Nutrient uptake and swimming particle motion in an active suspension

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Microorganisms and nutrient uptake

- The study of mass transfer in active suspensions is relevant for understanding the dynamics of living micro-organisms which consume nutrients in the fluid.
- The focus of this study is on the low Reynolds number motion of motile micro-organisms such as species of bacteria and green algae in confined environments.
- Confined environments of micro-organisms are typically found in experiments e.g. Soap films, fluid layers between glass slides, droplets, fluid baths and have higher volume fractions
- The results of numerical and analytical studies show distinct differences in dynamics between confined and open domains:
  - Longer range flow, larger collective motion of swimming particles, and particle accumulation near the surfaces

Numerical analysis of active suspensions

- The Stokes' dynamics method has been used in numerical studies by Ishikawa and Pedley (2008a, 2008b) to study active suspensions in unbounded domains and monolayers.
- Magar and Pedley (2003, 2005) conduct a mass transfer study of a single swimming particle and show that the mass flux increases with the Péclet number ($\mathrm{Sh} \sim Pe^{1/2}$)
- In the numerical analysis, the fluid and particle interactions are modeled using the Immersed Boundary Method developed by W.-P. Breugem (2012), which resolves particle interactions of more than two particles.
- The swimmer is treated as a spherical particle with an imposed tangential velocity at the surface representing the surface distortions of moving cilia or flagella.

Governing equations in dimensionless form

Fluid equations:

$$\frac{\partial \mathbf{u}}{\partial t} = -\frac{\partial p}{\partial \mathbf{x}} + \nabla^2 \mathbf{u} + \boldsymbol{f}_p$$

$$\nabla \cdot \mathbf{u} = 0$$

Mass transport equations:

$$\frac{\partial c}{\partial t} + \frac{Pe}{Sc} \nabla \cdot (\mathbf{u}c) = \frac{1}{Sc} \nabla^2 c + s$$

$$s = -Da_\nu c_s \delta(\boldsymbol{x} - \boldsymbol{x_s})$$

Characteristic variables:

$$\mathrm{Re} = \frac{Ud}{\nu} \qquad Pe = \frac{Ud}{D}$$

$$Sc = \frac{\nu}{D} \qquad Da_\nu = \frac{kd^2}{\nu}$$

Particle equations of motion:

$$\alpha V \frac{d\mathbf{U}_p}{dt} = \oint_S \boldsymbol{\tau} \cdot \mathbf{n} dS$$

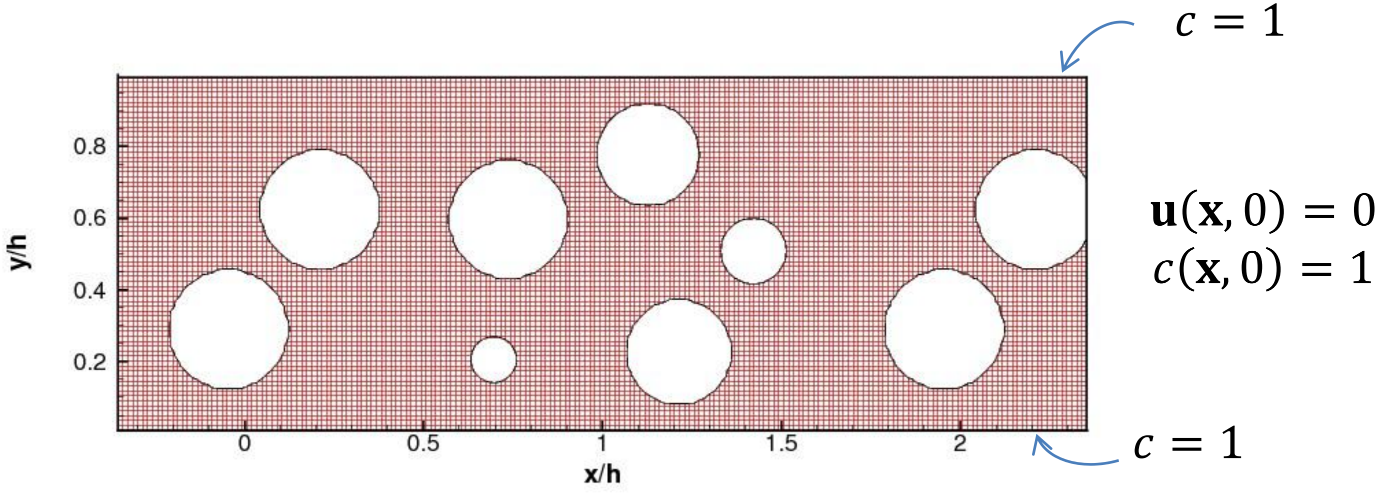
$$\bar{I} \frac{d\boldsymbol{\Omega}_p}{dt} = \oint_S \mathbf{r} \times \boldsymbol{\tau} \cdot \boldsymbol{n} dS$$

