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

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Abstract

Intermittent aeration conditions (30% aerobic, 70% anoxic) in single-reactor continuously fed completely mixed systems sustain the growth of the low food to micro-organism ratio (F/M, long sludge age) filaments, *Microthrix parvicella* and Types 0092, 0041, 0675, 0914 and 1851, to give diluted sludge volume index (DSVI) values of between 200 and 500 mℓ/g. Changing from intermittent to continuous aeration (DO, 2 to 4 mg O/ℓ) ameliorates the low F/M filament bulking to give DSVI values as low as 60 mℓ/g in the absence of a selector effect.

List of symbols

AVSS	=	active heterotrophic organism VSS concentration (mg AVSS/ℓ)
CFCM	=	continuously fed completely mixed
CFCM/SEL	=	continuously fed completely mixed with selectors
COD	=	chemical oxygen demand
CTRL	=	control
d	=	day
DO	=	dissolved oxygen (mg O/ℓ)
DSVI	=	diluted sludge volume index
EXP	=	experimental
F/M	=	food to micro-organism ratio
h	=	hour
IAND	=	intermittent aeration nitrification-denitrification
IFFD	=	intermittently fed fill and draw
m	=	meter
min	=	minute
MLSS	=	mixed liquor suspended solids
MLVSS	=	mixed liquor volatile suspended solids
MUCT	=	modified UCT
N	=	nitrogen
ND	=	nitrification-denitrification
NUR	=	nitrate utilisation rate as mg NO_3-N/(ℓ·h) or mg NO_3-N/(g AVSS·h)
OUR	=	oxygen utilisation rate in mg O/(ℓ·h) or mg O/(g AVSS·h)
P	=	phosphorus
RBCOD	=	readily biodegradable COD
s	=	second
TKN	=	total Kjeldahl nitrogen
µm	=	micro (10^{-6}) meters

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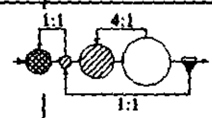
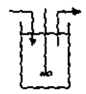
Introduction

The main objective of the investigation described by Still et al. (1996) of this series has been to evaluate the stimulation of the selector effect in activated sludge and its role in control of bulking by low F/M filaments. With regard to the stimulation of the selector effect, it was found that the alternating feed-starve conditions imposed by intermittent feeding to single reactor systems (IFFD) or continuously fed completely mixed systems, operated under aerobic or anoxic-aerobic conditions and incorporating aerobic selector reactors (CFCM/SEL), stimulate in the sludge a selector effect, i.e. a high readily biodegradable COD (RBCOD) uptake rate: This rate is 2 to 3 times higher than in systems which do not have alternating feed-starve conditions, such as continuously fed completely mixed systems. If the conditions are aerobic, the high RBCOD uptake rate gives rise to an associated high (initial) OUR under batch conditions and if the conditions are anoxic, it gives rise to an associated high (initial) NUR under batch conditions. It was found that the selector effect can be stimulated or eliminated in a sludge over a period of less than a sludge age in long sludge age systems by introducing or removing alternating feed-starve conditions respectively. The observations regarding the stimulation of a selector effect in a sludge subjected to alternating feed-starve conditions was in agreement with research reported in the literature.

With regard to the role of the selector effect in controlling bulking by low F/M filaments, this could not be investigated because none of the laboratory systems bulked with low F/M filaments. Indeed, the laboratory-scale systems, when started up with bulking sludges with low F/M filaments (DSVI > 250 mℓ/g and containing usually in varying proportions, type 0092, *Microthrix parvicella*, 0914, 0675, 1851 and 0041 filaments) from long sludge age full-scale nitrogen removal (anoxic-aerobic) plants, invariably ceased bulking (DSVI < 80 mℓ/g) within a month from start up, irrespective of whether or not the system incorporated alternating feed-starve conditions. Apparently bulking by low F/M filaments was ameliorated under fully aerobic or alternating anoxic (1 h) - aerobic (3 h) conditions whether or not a selector effect was present. That the low F/M filaments did not proliferate in the

TABLE 1
OPERATING PARAMETERS AND CONDITIONS FOR MUCT NUTRIENT (N AND P) REMOVAL SYSTEM AND 3 SINGLE REACTOR SYSTEMS STARTED WITH MUCT SLUDGE VIZ. ANOXIC/ANAEROBIC-AEROBIC INTERMITTENTLY FED FILL AND DRAW (IFFD1), FULLY AEROBIC INTERMITTENTLY FED FILL AND DRAW SYSTEM (IFFD2) AND FULLY AEROBIC CONTINUOUSLY FED COMPLETELY MIXED SYSTEM (CFCM)

System	MUCT	IFFD1	IFFD2	CFCM
Operating conditions	Continuously fed multi-reactor	Intermittently fed fill & draw	Intermittently fed fill & draw	Continuously fed completely mixed
Graphical representation				
Monitored from (day)	-	6	30	57
Aeration	Continuous (in aerobic)	6h off-16h on	Continuous (22h)	Continuous (24h)
DO concentration (mgO/ℓ)	2 - 4	>6 when on	>6	>6
Feed	Continuous (24h)	Intermittent (once daily)	Intermittent (once daily)	Continuous (24h)
Sludge source	Self	Laboratory MUCT		
Sewage source	Mitchell's Plain raw			
Mass of COD fed (mgCOD/d) Volume (ℓ/d) Concentration (mg/ℓ)	15000 10000 15* 10*† 1000 1000	15000 ~2* ~750	15000 ~2* ~750	15000 6 ~250*
MLSS concentration (mg/ℓ)	4350 2900	3250	3000	1500
MLVSS concentration (mg/ℓ)	3500 2350	2600	2400	1200
F/M [mgCOD/(mgVSS.d)]	0.22	0.20	0.20	0.20
Reactor volumes (ℓ)	6 2.5 4.5 9	3	3	6
Sludge age (d)	22	20	20	20
Nominal hydraulic retention time (h)	35	22	22	24
Temperature (°C)	21	21	21	21

* Required COD concentrations were obtained by appropriate dilution of a stronger sewage with tap water.

† On day 77 (Fig. 1) the MUCT system COD feed and sludge masses were reduced by half to provide starter sludge for a second MUCT system and (ii) bring relief to the clarifier in the event of severe bulking.

systems which stimulate the selector effect was expected since this effect was deemed to control proliferation of these filaments. However, it was a matter of concern that the low F/M filaments did not proliferate in the systems without the selector effect because without this it could not be verified unequivocally that the selector effect was controlling low F/M filaments in the systems which stimulated a selector effect. Because of claims that the selector effect controls bulking by low F/M filaments it was accepted that the CFCM (control) systems had the propensity to bulk by low F/M filaments but did not manifest bulking by these filaments due to the sporadic nature and uncertain stimuli for this condition. Nevertheless, without control systems supporting low F/M filament proliferation, it cannot unequivocally be demonstrated that the selector effect controls the proliferation of these filaments. In view of this, the objective in the research programme became to determine the environmental conditions and feeding patterns which, when imposed on laboratory-scale systems, will give rise to low F/M filament proliferation.

