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Wastewater treatment in a hybrid activated sludge baffled reactor

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Abstract

A novel hybrid activated sludge baffled reactor (HASBR), which contained both suspended and attached-growth biomass perfect mixing cells in series, was developed by installing standing and hanging baffles and introducing plastic brushes into a conventional activated sludge (CAS) reactor. It was used for the treatment of domestic wastewater. The effects on the operational performance of developing the suspended and attached-growth biomass and reactor configuration were investigated.

The change of the flow regime from complete-mix to plug-flow, and the addition of plastic brushes as a support for biofilm, resulted in considerable improvements in the COD, nitrogen removal efficiency of domestic wastewater and sludge settling properties. In steady state, approximately 98 ± 2% of the total COD and 98 ± 2% of the ammonia of the influent were removed in the HASBR, when the influent wastewater concentration was 593 ± 11 mg COD/L and 43 ± 5 mg N/L, respectively, at a HRT of 10 h. These results were 93 ± 3 and 6 ± 3% for the CAS reactor, respectively. Approximately 90 ± 7% of the total COD was removed in the HASBR, when the influent wastewater concentration was 654 ± 16 mg COD/L at a 3 h HRT, and in the organic loading rate (OLR) of 5.36 kg COD m^{-3} day^{-1}. The result for the CAS reactor was 60 ± 3%.

Existing CAS plants can be upgraded by changing the reactor configuration and introducing biofilm support media into the aeration tank.

Keywords: Wastewater treatment; Activated sludge; Hybrid activated sludge baffled reactor; Biofilm

1. Introduction

More than 80% of biological wastewater plants are based on the principle of activated sludge process, in which suspended bacteria oxidise the carbonaceous and nitrogen compounds to produce an effluent that is in accordance with legal standards, and that corresponds to a minimal environmental impact. The increase of organic and hydraulic loads, related to the improvement of wastewater collection, and the implementation of new European directives and national regulations, often leads to discharges which do not comply with the standards. A new deal for wastewater engineers is now to stretch the performance of existing infrastructure, which represents one of the most significant challenges to the practice of wastewater engineering [1]. Currently, innovative processes are on the market, like the sequencing batch reactor (SBR) [2], membrane processes [3] and attached or hybrid growth processes [4].

Upgrading overloaded conventional activated sludge (CAS) treatment plants is a promising solution, particularly when they have space limitations or need modifications that will require large investment. Upgrading activated sludge treatment plants for the enhancement of the COD removal, nitrification, denitrification and sludge settling properties, can be achieved by optimising the existing system by changing the bioreactor configuration, or/and changing to a higher biological capacity process, with a combination of suspended and attached-growth processes.

In the first case, it has been definitely shown that the hydrodynamics of the process have an effect on rates of pollution removal, on the global kinetics of organic matter degradation and on the sludge settling properties. The hydrodynamics of the process are primarily dependent on the geometric characteristics of the reactor system, such as the configuration and the size of the reactor, and on the characteristics of aeration dynamics [5–7]. Filamentous bulking can be controlled by changing the hydraulic regime of the reactor from complete-mix to plug-flow. Pilot scale experiments indicate that a plug-flow configuration produces sludge with significantly better settling characteris-

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tics than a conventional system [8]. Residence time distribution (RTD) experiments make it possible to characterise the hydrodynamics for different flow rates and geometrical parameters. Modelling the RTD may be carried out in a plug-flow reactor with an axial distribution; or in perfect mixing cells in series, with a back-mixing model [6].

The second way also widely accepts that CAS process, combined with biofilm support media in the aerobic zone, has been demonstrated as an alternative design for biological nitrogen removal, as well as a cost-effective option for retrofitting wastewater treatment plants [9–12]. The performance of an integrated fixed-film activated sludge (IFAS) system was compared to a CAS system, in the field of biological nutrient removal (BNR) [10].

A hybrid aerated submerged fixed film (HASFF) process system could be a viable option for upgrading activated sludge treatment plants, because the HASFF process achieved overall BOD_5 removal efficiencies of more than 94% at an HRT of 2 h with a four-fold increase of the organic loading rate, which indicated the robustness of hybrid reactors [11].

