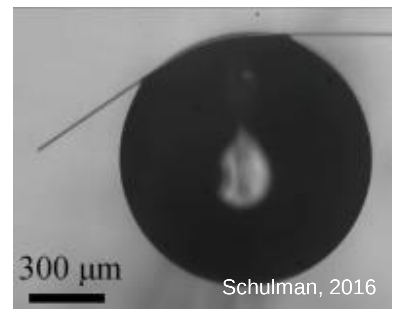
$$(L_{ec})^2 = \frac{E R_f^3}{\sigma}$$

Surface tension



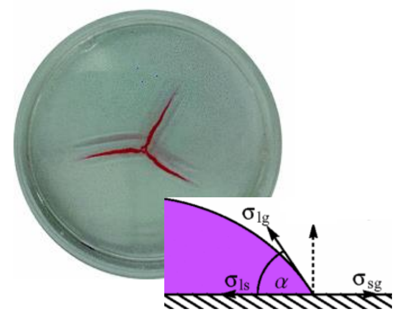
Schulman, 2016

$\frac{L_{ec}}{R} \lll 1$



Schulman, 2016

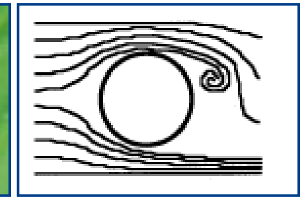
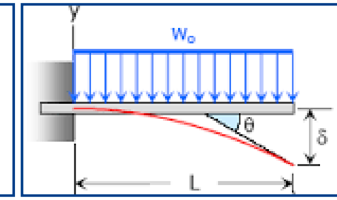
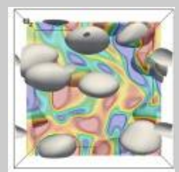
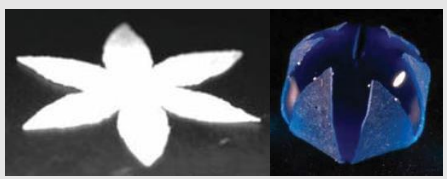
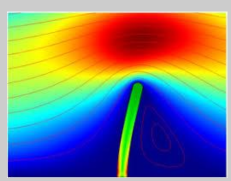
$\frac{L_{ec}}{R} \sim 1$



Bostwick, 2013, 2016

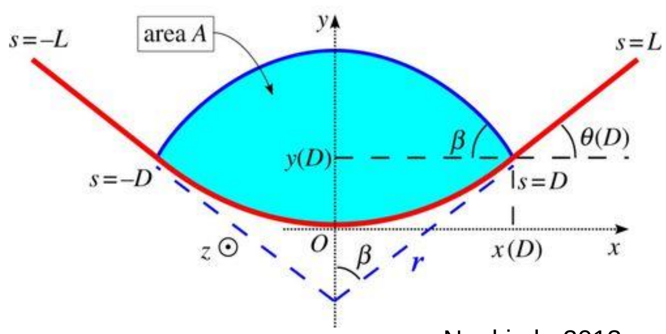
$\frac{L_{ec}}{R} \gg 1$

Can a single model combine all three effects?

		 Capillary effects	 Hydrodynamic effects	 Structural effects
Bubbly flows		✓	✓	✗
Micro origami		✓	✗	✓
Fluid structure interaction		✗	✓	✓

