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HYBACS: FUTURE-PROOFING AN AGING GENERATION OF ACTIVATED SLUDGE ASSETS

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Abstract

This paper describes a hybrid activated sludge process ('HYBACS®'), comprising an attached growth reactor upstream of a suspended growth aeration stage, in which settled sludge is recycled to the head of the process. The attached growth reactor provides rapid enzymatic hydrolysis of the macromolecular components of the wastewater, overcoming the main rate-limiting step and achieving a substantial enhancement in activated sludge performance. The process is well-suited to the upgrade of existing activated sludge plants for increased capacity or enhanced effluent quality.

The biochemical mechanisms occurring within the attached-growth reactor are discussed and data are presented from a recent case study at Tubli WPCC, Bahrain, in which the treatment capacity of two aeration lanes was upgraded using HYBACS from 40 MLD to 100 MLD (140,000 PE to 500,000 PE). The upgrade was achieved with minimal land take, without increasing aeration footprint and by reusing all existing civil structures, which made the upgrade very cost effective.

Apart from increasing treatment capacity of existing tanks, HYBACS produces sludge that contains large, dense activated sludge flocs with few filaments and excellent settling and thickening characteristics. This enables high solids loads to be applied to the clarification stage.

Keywords

Hybrid Activated Sludge, HYBACS, hydrolysis, SMART unit

Introduction

HYBACS, denoting HYBrid ACtivated Sludge, is a variant on the activated sludge process which combines a high-rate attached growth reactor with a conventional activated sludge process. HYBACS is particularly cost-effective as an upgrade to an existing activated sludge process, where it can achieve a doubling in capacity and/or a significant enhancement in final effluent quality without the need for substantial investment in new assets.

The process we now refer to as HYBACS was developed from a forerunner technology invented in South Korea during the 1980s and 1990s known as the Rotating Activated Bacillus Contactor (RABC) process (Kim *et al*, 2004). The first full-scale application was a 600 m^3/d industrial effluent treatment plant for Lotte Confectionary Co., built in 1999. This was followed by more than 20 installations on municipal wastewater treatment up to 110,000 PE and industrial applications for the food & drink, livestock and landfill sectors, mostly within South Korea.

In 2007 Bluewater Bio acquired the technology, following due diligence carried out by Dr Garry Hoyland (then Divisional Director at Mott MacDonald and now Chairman of Bluewater Bio Technologies). Initially, Bluewater Bio built two HYBACS pilot plants to demonstrate performance under European conditions and investigate the biochemical treatment mechanisms. The first plant was installed at Coleshill STW(Birmingham) and jointly assessed with Severn Trent Water Ltd; and a second identical plant was installed at Avila STW, NW of Madrid, with Aqualia SA.

Since 2007, a further six full-scale HYBACS plants have been commissioned, serving populations up to 500,000. This paper describes the function and configuration of the HYBACS process and summarises performance data from a recent large installation.

The HYBACS Process

Configuration of HYBACS

HYBACS comprises two biological stages: a unique attached growth reactor referred to as a SMART™ unit, and an activated sludge tank. The subsequent process is clarification (or another solids separation technique) and, crucially, some or all of the return activated sludge (RAS) is recycled to the SMART unit. A typical HYBACS configuration is illustrated in Figure 1.

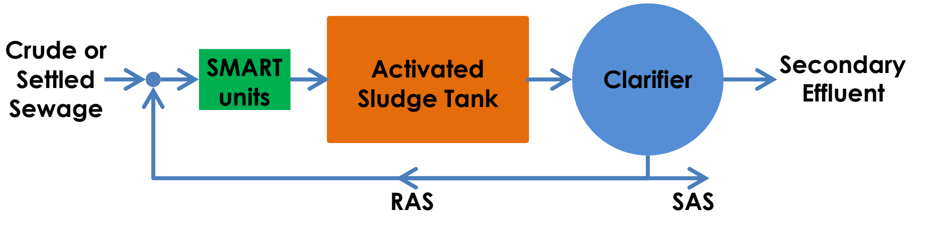

Figure 1: Typical HYBACS Configuration

The configuration can be adapted to achieve nitrogen and/or phosphorus removal by incorporating anoxic and anaerobic zones. In each case, the SMART units are located downstream of the point where incoming wastewater mixes with RAS, but upstream of the aeration tank or internal recycle. It is considered that maximising the COD concentration of the liquor passing through the SMART units also maximises the overall performance of the process.