Preliminary considerations

The unexpected *Sphaerotilus natans* proliferation in the laboratory CFCM systems (Still et al., 1996; Gabb et al., 1989) highlighted the problems of mimicking full-scale systems with laboratory-scale systems - in doing this a number of factors or influences can be inadvertently introduced into the laboratory-scale system which can significantly affect the behaviour of the system and the results it produces. Such unknown influences may have been introduced in the laboratory systems described in Papers 2 and 3 (Still et al., 1996; Ekama et al., 1996) in which sludges brought from a full-scale ND plant to start up the laboratory systems exhibited a decline in low F/M filaments. In an attempt to eliminate such influences on the experimental results, the IFFD and CFCM experiments described in Still et al. (1996) and Ekama et al. (1996) were repeated but instead of sludge from a full-scale ND plant, the systems were started up with a low F/M bulking sludge from a laboratory-scale MUCT system. If amelioration of low F/M filaments were to be observed in these systems while the parent MUCT system fed the same waste water continued to bulk with these filaments, then there would be greater surety that the results observed are a consequence of the system design and operating conditions rather than some inadvertently included laboratory system or operational artifact such as collection, transport, storage and feeding of waste water.

Examination of possible laboratory environment influences

System set-up

Three single-reactor systems were set up with a sludge age of 20 d, temperature 21°C, fed Mitchell's Plain raw sewage, and started up with sludge taken from a laboratory-scale MUCT system (Table 1). This system had been in operation throughout the time the experiments described in Still et al. (1996) and Ekama et al. (1996) were conducted and sustained a low F/M filament bulking sludge (see also Lakay et al., 1988). The sludge in this system typically had a DSVI > 150 mℓ/g with *M. parvicella* and types 0092 and 0914 the dominant filamentous organisms. It was fed Mitchell's Plain raw sewage (the same as that fed to the three single reactor systems) and was operated at 22 d sludge age and 21°C. The DO in the aeration reactor was kept between 2 and 4 mg/ℓ (see Table 1).

Two of the three single reactor systems were operated as IFFD systems fed once daily; the third was operated as a CFCM system (Table 1). The first of the IFFD systems (IFFD1) was not aerated for the first 6 h after feeding, followed by 16 h aeration and 2 h settling. The second IFFD system (IFFD2) was operated fully aerobic from the time of feeding for 22 h followed by 2 h settling. This aeration pattern was selected to resemble in proportion the anoxic-aerobic IFFD and CFCM systems described in Ekama et al. (1996). However, a direct comparison of performance of this (IFFD1) system with those described in Ekama et al. (1996) is not possible because the starter sludge for the former (IFFD1) was an N & P removal sludge (ex laboratory-scale MUCT system) which would manifest some P release and uptake during the unaerated-aeration conditions, whereas the starter sludge for the latter systems (Still et al., 1996; and Ekama et al., 1996) was an N removal sludge (ex full-scale ND plant) which would not manifest P release and uptake. In the fully aerobic IFFD system (IFFD2), aeration immediately after feeding was supplemented with pure oxygen to ensure that during the high initial OUR period, the DO remained above 6 mg/ℓ.

The MUCT system was monitored from day 1; the periodically aerated IFFD system (IFFD1) was started on day 6, the fully aerobic IFFD system (IFFD2) on day 30 and the fully aerobic CFCM system on day 57. Diluted SVI (DSVI) and mixed liquor suspended solids (MLSS) concentration measurements on the four systems, including the MUCT system, were monitored for a period of 120 d and are shown in Fig. 1. Test methods were conducted in accordance with the procedures described in Still et al. (1996). Total phosphorus was measured by persulphate digestion followed by the vanadomolybdo-phosphoric acid calorimetric method as described in *Standard Methods* (1985).

Results

In the periodically aerated IFFD1 system, the DSVI remained approximately the same as in the MUCT system (i.e. between 160 and 220 mℓ/g) from start-up to around day 95, i.e. for a period of 3 months or equivalently, 4.5 sludge ages. However, despite the similarities in DSVI, the filamentous organism populations differed somewhat after two weeks from start-up. In the MUCT system *M. parvicella*, types 0092 and 0914 were the main filaments whereas in IFFD1, *M. parvicella* declined and type 0092 became more abundant with types 0914 and 0675 at common level. It would seem that in the IFFD1 system, with intermittent feeding and periodic aeration, the growth of *M. parvicella* was reduced, and that of type 0092 enhanced compared with the MUCT system.

After three months (day 95) the DSVI in the periodically aerated IFFD1 and MUCT systems began to diverge: In the IFFD1 system, within 15 d from day 95 to day 110 the DSVI increased from around 170 mℓ/g to around 250 mℓ/g with type 0092 the dominant filament whereas in the MUCT system over the same period, the DSVI declined from about 160 mℓ/g to around 120 mℓ/g with *M. parvicella*, types 0092 and 0914 the dominant filaments (Fig. 1).

In the fully aerobic IFFD system (IFFD2) started on day 30, the DSVI decreased steadily from a start-up value of 202 mℓ/g on day 30 to 47 mℓ/g on day 80 i.e. in 50 d. Over the same period the DSVI in the MUCT system remained between 160 and 200 mℓ/g (see Fig. 1). Microscopic examination of the sludge, when the DSVI was low, showed large compact flocs with an almost complete absence of filamentous organisms.

In the fully aerobic CFCM system (CFCM) started on day 57, the DSVI also decreased steadily from a start-up value of 200 mℓ/g to around 100 mℓ/g on day 72, i.e. in only 17 d. Thereafter the DSVI increased slightly. Microscopic examination of the sludge indicated that *S. natans* had become the dominant filament. This was traced to *S. natans* seeding from the influent feed line walls (Still et al., 1996). Following regular cleaning of the influent feed line, *S. natans* disappeared and the DSVI declined to 40 mℓ/g by day 101. At this time the sludge manifested pin-point floc behaviour, a characteristic of such low DSVI sludges. Microscopic evaluation confirmed that the filaments *M. parvicella* and types 0092 and 0914, present at start-up, had been eliminated virtually completely from the sludge.

Conclusions

From the results of these experiments, it was observed that:

- During the entire experimental period the MUCT system sustained the proliferation of the low F/M filaments at bulking level, i.e. *M. parvicella*, type 0092 and type 0914.
- Continuous aeration inhibits the growth of the low F/M filaments *M. parvicella*, type 0092 and type 0914 whether the mixing regime is IFFD (with selector effect) or CFCM (without selector effect).
- In an IFFD system, imposition of an initial unaerated period of 6 h followed by an aerobic period of 16 h at a DO concentration