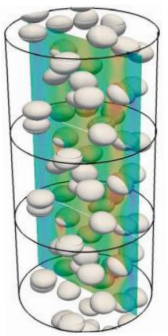
State of the art

Bubble-fiber theory



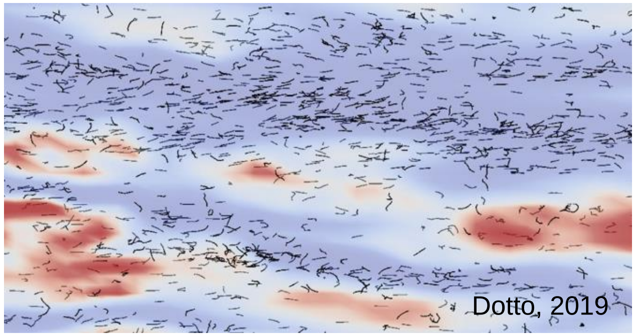
Neukirch, 2013

Bubbly flows

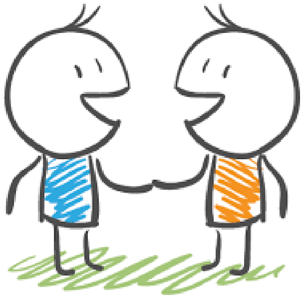


Balcazar, 2017

Fibers-laden flows



Dotto, 2019



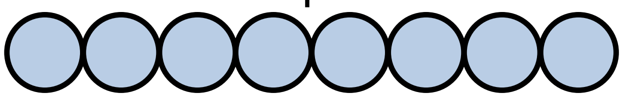
Transport of deformable fibers

in <u>binary</u> flows

Lagrangian fiber model

Original fibre

Decomposition



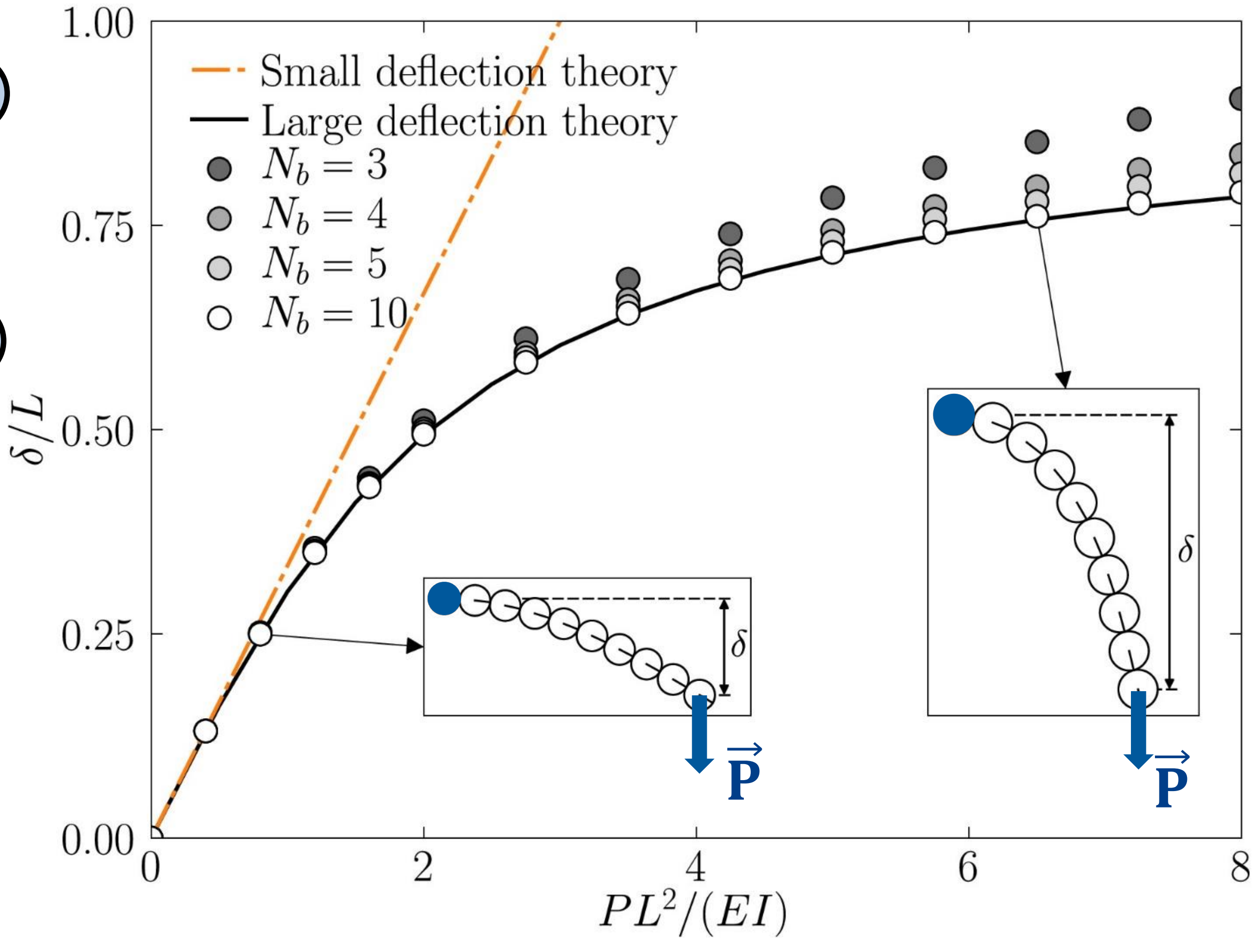
$$m\frac{\mathrm{d}\mathbf{V}}{\mathrm{d}t} = \mathbf{F}_s + \mathbf{F}_h + \mathbf{F}_c + \mathbf{F}_e$$

$$\mathbf{I}\cdot\frac{\mathrm{d}\boldsymbol{\Omega}}{\mathrm{d}t} = \mathbf{T}_s + \mathbf{T}_h + \mathbf{T}_c + \mathbf{T}_e$$

structrural

hydrodynamic

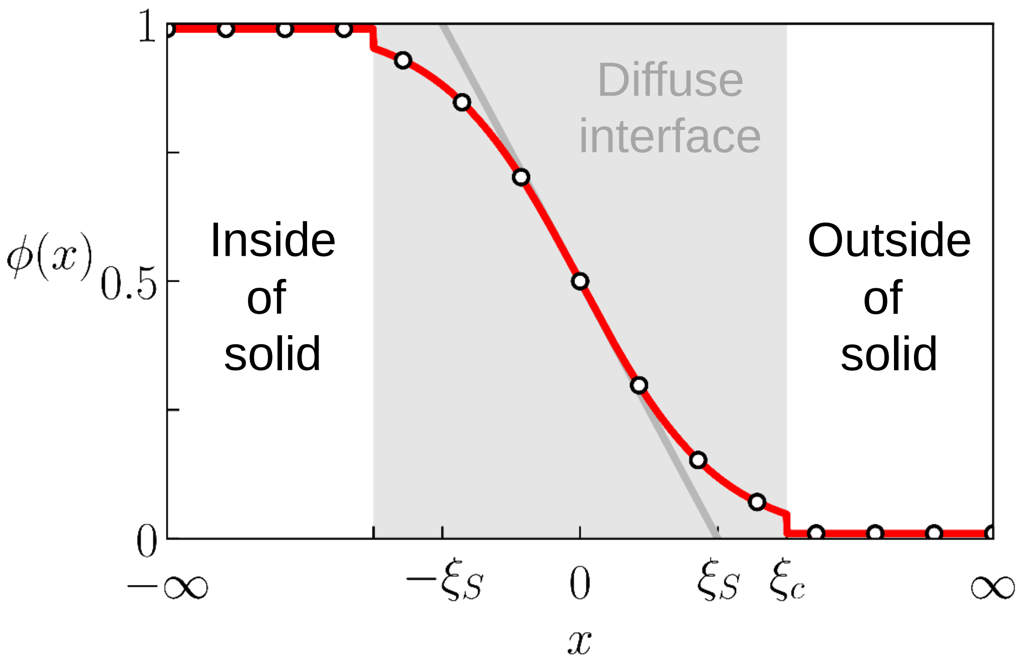
capillary



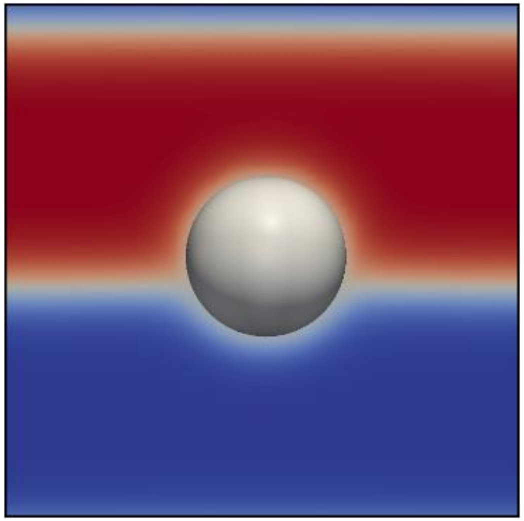
Lagrangian to Eulerian fiber description

