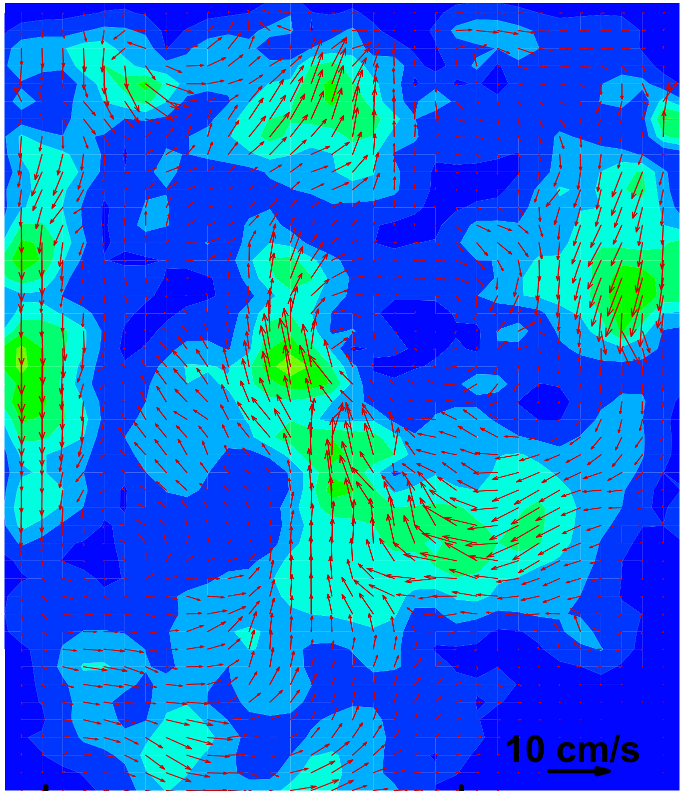
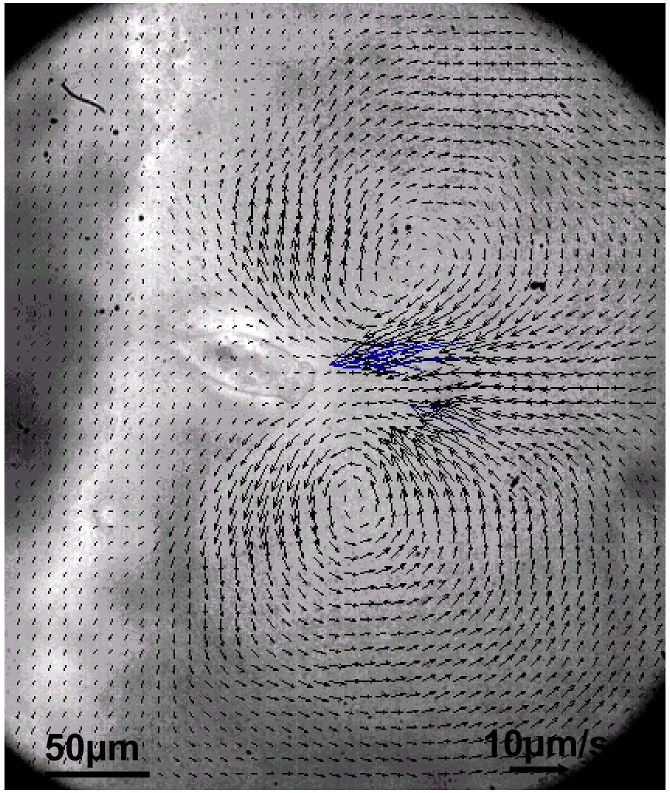
Impact of hydrodynamic transport on Granular Activated Sludge: micro and macro scale investigations



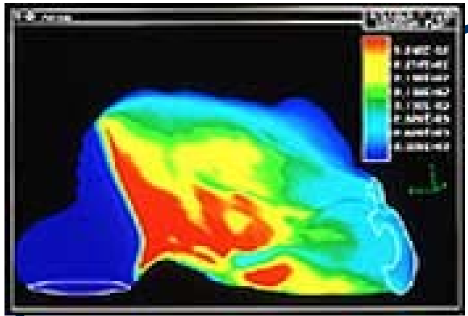


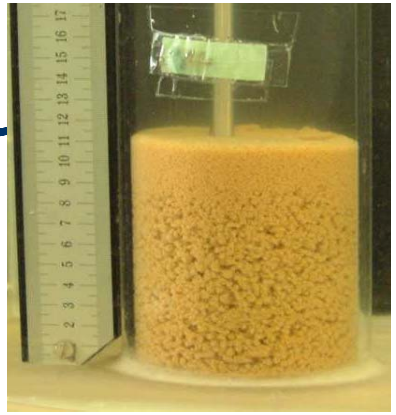
Bogumiła Ewelina Zima-Kulisiewicz

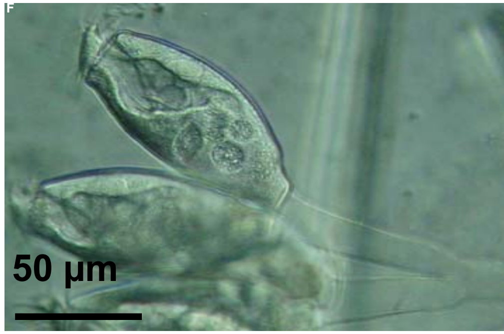
Fluid Mechanics Seminar at IPPT PAN 6.4.2011

MOTIVATION

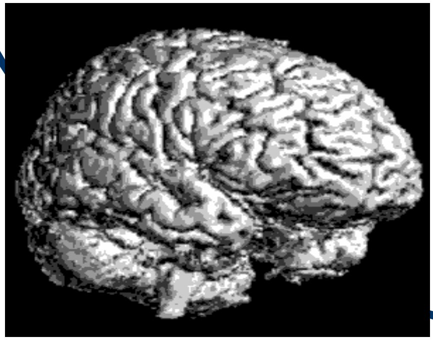
WASTEWATER TREATMENT

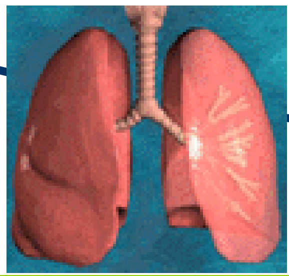






BIOFLOW

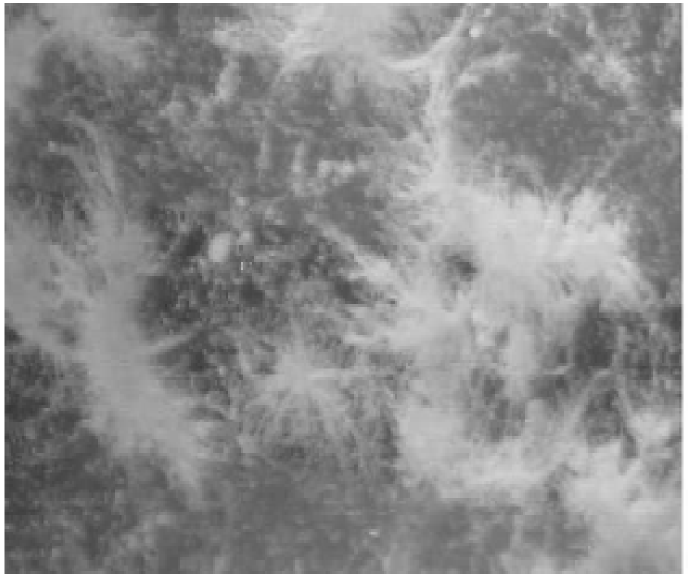




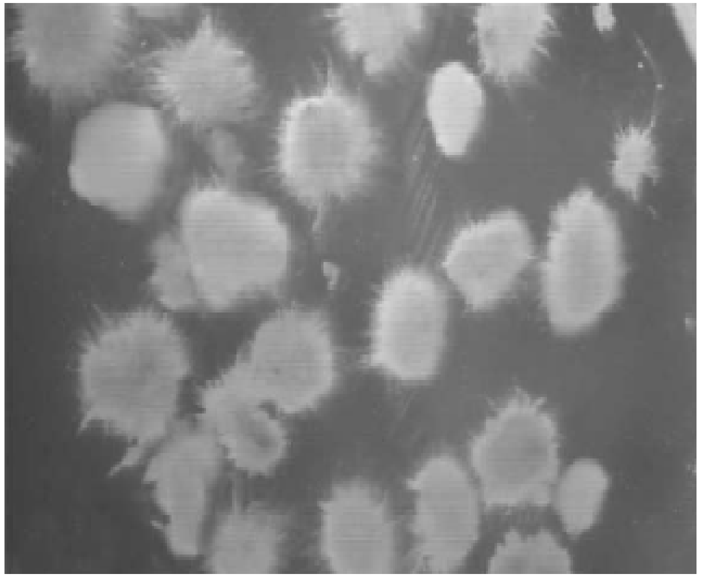
GAS AND CAS

- **Conventional Activated Sludge (CAS) and Granular Activated Sludge (GAS)**

CAS



GAS



ADVANTAGES OF GAS

- **Spherical and strong microbial structure**
- **Good settling ability**
- **High density – 1.05 g/ml**
- **Dimension up to 5 mm**

- **Aerobic granulation as a recent innovation in biological wastewater treatment**

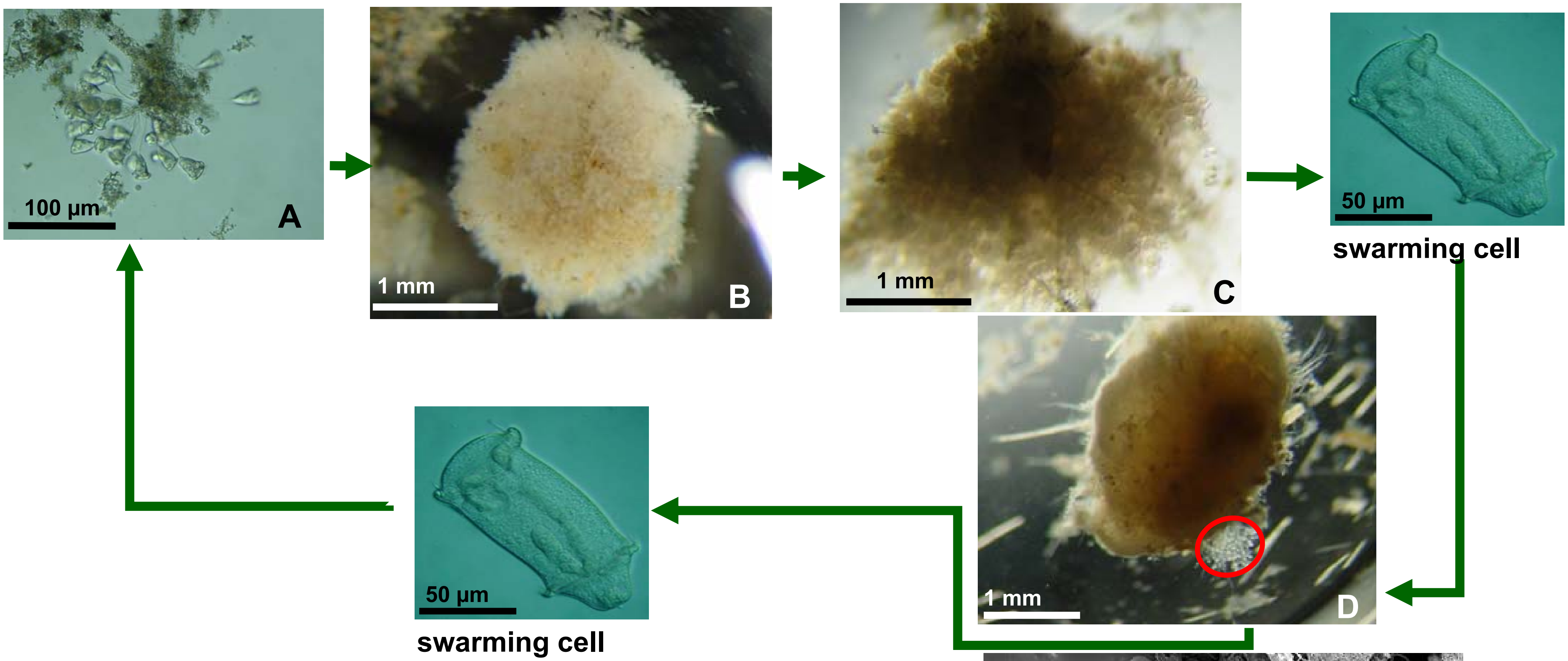
/Morgenroth et al. (1997), Peng et al. (1999), Buen et al.(1999), Etterer and Wilderer (2001), Tay et al. (2001)/

GAS DEFINITION

Granules making up aerobic granular activated sludge are to be understood as aggregates of microbial origin, which do not coagulate under reduced hydrodynamic shear, and which settle significantly faster than activated sludge flocs

(1st IWA Workshop of Aerobic Granular Sludge,TU München, 2004)

GRANULES FORMATION



Weber et al. (2007)

Phase 1: Flocs formation (A, B)

Phase 2: Granule growth and core zone development (C)

Phase 3: The mature granule (D, E)

Main factors influencing granules structure and formation

- **Superficial Gas Velocity (SGV)**
  /van Loosdrecht et al. (1995), Tay et al. (2001), Zima et al. (2007)/

- **Substrate type and concentration of synthetic wastewater food**
  /Zhu et al. (2001), Etterer and Wilderer (2001)/

- **Extracellular Polymeric Substances (EPS)**
  /Oashi and Harada (1994), Tay et al.(2001)/

- **Optimal bioreactor configuration**
  /Beun et al. (1999), Liu and Tay (2002), Zima-Kulisiewicz et al. (2008)/

- **Mechanical forces** /Zima et al. (2007)/

AIMS OF THE WORK

Multiscale flow visualization in SBR

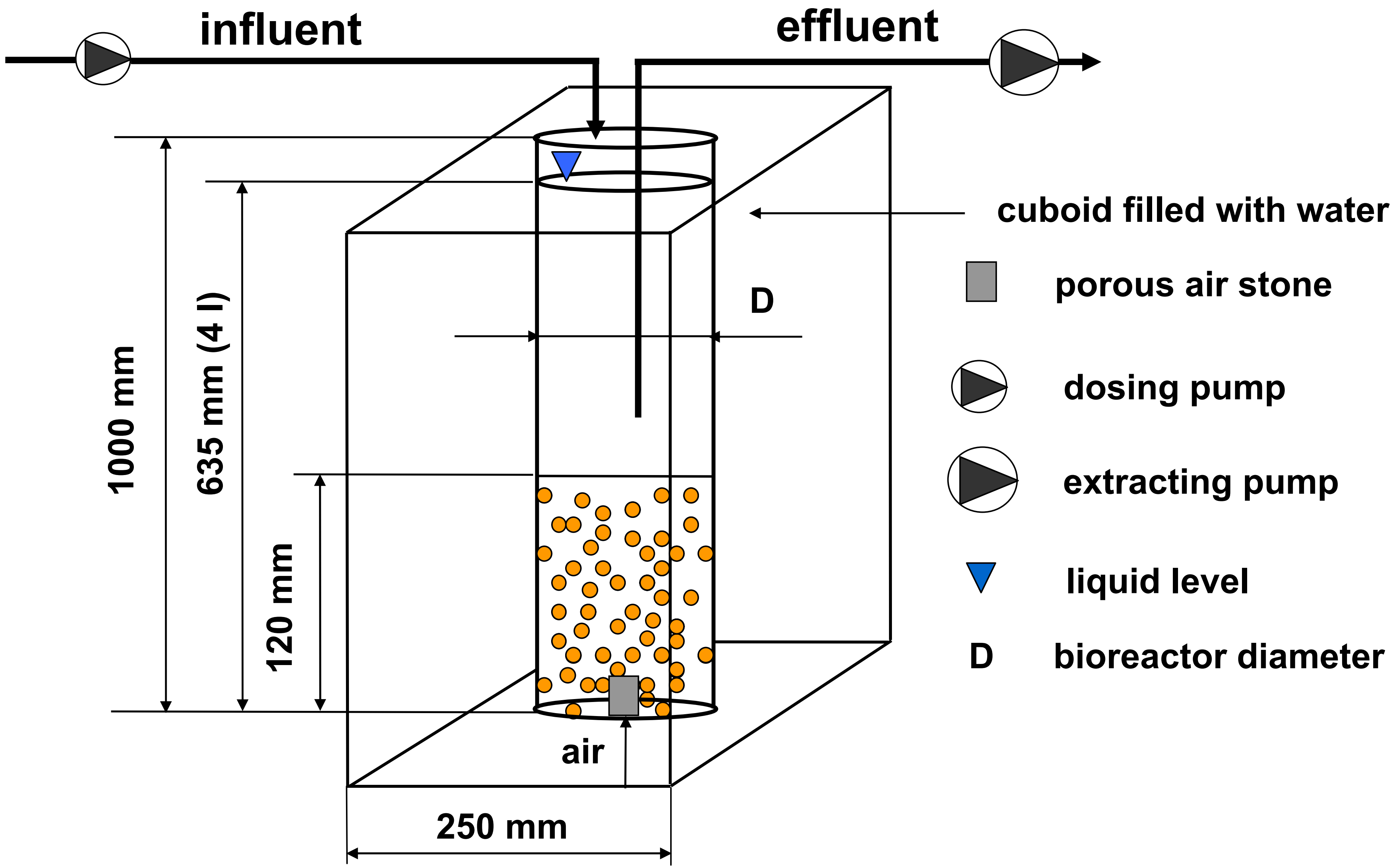
Fluid velocity field visualization in micro and macro scale

