Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2013.795874

52 (2014) 2465–2471
March

Taylor & Francis
Taylor & Francis Group

Improving the settling properties of activated sludge by gradually decreasing the settling time

Fatemeh Sadrzadeh, Ebru Dulekgurgen*

Department of Environmental Engineering, Istanbul Technical University, 34469 Maslak, Istanbul, Turkey
Tel. +90 212 2853776; email: dulekgurgen@itu.edu.tr

Received 10 October 2012; Accepted 7 April 2013

ABSTRACT

The study aims at evaluating the impact of gradually decreasing the settling time on settling properties of activated sludge removing organic matter. For that, a lab-scale sequencing batch reactor (SBR), fed with soluble starch and acetate, was seeded with floccular biomass. As the selected strategy to washout slowly settling flocks and retain biomass with improved settling capacity, settling time (T_s) was decreased gradually from 45 to 30, 15, 5 and 1 min. Long-term monitoring showed that each time the T_s was decreased to the next lower level, there was biomass washout. Yet high amount of biomass (10 g MLVSS/L) with improved settling properties (sludge volume index ⩽ 16 mL/g) and high chemical oxygen demand (COD) removal performance (97%) was maintained with a T_s as low as 5 min. Further decreasing T_s to 1 min did not impose any negative effect. Biomass maintenance, settling properties, and COD removal performance of the system were comparable with those of aerobic granular biomass. Yet, minimum settling velocities corresponding to 5 and 1 min settling times applied at the last two phases of operation (0.4 and 2.0 cm/min) were lower than those reported for granular biomass systems, hence the biomass remained floccular but the system had an exceptionally good settling capacity and COD removal efficiency.

Keywords: Hydraulic selection pressure; Sequencing batch reactor; Settling properties; Settling time; Sludge volume index

1. Introduction

Biological wastewater treatment (BioWWT) has two main goals of removing organic pollutants and nutrients from wastewater through biochemical conversions employed by activated sludge (AS) populations and separating the treated effluent from the biomass so that it becomes possible to discharge. Although conventional suspended AS-based technology has been in use for carbon and nutrient removal globally, one of the disadvantages of those systems is large plant footprint, mainly due to the need for large aeration tanks and secondary clarifiers in those systems [1,2]. Because of the floccular structure and poor settling characteristics of conventional suspended AS, it is necessary to devote large reaction volumes to maintain biomass in the system at a level sufficient for targeted removal efficiencies. This also requires recirculation of settled sludge from the secondary clarifiers, and thus adds to capital and operational costs. Floccular AS with poor settling properties also

*Corresponding author.

limits the hydraulic loading applicable in secondary clarifiers resulting in a need for large settling tanks.

Accordingly, research on developing biomass with improved settling properties intensified during the last decade and those efforts resulted in the development of aerobic granular sludge technology which provides solutions to the abovementioned shortcomings of conventional AS systems: aerobic biomass grown in sequencing batch reactor (SBR) systems has excellent settling properties and grows in granular form, rather than in floccular structure. Excellent settling capacity of biomass enables decreasing the time/volume devoted for sludge–liquid separation resulting in compact units with significantly low foot-print. Moreover, it is possible to maintain high biomass concentrations in those systems which translates into smaller reaction volumes and reduced foot-prints. SBR configuration eliminates the need for a separate settling volume thus decreasing the overall foot-print of the system. Moreover, there is no need for sludge recirculation pumps, which brings about an additional reduction in overall energy and maintenance costs in such systems. According to a study comparing the foot-prints and capital and operational costs of a full-scale conventional suspended AS WWTP and an Aerobic Granular Sludge-based system, the latter proves to be outcompeting the conventional alternative [1]: the foot-print of the granular SBR-based model is reported to be four times smaller than that of the conventional plant and the annual costs of the granular biomass-based alternative is 7–17% lower than those of the conventional model. Likewise, energy consumption for an aerobic granular sludge-based BNR (bio-nutrient removal) system is estimated to be 20% lower than that in a conventional alternative, mainly due to reduced pumping needs [2].

