Filamentous organism bulking in nutrient removal activated sludge systems. Paper 5: Experimental examination of aerobic selectors in anoxic-aerobic systems

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Abstract

Incorporation of correctly sized selector reactors at the head of an intermittently aerated (70% anoxic, 30% aerobic) system did not control the proliferation of low food to micro-organism ratio (F/M) filaments, viz. *Microthrix parvicella*, type 0092 and type 0914, even though the criteria indicating the induction of a selector effect had been met, i.e.:

- removal of essentially all the influent readily biodegradable chemical oxygen demand (RBCOD);
- the presence of a significant number of *Zooglea* colonies; and
- a high initial oxygen utilisation rate (OUR) and RBCOD uptake rate under batch test conditions.

List of symbols

COD = chemical oxygen demand
CFCM = continuously fed completely mixed
d = day
DO = dissolved oxygen
DSVI = diluted sludge volume index
F/M = food to micro-organism ratio
f_{ts} = fraction of the total influent COD (S_{ti}) that is readily biodegradable (S_{bsi})
h = hour
IAND = intermittent aeration nitrification-denitrification
IFFD = intermittently fed fill and draw
LF = load factor (mg COD/g VSS)
min = minute
MLSS = mixed liquor suspended solids
MLVSS = mixed liquor volatile suspended solids
N = nitrogen
OUR = oxygen utilisation rate in mg O/(ℓ·h) or mg O/(g AVSS·h)
P = phosphorus
RBCOD = readily biodegradable COD
RBCODUR = RBCOD utilisation rate [mg RBCOD/(g AVSS·h)]
TKN = total Kjeldahl nitrogen
VSS = volatile suspended solids
μm = micro (10^{-6}) meters

Introduction

Up to this point in the investigation it has not been possible to come to a definitive conclusion regarding the efficacy of selectors (aerobic or anoxic) in controlling bulking by low F/M filaments because it has not been possible to develop sludges with high proportions of low F/M filaments in laboratory-scale systems other than N & P removal ones. However, in Gabb et al. (1996) a system configuration and operating conditions were described which induce in laboratory-scale systems the proliferation of the low F/M filaments most common in South African full-scale systems (i.e. types 0092, 0914, *Microthrix parvicella*, type 1851, type 0675 and type 0041). The configuration and conditions are CFCM single-reactor systems operated with intermittent aeration with 30% aerated and 70% unaerated. These systems, called IAND systems, provide an opportunity to test the effect of selector reactors on low F/M filament proliferation in laboratory-scale systems.

Experimental set-up

Two systems were set up, both IAND with volume 7.5 ℓ, receiving a constant 10 ℓ/d influent flow of Mitchell's Plain raw sewage with a mean COD of 500 mg/ℓ. The systems were operated at a sludge age of 20 d and temperature 21°C with an aeration pattern to induce aerobic conditions for 3 to 4 min and an anoxic state for 6 to 7 min in a 10 min cycle. This set-up was the same as that in the IAND systems described by Gabb et al. (1996). The design and operating parameters are given in Table 1. For further details see Gabb et al. (1989).

To start up the systems, the two sludges from the IAND systems described by Gabb et al. (1996) (experimental and control) were mixed and divided equally between the two systems. The initial DSVIs in both systems were 190 mℓ/g (Fig. 1). The two systems were operated for 130 d. The day-to-day performance of the two systems i.e. influent and effluent COD, total phosphorus (as P), nitrate (as N) and TKN concentrations, is shown in Fig. 2. Also the DSVI was measured daily and microscopic evaluation of the sludge undertaken regularly, i.e. every 20 d (1 sludge age) (Fig. 1). In operation, nitrification was virtually complete, and to ensure that sufficient nitrate was present so that the systems remained anoxic throughout the unaerated periods, ammonia was added to the influent to give an average TKN of 60 to 100 mgN/ℓ (see Fig. 2). Test methods were conducted in accordance with the procedures as set out in Still et al. (1996) and Gabb et al. (1996).

