Mechanics of swimming microorganisms: nutrient uptake in thin films

March 17, 2014

Tufts Department of Mechanics

Ruth A. Lambert
Department of Civil and Environmental Engineering
University of California, Berkeley

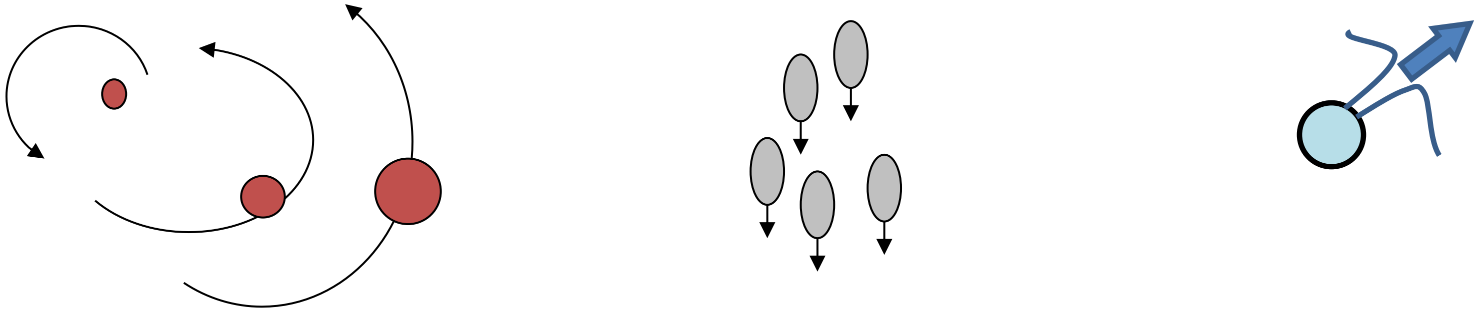
Introduction

- PhD in Multiphase Heat Transfer and Fluid Dynamics
- BS in Environmental Engineering

I use semi-analytical and numerical methods to solve small-scale fluid dynamics problems

My current research interests include:

- Particle collisions and size distributions
- Properties of suspensions of non-spherical particles
- Mixing and mass transport in highly porous media
- Mechanics of swimming micro-organisms and nutrient transport



Collaborators

Luca Brandt
KTH Mechanics
Stockholm, Sweden

Wim-Paul Breugem
Mechanical and Aerospace Engineering
TU – Delft, Netherlands

Francesco Picano
Industrial Engineering
University of Padova, Italy

Outline

Background

- Life in a viscous fluid
- Numerical methods

Numerical method for particle-laden flows

- Immersed Boundary Method (IBM)
- IBM applied to model swimming particles

Study: Suspension of model swimmers in a thin film

- Velocity profiles and swimmer distributions
- Mass transport and nutrient uptake

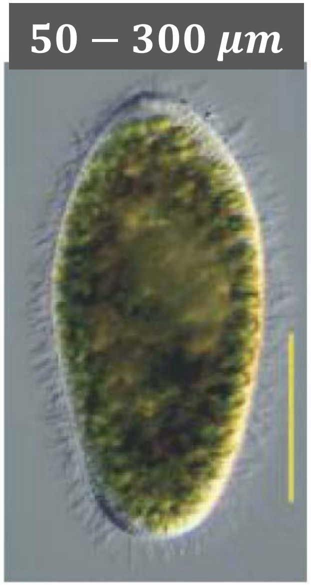
Conclusions

Future Work

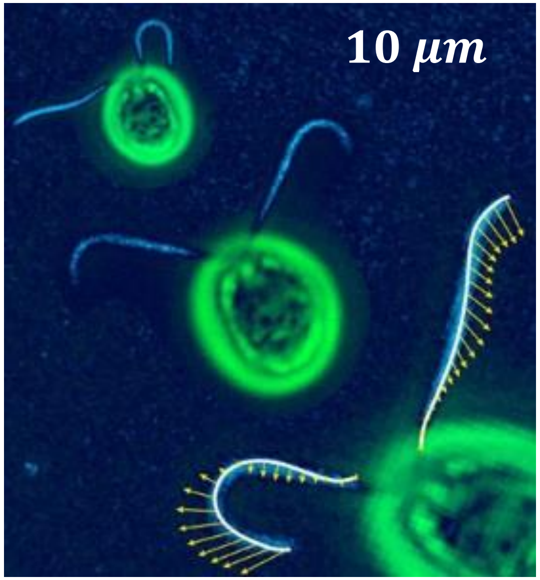
R.A. Lambert, F. Picano, L. Brandt, W.P. Breugem, J. Fluid Mech. 733 (2013) 528-557

Microorganisms: swimming with flagella

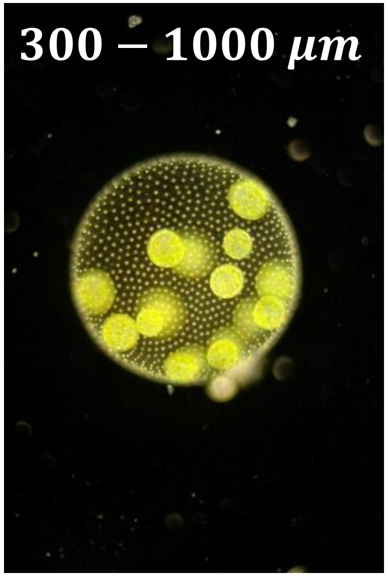
- Cilia and flagella are thin, hair-like structures that are attached to the surface of microorganisms – used for propulsion
- Groups of cilium can be distributed along a surface; synchronized beating results in translational motion.
- Actuation of two flagellum are the propulsion mechanism for microorganisms such as green algae



Paramecium
(Kreutz et al., J Euk. Micro., 59, 2012)

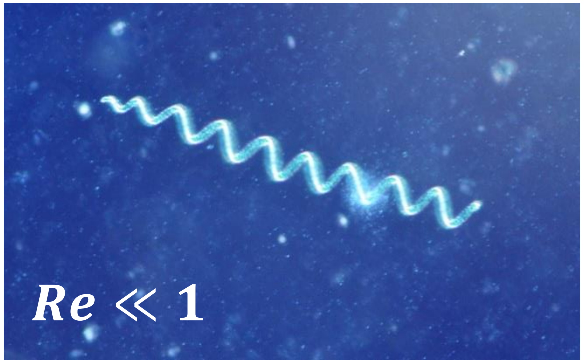


Green algae *Chlamydomonas*
(Geyer et al. PNAS , 21, 2013)



Volvox, colonies of green algae
(R.E. Goldstein, Univ. of Cambridge)

How do swimming cells relate to traditional fluid dynamics applications?



