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Settling Properties of Activated Sludge from a Sequencing Batch Reactor (SBR)

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Abstract

The purpose of this work was to examine the settling properties of activated sludge from a sequencing batch reactor (SBR). The experiments were carried out in a bench-scale reactor, fed with wastewater from the University of Olsztyn treatment plant.

Concentrations of the examined activated sludge varied between 2.5 and 6.0 kg SS m^{-3}. Laboratory analyses of the sludge comprised: sludge concentration, settleability, sedimentation velocity and sludge volume index (SVI).

The study revealed very good settling properties of the sludge. Low SVI (30 - 60 ml g^{-1} SS) was responsible for an intensive and quick sedimentation which shortened the settle phase to less than one hour. Moreover, low SVI prevented the sludge from bulking.

High dissolved oxygen concentrations in the aeration tank during the react phase resulted in little sludge biomass growth, which is very important from the viewpoint of sludge disposal at a wastewater treatment plant.

Keywords: sequencing batch reactor (SBR), sludge properties, settleability, sludge volume index (SVI).

Introduction

In the activated sludge method, separation of sludge from the effluent is a supplementary process to aeration. During sedimentation, concentration of suspended solids reaching a few thousand milligrams per litre must be lowered to less than 50 mg 1^{-1}. Therefore, it is very important to maintain the right parameters of activated sludge, allowing for its easy separation from the purified wastewater.

In practice, operation of a wastewater treatment plant with the activated sludge is related to a number of disturbances. Especially unfavourable are the processes causing turbid effluent, foaming in the aeration tank and secondary settling tank, and excessive hydration of activated sludge [11, 17].

The most problematic is excessive hydration of activated sludge, called sludge bulking. It may be caused by sludge overloading, lack of nutrients in wastewater, a deficit or too high dissolved oxygen concentration, low pH value, or finally also by technical reasons (e.g. inappropriate reactor shape). As a result, unwanted activated sludge microorganisms appear, especially the filamentous bacteria. These bacteria cause a distinct increase of the active surface of floes which in turn significantly slows down the sludge settling.

Although the problem of sludge bulking has been reported by numerous authors, its scale and arduousness call for further study. The current trend is to design treatment systems that will not be subject to this phenomenon.

Sludge bulking can be avoided in a sequencing batch reactor [2, 25]. In the SBR method, the fill phase is commenced without wastewater aeration. The basic parameters of the technological process, such as

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Correspondence to: Prof, dr hab. M. Krzemieniewski dissolved oxygen and organic compounds concentration, are a function of time.

SBRs are known not only for ease in sludge manipulation but also for other properties, such as high removal rate of phosphorus and nitrogen from wastewater, and considerable simplification of a treatment plant technological arrangement.

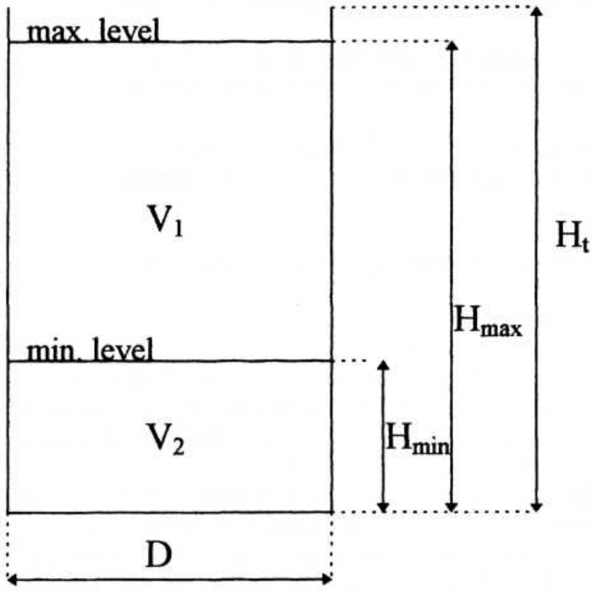
Having the above in mind, the authors of this paper decided to examine quality and quantity of the activated sludge from an SBR in order to verify its good settling properties.

Methods

Experimental model

The experiments were conducted in a bench-scale SBR, shown in Fig. 1. The reactor diameter was 60 cm, total height 125 cm, and total volume 318 litres.