Optical in – situ techniques

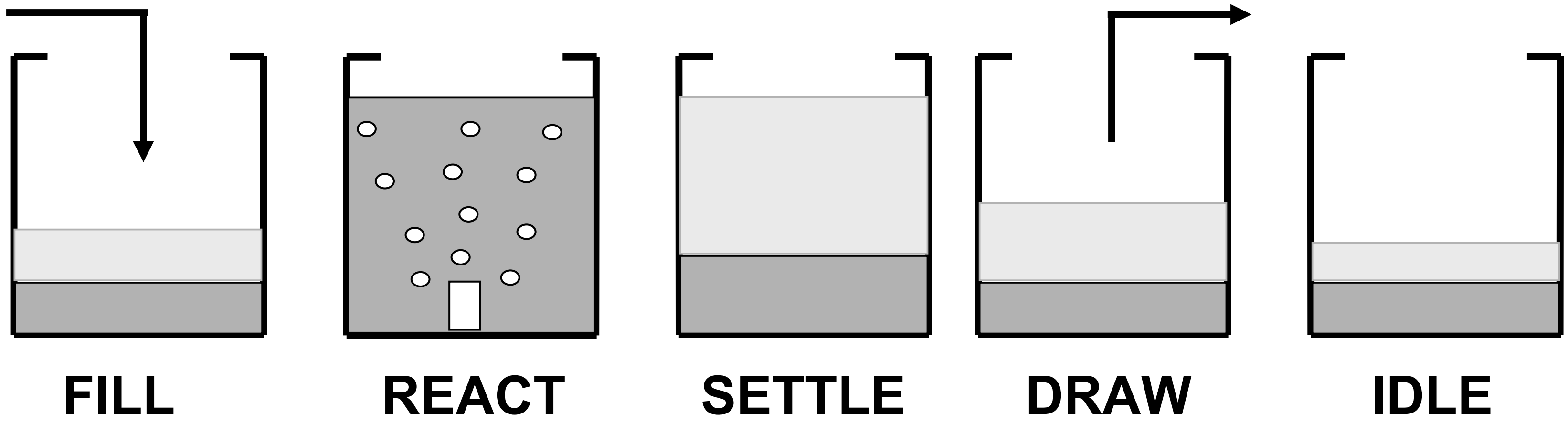
Experiments in distinct vertical coordinates

Investigations with different intervals from SBR wall

EXPERIMENTAL SETUP



SBR PROCESS

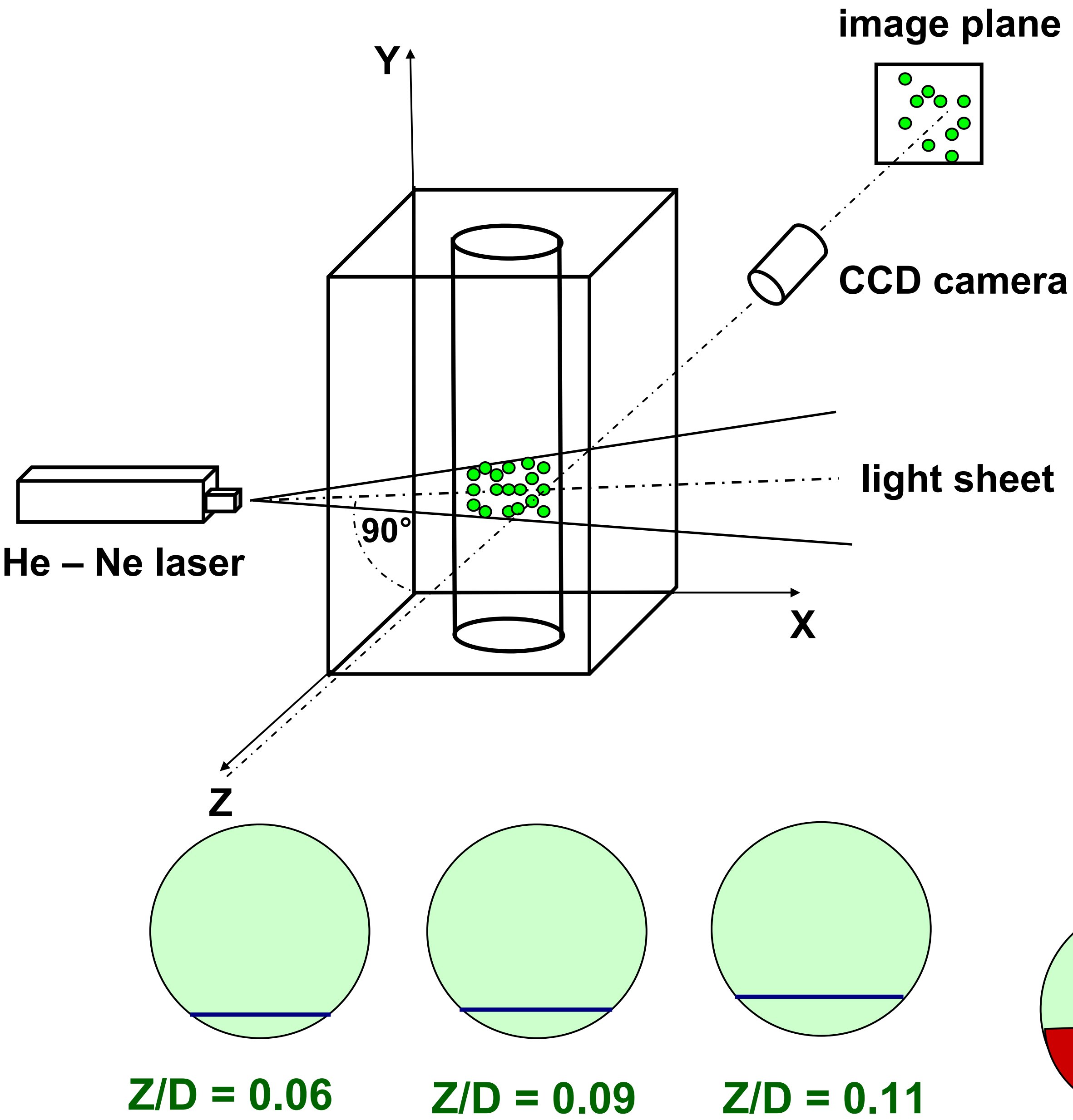


SBR ADVANTAGES

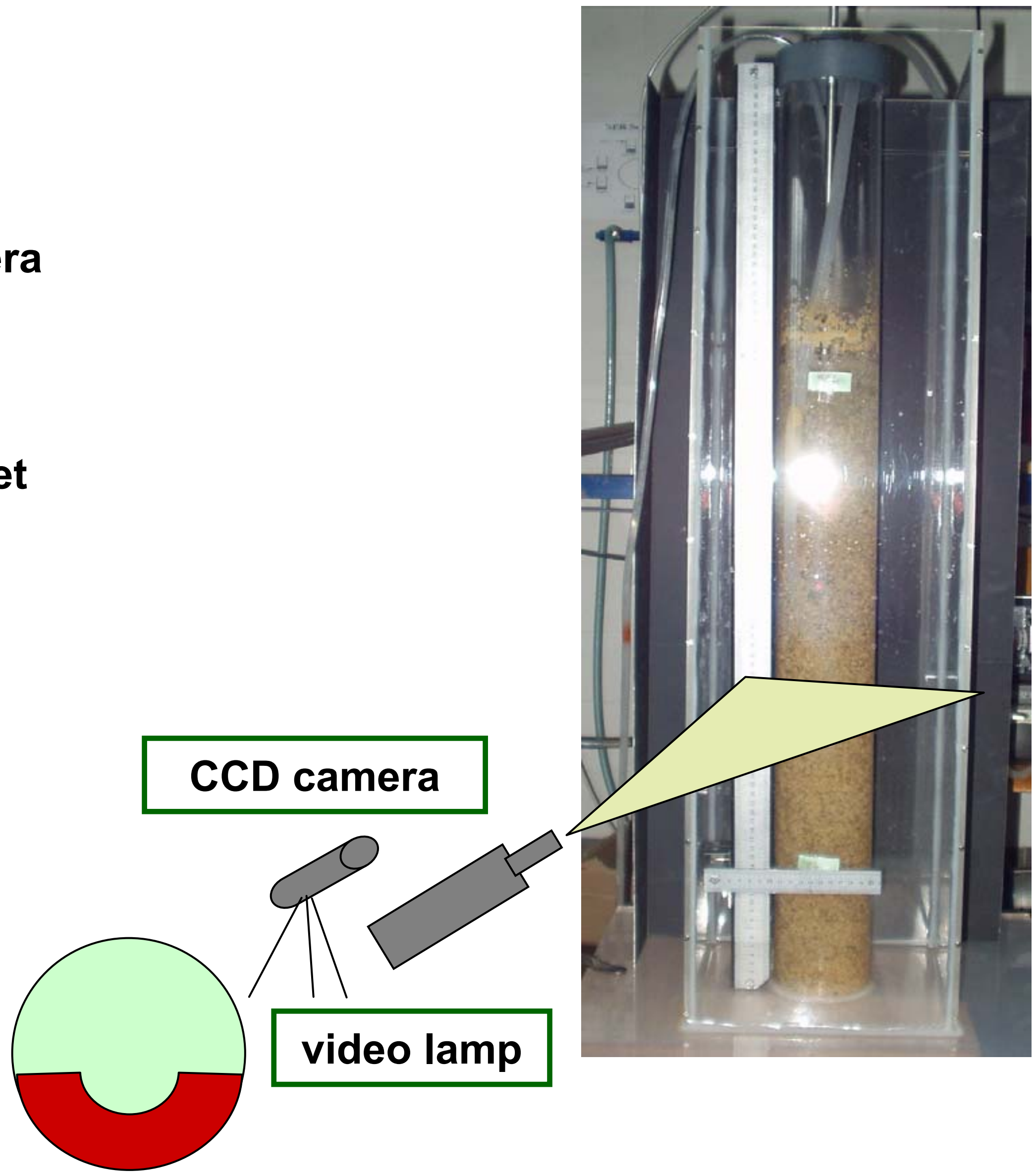
- All processes in one reactor
- Simple reactor design
- Compact structure of granules and high biomass concentration
- Good settling ability, no settling tank

OPTICAL IN-SITU TECHNIQUES

He-Ne laser



Video lamp



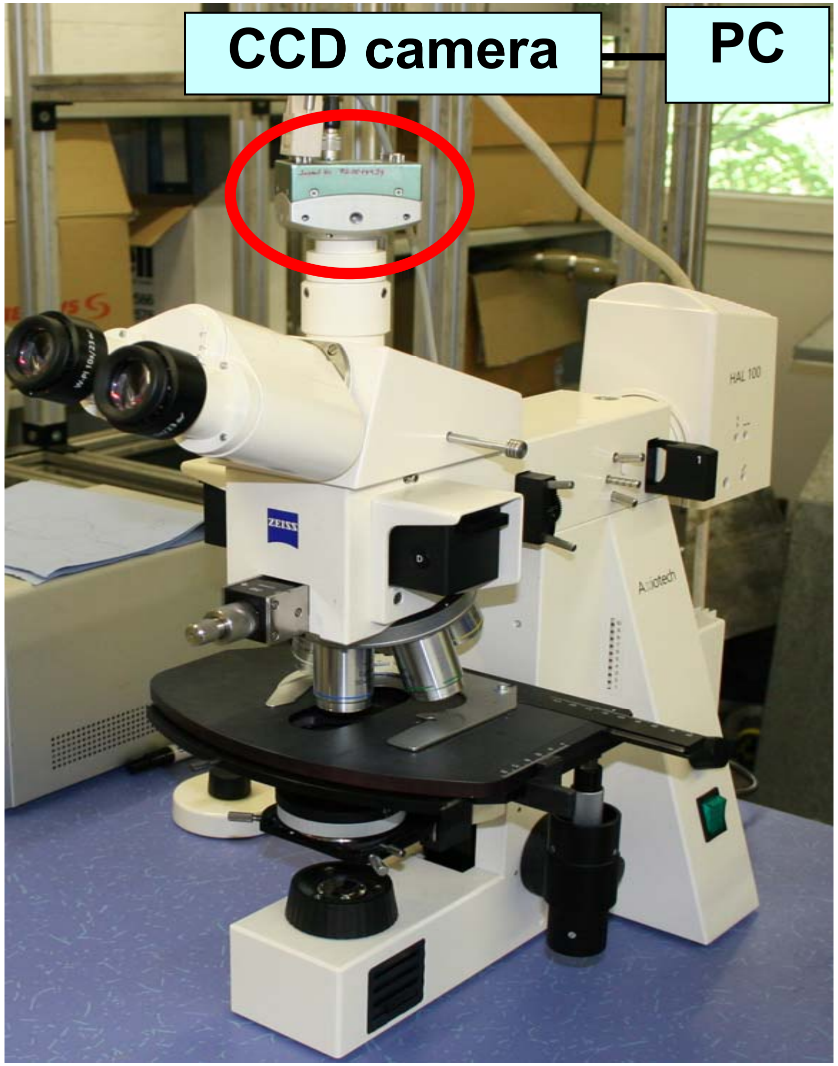
micro Particle Image Velocimetry

Microscope Carl Zeiss Axiotech 100

High speed CCD camera Mikrotron
Resolution of images 860x1024

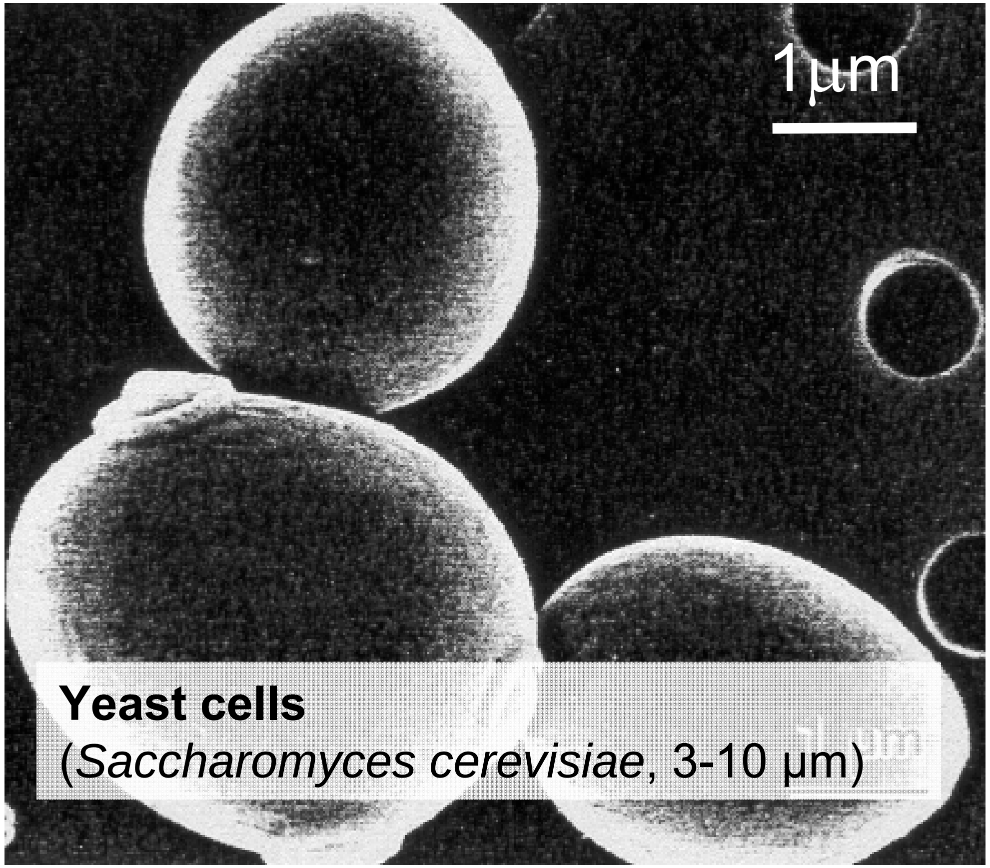
PIV Software PIVview 3C
Cross correlation mode
Interrogation window size 32x32 pixels
Grid size 20x20 pixels

Post processing with TECPLOT

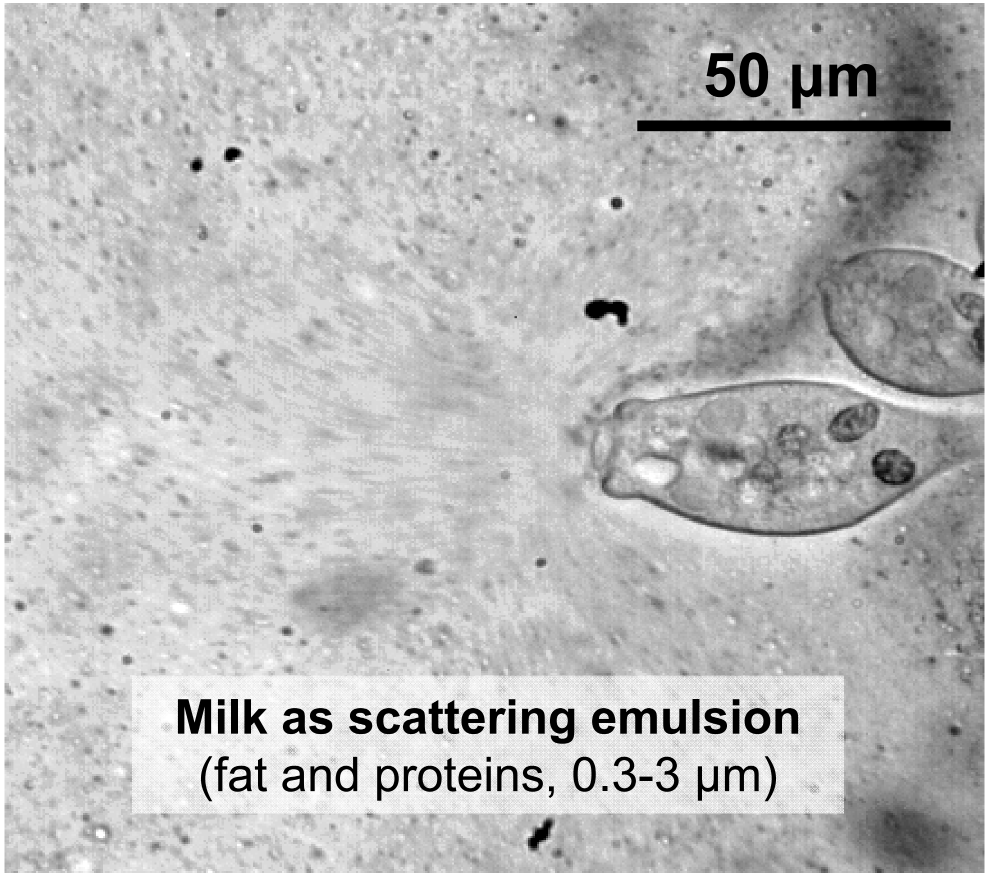


Appropriate tracer particles + suitable illumination

- **Artificial tracers are rejected**
- **Biocompatible tracer particles**



Yeast cells
(*Saccharomyces cerevisiae*, 3-10 μm)



Milk as scattering emulsion
(fat and proteins, 0.3-3 μm)