An activated sludge biofilm wastewater treatment system (ASBWTS), which is a CAS process combined with plastic nets fitted inside an aeration tank, presents the positive effect of the plastic nets on BOD_5 removal efficiency and sludge settling properties [13]. BOD_5 removal increases from 17.5 to 25%, according to the number of nets. Accordingly, wastewater treatment with an activated sludge system contained both suspended and attached growth and it can be called hybrid biological reactor (HBR) [14]. This technology has many advantages, like small area requirements, high biomass concentrations, high SRT and low sludge production rates, etc. There are, however, some disadvantages, such as biofilm control difficulties.

As far as the bibliography is concerned, the use of hybrid reactor systems for treating organic matter and nutrients in wastewater is an innovation that could be suitable for increasing the capacity and the efficiency of wastewater treatment plants (WWTP) [15].

To combine hydrodynamics effects and the adding of a carrier in a CAS reactor, a novel hybrid system, which uses suspended as well as attached biomass, has been developed and examined in this study. The hybrid activated sludge baffled reactor (HASBR) was constructed by installing the standing and hanging baffles and introducing a plastic support into a CAS reactor. The HASBR, with a novel configuration and biofilm support in the aerobic zone, may be an alternative design for upgrading the CAS process without increasing its physical tankage and to sustain nitrification, without significantly increasing the sludge quantity to be treated.

The objective was to investigate the system's feasibility as an upgrading tool to any existing activated sludge facilities for the anticipated increase in hydraulic and organic loading, without additional tank construction. It also was to examine the performance of the HASBR in terms of organic removal, under normal operating conditions, as well as under excessive hydraulic loading rates.

The performance of the HASBR was investigated by comparing this reactor to a CAS reactor, a hybrid activated sludge (HAS) reactor and to an activated sludge baffled reactor (ASBR).

The following outcomes were expected:

1. Reduction in the aeration tank volume upon introduction of biofilm support media and change in the flow regime in the aeration tank to meet a certain treatment objective.
2. An increase in the treatment system stability and performance in existing or newly developed CAS processes.

2. Materials and methods

2.1. Experimental set-up

Two sets of activated sludge reactors were operated concurrently. The experimental design used in this study is shown in Fig. 1. Table 1 presents the design details for two reactors (see

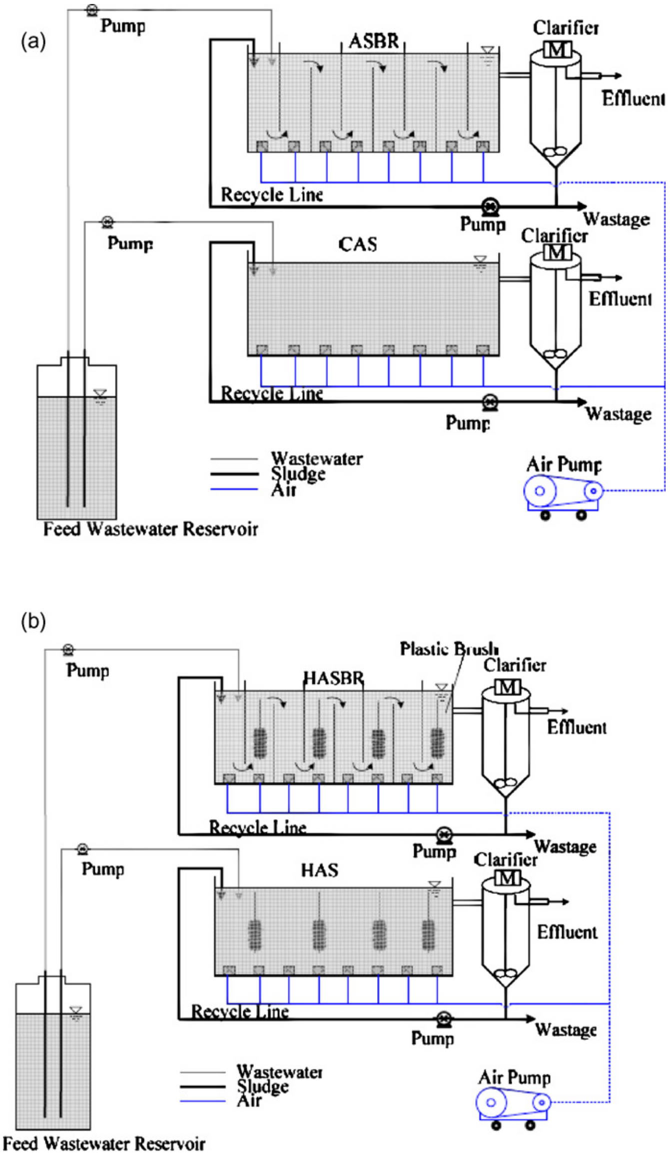

Fig. 1. Schematic diagram of experimental treatment of the suspended growth and the hybrid system.