$$\begin{cases} \text{if } |\mathbf{x}-\mathbf{X}_S| < r_S - \xi_c & \phi_S(\mathbf{x}) = 1 \\ \text{if } |\mathbf{x}-\mathbf{X}_S| > r_S + \xi_c & \phi_S(\mathbf{x}) = 0 \\ \text{else} & \phi_S(\mathbf{x}) = \frac{1}{2}\left[1 - \mathbf{tanh}\left(\frac{r_p - |\boldsymbol{x}-\boldsymbol{X}_p|}{\xi_S}\right)\right] \end{cases}$$

Smooth Profile Method $\phi_S(\mathbf{x})$



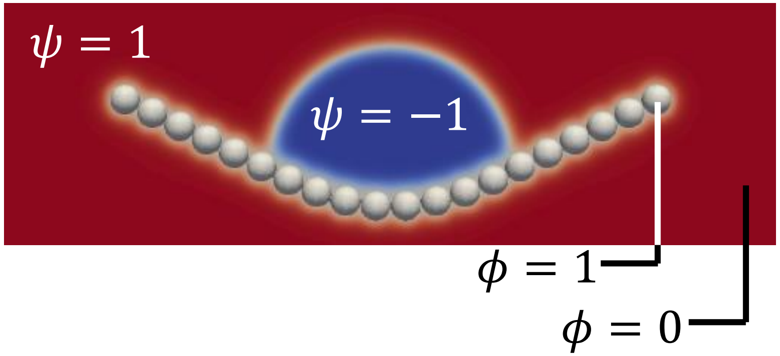
Particle at interface



Eulerian model

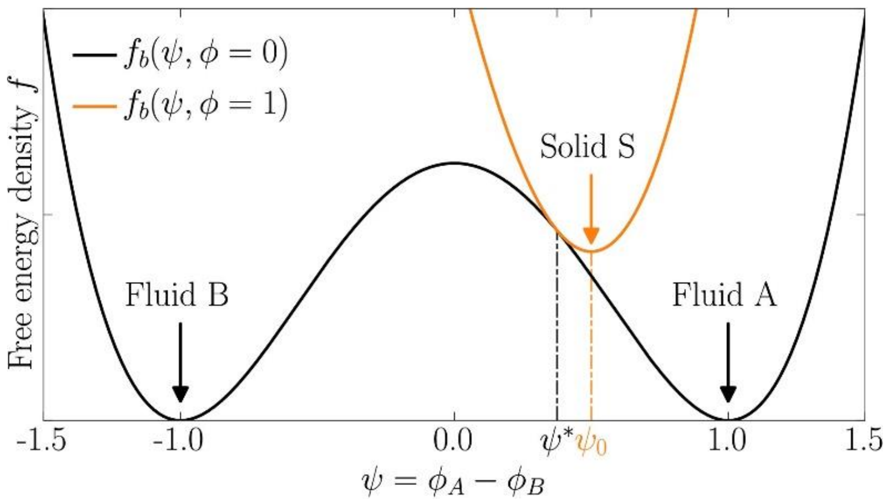
Fiber (*Yasuya Nakayama, PRE, 2005*)

$$\phi = \frac{1}{2} + \frac{1}{2}\tanh\left(\frac{R_\mathrm{b} - |\mathbf{x} - \mathbf{X}_b|}{\xi}\right)$$



Bubble (*Hiroyuki Shinto, APD, 2012*)

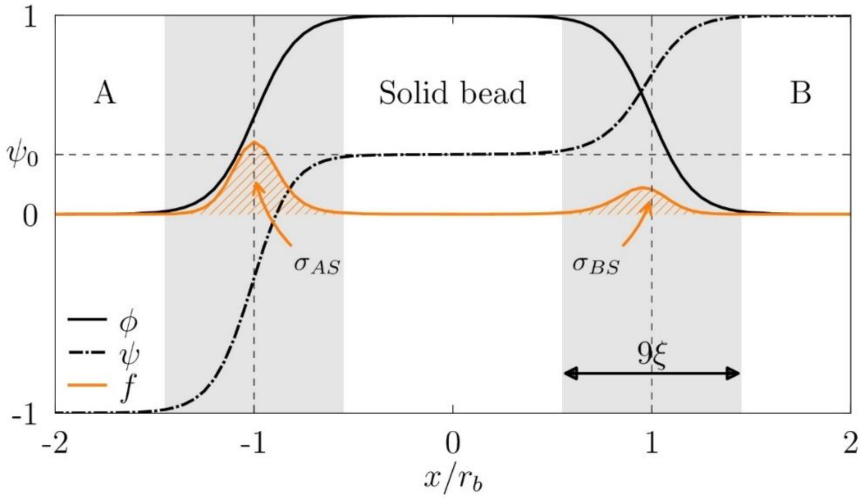
$$\frac{\partial \psi}{\partial t} + \mathbf{u} \cdot \nabla \psi = M \nabla^2 \left(\frac{\delta \mathcal{F}}{\delta \psi}\right)$$

