

ORGANIC AND HYDRAULIC SHOCK LOADINGS ON A BIOLOGICAL AERATED FILTER

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ABSTRACT

The performance of a biological aerated filter (BAF) during short-term (60 min) organic and hydraulic shock loads was investigated. The BAF used for the present experiment was not capable of absorbing high peak organic shock loads when the organic loads were increased from a normal load of 1.2-1.4 kg soluble chemical oxygen demand (sCOD) m⁻³ d⁻¹ to shock loads between 5.1-7.3 kg sCOD m⁻³ d⁻¹, based on empty bed volumes. Nevertheless, the effect on the biomass was limited as normal performance resumed very quickly. Increases in the hydraulic velocity from 0.7-1.0 m h⁻¹ to 1.5-2.9 m h⁻¹ had little effect on BAF performance in terms of soluble COD removal. Yet, sCOD effluent concentrations of <55 mg l⁻¹ (~22 mg l⁻¹ biochemical oxygen demand) were always achieved. The recovery of the reactor in both cases was fast, resuming normal performance within 60 min after the application of the shock load.

Keywords: Biological aerated filter, organic shock loads, hydraulic shock loads

INTRODUCTION

Wastewater treatment works have to be able to cope with changes in the composition of the wastewater and daily fluctuation in flow. Although the installation of flow-equalization, flow-splitting and bypass facilities should be able to deal with peaks, it is essential that the unit processes are sized to cope with variable flowrates. Sudden increases in substrate concentrations and peak hydraulic flowrates are often the cause for failing discharge consents [1].

It has been suggested that shock loads in continuous flow biofilm reactors such as biological aerated filters (BAFs) cause stratification and uneven distribution of the biomass thus limiting the ability of the reactor to respond [2]. However, there is no general consensus about the resistance of BAFs to shock loadings. Biological aerated filters can run under plug-flow conditions [3] and treat organic shock loadings through a gradual reduction in concentration [4]. According to some authors [5], plug-flow fixed-bed biofilm reactors tend to have species, population size and activity stratification along the reactor length in the direction of the flow. Therefore, if the feed concentration or the flowrate is increased, some components of the wastewater are

transported to zones of the reactor where the required microorganisms are not present in adequate numbers. Moreover, high peak loadings may cause breakthrough of organic matter [6]. Although it has been suggested that high concentrations of toxic matter, acids and alkalis have a negative impact on BAF performance, under normal circumstances recovery can be quick due to the adaptability of the biofilm [7]. This adaptability could make BAFs resistant to shock hydraulic and organic loads when treating wastewater with phenolic compounds [8].

On the other hand, disagreement exists concerning the most representative substrate to use for modelling. Some authors [9] used total organic loading as the design criterion to size the tank volume of BAFs. Moreover, filter design should be based on total organic loadings since it appears to give much better correlation between rates and loads than a design based on soluble organic matter [10]. However, since different wastewaters have different fractions of soluble biochemical oxygen demand (sBOD) and soluble chemical oxygen demand (sCOD), the use of total organic loading may be too simplistic [11]. Therefore, the impact of soluble organic loading must be considered for BAF design as the treatment performance of the system was better correlated with sCOD

volumetric loading rates [11].

In many wastewater treatment plants, peak influent flowrates as well as biochemical oxygen demand (BOD) and suspended solids (SS) loadings can reach two or more times average values [1]. Previous studies have found that BAFs are capable of treating seasonal changes in influent characteristics [12]. It has also been found that BAFs are capable of performing satisfactorily under unsteady-state conditions [13]. The study of the impact of hourly short-term variations on BAFs, e.g. those caused by the habits of community residents or industrial activities, have been limited [14]. Therefore, the objective of this work was to monitor the performance of a biological aerated filter during organic and hydraulic shock loads.

MATERIALS AND METHODS

Experiments were undertaken in a cylindrical polyvinyl chloride (PVC) reactor with an overall height of 3 m and diameter of 0.2 m (Figure 1). The reactor contained 38 l of quartz sand spherical media, with a diameter of 2-3.2 mm, a specific surface area of $1500 \text{ m}^2 \text{ m}^{-3}$ and 40% voidage. The reactor was operated in downflow mode through a media bed

2 m deep. Tracer studies previously undertaken to determine the hydraulic characteristics of the reactor demonstrated that plug-flow conditions prevailed within the media bed [15]. During all experiments, primary settled sewage was introduced at the top of the column at a flowrate of 0.4 l min^{-1} ($0.576 \text{ m}^3 \text{ d}^{-1}$; 1.8 m h^{-1}). The overall column of water was 3 m and was kept constant by means of an overflow at the top of the reactor. In order to determine if the zone without media would provide any changes in the removal capacity of the downflow BAF, wastewater samples were taken at heights of 2 and 3 m. Compressed air was supplied via three aerators (Degremont UK, Dunstable, UK) at a flowrate of 4 l min^{-1} . The reactor was backwashed daily using tap water to avoid clogging. The backwashing cycle of the reactor involved turning off the feed pump and air for 5 min; the backwashing air was then switched on for 5 min, followed by 10 min of backwash water (along with backwash air), 5 min of backwash water without air, 5 min without air water and finally the restoration of feed pump and air to resume normal operation.