Table 1
Characteristics of laboratory biological reactors

Biological reactor	HASBR	CAS
External dimension (cm)		
Length	58	58
Width	25	25
Height	28	28
Working volume (L)	27.5	27.5
No. of compartments	4	1
Compartment volume (L)	6.75	27.5
Liquid depth (cm)	20	20
Settling tank volume (L)	8.3	8.3

Fig. 1a). Two Plexiglas tanks with a 27.5 L effective volume were used as the aeration tank. The basic design for the CAS reactor was a rectangular reactor. The ASBR was a rectangular reactor with internal vertical baffles alternately hanging and standing. These baffles divided the ASBR into four compartments. Baffle spacing was determined by making the compartments equal in size, and keeping the same width to upward and downward flow in each compartment. In the hybrid case, plastic brushes were fitted into the CAS and ASBR reactors.

The aeration tank effluent was carried through an outlet connected by a 1.9 cm diameter pipe to the clarifier. Air was supplied through porous ceramic diffusers, located at the base of the tank. Adequate mixing was provided by the effect of the rising air bubbles. The secondary settling tank had an overall liquid depth of 50 cm and consisted of a 10 cm internal diameter cylinder joined to a conical bottom (10 cm in height). A wire, bent to conform to the inside of the cone, was rotated by 5 rpm. The clarifier volume was maintained constant at 8.3 L.

The experimental program consisted of two phases. In phase 1, an ASBR was compared to a CAS reactor (Fig. 1a). In phase 2, a HASBR was compared to HAS and CAS reactors (Fig. 1b). The attached biomass was developed on plastic brushes, 12 cm in length and 4 cm in diameter (Bioblock-France). Each brush had 5250 bristles 2.0 cm long, with a diameter of 0.3 mm, yielding a total surface area of 0.40 m^2 during the first run in the HAS and HASBR reactors, and 0.80 m^2 in the HASBR during the other runs. The brushes were completely immersed in the biological reactor. Organisms grow in the form of biofilm on the surfaces of the brush structures and rod surfaces. The biofilm area, per unit wastewater volume, was 14.8 $m^2\,m^{-3}$ during the first run in the HASBR and HAS reactors and 29.6 $m^2\,m^{-3}$ during the other runs in the HASBR. The biomass concentration in steady state on the rod and brush surface in form of biofilm was approximately $40 \pm 2\,g\,m^{-2}$. The volume fraction occupied by the plastic brushes without biofilm, varied from 3 to 6% of the effective volume of the tank.

The reactors were fed continuously with settled municipal wastewater by a Masterflex peristaltic pump (model 7529-90, Cole Parmer, USA) to the wastewater holding (100 cylindrical plastic tank) and then to the reactors, by two Masterflex peristaltic pumps (model 7518-10, Cole Parmer, USA). The effluent from the reactors was withdrawn by gravity. Activated sludge was recycled by two Masterflex pumps (model 7518-10, Cole Parmer, USA).

2.2. Operation conditions

The experimental study was carried out at the Limoges municipal WWTP (Limoges, France). The characteristics of the settled municipal wastewater during the different experimental runs are shown in Table 2.

Activated sludge taken from Limoges (France) municipal WWTP was inoculated into the reactors. For each start-up, approximately 10 L of recycled activated sludge was collected from the secondary clarifier recycling line and was inoculated on the same day to every reactor. A solid test was performed on the sludge to determine its concentration (7–9 $g\,L^{-1}$), and the sludge was diluted with water to a desired concentration about 3 $g\,L^{-1}$. The system was operated under batch mode for nearly 12 h without influent to aeration of the sludge. In phase 2, the reactors were operated under continuous aerobic conditions for

