DESIGN STUDY OF AN AEROBIC GRANULAR SLUDGE BIOREACTOR USING CFD

Corina BONCESCU[1], Adriana MIERLOIU[2], Diana ROBESCU[3]

Aerobic granular sludge technology has become very attractive for wastewater treatment because a lower footprint of bioreactor and important energy savings comparing with conventional biological treatment of wastewater. This technology is applied at full-scale only in sequential batch reactor (SBR) configuration. Using continuous flow bioreactor for AGS technology seems to be more convenient for upgrading existing wastewater treatment plant (WWTP) with conventional biological treatment. This paper presents a theoretical simulation study conducted using computational fluid dynamics technique (CFD) for the simulation domain consisting of the bioreactor and area for recycling of granules in order to identify the optimal geometry of an experimental installation. Turbulent k-epsilon 2D and 3D mixture model in FLUENT are considered. The flow in the domain of study is simulated in two situations: water and air-water mixture.

Keywords: AGS, FLUENT, SBR, wastewater treatment

1. Introduction

In recent years, aerobic granular sludge technology (AGS) has begun to grow and have proven to be very promising in the field of biological wastewater treatment. Biogranulation is based on the ability of bacteria to attach to one another, forming self-immobilized cells embedded in a matrix of extracellular polymeric substances. This technology is applied for wastewater treatment in anaerobic and aerobic environment. Anaerobic granular sludge can be observed in upflow anaerobic sludge blanket (UASB) type reactor [1]. Aerobic granular sludge technology (AGS) is an innovative efficient technology on wastewater treatment with extensive researches over past years. The first definition of aerobic granule, as aggregates of microbial origin, which do not coagulate under reduced hydrodynamic shear, and which settle significantly faster than activated sludge flocs, was established at the 1st International Water Association Workshop on Aerobic Granular Sludge that was held at Technical University of Munich, Germany in 2004 [2].

[1] Lecturer, eng., Dept. of Hydraulics, Hydraulic Machinery and Environmental Engineering, University POLITEHNICA of Bucharest, Romania, e-mail: corina.boncescu@gmail.com
[2] PhD Student, Dept. of Hydraulics, Hydraulic Machinery and Environmental Engineering, University POLITEHNICA of Bucharest, Romania, e-mail: e-mail: mierloiu.adriana@gmail.com
[3] Prof., Dept. of Hydraulics, Hydraulic Machinery and Environmental Engineering, University POLITEHNICA of Bucharest, Romania, e-mail: diana.robescu@upb.ro

Depending on the properties of the wastewater, several biological treatment technologies have been identified. The most used is biological treatment with continuous activated sludge used for domestic wastewater treatment. For waters with a high concentration of BOD_5, a fluidized-bed bioreactor is used because it has a proven efficiency in such situations. One of the latest technologies is the membrane bioreactor (MBR) where the secondary decanter is replaced with a polymeric membrane based on microfiltration or ultrafiltration units. This technology can reduce the concentration of BOD_5 up to 10 mg / l. The biofilter has the advantage of using biologic plastic filters that allow the growth of the microorganisms' development area necessary for the degradation of organic matter [3].

The aerobic granulation process is usually completed in sequencing batch reactors (SBR) with a well-structured cycle configuration. It is considered that ideal conditions for aerobic granulation such as the succession of hydraulic selection pressure and hydraulic shear forces appear or can be easily controlled in SBRs [4]. Research on granular sludge technology compared to traditional activated sludge processes (with and without the removal of biological phosphorus), an integrated activated sludge filtration process and a membrane bioreactor have shown to have a less carbon footprint by 40-50% and lower energy requirement by 23% [5]. It has also been observed that complete removal of organic substances and nitrogen can be achieved in SBR based on single granule with high efficiency and stable performance [6]. According to Pishgar, 2016, 0.1 g/l anaerobic granular sludge led to the elimination of 80-94% of the chemical oxygen demand (COD) (1000 mg / l in 7-8 days) for water pH = 6.7 -7.6 and temperature 15^oC . In aerobic conditions for the same amount of organic matter a 91% removal (1000 mg / l in 3-4 days) was obtained. However, supplemental nutrients should be provided concomitantly with aeration to encourage aerobic growth. Aerobic activity in granular sludge was optimized at ammonium nitrogen (NH4-N) concentration of 130 mg / l and a phosphate (PO4-P) concentration of 8 mg / l, corresponding to the COD / N / P ratio of 100/ 1 / 0.8 [7].