HYBACS is best applied as an upgrade to an existing activated sludge process. By adding an appropriate number of SMART units, the load to an existing aeration tank may be increased by up to 150%. Carbonaceous-only or nitrifying activated sludge plants may be upgraded to include nitrification or high nitrogen removal. Generally, the existing assets can be retained, giving a very simple and low-cost upgrade.

SMART Units

SMART units superficially resemble rotating biological contactors (RBC), having circular disks of media mounted upon a horizontal shaft. However, instead of impermeable disks which develop a biofilm with an active thickness of typically 200 microns, SMART units contain 50mm thick reticulated mesh disks which fill naturally with porous attached biomass. The repeated immersion and drainage of the mesh as the shaft rotates ensures very efficient convection of substrates and oxygen throughout the biomass within the porous plates. In addition, the convection of the liquor, which contains the RAS, renews the biomass within the plates, sustaining a high biomass activity in the long term.

A standard SMART unit is 4.8m long and 2.2m wide, containing 30 mesh disks each 2.0m diameter, and serves a population equivalent of 5-10,000 PE depending upon the strength of the wastewater. The mesh rotates at between 2 and 6 rpm (under DO control), driven by a 2.2kW motor. SMART units contain about 15% of the total active biomass of HYBACS plants.

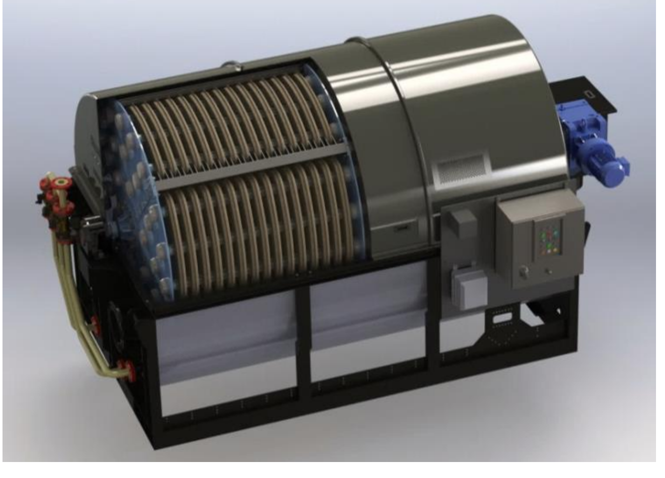

Figure 2: SMART Unit (cutaway to show mesh disks)

The SMART unit is also structurally different to a rotating biological contactor (RBC). It includes structural end-plates and interlinking beams to create a rigid cylindrical cage, which is inherently much stronger than the shaft of an RBC.

Biochemical Mechanisms in the SMART Unit

Overview

The volume of the SMART unit is very small in comparison to the associated activated sludge tank. For example, in the HYBACS plant at Tubli, Bahrain, (see case study) the total liquid volume in the SMART units represents 1.6% of the volume of the aeration tanks, yet the incorporation of SMART units has increased the capacity of the system 2.5-fold. Clearly the SMART units are not merely serving as additional biological capacity, but are fundamentally altering the performance of the system.

Research by Bluewater Bio and its US licensee, Infilco Degremont (Labban *et al* 2013), has identified the following key features of the biochemistry of the SMART unit, which contribute to its performance:

- High biomass density
- Enriched population of aerobic heterotrophs within the biomass
- Adsorption of particulate material onto attached biomass in the SMART unit
- Rapid enzymatic hydrolysis of particulate COD
- Absorption of soluble COD

Biomass Density

The mesh used within SMART units is unique within the water industry. It is fabricated from 0.6mm diameter fibres of a PVC-like plastic material, formed into 50mm thick sheets with a voidage of 96% (Figure 3). In use, the mesh rapidly fills with attached biomass (Figure 4). It is not a biofilm system so the specific surface area of the media is not a relevant parameter.