- G. I. Taylor (1950) - Studied the action of waving cylindrical tails
- Due to their small size, viscous forces are thousands of times larger than inertial forces

Reynolds number ~ $\frac{\text{stress in fluid due to inertia}}{\text{stress due to viscosity}}$;

Low Reynolds number applications:

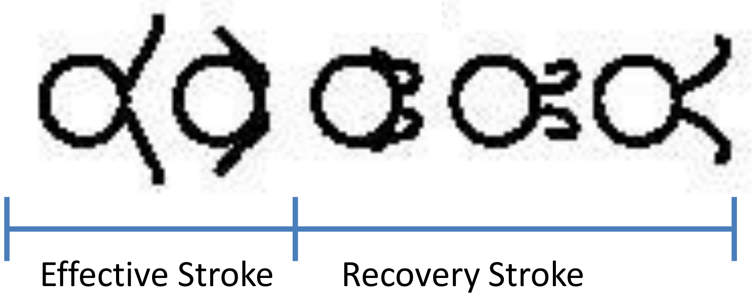
- Microfluidic device design - Fluid mixing and mass transport
- Micro-robots - mechanical and biological hybrids
- Identifying the role of mechanical forces in biological systems

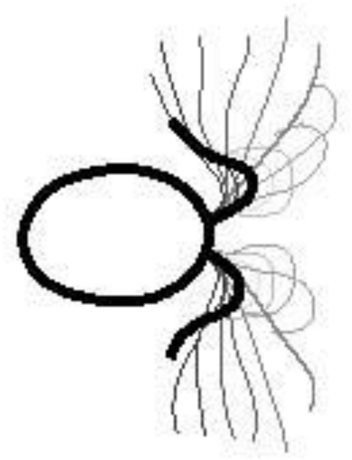
The focus of my talk today is the role of mechanical forces in understanding biological systems

Cyanobacteria (exploringtheinvisible.com)

Low Reynolds number propulsion

- Motion is time reversible at Re << 1.
- For net translation periodic motion of flagella must be non-symmetrical
- For synchronized beating, a phase difference must exist between neighboring cilia
- Three types of swimmers: pullers, pushers, and neutral
- Interplay of forces:
  - Actuation forces
  - Elastic forces
  - Fluid drag forces





Example: Puller

The effective and recovery stroke of a green algal cell

(D. Tam and A. E. Hosoi, PNAS, 108 (3) 2010)

Numerical models

- For low Reynolds number applications, numerical models use **Stokesian** methods that neglect inertial terms
- In this study, time dependency is retained, in order to incorporate additional physics such as mass transport

Numerical models[**] that have been developed to replicate swimming cells can be divided into two groups:

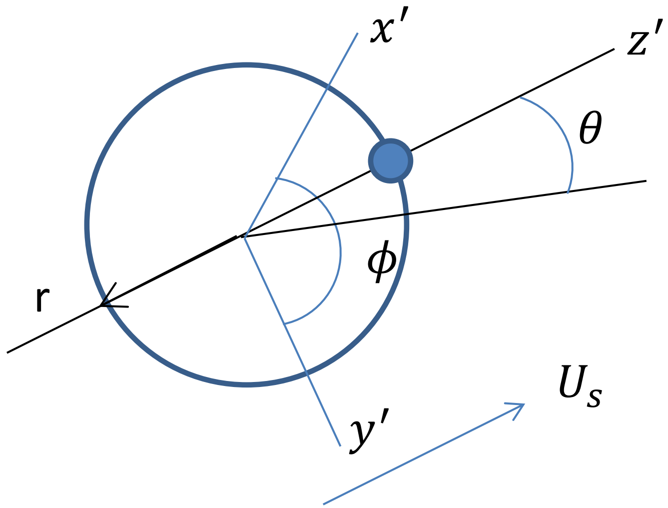
Exact models which include actuated flagella attached to a free moving body

Approximate (envelope) models which transform ciliar motion into an equivalent stress or velocity at the cell surface

[**] Numerical methods for *fluid flow*, *solid body motion*, *and fluid-structure interactions* are required

Swimming particle model

Propulsion is generated by deformation of the surface or the motion of cilia or flagella



Body shape is a perfect sphere

Tangential surface velocity

$$u_\theta = b_1 sin\theta(1 + \beta cos\theta)$$

Puller : $\beta > 0$
Pusher: $\beta < 0$
Neutral swimmer: $\beta = 0$

moving reference frame: (x', y', z')

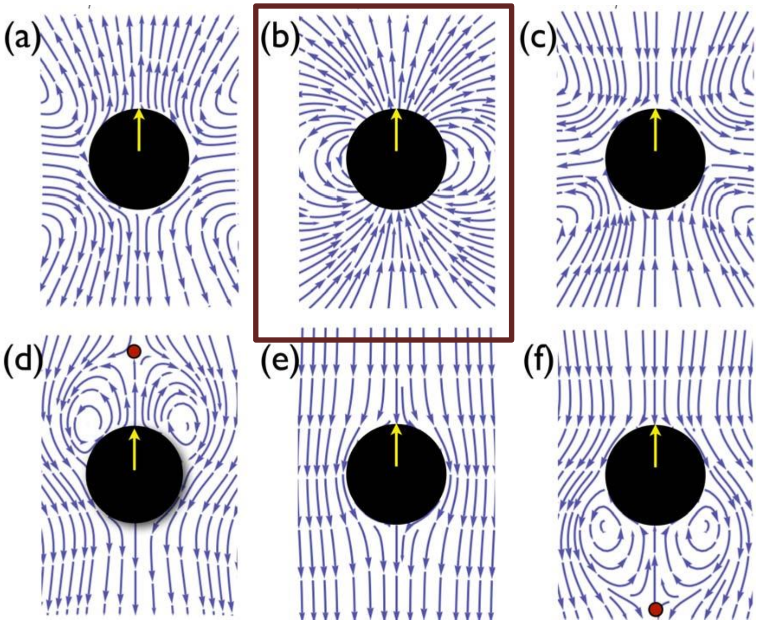
swimming coordinates: (θ, ϕ, r)

