Sequencing batch reactor (SBR) as optimal method for production of granular activated sludge (GAS) – fluid dynamic investigations

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Abstract Fluid dynamic investigations of multiphase flow (fluid, air, granules) in a sequencing batch reactor (SBR) are presented. SBR can be considered as an attractive technology for cultivation of granular activated sludge (GAS). Granulation is a complicated process and its mechanism is not fully understood yet. Many factors influence the formation and structure of aerobic granular sludge in a bioreactor. Extracellular polymer substances (EPS) and superficial gas velocity (SGV) play a crucial role for granules formation. Additionally, it is supposed that EPS production is stimulated by mechanical forces. It is also assumed that hydrodynamic effects have a major influence on the formation, shape and size of GAS in SBR under aerobic conditions. However, the influence of stress on granulation is poorly investigated. Thus, in the present paper, fluid dynamic investigations of multiphase flow in a SBR, particularly effect of normal and shear strain, are reported. In order to analyse multiphase flow in the SBR, optical in-situ techniques with particle image velocimetry (PIV) and particle tracking velocimetry (PTV) are implemented. Obtained results show a characteristic flow pattern in a SBR. It is pointed out that additional effects like particle-wall collisions, inter particle collisions, erosion can also affect significantly granules formation.

Keywords Granular activated sludge; mechanical forces; particle image velocimetry; particle tracking velocimetry; sequencing batch reactor

Introduction

Aerobic granulation is a promising technique in biological purification of waste water. Nevertheless, the anaerobic technology, firstly reported in the 1980s, is currently the main process operated by hundreds of wastewater treatment plants. Although granular sludge is well documented in anaerobic system, only limited information is available concerning aerobic processes. Aerobic granulation can be described as a gradual process from suspended sludge flocs to the mature aerobic granules (McSwain et al., 2004, Tay et al., 2004). So far, nearly all aerobic granules are formed in sequencing batch reactors (SBR). GAS in comparison with conventional activated sludge (CAS) has better settleability and a higher capacity for biomass retention, which permits the easy separation of the granules from the purified water. Granules have an ellipsoidal form with a typical length up to 5 mm and density ca 1.05 g/mL. Due to these capabilities, GAS can be used in the biological purification of wastewater (Etterer and Wilderer, 2001).

Many factors influence the formation and structure of aerobic granular sludge in the SBR. Composition of the substrate and its concentration has an important impact on granules formation (Buen et al., 1999, Etterer and Wilderer, 2001). Additionally, feast-famine regime and settling time are necessary for spherical, compact granules formation (McSwain et al., 2004). Also, the superficial gas velocity (SGV) has a crucial effect for...
granulation (Tay et al., 2001a, b, De Kreuk et al., 2004). Higher SGV granules obtained spherical, more compacted structures. Different research groups investigate different air flow rates and SGV. For example, experiments of three bioreactors with the same working volume (2.0 L) and geometrical configuration (800 mm height and 60 mm diameter) are investigated by Tay et al. (2001a,b). In the cited contribution, granulation process is observed for different SGV of 0.3, 1.2 and 2.4 cm/s, equivalent to an air flow rate of 0.5, 2.0 and 4.0 L/min, respectively. Due to those investigations, no granules appear in the first case, the best results are reached with the highest SGV. It is concluded that extracellular polymer substances (EPS) play a crucial role in the formation, maintenance of the granules structure, their architecture and stability. EPS bridge the bacterial cells and hold granules together.

Consequently, it can be supposed that mechanical forces caused by particle-wall and inter-particle collisions as well as normal and tangential strains, significantly affect both granules formation and destruction. The wall collision effect may be determined by particle mass loading, particle shape and wall roughness, combination of particle and wall material or hydrodynamic interactions. Relative motion between particles is crucial for inter-particle collision. There are some factors which influence relative motion, e.g. laminar or turbulent fluid shear, particle inertia in turbulent flow (Sommerfeld, 2000). The mechanical stresses acting on granules can be divided into normal and tangential stress (Esterl et al., 2002). The shear stress acting on particles is due to relative velocity between the particles and fluid (Henzler, 2000). Although the effect of shear stress is well studied in the literature, the role of normal stress is poorly investigated. Elongation flow can influence biological material more effectively than pure shear flow (Nirschl and Delgado, 1997).