In this process granular sludge replaces the active sludge from the conventional biological treatment. Granular aerobic sludge is a microbial community that allows simultaneous removal of nitrogen, phosphorus, carbon and other pollutants into a single sludge system. It is a type of sludge that can self-immobilize flocs and microorganisms into spherical and compact structures from microns to maximum 2.5 cm [8-9]. The most recent investigators have shown that the size of the granules between 0.6-1.2 mm has led to an increase in nitrogen removal efficiency, with a specific oxygen absorption rate for the amorphous oxidative bacteria of 25.93 mg O_2 / g MLVSS / h) [10]. Granular aerobic sludge has many advantages overactive sludge. One of these is good sedimentation capacity (sludge volume index (SVI) <50 mL/g), high biomass retention (up to 20 g_{SSL}^{-1}). In 2012, the grain stability coefficient (S), representing the ratio of the total dry weight of the granules to the total dry weight of the decanted material, was introduced. This indicator describes their resistance to contact with wastewater and helps to classify the granules into three levels of resistance, ie very strong (very stable), strong (stable) and weak (not stable). The results showed that the aerobic granules were stronger (high solid density > 150 g $_{T\,SSL}^{-1}$) [11].

For its cultivation, activated sludge is introduced into the reactors and operates in SBR mode with bubble aeration and short stabilization times [12]. Numerous studies have been carried out in the field of aerobic granular sludge treatment to remove recalcitrant pollutants such as phenol and nitrobenzene [13]. One of the key factors leading to a stable granular sludge in SBR could be the cultivation of beneficial microorganisms such as glycogen or phosphate accumulating organisms [14]. Based on the research and the mathematical modelling analysis of aerobic granular sludge, it has been shown that it can provide an attractive alternative for biological wastewater treatment. Although existing technologies are still limited, they are expected to evolve due to their purification capacity, being considered an environmental advantage [15].

One of the main disadvantages of the treatment of activated sludge water is that it requires a large area of formation and sedimentation [16]. Thus, great emphasis has been put on technologies based on aerobic granular sludge. Over the last decade, this technology has been developed at the laboratory level until the pilot station stage [17]. Granules are large suspended biofilms of regular shape and dense and layered structure with advantageous qualities compared to flocculation sludges, among which: high sedimentation rate, high biomass retention capable of withstanding high waste water and shock loads, improved dehydration, simultaneous removal of nitrogen and phosphorus, tolerance to high toxicity [18-19]. These advantages have led the granular sludge reactor to be considered one of the most prosperous biological wastewater treatment technologies. Research shows that they have a much higher return when experiments are done in a controlled environment: time-controlled velocity, regular sludge discharge, continuous and uniform hydraulic shear force [20].

Numerous investigations have been made over time to improve the treatment process with granular sludge. The sludge retention time has been studied and whether this is a decisive factor for aerobic granulation in SBR. They thus concluded that in order to investigate the retention time on aerobic granules in the SBR, it is necessary to avoid the interference of the hydraulic pressure. It has been observed that aerobic granulation is little dependent on retention time [21]. Another important parameter that has been studied is the temperature. It has been noted that at low temperatures there is process instability due to the abusive growth of filamentous microorganisms, thus affecting microbial metabolism and community structures [22]. AGS technologies to have high performance at low temperatures require the use of cold-adapted biomass as inoculums [23].

The size of the particles and how they influence the purification process has been studied by several authors. Grain size has been shown to be a key parameter in the nitrification / denitrification process. Research has shown that small granules reduce the accumulation of nitrite by the presence of nitrite oxidizing bacteria (NOB) [24], and large granules tend to inhibit the use of nutrients and oxygen inside granules due to mass transfer limitation [25]. The studies noted that the granules remained stable due to variations in the operating conditions, the breakage of the granules being negligible [26].

In this paper are presented simulations using CFD, for the study of AGS technology in continuous flow for an experimental installation made by National Institute for Research and Development in Industrial Ecology - ECOIND, Bucharest, Romania. Following experimental research has been identified the main problem: in the recirculation zone the granules are maintain in suspension. The aim of this research is to identify the optimal geometry of the installation to achieve the recirculation of granular sludge.

CFD math models are based on the Navier-Stokes equations. The first mathematical models have first developed methods to solve the linearized equations. Then two-dimensional methods (2D) appeared in 1930, using the conformational transformations of the flow around a cylinder with the flow around an air profile. Currently, the most commonly used software for fluid dynamics modelling is ANSYS FLUENT. This Software has the ability to simulate flow rate, heat transfer and chemical reactions for industrial applications. Fluent includes a wide range, including special models, with the ability to model combustion, aero-acoustics, turbomachines and multiphase systems [27-28].

2. Material and methods

The installation consists of a rectangular shape bioreactor, 7, an area for settling and recycling of granules, 4, followed by a settling tank, 5. Wastewater is supplied with a peristaltic pump through a hose, 1, at 1.1 L/h. A perforated hose, 8, is used for air supplying at 10 L/min. The inlet and outlet area for granules recycling is provided with blades with a length of 3 cm and inclined to 45 degrees, superior 2 and inferior 6. Treated wastewater is discharged into the area 3 (Fig.1).

