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)/
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**

---

**Phase 1:** Flocs formation (A, B)

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

**Phase 3:** The mature granule (D, E)

Weber et al. (2007)
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

- Cuboid filled with water
- Porous air stone
- Dosing pump
- Extracting pump
- Liquid level
- Bioreactor diameter

Dimensions:
- Cuboid: 1000 mm (4 l) x 635 mm x 120 mm
- Air: 250 mm

Diagram shows the setup with influent and effluent flow paths.
B.E. Zima-Kulisiewicz

**SBR PROCESS**

**FILL** | **REACT** | **SETTLE** | **DRAW** | **IDLE**

**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

CCD camera

image plane

light sheet

He – Ne laser

90°

X

Y

Z

Z/D = 0.06

Z/D = 0.09

Z/D = 0.11
OPTICAL IN-SITU TECHNIQUES

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**

<table>
<thead>
<tr>
<th>Time</th>
<th>( t = \frac{t}{t_s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid velocity</td>
<td>( u_w = \frac{u_w}{SGV} )</td>
</tr>
<tr>
<td>Liquid velocity components</td>
<td>( u_w = \frac{u_w}{SGV} ) ( v_w = \frac{v_w}{SGV} )</td>
</tr>
<tr>
<td>Shear strain rate</td>
<td>( \dot{\gamma} = \frac{\dot{\gamma}}{\dot{\gamma}_{max}} )</td>
</tr>
<tr>
<td>Normal strain rate</td>
<td>( \dot{\varepsilon} = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_{max}} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Forces</th>
<th>( \tilde{F}_i = \frac{F_i}{F_G} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid velocity on micro scale</td>
<td>( u = \frac{u}{u_{max}} )</td>
</tr>
<tr>
<td>X axis</td>
<td>( X ) ( D )</td>
</tr>
<tr>
<td>Y axis</td>
<td>( Y ) ( H_{max} )</td>
</tr>
<tr>
<td>Z axis</td>
<td>( Z ) ( D )</td>
</tr>
</tbody>
</table>
PIV RESULTS

OBSERVABLE FLUID FLOW PATTERNS

DIMENSIONLESS FLUID VELOCITY
increasing tendency with height in SBR

large vortex
smaller eddies
the smallest observable eddies

B.E. Zima-Kulisiewicz
PIV RESULTS

NON-STATIONARITY OF THE FLOW

Velocity

<table>
<thead>
<tr>
<th>X/D</th>
<th>Y/H_max</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.12</td>
</tr>
<tr>
<td>0.33</td>
<td>0.22</td>
</tr>
<tr>
<td>0.67</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Magnitude

<table>
<thead>
<tr>
<th>X/D</th>
<th>Y/H_max</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>0.33</td>
<td>0.15</td>
</tr>
<tr>
<td>0.67</td>
<td>0.20</td>
</tr>
</tbody>
</table>

B.E. Zima-Kulisiewicz
PIV RESULTS

INFLUENCE OF WASTING

without wasting

with wasting
PIV RESULTS

INFLUENCE OF WASTING

\[ Y/H_{\text{max}} \]

\[ u_W \]

- \( u_W \) (without wasting)
- \( u_W \) (with wasting)
PIV RESULTS

INFLUENCE OF WASTING

without wasting  with wasting

B.E. Zima-Kulisiewicz
PIV RESULTS

DIMENSIONLESS NORMAL STRAIN RATE

- Non-stationary flow
- Normal strain influences granulation significantly, substantial elongation of the flocs already appears at $\varepsilon \approx 0.12$

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

DIMENSIONLESS NORMAL STRAIN RATE

$Z/D = 0.06$

<table>
<thead>
<tr>
<th>$Y/H_{\text{max}}$</th>
<th>$X/D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.14</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>0.89</td>
</tr>
</tbody>
</table>

$Z/D = 0.11$

<table>
<thead>
<tr>
<th>$Y/H_{\text{max}}$</th>
<th>$X/D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.14</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>0.89</td>
</tr>
</tbody>
</table>

$u_w = 10$

B.E. Zima-Kulisiewicz
PIV RESULTS

DIMENSIONLESS SHEAR STRAIN RATE

\begin{align*}
\text{Dimensionless Shear Strain Rate} & = \frac{\text{strain rate}}{\text{strain rate}_{\text{max}}} \\
\text{Y/H}_\text{max} & = 0.02, 0.03, 0.04, 0.06, 0.08, 0.12, 0.14 \\
\text{X/D} & = 0.22, 0.44, 0.67, 0.89 \\
\text{Z/D} & = 0.09, 0.11
\end{align*}
# FLUID DYNAMIC FORCES

## Forces caused by external fields

**Buoyancy force**
\[ \vec{F}_G = \vec{g} (\rho_W - \rho_P) \]
\[ \vec{F}_G = 1 \]

## Forces between particles and walls

**Equivalent time averaged collisional force**
\[ \vec{F}_C = \frac{m_P \vec{u}_P}{t_E} \]
\[ \vec{F}_C = 1.47 \times 10^{-1} \]