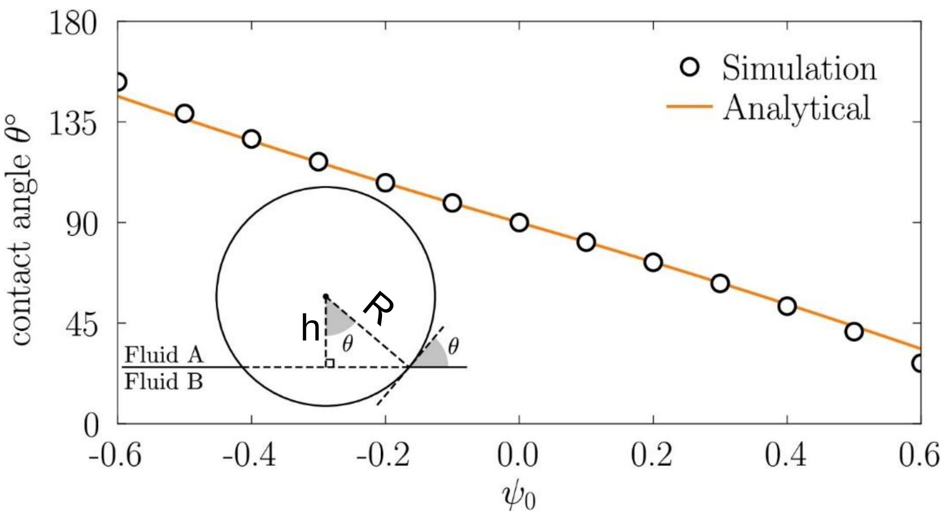


Momentum (*Ryoichi Yamamoto, SM, 2021*)

$$\frac{\partial \mathbf{u}}{\partial t} = -\nabla p + \underbrace{\eta \nabla^2 \mathbf{u}}_{\text{Viscous term}} + \underbrace{\rho \phi \mathbf{f}_\phi}_{\text{Fiber term}} \underbrace{- \psi \nabla \left(\frac{\delta \mathcal{F}}{\delta \psi}\right) - \phi \nabla \left(\frac{\delta \mathcal{F}}{\delta \phi}\right)}_{\text{Capillary term}}$$

Validation of the capillary model



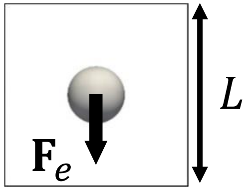


$$\theta = \cos^{-1}\left(\frac{\sigma_{AS} - \sigma_{BS}}{\sigma_{AB}}\right)$$

$$\theta = \cos^{-1}\left(\frac{h}{R}\right)$$

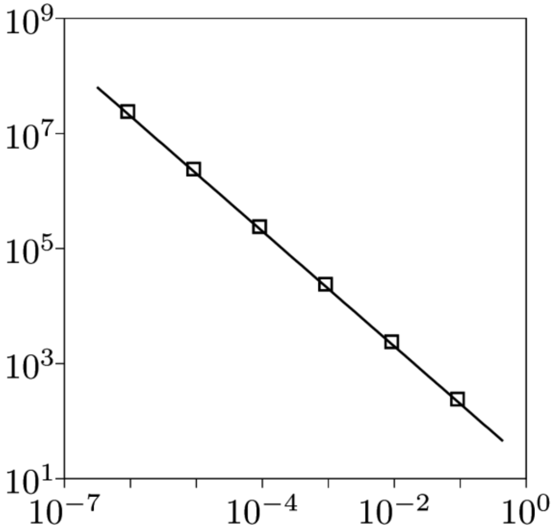
Validation of the hydrodynamic model

Spherical particle subject to a constant external force



Two dimensional

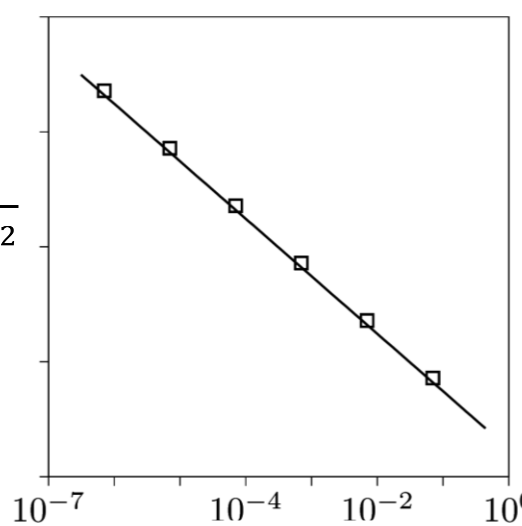
$$C_d = \frac{|\mathbf{F}_e|}{\rho r_S \Delta |\mathbf{V}_S|^2}$$