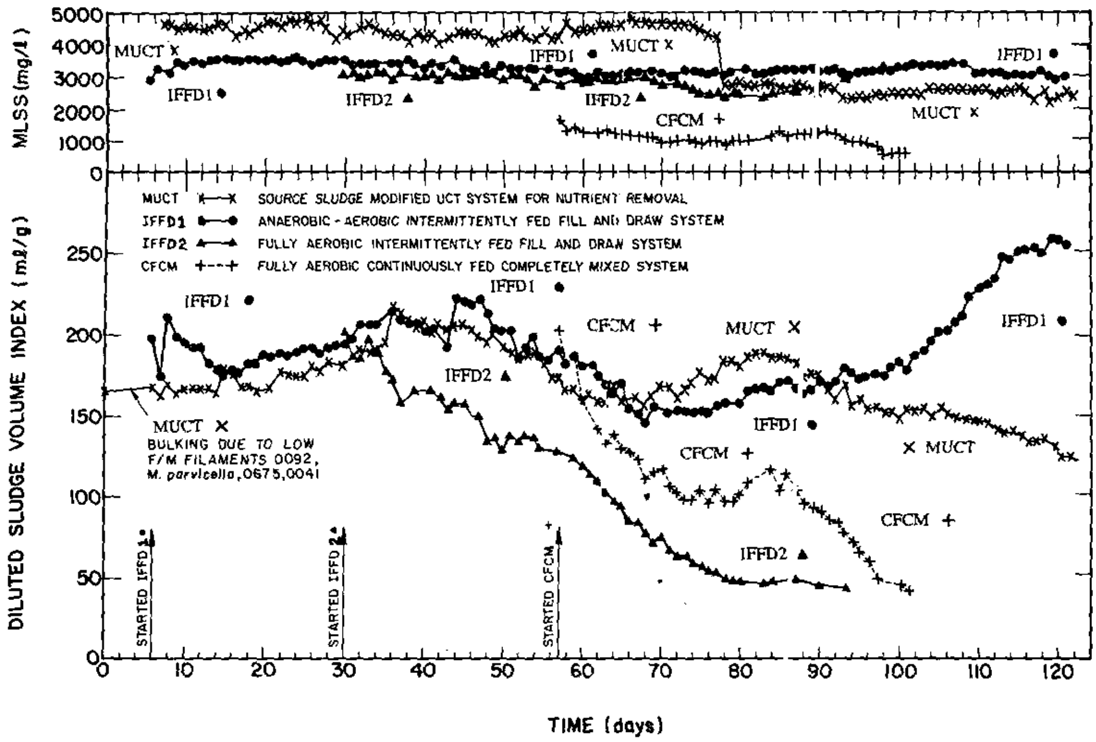


Figure 1

Sludge settleability in DSVI (bottom) and MLSS concentration (top) with time in a MUCT nutrient (N & P) removal system and 3 single reactor systems started up with sludge from the MUCT system, all systems receiving the same sewage (Mitchell's Plain raw) and operated at the same sludge age (20 d) and temperature (21°C). Two of the single reactor systems (IFFD2, CFCM), were fully aerobic, one IFFD, the other CFCM; the third single reactor system IFFD1) was IFFD with an anoxic (½ h) and anaerobic (5½ h) period for 6 h after feeding and an aerobic period of 16 h thereafter (and 2 h settling). Note that the DSVI in the two fully aerobic systems i.e. IFFD2 and CFCM gradually declined from 200 to below 50 mℓ/g, while the DSVI in the systems with unaerated/aerated conditions i.e. MUCT and IFFD1, remained above 150 mℓ/g.

above 6 mg/ℓ, sustains the growth of some low F/M filaments; the growth of *M. parvicella* is reduced but the growth of type 0092 is enhanced compared to the parent MUCT system. During the 6 h unaerated period after feeding, all of the RBCOD would be taken up, some by denitrification organisms and some by polyp organisms. Because these processes happen simultaneously, the RBCOD concentration may be too low to stimulate a selector effect and produce complete nitrate removal.

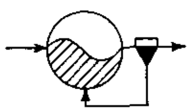
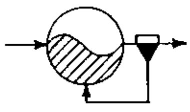
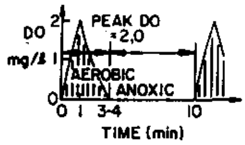
- Amelioration of low F/M filament bulking under fully aerobic IFFD and CFCM conditions in a laboratory-grown low F/M filament sludge fed the same wastewater, indicates that it was unlikely that the inadvertent influences of the laboratory environment was the reason for the inability of the CFCM systems operated earlier (Still et al., 1996; Ekama et al., 1996) to sustain low F/M filament bulking sludges. The results therefore indicate that the system operating conditions have a marked influence on the proliferation or not of low F/M filaments. In this regard the aeration pattern appears to be a more powerful influence than the selector effect induced by alternating feed-starve conditions.

Having confirmed that in all likelihood inadvertent laboratory environmental influences did not affect the proliferation or decline of low F/M filaments in the laboratory systems operated so far, attention was directed at identifying the system conditions that cause the decline or proliferation of these filaments. As a starting point for this, the results of the full-scale plant surveys conducted by Blackbeard et al. (1986; 1988) formed a guide.

Identification of system operating conditions that stimulate low F/M filament proliferation

In examining the data collected in the surveys described by Blackbeard et al., (1986; 1988), it became clear that low F/M filament bulking problems are frequently associated with N and N & P removal systems operating at long sludge ages (10 to 30 d). In N removal systems, bulking by low F/M filaments frequently occurred, in particular in Carousel, Orbal and ditch type plants of which there are many in South Africa. These plants consist of a channel circuit along which the mixed liquor is moved at a relatively high velocity (~1 m/s), by aerators at one or more points in the line of flow. At the aerator the DO is raised to 1 to 2 mg O/ℓ but is reduced to zero at some point in the line of flow, thereafter denitrification takes place in the line of flow up to the next aerator. A slug of mixed liquor passes around the circuit once every 15 to 20 min so that the system essentially is completely mixed with the mixed liquor subjected to short alternating anoxic/aerobic periods (Drews and Greeff, 1973). With regard to N & P removal systems, bulking by low F/M filaments also frequently occurred in the modified Bardenpho, UCT and MUCT systems. Frequency of

TABLE 2
OPERATING PARAMETERS AND CONDITIONS FOR THE SINGLE REACTOR CONTINUOUSLY FED COMPLETELY MIXED INTERMITTENT AERATION NITRIFICATION DENITRIFICATION SYSTEMS (IAND) (EXPERIMENTAL, EXP AND CONTROL, CTRL)

SYSTEM	EXP	CTRL
Operating conditions	Continuously fed, single reactor	
Graphical representation		
Aeration - Day 1 - 103	Intermittent	Intermittent
104 - 176	Continuous	Intermittent
176 - 304	Intermittent	Intermittent
305 - 362	Intermittent	Continuous
DO concentration (mgO/ℓ)		
for intermittent aeration	0 - 2	0 - 2
for continuous aeration	2 - 4	2 - 4
DO profile for reactor		
Feed	Continuous (24h)	
Sewage source	Mitchell's Plain raw	
Sludge source	Laboratory MUCT system	
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
MLVSS concentration (mg/ℓ)	2800	2800
MLSS concentration (mg/ℓ)	3500	3500
F/M [mgCOD/(mgVSS.d)]	0.24	0.24
Underflow recycle ratio	1:1	1:1
pH of mixed liquor	7.3 - 7.5	7.3 - 7.5

alternation between anoxic and aerobic conditions in these systems is much lower than in the ditch type N removal systems because of the spatial separation of the anaerobic, anoxic and aerobic zones with inter-reactor recycle flows in these systems.

A common feature of the full-scale N and N & P removal systems, both types of which sustained low F/M filaments at bulking proportions, is N removal. This is effected by exposure of the sludge to sequential aerated (aerobic) and non-aerated (anoxic) conditions either in separated aerobic and anoxic reactors or in a single reactor with intermittent aeration, as in the ditch type N removal systems. From these observations, a working hypothesis was formed:

> "that low F/M filaments proliferate under the anoxic-aerobic conditions required for N removal."

This hypothesis was tested in the next series of experiments described below.