During organic shock loadings the hydraulic flowrate remained constant and the organic loading was increased by adding artificial sewage to the primary settled sewage until it

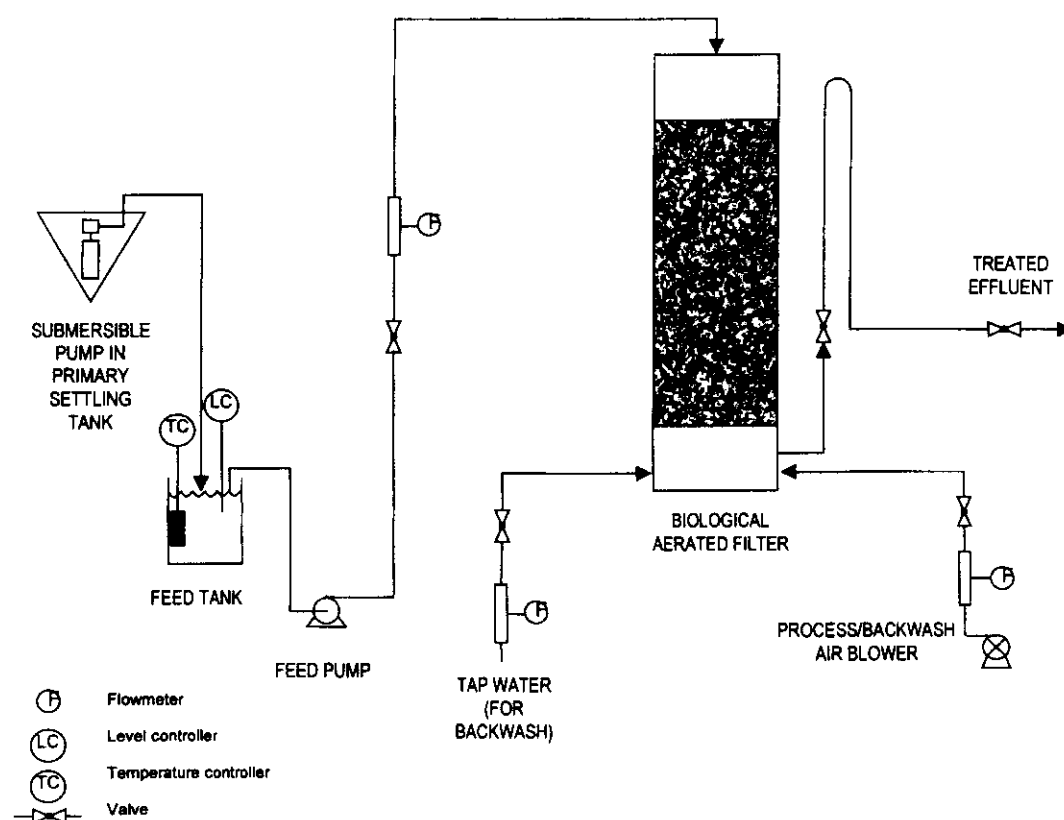


Figure 1. Schematic diagram of the downflow BAF.

reached the desired strength. Due to the composition of the artificial sewage (Table 1), the chemical oxygen demand (COD) of the wastewater was increased but the concentration of suspended solids (SS) was not affected.

Five organic shock loadings (OSL) were applied (Table 2). Due to the variable characteristics of the wastewater, a

Table 1. Artificial sewage composition (from Sterritt and Lester, 1981) [16].

Reagent	g l ⁻¹
Neutralised Bacterial Peptone (L34) [†]	7.80
Lab Lemco (L29) [†]	5.20
NH ₄ Cl [‡]	2.40
NaCl [‡]	0.30
KH ₂ PO ₄ [‡]	0.20
CaCl ₂ [‡]	0.16
MgSO ₄ · 7H ₂ O [‡]	0.05

[†]Oxoid Ltd, Milton Keynes, UK

[‡]Merck Ltd, Leicester, UK

constant organic loading for all shock loads was not reached but fell within a range (Table 2). Shock load conditions lasted for 60 min after which normal operating conditions were resumed.