After 21 d of operation, the DSVI in both systems had increased from 190 to 340 mℓ/g (Fig. 1). On day 21, two 250 mℓ aerated

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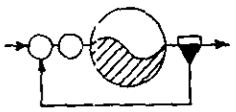
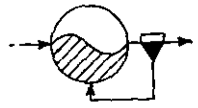
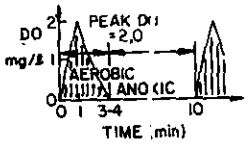
TABLE 1
OPERATING PARAMETERS AND CONDITIONS FOR THE SINGLE REACTOR CONTINUOUSLY FED COMPLETELY MIXED INTERMITTENT AERATION SYSTEMS, ONE WITH AEROBIC SELECTORS (EXPERIMENTAL, EXP) AND ONE WITHOUT AEROBIC SELECTORS (CONTROL, CTRL) (EXPERIMENTAL, EXP AND CONTROL, CTRL)

SYSTEM	EXP	CTRL
Operating conditions	Continuously fed, single reactor	
	with selectors (from day 21)	without selectors
Graphical representation		
Aeration - Main reactor - Selector	Intermittent Continuous	Intermittent Continuous
DO concentration (mgO/ℓ)		
- Main reactor	0 - 2	0 - 2
- Selector	2 - 4	-
DO profile for main reactor		
Feed	Continuous (24h)	
Sewage source	Mitchell's Plain raw	
Sludge source	Laboratory IAND systems (see Gabb et al. 1996)	
Mass of COD fed (mg/d)	5000	5000
Voume of feed (ℓ/d)	10	10
Concentration (mg/ℓ)	500	500
Influent TKN (mgN/ℓ)	60 -100	60 -100
Sludge age (d)	20	20
Temperature (°C)	21	21
Volume of main reactor (ℓ)	7.5	7,5
Selectors - from day 21	each 0.25	-
- from day 73	0.10 ; 0.25	-
MLVSS concentration (mg/ℓ)	2800	2800
MLSS concentration (mg/ℓ)	3500	3500
F/M [mgCOD/(gVSS.d)]	240	240
Hydraulic retention time (h)		
Main reactor	18 h	18 h
Selectors - from day 21	each 36 (min)	-
- from day 73	14 ; 36 (min)	-
Underflow recycle ratio	1:1	1:1
pH of mixed liquor	7.3 - 7.5	7.3 - 7.5

selectors were installed in series ahead of the intermittently aerated main reactor of one of the systems. The first selector received the influent and underflow streams; the effluent of the first selector passed to the second selector and its effluent passed to the main IAND reactor. The size of the selectors was based on the uptake rate of RBCOD measured in the IFFD system described by Still et al. (1996). With the aid of this uptake rate, taking note of the concentration of RBCOD fraction (f_{bs}) in the raw waste water and the system parameters, the fractional size of the selector to remove more than 95% of the RBCOD was calculated to be 1/30th of the total process volume i.e. 250 mℓ in 7.5 ℓ. To take into account variability in the RBCOD uptake rate and in the influent RBCOD