Anoxic-aerobic systems

System set-up

In an attempt to grow low F/M filaments at laboratory-scale in systems other than N & P (nutrient) removal ones, two completely mixed continuously fed single reactor IAND systems were set up to simulate full-scale ditch type plants - one was designated experimental (EXP) and the other control (CTRL). Both systems had the same sludge age (20 d), temperature (21 °C), reactor volume (7.5 ℓ), nominal hydraulic retention time (18 h) and influent flow rate (10ℓ/d). The influent feed to both systems was Mitchell's Plain raw sewage diluted to produce a COD of 500 mg/ℓ (see Table 2).

To mimic the ditch type plants, the aeration cycle was set as follows: In a cycle time of 10 min, the air-on/air-off periods were set such that the system was aerobic for 3 to 4 min and anoxic for

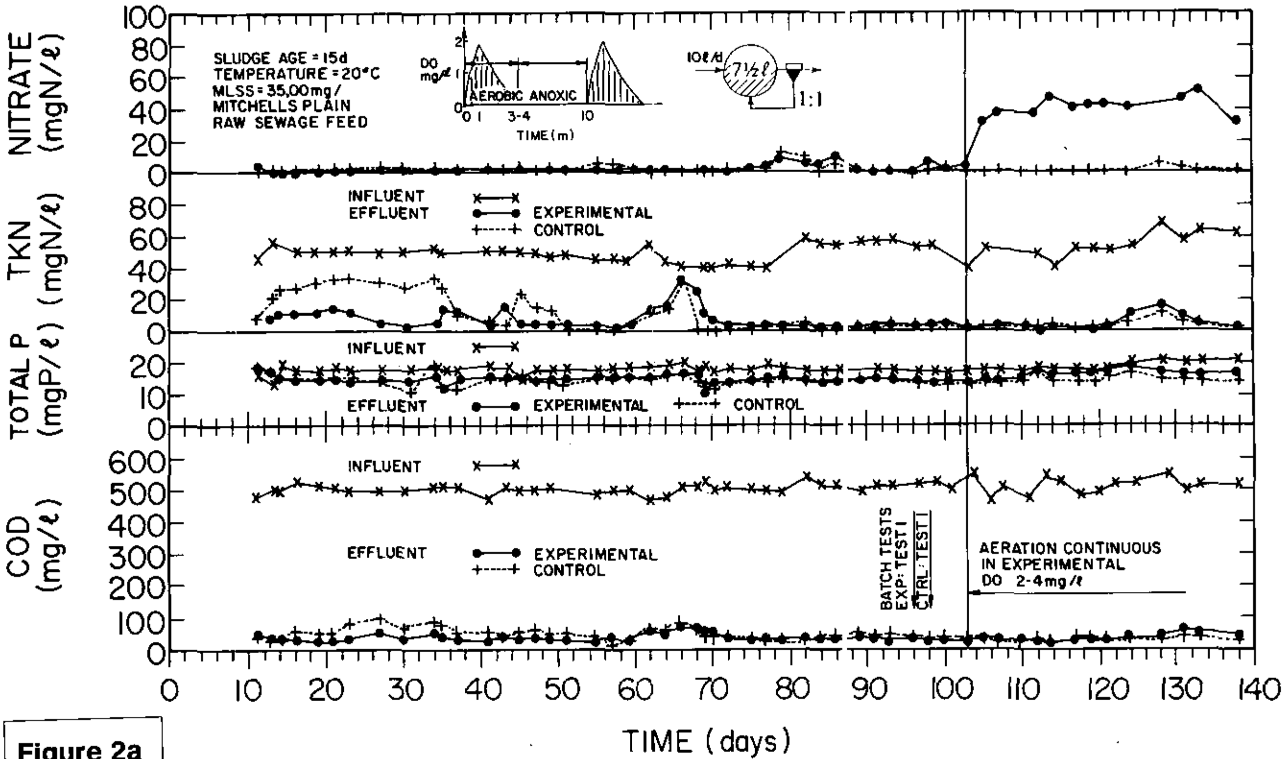


Figure 2a

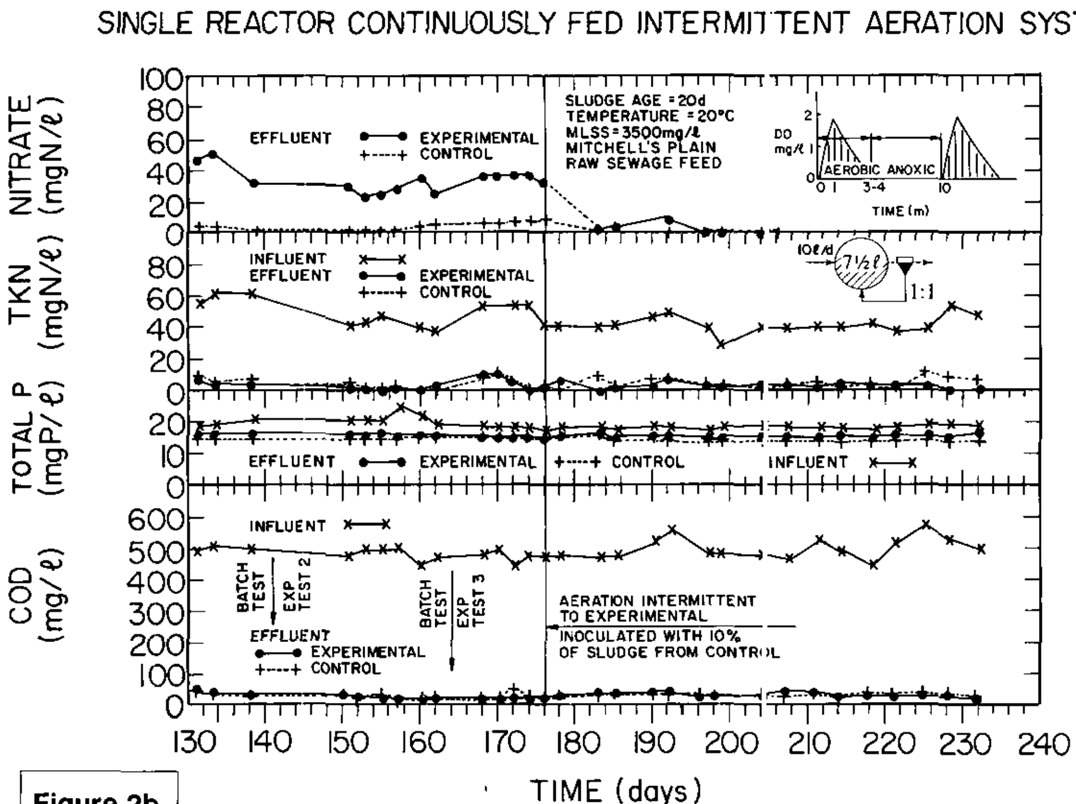


Figure 2b

Figure 2

Influent and effluent COD (lower), total phosphorus (as P) (mid lower), nitrate (as N) (mid upper), and TKN (as N) (upper) concentrations with time in two, one experimental (EXP) the other 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) for 232 d (day 1 to 140 Fig 2a; day 140 to 232 Fig. 2b). Note the high effluent nitrate concentration from day 103 to day 176 (Fig. 2b) due to the absence of denitrification, when the experimental system was operated with continuous aeration (data from day 233 to 362 not given).