Four hydraulic shock loads (HSL) were undertaken at 2 times the normal hydraulic flowrate for a period of 60 min (Table 3). A fifth hydraulic shock load was applied at 3 times the normal operating hydraulic flowrate of the BAF (HSL 5). Tap water was used to dilute the primary sewage so that the volumetric organic loading remained similar.

During organic shock loadings application, samples of the influent and effluent were taken every 20 min. After the end of the organic shock loads, wastewater sampling was undertaken every 10 min until steady-state conditions were resumed. Influent and effluent samples were taken every 15 min during hydraulic shock loadings. All wastewater samples were analysed for suspended solids (SS) and soluble chemical oxygen demand (sCOD) using standard methods [17].

Table 2. Organic loadings during normal operation and organic shock loads (hydraulic flowrate 0.58 m³ d⁻¹; hydraulic velocity 1.8 m h⁻¹; hydraulic retention time in section with media 63 min).

	Normal operation		Shock load	
	Organic loading based on total EBV*	Organic loading based on media volume	Organic loading based on total EBV*	Organic loading based on media volume
	(kg m ⁻³ d ⁻¹)	(kg m ⁻³ d ⁻¹)	(kg m ⁻³ d ⁻¹)	(kg m ⁻³ d ⁻¹)
OSL 1	1.53	2.26	3.14	4.62
OSL 2	1.59	2.35	4.29	7.06
OSL 3	1.76	2.59	5.26	7.75
OSL 4	1.83	2.70	5.91	8.72
OSL 5	1.82	2.68	6.21	9.16

*empty bed volume

Table 3. Organic loadings during normal operation and hydraulic shock loads.

	Normal operation				Shock load			
	Hydraulic flowrate (m ³ d ⁻¹)	Hydraulic velocity (m h ⁻¹)	Organic loading based on total EBV*	Organic loading based on total EBV*	Hydraulic flowrate (m ³ d ⁻¹)	Hydraulic velocity (m h ⁻¹)	Organic loading based on media volume	Organic loading based on media volume
			(kg m ⁻³ d ⁻¹)	(kg m ⁻³ d ⁻¹)			(kg m ⁻³ d ⁻¹)	(kg m ⁻³ d ⁻¹)
HSL 1	0.58	1.8	1.03	1.52	1.25	3.7	0.67	0.99
HSL 2	0.72	2.2	1.67	2.46	1.34	4.0	1.67	2.47
HSL 3	0.72	2.2	1.16	1.71	1.22	3.7	1.09	1.61
HSL 4	0.50	1.6	0.68	0.93	1.15	3.6	0.82	1.21
HSL 5	0.50	1.6	0.81	1.19	2.16	7.4	2.7	3.9

*empty bed volume

Dissolved oxygen (DO) and temperature were measured using a Jenway DO-9071 meter (Merck Ltd, Leicester, UK). Removal percentages were calculated based on parameter concentration at the inlet and the outlet.

RESULTS

Water samples taken at reactor heights of 2m and 3m presented the same concentration of SS, sCOD, tCOD and $\text{NH}_3\text{-N}$ hence, demonstrating that the section above the media was completely mixed and did not provide any further improvement in terms of wastewater treatment.

All time values were transformed into dimensionless

time (τ) by dividing the actual time by the theoretical hydraulic retention time of the reactor (Table 2); hence, a dimensionless value of 1 is equal to 63 min. During all the shock loads, the concentration of sCOD in the effluent started to increase between τ values of 0.6 and 1.3 with the maximum at τ values between 1 and 1.7 (Figures 2-6). Maximum concentration breakthrough appeared during shock load 3 (Figure 4), when the effluent concentration reached more than 200 mg l^{-1} . However, in most cases the maximum effluent sCOD concentration did not exceed 150 mg l^{-1} . In all cases the effluent concentrations of SS and sCOD returned to normal within 2τ .

In all cases, the reactor presented an increase in effluent concentration during an approximate 60 min period.

