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OPTICAL IN-SITU TECHNIQUES FOR INVESTIGATIONS OF A MULTIPHASE FLOW IN SEQUENCING BATCH REACTOR

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PIV, PTV, LDA, µ-PIV, multiphase flow, GAS, SBR

Abstract

The novel wastewater treatment basing on Granular Activated Sludge (GAS) presents several advantages in comparison to Conventional Activated Sludge (CAS). The compacter, bigger and denser aerobic aggregates show better settling ability and higher biomass retention than CAS. Nowadays, the complex granulation process is not well understood. Many investigations of this phenomenon have been carried out from the bio-chemical point of view. However, there is a lack of deep analysis of the fluid mechanical effect on the formation, characteristics and destruction of the granules. In order to understand the complexity of multiphase flow in SBR optical insitu techniques in macro scale with Particle Image Velocimetry (PIV), Particle Tracking Velocimetry (PTV) and Laser Doppler Anemometry (LDA) are implemented. Moreover, PIV investigations in micro scale (µ-PIV) are carried out to determine flow induced by *Opercularia Asymmetrica* settling on the GAS surface.

Introduction

The wastewater treatment by means of Granular Activated Sludge (GAS) is a new promising technique which presents many advantages in comparison to Conventional Activated Sludge (CAS). The GAS has better settling ability than CAS due to denser and compacter structure, higher diameter up to 5 mm and density of 1.05 g/ml. These properties lead to higher biomass retention, faster degradation of pollutants as well as compact reactor dimension. Although nowadays the majority of wastewater treatment plants are operated under anaerobic regime, aerobic granulation becomes the novel technology which overcomes many disadvantages of CAS processes (Etterer & Wilderer 2001, McSwain et al., 2004a).

According to Weber et al. (2006) the development of the aerobic microbial aggregates can be described as a three phase process. In the first one, ciliates are attached to other microorganisms or particles. In consequence the bulky growth of them is followed by bacterial colonization. During the second phase granula grows and core zone is developed. Moreover, a lot of ciliates die due to overgrown by bacteria. Finally, the mature granule is achieved with two differentiated zones, i.e. the core zone and the loose structured fringe zone which serves as substrate for swarming ciliates.

The first aerobic studies were done by Mishima and Nakamura (Mishima&Nakamura, 1991) in a continuous aerobic upflow sludge blanket reactor in 1991. The Sequencing Batch Reactor (SBR) can be treated as the optimal technology for the cultivation of GAS (McSwain et al., 2004b). Up to now almost all aerobic bioreactors have been operated in laboratory scale SBR. The first investigations of a pilot aerobic wastewater treatment plant with 5m^3/h hydraulic capacity are carried out by De Bruin (De Bruin et al., 2005).

A granulation process remains still not completely understood in many aspects. De Kreuk et al. (2005b) show the crucial effect of substrate type as well as organic and nitrogen loads in granula formation. Moreover, feast-famine regimes with pulse feeding are necessary for a compacted granula formation (McSwain et al., 2004a). Additionally, the architecture and stability of the granules is influenced by the production of Extracellular Polymer Substances (EPS). Those substances are able to change the negative charge of bacterial surfaces and bridge the neighbouring cells in biofilm. Their production can be simulated by the hydrodynamic shear forces. Another factor which should be taken into account in the production of GAS is the Superficial Gas Velocity (SGV). Tay et al. (2001) conclude that granulation is only achievable under specific conditions of SGV, not lower than 1.2 cms^{-1}, inducing mechanical stress in the aggregates.

It should not be forgotten that mechanical forces due to particle-wall and particle-particle collisions influence significantly the formation and destruction of the granules. Thus, the shear stresses acting on the granules are caused by the relative velocity between particles and fluid (Henzler, 2000), interparticle interactions as well as collisions of bare carrier with biofilm (Gjaltema et al., 1997, De Kreuk et al., 2005a). Additionally, it is well known that the granulation process depends not only on the tangential stress but even more on the elongational load (Nirschl & Delgado, 1997, Zima et al., 2007).

Currently, there is a lack of deep analysis of the hydrodynamic effects on granulation process. The understanding of such sophisticated fluid dynamical phenomenon implies the employment of experimental techniques which results contribute to the deeper analysis of the multiphase flow in the bioreactor. In this paper, optical in-situ techniques are applied to the study of a laboratory scale SBR. The implementation of Particle Image Velocimetry (PIV), micro Particle Image Velocimetry (µ-PIV), Particle Tracking Velocimetry (PTV) and Laser Doppler Anemometry (LDA) enables obtaining of valuable information about the velocity fields and the turbulent regime in the reactor.