Table 2
Operating parameters of the reactors

Parameters	Phase 1	Phase 2 Run 1	Phase 2 Run 2	Phase 2 Run 3	Phase 2 Run 4	Phase 2 Run 5
Time (day)	50	1–64	65–90	90–115	116–142	143–174
Influent Organic loading (mg COD/L)	545 ± 73	443 ± 134	593 ± 11	590 ± 106	674.5 ± 56	654 ± 16
NH_4^+-N influent loading ($mg\,L^{-1}$)	–	37 ± 9	43 ± 5	46 ± 9	48 ± 5	42 ± 7
HRT (h)	10	10	10	7	5	3
SRT (day)	13	13	13	13	13	13
TSS ($g\,L^{-1}$)						
HASBR	2.4–3.5	2.2–3.3	2.2–3.3	2.2–3.3	2.2–3.3	2.2–3.3
CAS	2.2–3.4	2.2–3.3	2.2–3.3	2.2–3.3	2.2–3.3	2.2–3.3
Total surface area of plastic brushes (m^2)						
HASBR	0	0.4	0.8	0.8	0.8	0.8
CAS	0	0.4	0	0	0	0
Biofilm area per unit wastewater volume ($m^2\,m^{-3}$)						
HASBR	0	14.8	29.6	29.6	29.6	29.6
CAS	0	14.8	0	0	0	0
Average OLR (kg COD $m^{-3}\,day^{-1}$)	1.6	0.98	1.42	2.04	3.24	5.36

1 month, in order to grow biofilm on continuously fed wastewater. Sludge wasting was manually performed and the wasted volume was recorded on a daily basis. The experiments were conducted indoors, at an operation temperature of 18–22 °C. The steady-state condition was considered reached when repetitive analytical results were obtained.

2.3. Operation procedures

Detailed operation parameters are shown in Table 2. Each experimental run lasted in 3–4 weeks. We aimed to take the grab samples at the same time of each experimental day. Hydrodynamics model of every reactor was determined by RTD techniques. Tracer tests with NaCl pulse addition were used to investigate the hydraulics of the tank. The conductivity in the effluent was detected and RTD curves were generated. For the RTD analysis, the following procedure was used: after calculating RTD curves or $E(t)$ values, the RTD curves were standardised for the experimental RTD. To simulate the reactors, the DTS, PRO v.4.2 was used [16]. It made possible the construction of properly interconnected complex network of elementary reactors (such as plug-flow reactors, perfect mixing cells in series and perfect mixing cells in series exchanging with a dead zone) and the optimisation of the parameters of the experimental curves.

2.4. Analytical procedures

The TSS, VSS and SVI were analysed in accordance with Standard Methods for the Examination of Water and Wastewater [17] (after filtration with a 1.2 μm membrane). The COD and, NH_4^+-N, were analysed according to Dr. Lange's test, (LCK 414, LCK 114), (LCK303), respectively. Temperature, pH, dissolved oxygen (DO) were also determined using a WTW Multiline P4.

3. Results and discussion

Under the same influent wastewater concentrations, the effect of the reactor configuration and fixed-film biomass on COD removal efficiency, nitrification performance and sludge settling properties were studied by comparing the performance the ASBR to the CAS reactor, the performance of the HASBR to the CAS and to the HAS reactors. These treatment regimes were tested in parallel in the reactors.

3.1. Reactor hydrodynamics studies

First of all, the hydrodynamics behaviour of the reactors treating municipal wastewater was characterized by means of a RTD technique, using NaCl as a tracer, to monitor hydraulic flow regime in the ASBR and the CAS reactors and the presence of dead spaces, or short cuts, in the reactors. During the RTD experiments, the working flow was 2.75 L h^{-1}, which implied a mean residence time of 10 h for each reactor, without water recirculation. To ensure proper mixing, air is dispatched into the biological reactors through many diffusers.

As shown Fig. 2, little difference in mixing or dead space was observed in this test, because the obtained curves look like theoretical RTD, without significant loss of shape. A little short cut noticed in the first compartment of the ASBR, and the average dead zones measured within the reactors, were between 1.5 and 10.1%. Flow patterns within the compartments of the ASBR showed an intermediate behaviour between plug-flow and ideally mixed. The RTD experimental results represent the main flow in the compartments and the obtained theoretical volume in each compartment were nearly equal (≤±10.1).

A model, including ideal perfect mixing cells in series, has two parameters: the mean residence time (τ) and the number of mixing cells (J) were used. Fig. 2 shows the comparison between experimental (Fig. 2a and c) and theoretical RTD results (Fig. 2b