In this paper, to find a better bioreactor configuration than the existing one, a simulation study is performed using turbulent k-epsilon 2D and 3D mixture model in FLUENT. Gambit is used to develop the simulation domain and the 0.002 m integration network. The model is meshed using an unstructured mesh and the solver used is a segregated solver as the flow is incompressible. The aerobic granular sludge bioreactor has a height of 0.274 m and a width of 0.20 m, according to the design data. The water is introduced at the bottom of the bioreactor at a distance of 0.010 m from the bottom. The pre-sedimentation zone has a width of 0.02 m, and the recirculation is through an aperture of 0.025 m. The aeration system used consists of 8 mm diameter tubing, provided with oxygen dispersion holes. The water inlet velocity is 0.006 m/s and for air 0.012 m/s with 1 mm air bubble diameter. The physical properties of the water were constant pH = 7, temperature 15ºC and density 1000 kg / m^3.

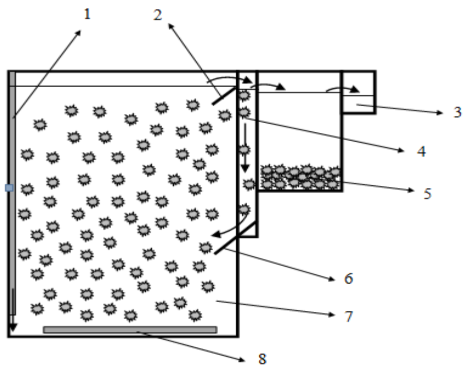

Fig. 1. Configuration of the installation

3. Results and Discussion

In the case of these simulations it was studied the optimization of the bioreactor geometry only from the point of view of the flow characteristics. The objectives of this research was to identify the geometry so as to achieve the recirculation of the granular sludge and to make movement in the bioreactor so as to avoid the formation of sludge deposits.

The first simulations are in the 3D field, using the k-epsilon turbulent flow model, to visualize the flow of water into the bioreactor. Fig. 2a shows the contour of the velocity in the tank for three transverse planes: at the entrance to the tank, in the granular sludge recirculation zone and at the exit. Fig. 2b shows the contour of the velocity in the tank for three longitudinal planes: the left plane, the middle and the right plane. The results of these simulations show that in the central area (Fig. 2.a) and below inferior blade of recirculation zone (Fig. 2.b) the water velocity is zero, leading to the occurrence of granular sludge deposits. To avoid this, aeration systems should be located in these areas.

Next simulations of the biphasic mixture are carried out in the 2D domain. The initial aeration system is considered on the bottom of the bioreactor, laid out in a circular form. Several cases have been analyzed starting from a centrally located aeration system up to six parallel aeration systems. Placement of a single aeration system in the middle of the tank has only disadvantages. In this case, the velocity generated and induced is not uniform into the tank and in the corners area the velocity is zero causing the formation of granular sludge deposits. In the case of 6 aeration systems, the velocity ensures movement in the tank but in the middle of the tank there is a vortex that could prevent the dispersion of oxygen in the water and also the granule movement [29]. As a result, it can be noted that if there are too few aeration systems in the corner area, the mixture velocity remains zero. If there are too many aeration systems, the degree of turbulence is high and there is no recirculation.

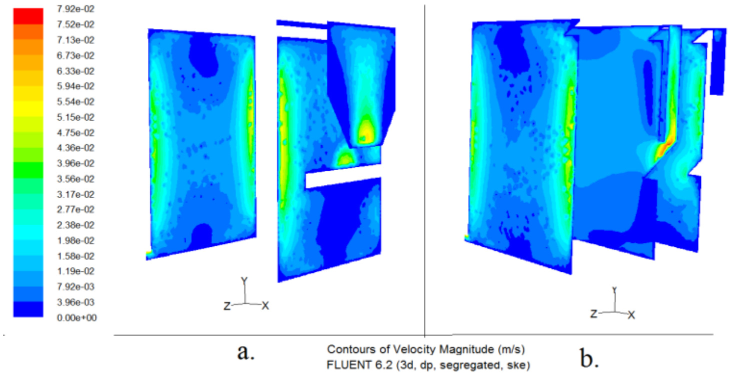

Fig. 2. Contour of water velocity: a) three transverse planes, b) three longitudinal planes

To prevent the deposition of the sludge in the corners of the aeration bioreactor, a wall was mounted at 30 degrees. After this change the first analyzed situation was with two aeration systems mounted in parallel and the lower blade for the recirculation zone was 2 cm longer (Fig. 3).