The reactor was fed with wastewater from the treatment plant at the University in Olsztyn. The treatment system with the SBR model was designed in the first row for high-rate nitrogen and phosphorus removal (Janczukowicz, 1995). Before the wastewater was pumped to the reactor, it was introduced in the raw-wastewater, overflow tank. The volume of 218 litres of wastewater was dosed in a single batch. The reactor was equipped with a mechanical stirrer and a compressor with dome diffuser for the wastewater aeration. Fig. 2 shows the scheme of the experimental model.



D = 60 cm

H_{min} = 35 cm

Vi = 218 litres

H_{max} = 112 cm

V_2 = 100 litres

H_t = 125 cm

Fig. 1. Experimental reactor dimensions.

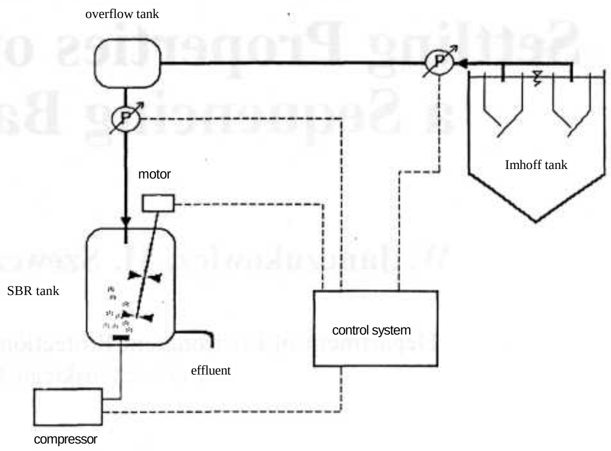


Fig. 2. Scheme of experimental model.

After the start of the fill phase (wastewater pumped to the reactor tank), the control system was turning on the mechanical stirrer. Next was the mix phase, lasting 2 h 20 min. Mixing was followed by aeration (react phase) when compressed air was introduced in the reactor for 2 h 40 min. Finally, during the settle phase, the tank content was subjected to sedimentation for 1 h. Decantation (draw phase) was performed until wastewater reached the minimum level (35 cm), closing the whole cycle. The full treatment cycle lasted approximately 6 h 20 min.

Analytical Procedures

Analyses of the physico-chemical parameters of the wastewater and sludge parameters were performed according to Hermanowicz *et al.* [12]. Wastewater examinations comprised of dissolved oxygen (DO), biochemical oxygen demand (BOD_5 at 20°C), chemical oxygen demand (COD), ammonia, nitrates, total nitrogen, phosphates, total phosphorus, pH, temperature, suspended solids (SS). DO was measured with a dissolved oxygen probe HI 9143. To determine the settling properties of sludge, concentration, settleability and sludge volume index (SVI) were analysed. Additionally, to illustrate the course of sedimentation process, total suspended solids (TSS) in the effluent were measured. Effluent turbidity was not measured because it is excluded from the Polish effluent quality standards and is not required by wastewater discharge permits.

. Samples for wastewater and sludge analyses were taken once a month for the period of 1.5 years (Jan. 1995 through April 1996). Wastewater for analyses was sampled from the overflow tank. Samples for sludge and SS analyses were taken from three depths in the reactor i.e. maximum level (liquid surface), middle of the reactor height and minimum level, five minutes after the start of sedimentation and ten minutes before its termination.

Results of the wastewater and sludge analyses presented in Tables 1 and 2 are the averages from the experimental period.

Table 1. Raw wastewater quality characteristics.

Contaminant	Unit	Min value	Mean value	Max value
BOD_5	mg $O_2 l^{-1}$	31	72	88
COD	mg $O_2 l^{-1}$	68	135	152
Ammonia nitrogen	mg $N\text{-}NH_4 l^{-1}$	14.6	17.6	56.8
Nitrates	mg $N\text{-}NO_3 l^{-1}$	0.007	0.1	0.36
Total nitrogen	mg N l^{-1}	17.6	25.3	29.1
Phosphates	mg $P\text{-}PO_4 l^{-1}$	1.02	6.1	13.5
Total phosphorus	mg P l^{-1}	1.3	6.2	15.7
DO	mg $O_2 l^{-1}$	1.6	4.2	6.6
PH	–	7.52	7.75	8.08
Temperature	°C	8.2	9.8	15.5
TSS	mgl^{-1}	109.5	202.8	245.5

Table 2. Activated sludge characteristics.