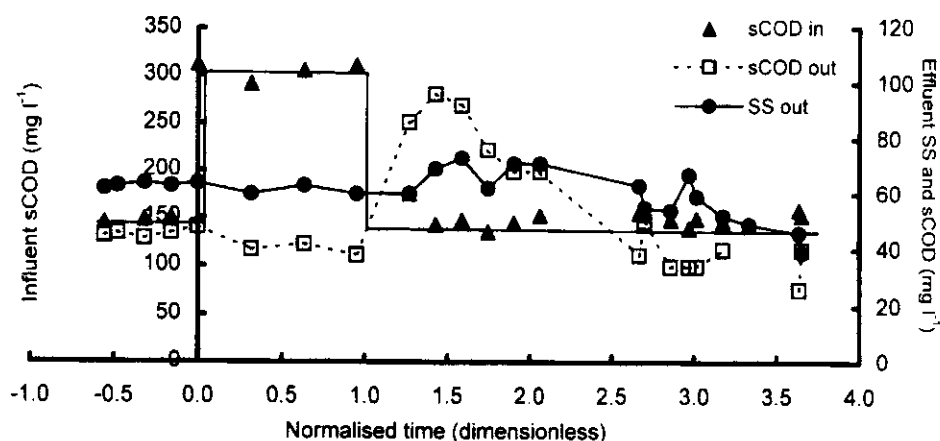


Figure 2. Influent and effluent soluble COD and effluent SS variation during organic shock load 1 (OSL1). The solid line represents the average influent concentration of sCOD.

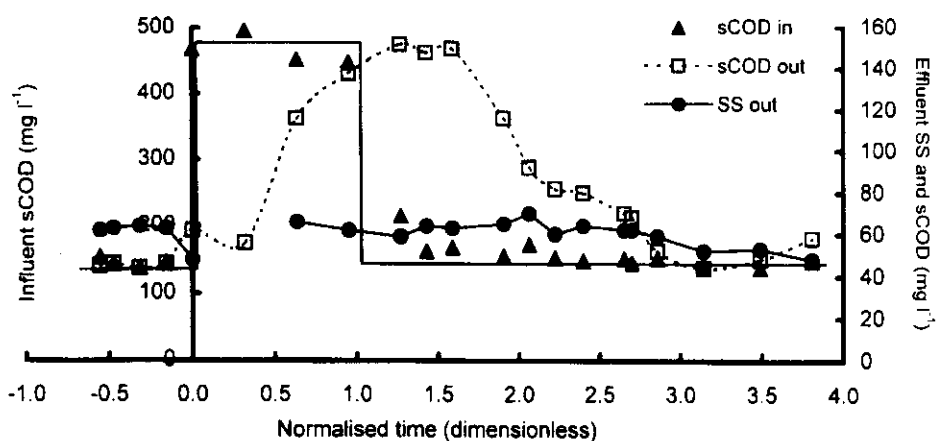


Figure 3. Influent and effluent soluble COD and effluent SS variation during organic shock load 2 (OSL2). The solid line represents the average influent concentration of sCOD.

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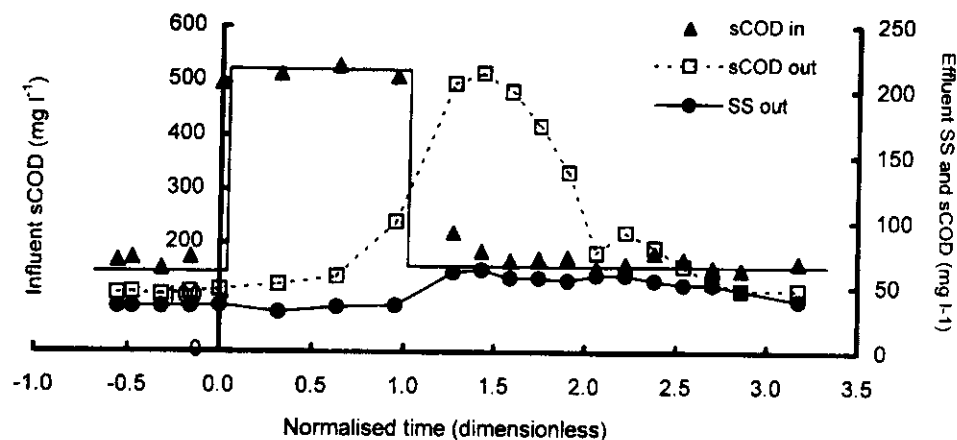


Figure 4. Influent and effluent soluble COD and effluent SS variation during organic shock load 3 (OSL3). The solid line represents the average influent concentration of sCOD.