6 to 7 min. The duration of aeration depended on the OUR, nitrification and the MLSS concentration. The air-on/air-off period which was adopted once the systems had stabilised, was 1 min on and 9 min off respectively. During the 1 min air-on period, the DO increased to around 2.0 mg/ℓ; over the next 2 to 3 min the DO decreased to zero and for the remaining 6 to 7 min the systems were anoxic (nitrate was present throughout the cycle, see below). During the aerobic period it was found that the OUR is affected primarily by the concentration of ammonium in the influent. Consequently, in order to ensure a high OUR so that the DO would drop sufficiently rapidly after aeration ceases, additional ammonium was added to the influent to stimulate a high nitrification OUR. The additional nitrate generated also ensured that denitrification did not reduce the nitrate concentration to zero by the end of the cycle, so that anaerobic conditions, with its associated complexity of biological P removal, would not occur in the systems.

Results

The two systems were started with Mitchell's Plain (a full-scale ND system with separated anoxic-aerobic reactors) sludge which contained low F/M filaments, type 0092 and *Nocardia* sp. and had a DSVI of about 140 mℓ/g. The overall performance of the systems was monitored by regularly measuring the influent and effluent (24 h composite) COD, TKN, nitrate (as N) and total phosphorus (as P) concentrations; the data measured from day 10 to day 232 are shown in Figs. 2a and b. The sludge settleability measured as DSVI, reactor MLSS concentration and filament populations were monitored regularly; the information collected in the investigation (day 1 to 362) is shown in Figs. 3a, b and c. Test methods were conducted in accordance with the procedures described above.

During the first 28 d while the systems were stabilising, the air-on time and airflow rates were adjusted to give the aeration pattern described above. During this period the DSVI in both systems increased to about 160 mℓ/g (Fig. 3a). Over the next 47 d the DSVI in both systems increased gradually to about 200 mℓ/g (by day 76). Microscopic examination of the sludges on day 67 indicated that the levels of type 0092 and *Nocardia* sp. had declined significantly, but that *M. parvicella*, a filament not observed in the starter sludge, had become abundant. From day 76 to day 100, the DSVI in both systems increased sharply to around 500 mℓ/g, caused by proliferation of *M. parvicella*. Other filaments in the sludge were types 1851, 0092 and 0914 (see Fig. 3a).

On days 85 and 87, aerobic batch tests (with nitrification) were conducted on the experimental and control systems respectively to check whether or not the sludges had a selector effect; in these batch tests the OUR, soluble (0.45μm filtered) COD, TKN, nitrate (as N) and total phosphorus (as P) concentrations were measured over a 24 h period (see Figs. 4 and 5). From the soluble COD concentration and OUR measurements (the latter appropriately corrected for nitrification) it was found that the RBCOD uptake rate was low [110 mg COD/(g AVSS·h) based on soluble COD results - compare with similar low values in Table 2 of Ekama et al. (1996)] indicating that a selector effect was absent in both system sludges.

On day 103 the aeration to the experimental system was changed from intermittent to continuous with the DO concentration controlled between 2 and 4 mg/ℓ. The system response to this is reflected in the effluent nitrate concentration which increased from between 3 and 5 mg N/ℓ to over 40 mg N/ℓ due to the absence of denitrification (Figs. 2a and b). The DSVI immediately began to decrease rapidly; from 480 to 92 mℓ/g in 20 d. The DSVI in the control system, still intermittently aerated, remained at around 560 mℓ/g. On day 123, microscopic examination of the sludges indicated that: The experimental system (continuous aeration) had large compact flocs with few filaments; the filaments, in decreasing order of abundance, were types 0041, 0092 and *M. parvicella*; the control system (intermittent aeration) had open and diffuse flocs with bridging; the filaments, in decreasing order of abundance, were *M. parvicella* at "excessive" level, types 1851 and 0914 at "very common" level and 0092 at "some" level.

On days 131 and 163 while the experimental system had a low DSVI, aerobic batch tests (with nitrification) were conducted on the system sludge, with the objective of checking whether or not the sludge had a selector effect; as in the earlier two batch tests, the OUR, soluble (0.45μm filtered) COD, TKN, nitrate and phosphate concentrations were measured over a 24 h period (see Figs. 6 and 7). These tests showed that the RBCOD uptake rate still was low [~100 mg COD/(g AVSS·h) based on the COD results] indicating that a selector effect still was absent in the system. Consequently the reduction in DSVI and amelioration of low F/M filament bulking could not have been the result of a selector effect.

On day 176 (Fig. 3b) the continuous aeration in the experimental system was changed back to intermittent. Because the filaments had been reduced to such a low level in the experimental system (DSVI - 70 mℓ/g), 10% of the mixed liquor was wasted from this system and replaced with heavily filamentous sludge from the control system. The system response again is reflected in the effluent nitrate concentration, which decreased to 3 to 5 mg N/ℓ due to the reinstatement of denitrification (Fig. 2b). The DSVI in the experimental system began to increase slowly and on day 202 stabilised at 120 mℓ/g. Inspection of the DO concentration profile during the 10 min aeration cycle indicated that the peak DO concentration was only 1.3 mg/ℓ (not 2.0 mg/ℓ as earlier). Consequently on day 217 the airflow rate was increased so that the DO reached 2.0 mg/ℓ. Following this change, the DSVI in the experimental system increased, attaining over 200 mℓ/g on day 238. In the control system (intermittent aeration) the DSVI decreased slowly over this same period from about 550 mℓ/g around day 140 to below 300 mℓ/g around day 217. It is possible that this steady decline in the DSVI also was caused by the low airflow rate resulting in a low peak DO concentration. It is interesting to note that during this decline in DSVI, numbers of the filament *M. parvicella* also declined. The morphology of this filament is such that it has a large impact on the sludge settleability, much more so than type 0092. On day 217 the air flow rate to the control system also was increased, as for the experimental system mentioned earlier. The DSVI in the control system now remained relatively stable, but that of the experimental system increased slowly so that by day 270 (Fig. 3b), the DSVIs of both systems were about the same at 240 mℓ/g. However, the filamentous organism populations were somewhat different: type 0041 was the most dominant in the experimental system whereas *M. parvicella* and type 0092 were most dominant in the control system.

For the next 32 d the systems were carefully observed to check whether or not the filamentous populations would become similar. When this did not happen, on day 302 the sludges were mixed and divided equally between the two systems. After mixing, the DSVIs in both systems were around 310 mℓ/g (see Fig. 3c).