Experimental Setup

Our laboratory scale SBR is based on the work of McSwain et al. (2004a). It consists of a plexiglas cylinder of 1m height and 9 cm internal diameter, filled with 4 l of fluid. The inoculated granules from McSwains's are transferred to our SBR. Here granules formation takes place under appropriate flow rate (4 l/min).

Every SBR cycle consists of five different phases, i. e. fill, react, settle, draw and idle. During 10 minutes of filling time, 2 l of synthetic wastewater, composed of glucose, peptone and nutrients are transferred to the reactor. Later, SBR is aerated for a period of 320 minutes. Because it is the longest phase and mostly interactions between the fluid, granules and air takes place during this stage it is the subject of the study. Later, after two minutes of settling time, 2 l are extracted by an effluent pump. The cycle is finished with an idle period of 21 minutes. The reactor is controlled automatically, being operated four cycles per day.

In order to avoid the light reflection effects, the round shaped SBR is submerged in a cuboid of plexiglas filled with water. The SBR system is displayed in Fig. 1.

Optical Insitu Techniques

Multiphase flow visualization in SBR is enabled by implementing optical insitu techniques. Because of the complexity of the examined flow, fluid and solid phase is analyzed separately. Due to the local character of flow pattern investigations are carried out in several subdomains of the SBR. The visualization of the velocity distribution of the continuous liquid phase is performed by Particle Image Velocimetry (PIV). In the case of the solid phase, Particle Tracking Velocimetry (PTV) is selected as the optimal technique. As light source, a He - Ne Laser and video lamp are implemented. The He - Ne Laser is placed perpendicularly to the optical axis of the CCD camera (see Fig. 2). The video lamp is set parallel to the CCD camera. In both cases, a high speed CCD camera (MIKROTRON GmbH) with a maximum speed of 520 frames/sec and macro zoom objective, situated in front of the SBR records pictures. The obtained frames are directly transferred to PC.

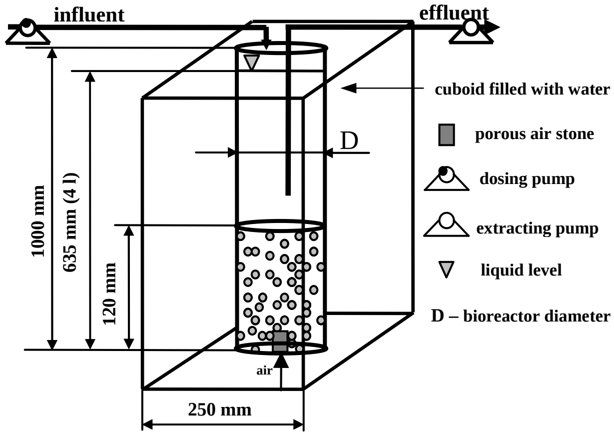


Fig. 1: Experimental Setup

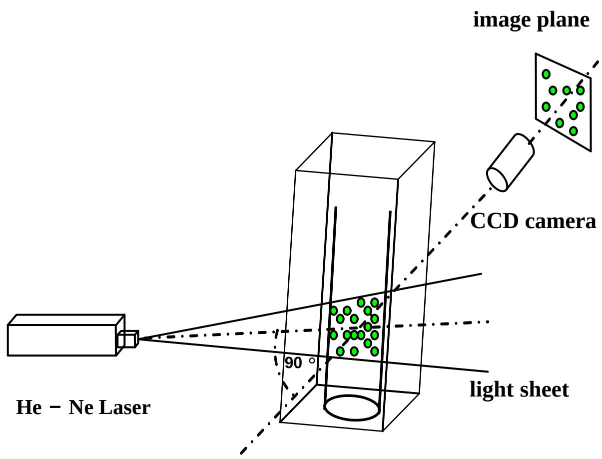


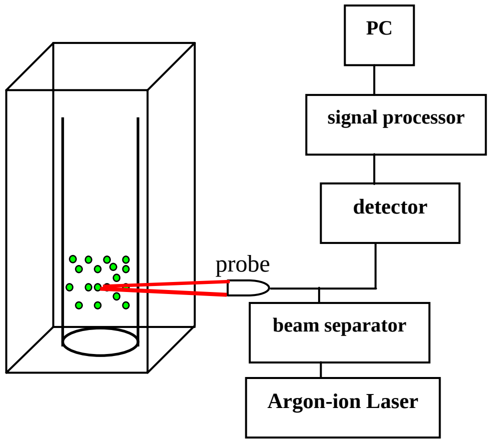
Fig.2: Optical system with He – Ne Laser

Hollow glass spheres with diameter of 2 - 20 µm and density 1.1 g/cm^3 (DANTEC DYNAMICS) are employed as tracer particles for PIV. The experiments with He – Ne Laser are performed with different interval from SBR wall (0.5, 0.8 and 1.0 cm). The granules themselves are employed as tracers in the investigations with the video lamp.