Swimming speed: $U_s = \frac{2}{3} b_1$

Disadvantages: neglects change in body shape, uses average swimming speed

The average flow field

Type A **B** C



fixed reference frame

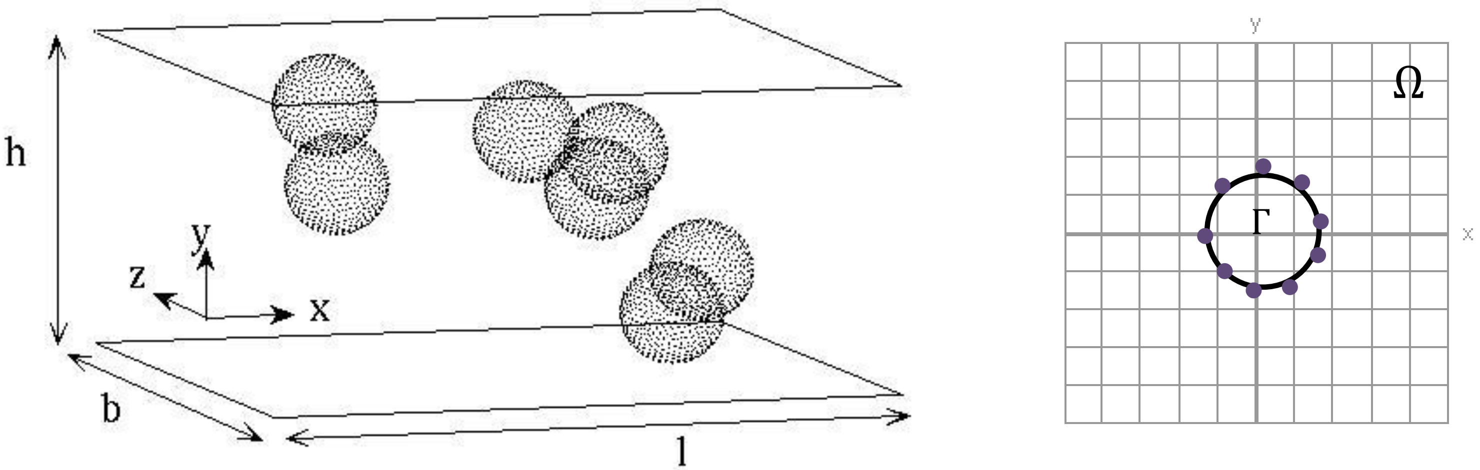
moving reference frame

(Evans et al., Phys. Fluids 23, 111702 **2011**)

Type A: Pusher with rear propulsion i.e. flagella at the rear, bacteria
Type B: Neutral swimmer i.e. symmetric streamlines, opalina
Type C: Puller with forward propulsion i.e. flagella at the front, algae

Overview of numerical method

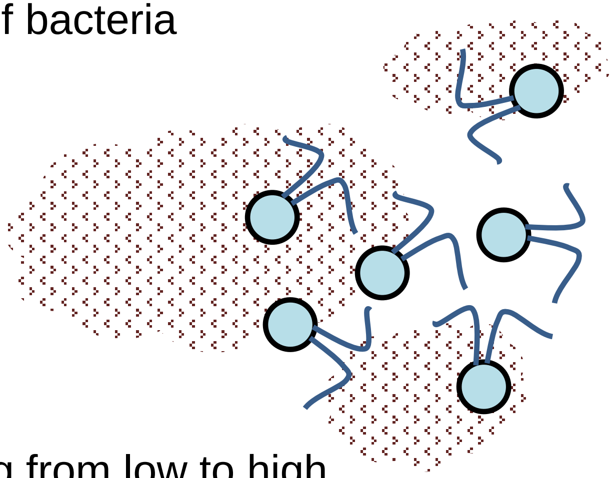
- Immersed Boundary Method allows for a stationary background grid
- Multiple spherical particles, particle collisions, and collisions with surfaces.
- Fluid and solid interactions are enforced using distributed Lagrange multipliers, $\boldsymbol{\lambda}$
- Lagrange force multipliers are applied on the background grid at the fluid and solid interface



Lagrangian force distribution on the background grid

Study: Microorganisms in suspension

- The study of mass transfer of active suspensions is relevant for the understanding microorganism ecosystems
- Examples include algal blooms, suspensions of bacteria
- The nutrients (scalar) include,
  - dissolved gasses
  - proteins
  - organic compounds
  - small particles
- Enhanced consumption results from swimming from low to high nutrient concentration regions and induced fluid flow.
- The role of hydrodynamics on the mass transfer process for microorganisms in suspension is not well understood.



Suspensions in thin films

- Swimming microorganisms (swimming particles) can be found in confined environments: thickness $h \geq d,$ particle diameter
  - cellular environments and tissues
  - soap films
  - droplet suspensions
  - aqueous layers between glass slides, petri dishes
- Swimming particles have strong preferential clustering near surfaces
- Experimental and numerical studies show that preferential clustering the result of hydrodynamic effects
- Nutrient is replenished at the open interface

Values of relevant parameters

diameter, *d*: $1 - 10\ \mu\text{m}$ bacterium – ciliate protozoon

diffusivity, *D* : $10^{-7} - 10^{-11}\text{m}^2/s$ heat – proteins

$$Pe \sim \frac{\text{convective transport}}{\text{diffusive transport}}$$

$\text{Re} = Ud/\nu$: $10^{-5} - 10^{-1}$ bacterium – ciliate protozoon

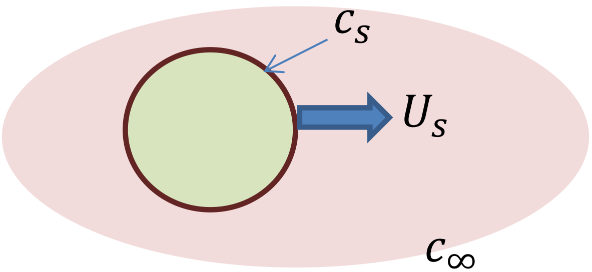
$Pe = Ud/D$: $10^{-3} - 10^{2}$ bacterium – ciliate protozoon