On day 304 the air supply to the control system, was changed from intermittent to continuous. The control system was changed this time to ensure that the decline in DSVI in the experimental system was not an artifact of the system. The DSVI of the control system decreased rapidly from 317 to 104 mℓ/g in only 10 d and thereafter continued to decline, but more slowly so that by day 350 i.e. 46 days after changing to continuous aeration, the DSVI was 60

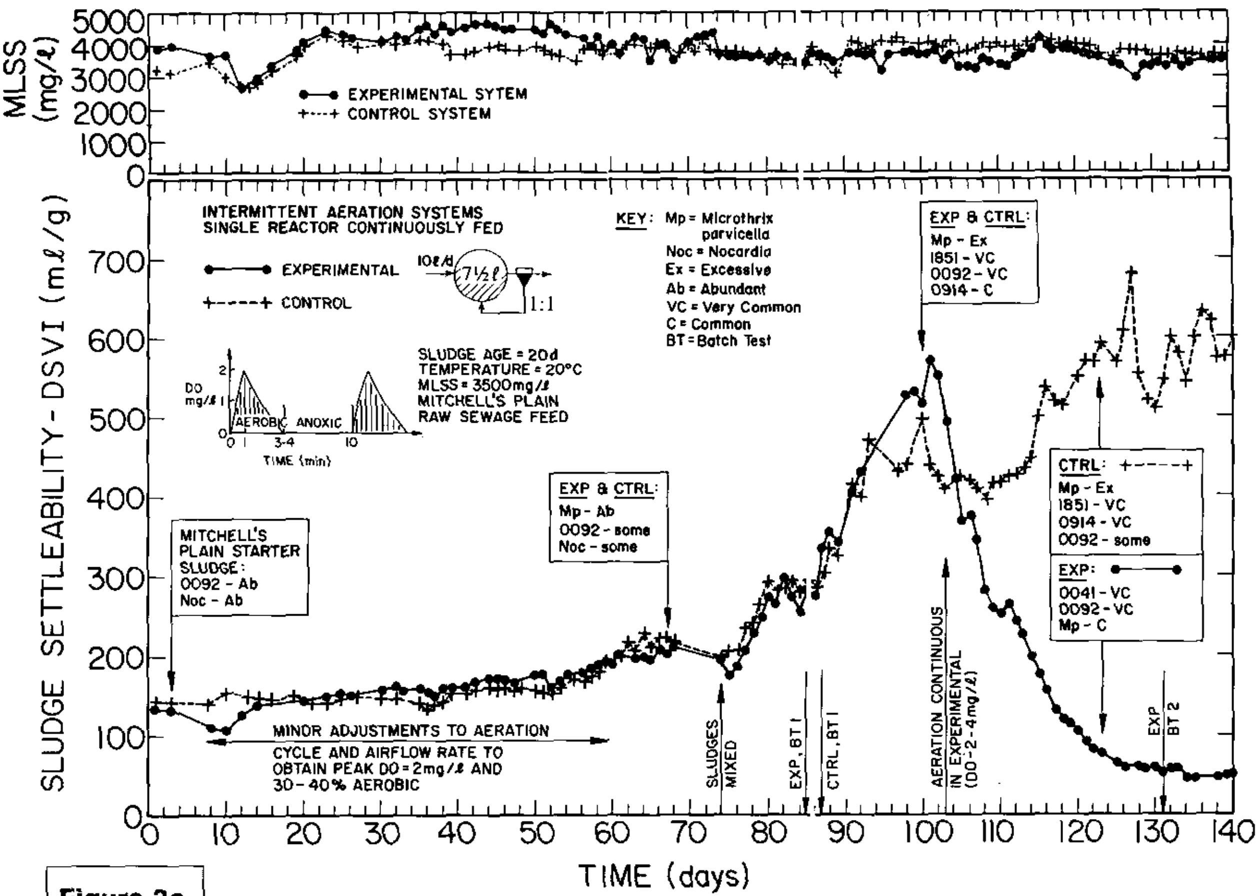


Figure 3a

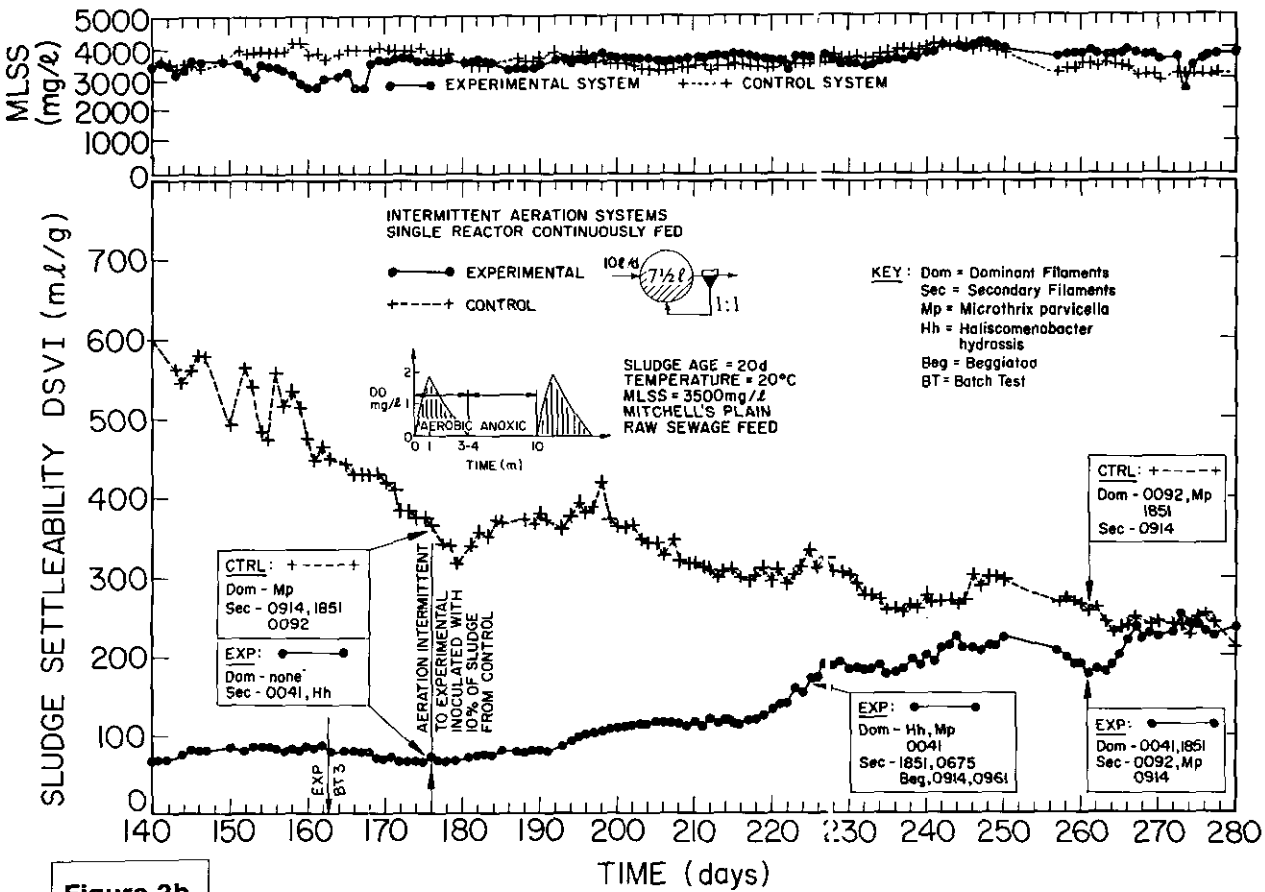


Figure 3b

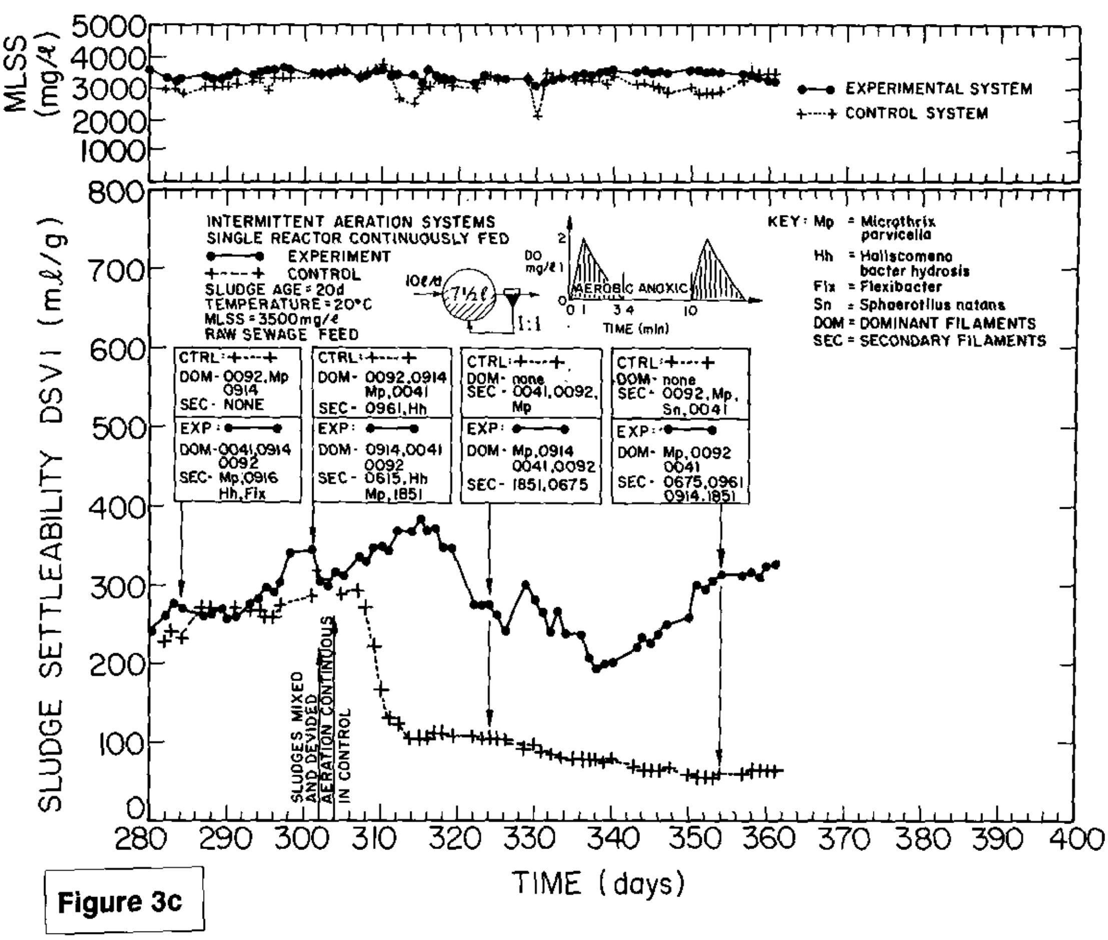


Figure 3c

Figure 3

Sludge settleability in DSVI with time in two (one experimental, EXP; one control, CTRL) single reactor continuously fed intermittent aeration systems receiving the same sewage (Mitchell's Plain raw) and operated at the same sludge age (20 d) and temperature (21°C) for 362 d (day 1 to 140 Fig. 3a; day 140 to 280 Fig. 3b; day 280 to 362 Fig. 3c). Note (1) increase in DSVI and concomitant proliferation of low F/M filaments, in particular M. parvicella from day 0 to 103 when aeration is intermittent (Fig. 3a); (2) decline in DSVI (to below 100 mℓ/g) and in low F/M filaments from day 103 to 140 when aeration is continuous (DO = 2 to 4 mg/ℓ) in the experimental system while the DSVI in the control system remains high (> 300 mℓ/g) (Fig. 3a); (3) low DSVI in the experimental system when aeration is continuous whereas it is high in the control system, caused by low F/M filaments, when aeration is intermittent (day 140 to 176, Fig. 3b); (4) increase in DSVI in the experimental system with a concomitant proliferation in low F/M filaments, when aeration is changed from continuous to intermittent (day 176 to 280, Fig. 3b); (5) decrease in DSVI and concomitantly in low F/M filaments when aeration in the control system is changed from intermittent to continuous (day 304 to 361, Fig. 3c) while in the experimental system the DSVI remains high (> 200 mℓ/g) with intermittent aeration.