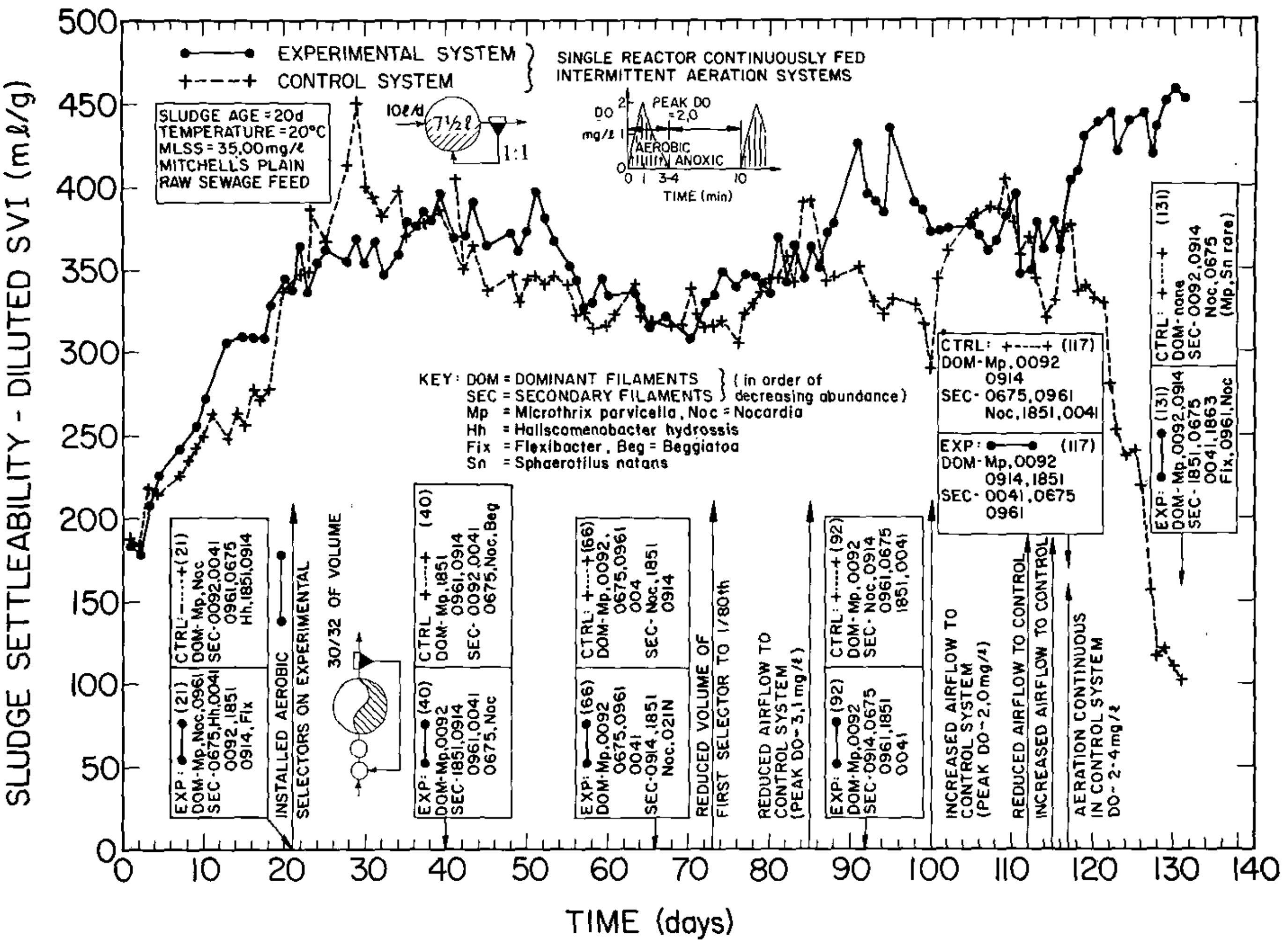


Figure 1

Sludge settleability in DSVI with time in two (experimental and control) single reactor continuously fed intermittent aeration systems fed the same sewage (Mitchell's plain raw) and operated at the same sludge age (20 d) and temperature (21°C). Note that installation of aerobic selectors in the experimental system (correctly sized) (on day 21) did not ameliorate bulking by low F/M filaments over a period of 5 sludge ages (day 21 to 117) but changing the aeration in the Control system from intermittent to continuous, causes a sharp decline in DSVI in less than 1 sludge age (day 117 to 131) and a concomitant decrease in low F/M filaments.

fraction of the waste water, two 250 mℓ selectors in series were installed without reducing the volume of the main reactor. Consequently the two selectors were each 1/32nd of the total system volume. The DO concentration in each selector was maintained at between 2 and 4 mg/ℓ. For convenience, the system with the selector reactors will be called the experimental (EXP) system and the system without selector reactors the control (CTRL) system.

After installation of the aerobic selectors in the experimental system, both experimental and control systems were operated and monitored daily for a period of 5½ sludge ages (days 21 to 130). During this period, batch tests were undertaken on sludge harvested from the two systems to establish whether or not the selector effect had been induced in the experimental system. The results of the daily monitoring and batch tests are presented below.

Results and discussion

Selector effect

In Still et al. (1996), the three criteria identified by Jenkins et al. (1984) to assess whether or not a selector effect has been induced in a sludge and a selector reactor is functioning properly, were mentioned, viz:

- a high initial OUR and soluble COD (RBCOD) uptake rate under batch conditions;
- virtually complete removal of soluble biodegradable COD (or RBCOD) in the selector; and
- the presence of a significant number of *Zoogloea* colonies in the sludge.

These three criteria were evaluated by a series of aerobic batch tests on sludge harvested from both systems; measuring the soluble