Apparently, biomass settling properties are critical in the design and operation of AS systems; determining the volume of aeration tanks and secondary clarifiers in continuous systems and the time devoted for liquid-sludge separation in batch configurations like SBRs. Therefore, to benefit from the abovementioned advantages of excellently settling AS-based systems, it becomes crucial to develop and maintain biomass with improved settling properties. For that, it is important to test and apply strategies to obtain an appreciable amount of rapidly settling biomass. According to the "selection pressure theory", it is possible to select for microbial populations with certain desired properties by imposing external stress factors on biomass and creating hydraulic, kinetic, and/or metabolic selection pressures [3]. Among those external factors, settling time (T_s) has been recognized as one of the main hydraulic selection pressures to wash out slowly settling flocks, hence help maintain rapidly settling biomass in SBRs [1,2,4].

In view of these, impact of gradually increasing this hydraulic selection pressure—that is gradually decreasing the T_s–on settling properties of activated sludge in a 2 L lab-scale SBR was investigated in this study. For that, the system was operated at an anaerobic/aerobic sequential mode and fed with a synthetic wastewater to provide 854 mg COD/L in the reactor at the beginning of each cycle. After the start-up period (approx. 1 month), the T_s was decreased gradually from 45 to 30, 15, 5, and finally to 1 min and the system was monitored for biomass production, biomass washout, settling properties, and chemical oxygen demand (COD) removal performance for a total of seven months.

2. Materials and methods

2.1. Reactor set-up and cycle configuration

The experimental set-up used in the study was a 2 L (working volume) glass vessel with an H_W/D (height to diameter) of 1.2. The bioreactor was equipped with a stirrer drive providing mechanical mixing, probes measuring temperature, pH, and dissolved oxygen, a diffuser system and a gas-line for introduction of desired gases to the system. All probes and mechanical parts (i.e. influent and acid–base pumps) were connected to an interfacial unit collecting data from the reactor and receiving commands from a software enabling data collection and automated operation. pH was controlled at 6.8–7.3. Dissolved oxygen inside the reactor was controlled with the help of a mass flow meter at 0% of saturation during the anaerobic period and at 40% during the aerobic period.

The system was operated as a sequencing batch reactor for about seven months. For the start-up period (days 1–25), cycle configuration is as follows: feeding (T_f): 5.5 min, nitrogen purging (T_{N2}): 15 min, mechanical mixing (T_{stir}): 99.5 min, anaerobic period (T_{anaer}): 120 min ($T_{anaer} = T_f + T_{N2} + T_{stir}$), aerobic period ($T_{aer}$): 180 min, settling ($T_s$): 45 min, discharge ($T_w$): 6 min, idle period ($T_i$): 9 min. This cycle configuration is schematically presented in Fig. 1. Total cycle time (T_c) was six hours per cycle.

The study was divided into five phases and the main operational parameter altered during that time was the T_s. At Phase-I (start-up period), biomass was let to settle for 45 min at the end of each cycle. Then, the T_s was decreased gradually from 45 to 30, 15, 5,

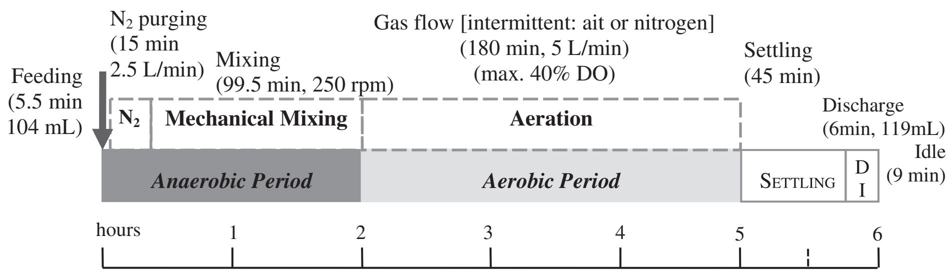

Fig. 1. Cycle configuration during start-up (days 1–25).