- Stokes flow regime – viscous forces dominate inertial forces in the flow
- Mass transport is governed both by diffusion and advection

Nutrient uptake by the model swimmers

Nutrient uptake (or consumption): first order reaction rate equation

$$\frac{dc_s}{dt} = kc_s$$



c_s - cell surface concentration
k - first order reaction rate

The viscous Damkhöler number ~ $\frac{\text{nutrient uptake rate}}{\text{rate of viscous diffusion}}$

$$Da_\nu = \frac{kd^2}{\nu}$$

The mass transfer to the model swimmer is determined by the Sherwood number

$$Sh \sim \frac{\text{total mass flux}}{\text{diffusive mass flux}}$$

$$Sh = \frac{1}{\pi d c_\infty} \int_S \frac{\partial c}{\partial \mathbf{x}} \cdot \mathbf{n} dS$$

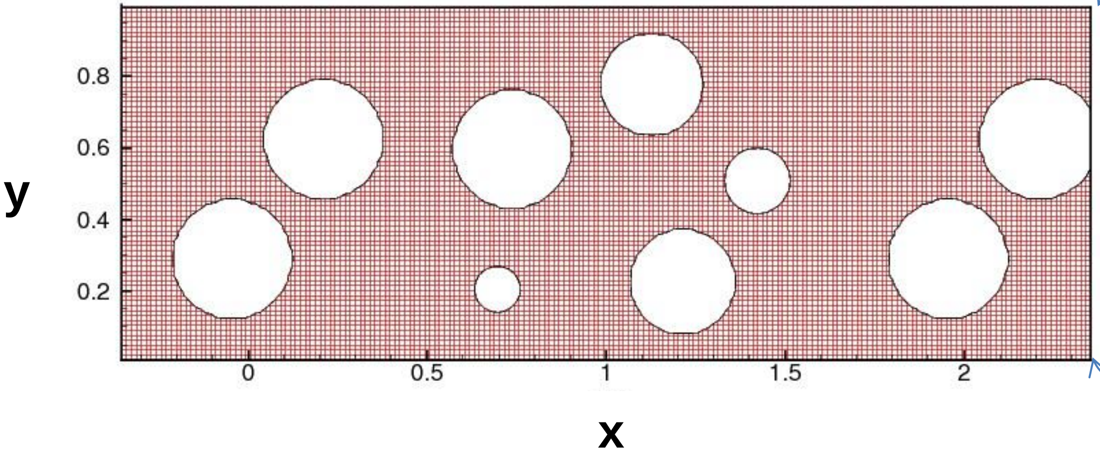
Thin film description

- Thin film with two free surfaces and periodic boundary conditions in (x, z)
- The population of swimming particles (ϕ): N = 16, 32, 50
- Fluid is initially saturated at t = 0
- Scalar concentration is replenished at the free surfaces
- Boundary conditions:

$$\frac{du}{dy} = 0, \qquad \frac{dw}{dy} = 0 \quad \text{at } y/h = 0, 1$$

$$\mathrm{v} = 0, \qquad c = 1 \quad \text{at } y/h = 0, 1$$

$c = 1$



$$\mathbf{u}(\mathbf{x}, 0) = 0$$
$$c(\mathbf{x}, 0) = 1$$

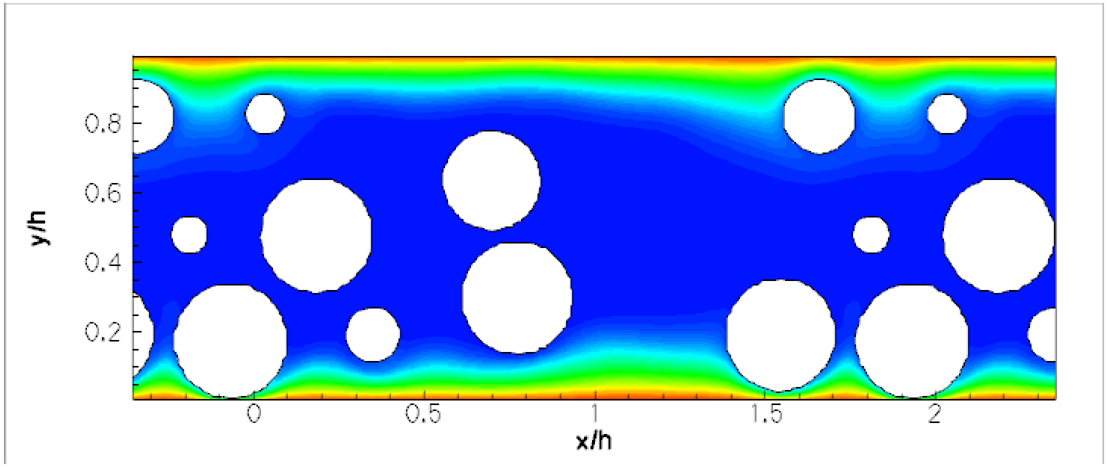
$c = 1$

Background grid with model swimming particles

Animation of nutrient uptake in a thin film

$Da_v = 10, \qquad Sc = 100, \qquad \phi = 0.24$

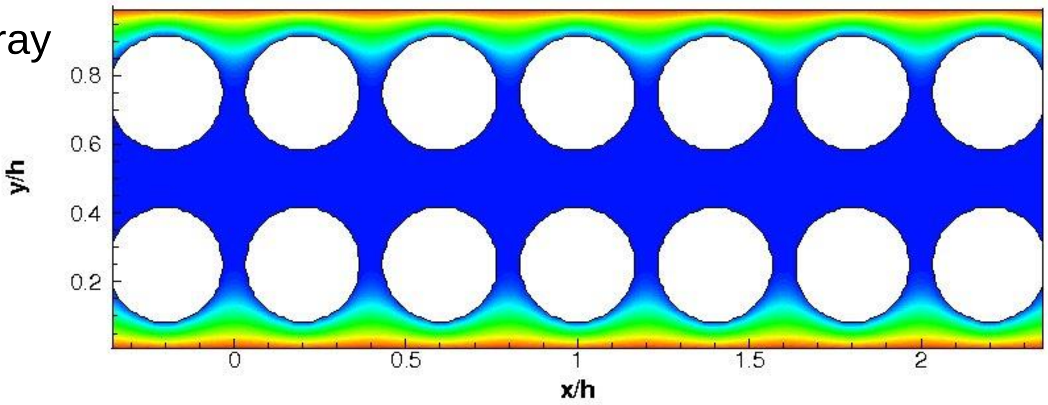
$Pe = 100$
$z_o = 0.5\,Z$



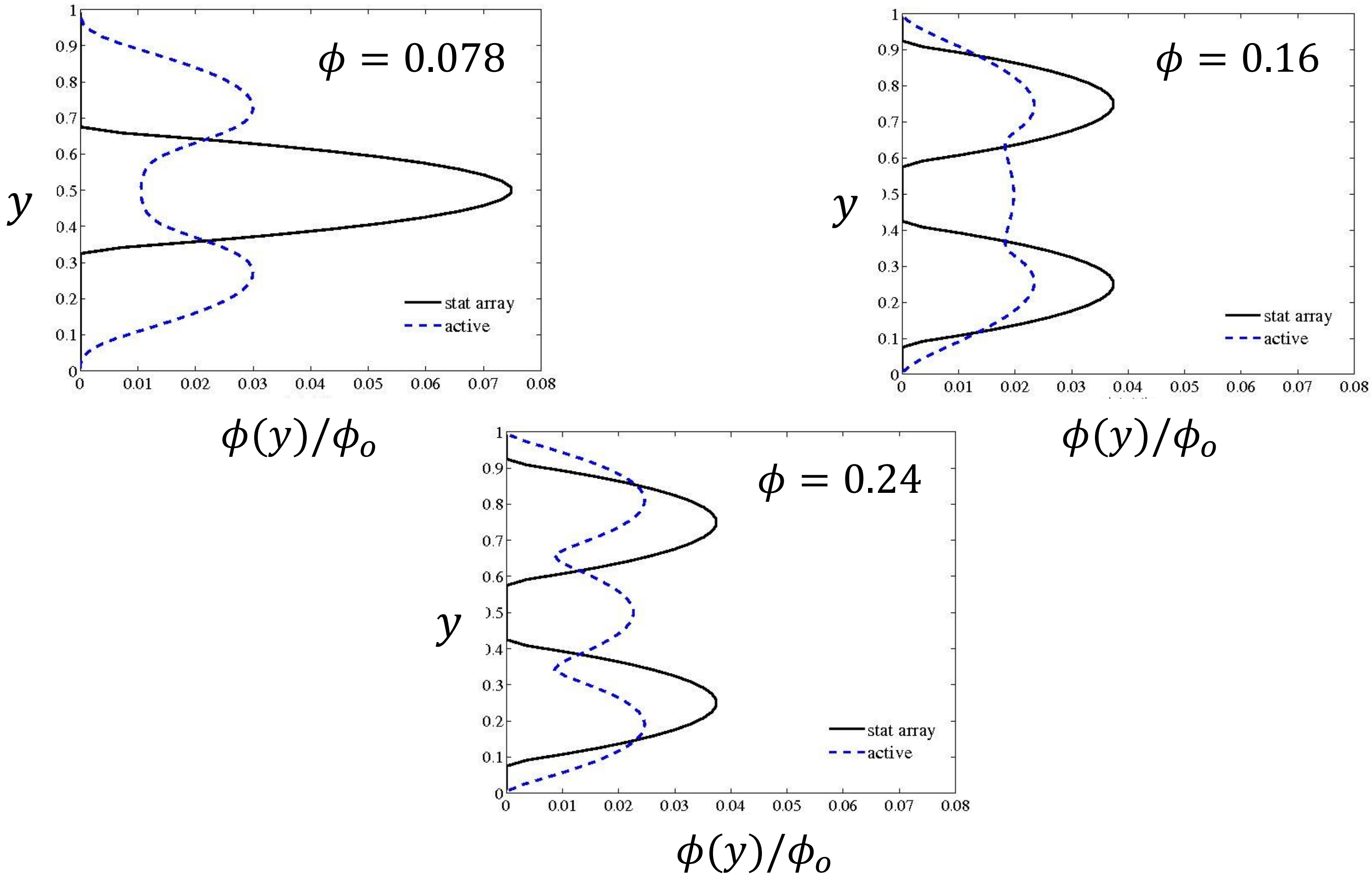