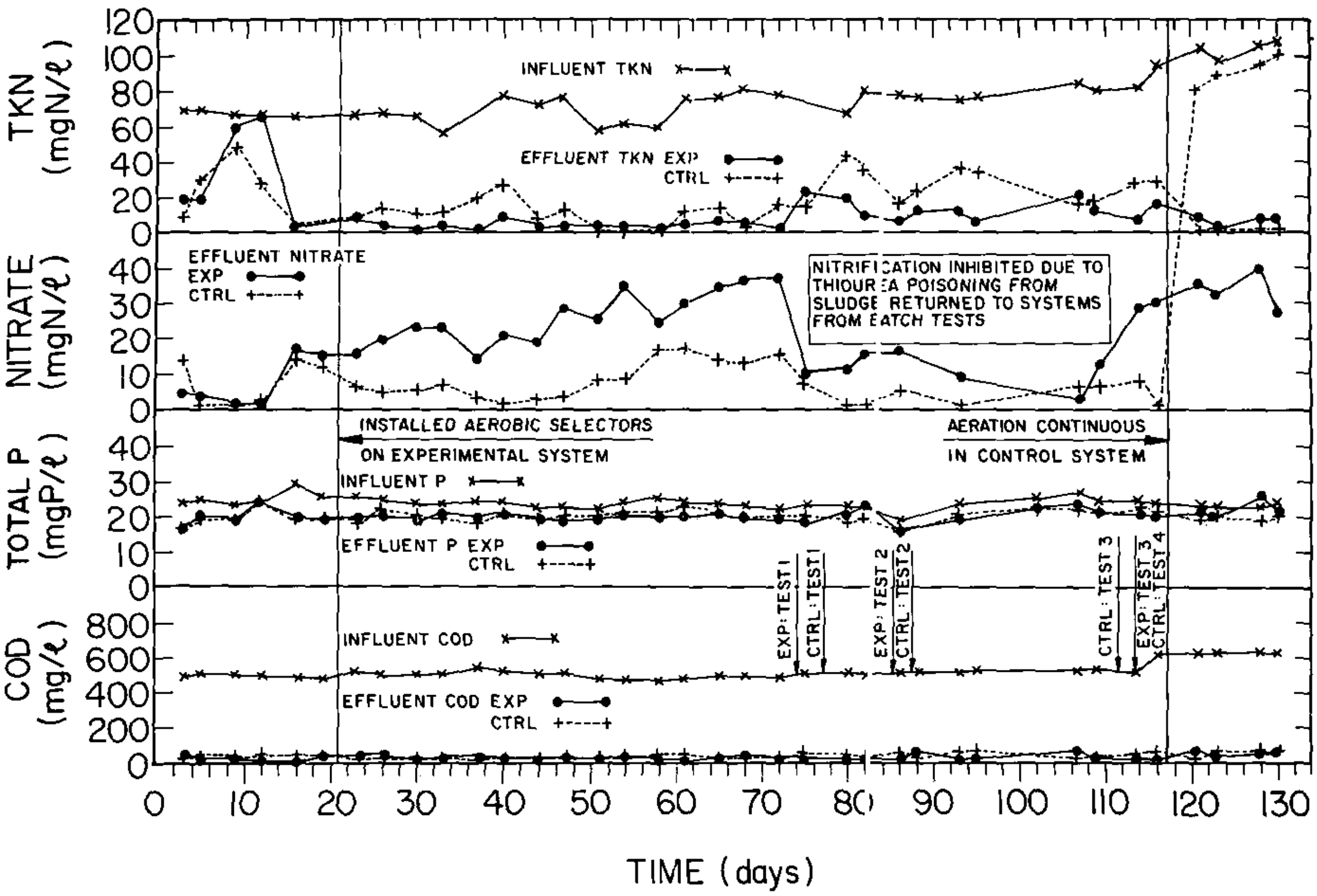


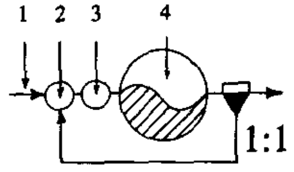
Figure 2

Influent and effluent COD (lower) total phosphorus (as P) (mid-lower), nitrate (as N) (mid-upper) and TKN (upper) concentrations with time in two, one experimental (EXP) and one control (CTRL) single-reactor continuously fed intermittent aeration systems fed the same sewage (Mitchell's Plain raw) and operated at the same sludge age (20 d) and temperature (21°C). Note that (1) the installation of the aerobic selectors caused an increase in effluent nitrate concentration in the Experimental system due to utilisation of influent readily biodegradable COD in the aerobic selector, and (2) switching from intermittent to continuous aeration in the control system (day 117) caused a dramatic increase in the effluent nitrate concentration due to the absence of denitrification.

(0.45 µm filtered) COD profile through the selector and main reactor of the experimental system; and microscopic examination of sludge taken from both the experimental and control systems. On days 74 and 77, aerobic batch tests (nitrification inhibited) were conducted on sludges harvested from the experimental and control systems respectively, during which the OUR was measured for 24 h (Fig. 3); from these tests, it can be seen that for the experimental system sludge, the initial OUR was about 1.6 times higher than that in the control system sludge giving RBCOD uptake rates of 183 and 81 mg RBCOD/(g AVSS·h) for the experimental and control systems respectively. On day 72, the soluble (0.45 µm filtered) COD concentration was measured in the influent and in the selector and main reactors of the experimental system. From these measurements, a profile of soluble COD concentrations through the system was established, from which it was calculated that essentially none of the soluble biodegradable COD entered the main reactor (Table 2). Microscopic examination of the sludges in the two systems on day 79 indicated that the sludge in the experimental system contained significantly more *Zoogloea* colonies than the sludge in the control system. Since the three selector effect criteria listed above were satisfied for the experimental system but none were satisfied for the control system, it can be concluded that a selector effect had been induced in the experimental system sludge but not in the control system sludge.