From the statements above it can be seen that aerobic granulation is a complex process and it is not fully understood what factors influence granules formation. Several researches focus on the investigation of chemical, biological, microbiological and physical aspects. Hitherto, only few information concerning hydrodynamic effects is available. Thus, in the current paper, fluid dynamic investigations of multiphase flow in a SBR with optical in situ techniques are applied.

**Methods**

**Experimental setup**

GAS is grown in a laboratory scale SBR. The SBR used in our laboratory is based on McSwains et al.’s (2004) bioreactor. Our SBR is constructed as a plexiglas tube of 90 mm diameter, 1,000 mm high, filled with 4 L of fluid. Inoculated granules come from McSwains bioreactor where they are grown from a municipal wastewater treatment plant (initial Mixed Liquor Suspended Solids 2.5 gL⁻¹). SBR is fed with synthetic wastewater with glucose, peptone as a carbon source and nutrients. Influent is dosed on the top of bioreactor and the effluent is extracted from the half of fluid part height. Bioreactor walls are cleaned every week, biofilm growth is discarded every day (McSwain et al., 2004). The wasted volume is:

\[ V_{w/day} = \frac{V_r}{t}, \]

where \( V_r \) indicates reactor volume and \( t \) is sludge residence time (SRT). After 40 days of bioreactor operation, \( V_{w/day} \) amounts to 100 mL wasted/day.

The round shape of the bioreactor is proper for practical purposes in waste water cleaning but unsuitable for optical investigations due to light reflection effects. In order to improve optical accessibility of the SBR interior, the bioreactor is surrounded by a
plexiglas cuboid, in which the gap between bioreactor and rectangular prism is filled with water. Figure 1 shows the experimental setup.

The total cycle time is 6 h (four cycles per day). The whole process is controlled automatically. Every cycle consists of five steps. At the beginning, 10 min feeding of 2 L synthetic wastewater food takes place. Later, aeration comes, which is the longest part of the cycle. This step lasts 320 min and optical experiments presented here concern only this period. At this stage, interactions between granules, air and fluid appear. Aeration comes from the bottom of the SBR. A characteristic air flow rate of 4 L/min (McSwain et al., 2004) enables successful granulation in our system. Later, 2 min is destined for settling. When this step is over, 7 min of drawing of 2 L effluent follows. Idling (the last part of the cycle) takes 21 min.

In order to observe granules behaviour under different flow mechanical conditions, another two bioreactors with the same working volume and geometrical configuration, but higher flow rates of 6 and 8 L/min, are investigated recently.

**In situ techniques**

Optical *in situ* methods enable analysis of multiphase flow (water, air, granules) in an SBR. As a light sources He−Ne Laser and video lamp are applied. Two various optical systems are situated in different positions in the SBR. The plane of He−Ne laser is set perpendicular to the image plane. In the second case, with video lamp measurements, light is situated ahead of the bioreactor, parallel to the CCD camera. In the present experiments, high speed CCD camera (MIKROTRON GmbH), placed in the front of bioreactor is employed to acquire pictures. Figure 2 shows optical *in situ* system with He−Ne Laser.

Tracer particles are employed to visualise the fluid flow pattern. For experiments with He−Ne Laser hollow glass spheres with density 1.1 g/cm³ and diameter of 2–20 μm are applied. Because of the complexity of the three phase flow, local character of flow pattern, in order to improve investigations with He−Ne Laser, tests with different interval from the SBR wall (0.5, 0.8 and 1.0 cm) and higher vertical coordinate ranges are implemented, recently. For studies with the video lamp, granules themselves serve as trace objects for flow pattern visualisation. Velocity distribution of the liquid phase in the bioreactor is determined by use of the PIV method. PTV is implemented to observe velocity field of individual granules (solid phase).