The software for the analysis of continuous phase is PIVview2C (PIVTEC GmbH), developed by Raffel et al. (1998). In order to increase the data yield by higher amount of matched particles and reduce the bias error, the multiple pass interrogation algorithm is implemented (Westerweel et al., 1997). The resolution of the images is 860x1024 pixels, the interrogation window size 32x32 pixels and the grid size 16x16 pixels. Sub-pixel displacement of the correlation peak is calculated selecting the four closest neighbours of a correlation maximum and fitting a 3-point Gaussian curve each of the major axis, by means of the 3-Point Gauss Fit (Willert & Gharib, 1991). In the case of PTV investigations OPTIMAS (Media Cybernetics, L. P.) is implemented. The displacement of marked granules is determined manually from the comparison of two consecutive in time images. PIV and PTV data velocities are further processed with TECPLOT (Amtec Engineering).

The analysis of turbulence in the bioreactor is carried out by Laser Doppler Anemometry (LDA) system (TSI). It consists of an Argon-ion Laser (300 mW) and a colorburst multicolour beam separator Model 9201. The light is transmitted through a fiber optic cable and probe. Following, the same probe detects the scattered light. Finally, the data are processed by a signal processor and sent to a PC (see Fig. 3). One component LDA is operated in backscattered mode. As seeding particles hollow glass spheres (DANTEC DYNAMICS) are employed. LDA investigations are operated under 2, 3 and 4 l/min for two (water and air) and three (water, air and granules) phase flow. Measurement points are chosen at 3 mm steps. Moreover, studies are performed at different vertical coordinates Y/H_{max} (0.32, 0.44, 0.65).

The turbulence power spectra analysis is accomplished by the implementation of the novel Slot Correlation (SC) algorithm (Nobach et al., 1998, Benedict et al., 2000, Gjelstrup et al., 2000, Nobach, 2000) which enables the achievement of turbulence spectra even at low data rates. The autocorrelation function (ACF) is estimated from the flow velocity fluctuations. The power spectral density (PSD) is obtained from the Fourier transformation of ACF.



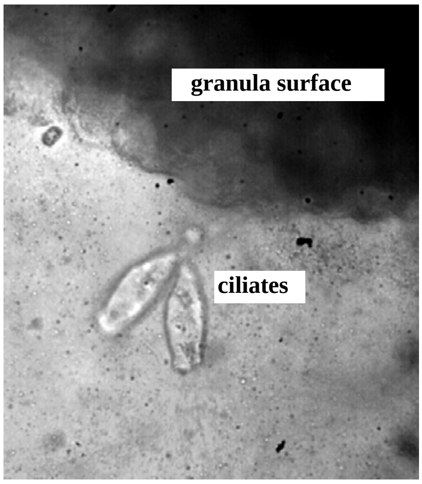


Fig. 3: LDA system **Fig. 4: Ciliates on granula surface**

Granulation process is multiscale phenomena. Thus, investigations in micro scale should be also considered. The surface of GAS aggregates is covered by sessile protozoa *Opercularia Asymmetrica* (see Fig. 4) which generate micro flow fields, influencing the granula formation. In order to analyse the velocity field created by *Opercularia Asymmetrica*, micro Particle Image Velocimetry (µ-PIV) investigations are performed. An Axiotech 100 (Carl Zeiss) microscope with 20- and 50-fold optical magnification is employed. Microscopic illumination is applied as a light source. Measurements in microorganismic flows are strongly influenced by the biocompatibility of the employed technique (Kowalczyk et al., 2007, Petermeier et al., 2006, Hartmann et al., 2007). Therefore, yeast cells (*Saccharomyces cerevisiae*) of about 3-10 µm and milk being emulsion with scattering particles (fat and proteins) of 0.3-3 µm are employed as biotracers. The high speed camera as well as resolution, software and algorithms are the same as in PIV. Unlike previous, the selected grid size amounts 20x20 pixels in this case.