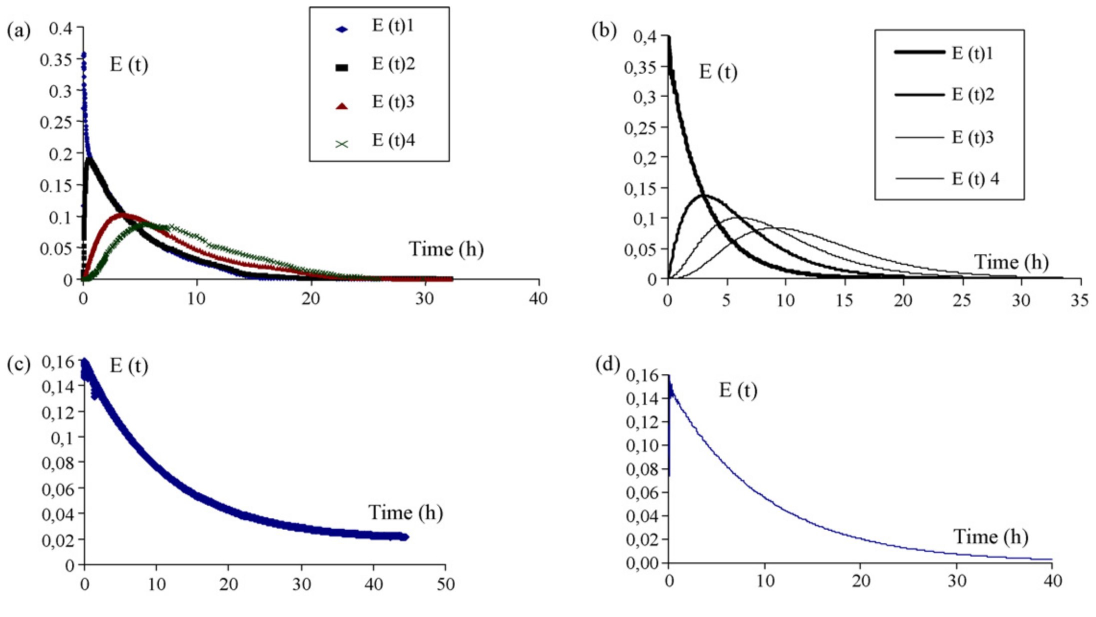

Fig. 2. Comparison between experimental and theoretical RTD in each compartment of the HASBR for $J = 4$ (a and b) and in the CAS reactor for $J = 1$ (c and d).

and d), using $J=1$ for the CAS reactor (Fig. 2d) and $J=4$ for the ASBR (Fig. 2b). The agreement between the experimental and theoretical results, and the consistency of the parameters, demonstrate the validity of the proposed model. Fig. 2b shows the result of simulation in each compartment carried out with $J=4$, that is to say four reactors in series. The value of $J=4$ is sufficient for global simulation of flow regime into the ASBR (curve $E(t)$ 4 in Fig. 2a and b). It is possible to consider, in a simple approach, that the CAS reactor is really a completely mixed reactor and that the hydrodynamics in the ASBR tend towards a cascade reactor with an axial dispersion, modelled with four perfect mixing cells in series. The same experiments were done including plastic brushes (but without biomass) and the difference between experimental results, with and without plastic brushes, was negligible for two reactors, because the volume of the plastic brushes was negligible in the reactors (3–6% of total volume). This result could be used in further studies in order to combine biological reactions and the hydrodynamics model [6].

3.2. Reactor performance

Fig. 3 shows the total COD and $NH_4{}^+$-N removal efficiency and sludge settling properties (in term of SVI-values). The operation conditions were similar in respect to organic loading rate (OLR) of 1.4 kg COD m^{-3} day^{-1}, SRT of 13 days and hydraulic retention time (HRT) of 10 h. The organic (volumetric) loading rate defined as the amount of COD applied to the aeration tank volume per day. The average dissolved oxygen (DO) was maintained above 2 mg L^{-1} in the reactors, allowing oxygen to penetrate into the biofilm. The average of 87% and 97% total COD removal efficiencies were obtained in steady state, for the CAS reactor and the HASBR, respectively, as the minimum and maximum of the total COD removal efficiency among four reactors. The reduction of the total COD in the hybrid systems (HAS and HASBR) was better than the suspended growth reactors (CAS and ASBR); and in the ASBR, it was better than the CAS reactor in the same operation mode (Fig. 3). The difference is due to the existence of the biofilm in the hybrid reactors and the plug-flow hydraulic regime in the ASBR. These results confirm the competence of our hypotheses and agree well with data from the literature [8,18–20].