Figure 3: Clean mesh prior to use

Figure 4: Biomass within mesh

The concentration of biomass within the mesh varies in proportion to the strength of the wastewater, typically in the range 50 – 60,000 mg per litre of mesh volume.

Concentration of Aerobic Heterotrophs

The attached biomass within the SMART unit is continuously exposed to a high COD, owing to its location in the process. These conditions favour the development of a highly-active biomass containing a high proportion of aerobic heterotrophs.

Microbiological plating techniques were used to quantify the aerobic heterotrophs in 1 g of volatile matter (VSS) of activated sludge from a HYBACS pilot plant at Severn Trent's Coleshill STW (Hoyland *et al.,* 2010). Samples were also taken from different locations within the SMART unit: a composite sample of biomass from throughout the depth of the mesh, a sample of biomass from the centre of the mesh and a sample from the surface.

Table 1: Aerobic Heterotroph Concentrations in HYBACS

Date	Temp. (°C)	Conc. of aerobic heterotrophs (x10^6 CFU/gVSS)			
		Activated sludge	SMART unit		
			Composite	Middle	Outside
19/05/2010	15.8	260	2,782		
16/06/2010	17.1	850	6,800		
29/07/2010	19.1	1,300	3,770		
12/10/2010	17.1	1,300	1,560		
28/10/2010	16.0	790		790	2,370
09/12/2010	11.0	520		2,704	2,808
18/01/2011	11.4	400		600	2,760
10/02/2011	12.6	360		3,204	5,904
16/02/2011	11.2	380		1,178	13,566
Mean	**14.6**	**684**	**3,728**	**1,695**	**5,482**
Mean ratio to A.S. *	**-**	**-**	**5.7**	**3.9**	**13.5**

* The mean ratio is calculated as the mean of each of the ratios of aerobic heterotroph concentration in the SMART unit, compared to the activated sludge, measured at different temperatures.

The results indicate that SMART units contain a substantially enhanced proportion of aerobic heterotrophs within the volatile matter, compared to the suspended growth (activated sludge) stage of the same plant. This is due to two major factors:

- the location of the SMART units at the head of the process, providing a continuous high-COD environment within the reactors; and
- the efficient aeration provided by rotary motion, which enables all parts of the media to remain aerobic.

Hydrolysis of Particulate COD

It has been established that particulate COD and dissolved macromolecules must be hydrolysed into monomers and small oligomers before they can be assimilated and subsequently oxidised by bacteria (Banerji *et al* 1967; Law 1980). Further, over 75% of hydrolytic enzyme activity in an activated sludge process is associated with bacterial cell walls (Confer & Logan 1998, Li & Chróst 2006). The products of hydrolysis are released into the bulk solution for assimilation or further hydrolysis.

Within the SMART unit, we have established that there is a high concentration of volatile matter, and that this matter contains enhanced proportions of aerobic heterotrophs. It can therefore be inferred that the SMART units contain greatly enhanced concentrations of hydrolytic enzymes within the attached biomass. Experiments are ongoing to quantify the enzymatic activity of the SMART units at Cranfield University, comparing it to conventional activated sludge processes.

There are several competing mechanisms occurring within a SMART Unit as illustrated in Figure 5. Particulate COD is hydrolysed either in the bulk liquid or, more likely, following entrapment or adsorption within the attached biomass where the concentration of cell-associated hydrolytic enzymes is highest. The entrapment of particulate matter within the mesh of the SMART unit also provides an extended retention time for hydrolysis to occur. There is some evidence to indicate a reduced residual (or 'recalcitrant') COD concentration in HYBACS plants.

The products of hydrolysis may be assimilated directly into the attached biomass, but the assimilatory capacity of these cells is limited by their ability to metabolise substrates. Hence our hypothesis is that the hydrolysis products are assimilated into the suspended biomass within the SMART unit but mostly in the downstream activated sludge process. Thus, the SMART units accelerate the hydrolysis of particulate COD, which is the rate-limiting step in a biological wastewater treatment process, thereby enabling a much higher loading rate.