Time interval:
$t = 80 - 160$

c
🟦 0
🟥 1

Stationary array
$z_o = 0.5\,Z$

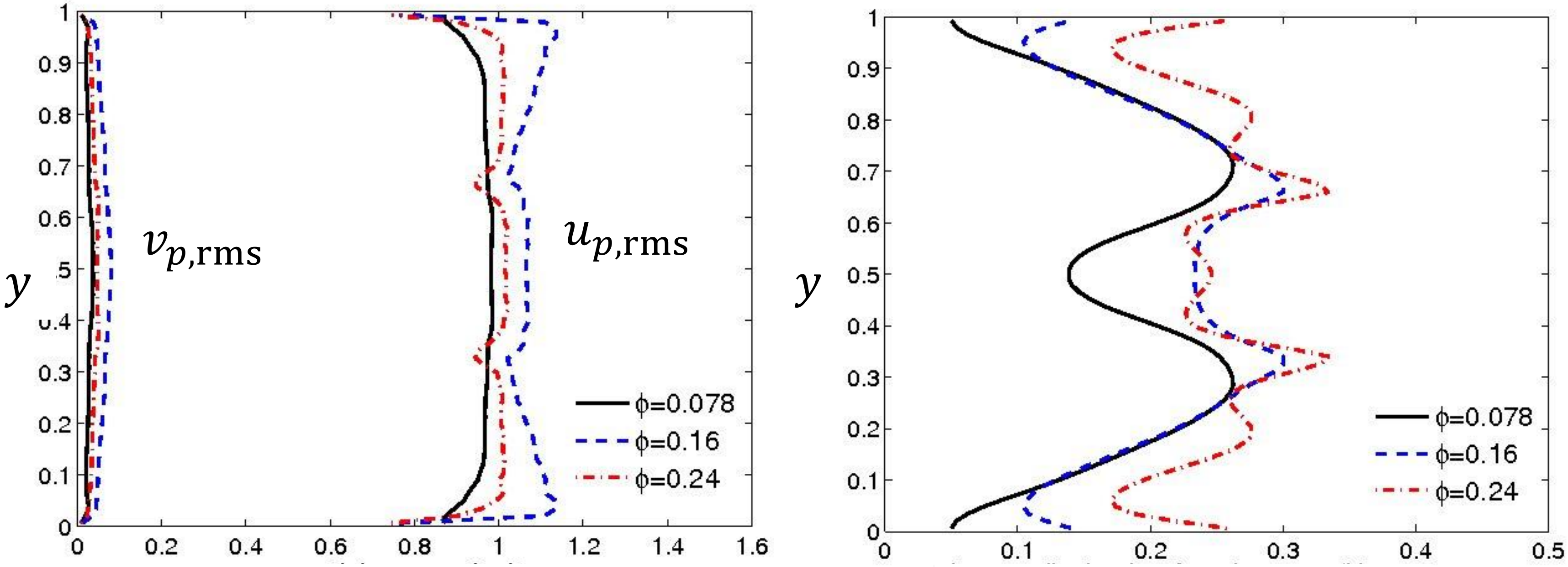


Particle volume fraction profile in the fluid



Volume fraction distribution along the film cross section

Particle motion in a thin film



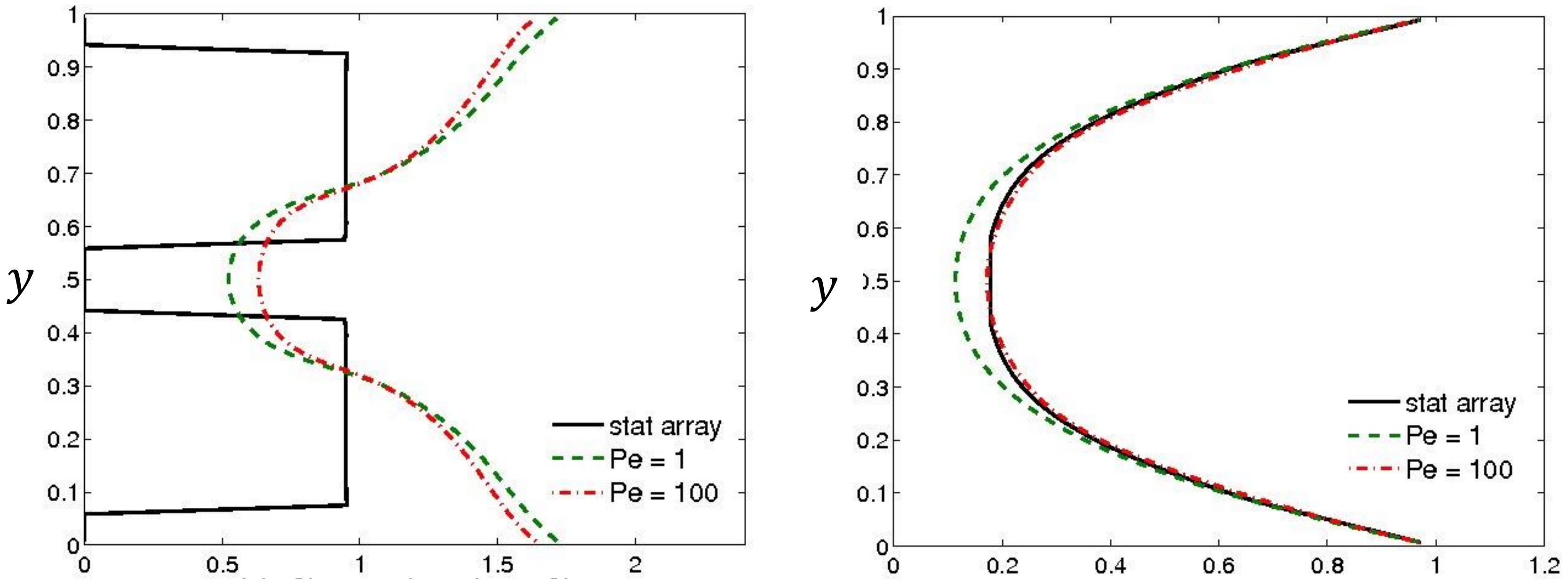
particle rms velocity

viscous dissipation rate

Vertical profiles of the a) particle rms velocity in the planar and vertical direction and b) the viscous dissipation function