Results and Discussion

All presented results are expressed in non-dimensional way. The ratio of experimental horizontal position X to reactor diameter D (9 cm) defines X axis. Y axis is determined as vertical experimental position Y and maximum liquid level in SBR (63 cm). Velocity of dispersed phase (u_G) or continuous phase velocity (u_W) and its horizontal and vertical components (U and V) are expressed as a ratio of solid, liquid velocity, liquid velocity components and SGV (1.05 cm/s). The normal and shear strains are computed as ratio of strain rates and experimentally obtained maximum normal and tangential strain rates of $\dot{\varepsilon} = 15\ s^{-1}$ and $\dot{\gamma} = 15\ s^{-1}$, respectively.

PIV as well as PTV results show characteristic flow pattern in the SBR. On the bottom huge torus vortex appears, with increasing vertical coordinates smaller eddies exist (see also Zima et al., 2007).

Taking into account PTV results, the velocity distribution of dispersed phase (granules) decreases with increasing vertical coordinates (see Figure 5). The average granules velocity in the lower subdomain of the bioreactor amounts $u_G = 9.6$. In the higher SBR part the average solid velocity equals $u_G = 7.3$.

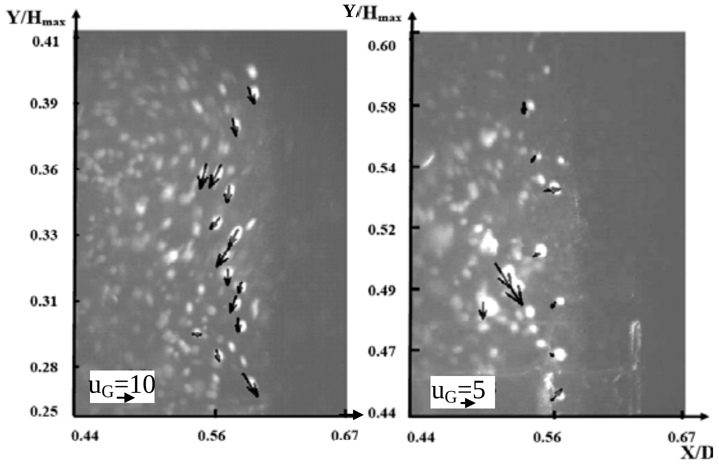


Fig. 5 Dimensionless velocity distribution of granules

In contrary, liquid velocity increases with higher vertical coordinate. For example in the lower SBR subdomain for Y/H_{max} = 0.12 and X/D = 0.56 the dimensionless velocity amounts u_W = 3.4 and u_W = 5.7 for Y/H_{max} = 0.19 and X/D = 0.50. While, in the higher vertical coordinate Y/H_{max} = 0.37, X/D = 0.40, Y/H_{max} = 0.43, X/D = 0.67 and Y/H_{max} = 0.56, X/D = 0.56 following liquid velocities of u_W = 7.6, u_W = 9.5 and u_W = 12.4 are observed.

The investigations with video lamp presents that the normal as well as shear strain rate have a crucial influence on granules formation and destruction. The dimensionless elongation rate reaches relatively high values of $\dot{\varepsilon}$ = 1. Like in the case of the velocity distribution the normal strain increases with higher vertical coordinates. Höfer et al. (2004) report that substantial elongation of the CAS flocs already appears at $\dot{\varepsilon}$ = 0.2. In comparison to those results it can be stated that the normal strain rate observed in the present study influence significantly granulation process.

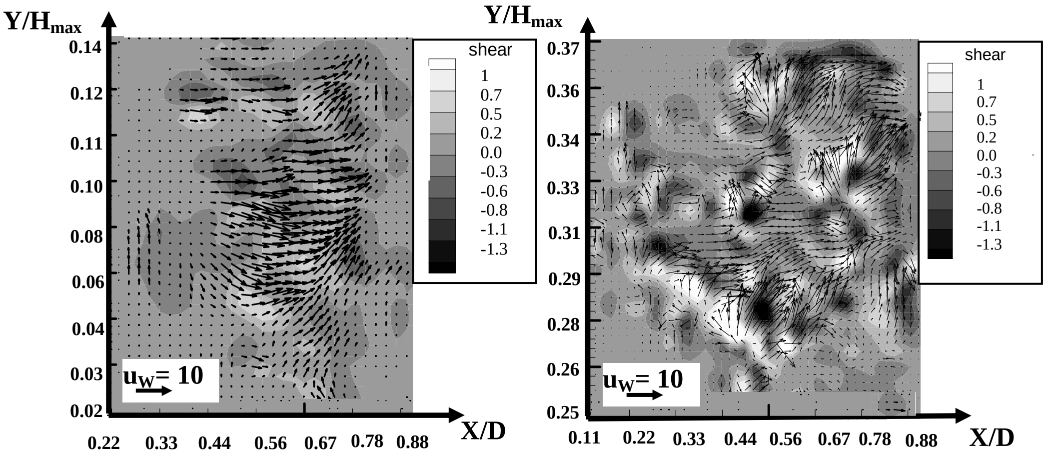


Fig. 6 Dimensionless shear strain and velocity distribution in different vertical coordinates