Table 1
Changes in cycle configuration throughout the study (durations of cyclic periods in minutes)

Phases (weeks)	Days	T_f	T_{N2}	T_{stir}	T_{anaer}	T_{aer}	T_s	T_w	T_i	T_c
I (3.5)	1–25	5.5	15	99.5	120	180	**45**	6	9	360
II (5.5)	25–64	11.7	15	93.3	120	180	**30**	10.6	20	361
III (4)	65–94	11.3	15	93.7	120	195	**15**	11.0	18	359
IV (7)	95–145	11.5	15	113.5	140	190	**5**	10.5	14.5	360
IV (6)	146–189	11.5	15	303.5[a]	140	190	**5**	10.5	14.5	360
V (3)	190–210	11.5	15	303.5[a]	140	190	**1**	10.5	18.5	360

[a]Mechanical mixing was extended to the aerobic period to meet increased mixing requirements due to significant biomass build-up. T_{stir} = 113.5 (anaerobic) + 190 (aerobic) = 303.5 min, Q_{air} = 3 L/min.

and 1 min. The system was operated at least for about 1 month before changing the operational conditions for the next phase of the study. Durations of cyclic periods applied at each phase of the study are summarized in Table 1.

2.2. Seed biomass, feed composition, analytical measurements

The lab-scale SBR was inoculated with a floccular biomass collected from the aeration tank of a full-scale BioWWTP receiving industrial wastewater from alcoholic beverage production. Suspended solids concentration of the seed biomass was 5.2 g MLSS/L and the sludge volume index (SVI) was approx. 120 mL/g.

The system was fed under anaerobic conditions with a 10× concentrated synthetic feed stock, including acetate (35%) and soluble starch (65%) as the sole carbon sources. Volumetric exchange rate (V_f/V_T) was 5% during start-up and 10% for the rest of the study. Accordingly, COD concentration inside the reactor originating from the synthetic influent was 854 mg/L at the beginning of each cycle. Daily biomass withdrawal was not applied; hence biomass wastage was due to particles escaping to the effluent.

To monitor the changes in biomass concentration, settling properties, effluent quality, and COD removal performance, the system was sampled once or twice a week for a total of seven months. SVI_{30} were determined by collecting mixed liquor samples from the system for approximately 30–35 min before the end of aeration and recording the settled sludge volume after 30 min, as outlined in the *Standard Methods* [5]. Additionally, values after 10 min of settling were also recorded and used for determining SVI_{10}. To determine the suspended solids inside the reactor, mixed liquor samples were collected from the reactor right before the end of aeration and MLSS and MLVSS in fresh, homogenous samples were measured in duplicate [5]. For each cycle to be evaluated, all of the effluent discharged from the system was collected, mixed well, and subjected to suspended and volatile suspended solids measurements in duplicate (SS_{effl} and VSS_{effl}, respectively). To determine the COD removal performance of the system, aliquots of effluent samples were filtered (pore size: 0.45 μm) and the soluble COD (sCOD) concentrations in those filtered samples were measured in duplicate by the closed reflux method in accordance with the *International Standards ISO 6060* [6].

3. Results and discussion

The lab-scale SBR was operated for a total of seven months divided into five subsequent phases—determined by altered settling times—and the system was monitored for biomass production,