**Van der Waals force**
\[ \vec{F}_W = \frac{Ad}{12z^2} \]
\[ \vec{F}_W = 2.69 \times 10^{-11} \]

## Forces between fluid and particles

<table>
<thead>
<tr>
<th>Force Type</th>
<th>Force Equation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drag force</td>
<td>[ \vec{F}_D = C_D A_p \rho_W \frac{\rho_W}{2} \left</td>
<td>\vec{u}_W - \vec{u}_P \right</td>
</tr>
<tr>
<td>Basset force</td>
<td>[ \vec{F}_B = \frac{3}{2} D_p^2 \sqrt{\pi \rho_W \mu_W} \left[ \int_0^t \frac{d}{dt} \left( \vec{u}_W - \vec{u}_P \right) \right] ]</td>
<td>[ \vec{F}_B = 2.42 \times 10^{-3} ]</td>
</tr>
<tr>
<td>Added mass force</td>
<td>[ \vec{F}_A = \frac{1}{2} C_A \rho_W \frac{m_P}{\rho_P} \frac{d}{dt} (\vec{u}_W - \vec{u}_P) ]</td>
<td>[ \vec{F}_A = 2.74 \times 10^{-3} ]</td>
</tr>
<tr>
<td>Saffman force</td>
<td>[ \vec{F}_S = 1.61D_p^2 \sqrt{\rho_W \mu_W} \frac{1}{\vec{\omega}_W} \left[ (\vec{u}_W - \vec{u}_P) \times \vec{\omega}_W \right] ]</td>
<td>[ \vec{F}_S = 7.17 \times 10^{-2} ]</td>
</tr>
<tr>
<td>Magnus force</td>
<td>[ \vec{F}<em>M = C</em>{LR} A_p \rho_W \frac{D_p}{2} \left</td>
<td>\vec{u}_W - \vec{u}_P \right</td>
</tr>
<tr>
<td>Lift rotational force</td>
<td>[ \vec{T}_R = \frac{\rho_W}{2} \left( \frac{D_p}{2} \right)^5 C_R \left</td>
<td>\vec{\omega} \right</td>
</tr>
</tbody>
</table>
3 bioreactors with the same working volume, the same geometrical configuration and different flow rate

- 4 l/min: compact, spherical granules during whole process
- 6 l/min: floc-aggregates with substantially decreased settling ability
- 8 l/min: destroyed granules

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**
HYDRODYNAMIC SELECTION OF MICROORGANISMS

MICROSCOPIC ANALYSIS

BIG DIVERSITY OF MICROORGANISMS UNDER DIFFERENT FLOW RATES

/Zima et al. (2007)/
μPIV RESULTS

CHARACTERISTIC FLOW PATTERN
μPIV RESULTS

DIFFERENT SEEDING PARTICLES

Yeast cells 3-10 μm

Milk 0.3-3 μm
μPIV RESULTS

VELOCITY

\[ u_{\text{max}} = 0.20 \]
\[ u_{\text{max}} = 0.48 \]
\[ u_{\text{max}} = 0.86 \]
**μPIV RESULTS**

CONVECTIVE KINETIC ENERGY

One ciliate colony

- Kinetic energy $\mu W/m^3$

Colony

- Kinetic energy $\mu W/m^3$

Synergy factor 1.7

B.E. Zima-Kulisiewicz
μPIV RESULTS

NORMAL STRAIN RATE

one ciliate

colony

synergy factor 3.3

B.E. Zima-Kulisiewicz
μPIV RESULTS

SHEAR STRAIN RATE

one ciliate

colony

synergy factor 2.7
µPIV RESULTS

VELOCITY

1:1

\[ u_{max} = 0.17 \]

1:4

\[ u_{max} = 1 \]
**μPIV RESULTS**

**CONVECTIVE KINETIC ENERGY**

### 1:1

![Graph 1:1](Image)

**Kinetic energy**

- 8.00E+03
- 6.86E+03
- 5.71E+03
- 4.57E+03
- 3.43E+03
- 2.29E+03
- 1.14E+03
- 0.00E+00
- -1.14E+03
- -2.29E+03
- -3.43E+03
- -4.57E+03
- -5.71E+03
- -6.86E+03
- -8.00E+03

**μW/m³**

### 1:4

![Graph 1:4](Image)

**Kinetic energy**

- 1.23E+05
- 8.92E+04
- 5.54E+04
- 2.16E+04
- -1.21E+04
- -4.59E+04
- -7.97E+04
- -1.14E+05
- -1.47E+05
- -1.81E+05
- -2.15E+05
- -2.49E+05
- -2.82E+05
- -3.16E+05
- -3.50E+05

**μW/m³**

### Synergy factor 30
μPIV RESULTS

NORMAL STRAIN RATE

synergy factor 3.8

DIFFERENT MILK / WATER RATIO

NORMAL STRAIN RATE

1:1

1:4

nstrain rate

0.40
0.32
0.24
0.16
0.08
0.00
-0.08
-0.16
-0.24
-0.32
-0.40
-0.48
-0.56

nstrain rate

0.26
0.16
0.06
-0.03
-0.13
-0.22
-0.32
-0.42
-0.51
-0.61
-0.71
-0.80
-0.90
**μPIV RESULTS**

**SHEAR STRAIN RATE**

\[
\begin{array}{c|c|c|c|c|c|c|c}
\text{sstrain rate} & 1.20 & 1.02 & 0.83 & 0.65 & 0.47 & 0.28 & 0.10 \\
\text{1:1} & -0.08 & -0.27 & -0.45 & -0.63 & -0.82 & -1.00 \\
\text{1:4} & 0.10 & 0.24 & 0.38 & 0.52 & 0.66 & 0.80 & 0.94 & 1.08 \\
\end{array}
\]

synergy factor 5

B.E. Zima-Kulisiewicz
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