Thin film description

- Thin film with two free surfaces and periodic boundary conditions in (x, z)
- Fluid is initially saturated at t = 0
- Scalar concentration is replenished at the free surfaces
- Boundary conditions:

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

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



Concentration contours

$Pe = 100, \quad Sc = 100, \quad t = 240$

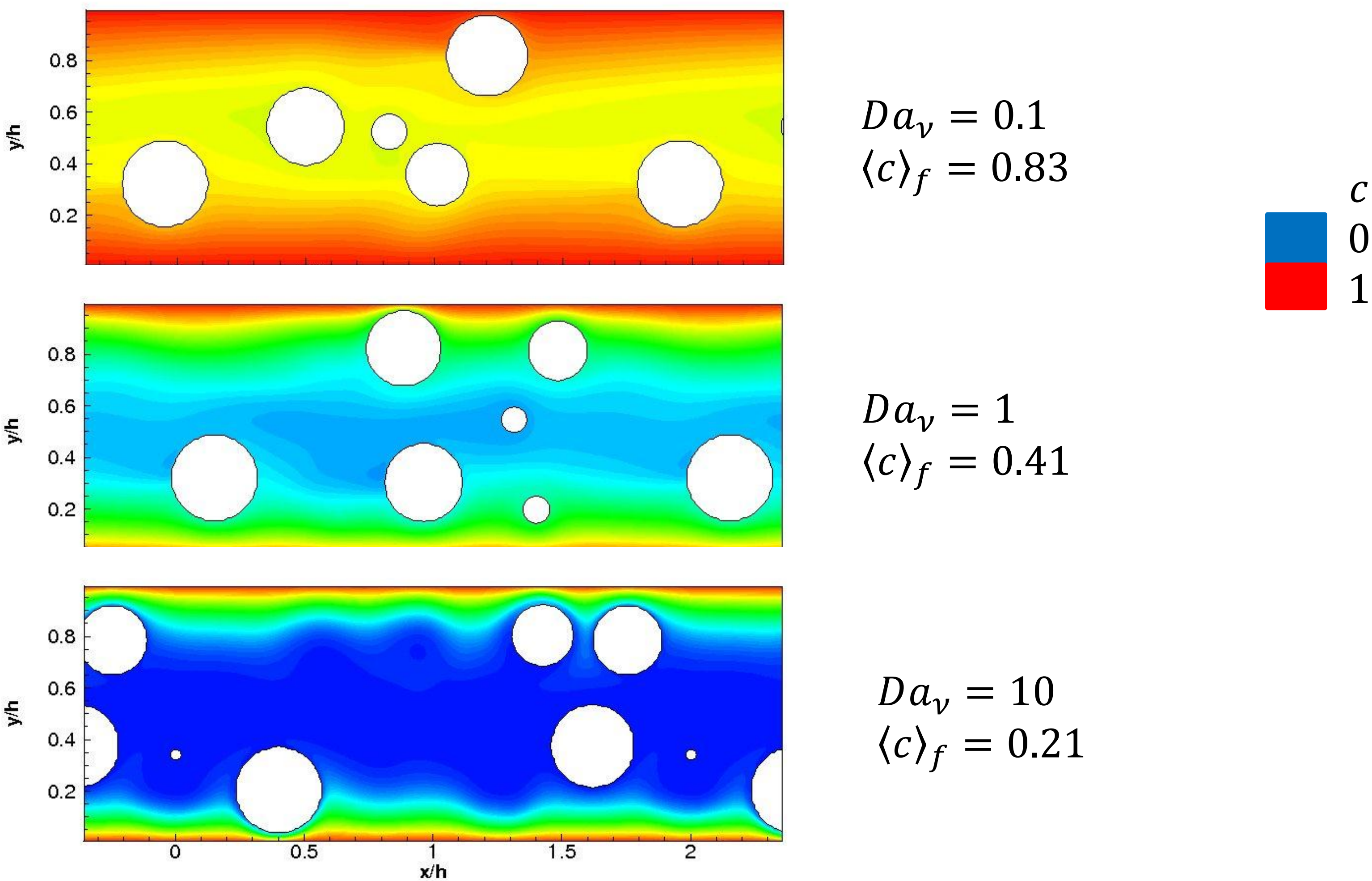
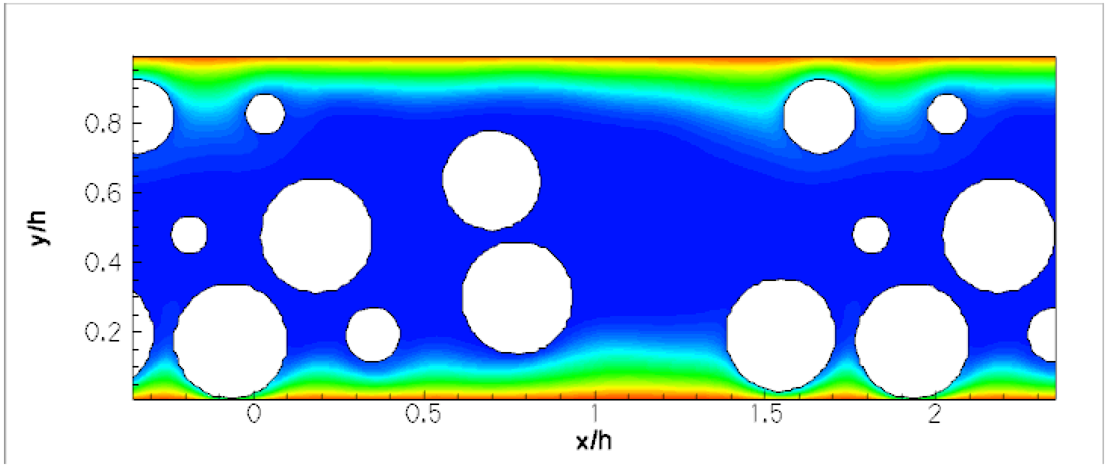