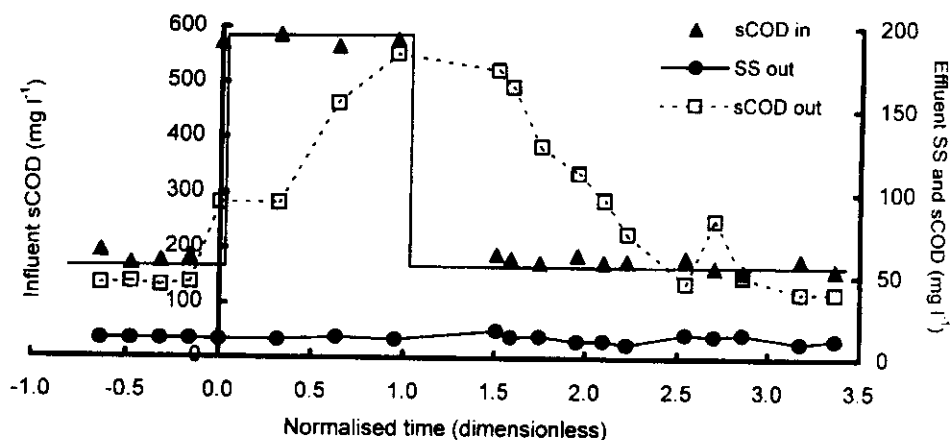


Figure 5. Influent and effluent soluble COD and effluent SS variation during organic shock load 4 (OSL4). The solid line represents the average influent concentration of sCOD.

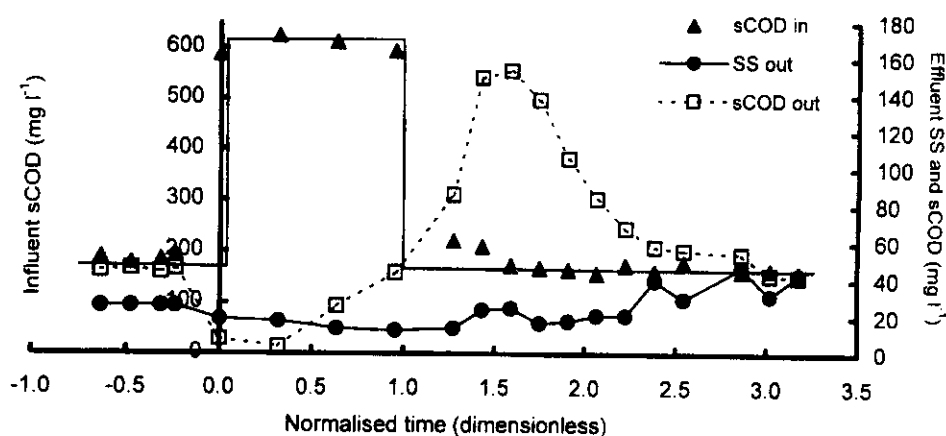


Figure 6. Influent and effluent soluble COD and effluent SS variation during organic shock load 5 (OSL5). The solid line represents the average influent concentration of sCOD.

Due to the fact that the section of the reactor above the media was completely mixed, the high organic concentrations during shock loading (although diluted) were present immediately at the beginning of the media section. In general, the greater effect of the organic shock load was detected at approximately 1τ (63 min) and it took another 63 min for the effects of the shock load to dissipate.

In all runs, the reactor achieved very similar percentages of removal of sCOD before the shock loads were applied, when $\tau < 0$, (Table 4). During the actual application

of the shock loads, the removal initially increased but once the high organic loading moved through the reactor ($1 < \tau < 2$) the removal dropped dramatically. Between values 2τ and 3τ the BAF was still recovering and when $\tau > 3$ removal returned to normal values.

The influent was diluted in order to keep a constant organic loading during the hydraulic shock load experiments, thus simulating storm conditions. The increase in the influent flowrate did not affect the performance of the system (Figures 7-11) in the same way as the organic shock loading.

Table 4. Amount of sCOD in mg l^{-1} being removed and efficiency of removal (in brackets and *italics*) before, during and after organic shock loads (OSL).

	OSL 1	OSL 2	OSL 3	OSL 4	OSL 5
$\tau < 0$	103 (71)	100 (71)	122 (70)	137 (72)	140 (72)
$0 < \tau < 1$	263 (87)	373 (81)	446 (88)	444 (77)	584 (97)
$1 < \tau < 2$	65 (46)	34 (9)	-3 (-24)	39 (10)	61 (21)
$2 < \tau < 3$	105 (69)	80 (52)	94 (54)	102 (56)	103 (60)
$\tau > 3$	121 (78)	92 (69)	117 (68)	131 (75)	120 (73)