Sample No.	Sludge concentration	SVI	Settling velocity	Sludge age
	(kg m^{-3})	(ml g^{-1})	(m h^{-1})	(d)
1	4.59	34.8	10.90	10.7
2	4.29	43.6	10.27	19.5
3	3.45	40.6	10.46	18.3
4	3.49	57.3	9.55	24.2
5	3.26	36.8	10.74	16.6
6	4.82	31.1	11.23	13.8
7	5.02	35.1	10.88	15.8
8	5.08	46.0	10.12	20.5
9	6.20	35.5	10.80	16.1
10	4.53	60.9	9.39	25.3
11	3.87	76.5	8.84	29.2
12	5.71	49.8	9.91	21.8
13	4.31	37.1	10.72	16.8
14	2.67	96.8	8.30	33.2
15	5.51	45.4	10.16	20.2
16	4.54	61.6	9.36	25.5

The sequence and duration of phases during the whole experiment were the same but the wastewater loadings varied, depending on the season, day of the week and time of the day.

The laboratory analyses were carried out for the sludge concentrations between 2.5 and 6.0 kg SS mg^{-3}. Sludge loading varied from 0.0015 to 0.05 kg BOD_5 kg^{-1} SS d^{-1}.

Results and Discussion

Sludge Volume Index (SVI)

The measured values of SVI, (Table 2) reveal little variability and are mainly in the range from 30 to 60 ml g^{-1} SS. A break-down of the stirrer and the aeration system was the reason for the very high SVI value of 96.8 ml g^{-1} (Feb. 1996). No correlation was observed between sludge concentration and SVI.

Many authors recognise SVI as the parameter best characterising sludge settling properties. SVI is also a good indicator of sludge bulking. In practice, SVI can vary from 30 to 400 ml g^{-1} [10, 17]. However, it usually does not exceed the value of 150 ml g^{-1} which is an indicator of good settling properties of the sludge. Palm and Jenkins [23] reported that sludge of the SVI over 150 ml g^1 is often classified as bulking sludge. The same authors also pointed out the dangers associated with too low SVI in the conventional wastewater treatment systems. They have found out that quickly settling sludge (SVI below 70 ml g^{-1}) can be the reason for turbid effluent, caused by weakly structured and small floes.

A proper SVI value, especially below 100 ml g^{-1}, is of major importance in the activated sludge method. Although Rensink and Donker [24] have demonstrated that organic compounds are better removed by well-settling sludge (of low SVI), a high SVI sludge can work effectively. However, in the conventional sedimentation time, activated sludge with low SVI does 1 and can be carried over to the effluent [6]. This tendency has not been observed in SBRs; the current study also confirms that.

The SVI values obtained in the experiment are rather low, compared to the results reported by other authors. Malej [21] obtained in two aeration tanks at the wastewater treatment plant in Koszalin the SVI of 87-148 ml g^{-1} and 92-157 ml g^{-1}, regarded by him as optimal in the conventional activated sludge system. Klimiuk and Janczukowicz [18] observed at the wastewater treatment plant in Olsztynek that sludge of the SVI 127-258 ml g^{-1} had a tendency to bulk. Albertson [2] obtained in four tanks working in a row: 517 ml g^{-1} in the first tank, 300 ml g^{-1} in the second, 91 ml g^{-1} in the third, and 51 ml g^{-1} in the fourth. Similar results were reported by Daigger and Roper [7], Daigger [8], Lee *et al.* [20], Chang *et al* [5], and Eliosov *et al* [9].