Fig. 1 – Scalar contours for finite absorption rate and ϕ = 0.16.

Animation of nutrient uptake in a thin film

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

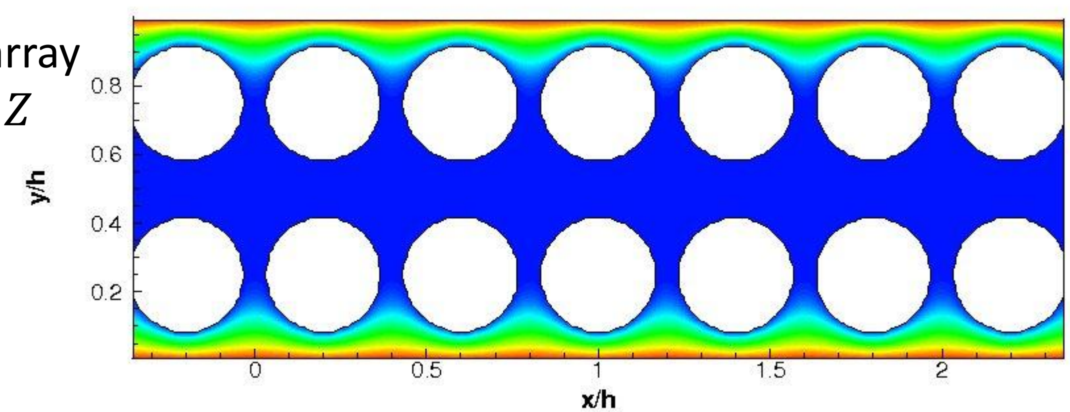
$Pe = 100$
$z_o = 0.5\,Z$



Time interval:
$t = 80 - 160$

c
0
1

Stationary array
$z_o = 0.5\,Z$



Particle volume fraction profile in the fluid