Additionally, obtained PIV results with He – Ne Laser present similar situation to that with video lamp. It is clearly seen that the fluid velocity as well as strains increase with higher vertical coordinate, especially in the lower SBR subdomain up to Y/H_{max} = 0.51. Moreover, detailed experimental analysis with different distance from the wall shows that the velocity distributions as well as the strains are higher far from the wall. Figure 6 depicts two different situations: left - first experimental subdomain (Y/H_{max} up to 0.14), close to the wall (wall interval of 0.5 cm), right - higher vertical coordinate (up to Y/H_{max} = 0.37) and higher wall distance (1 cm).

Taking into account LDA results increasing tendency of liquid velocity with higher vertical coordinates (for both cases two and three phase flow) is observed. Moreover, the liquid velocity slightly increases with bigger distance from SBR wall. As expected, the liquid velocity in the two phase flow is higher than in the three phase one. It indicates big influence of granules on flow pattern. First estimation of turbulence power spectra for two and three phase flow show that Kolmogorov -5/3 law is not obeyed. Obtained spectra show laminar character of analysed flow. Figure 7 shows typical three phase flow power spectral density (PSD) for two vertical coordinates, i.e. Y/H_{max}=0.32 and Y/H_{max}=0.65.

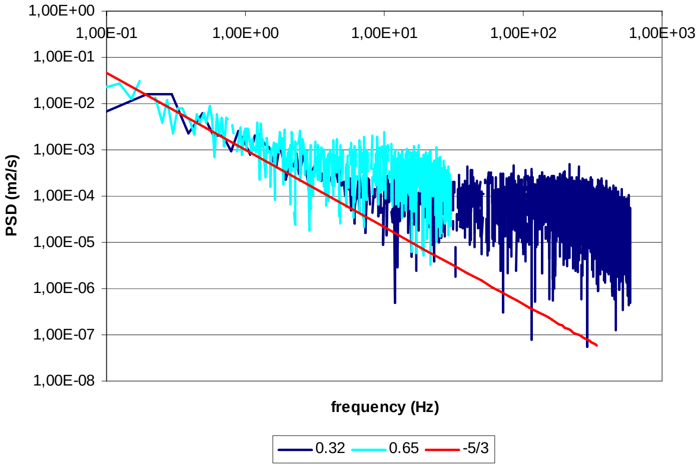


Fig. 7 Turbulent power spectra for different vertical coordinates under 4 l/min

µPIV results present a characteristic micro flow pattern with two vortices generated by cilia beats. More detailed flow visualization is possible for higher optical magnification and milk as tracer particles. Thus, analysed data are presented for 50 fold optical magnification. Analysing all results it is seen that the fluid velocity amounts up to 45 µm/s, whereby the highest velocity is observed in the zooid vicinity. Figure 8 depicts analysed situation for one ciliate as well as for colony. In both cases characteristic two vortices can be observed.

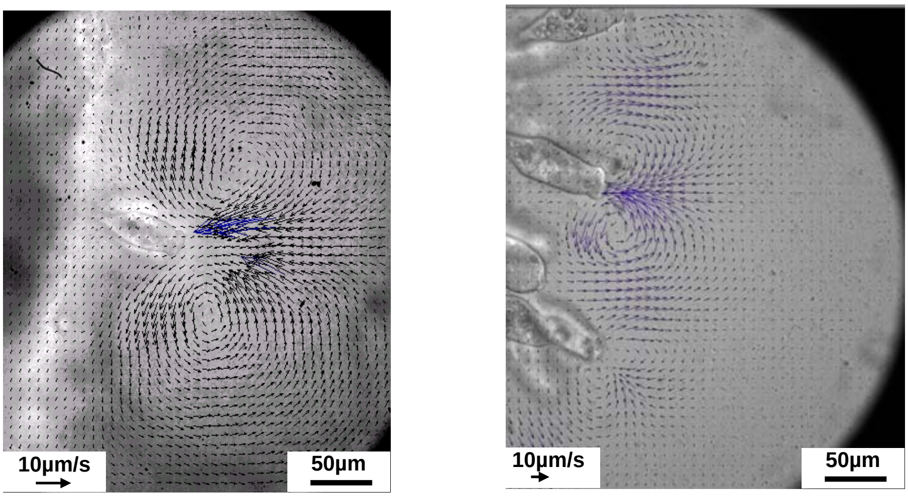


Fig. 8 Characteristic flow pattern generated by one ciliate (left side) and colony (right side) observed at 50 fold magnification