mℓ/g. The DSVI remained at this level until the end of the experiment on day 362. Over the same period, the DSVI in the experimental system (intermittent aeration), initially increased to 371 mℓ/g, then decreased to around 200 mℓ/g and then increased again to 340 mℓ/g by the end of the experiment (day 362). The filamentous organisms dominant in the experimental system during this period were *M. parvicella* and types 0914, 0092 and 0041.

Conclusions

From the experiments with the single reactor continuously fed intermittent/continuous aeration systems, it was concluded that:

- Intermittent aeration in continuously fed completely mixed systems, with short alternating anoxic-aerobic periods, promotes and sustains the growth of low F/M (long sludge age) filaments *M. parvicella*, 0092, 0041, 0675, 0914 and 1851, giving rise to DSVIs of 200 to 500 mℓ/g. The very high DSVIs were principally due to *M. parvicella*.
- Changing from intermittent to continuous aeration (2 to 4 mg O/ℓ) reduces the low F/M filament abundance over a period less than a sludge age, to give DSVI values as low as 60 mℓ/g in the absence of a selector effect.
- No problems with *S. natans* bulking were encountered in the systems, even though the feed lines were not regularly cleaned, indicating that large anoxic mass fractions (60 to 70%) inhibit the growth of this filament even though through continuous feeding (and possibly seeding) the system receives RBCOD during (short) aerobic periods.

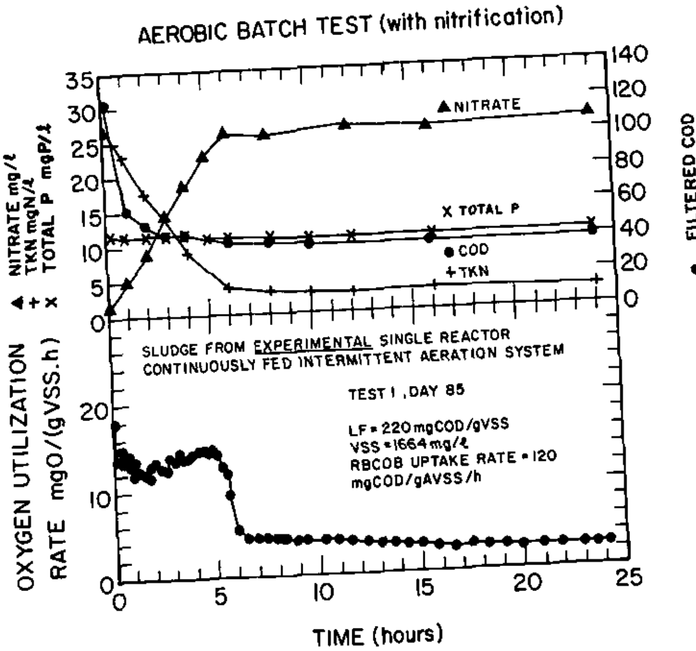


Figure 4
OUR [in mg O/(g VSS·h)] (bottom), and soluble COD (<0.45 µm), TKN, nitrate (as N) and total phosphorus (as P) concentrations (top) in the first aerobic batch test (with nitrification) (day 85) at a load factor of 220 mg COD/g VSS on sludge harvested from the experimental single reactor continuously fed intermittent aeration system. Note that the RBCOD uptake rate (calculated from the soluble COD concentrations) is slow at 120 mg COD/(g AVSS·h) indicating the absence of a selector effect.