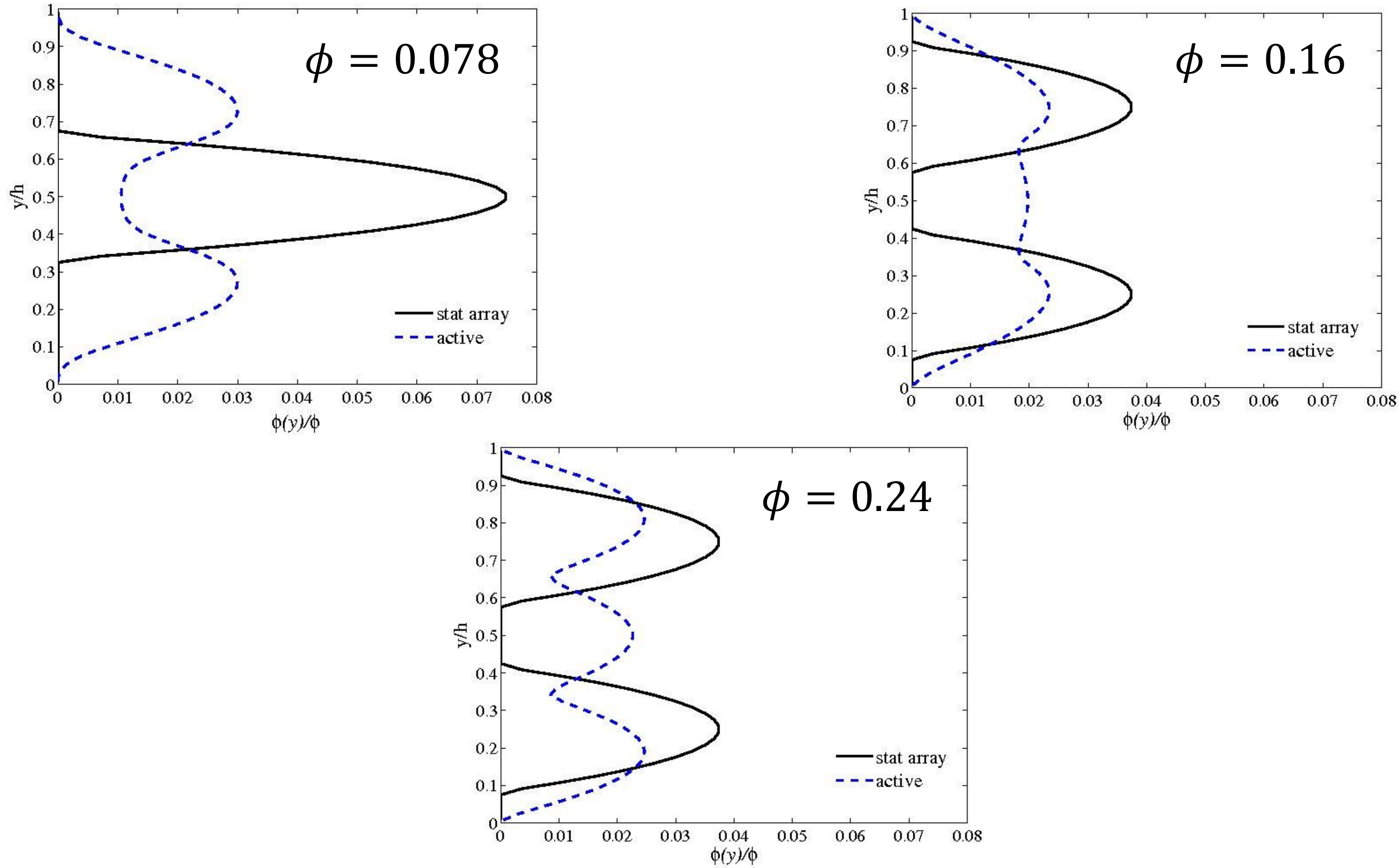


Fig. 2 – Volume fraction distribution along the film cross section

Particle motion in the thin film

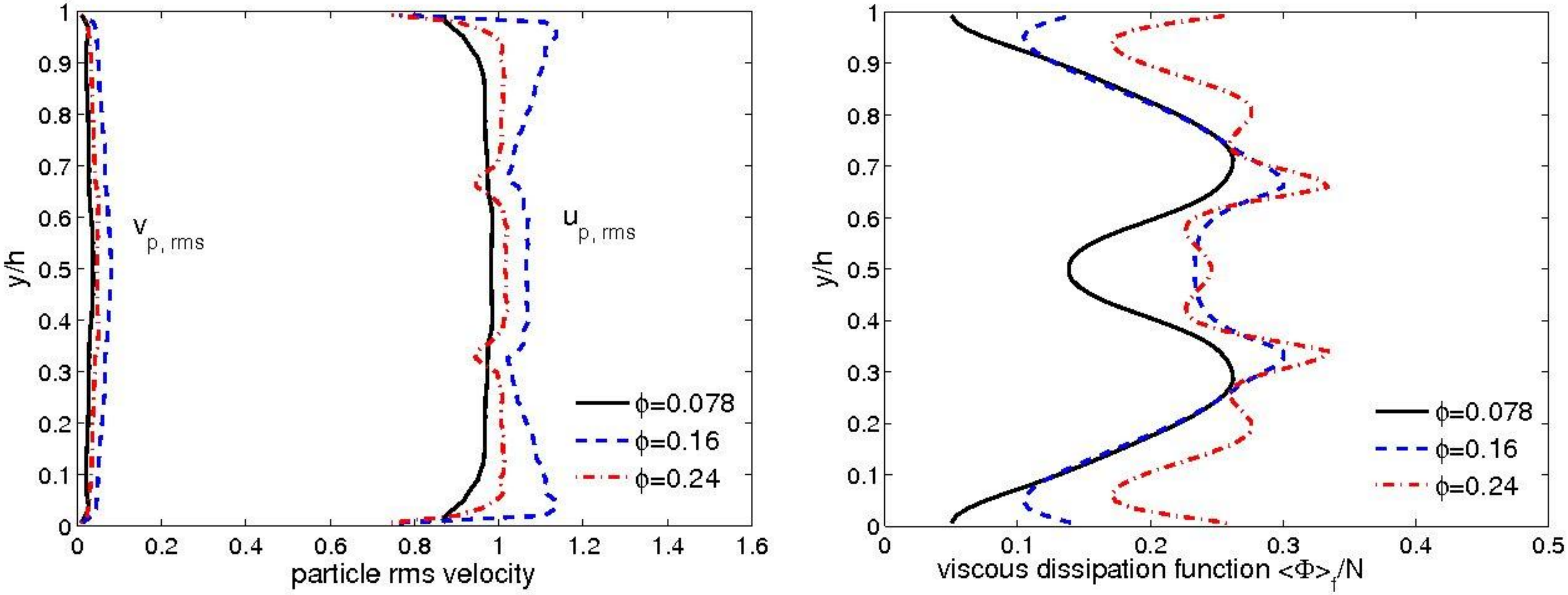


Fig. 3 – Vertical profiles of the a) particle rms velocity in the planar and vertical direction and b) the viscous dissipation function