Previous works by Hartmann et al. (2007), Kowalczyk et al. (2007), Petermeier et al. (2007), show that flow induced by ciliates is treated as efficient way for nutrient transport to the biofilm by minimum energy requirement. From above statements it can be supposed that flow generated by ciliates living on granules surface plays an important role for granules formation. Due to this characteristic motion, flocs and microorganisms are kept together and as a result compacted GAS appears. Moreover µPIV studies depict effective, cooperative ciliates transport. As can be concluded from Figure 9 ciliates living in colony produce more kinetic energy per single organism than the living alone ciliate. The synergy factor amounts approximately 1.7.

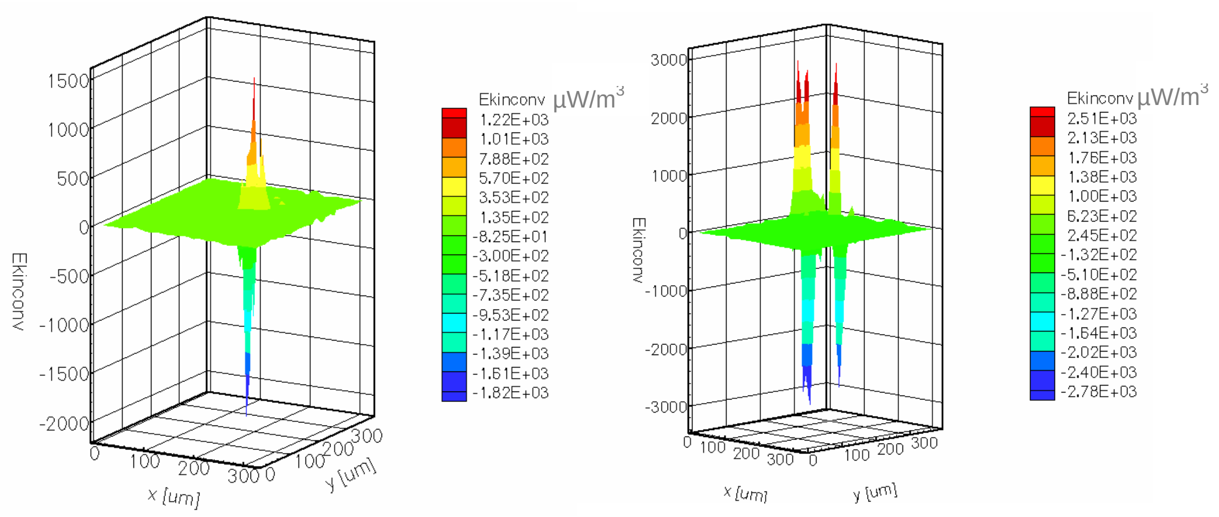


Fig. 9 Kinetic energy for one ciliate (left part) and colony (right part) at 50 fold optical magnification

Conslusion

Reassuming above studies it must be said that aerobic granulation is complex, multiscale phenomena. Presented results play a crucial role for better understanding of this process. Due to PIV investigations in macro scale characteristic flow pattern in the bioreactor is recognized. Moreover, liquid velocity increases with higher vertical coordinate. The same tendency appears for normal and shear strain rate. Obtained results depict that normal and shear strain rates affect significantly granules formation. The dimensionless strain rates reach values of $\dot{\varepsilon} = 1$, $\dot{\gamma} = 1$. On the contrary, velocity distribution of dispersed phase decreases with increasing vertical coordinate.

µPIV results present characteristic flow pattern induced by ciliates which significant influences the granules development. Furthermore, by ciliates living in colonies an energetic synergy effect of 1.7 is observed.

LDA data confirms liquid velocity tendency obtained by PIV. Additionally, LDA measurements show big influence of third phase (granules) on flow pattern. First estimation of turbulence power spectra presents laminar character of analyzed flow.

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