Mass flux and nutrient concentration profiles

$Da_\nu = 1, \qquad Sc = 100, \qquad Pe = 0 - 100$



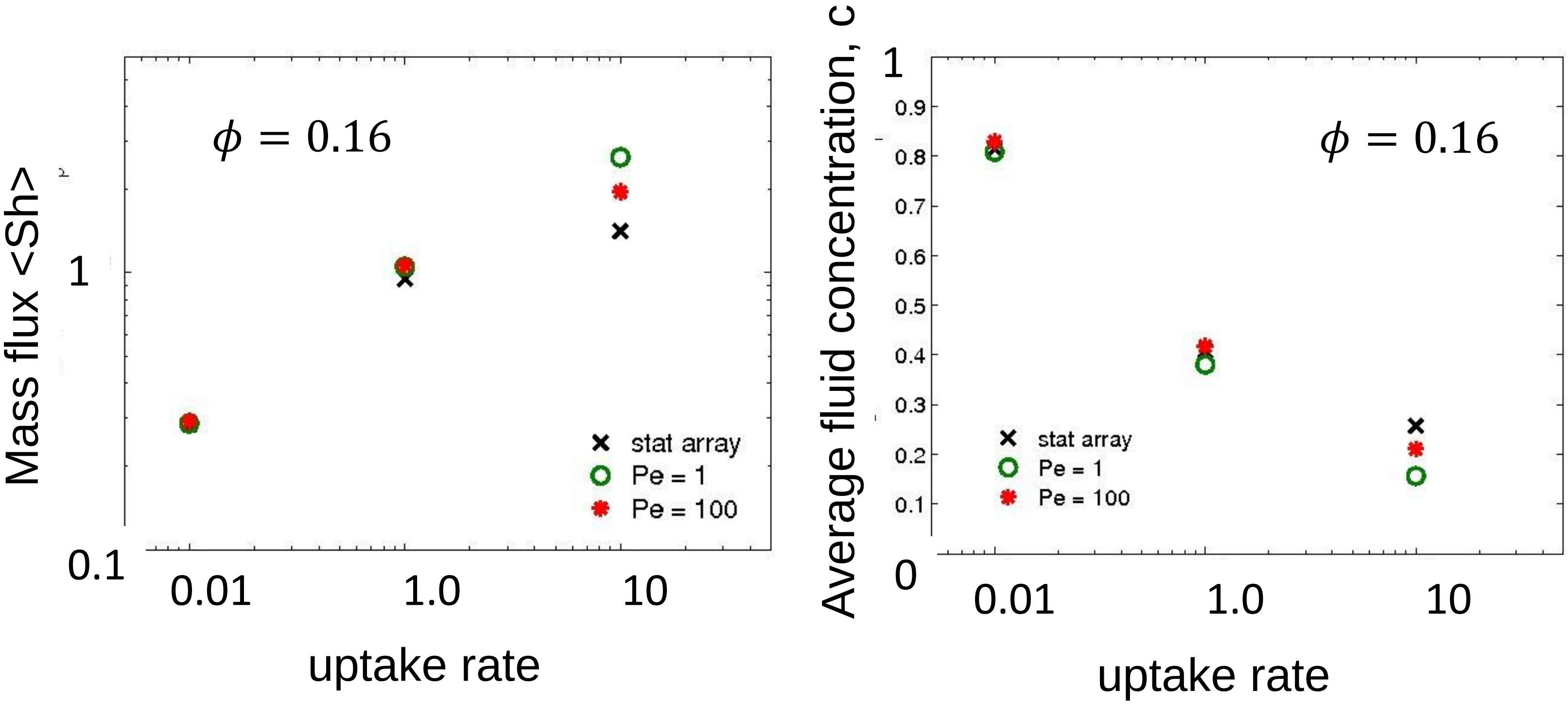
Mass flux <Sh>

Fluid nutrient concentration

Profiles of the a) mass flux $\langle Sh \rangle_p$ and b) fluid concentration $\langle c \rangle_f$ along thin film cross section for a stationary and active suspension and $\phi = 0.16$.

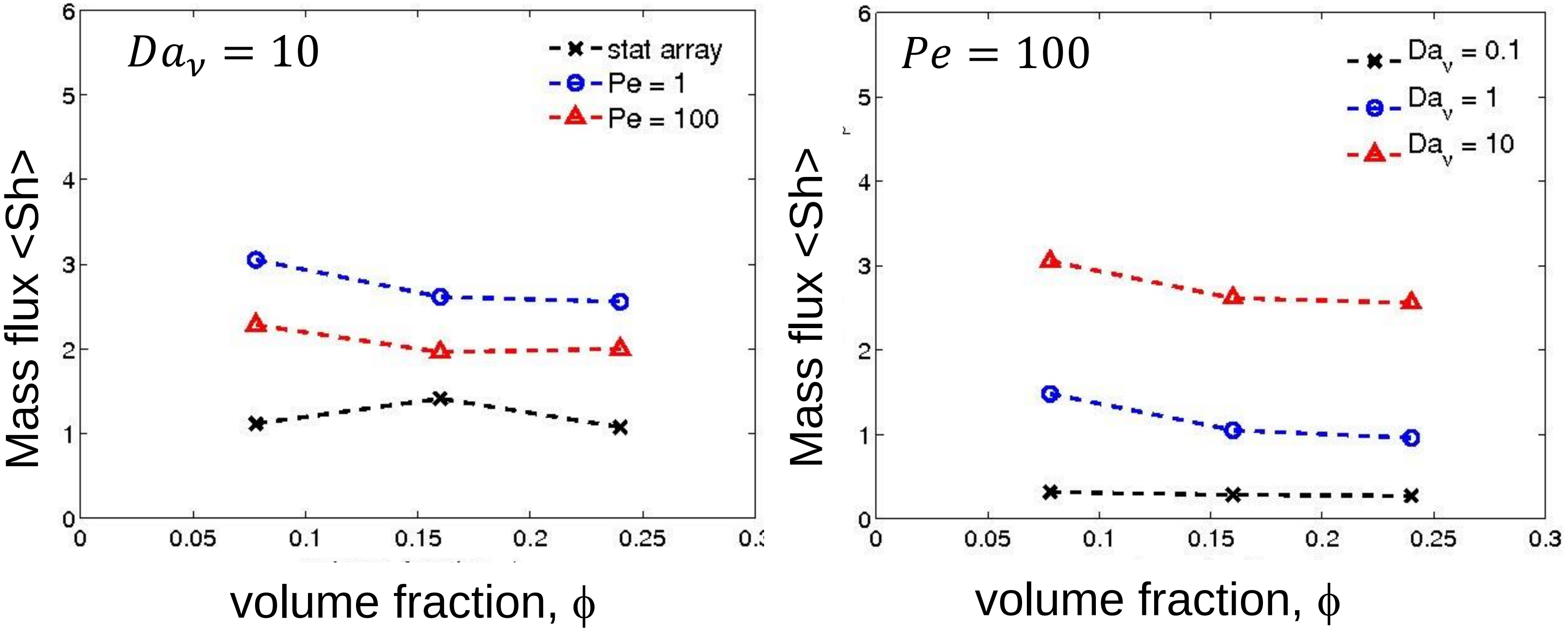
Ensemble averages

$$Sc = 100\,, \qquad Pe = 0\ - 100$$



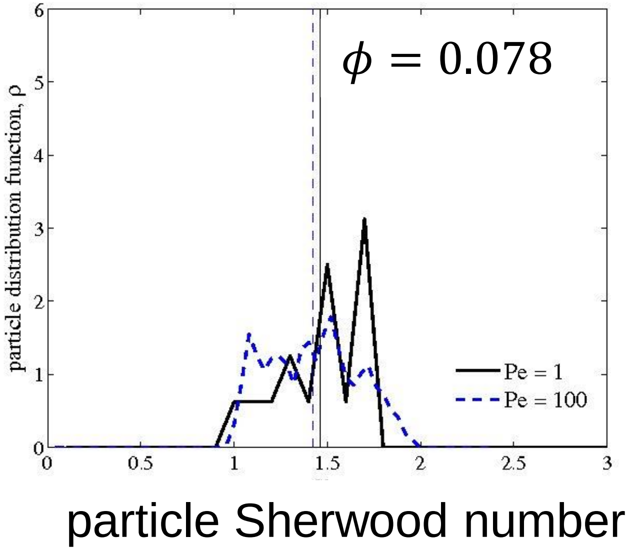
Ensemble averages of a) $\langle Sh \rangle_p$ and b) $\langle c \rangle_f$ for range in Da_v