In order to check that a reduced selector volume possibly may enhance the selector effect, the first selector reactor of the experimental system was reduced in volume from 250 mℓ to 100 mℓ on day 72. [The batch tests (day 74) and microscopic examination (day 79) were done soon after this change (day 72) and it is unlikely that the smaller first selector volume significantly contributed to the measured high RBCOD uptake rate, since as illustrated by Still et al. (1996), induction of a selector effect may take up to a sludge age]. After this change, soluble COD profiles in the experimental system were measured regularly (days 84, 104 and 121; see Table 2). As previously, these profiles indicated that practically all the RBCOD was removed in the selector reactors. Batch tests (nitrification inhibited) were conducted on sludges harvested from the experimental system (days 85 and 113) and from the control system (days 84 and 111) (see Figs. 4 and 5). From these tests, the initial OUR in the experimental system was more than 1.4 times greater than that in the control system giving average RBCOD uptake rates of 137 and 61 mg RBCOD/(g AVSS·h) for the

TABLE 2
SOLUBLE (<0.45 µm FILTERED) COD (SCOD) CONCENTRATION IN THE INFLUENT, SELECTOR REACTORS AND MAIN REACTOR OF THE EXPERIMENTAL SYSTEM ON DAYS 72, 84, 104 AND 121 AND SOLUBLE COD REMOVALS IN THESE REACTORS

POSITION / DAY	72	84	104	121
	(mgCOD/ℓ)	(mgCOD/ℓ)	(mgCOD/ℓ)	(mgCOD/ℓ)
1) Into 1st selector	124.5	108	104	160
2) In 1st selector	65.7	76	74	90
3) In 2nd selector	57.5	54	66	74
4) In main reactor	57.5	54	60	70
Reduction in				
1st selector	57.8	32	30	70
2nd selector	8.2	22	8	16
1st and 2nd selector	66.0	54	38	87
Main reactor	0.0	0	6	4
Position 1 2 3 4 				

experimental and control systems respectively. In the batch test conducted on sludge from the experimental system on day 113 and in an additional test on sludge from the control system on day 113, the soluble COD concentration and OUR was measured for the first 6 h (see Fig. 6). These tests confirm the relationship between high initial OUR values and high initial RBCOD uptake rates described by Still et al. (1996); the high initial OUR is associated with an equivalently high initial RBCOD uptake rate and the precipitous decrease takes place concomitantly with the depletion of the RBCOD. Sludge microscopic evaluation from days 92 to 131 indicated that the sludge in the experimental system continued to contain significantly more *Zooglea* colonies than the sludge in the control system.

From the above it can be seen that in terms of the criteria for evaluating whether or not a selector effect is present in a sludge (high initial OUR, high soluble COD uptake rate, presence of *Zooglea* colonies), the selector reactors in the experimental system did indeed induce the selector effect and therefore it can be concluded that the selectors were correctly sized.

Sludge settleability

Two and a half sludge ages (50 d) after installing the selectors (day 71) the DSVI in both systems was still the same; each had a DSVI of around 320 mℓ/g (Fig. 1). Microscopic examination of the sludges indicated that the filaments in the sludge also were essentially the same and the dominant filaments, in decreasing order of abundance, were *M. parvicella*, and types 0092, 0675, 0961 and 0041

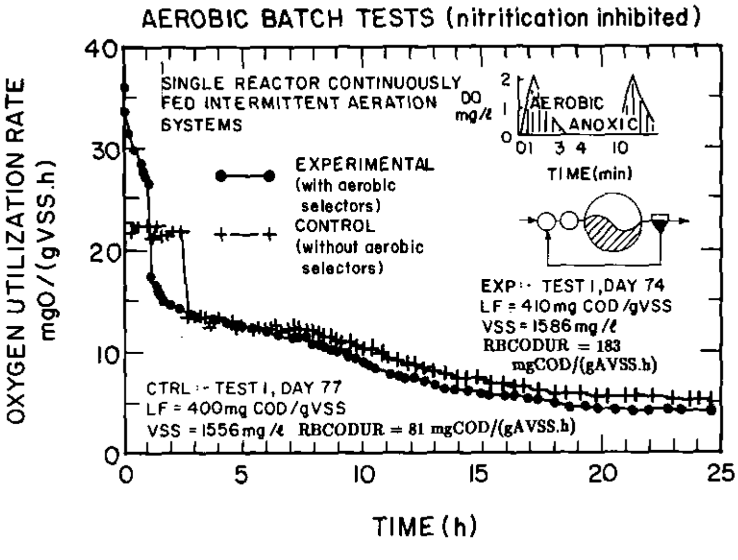


Figure 3
OUR in mgO/(gVSS·h) in the first set of aerobic batch tests (nitrification inhibited) on days 74 and 77 at the same load factor (LF ~ 400 mg COD added per g VSS) on sludges harvested from two single reactor continuously fed intermittent aeration systems, one with aerobic selectors (experimental, EXP; ●—●, day 74), the other without aerobic selectors (control, CTRL; +——+, day 77). Note that the initial OUR is about 1.6 times higher in the Experimental system sludge (with selectors) than that in the control system sludge (without selectors).