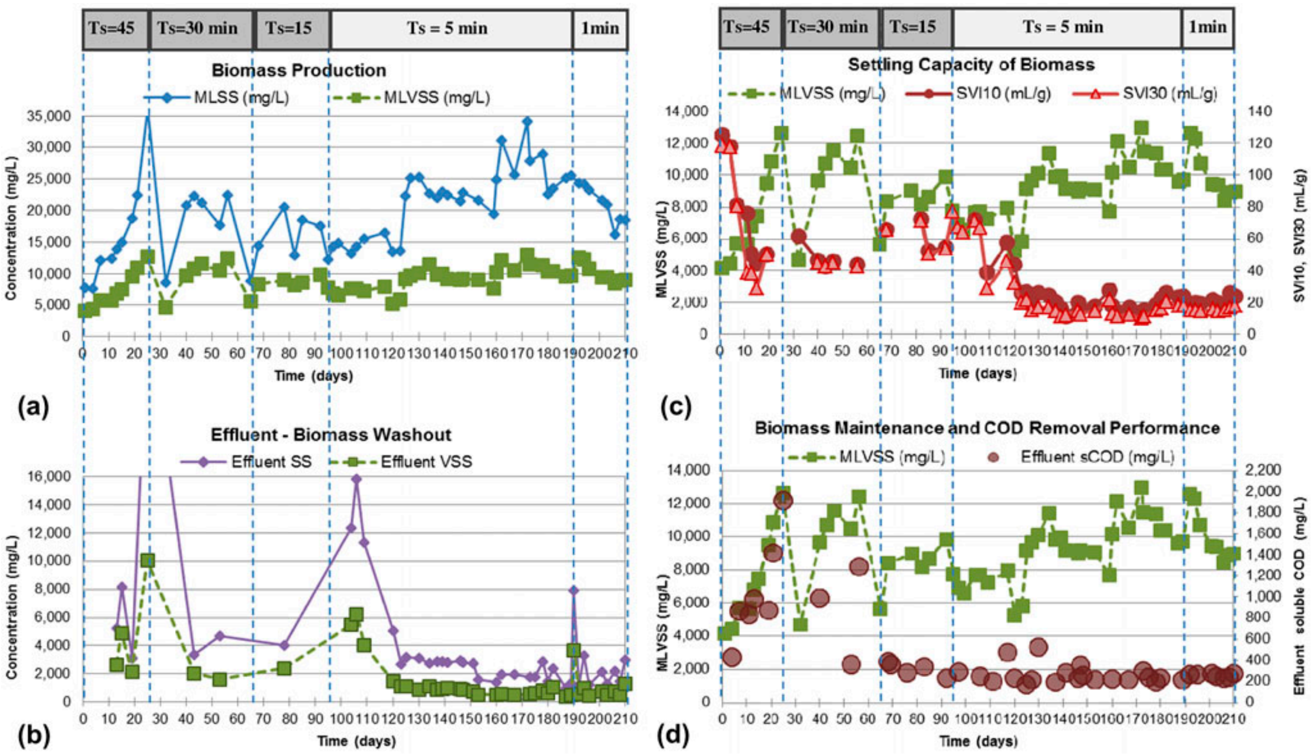

Fig. 2. Long-term monitoring for determining the impact of gradually decreased T_s: (a) biomass production (MLSS and MLVSS), (b) biomass washout (SS and VSS in the effluent), (c) settling properties (MLVSS and SVI), and (d) COD removal (soluble COD in the effluent).

settling properties, biomass washout, and effluent quality, as well as for COD removal efficiency at each phase to determine the response to the gradual decrease in the T_s from 45 to 1 min. Results of this long-term monitoring are shown in detail in Fig. 2, panels a, b, c, and d, respectively, and explained below.

3.1. Biomass characteristics

As apparent from Fig. 2(a), biomass concentration in the reactor increased three- to five-folds of the starting values during the first month of reactor operation (Phase-I). This significant build-up in solids was due to applying a T_s of 45 min, which allowed majority of the floccular inoculum as well as the developing biomass, to remain in the system. In the meantime, settling properties of the newly developing biomass improved, as revealed by the sharp decrease in SVI from 119 to 50 mL/g within the first 25 days (Fig. 2(b)). Suspended solids concentrations in the effluent revealed that there was biomass escaping to the effluent during the start-up period (Fig. 2(c)). Accumulation of biomass in the system combined with the constant COD loading resulted in a low F/M ratio and caused decrease in viability of the biomass as revealed by the decreasing MLVSS/MLSS values, which dropped from 54 to 39% during this phase.

To washout the floccular biomass with decreased viability and to apply a higher hydraulic selection pressure for removing the slowly settling portion of the biomass, the T_s was decreased from 45 to 30 min on day-25. As intended by this operational change, a major biomass washout was observed right after decreasing the T_s to 30 min: 27.9 g/L of suspended solids was washed out and appeared in the effluent at the end of the first cycle of Phase-II (Fig. 2(c)). Accordingly, biomass in the reactor dropped from 36.1 to 8.6 g MLSS/L at the next cycle (Fig. 2(a)). After this post-incident response, MLSS and MLVSS values quickly increased and stabilized at around 20.9 and 11 g/L, respectively (Fig. 2(a)). Likewise, SS and VSS in the effluent decreased promptly and leveled at around 4 and 1.8 g/L, respectively (Fig. 2(c)). During 5.5 weeks of operation with 30 min settling (Phase-II), there was no apparent change in the settling capacity of the biomass and the SVI values were leveled at around 44 mL/g, which indicated that the biomass in the system had already acquired good settling properties.