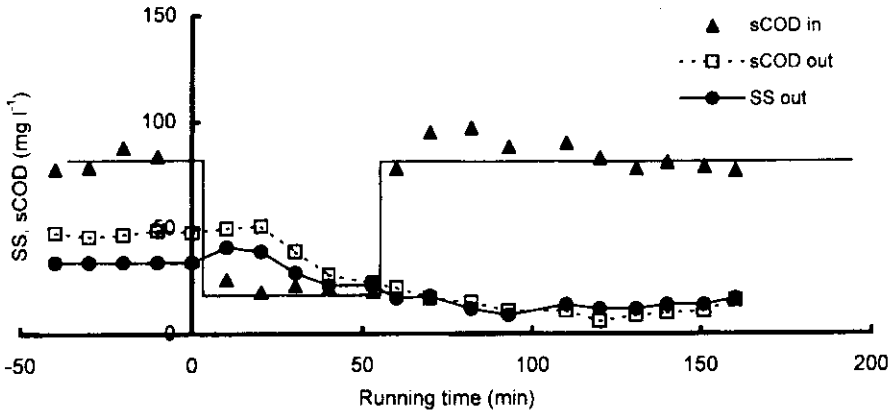


Figure 7. Influent and effluent soluble COD and effluent SS variation during hydraulic shock load 1 (HSL1). The solid line represents the average influent concentration of sCOD.

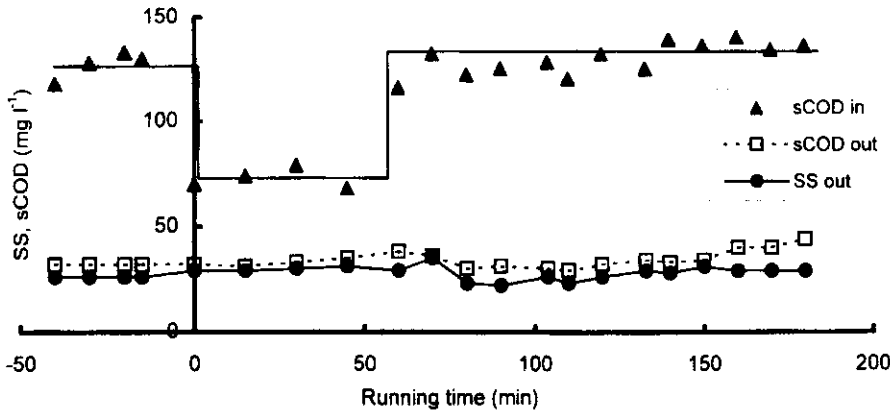


Figure 8. Influent and effluent soluble COD and effluent SS variation during hydraulic shock load 2 (HSL2). The solid line represents the average influent concentration of sCOD.

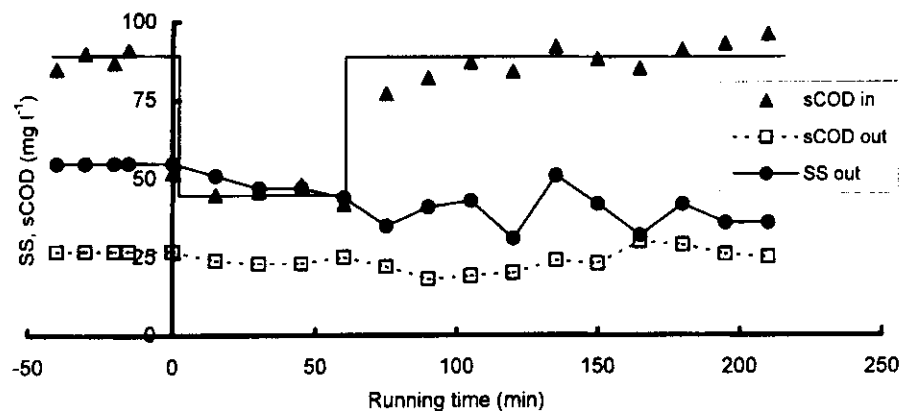


Figure 9. Influent and effluent soluble COD and effluent SS variation during hydraulic shock load 3 (HSL3). The solid line represents the average influent concentration of sCOD.

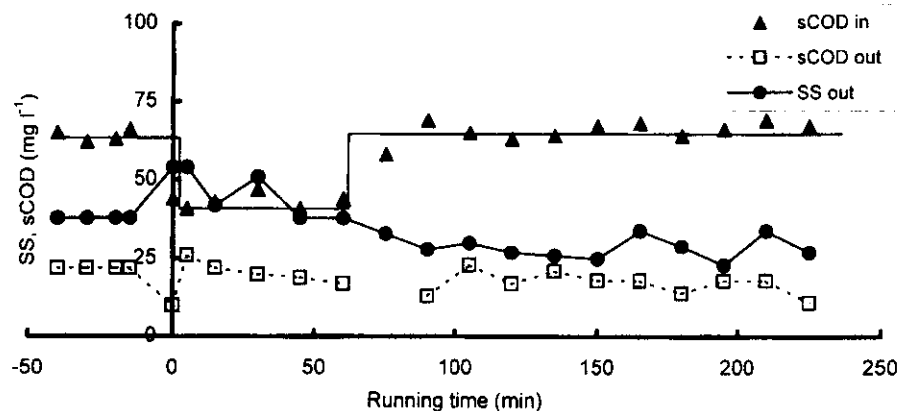


Figure 10. Influent and effluent soluble COD and effluent SS variation during hydraulic shock load 4 (HSL4). The solid line represents the average influent concentration of sCOD.