The recorded images are analysed with the help of two different programs: PIVview2C (PIVTEC GmbH), developed by Raffel et al. (1998) and implemented
for calculation of velocities of continuous phase, velocity distribution of dispersed phase is computed by using OPTIMAS (Media Cybernetics, L. P.). For both cases, cross-correlation mode is used. Analysed images have a resolution of 860 × 1024 pixels, the interrogation window size is chosen as 32 × 32 pixels, the grid size as 16 × 16 pixels. Obtained velocity data from PIVview2C and OPTIMAS are further processed with the help of TECPLOT (Amtec Engineering).

The full velocity gradient tensor or deformation tensor \( \frac{d\mathbf{U}}{d\mathbf{X}} \) is given by:

\[
\frac{d\mathbf{U}}{d\mathbf{X}} = \begin{bmatrix}
\frac{\partial U}{\partial X} & \frac{\partial V}{\partial X} \\
\frac{\partial U}{\partial Y} & \frac{\partial V}{\partial Y}
\end{bmatrix} + \begin{bmatrix}
0 & \frac{1}{2} (\frac{\partial U}{\partial X} - \frac{\partial V}{\partial Y}) \\
\frac{1}{2} (\frac{\partial U}{\partial Y} + \frac{\partial V}{\partial X}) & 0
\end{bmatrix}
\]

is determined within the present study for 2D system (Raffel et al., 1998). The deformation tensor can be divided into symmetric and asymmetric part, where \( U, V \) means velocity components, \( X, Y \) – flow field coordinate system.

It must be mentioned that all results are shown in a non–dimensional way. Fluid and solid velocities (\( u_w, u_G \)) are calculated as a ratio of liquid or solid velocity and SGV. SGV (\( u_{ref} \)) amounts to 1.05 (cm/s). Normal and shear strain are normalised as a ratio of strain rate and experimentally obtained maximum strain rate (\( \dot{\varepsilon} = 15\, s^{-1}, \dot{\gamma} = 15\, s^{-1} \)).

The X axis is presented as a ratio of experimental position in horizontal direction to bioreactor diameter (D), the Y axis, as a ratio of vertical SBR coordinate to maximum liquid level (\( H_{max} \)).

Results and discussion
Analysed PTV results show that with increasing SBR vertical coordinate granules velocity decreases (see Figure 3). Close to the bottom average dimensionless granules velocity reaches values \( u_G = 9.6 \), in the upper part \( u_G = 7.3 \).

In turn, fluid velocity, calculated with help of PIV, is higher with increasing vertical coordinate. Furthermore, comparing all video lamp results, characteristic flow pattern in SBR can be recognised (see Figure 4). On the bottom, a large vortex exists. With increasing vertical coordinates smaller eddies appear. Moreover, examined results show transient flow, e.g. in the first subdomain after 0.5 s of experimental time, analysed flow has significantly different structure in comparison to initial conditions. Also, the range of velocity distribution as well as normal and shear strain rate have different values in those cases, at the beginning velocity varies between 0.74 and 11.43, normal strain \(-13.4 \) and \(-13.8 \), shear strain \(-1.01 \) and \(-1.28 \) after 0.5 s velocity range changes between 0.95 and 15.2, afterwards normal strain between \(-1.43 \) and 1.8, shear strain \(-1.1 \) and 1.2.
As written in the introduction, shear strain rate as well as normal strain rate seem to have a significant influence on granules structure. As shown in Figure 4, the elongation rate obtained with the help of the PIVview2C program reaches a relatively high value, up to $\dot{\varepsilon} = 1$ or even higher in some cases. The brightest field marks the highest value. Analysing above results, it is observed that a higher normal strain rate occurs in the upper part. Taking into consideration investigations carried out by Höfer et al. (2004) with CAS where significant elongation of the flocs appears at $\dot{\varepsilon} = 0.2$, it can be concluded that strain rates observed in the present study substantially affect the granulation process.