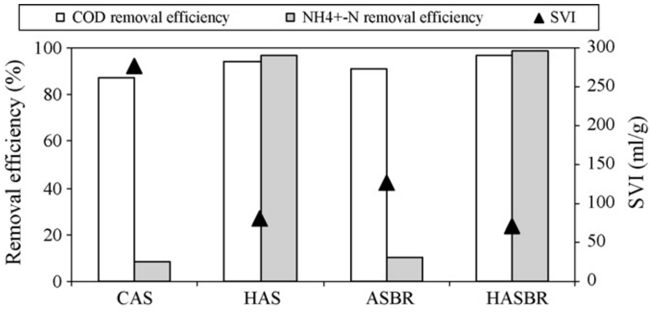

Fig. 3. The average total COD and $NH_4{}^+$-N removal efficiencies and the average SVI values in four reactors.

Fig. 3 also shows the character of $NH_4{}^+$-N removal in the reactors. The positive effect of fixed biomass on $NH_4{}^+$-N removal efficiency can be clearly demonstrated in the reactors. The removal of $NH_4{}^+$-N in steady state, was about 97 and 98% on average, for the HAS reactor and the HASBR, respectively. The removal of $NH_4{}^+$-N in steady state in the CAS reactor and the ASBR are less than 10% in average.

The important factor that may have contributed to these results is the presence of biofilm support media in which a nitrifying population was established. A previous study showed that all the consumption of $NH_4{}^+$-N was due to the biofilm synthesis in a hybrid system [21].

The average SVI-values in steady state are shown in Fig. 3. As the SVI decreases, the settling efficiency increases [8]. SVI-values in steady state were about 277 and 126 mL g^{-1} on average in the CAS and ASBR reactors, respectively. The sludge had very poor settling properties in the CAS reactor, but they were much better in the ASBR. In the previous study, it was showed that SVI was lower than 250 mL g^{-1} in plug-flow reactor but it did exceed to 800 mL g^{-1} in the CAS reactor, under the same operation conditions [8]. The other study carried out by Roche [22] indicated that, changing the hydraulic regime of a reactor from complete-mix to plug-flow regime has a significant effect on the sludge settling properties.

No problems have been noticed with the excessive growth of filamentous microorganisms in the HAS and HASBR. The SVI-values in the hybrid systems (HAS, HASBR) did not exceed 100 mL g^{-1}. Moreover, the sludge settling properties are maintained in the processes (e.g. SVI, settling rate, ...) [23]. The results presented in Fig. 3 agree well with the data from literature [21]. In the other study, the SVI decreased from 350 to 38 mL g^{-1}, after the addition of the biofilm into the CAS system [13].

3.3. Effects of increasing the organic loading rate on COD removal efficiency and sludge settling in the CAS and HASBR

The effect of the organic loading rate on the COD removal efficiency of CAS and HASBR reactors was evaluated (Fig. 4a). The OLR was increased from 1.4 to 5.6 kg COD m^{-3} day^{-1}, at four different HRT of 10, 7, 5 and 3 h.

The HASBR clearly demonstrates greater total COD removal efficiency than the CAS reactor.

The average total COD removal efficiency at 1.4, 2.1, 3.24 and 5.6 kg COD m^{-3} day^{-1} corresponds to HRT of 10, 7, 5 and 3 h were 93, 91, 86 and 60% in CAS reactor and 98, 97, 96 and 90% in HASBR. The total COD removal efficiency of the CAS reactor decreased by 33%, but it decreased by 8% in the HASBR reactor, while increasing the organic loading rate to four-fold. Previous studies showed that the reduction of COD increased from 51 to 90% in an upgraded activated sludge system with floating carriers [20]. These results indicate that the hybrid system is resilient to organic shock loads, thereby offering a viable upgrading option for CAS treatment plants [11].

The SVI-values of the CAS and HASBR reactors is shown in Fig. 4b. When the HRT was decreased, filamentous bulking took