Mass flux and nutrient concentration profiles

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

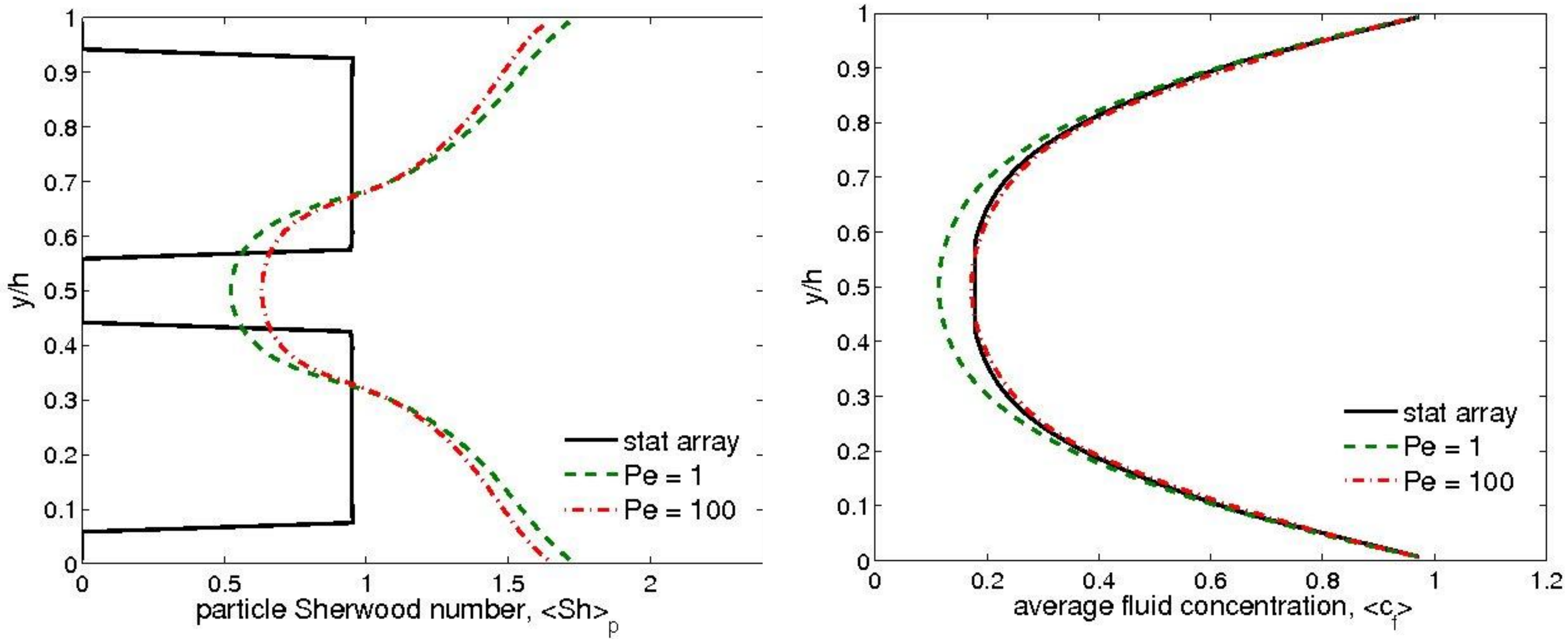


Fig. 3 – Profiles of the a) mass flux $\langle Sh \rangle_p$ and b) fluid concentration $\langle c \rangle_f$ along thin film cross section for a stationary and active suspension and $\phi = 0.16$.