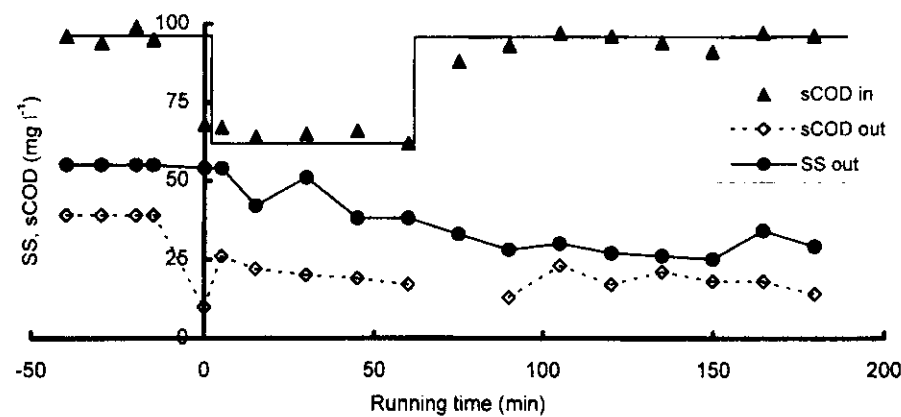


Figure 11. Influent and effluent soluble COD and effluent SS variation during hydraulic shock load 5 (HSL5). The solid line represents the average influent concentration of sCOD.

During hydraulic shock loads, time values were not converted into dimensionless time (τ) because tHRT would have varied once the hydraulic flowrate was increased during the shock load application.

When the hydraulic flowrate was increased to 3 times greater than normal (HSL 5), the performance of the BAF did not deteriorate; the effluent concentrations of SS and sCOD were lower than the values prior to the shock load application (Figure 11). Once the shock load was over, effluent values returned to the levels lower to those observed prior to the shock load application.

Due to the fact that the organic loading during the hydraulic shock loads was not increased, the percentage of sCOD removal was only slightly reduced during the actual application of the hydraulic shock load (Table 5). After each shock load the percentage of removal was greater than that obtained prior to the change in hydraulic conditions.

DISCUSSION

The capability of fixed-film reactors for treating organic shock loads is strongly dictated by the hydraulic conditions within the system. Flow characteristics in BAFs are influenced by the liquid and air input, as well as by the media [18]. At the same time, the hydrodynamics of reactors affect the physical and physiological structure of biofilms [19]. BAFs with completely mixed conditions and with channeling and backmixing [20, 21] are more resistant to shock loads than those with plug flow conditions. Investigations of fixed-film systems with completely mixed hydraulic conditions have demonstrated that they perform better than suspended growth reactors during shock loadings of primary settled sewage [22]. Moreover, stable operation, long retention of biomass solids and ability to cope with toxic substances are some advantages of using fixed-film reactors [23]. Therefore, properly designed fixed-film processes are generally reliable and resistant to hydraulic and shock loadings due to the large amount of biomass that they can sustain [23].

However, in most cases, flow patterns within BAFs are close to plug flow [3, 15]. In the present experiment, the reactor appeared to present a limited resistance to organic shock loads yet its recovery was fast. Results confirmed that the plug-flow conditions prevailing in the BAF caused slow

dispersion of the effect of shock loads and organic breakthrough due to limited treatment efficiency as highlighted in other studies [4, 6]. The response to shock loads in plug-flow reactors would depend on the growth rate and yield of the biological population involved, on the mass loading variations (i.e. how much is being applied) and on the duration of the shock loading conditions [5]. Thus, the fact that the reactor could reach levels of removal similar to those obtained prior to the shock loads application (Table 4) suggested that the effect of the shock loads on the biomass was limited probably due to its good acclimatisation to the substrate, the fact that the biomass was not washed out during the high loadings and the hydraulic configuration of the reactor.