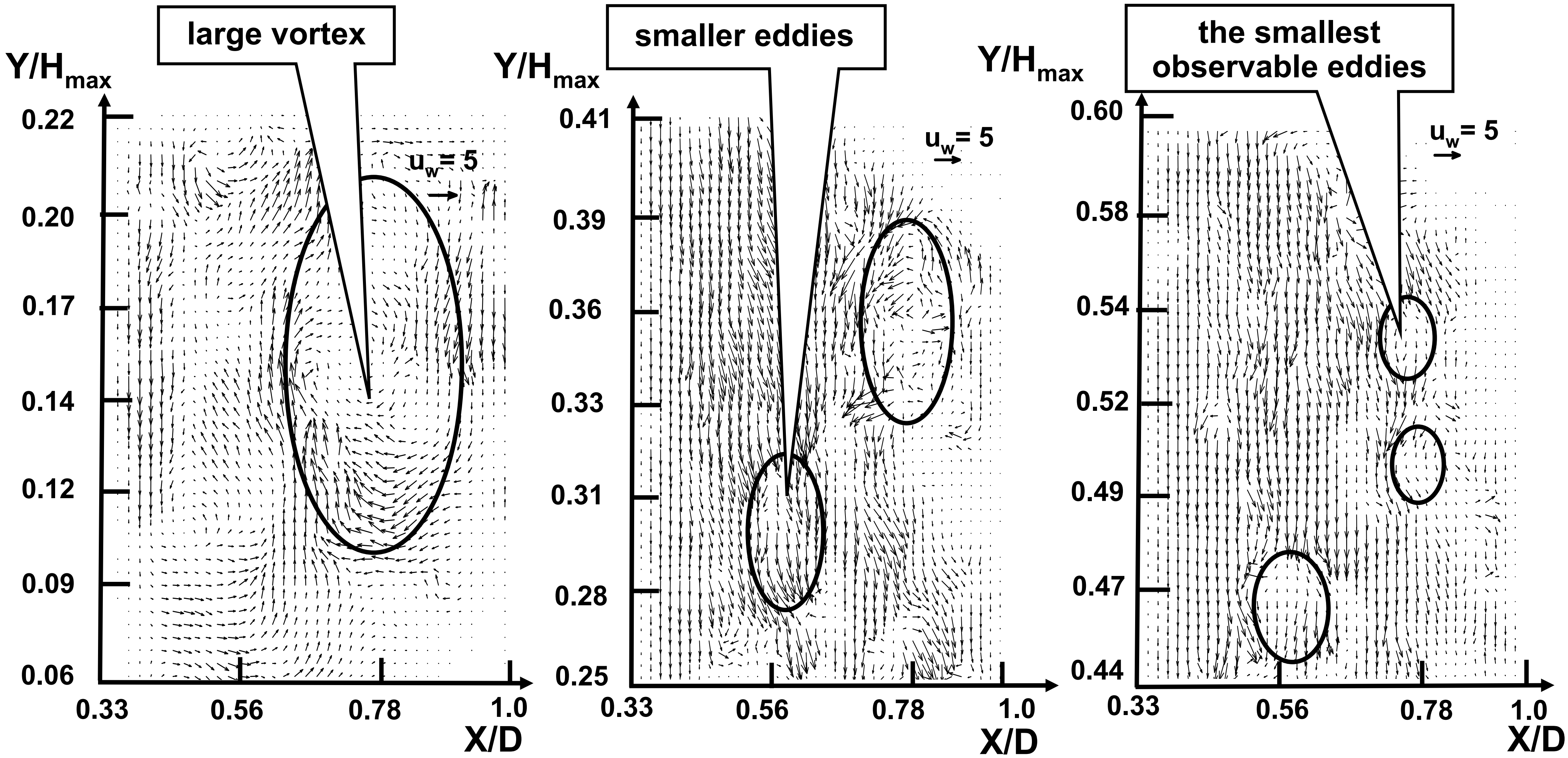
DIMENSIONLESS REPRESENTATION OF THE RESULTS

Time	$\underline{t} = \frac{t}{t_s}$
Liquid velocity	$\underline{u_W} = \frac{u_W}{SGV}$
Liquid velocity components	$\underline{u_W} = \frac{u_W}{SGV}$ $\quad \underline{v_W} = \frac{v_W}{SGV}$
Shear strain rate	$\underline{\dot{\gamma}} = \frac{\dot{\gamma}}{\dot{\gamma}_{max}}$
Normal strain rate	$\underline{\dot{\varepsilon}} = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_{max}}$

Forces	$\underline{\vec{F}_i} = \frac{\vec{F}_i}{\vec{F}_G}$
Liquid velocity on micro scale	$\underline{u} = \frac{u}{u_{max}}$
X axis	$\frac{X}{D}$
Y axis	$\frac{Y}{H_{max}}$
Z axis	$\frac{Z}{D}$