$$Re_S = \frac{2\rho |\mathbf{V}_S| r_S}{\eta}$$

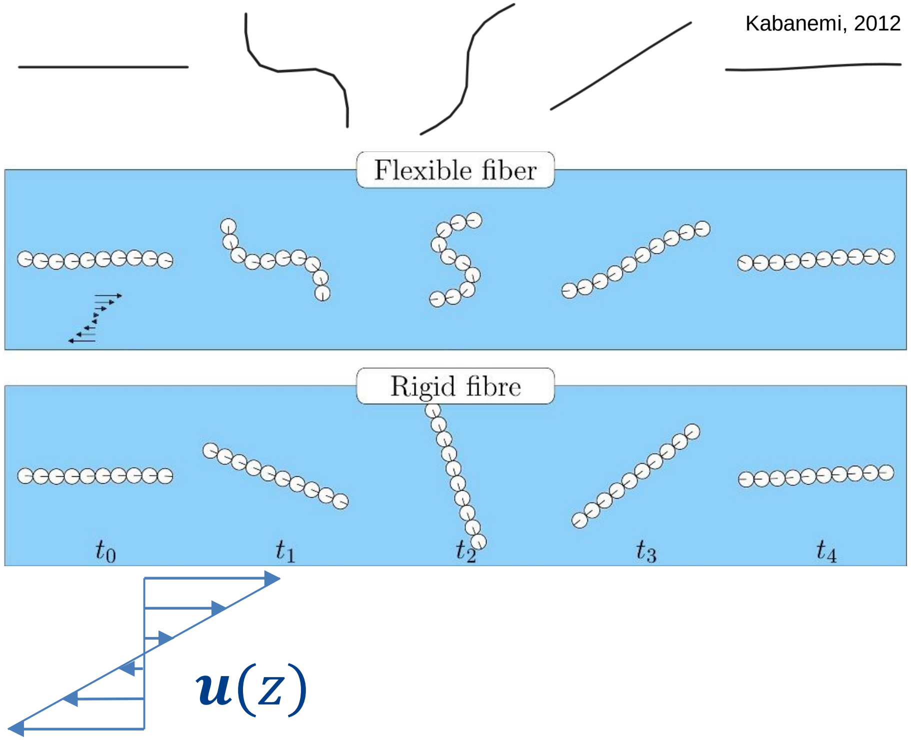
Three dimensional

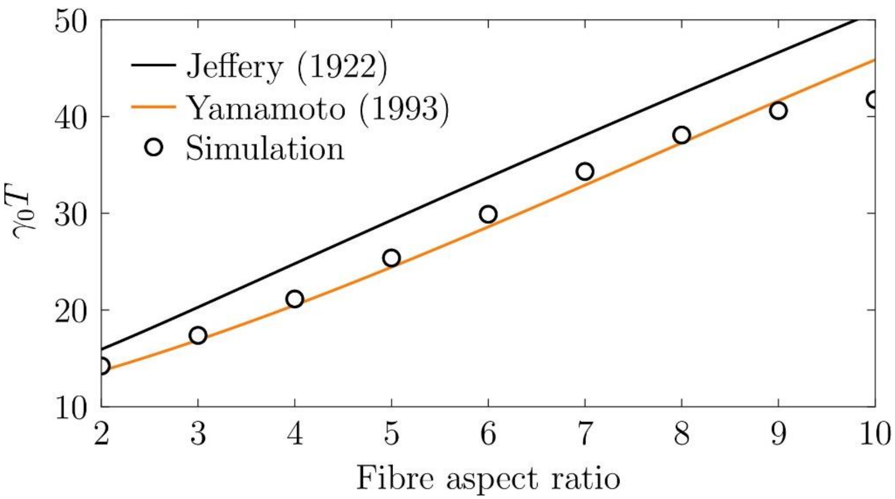
$$C_d = \frac{|\mathbf{F}_e|}{\rho \frac{\pi}{2} r_S^2 |\mathbf{V}_S|^2}$$



$$Re_S = \frac{2\rho |\mathbf{V}_S| r_S}{\eta}$$

Validation of the hydrodynamic model

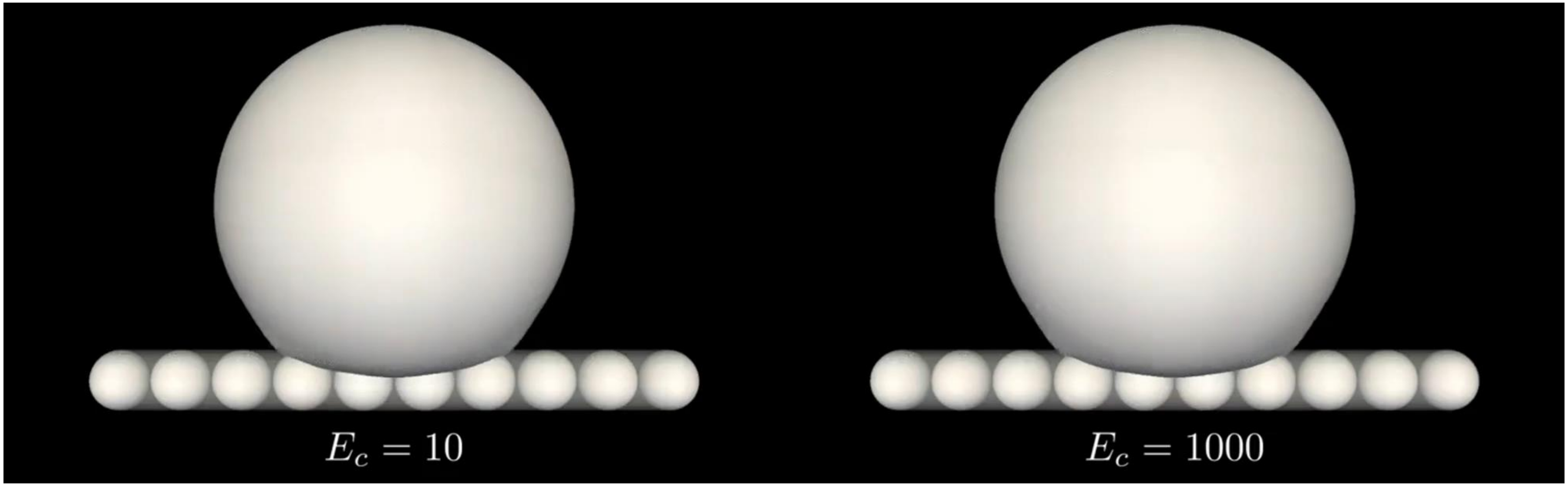




Three-dimensional simulations

Deformable fibre

Rigid fibre



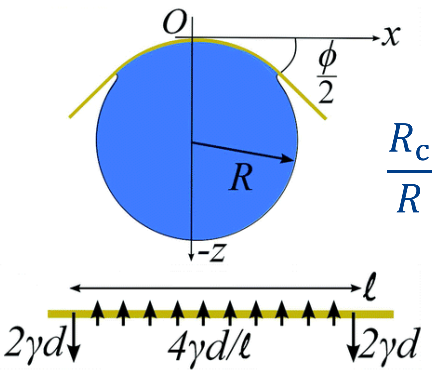
$Re = 0.01$ (over-damped system)