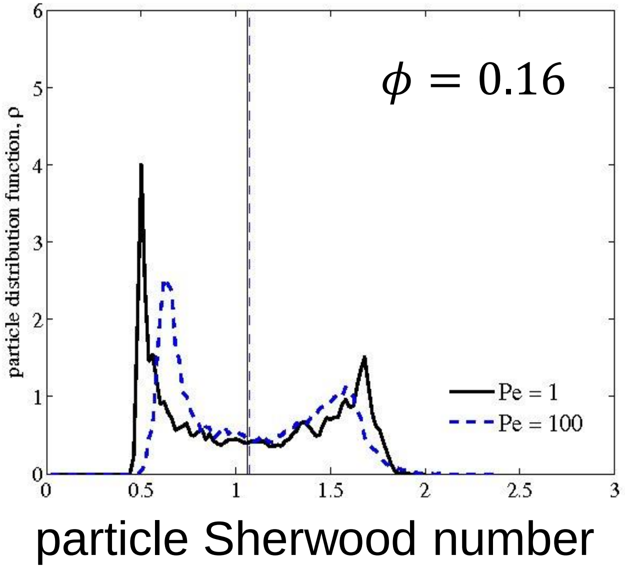
Mass flux variation with volume fraction



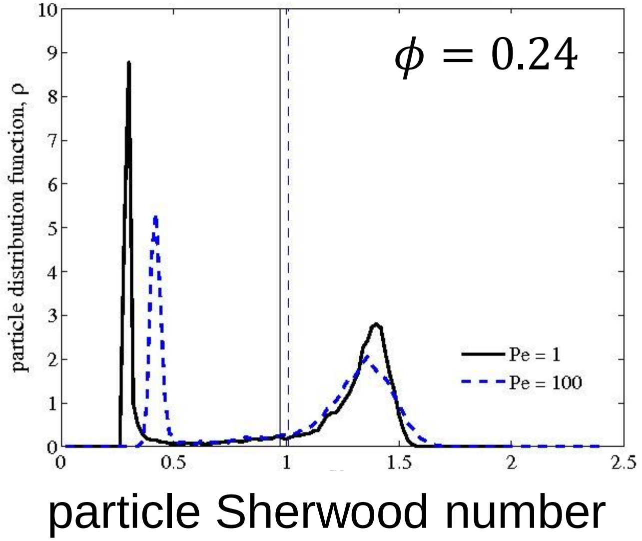
Average particle $\langle Sh \rangle_p$ for a range in ϕ with a) constant Pe and b) constant absorption rate

Mass flux distribution function





$Sc = 100$
$Da_v = 1$



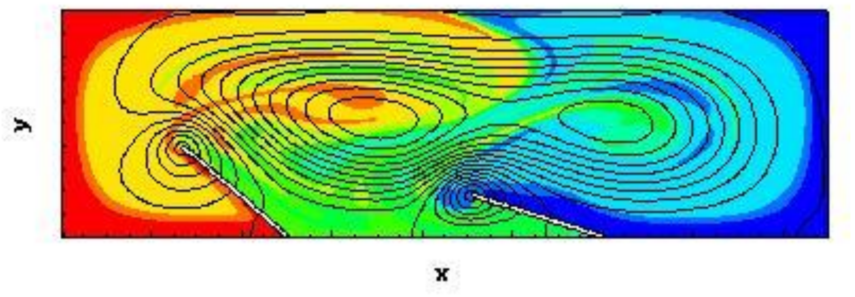
Probability distribution function of the particle mass flux, Sh_p

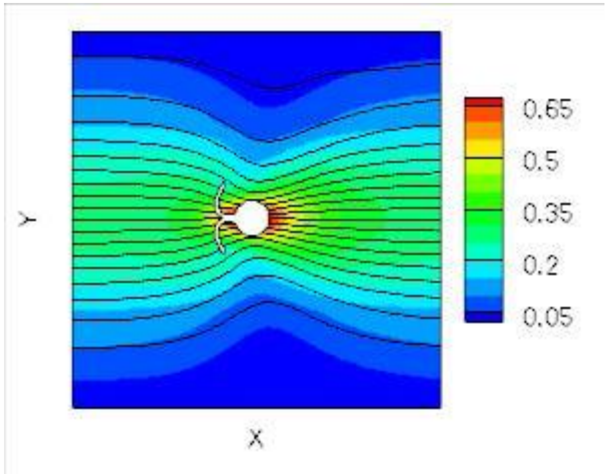
Conclusions

- The Immersed Boundary Method was used to study model swimming microorganisms and nutrient transport in a thin film.
- In a thin film, swimming particles are distributed into layers, with a preference in between the thin film centerline and the surface.
- The mass flux in the in the thin film varies spatially with lower mass flux in the film core.
- The mass flux at higher uptake rates is adversely affected by fluid advection attributed to the lower concentration wakes of neighboring particles.
- In spite of nutrient wake effects, swimming by microorganisms is advantageous and enhances nutrient consumption.

Future work

- Develop an exact numerical model of a swimming green algal cell with flagella actuated by an internal strain mechanism
- Examine the effect of an array of actuated cilia on mass transport in a channel
- Nutrient transport for different types of microorganism swimming modes





Funding Opportunities

NSF:
- Division of Chemical, Bioengineering, Environmental and Transport Systems
  - Interfacial Processes and Thermodynamics (August – September)
  - Fluid Dynamics Program (January – February)
  - Particulate and Multiphase Processes (January – February)
  - Physics of Living Systems (October)
- CAREER, RAPID, EAGER

Tufts Office of Proposal Development
- Grant proposal database
- Industrial partnerships
- Tufts internal research programs

Thank you!

Any Questions?