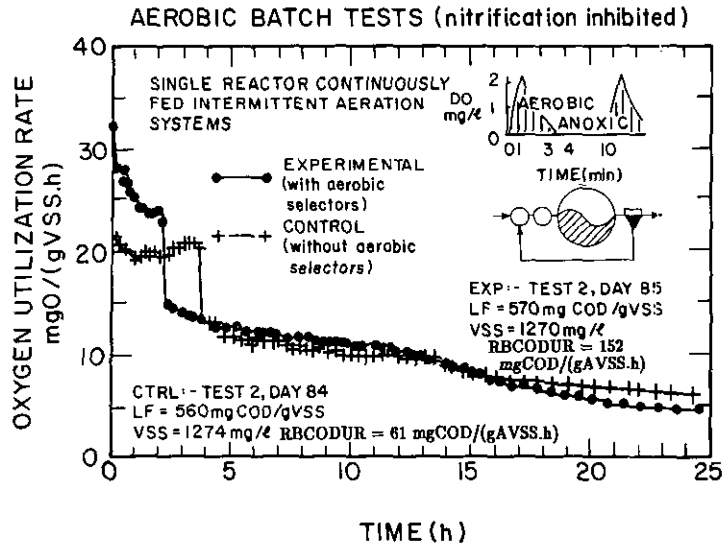


Figure 4

OUR in mg O/(g VSS·h) in the second set of aerobic batch tests (nitrification inhibited) on days 85 and 84 at the same load factor (LF ~ 560 mg COD added per g VSS) on sludges harvested from two single reactor continuously fed intermittent aeration systems, one with aerobic selectors (experimental, EXP; ●—●, day 85), the other without aerobic selectors (control, CTRL; +—+, day 84). Note that the initial OUR is about 1.4 times higher in the experimental system sludge (with selectors) than that in the control system sludge (without selectors).

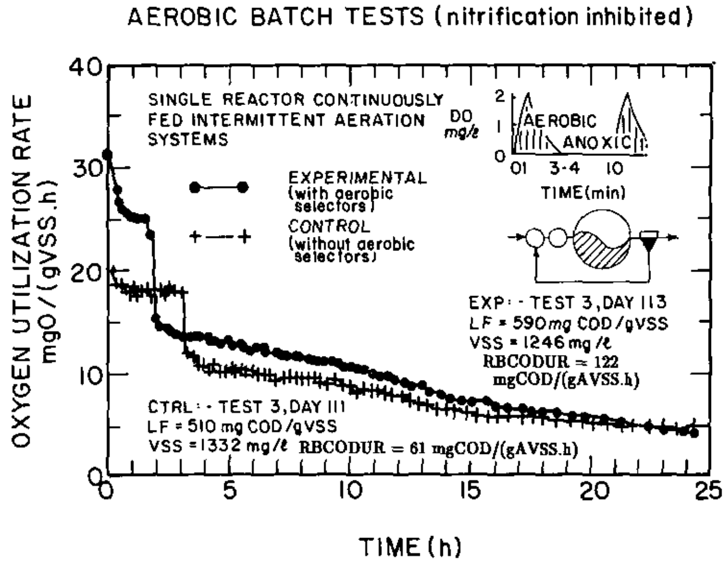


Figure 5

OUR in mg O/(g VSS·h) in the third set of aerobic batch tests (nitrification inhibited) on days 113 and 111 at the same load factor (LF ~ 550 mg COD added per g VSS) on sludges harvested from two single reactor continuously fed intermittent aeration systems, one with aerobic selectors (experimental, EXP; ●—●, day 113), the other without aerobic selectors (control, CTRL; +—+, day 111). Note that the initial OUR is about 1.6 times higher in the experimental system sludge (with selectors) than that in the control system sludge (without selectors).

(see Fig. 1).

After reducing the selector volume on day 72, the DSVI in the experimental system increased from 349 to over 400 mℓ/g by day 131. During this period, in the control system the DSVI also increased and decreased but remained above 300 mℓ/g.