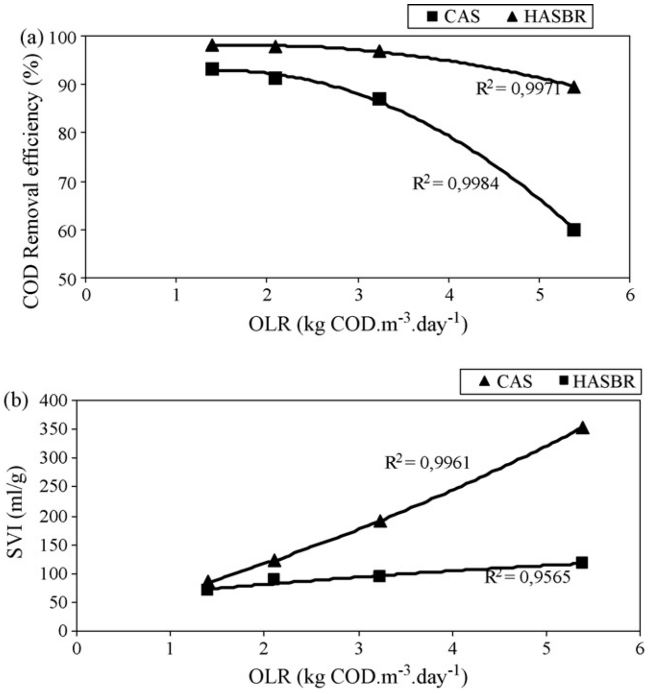

Fig. 4. The effect of organic loading rate (OLR) on average COD removal efficiency (a) and sludge settling (b) in the CAS and HASBR.

place in the CAS reactor. On OLR of 5.6 kg COD m^{-3} day^{-1} (HRT of 3 h), the SVI value in average increased rapidly and exceeded 400 mL g^{-1} in the CAS reactor, but in the HASBR, the SVI value in average was about 110 mL g^{-1} in the same operation mode. In a previous study, an improvement of the sludge settling rate after adding fixed-film support media was reported [21]. No problems associated with excessive growth of filamentous microorganisms were reported for hybrid reactors [9].

3.4. *Effects of decreasing the HRT on the nitrification performance of the CAS and HASBR reactor*

Fig. 5 shows the NH_4^+-N removal efficiency values in average in the CAS and HASBR reactors. The positive effect of fixed biomass on NH_4^+-N removal efficiency can demonstrate in the HASBR reactor. The HASBR and the CAS reactors were operated at a SRT of 13 days in different HRT of 10, 7, 5 and 3 h. In the CAS, average NH_4^+-N removal efficiencies at 10, 7, 5 and 3 h were 8, 9, 10 and 9% in average corresponding to 98, 55, 37 and 27% in an average of the HASBR (Fig. 5). During the operation of the CAS, no significant consumption of NH_4^+-N was observed in this system. All NH_4^+-N consumption in the HASBR was due to the attached biomass synthesis, because the HRT value was small to admit the growth of the nitrifying bacteria. The NH_4^+-N removal efficiency in the HASBR significantly decreased, with decreasing the HRT, but it was about 27% at a low HRT (Fig. 5). These results agree well with the data from literature [14,24].

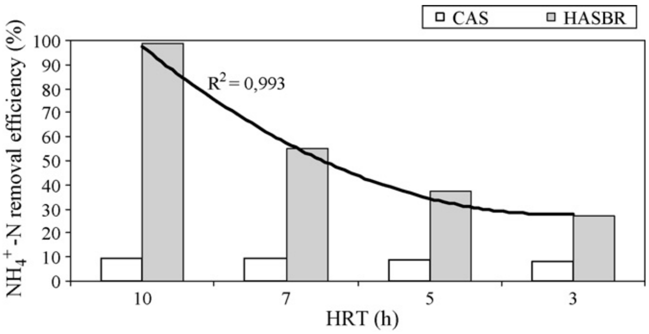

Fig. 5. Effect of HRT on NH_4^+-N removal efficiency of the CAS and HASBR reactors.

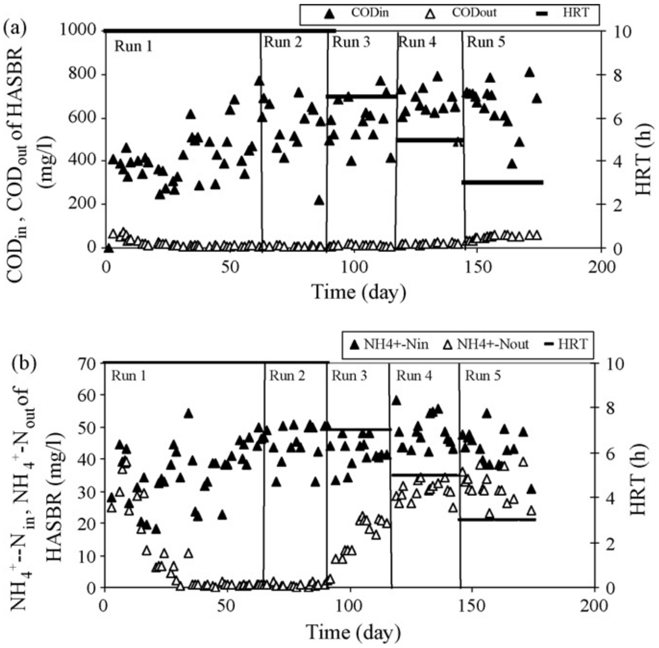

Fig. 6. Course of total COD (a) and NH_4^+-N (b) concentrations in influent and effluent of HASBR reactor.