Those results confirmed that it was possible to washout the undesired portion of the biomass from the system and develop a biomass with better settling properties by decreasing the T_s. Consequently, for the next phase of operation (Phase-III), T_s was decreased from 30 to 15 min on day-65 to provide a more stringent hydraulic selection pressure and the system was operated for another month. Similar to the previous case, a major washout occurred right after decreasing the T_s to 15 min, which resulted in a sharp decrease of biomass content of the system from 22.4 to 8.8 g MLSS/L at the first cycle. Yet, MLSS and MLVSS values recovered rapidly and biomass concentrations fluctuated between 12.9 and 20.5 g MLSS/L and 8.2 and 9.9 g MLVSS/L during Phase-III (Fig. 2(a)). SVI fluctuated between 51 and 71 mL/g during this period (Fig. 2(b)).

To continue washing out the slowly settling flocks and maintain a considerable amount of biomass with enhanced settling properties along with high COD removal at the next phase, a more stringent hydraulic selection pressure was introduced to the system on day-95 (start of Phase-IV) and the T_s was decreased from 15 to 5 min. The system was operated under those stress conditions for more than three months. Again, biomass washout occurred upon decreasing the T_s to 5 min, yet system's response to the new and increased stress condition was much smoother: MLSS decreased to 12.2 g/L at the first cycle but then increased to around 14.5 g/L in two days and fluctuated around that level during the following month (days 95–125). MLVSS was around 6.9 g/L at that period (Fig. 2(a)). In the meantime, settling properties and capacity of the biomass improved significantly and SVI decreased from 77 to 20 mL/g (Fig. 2(b)). The amount of biomass escaping from the system was at a considerable level at the beginning of Phase-IV, yet parallel to improvements in biomass settling properties, SS and VSS in the effluent also dropped (Fig. 2 (c)). Within one month, the system reached to a stable level, in terms of settling properties and sCOD removal performance (day-125) and remained so during the following two months (between days 125 and 189). MLSS and MLVSS values leveled at around 24.8 and 10.1 g/L, respectively, SVI was as low as 15 mL/g, and suspended solids in the effluent was around 2.3 g/L (Fig. 2(a–c)).

Considerably high solids concentration in the system along with significantly low SVI values obtained at Phase-IV implied that the biomass maintained in the reactor under the stress condition of 5 min settling had exceptionally good settling properties and capacity. Comparative evaluation of all results of this long-term monitoring study confirmed that decreasing the T_s in a step-wise manner improved the settling properties of the biomass and in contrast to the general expectations, resulted in better effluent quality.

At the final stage of reactor operation (Phase-V), the system was operated with the highest hydraulic selection pressure to confirm the response of the system and the findings obtained at the previous phase. Upon decreasing the T_s from 5 to 1 min on day-189, some biomass washed out, but this was apparent only from the solids concentration in the effluent by the end of the first cycle (7.9 g SS/L in the effluent), rather than the biomass concentration in the reactor, which remained approximately at the same level as that of the previous phase (Fig. 2(a)). Effluent quality recovered quickly and fluctuated between 1.2 and 3.3 g SS/L with an average of 1.8 g SS/L and between 0.4 and 0.9 g VSS/L with an average of 0.6 g VSS/L (Fig. 2(c)). Settling properties of the biomass were still considerably good and SVI was stable at a level as low as 16 mL/g (Fig. 2(b)).

These results confirmed that when appropriate operational strategies are applied and the system is given sufficient time to adapt to new conditions, it is possible to maintain considerable amount of biomass with remarkably good settling properties, even under stress conditions of 5 and 1 min T_s.