It was evident that the increase in the feed concentration of the BAF caused a deterioration in the quality of the effluent due to breakthrough, in accordance with other studies on fixed-film systems [5]. Investigations on the ratio between BOD_5 and COD of the settled domestic sewage used during the present experiments revealed that the sCOD:COD after biological treatment was 1:2. Likewise, the tCOD: BOD_5 ratio after biological treatment was 5:1. Hence, according to Figures 2-6, the effluent concentration of BOD_5 appeared to vary between 40-80 $mg\ l^{-1}$. Most of the sewage treatment plants in the UK [1] need to meet a discharge consent of 11-20 $mg\ l^{-1}$ hence, the reactor failed to meet the discharge consent during organic shock load applications.

When hydraulic shock loads were applied, the BAF performance in terms of sCOD removal was not adversely affected. Soluble COD effluent concentrations of <40 $mg\ l^{-1}$ (~16 $mg\ l^{-1}$ BOD_5) were detected thus meeting most discharge consents in UK sewage works. Although suspended solids removal deteriorated, recovery of the reactor was fast. Performance of BAFs has been found to be adversely affected by step-increases to their hydraulic (and organic) loading [13]. Investigations of the impact of peak flows and the response to shock loading in a pilot-scale three-stage BAF plant have concluded that short-term fluctuations in the wastewater flowrate directly affected the removal of organic carbon [23]. Previous studies [24] found that increases in carbonaceous material can promote the growth of heterotrophic bacteria and thus limit the growth of autotrophic bacteria, reducing nitrification. Only when the concentration of organic matter

Table 5. Amount of sCOD in $mg\ l^{-1}$ being removed and efficiency of removal (in brackets and italics) before, during and after hydraulic shock loads (HSL).

	HSL 1	HSL 2	HSL 3	HSL 4	HSL 5
Before shock load	57 (36)	95 (75)	61 (69)	42 (63)	57 (55)
During shock load	1- (-56)	48 (54)	22 (46)	24 (58)	46 (72)
0-60 min after shock load	87 (83)	95 (76)	63 (77)	52 (70)	80 (80)
61-120 min after shock load	90 (84)	98 (71)	63 (70)	48 (70)	77 (79)
>121 min after shock load	-	-	69 (71)	52 (73)	-

decreases, do the autotrophs have a real chance to grow. Thus, it would be expected that in downflow columns the heterotrophs would tend to be located at the top of the reactor. The present study only evaluated effects on COD removal yet, it can be implied that nitrification would also have been effected.

Other authors [25] found that high hydraulic flowrates had a negative affect on the COD removal efficiency of a full-scale sunken media BAF running in upflow mode. Yet, previous BAF experiments using wastewater with low suspended solids concentration as a feed have demonstrated that high liquid velocities increase mass transfer rates, resulting in greater percentages of suspended solids, carbonaceous matter and ammonia removal [26]. Although high water velocities promote the even distribution of solids across the media bed [26], at suspended solids concentrations generally encountered in domestic primary settled sewage (150 mg l^{-1}) [1] there is a potential for the media bed to block. In the present study this problem did not occur because the actual hydraulic shock load was applied for a short period of time (60 min). Hence, the reactor was not affected by an increase in the operating hydraulic velocity, though it could be possible that an increase in the period of application of such conditions would cause deterioration of BAF performance leading to eventual blockage if the backwashing regime for the reactor is not modified. It is more likely that increases in the hydraulic flowrate would cause an increment in the shear stress due to biofilm erosion [26], causing an increase in biofilm detachment [13], increasing the amount of

suspended solids in the effluent and thus reducing reactor efficiency.

Thus, in order to avoid breakthrough of suspended solids and/or soluble organic matter, to achieve continuously efficient secondary treatment of wastewater under variable nutrient loading in BAFs, buffer tanks or variations in the number of operating filters should be considered as highlighted previously [27].

CONCLUSIONS

The BAF used for the present experiment was not capable of absorbing high peak organic shock loads when the organic loads were increased from a normal load of $1.2\text{--}1.4 \text{ kg sCOD m}^{-3} \text{ d}^{-1}$ to shock loads between $5.1\text{--}7.3 \text{ kg sCOD m}^{-3} \text{ d}^{-1}$, based on empty bed volumes. Nevertheless, the effect on the biomass was limited as normal performance resumed quickly ($<63 \text{ min}$ after the application of the shock load). Increases in the hydraulic velocity from $0.7\text{--}1.0 \text{ m h}^{-1}$ to $1.5\text{--}2.9 \text{ m h}^{-1}$ had little effect on BAF performance in terms of soluble COD removal. Soluble COD effluent concentrations of $<40 \text{ mg l}^{-1}$ ($\sim 16 \text{ mg l}^{-1} \text{ BOD}_5$) were detected.

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