Ensemble averages

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

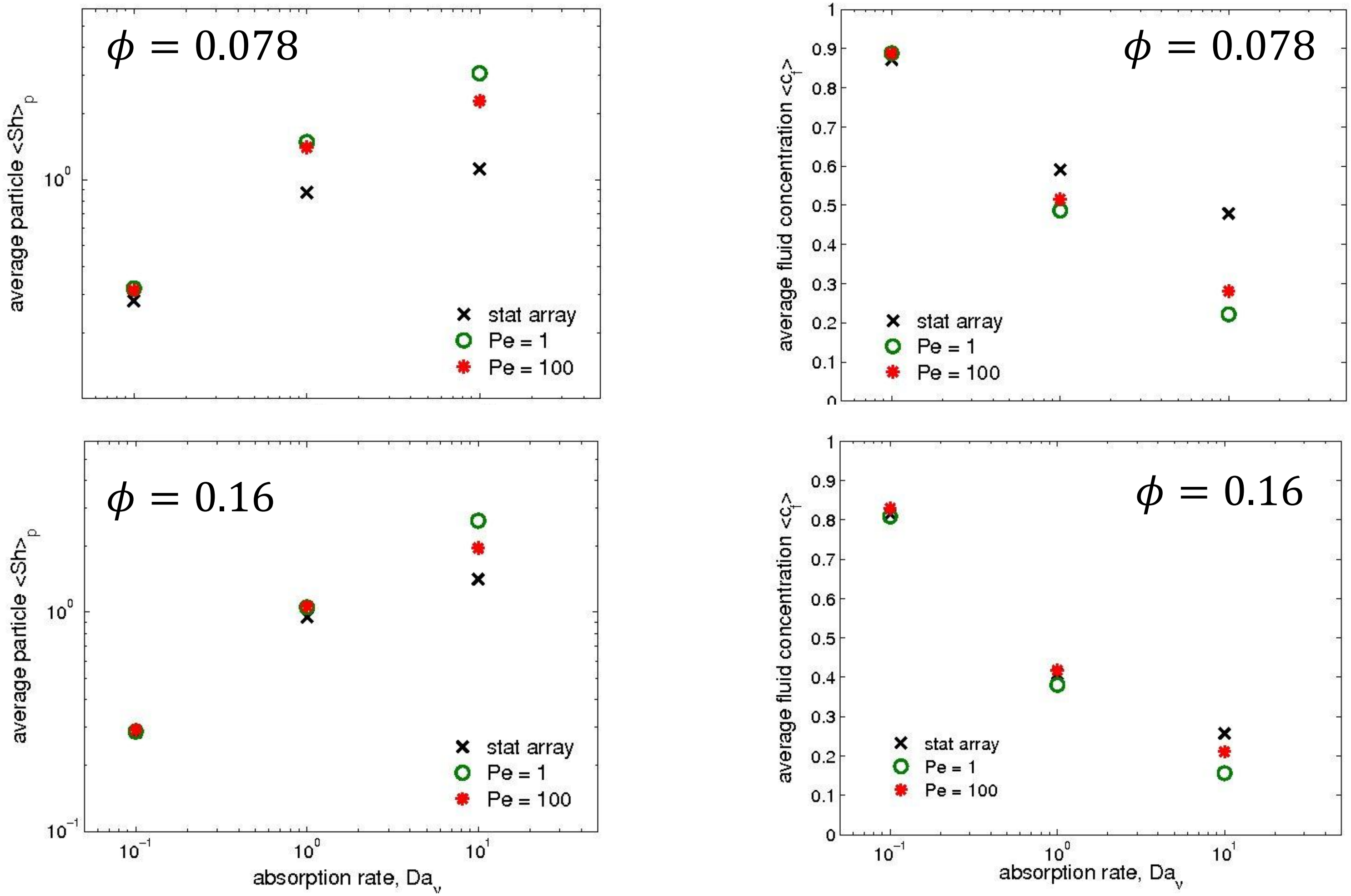


Fig. 5 – Ensemble averages of a) $\langle Sh \rangle_p$ and b) $\langle c \rangle_f$ for range in Da_v