$We = 0.1$

$$E_c = \left(\frac{L_{ec}}{R}\right)^2$$

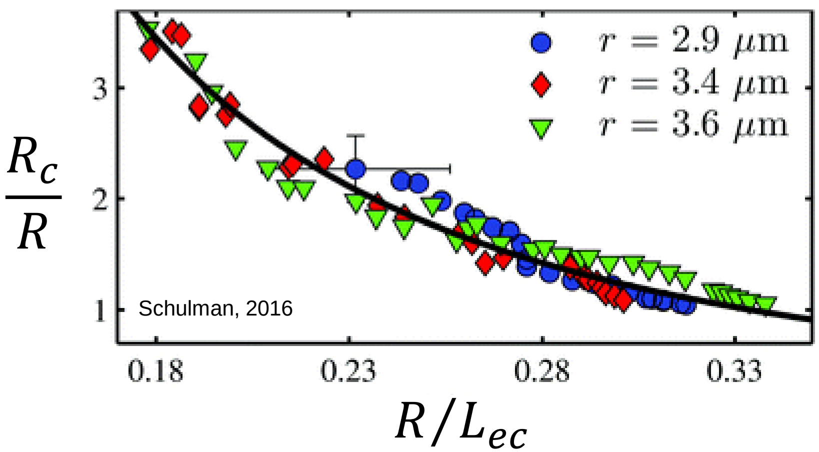
Results

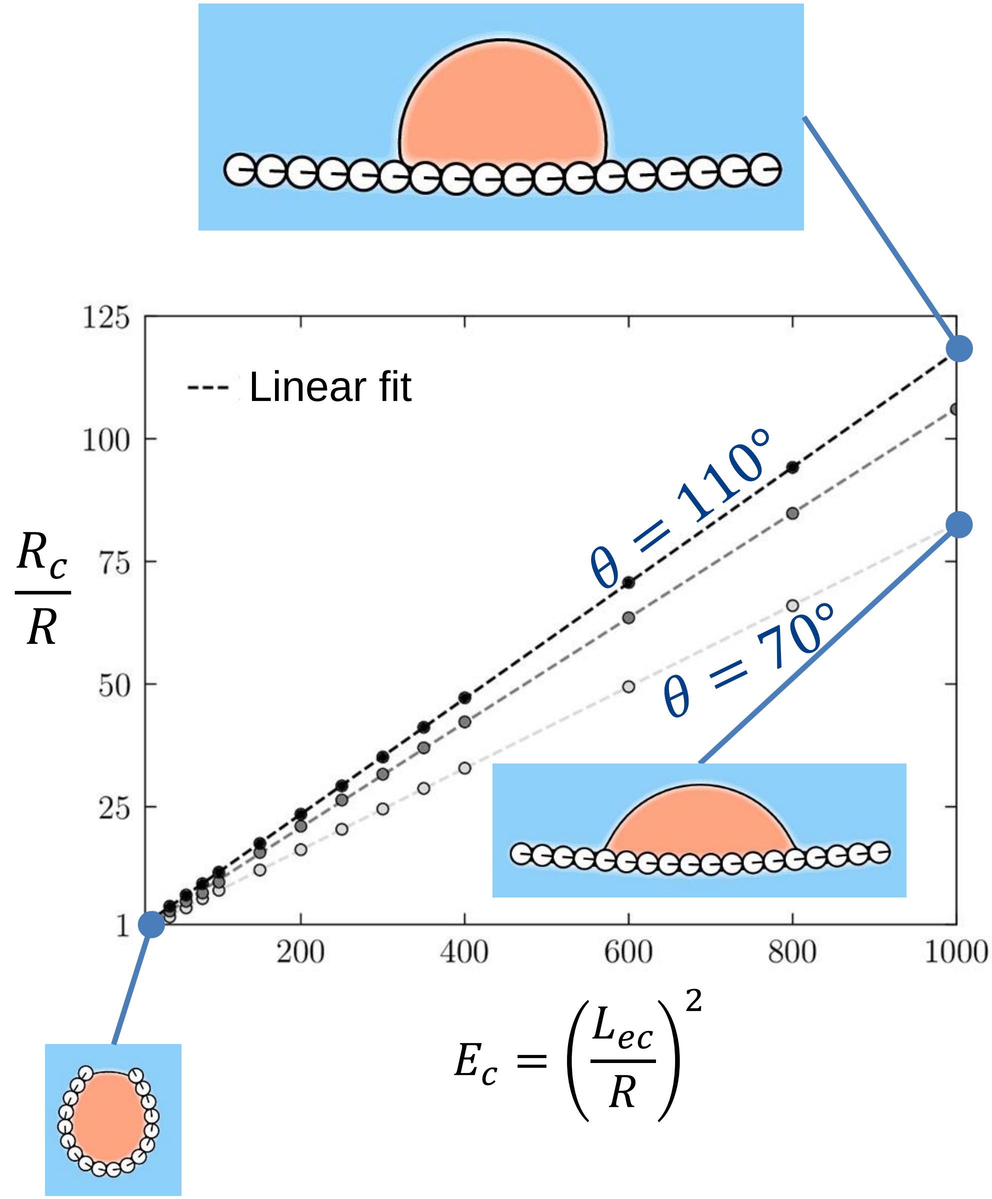
Small deformation theory



$$\frac{R_c}{R} \sim \left(\frac{L_{ec}}{R}\right)^2$$

$$z(x) = \frac{d\ell^3}{\pi r L_{BC}^2}\left[\frac{2}{3}\left(\frac{x}{\ell}\right)^4 - \left(\frac{x}{\ell}\right)^2\right]$$