PIV RESULTS

OBSERVABLE FLUID FLOW PATTERNS

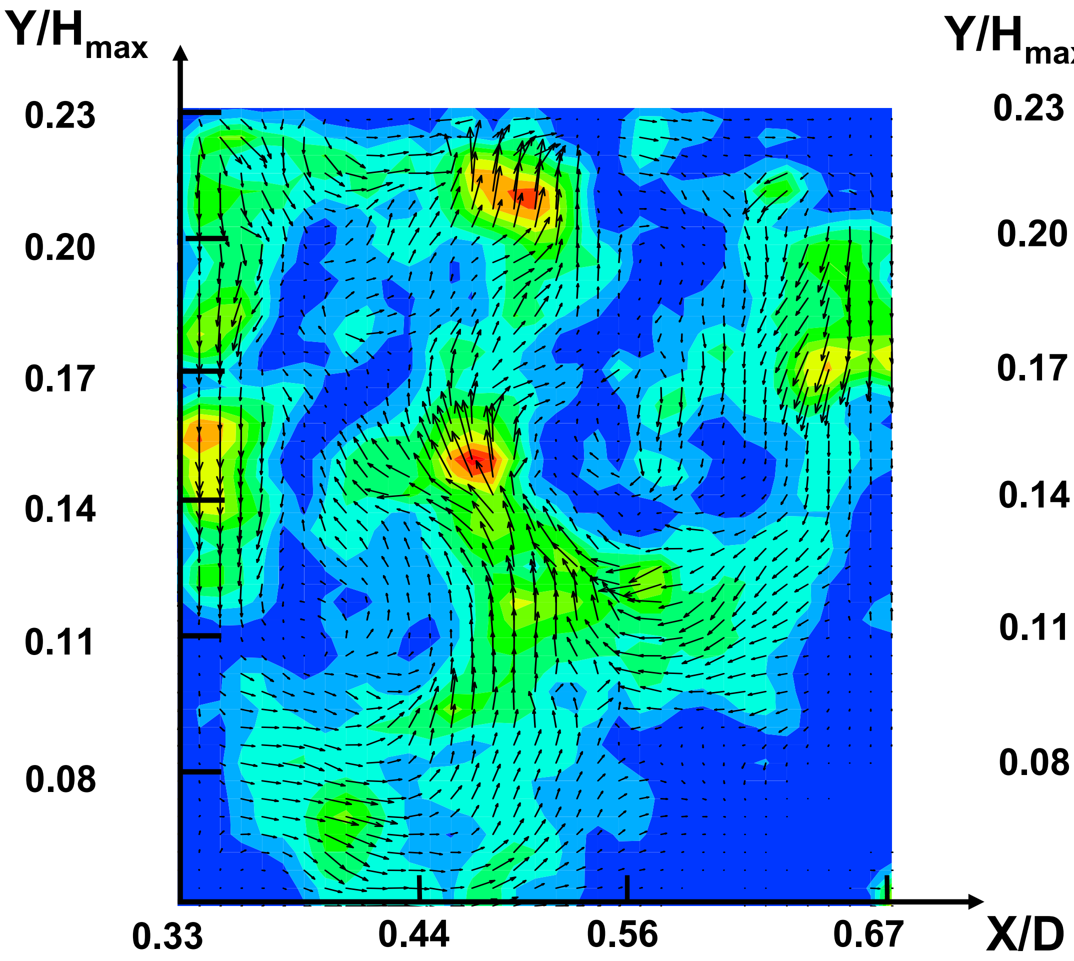


DIMENSIONLESS FLUID VELOCITY

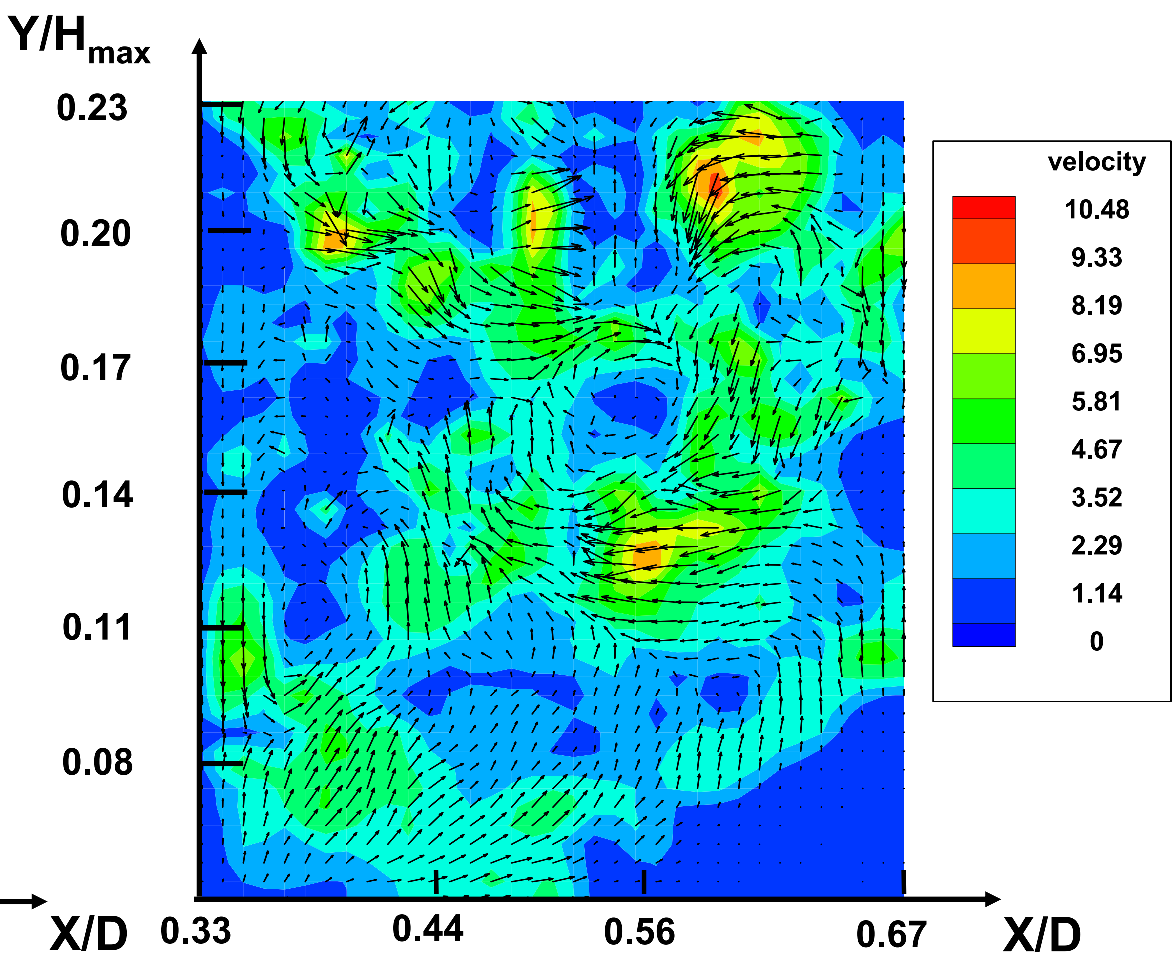
increasing tendency with height in SBR

PIV RESULTS

NON-STATIONARITY OF THE FLOW



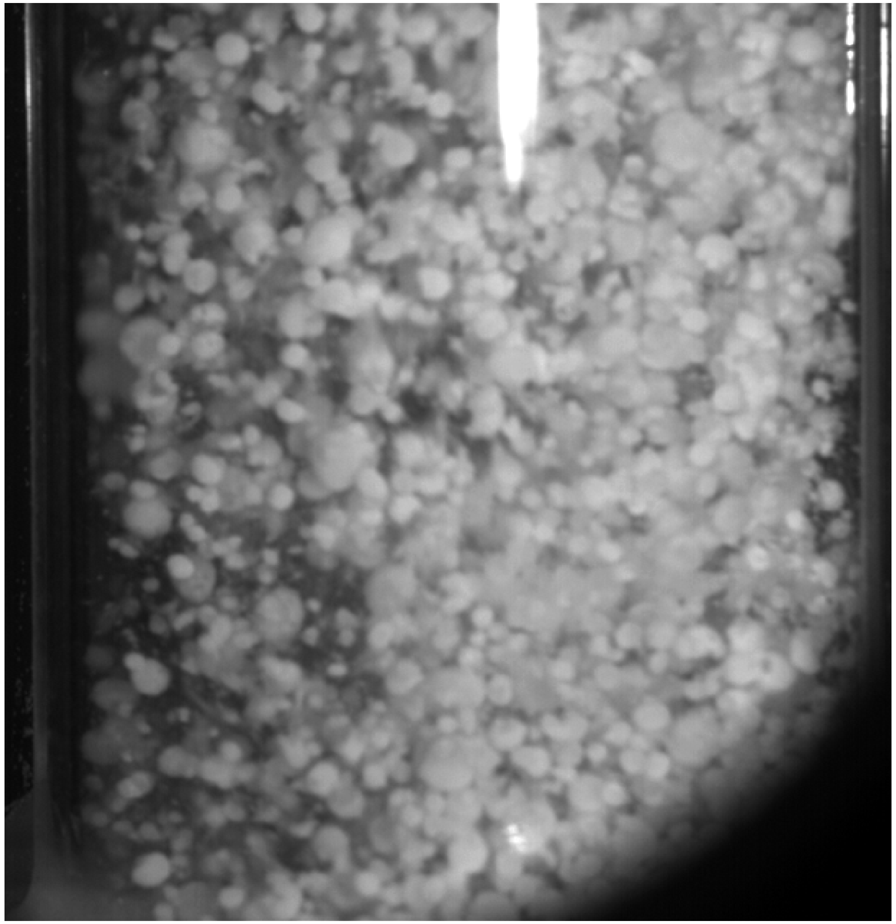
t = 0



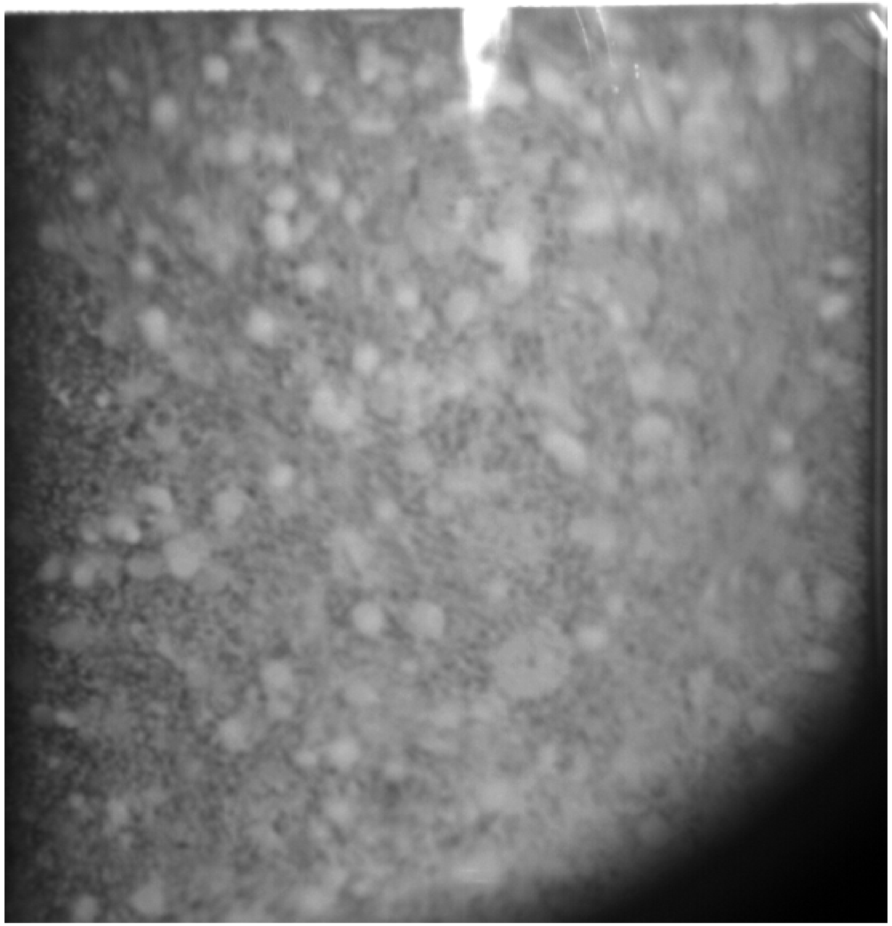
t = 0.03

PIV RESULTS

INFLUENCE OF WASTING



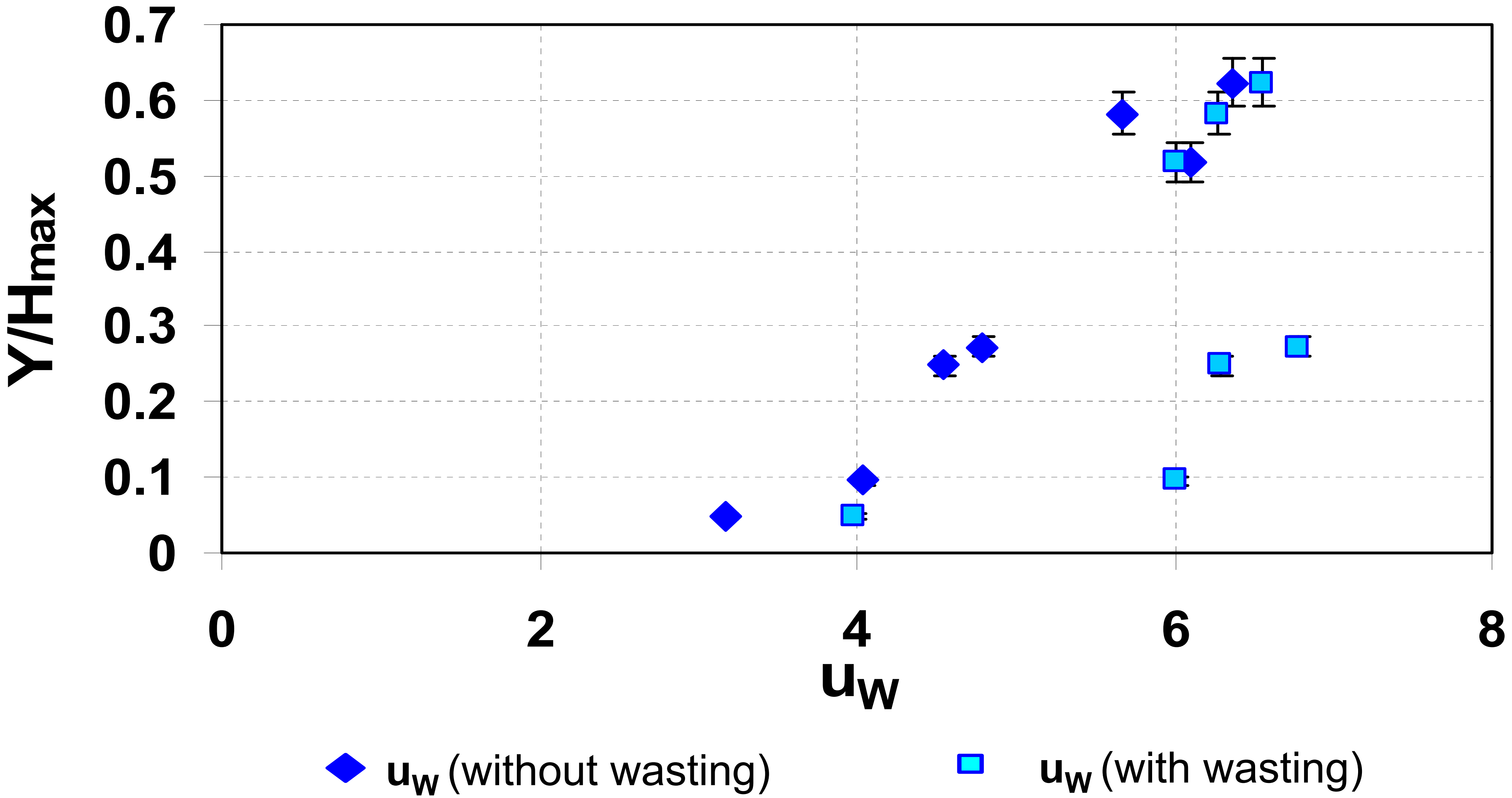
without wasting



with wasting

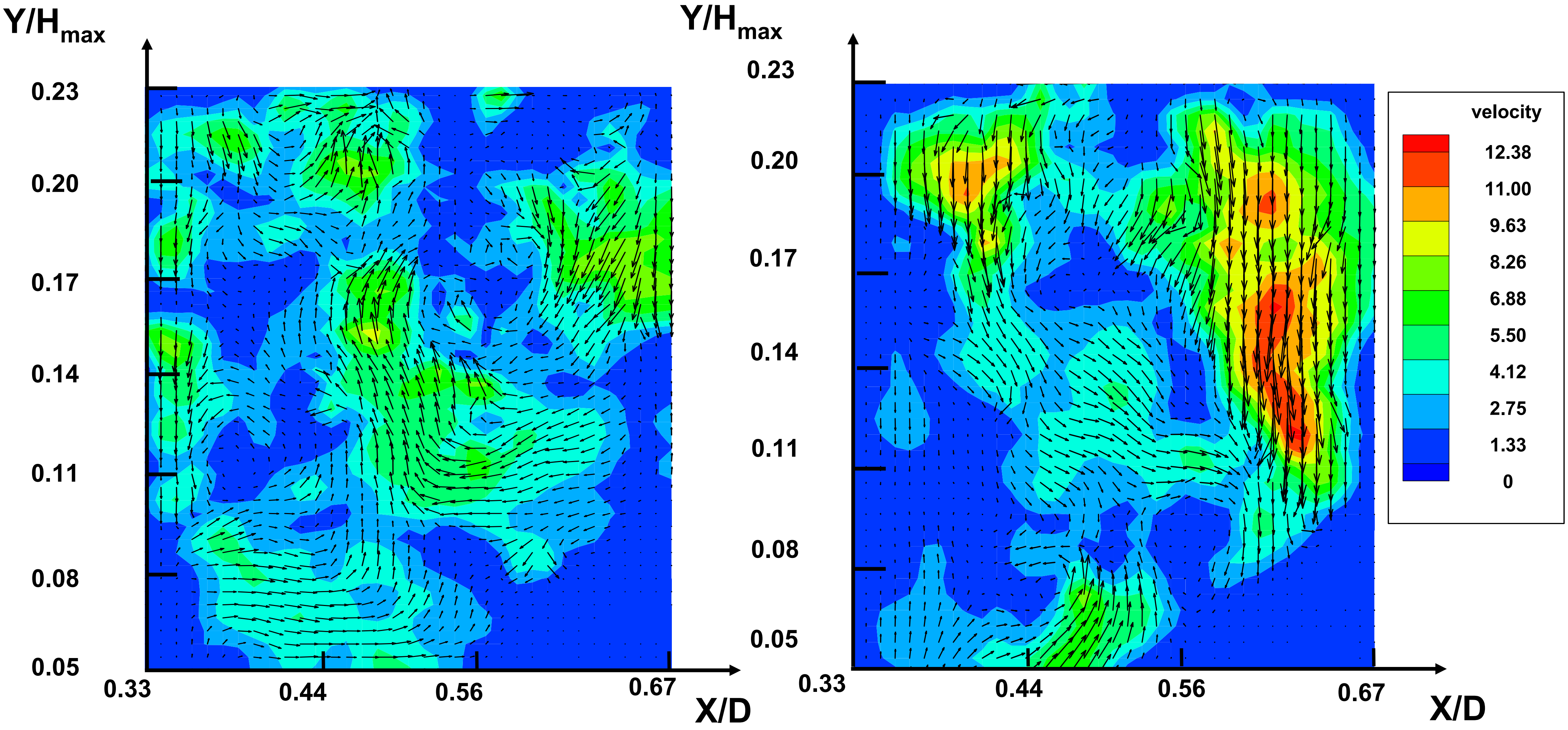
PIV RESULTS

INFLUENCE OF WASTING



PIV RESULTS

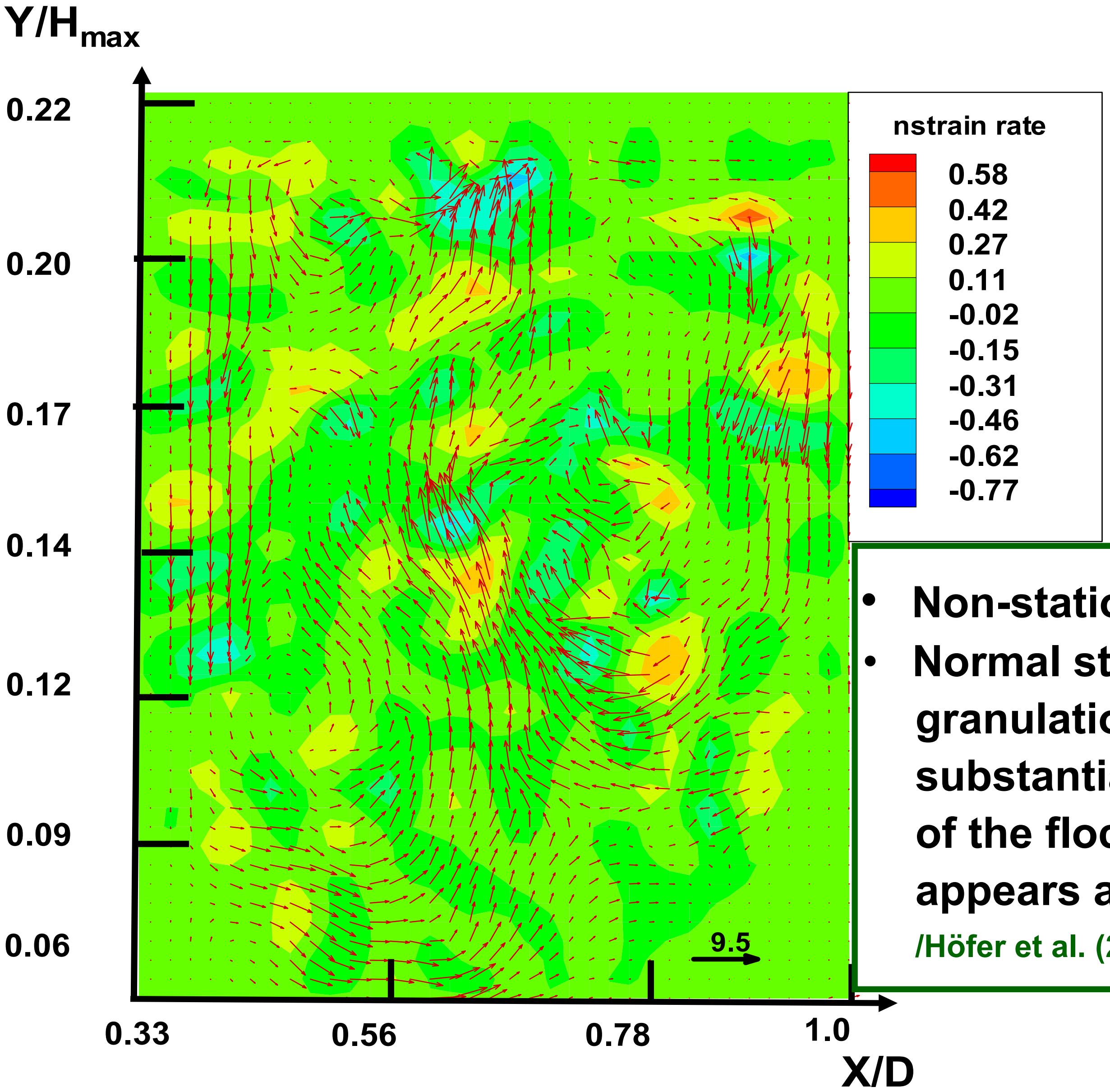
INFLUENCE OF WASTING



without wasting **with wasting**

PIV RESULTS

DIMENSIONLESS NORMAL STRAIN RATE

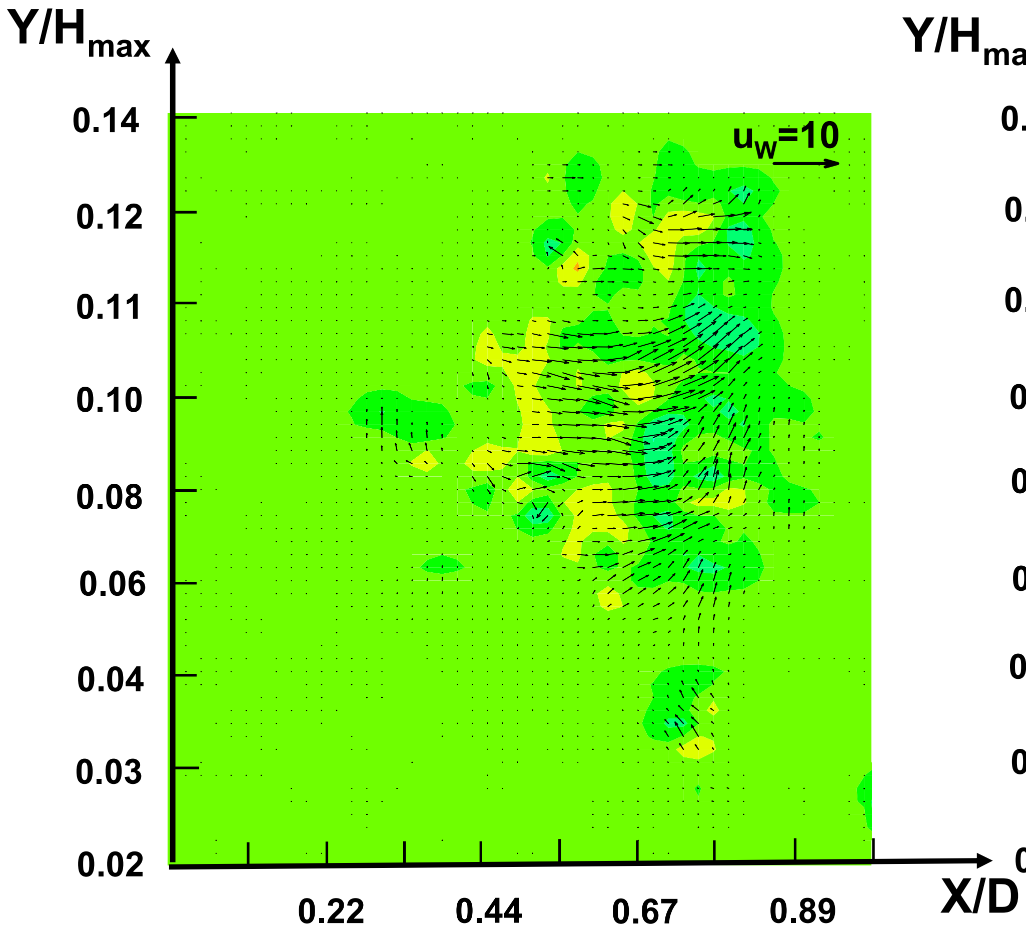


- **Non-stationary flow**
- **Normal strain influences granulation significantly, substantial elongation of the flocs already appears at $\dot{\varepsilon} = 0.12$**

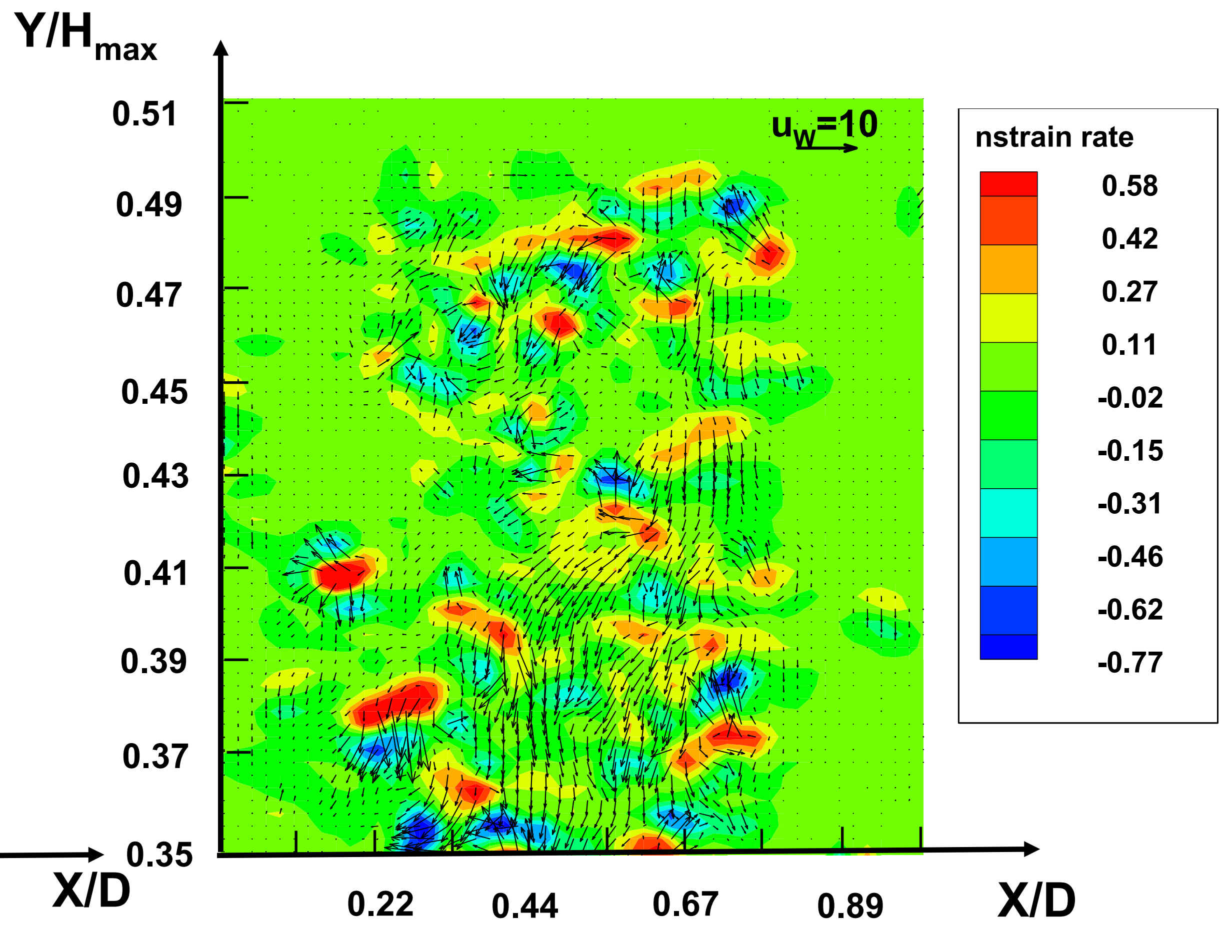
/Höfer et al. (2004), Zima et al. (2007)/