3.2. COD removal performance

During the 4th day of reactor operation, the COD removal performance was 95%. Yet, during the following 20 days, there was a continuous increase in effluent sCOD values (Fig. 2(d)) and the COD removal capacity decreased down to 78% by the end of the start-up period. Upon decreasing the T_s from 45 to 30 min on day-25, a significant portion of the biomass was washed out and parallel to the growth of new biomass in the system, COD removal capacity recovered quickly and increased to 85–96% at Phase-II (Fig. 2(d)). Further decreasing the T_s to 15 min on day-64 allowed washing out some more biomass and helped develop some new biomass with improved COD removal capacity at the following phase. Accordingly, COD removal efficiency increased and stabilized at around 96% at Phase-III (Fig. 2(d)). Comparative evaluation of the MLSS, MLVSS results (Fig. 2(a)), SVI values (Fig. 2 (b)), and the stable COD removal performance (Fig. 2 (d)) indicated that the biomass remaining in the system after 15 min of settling not only had good settling properties, but also adapted to metabolizing the organics in the influent—the soluble starch and acetate with 65 and 35% contributions to 854 mg/L of sCOD in the reactor at the beginning of each cycle. It was considered that the enzymes required for anaerobic/aerobic hydrolysis of soluble starch, which was the slowly biodegradable fraction (S_H) of the influent COD, and the enzymes for utilization of acetate forming the readily biodegradable fraction (S_S) were transcribed by the biomass at a sufficient level and were active, hence those biochemical conversions were operating efficiently. Results of semi-quantitative enzyme-activity tests (API ZYM®, bioMérieux) supported those assumptions (data not shown).

There was no capacity loss in COD removal performance when the T_s was decreased to 5 min on day-95 (Phase-IV) and to 1 min on day-189 (Phase-V) (Fig. 2(d)): COD removal efficiency of the system stabilized at 97% at Phase-IV and remained at this high level till the end of reactor operation at Phase-V (Fig. 2(d)).

In summary, there was a significant biomass washout each time the T_s was decreased to the next lower level, yet those were one-time, post-incident responses, and got less dramatic in time (Fig. 2(a) and (b)). After decreasing the T_s to 5 min, a biomass stable not only in terms of exceptionally good settling properties but also in terms of high COD removal performance was maintained in the system. Decreasing T_s further to 1 min did not impose deterioration in those features.

Performance of the system in terms of biomass maintenance, settling properties, and COD removal efficiency recorded at the second-half of reactor operation (Phases-IV and V) was comparable with those reported for aerobic granular biomass systems [i.e. 4,8,10]. Yet, due to limitations of reactor set-up, the exchange ratio in this study was only 10% and thus, the minimum settling velocities (v_{min}) corresponding to 5 and 1 min settling times applied during Phase-IV and V were 0.4 and 2.0 cm/min, which were considerably lower than or at the limit of those reported for granular biomass systems. Consequently, the biomass remained floccular and there were still biomass particles escaping to the effluent, even though the settling properties were exceptionally good as revealed by significantly low SVI values. Some v_{min} values reported in the literature for developing and/or maintaining aerobic granular biomass characterized by excellent settling properties are as follows: Liu et al. reported the lower limit of v_{min} as 1.67 cm/min for fully aerated systems [7]. Dulekgurgen et al. reported developing and maintaining aerobic granular EBPR biomass with improved settling properties and excellent C-removal and EBPR performance even with application of 15 min settling, corresponding to a v_{min} as low as 0.95 cm/min [8]. In another study, they developed aerobic granular biomass in an anaerobic/aerobic SBR where the settling velocity was 11 cm/min and the main hydraulic selection pressure was the shearing forces [9]. de Kreuk and de Bruin applied a settling velocity of 16.7 cm/min to develop aerobic granular EBPR biomass in column SBRs [10]. de Bruin et al. referred to the results of lab-scale studies where settling velocities of around 20 cm/min ensured development and maintenance of stable aerobic granular biomass with excellent settling properties in SBR systems [1].

Those remarks in the literature and the findings obtained in this study together suggest adoption of minimum settling velocity (v_{min}) along with T_s as an appropriate descriptive of hydraulic selection pressure for washing out slowly settling flocks, maintaining rapidly settling biomass and ensuring good effluent quality, as well as developing aerobic granular biomass.