The results show that the location of the wall in the corner of the bioreactor reduces the risk of the formation of sludge deposits but the velocity of the mixture is very low $6*10^{-5}$ m/s. Increasing the size of the lower recirculation blade prevents recirculation of granular sludge. Preventing the recycling of granular sludge can lead to a reduction in the efficiency of the treatment process by up to 50%. In the following case, it returned to the initial size of the lower recirculation blade, the wall was tilted to 30 degrees and four parallel aeration systems were considered (Fig. 4). It is noticed that after the inclined wall was placed, the risk of sludge deposits in the corner of the bioreactor was eliminated. The four aeration systems caused a uniform motion in the bioreactor, but no movement was achieved in the granule recirculation zone.

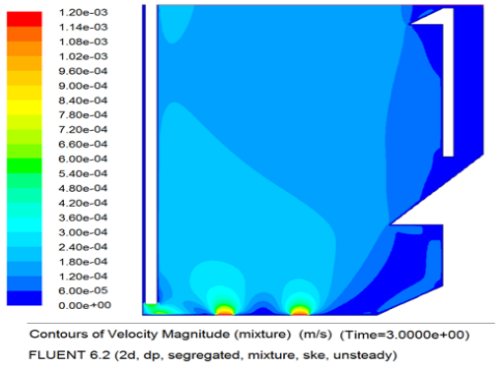

Fig. 3. Two aeration systems placed on the bottom of the bioreactor and a wall at 30 degrees in the corner

To achieve movement in the recirculation area, it has been gathered to improve the previous case by installing the aeration systems at a distance of 10 mm from the bottom of the bioreactor (Fig. 5). This solution offers movement into entire bioreactor. The very low velocity area occurring in the right corner does not have direct contact with the wall. The rate of wall velocity is sufficient to keep the granular sludge in motion.

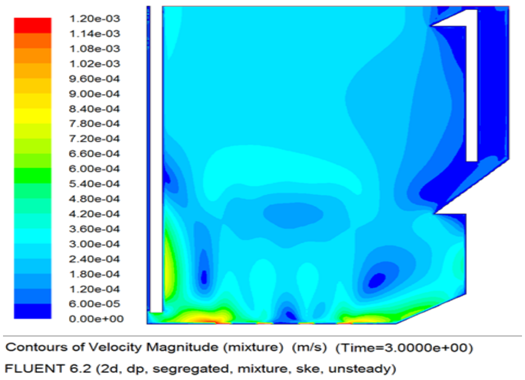

Fig. 4. Four aeration systems placed on the bottom of the bioreactor and a wall at 30 degrees in the corner

The mathematical models were followed to obtain the geometric shape of the tank for which the following conditions were met: the velocity in the thank is uniform so that it does not appear sludge deposits and recirculation of the sludge from the separation zone to the reaction zone was achieved (Fig. 5).

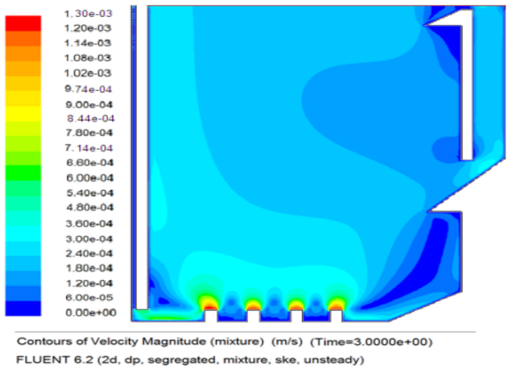

Fig. 5. Four aeration systems placed at 10 mm from the bottom of the bioreactor and a wall at 30 degrees in the corners

After that experimental research will show the efficiency of the process in this case. It also aims to achieve the industrial scale of the plant. But the biological process is a complex one from a chemical, biological and hydraulic point of view. Unfortunately, the criteria of classical similarity for this process can't be applied. For this purpose, we can first realize an experimental model 1:1 scale, then we want do a pilot installation followed by the industrial scale implementation. At the moment, this technology is used as a test.

4. Conclusions

AGS technology is an innovative method in biological wastewater treatment that can be a good alternative to retrofit activated sludge system. This paper deals with a theoretical simulation study, based on experimental research results, to improve water flow in bioreactor and granules recirculation zone of a lab-scale experimental installation.

In the first case it can be noticed that the velocity generated and induced is not uniform in the bioreactor and in the corners area the velocity is zero leading to the formation of sludge deposits. Installation of four parallel aeration systems determines a uniform distribution of velocity in the bioreactor and a better mixing of water into bioreactor. The aeration systems placed at 10 mm from the bottom of the tank increases the velocity in the recirculation of granular sludge area. According to simulation results the installation of a 30 degrees profiled wall in the right corner is the optimal solution for avoiding sludge deposits in this area.

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