PIV RESULTS

DIMENSIONLESS NORMAL STRAIN RATE

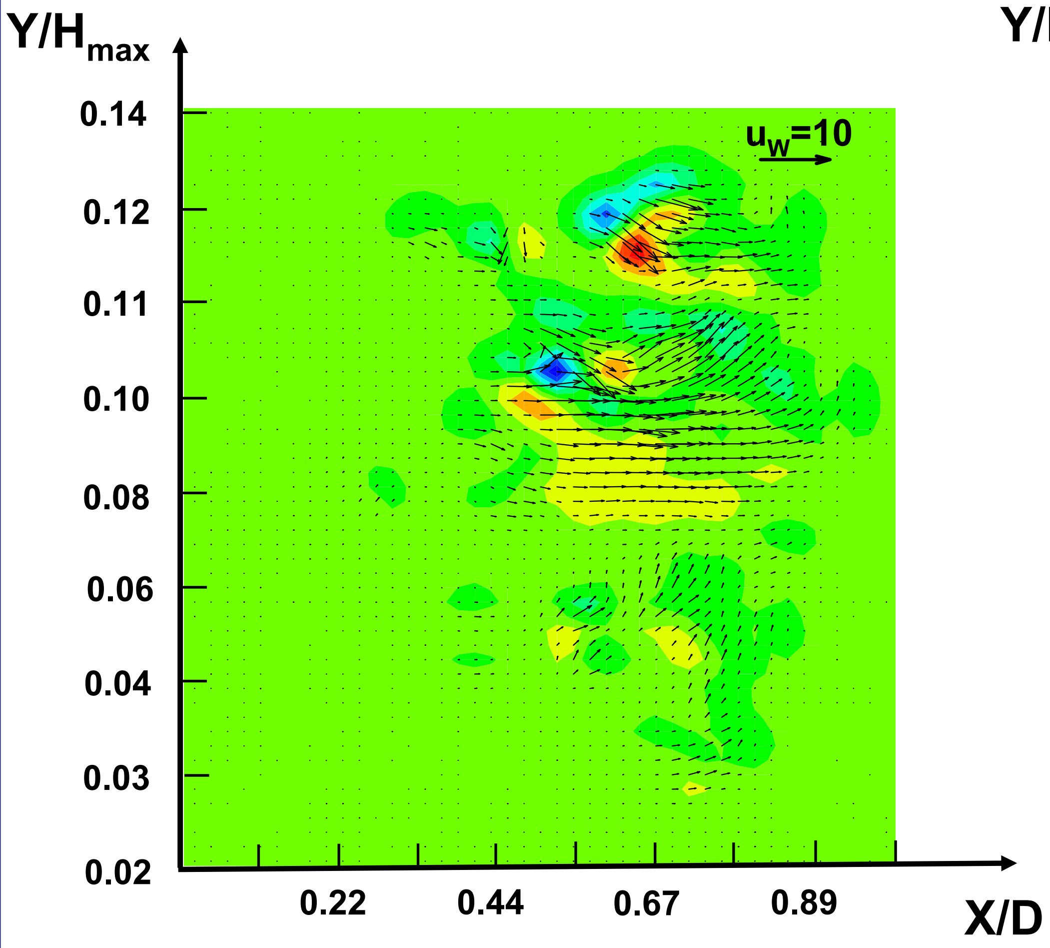


Z/D = 0.06

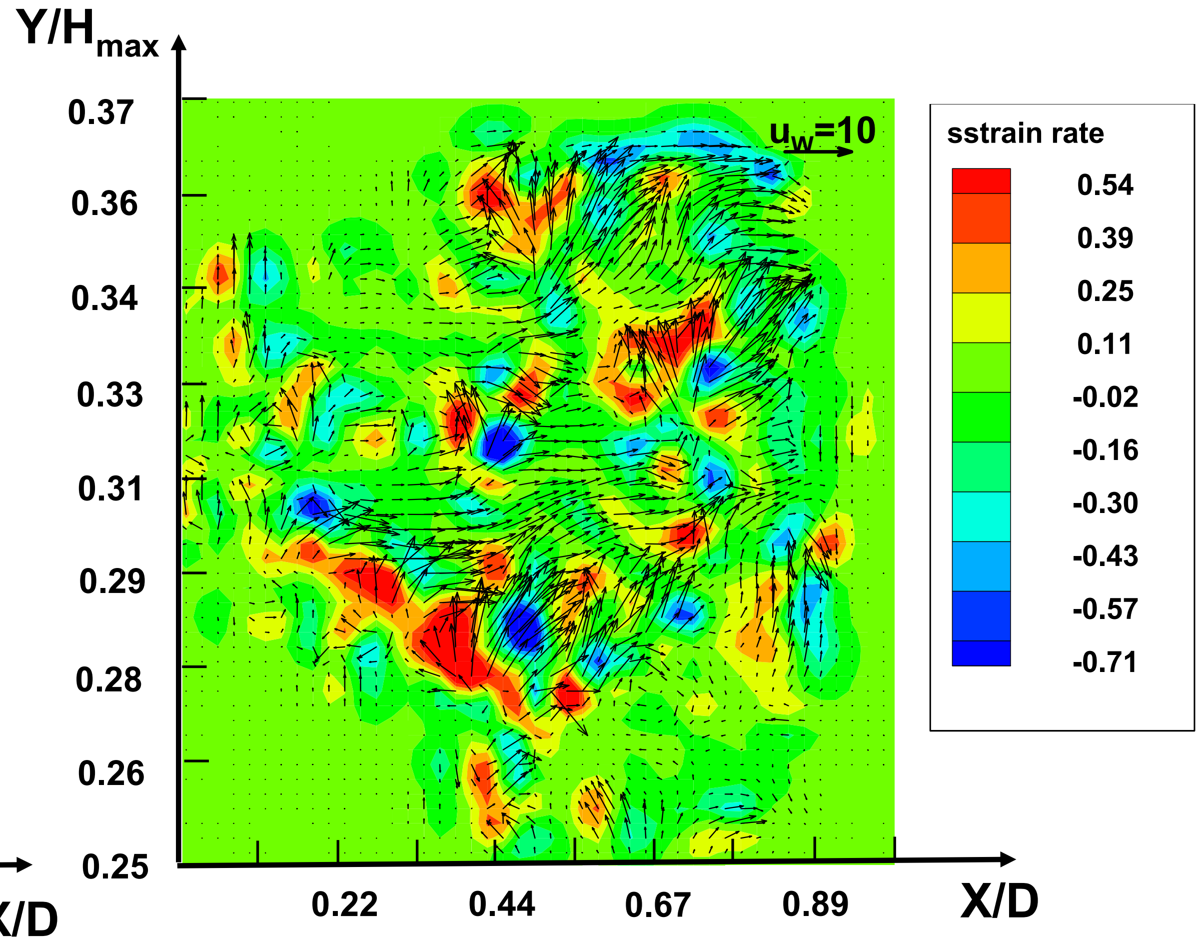


Z/D = 0.11

DIMENSIONLESS SHEAR STRAIN RATE



Z/D = 0.09



Z/D = 0.11

FLUID DYNAMIC FORCES

Forces caused by external fields

Buoyancy force $\underline{\vec{F}_G} = \vec{g}(\rho_W - \rho_P)$	$\vec{F}_G = 1$

Forces between particles and walls

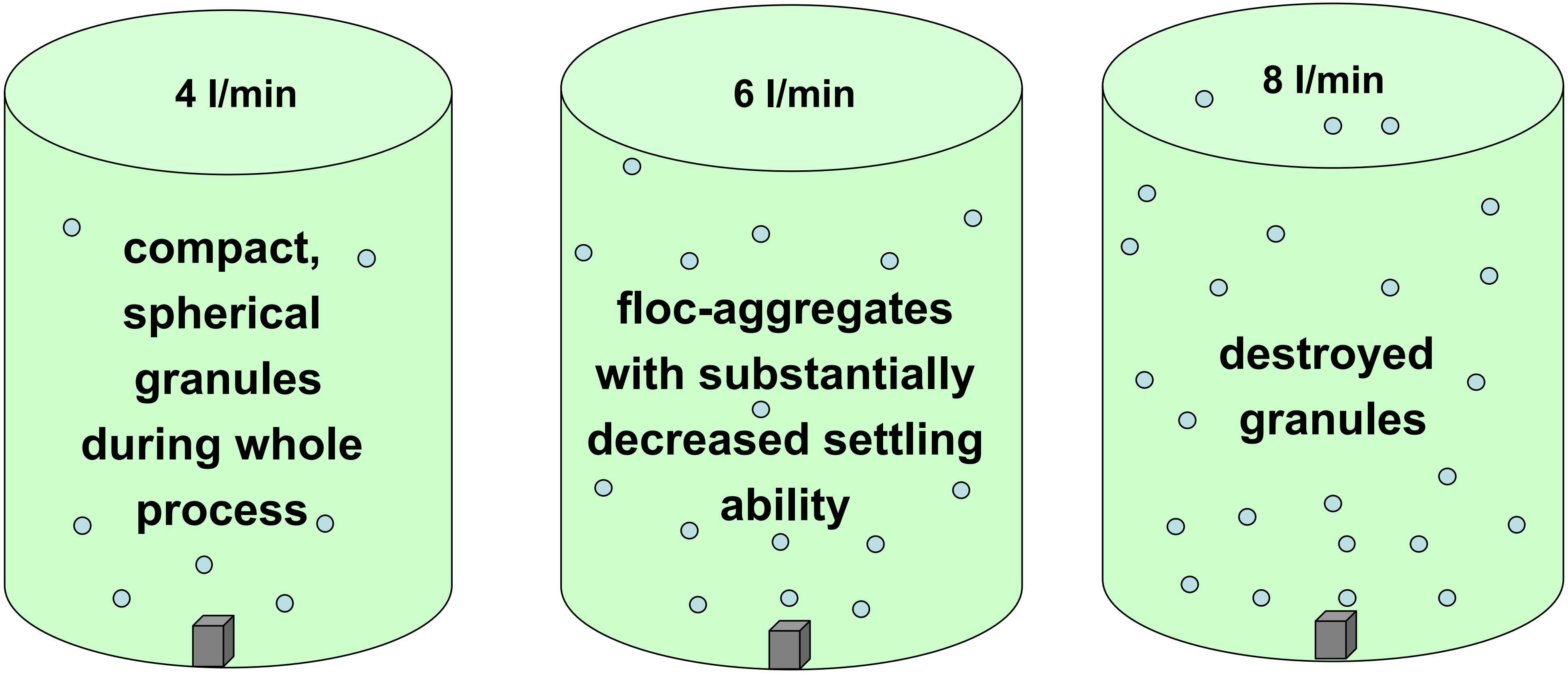
Equivalent time avaraged collisional force	$\underline{\vec{F}_C} = \dfrac{m_P \vec{u}_P}{t_E}$	$\vec{F}_C = 1.47 \times 10^{-1}$
Van der Waals force	$\underline{\vec{F}_W} = \dfrac{Ad}{12z^2}$	$\vec{F}_W = 2.69 \times 10^{-11}$

Forces between fluid and particles

Drag force	$\underline{\vec{F}_D} = C_D A_p \dfrac{\rho_W}{2} \left|\vec{u}_W - \vec{u}_P\right| \left(\vec{u}_W - \vec{u}_P\right)$	$\vec{F}_D = 1.31 \times 10^{-1}$
Basset force	$\underline{\vec{F}_B} = \dfrac{3}{2} D_P^2 \sqrt{\pi \rho_W \mu_W} \left[\int_0^t \dfrac{\frac{d}{dt}\left(\vec{u}_W - \vec{u}_P\right)}{\sqrt{t - t'}} dt' + \dfrac{\left(\vec{u}_W - \vec{u}_P\right)_0}{\sqrt{t}} \right]$	$\vec{F}_B = 2.42 \times 10^{-3}$
Added mass force	$\underline{\vec{F}_A} = \dfrac{1}{2} C_A \rho_W \dfrac{m_P}{\rho_P} \dfrac{d}{dt} \left(\vec{u}_W - \vec{u}_P\right)$	$\vec{F}_A = 2.74 \times 10^{-3}$
Saffman force	$\underline{\vec{F}_S} = 1.61 D_P^2 \sqrt{\rho_W \mu_W \dfrac{1}{\left|\vec{\omega}_W\right|}} \left[\left(\vec{u}_W - \vec{u}_P\right) \times \vec{\omega}_W\right]$	$\vec{F}_S = 7.17 \times 10^{-2}$
Magnus force	$\underline{\vec{F}_M} = C_{LR} A_P \dfrac{\rho_W}{2} \left|\vec{u}_W - \vec{u}_P\right| \dfrac{\vec{\Omega} \times \left(\vec{u}_W - \vec{u}_P\right)}{\left|\vec{\Omega}\right|}$	$\vec{F}_M = 2.43 \times 10^{-2}$
Lift rotational force	$\underline{\vec{T}_R} = \dfrac{\rho_W}{2} \left(\dfrac{D_P}{2}\right)^5 C_R \left|\vec{\Omega}\right| \vec{\Omega}$	$\vec{T}_R = 5.86 \times 10^{-3}$

MICROSCOPIC ANALYSIS

3 bioreactors with the same working volume, the same geometrical configuration and different flow rate

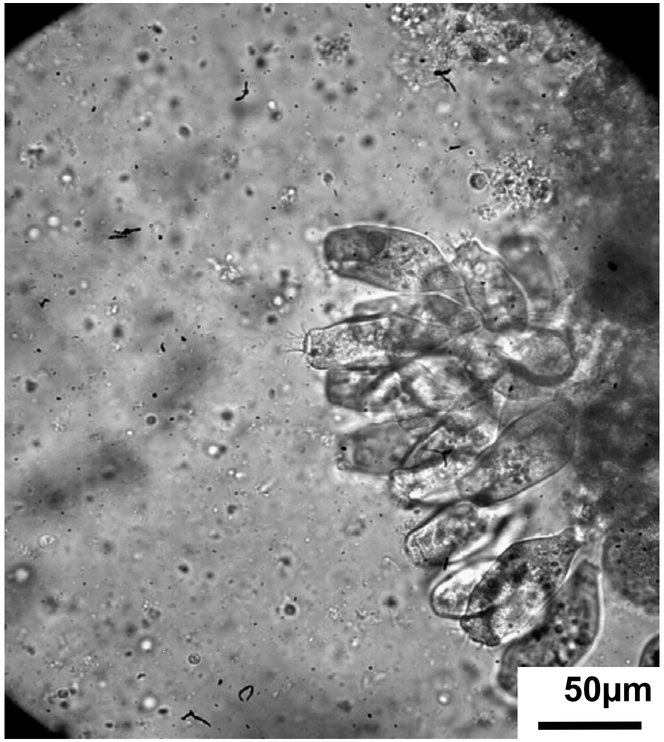


influence of mechanical forces not only depends on the load magnitude but also on duration of the process /Esterl et al. (2002), Zima et al. (2007)/

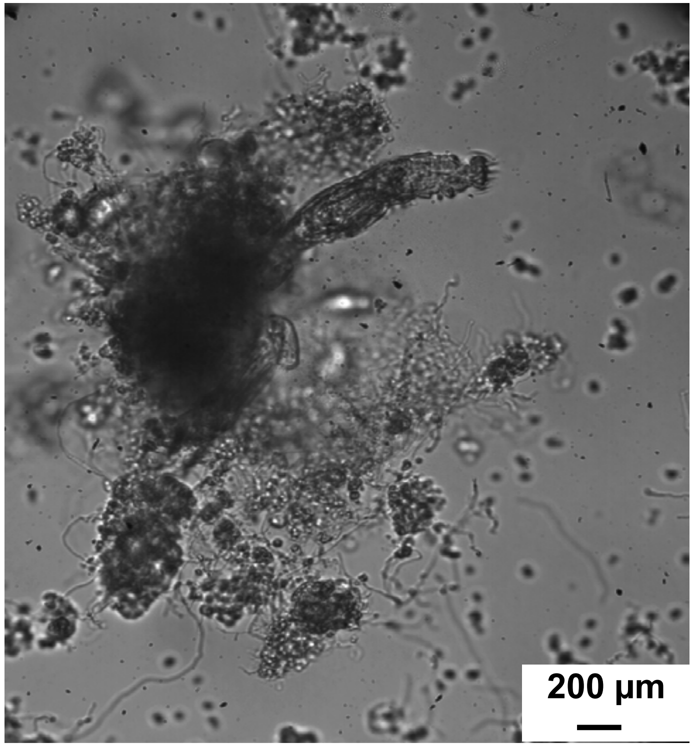
FATIGUE EFFECT

MICROSCOPIC ANALYSIS

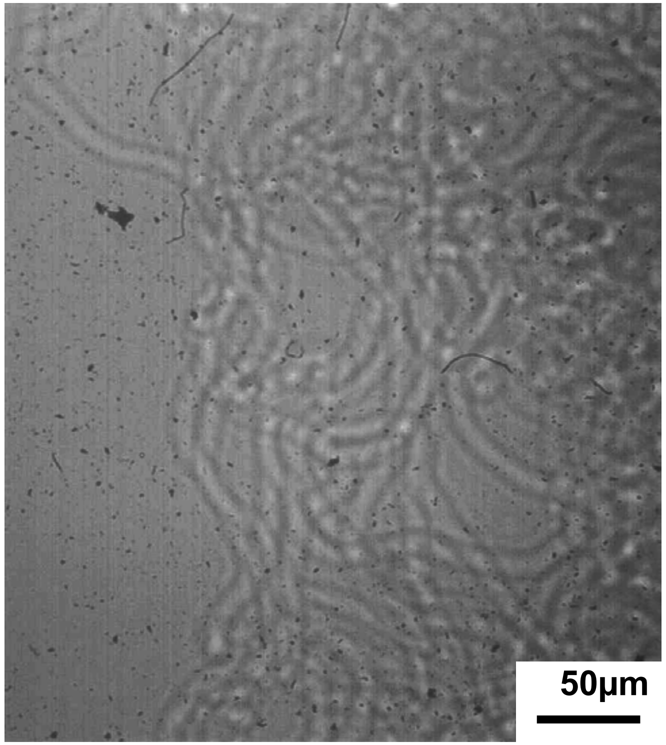
HYDRODYNAMIC SELECTION OF MICROORGANISMS