4. Conclusions

The strategy of gradually decreasing the T_s was proved to be suitable for removing slowly settling flocks and retaining high amounts of biomass with improved settling properties: substantial biomass washout occurred each time the T_s was shortened, yet those were post-incident responses and a stable biomass with significantly improved settling properties and high COD removal performance was obtained with 5 min of settling. No deterioration was observed when the T_s was decreased to 1 min and the system remained stable in terms of good settling properties and high COD removal performance.

High biomass concentrations, good settling properties, and high COD removal performance obtained with floccular biomass in this study are comparable with those reported for aerobic granular biomass systems, even though there was no granulation in the system and the effluent quality (in terms of SS) needed improvement. These factors draw attention to adopting minimum settling velocity (v_{min}) as an appropriate hydraulic selection pressure parameter as well. Minimum settling velocity is not only a function of T_s, but also related to factors like reactor geometry (H_w/D), exchange rate (thus H_{min}/D), and cycle configuration. Hence, future work needs focusing on optimization of reactor configuration and cycle operation to provide appropriate minimum settling velocities and thus to further enhance biomass settling properties and effluent quality along with the possibility of developing aerobic granules in SBRs. Research with this perspective is currently in progress and preliminary results confirmed maintenance of a totally granular biomass in a bubble column SBR with an H_w/D ratio of 9.7, an exchange rate of 50%, a T_s of 1.5 min, and a minimum settling velocity of 24 cm/min.

Attaining high biomass concentrations in anaerobic/aerobic SBRs combined with improved settling properties, and good removal efficiencies, as obtained in this study and further developing aerobic granular biomass in such systems will enable optimization of process configurations and the advantages of SBRs, and excellently settling compact biomass will provide a potential for designing and operating BioWWTPs with considerably smaller foot-prints, lower capital, and operational costs.

Acknowledgment

This study was financially supported by TUBITAK (The Scientific and Technical Research Council of Turkey) through the Starting Grant-Project No: 108Y313.

References

[1] L.M.M de Bruin, M.K. de Kreuk, H.F.R. van der Roest, C. Uljterlinde, M.C.M. van Loosdrecht, Aerobic granular sludge technology: An alternative to activated sludge? Water Sci. Technol. 49 (2004) 1–7.

[2] A. Giesen, R. Niermans, M.C.M. van Loosdrecht. Aerobic granular biomass: The new standard for domestic and industrial wastewater treatment? Water21-April 2012. 2012: 28–30, Magazine of the International Water Association, IWA 2012, ISSN 1561–9508.

[3] J. Wanner, Activated sludge bulking and foaming control, Technomic, Basel, 1994.

[4] L. Qin, Y. Liu, J.-H. Tay, Effect of settling time on aerobic granulation in sequencing batch reactor, Biochem. Eng. J. 21 (2004) 47–52.

[5] APHA, WEF, AWWA, Standard methods for the examination of water and wastewater. 21st ed. in: L.S. Clesceri, A.E. Greenberg, A.D. Eaton (Eds.), Washington, DC, American Public Health Association, 2005, Sections 2540D, 2540E, 2540F, 2710D.

[6] International Organization for Standardization, in: Technical Committee ISO/TC 147 (Eds.), International Standard ISO 6060: Water Quality-Determination of the Chemical Oxygen Demand, first ed. Reference No. ISO 6060–1986(E), ISO, Switzerland, 1986.

[7] Y. Liu, Z.-W. Wang, J.-H. Tay, A unified theory for upscaling aerobic granular sludge sequencing batch reactors, Biotechnol. Adv. 23 (2005) 335–344.

[8] E. Dulekgurgen, S. Ovez, N. Artan, D. Orhon, Enhanced biological phosphorus removal by granular sludge in a sequencing batch reactor, Biotechnol. Lett. 25 (2003) 687–693.

[9] E. Dulekgurgen, N. Artan, D. Orhon, P.A. Wilderer, How does shear affect aggregation in granular sludge SBRs? Relations between shear, hydrophobicity and EPS, Water Sci. Technol. 58 (2008) 267–276.

[10] M.K. de Kreuk, L.M.M. de Bruin, Aerobic Granular Reactor Technology, Water and Wastewater Practitioner Series: STOWA Report, IWA, London, 2004, p. 3.