Mass flux variation with volume fraction

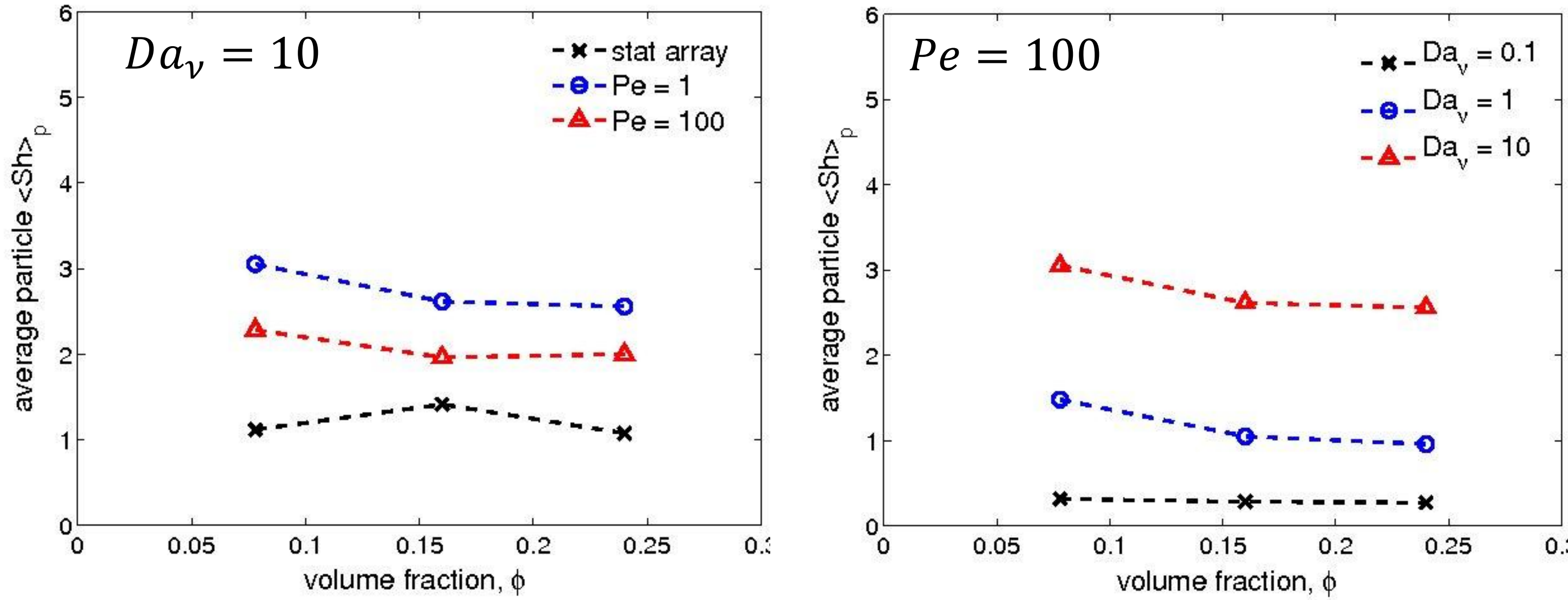


Fig. 6 – Average particle $\langle Sh \rangle_p$ for a range in ϕ with a) constant Pe and b) constant absorption rate