4 l/min



6 l/min

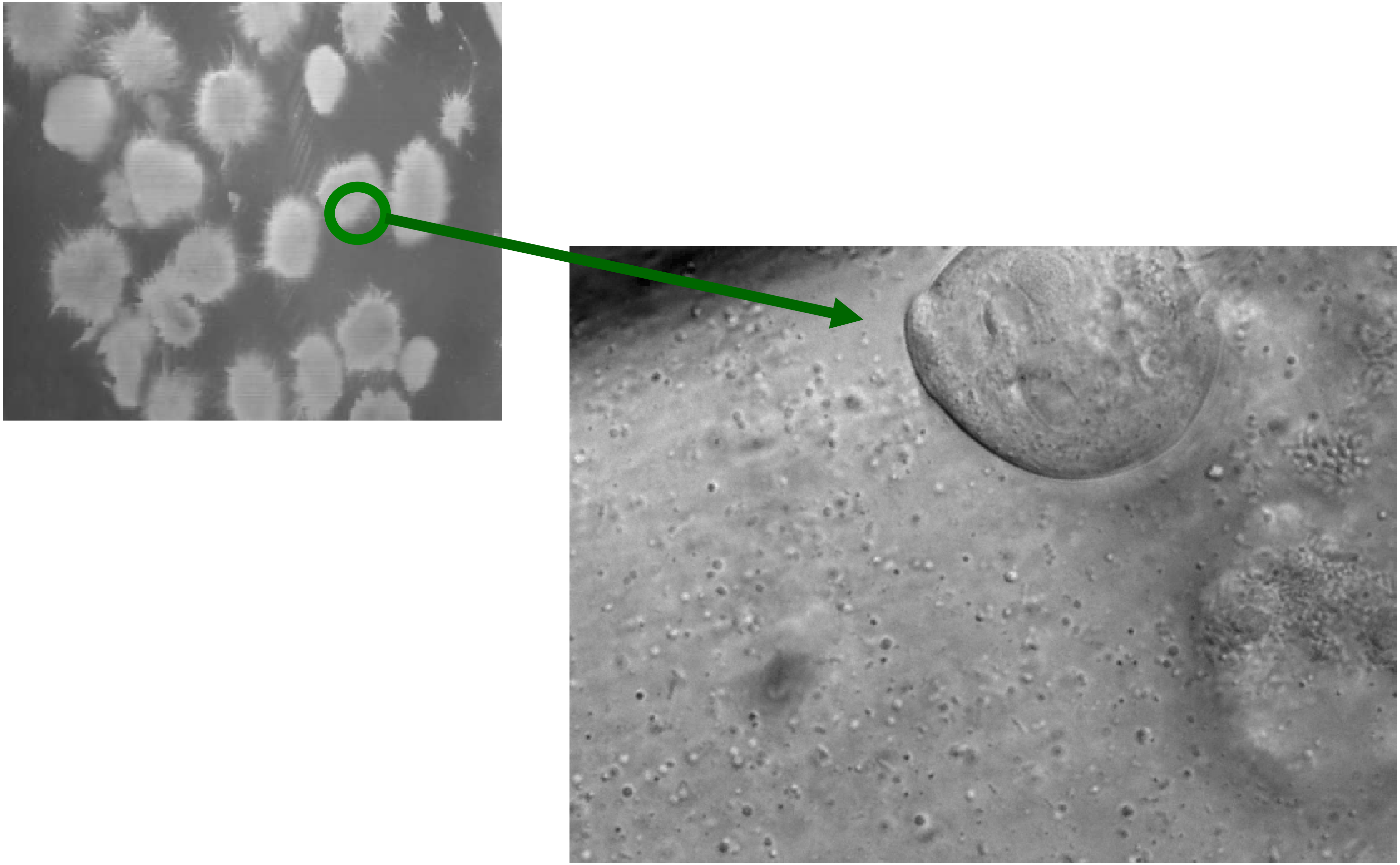


8 l/min

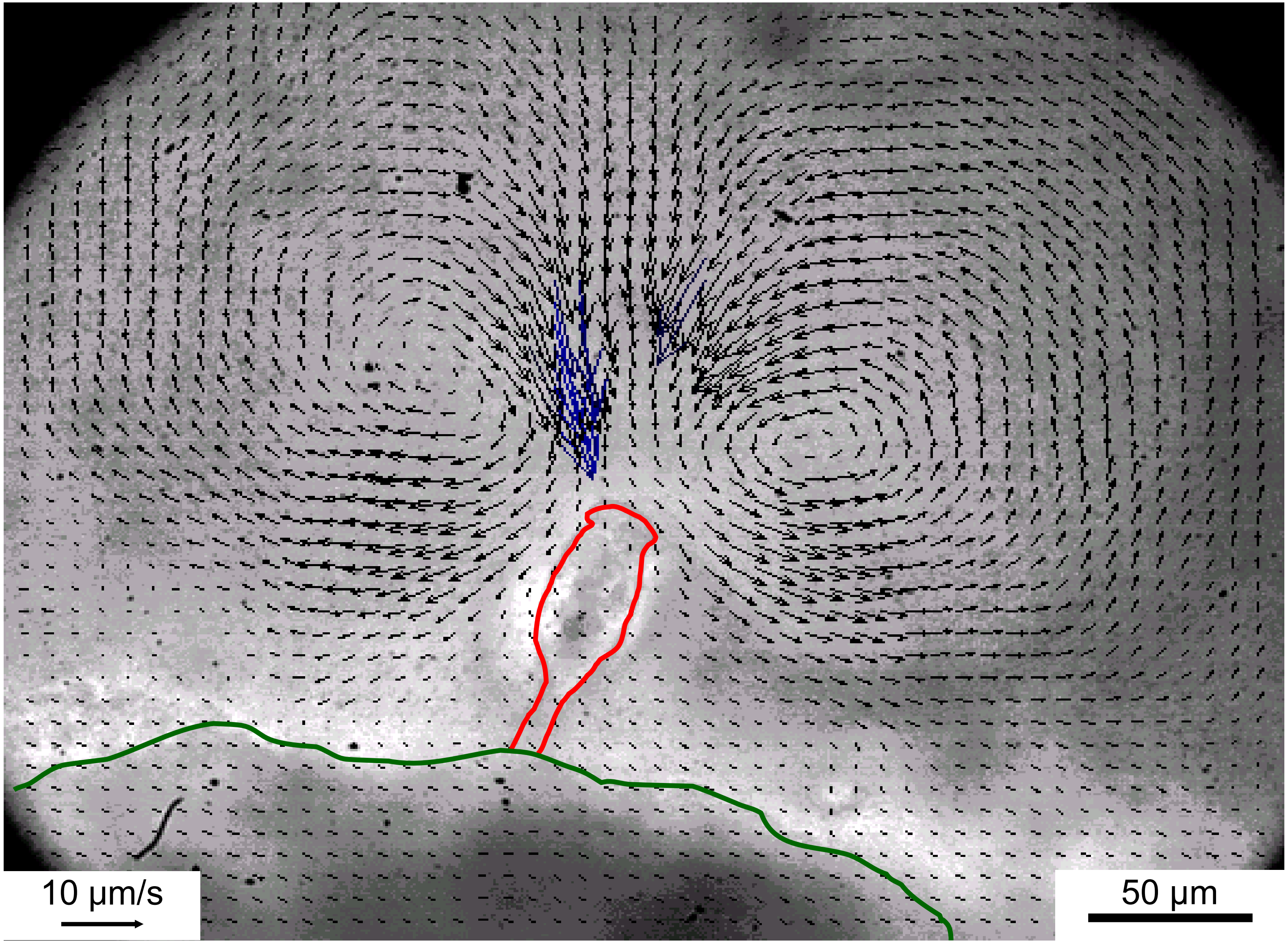
BIG DIVERSITY OF MICROORGANISMS UNDER DIFFERENT FLOW RATES

/Zima et al. (2007)/

MICROORGANISMIC FLOW



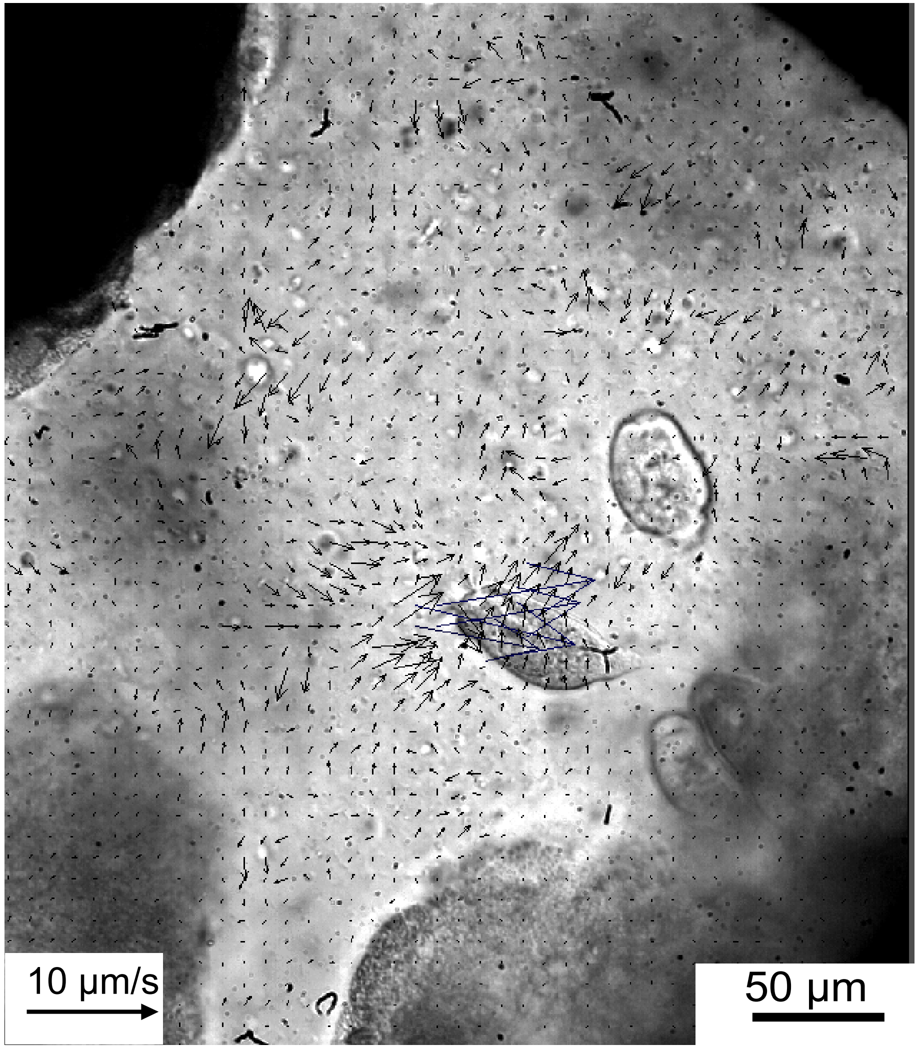
CHARACTERISTIC FLOW PATTERN



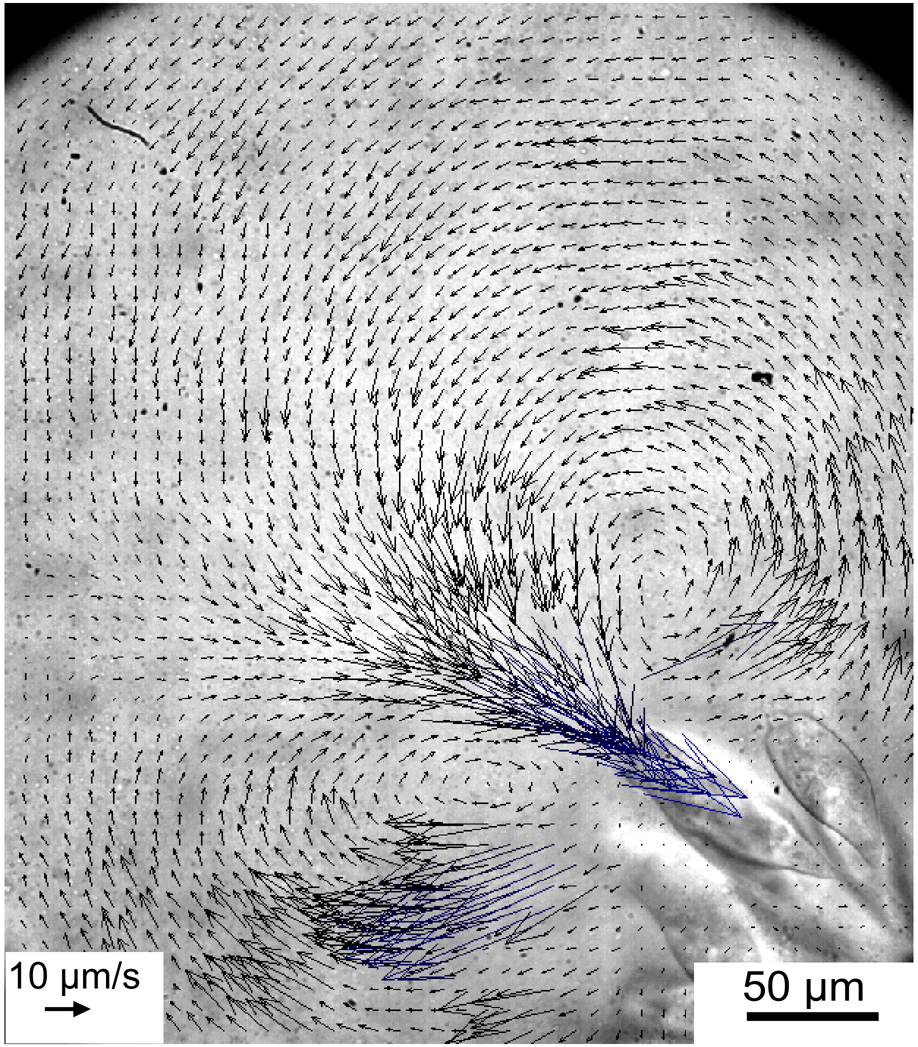
µPIV RESULTS

DIFFERENT SEEDING PARTICLES

Yeast cells 3-10 µm

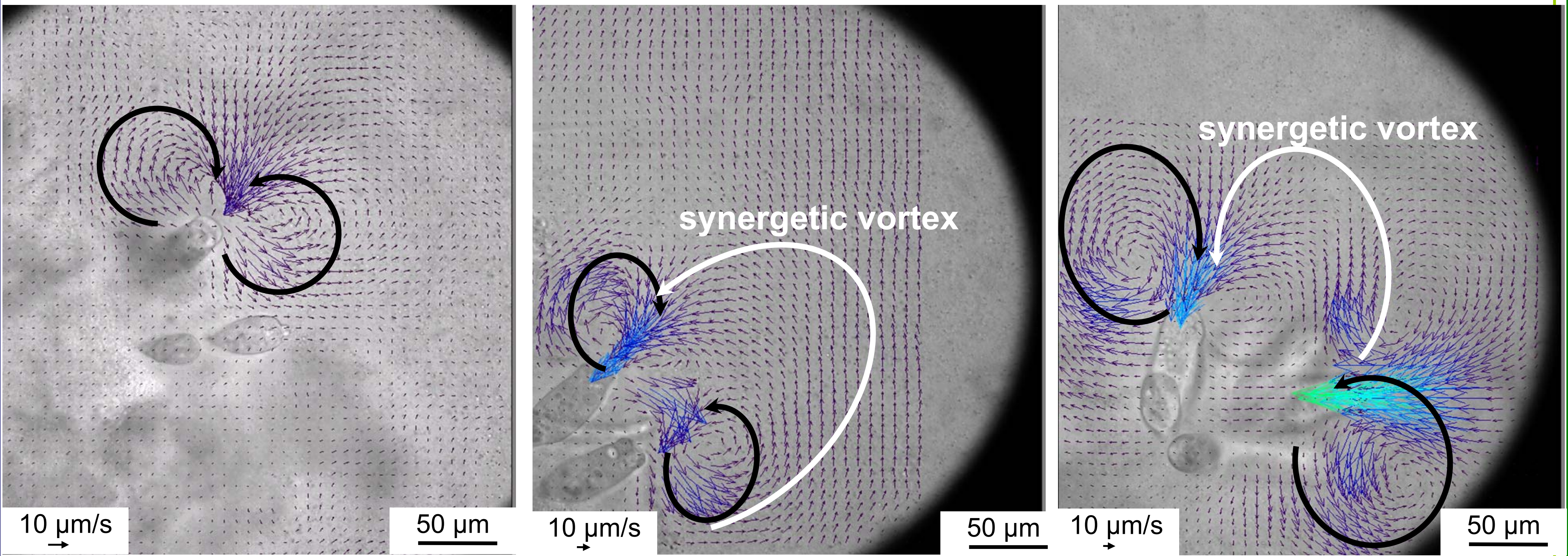


Milk 0.3-3 µm



μPIV RESULTS

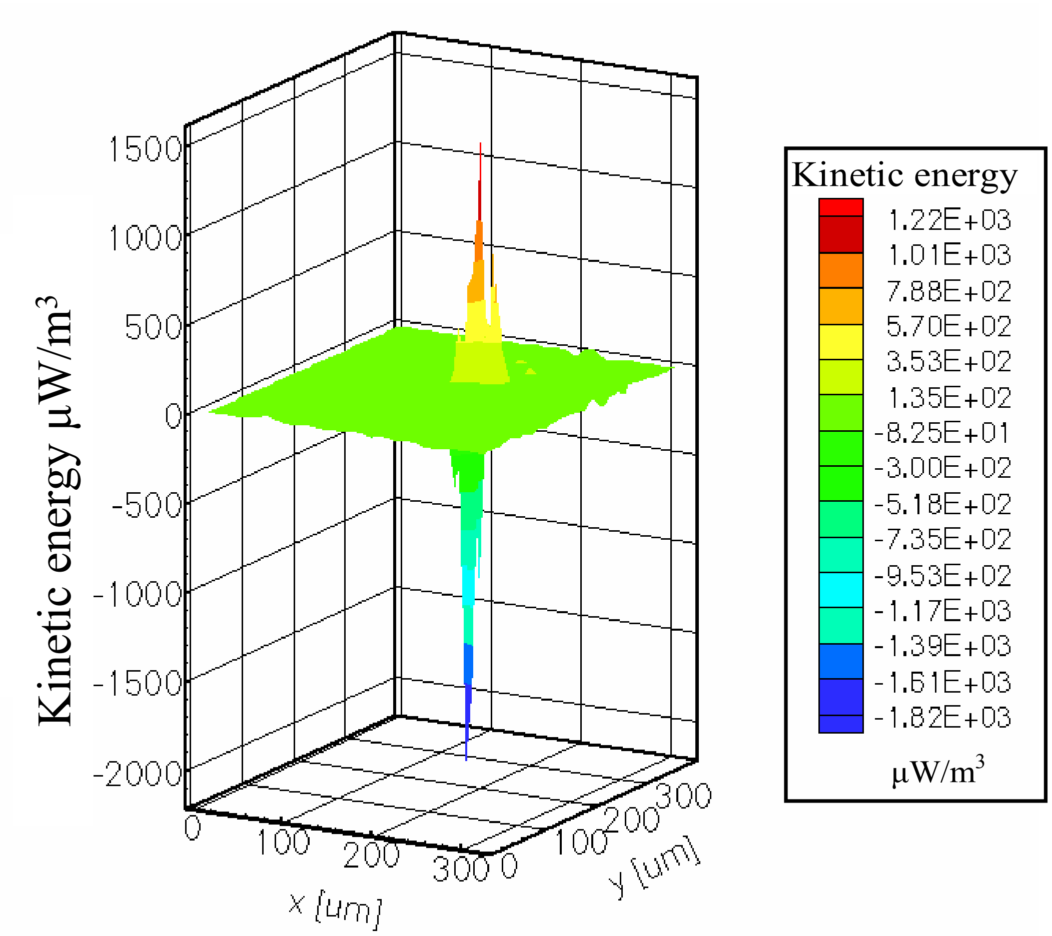
VELOCITY



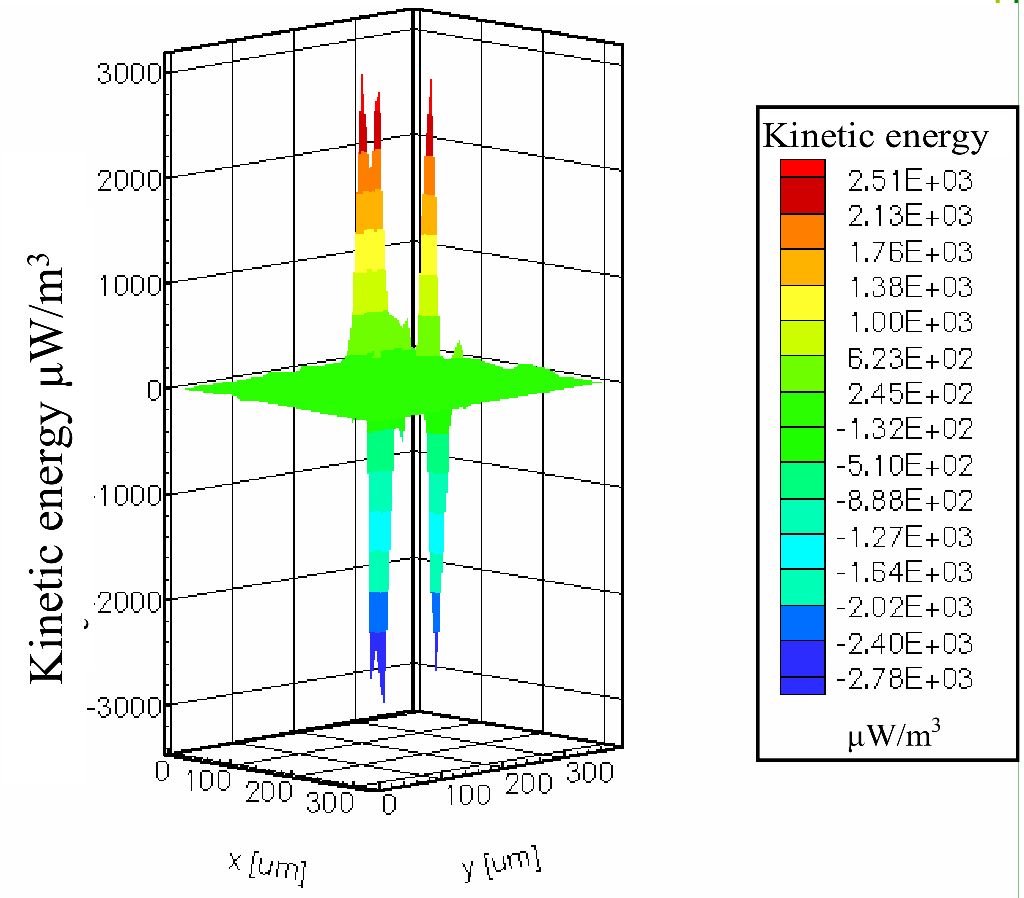
u_{max}= 0.20 u_{max}= 0.48 u_{max}= 0.86