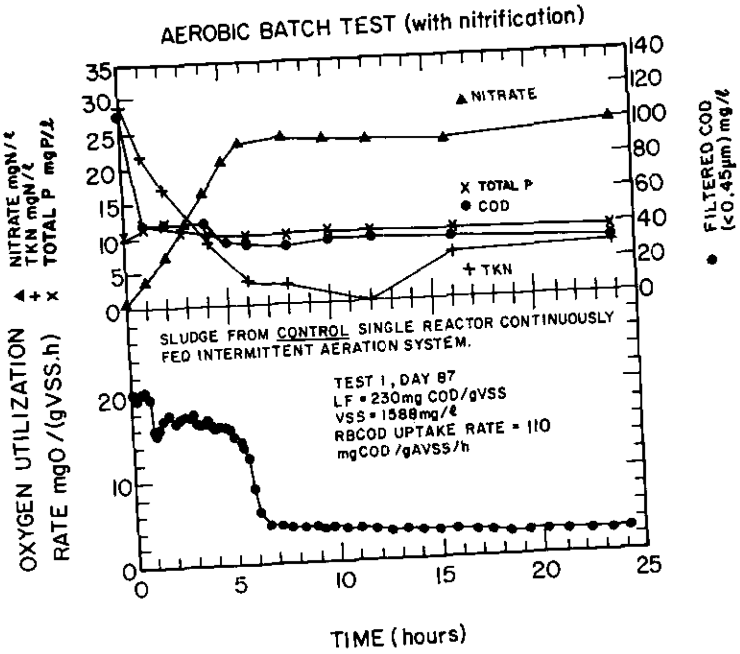


Figure 5
OUR [in mg O/(g VSS·h)] (bottom), and soluble COD (<0.45 µm), TKN, nitrate (as N) and total phosphorus (as P) concentrations (top) in the first aerobic batch test (with nitrification) (day 87) at a load factor of 230 mg COD/g VSS on sludge harvested from the control single reactor continuously fed intermittent aeration system. Note that the RBCOD uptake rate (calculated from the soluble COD concentrations) is slow at 110 mg COD/(g AVSS·h) indicating the absence of a selector effect.

Closure

Having developed a laboratory-scale system other than N & P removal ones in which low F/M filaments are known to proliferate allows further experimental work to determine whether the presence of a selector effect (induced by selector reactors) can control growth of low F/M filaments. An investigation into the influence of the selector effect (as stimulated by aerobic selectors) on the low F/M filaments in continuously fed intermittent aeration systems is presented in Gabb et al. (1996).

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Figure 6

OUR [in mg O/(g VSS·h)] (bottom), and soluble COD (<0.45 µm), TKN, nitrate (as N) and total phosphorus (as P) concentrations (top) in the second aerobic batch test (with nitrification (day 131) at a load factor of 220 mg COD/g VSS on sludge harvested from the experimental single reactor continuously fed intermittent aeration system. Note that the RBCOD uptake rate (calculated from the soluble COD concentrations) is slow at 100 mg COD/(g AVSS·h) indicating the absence of a selector effect.

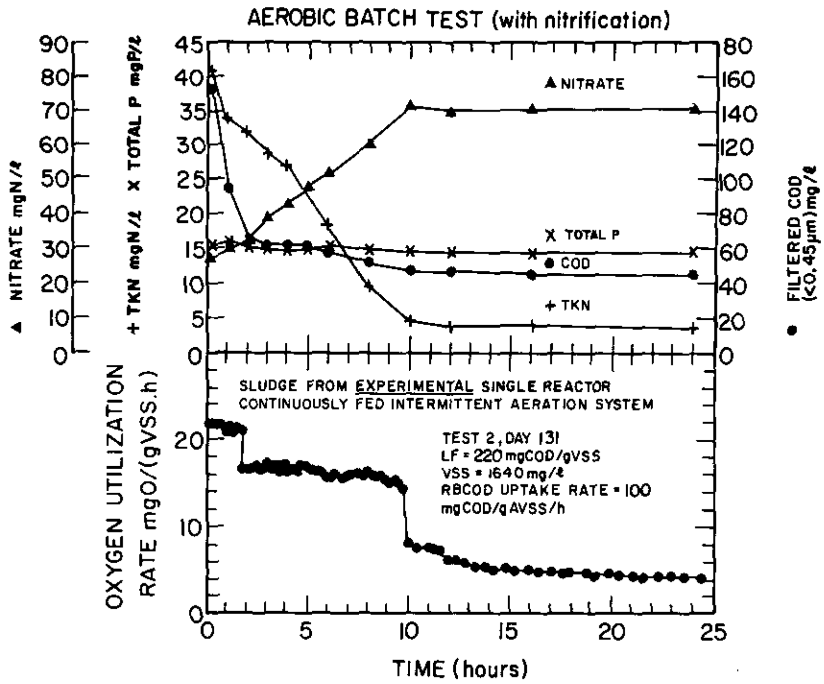
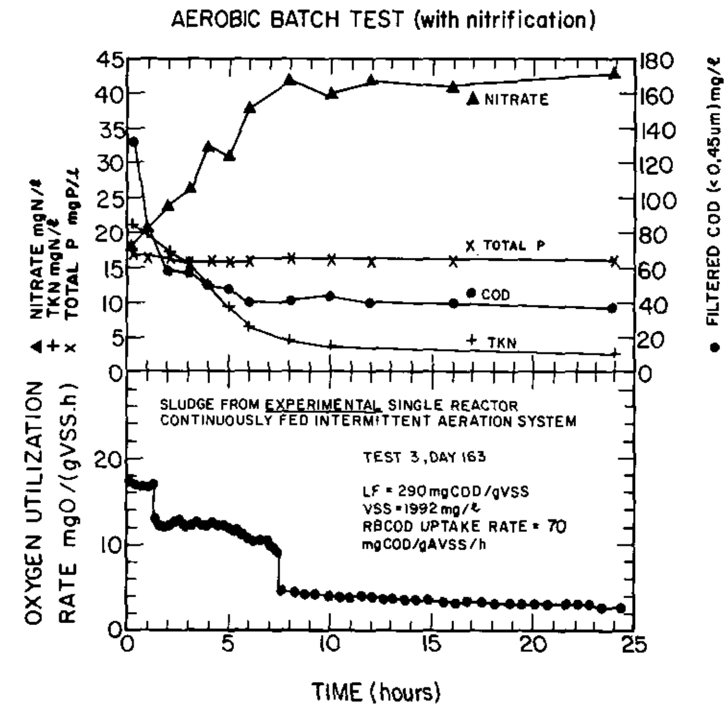


Figure 7

OUR [in mg O/(g VSS·h)] (bottom), and soluble COD (<0.45 µm), TKN, nitrate (as N) and total phosphorus (as P) concentrations (top) in the third aerobic batch test (with nitrification) (day 163) at a load factor of 290 mg COD/g VSS on sludge harvested from the experimental single reactor continuously fed intermittent aeration system. Note that the RBCOD uptake rate (calculated from the soluble COD concentrations) is slow at 70 mg COD/(g AVSS·h) indicating the absence of a selector effect.



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