Microscopic examination of the sludges from the control and experimental system with reduced selector volumes (on days 79, 92, 109, 117) indicated that the dominant filamentous populations in the two systems remained essentially similar; in decreasing order of dominance, the filaments in the control system were *M. parvicella*, and types 0092, 0914 and 0961 and in the experimental system the filaments were *M. parvicella*, and types 0092, 0914 and 1851 (see Fig. 1).

In Gabb et al. (1996), in the intermittent aeration experiments, it was noticed that the mass of oxygen input per 10 min cycle (as a result of changing the peak DO during the intermittent aeration cycle) appeared to influence the sludge settleability. In an attempt to evaluate the influence of oxygen input on DSVI, the airflow rate to the control system was reduced on day 85 so that during the air-on period the peak DO was 1.3 instead of 2.0 mg/ℓ. The system responded with a decline in DSVI, from 392 to 289 mℓ/g by day 100 (Fig. 1). On day 100, the airflow rate was increased so that the peak DO increased to 2.3 mg/ℓ. The system responded with an increase in DSVI from 289 to 386 mℓ/g on day 107. This behaviour was similar to that observed in the intermittently aerated systems discussed by Gabb et al. (1996) and further support for this finding is described by Lakay et al. (In prep.). From this, it appears that too little oxygen input adversely affects the proliferation of some of the low F/M filaments, in particular *M. parvicella*. The lower oxygen input is reflected in the higher effluent TKN and lower nitrate concentrations of the control system (Fig. 2) indicating that nitrification was not complete but denitrification more complete. However, the increase in effluent TKN also is in part due to the return to the system of mixed liquor containing thiourea from the nitrification-inhibited batch tests.

On day 117, the aeration pattern in the control system was changed from intermittent to continuous and the DO was controlled between 2 and 4 mg/ℓ. At this time the dominant filaments in the

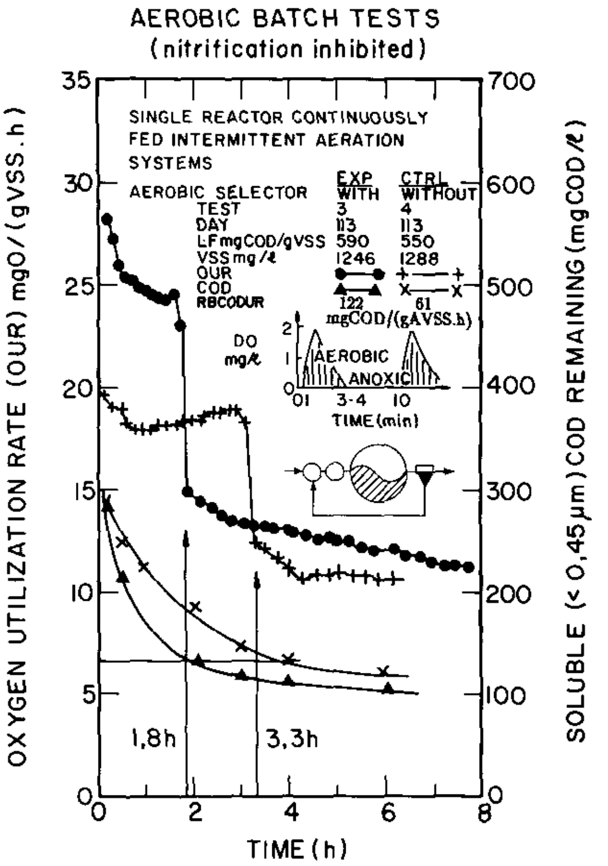


Figure 6

OUR in mg O/(g VSS·h) and soluble COD <0.45 µm) concentration in the fourth set of aerobic batch tests (nitrification inhibited) on day 113 at the same load factor (LF 570 mg COD added per g VSS) on sludges harvested from two single reactor continuously fed intermittent aeration systems, one with aerobic selectors experimental, EXP; ●—●, day 113), the other without aerobic selectors control, CTRL; +----+, day 113). Note that (i) the initial OUR and soluble COD uptake is about 1.4 times faster in the experimental system sludge (with selectors) than in the control system sludge (without selectors) and (ii) the precipitous decrease in OUR occurs at approximately the time as the depletion of the biodegradable soluble (or readily biodegradable) COD.

control system were *M. parvicella* (abundant), type 0092 (very common) and type 0914 (common) and the secondary filaments in decreasing order of abundance were type 0675, type 0961, *Nocardia* sp., and types 1851 and 0041 (see Fig. 1). The DSVI in the control system decreased rapidly from 376 mℓ/g on day 117 to 103 mℓ/g on day 132, (15 d) (see Fig. 1), at which time the filaments in the control system were type 0092 (some to common), type 0914 (some), *Nocardia* sp. (some), type 0675 (some) and *M. parvicella* (few). Over the same period (day 117 to 132) in the experimental system, in which intermittent aeration was maintained in the main reactor, the DSVI remained high (> 400 mℓ/g), the dominant filaments were *M. parvicella*, and types 0092 and 0914 with secondary filaments types 1851, 0675 and 0041, *Nocardia* sp. and type 0961.