It should also be noted that the HYBACS process generates sufficient readily-degradable COD to support enhanced denitrification in a downstream anoxic reactor. This is consistent with observed performance of HYBACS plants around the world, which can achieve total nitrogen removal of at least 80% without the need for a supplementary carbon source.

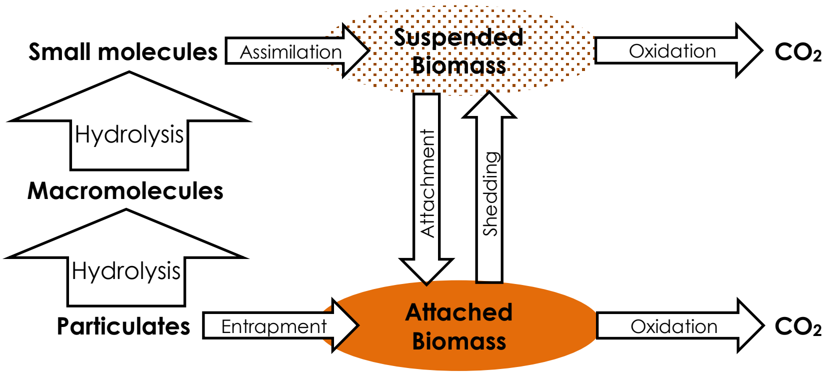

Figure 5: Reactions affecting COD in the SMART Unit

Some oxidation of COD takes place within the SMART unit, but most occurs in the activated sludge process downstream. Likewise there may be a minor reduction in ammonia and nitrate concentrations during passage through the SMART unit through assimilation, but most nitrogen removal occurs in the activated sludge stage in the conventional way.

Case Study: Tubli WPCC

Overview

Tubli Wastewater Pollution Control Centre (WPCC) serves the city of Manama, Bahrain. It was built in phases, the last being in 2002 when the design capacity was 200,000 m^3/d (200 MLD) and 41,000 kg/d BOD, representing a population equivalent (PE) of approximately 700,000.

The process comprised preliminary treatment, 10 aeration lanes and 12 clarifiers. Thus each aeration lane has a design capacity of 20 MLD and each clarifier has a design capacity of 17 MLD. A proportion of the secondary effluent is ozonated and filtered to produce treated sewage effluent (TSE) which is pumped for irrigation purposes around the city; the remainder is discharged into Tubli Bay. The quality standard applying to discharges to the sea is currently 20 mg/l BOD, 20 mg/l suspended solids and 3 mg/l ammonia-N, though new limits of 10 mg/l total nitrogen (TN) and 1 mg/l ammonia-N are due to be applied in future.

The population of Bahrain has grown rapidly and Tubli WPCC became overloaded. In 2010, the average wastewater flow received was 303 MLD and the BOD load recorded was 53,200 kg/d, representing approximately 890,000 PE. A solution comprising a new 200 MLD membrane bioreactor (MBR) process, operating in parallel with the existing works, was considered by the Bahraini Ministry of Works. This met the objective of expanding capacity within the existing site boundary, but was rejected owing to the high cost. Instead, an interim upgrade solution was selected in 2011, comprising the conversion of two aeration lanes and four clarifiers into a HYBACS process, with a capacity of 100 MLD.