Sedimentation Velocity

Sedimentation velocity was calculated based on the mathematical formula by Akca [1]:

$$V_o = 28.1\,(SVI)^{-02667}$$

Results of the calculations are shown in Table 2. Although the obtained values are approximations, due to certain simplifications in the mathematical model, a strong dependence between the SVI reduction and the increase of sedimentation velocity can be observed (correlation factor $R^2 = 0.953$). The formula does not incorporate the influence of sludge concentration, although according to Daigger and Roper [7] and Daigger [8] an increase of sludge concentration decreases sedimentation velocity because settling is hindered by the high quantity of floes. The mean value of sedimentation velocity in the experimental SBR was 10.5 m h^{-1}, and was similar to obtained by Akca *et al.* [1] who reported the value of 9.9 m h^{-1}. Also Wahlberg and Keinath [26] obtained similar settling velocity; the value they reported was 12.2 m h^{-1} (In both cases the SVI amounted to 50 ml g^{1}). Daigger and Roper [7] in their study observed the settling velocity of 7.8 m h^{-1}.

Dissolved Oxygen Concentration (DO)

Researchers who have analysed factors influencing SVI and sedimentation velocity emphasise the importance of quantity of filamentous forms in sludge, especially bacteria. Palm and Jenkins [23] demonstrated that if the number of filamentous forms in a floe is about 10^4 per millilitre of sludge, the SVI is lower than 100 ml g^{-1}. However, if the number raises to 10^5, the SVI increases to 300-800 ml g^{-1}.

The same authors reported also that high DO concentration in wastewater has a positive impact on reduction of the number of filamentous forms in floes. This phenomenon, observed also by other authors [2, 28, 17] allows to prevent the sludge from bulking in well-aerated treatment systems.

Oxygen concentrations obtained during the aeration phase indicate very good oxygen conditions in the experimental SBR. At the end of this phase it was recorded that the oxygen concentration reached 8-9 mg O_2 1^{-1} which should be regarded as very high. Authors of this study assume that this was the reason for the low SVI obtained in the experiment.

Akca *et al.* [1] related the presence of filamentous forms in sludge floes to the sludge age. They formulated a term "critical DO concentration". In aeration tank, depending on the sludge age, it is the concentration below which the most favourable conditions for sludge bulking are created. Sludge age in this study was calculated based on the mathematical model derived by Akca *et al.* The results are shown in Table 2. The "critical DO concentration" for the min calculated sludge age of 10.7 d was 0.4 mg 1^{-1} and for the max sludge age of 33.2 d it was 0.008 mg 1^{-1}, and was many times lower than the actual values observed in the experimental SBR.

Many researchers [28, 4, 3, 20] are of the opinion that temporary anaerobic conditions have a positive influence on SVI. Anaerobic conditions increase the aggregation of floes which prevents turbidity in the effluent, provided the SVI is below 70 ml g^{-1} (which was the case in the experimental SBR). In the conventional activated sludge method aerobic and anaerobic conditions are hard to obtain in one reactor. In the SBR oxic and anoxic conditions are secured sequentially in the same tank. As a result, sludge has very low volume index and separates very well from purified wastewater. Relation between SVI and the reactor type is shown in Table 3 [27, 19, 8].

Table 3. Relation between SVI and reactor type.

Reactor type	SVI (ml g^{-1})
Continuous flow	20 - 600
Discontinuous flow	100 - 500
Continuous flow with mixing tank before the reactor	70
SBR	40-60
Experimental SBR	30-50

acc. [27, 19, 8].

Low SVI values in SBRs seem to be strongly related to duration of the treatment cycle phases, especially mix phase and react phase. A substantial increase of the initial substrate concentration during mixing phase and prolonged starvation period with very high DO concentration, may have an effect on sludge settleability [15]. Results obtained in the experiment have confirmed this thesis. In the mix phase, lasting 2 h, the SVI was 30 ml g^{-1}. After 2.8 h of aeration it reached 50 ml g^{-1}. Irvine *et al.* [14, 15] in two SBRs at the treatment plant in Culver obtained: 110-200 ml g^{-1} in the first reactor, and 90-150 ml g^{-1} in the second. Mix and react phases lasted 0.2 h and 2.2 h in the first, and 0.4 h and 2.1 h in the second.

Sludge Settleability

This parameter was analysed based on the settling curves [29]. The curves present sludge volume decrease in time. In the experiment, the curves were prepared for the concentrations: 2.5 kg m^{-3}, 3 kg m^{-3}, 3.5 kg m^{-3}, 4 kg m^{-3}, 4.5 kg m^{-3}, 5.5 kg m^{-3} and 6 kg m^{-3}.