Detailed analysis of the flow pattern by using He–Ne laser shows a similar tendency as with video lamp experiments, fluid velocity increases with higher vertical coordinates. It is particularly observed in the first SBR part, $Y/H_{\text{max}}$ up to 0.51. Because of non-stationary flow characters, this tendency is not stable. Additionally, velocity is higher with increasing distance from the SBR wall, for 1.0 cm it is higher ($u_W = 0.13$, $X/D = 0.44$, $Y/H_{\text{max}} = 0.28$) than for 0.5 ($u_W = 0.05$, $X/D = 0.56$, $Y/H_{\text{max}} = 0.09$). Similar recognitions are made for normal and shear strain rate. Figure 5 presents results for shear strain rate.

The left image presents results close to the SBR wall (distance 0.5 cm), in the lowest bioreactor subdomain for $Y/H_{\text{max}}$ up to 0.14. The right one depicts data for wall interval 1.0 cm and higher vertical coordinate ($Y/H_{\text{max}}$ amounts from 0.25 up to 0.37). As in previous investigations, the brightest fields mark the highest value of the shear strain. More light parts are present in the second case, for higher vertical coordinate and larger distance from the SBR wall, where $\dot{\gamma}$ is up to 1.7.

The fluid dynamical strain rate which acts on granules is associated with relative velocity between fluid and granules. Because of the difficulties in calculations of relative velocity by using experimental data, numerical simulation with Euler–Euler model is carried out. As shown in Figure 6, relative velocity between granules ($u_G$) and fluid ($u_W$), calculated in a non-dimensional way, changes with increasing process time. At the beginning (because of $\bar{u} = 0$ for initial conditions) the highest value is seen, with duration time relative velocity decreases. The highest values ($u_G - u_W = 3$) are observed in the middle...
Figure 4 Normal strain and velocity distribution in different bioreactor subdomains
part of SBR through the whole observation time. Thus, the relative velocity can be seen as a function of time and place in SBR.

As discussed previously, in order to observe granules behaviour under different flow mechanical conditions, another two bioreactors with higher air flow rate are operated. Comparing all SBR processes, different granules behaviour can be observed. An air flow rate of 4 L/min induces the best conditions for granulation process, here granules are spherical and compact. For investigations carried out with 6 and 8 L/min, inoculated granules from 4 L/min are given as initial GAS. At the beginning of the process, granulation takes place but with increasing process time the situation is changed. For 6 L/min, granules are destroyed and split into floc-aggregates with substantially decreased settleability. In the third case (8 L/min), with increasing process time the granulation process does not take place. After around 2 weeks, fluffy flocs appear with very long settling time. It can be supposed that, additionally to biochemical phenomena, fatigue effects take place. According to Esterl et al. (2002), the influence of mechanical forces not only depends on their magnitude but also on the time period.
Conclusion

Aerobic granulation is a multi-aspect process, thus scientific investigations with different points of view are carried out and presented in the literature, e.g. Buen et al. (1999), Etterer and Wilderer (2001), De Kreuk et al. (2004), McSwain et al. (2004). In the present paper, fluid dynamic considerations are used for better understanding of granules formation. Experimental results show a characteristic flow pattern in an SBR during aeration phase. On the bottom, a large vortex exists, in the upper bioreactor part smaller eddies appear. Mechanical forces seem to substantially affect granules formation and destruction. Relative velocity, as well as fluid dynamical stresses, acts on GAS. Moreover, stresses depend on relative velocity which is temporal and place function. The experimental and numerical results show clearly functional dependency on time and place in SBR. Computed tangential and normal strain amounts up to a dimensionless value of 1. The latter seems to be a significant factor influencing granulation. It is shown that with an increasing vertical coordinate, fluid velocity as well as strain rate increases. Furthermore, those parameters are lower close to the bioreactor wall. Apparently, different process parameters (e.g. air flow rate) inducing specific flow mechanical conditions influence granulation process. It must be mentioned that mechanical effects like inter–particle collisions, wall–particle collisions, erosion, which are not studied in the present contribution, are supposed to also have an important impact on the granulation.

References