CONVECTIVE KINETIC ENERGY

one ciliate



colony

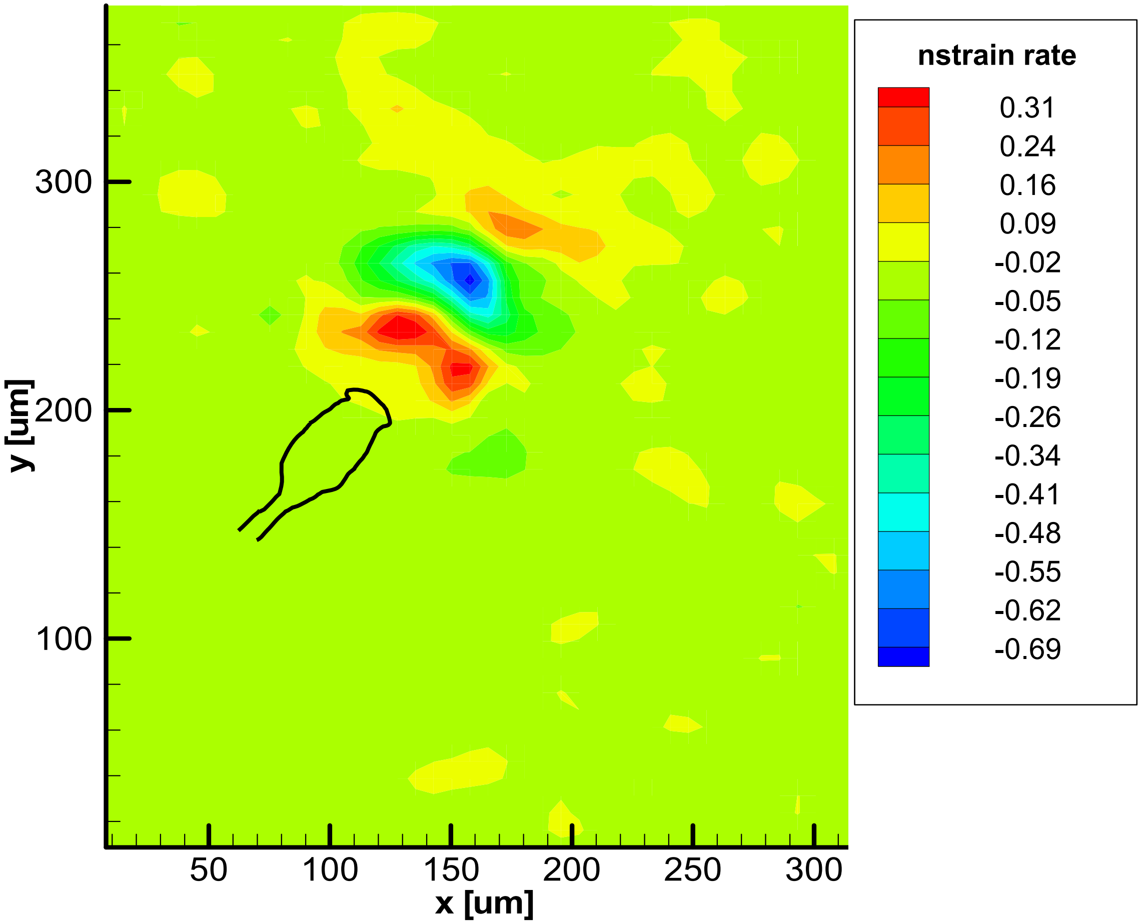


synergy factor 1.7

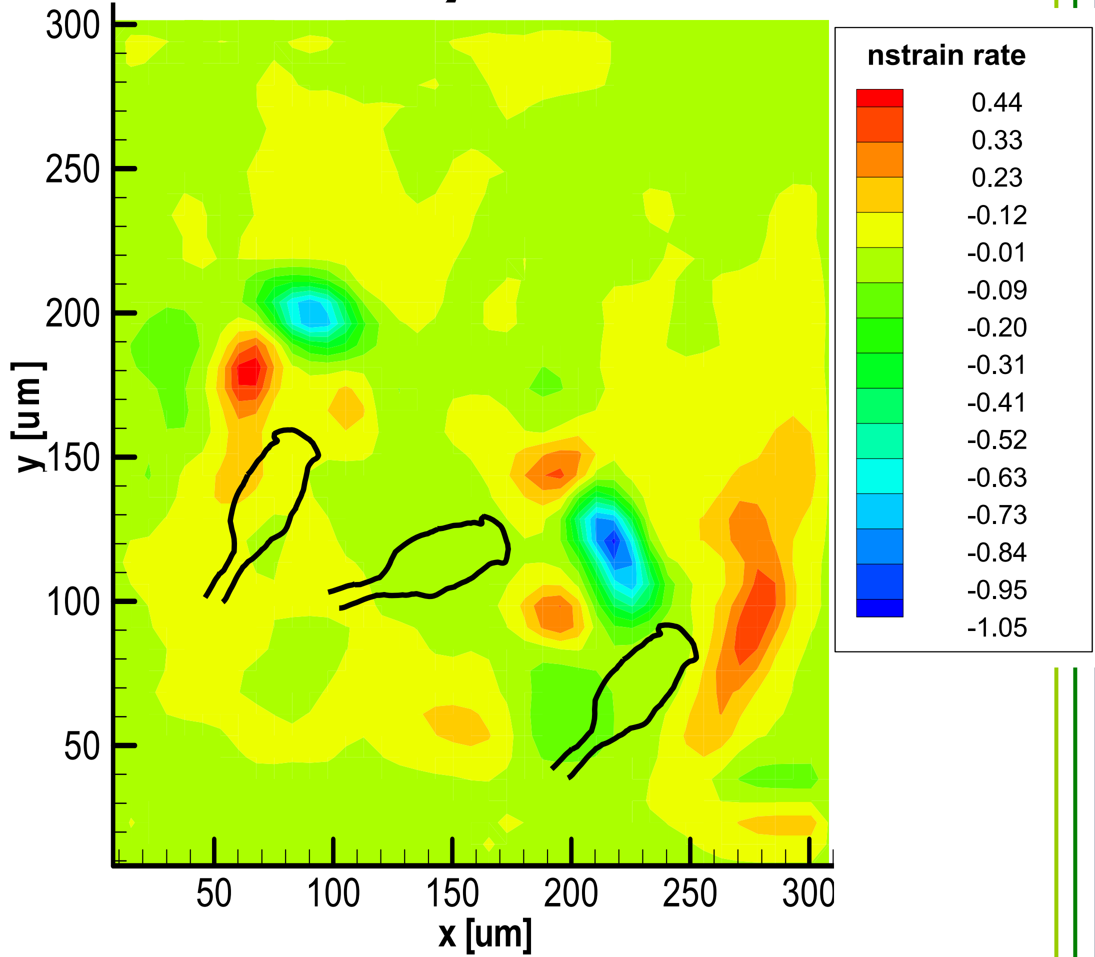
μPIV RESULTS

NORMAL STRAIN RATE

one ciliate



colony

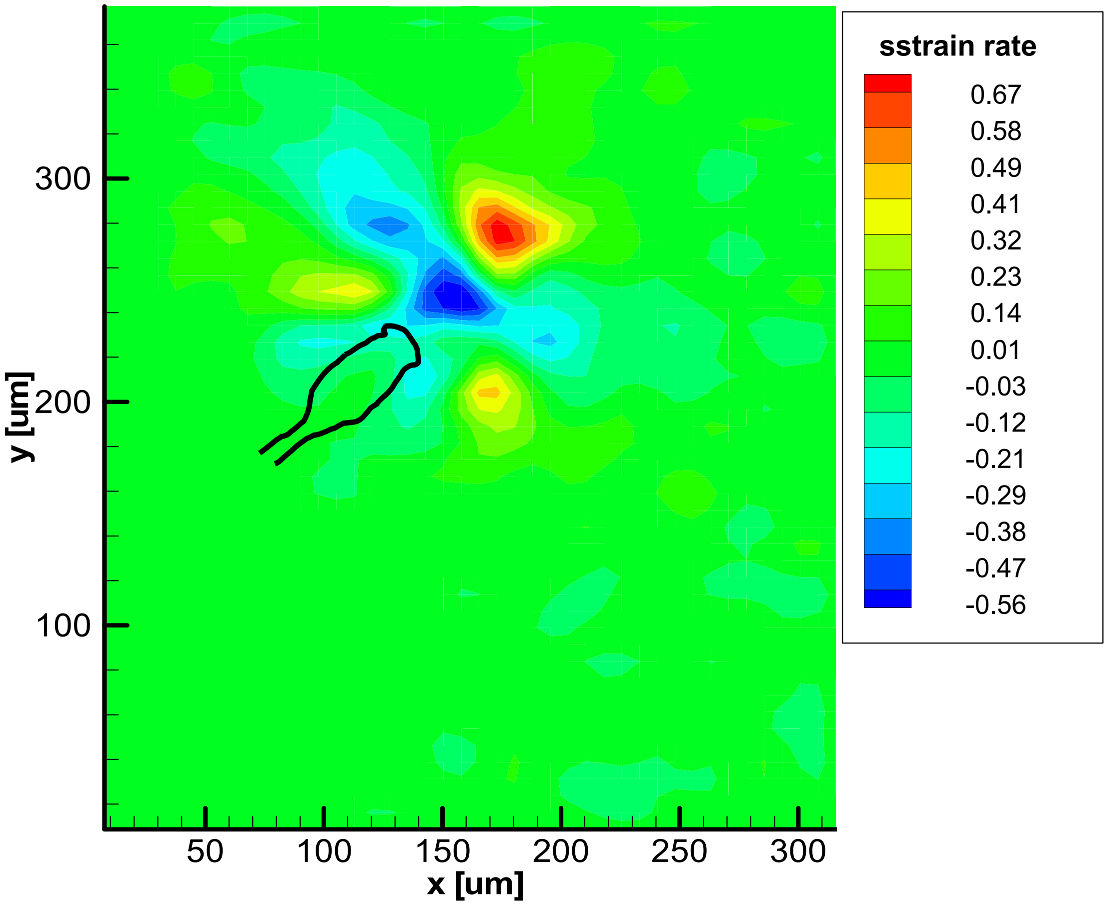


synergy factor 3.3

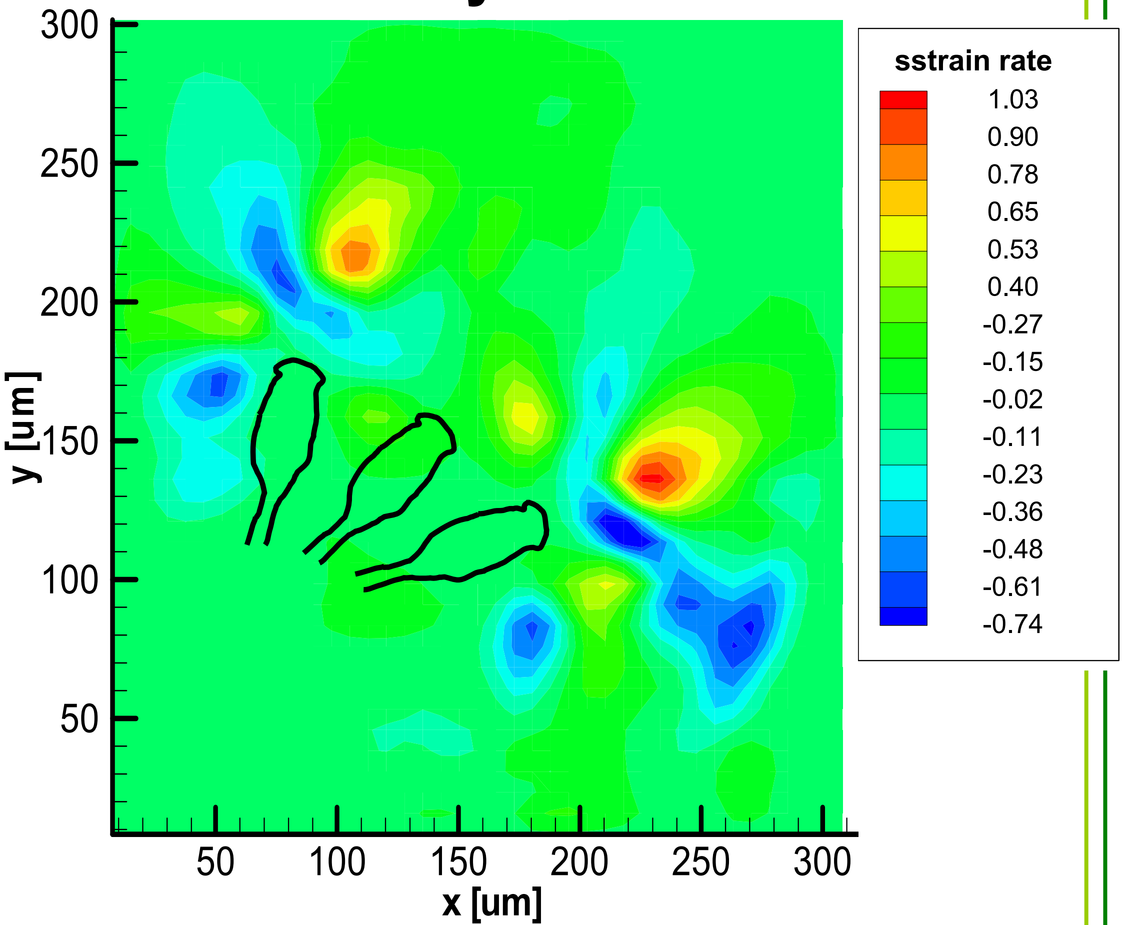
µPIV RESULTS

SHEAR STRAIN RATE

one ciliate



colony

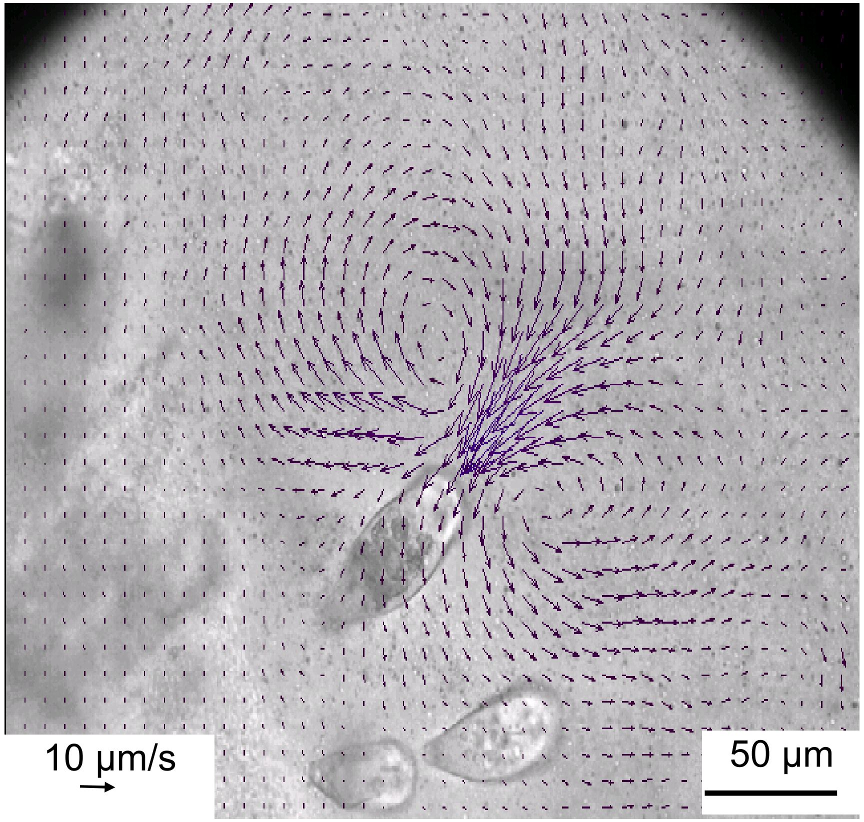


synergy factor 2.7

μPIV RESULTS

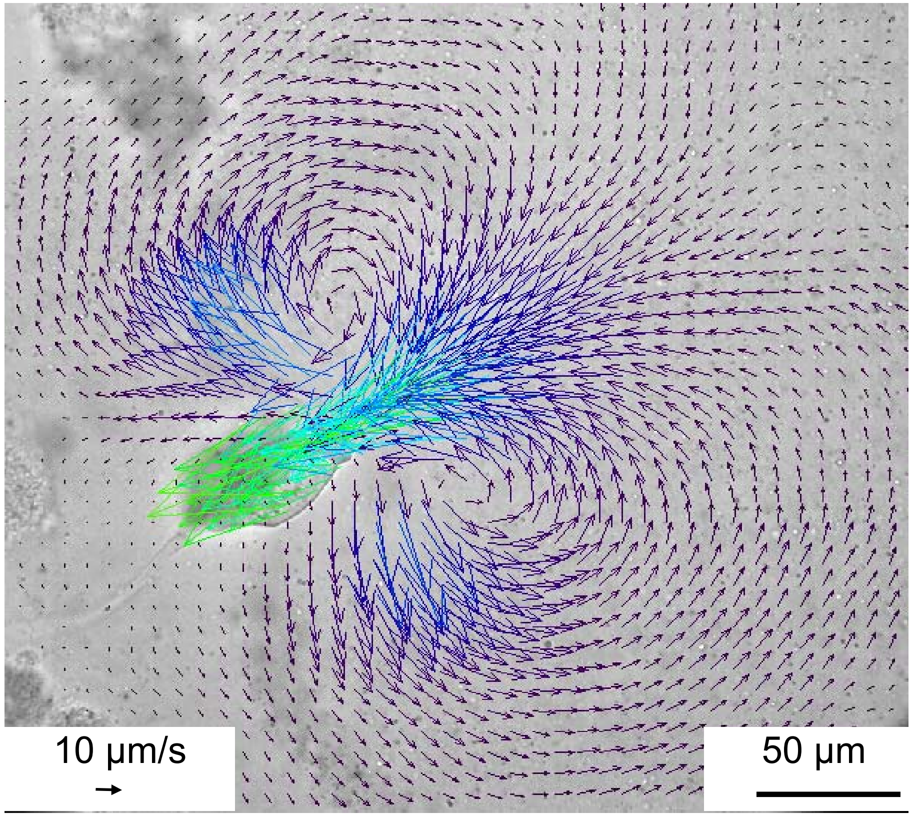
VELOCITY

1:1



u_{max}= 0.17

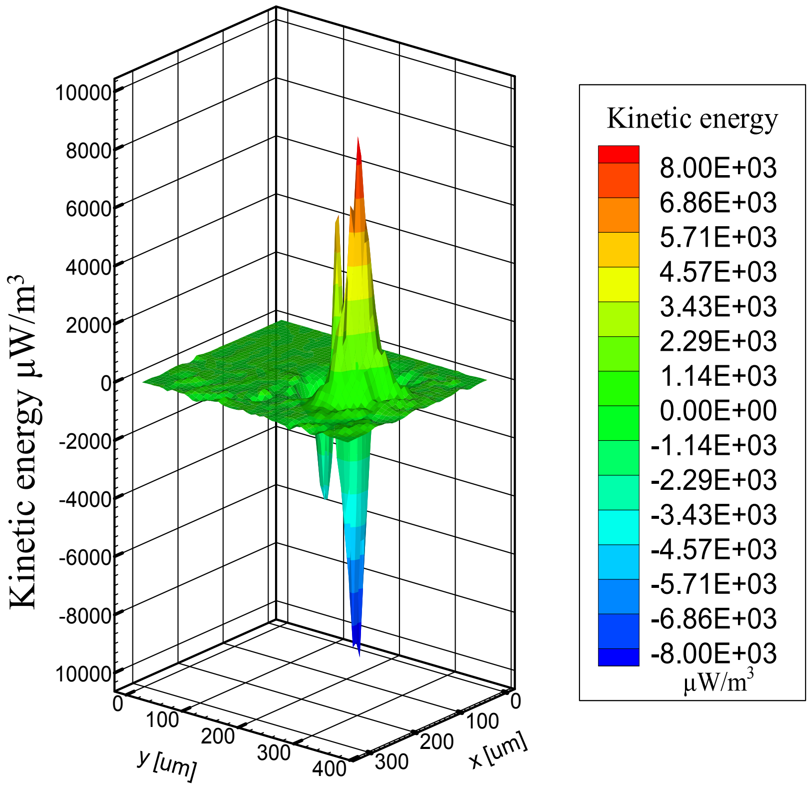
1:4



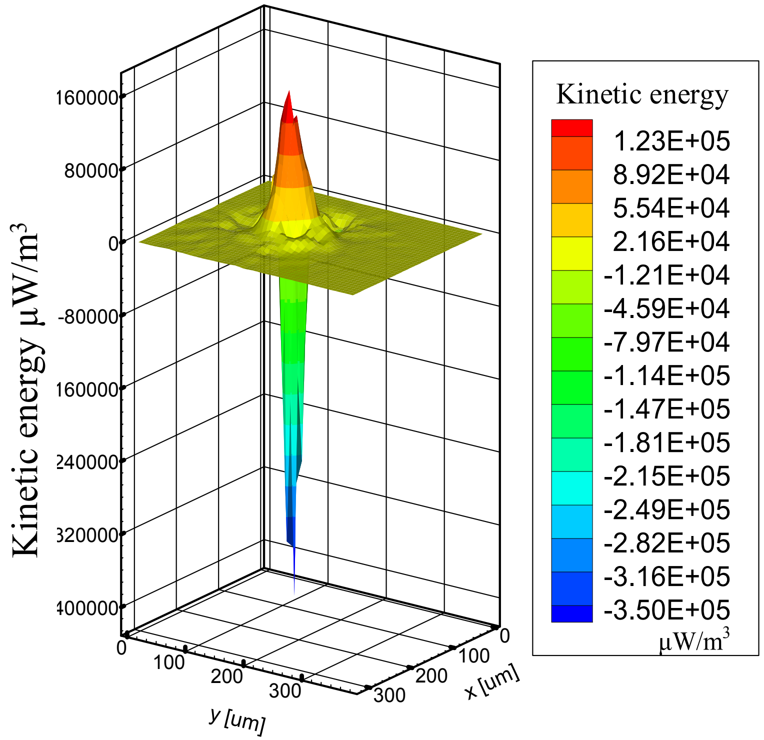
u_{max}= 1

CONVECTIVE KINETIC ENERGY

1:1



1:4

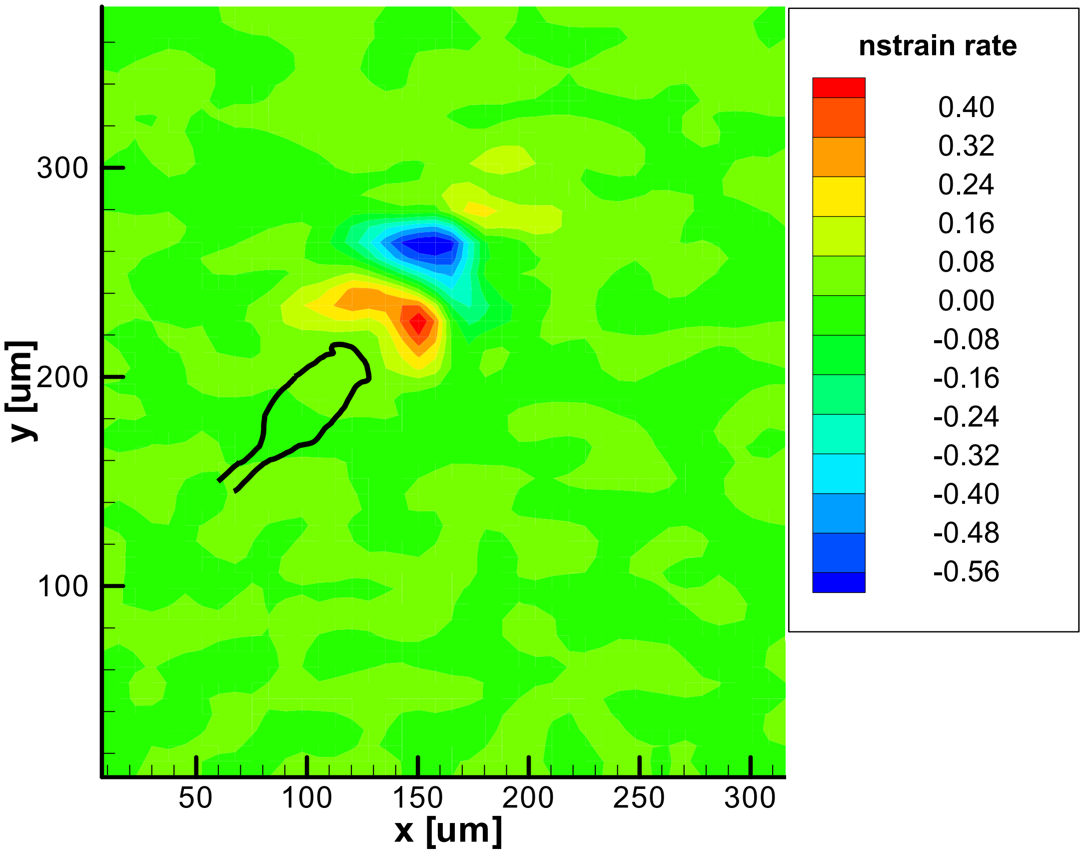


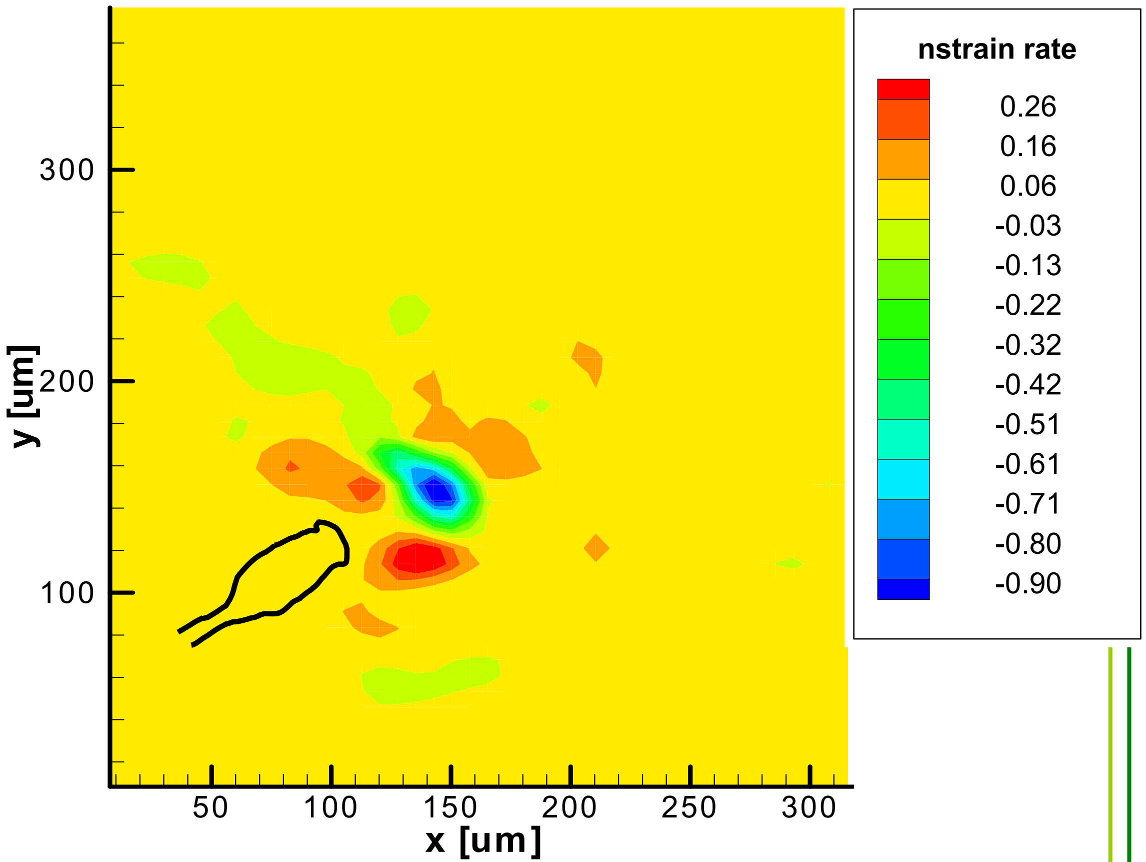
synergy factor 30

μPIV RESULTS

NORMAL STRAIN RATE