For the sludge concentrations between 2.5 and 4 kg m^{-3}, the free settling phase was clearly shown by the curves. The phase lasted till the so-called compression point, which in the experiment was reached after about 10 minutes of the sludge sedimentation. Free settling was followed by the compression settling which resulted in deterioration of the macro structure of floes. The sludge concentration increased significantly, up to 20 kg m^{-3}. Hanel [11] reported that in well settling sludge, at very long sedimentation time, sludge concentration can rise even to 25 kg m^{-3}. However, it can only reach 1-2 kg m^{-3} in bulking sludge.

In the sludge concentrations over 4 kg m^{-3} it was hard, or even impossible, to distinguish the compression point. Increase of sludge quantity per volume unit decreases sedimentation velocity through the mutual impediment of settling floes. This phenomenon is called "hindrance effect".

In the sludge concentrations of 4.5 kg m^{-3} and 5 kg m^{-3} settling was strongly hindered. For most of the 1-hour test the compression settling took place, and in the concentration over 5 kg m^{-3} only compression was observed.

Generally, it was observed that with the sludge concentration increase, settling velocity decreased, and also the "steepness" of the settling curves. However, this tendency was not so clearly visible as in the case of activated sludge from the conventional systems [11, 29]. Shape of a settling curve (and thus the sludge settleability) is more determined by technological parameters, such as loading, wastewater temperature and DO concentration, than by sludge concentration. The ratio of SVI after 15-minute sedimentation to SVI after 30-minute sedimentation confirms that. As shown in Table 4, the ratio is optimal in low sludge concentrations, then gradually rises with the concentration increase, but again reaches the optimum value at the highest sludge concentration. In the experiment, the optimal ratio of 1.21 was observed at the sludge concentration of 6 kg m m^{-1}. The obtained ratio values ranged between 1.21 and 1.34 which means that irrespective of the sludge concentration in the examined range, the sludge settleability in the experimental SBR was good. In consequence, it is possible to shorten the settle phase and to prolong the mix and react phases, within the same length of the whole cycle. Such modification should increase the treatment efficiency.

Table 4. Ratio of sludge volume after 15-min settlement to 30-min settlement.

Sludge concentration (kgm^3)	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
SVI 15 min/30 min	1.27	1.25	1.29	1.25	1.29	1.31	1.34	1.21

The rate of SS concentration change during the settle phase, measured at three depths of the reactor, is more evidence of good sludge settleability. As presented in Table 5, SS concentration at the end of the settle phase decreased distinctly below 30 mg 1^{-1}. The concentration was relatively high at the surface (max sampling level) which was related to the presence of colloidal fractions of SS.

Table 5. Suspended solids concentration in settling wastewater.

Sampling level	Sludge concentration (mg 1^{-1})					
	2.7 (kg m^{-1})		4.5 (kg m^{-1})		5.5 (kg m^{-1})	
	S(a)	E(b)	S	E	S	E
Max	2 640	10.2	4 080	24.5	5 046	28.5
Mean	2 964	8.7	5 200	18.3	6 730	9.5
Min	3 873	9.5	5 846	23.3	8 430	26.1

(a) - sampled 5 min after settle phase start (S)
(b) - sampled 10 min before settle phase end (E)

In the examined range of the activated sludge loadings, the surplus sludge production ranged from 0.21 to 0.40 kg SS kg^{-1} BOD_5. Low sludge loadings, high values of the sludge age and the very high DO concentrations in the reactor during the react phase can be the reason for such small sludge growth.

Conclusions

The results of the experiment allow the authors to make the following conclusions:

1. Proper oxygen conditions i.e. anaerobic stress, applied in succession with highly aerobic conditions, resulted in very good settling qualities of the sludge biomass.
2. Low SVI and high settling velocity were responsible for an intense and short sedimentation, and at the same time prevented the sludge from bulking.
3. High velocity of sludge settling allows a shortening of the settle phase to less than one hour and still to assure good separation of the sludge from the treated wastewater.
4. Despite very low SVI, there is no threat of turbid effluent from the SBR, so typical for the conventional treatment methods.
5. A high concentration of DO during aeration combined with low sludge loadings resulted in a small sludge biomass growth. It may be of key importance for sludge disposal due to small surplus sludge production and its preliminary stabilisation in the reactor.

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