3.5. *Long period experiments of the CAS and HASBR reactors*

Fig. 6a shows the characters of COD removal under five different conditions, which included influent and effluent total COD. In the first run, the HASBR was compared to the HAS reactor and in runs 2–5, the HASBR, was compared to the CAS reactor, under the same operation conditions (Table 2). The total HRT was 10, 7, 5 and 3 h, respectively, excluding the time in the clarifier. The results of the HASBR for the influent and effluent total COD concentrations are shown in Fig. 6a.

It was observed that average total COD in the effluent was 8 mg L^{-1} at an HRT of 10 h, but it was 48 mg L^{-1} at an HRT of 3 h, in the reactor in steady state. As seen in Fig. 6a, the effluent total COD concentration decreased slightly with a fourfold increase of OLR.

The average effluent concentration of NH_4^+-N in the HASBR is presented in Fig. 6b. The effluent concentrations of NH_4^+-N in steady state were about 0.8, 0.6, 18, 32 and 32 mg L^{-1} on average, corresponding to 36, 46, 43, 49 and 42 mg L^{-1} of influent concentration of NH_4^+-N. In the second run, as the biofilm area per unit wastewater volume was increased from

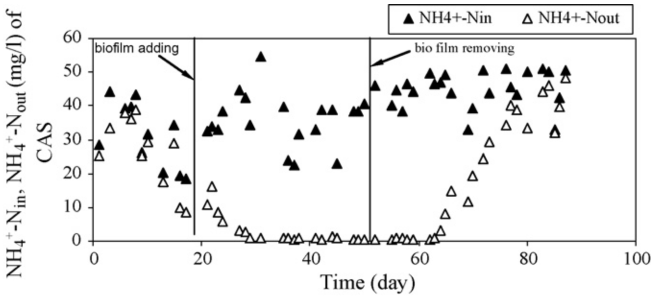

Fig. 7. Course of NH_4^+-N concentrations in influent and effluent in the CAS reactor at HRT = 10 h.

14.6 to 29.8 $m^2\,m^{-3}$, the effluent concentrations of NH_4^+-N then decreased very slightly; but it increased significantly when the HRT decreased. The best NH_4^+-N removal efficiency was occurred at HRT of 10 h. Yang and co-workers [25] reported that, the removal of ammonia in a submerged membrane bioreactor at a HRT ≥10 h was over 98%, whereas this rate was significantly lower in CAS reactor in the same operation conditions.

Fig. 7 shows the NH_4^+-N concentration values in the influent and effluent of the CAS reactor in the first and second runs. About 3 weeks after adding biofilm support media, the effluent NH_4^+-N started to decrease significantly and any days after removing the biofilm support media, the effluent NH_4^+-N concentration started to increase significantly.

4. Conclusion

The following conclusions were drawn from the results obtained during this investigation.

1. Approximately 98 ± 2% of total COD and 98 ± 2% of ammonia of the influent was removed in the HASBR, when the influent wastewater concentration was 593 ± 11 and 43 ± 5 $mg\,L^{-1}$, respectively, at HRT of 10 h. These results were 93 ± 3 and 6 ± 3%, respectively, for the CAS reactor.
2. Approximately 90 ± 7% of total COD was removed in the HASBR, when the influent wastewater concentration was 654 ± 17 $mg\,L^{-1}$ at HRT of 3 h and an OLR of 5.36 $kg\,COD\,m^{-3}\,day^{-1}$. The result for the CAS reactor was 60 ± 3%.
3. The SVI-values were 400 and 112 $mL\,g^{-1}$ at HRT of 3 h in the CAS and the HASBR reactors, respectively.

Some of the implications derived from this study are:

- Existing activated sludge systems can be upgraded easily, by simply fitting baffles and biofilm support media inside the aeration tank, thus eliminating the need for constructing new extensions.
- COD and nitrogen removal efficiency and system stability can be increased in existing activated sludge systems. The HASBR gives more flexibility in the operation of an overloaded wastewater treatment plant. Increasing the organic loading rate by four-fold had a minor effect on the total COD removal efficiency in the HASBR.

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