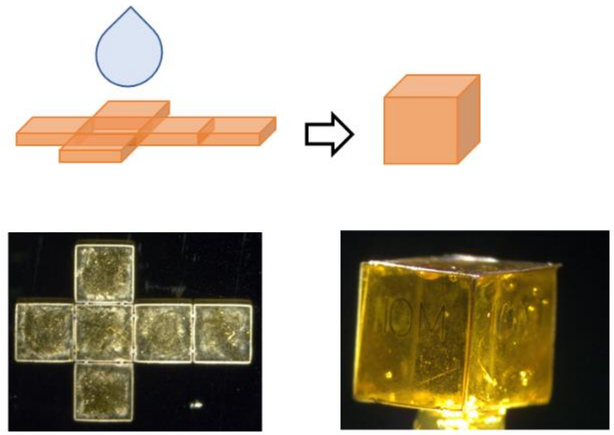




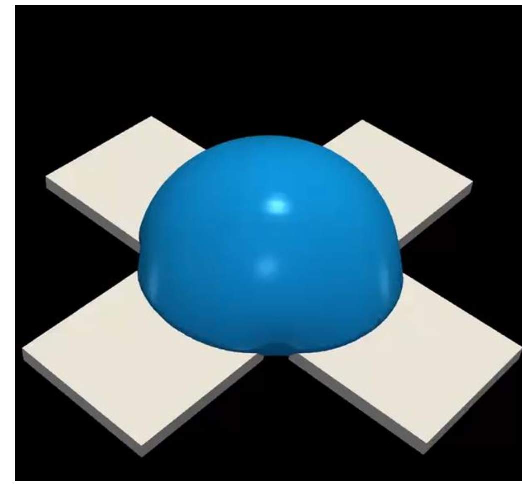
$$E_c = \left(\frac{L_{ec}}{R}\right)^2$$

Further three-phase systems

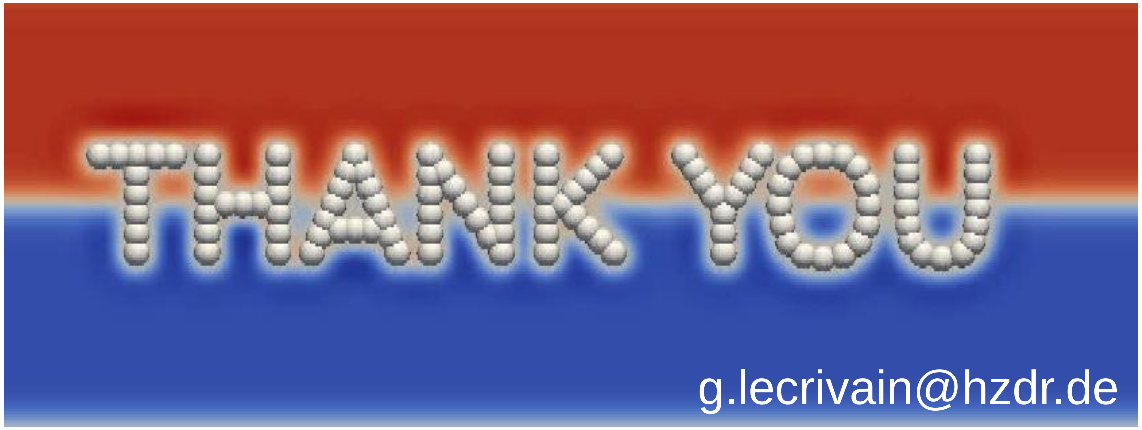
Micro origami (おりがみ)



Microfabrication



Simulation



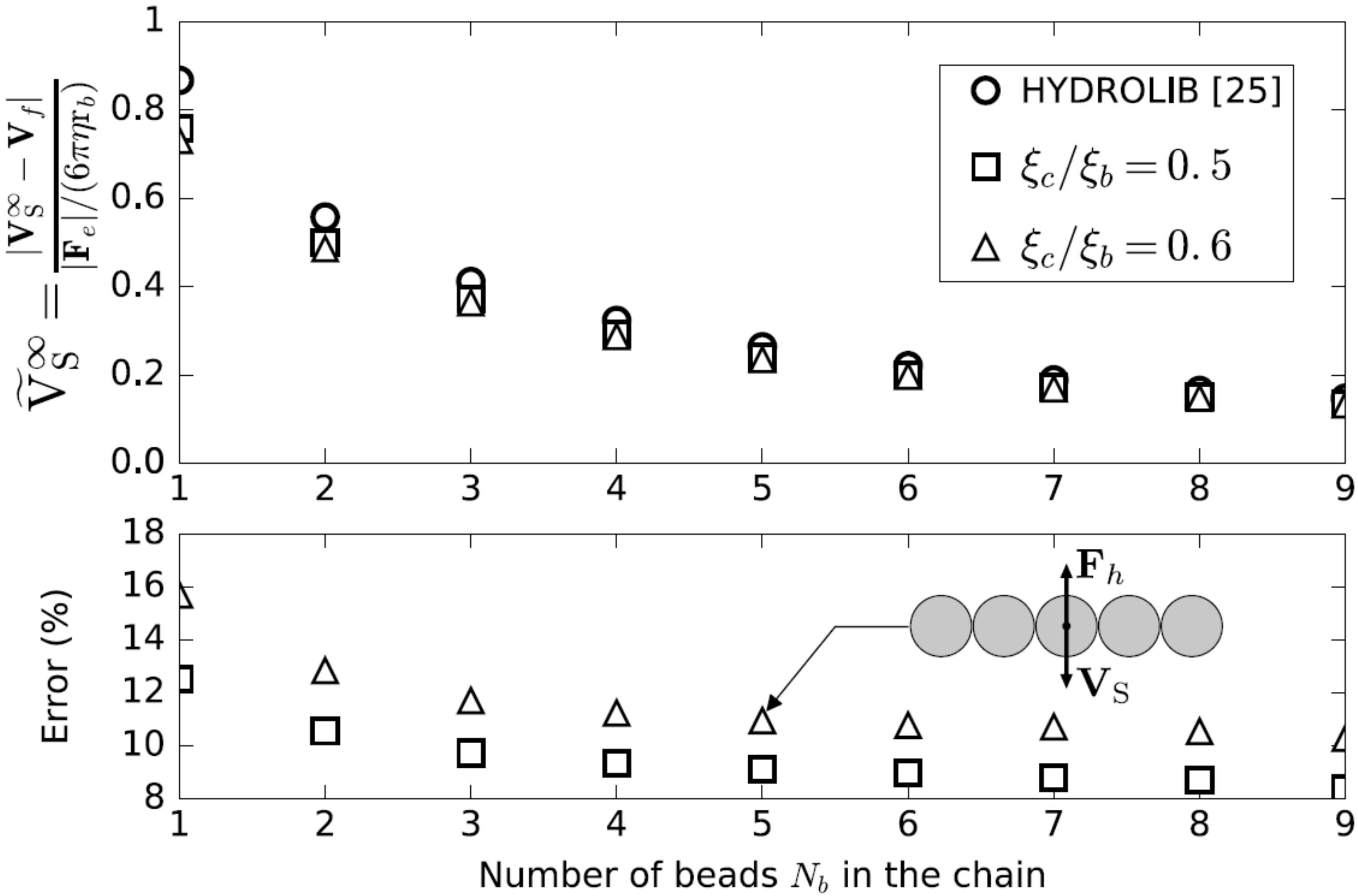
Further reading:

- Gregory Lecrivain, Uwe Hampel, Ryoichi Yamamoto, Takashi Taniguchi, Eulerian/Lagrangian formulation for the elasto-capillary deformation of a flexible fibre, **Journal of Computational Physics**, 2020
- Nozomi Arai, Satoshi Watanabe, Minoru T. Miyahara, Ryoichi Yamamoto, Uwe Hampel, Gregory Lecrivain, Direct observation of the attachment behavior of hydrophobic colloidal particles onto a bubble surface, **Soft Matter**, 2020
- Gregory Lecrivain, Yuki Kotani, Ryoichi Yamamoto, Uwe Hampel, Takashi Taniguchi, Diffuse interface model to simulate the rise of a fluid droplet across a cloud of particles, **Physical Review Fluids**, 2018
- Gregory Lecrivain, Ryoichi Yamamoto, Uwe Hampel, Takashi Taniguchi, Direct numerical simulation of an arbitrarily shaped particle at a fluidic interface, **Physical Review E**, 2017

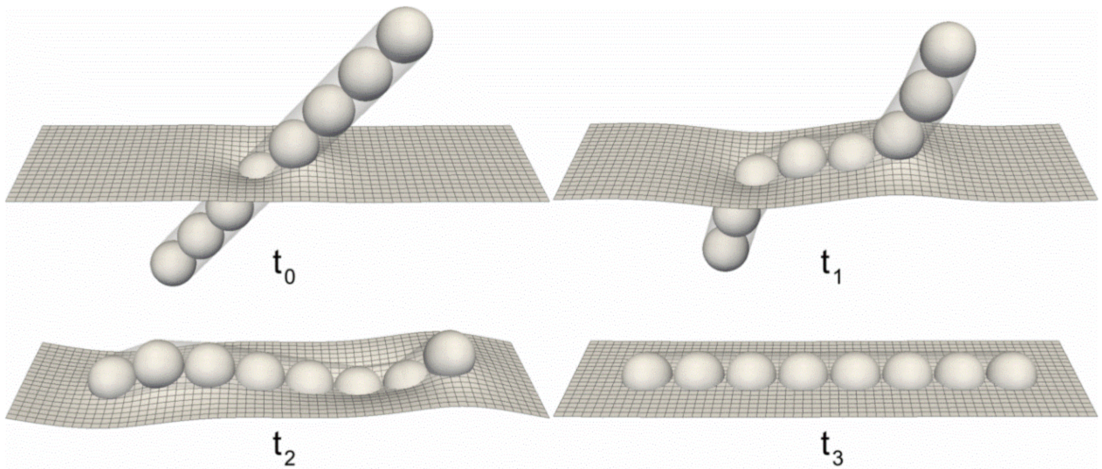
16th International Conference on Gas–Liquid and Gas–Liquid–Solid Reactor Engineering (GLS-16)

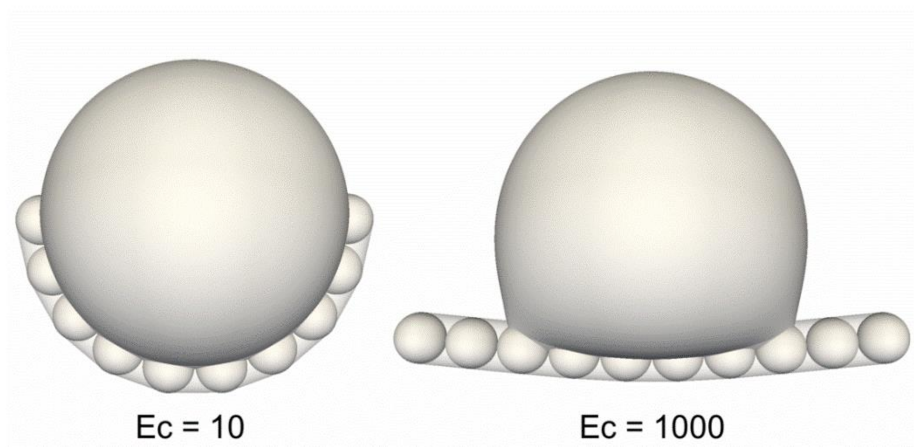
Dresden, September 2 – 5, 2024

Hydrodynamic model validation



Three-dimensional simulations





Text (20 pt)

Head Text (20 pt)

- Folie 1 (18 pt)
  - Folie 1.1 (16 pt)
  - Folie 1.2
  - Folie 1.3

Schriftgrößen können angepasst werden!

Partnerlogo