1:1 **1:4**



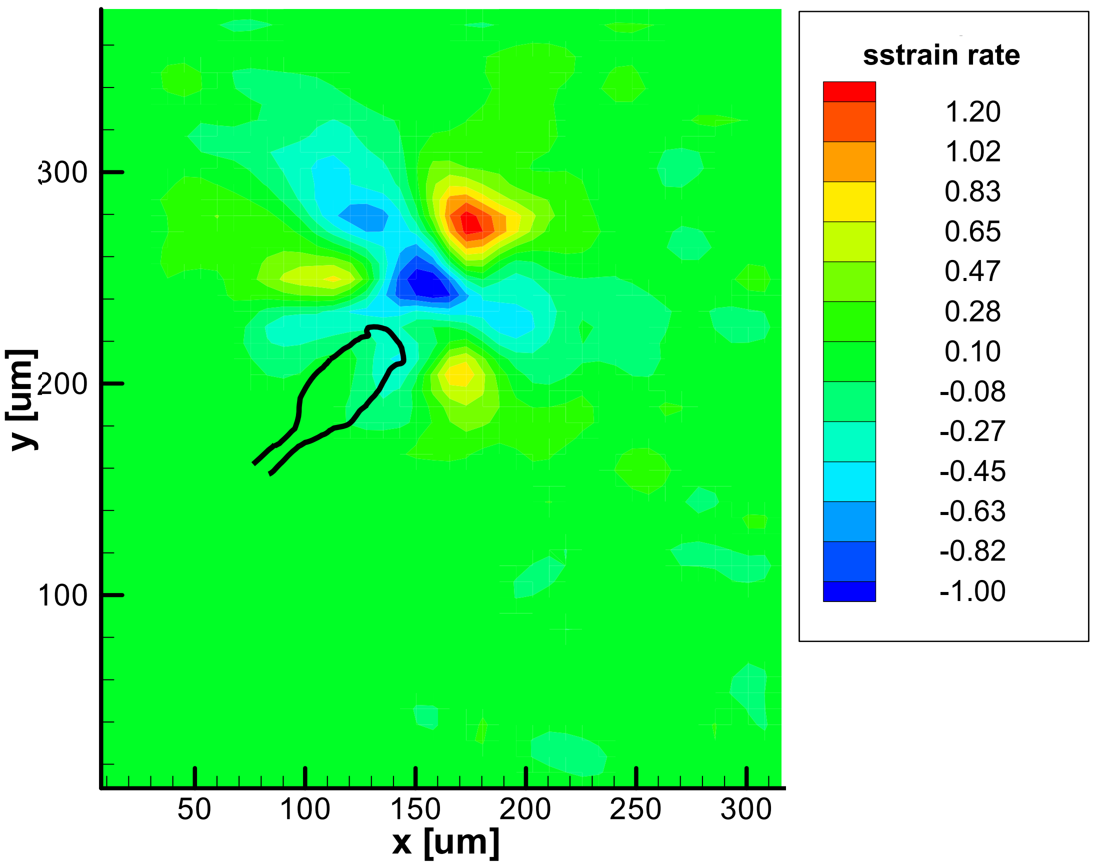


synergy factor 3.8

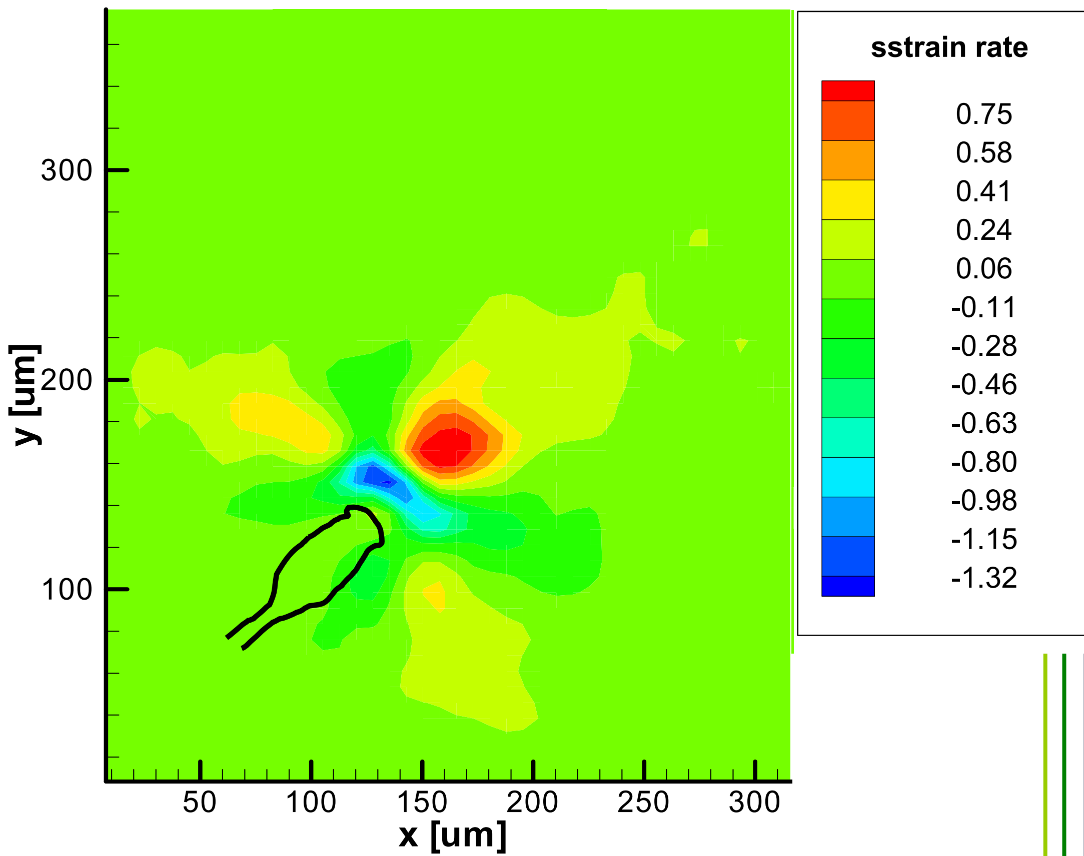
μPIV RESULTS

SHEAR STRAIN RATE

1:1



1:4



synergy factor 5

CONCLUSIONS

- ✓characteristic flow pattern in SBR (micro and macro scale)
- ✓big influence of granules on the flow pattern
- ✓granulation – only under appropriate flow conditions
- ✓normal and shear strain rates – significant effect on granules formation
- ✓buoyancy, drag, collisional, lift forces – crucial role in SBR
- ✓different flow conditions – biomechanical fatigue effect, hydrodynamic selections of microorganisms
- ✓ciliates – important role for granules formation
- ✓flow induced by ciliates – efficient way for nutrient transport with minimum energy requirement
- ✓efficient cooperative colony work