Mass flux distribution function

$Sc = 100\,, \qquad Da_v = 1$

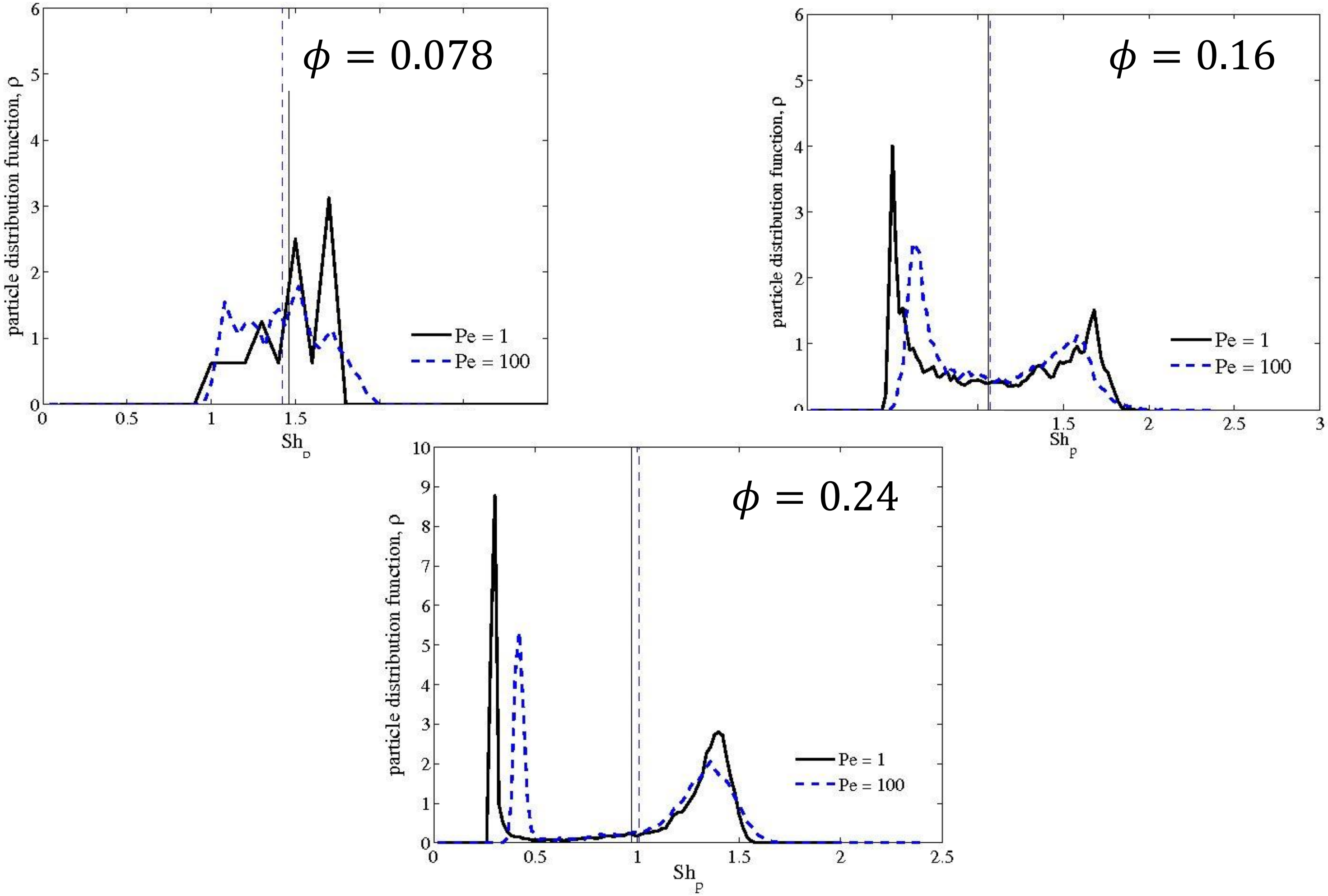


Fig. 7 – Probability distribution function of the particle mass flux, Sh_p

Conclusions

- In a thin film, 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.
- Two mass transfer regimes are apparent:
  - For smaller absorption rates, the mass flux is limited by the absorption rate and particle motion has no effect.
  - For larger uptake rates, mass transfer is limited by the advection and diffusion time.
- The mass flux at higher uptake rates is adversely affected by fluid advection attributed to the lower concentration wakes of neighboring particles.

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