Conclusions

From these experiments it can be concluded that:

- In long sludge age single reactor completely mixed continuously fed IAND systems (7 min anoxic, 3 min aerobic), low F/M filaments proliferated.
- Incorporation of a correctly sized aerobic selector which stimulated a selector effect at the head of the IAND system, receiving the influent and underflow recycle, did not control the proliferation of the low F/M filaments, viz. *M. parvicella*, types 0092, 0914; other filaments remaining at secondary levels were types 1851, 0675, 0041, *Nocardia* spp. and 0961.
- The selector effect as stimulated by alternating feed-starve conditions imposed by the aerobic selectors does not appear to control bulking by low F/M filamentous organisms.
- Changing the aeration pattern from intermittent (anoxic-aerobic) to continuous (aerobic) causes amelioration of bulking by low F/M filaments in a short time (DSVI decreases from >400 to <100 mℓ/g in 15 d). This has been repeatedly observed in the investigation so far (Still et al., 1996; Ekama et al., 1996a; Gabb et al., 1996).
- Because aerobic selectors (and anoxic by implication) stimulate rapid removal of RBCOD by floc formers and this does not control low F/M filament proliferation, it would appear that the influent RBCOD does not play an important role in the proliferation of low F/M filaments.

Closure

The research presented in this series of papers so far provides strong evidence that the promoted specific control method against low F/M filament bulking, i.e. selector reactors and by implication alternating feed-starve conditions, is not successful in their control. This conclusion was disappointing because it eliminated the only apparently viable specific control measure against low F/M filaments and provided no further incentive to pursue the selector effect approach for control of bulking by these filaments. However, not only in this research programme but also in many others (see Still et al., 1996) it was established that this approach is appropriate for control of other filamentous organisms such as *Sphaerotilus natans* and *Thiothrix*. Perplexingly *S. natans*, which is categorised as a low DO filament is controlled by the selector effect, whereas the low F/M filaments (e.g. types 0092, 0675, *M. parvicella* and 0041), which were thought to be controlled by the selector effect but in fact are not, are controlled by continuous aeration. In the light of this anomalous situation it is necessary to consolidate the observations and conclusions of the investigation so far and evaluate these in relation to other published research with the view of establishing new research directions for specific control of low F/M filament bulking. This is presented in the next paper of the series (Ekama et al., 1996b).

Acknowledgements

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References

EKAMA GA, WENTZEL MC, CASEY TG and MARAIS GvR (1996a) Filamentous organism bulking in nutrient removal activated sludge systems. Paper 3: Stimulation of the selector effect under anoxic conditions. *Water SA* **22** (2) 119-126.

EKAMA GA, WENTZEL MC, CASEY TG and MARAIS GvR (1996b) Filamentous organism bulking in nutrient removal activated sludge systems. Paper 6: Review, evaluation and consolidation of results. *Water SA* **22** (2) 147-152.

GABB DMD, STILL DA, EKAMA GA, JENKINS D, WENTZEL MC and MARAIS GvR (1989) Development and full-scale evaluation of preventative and remedial methods for control of activated sludge bulking. WRC Report No. 165/1/89, (UCT Report No. W62), Water Research Commission, PO Box 824, Pretoria 0001, RSA.

GABB DMD, EKAMA GA, JENKINS D, WENTZEL MC, CASEY TG and MARAIS GvR (1996) Filamentous organism bulking in nutrient removal activated sludge systems. Paper 4: System configurations and operating conditions to develop low F/M filament bulking sludges at laboratory-scale. *Water SA* **22** (2) 127-138.

JENKINS D, RICHARD MG and DAIGGER GT (1984) Manual on the Causes and Control of Activated Sludge Bulking and Foaming. Published by Water Research Commission, PO Box 824, Pretoria 0001.

LAKAY MT, HULSMAN A, KETLEY D, WARBURTON C, DE VILLIERS M, CASEY TG, WENTZEL MC and EKAMA GA (In preparation) Filamentous organism bulking in nutrient removal activated sludge systems. Paper 7: Exploratory experimental investigations. *Water SA*.

STILL DA, EKAMA GA, WENTZEL MC, CASEY TG and MARAIS GvR (1996) Filamentous organism bulking in nutrient removal activated sludge systems. Paper 2: Stimulation of the selector effect under aerobic conditions. *Water SA* **22** (2) 97-118.