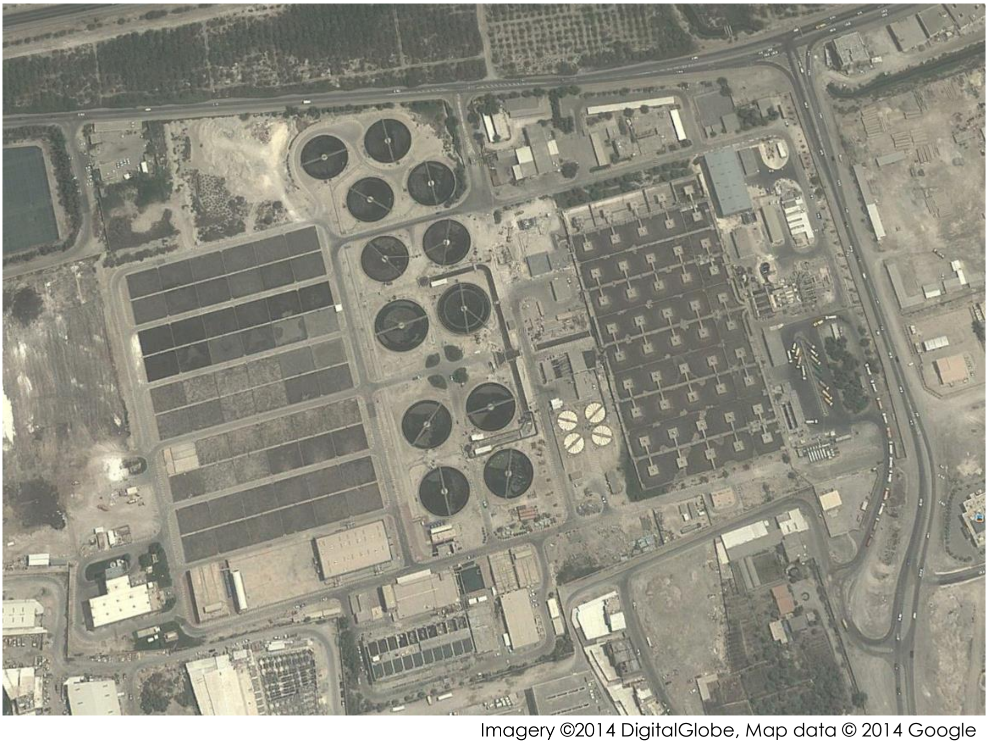

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Figure 6: Aerial Photograph of Tubli WPCC

The upgrade comprised:

- Installation of 42 SMART units upstream of the existing aeration tanks
- Construction of an anoxic zone within the two aeration lanes
- Replacement of the old surface aerators with a fine bubble diffused aeration system in the two aeration lanes
- A new clarifier distribution chamber and RAS pumping station to separate the four HYBACS clarifiers from the eight conventional clarifiers
- Ancillary works, including a new grit trap, motor control centres and a HYBACS feed pump station

The photograph in Figure 6 was taken during the upgrade project. The two aeration lanes upgraded to HYBACS are at the northern end of the block (one lane has been drained). The SMART unit building can be seen immediately to the east of these lanes. The HYBACS clarifiers are the northern block of four. Note the limited land available for upgrading the plant.

Figure 7: One of the two aeration lanes converted to HYBACS, with SMART unit building in the background

The contract, valued at £14m, was awarded in July 2011 and the HYBACS upgrade was commissioned in two phases in June and October 2013.

Design Loadings for HYBACS

The flows and loads used for design purposes are compared in Table 2 against the original design capacity for the aeration lanes and clarifiers incorporated into the upgrade, and the actual loads received during the performance testing period (10 December 2013 – 6 January 2014).

Table 2: Comparison of Design Flows & Loads for HYBACS Plant

Parameter	Original Design Capacity	Average during Performance Test
Average flow (MLD)	40	101
BOD load (kg/d)	8,200	30,300
COD load (kg/d)	-	65,250
SS load (kg/d)	-	48,200
NH_3-N load (kg/d)	-	2,200
Total phosphorus load (kg/d)	-	515
Population equiv. (PE)	137,000	505,000

Key Design Parameters

The design process for HYBACS is performed using a proprietary model, based upon the performance of HYBACS plants and predecessor technologies in the UK, USA, South Africa and South Korea. For projects such as Tubli WPCC, where the aeration tank volume is fixed, the design model determines the number of SMART units required to achieve the necessary upgrade. In this case, 42 SMART units were required, giving a loading of 840 kg COD per SMART unit.

The existing aeration lanes were 112.6m long, 22.5m wide and 4.5m deep. The depth was increased to 4.95m by raising the outlet weirs, giving a volume of 12,500 m^3 per lane, or 25,000 m^3 for the HYBACS plant. Of this, 20% (5,000 m^3) is an anoxic zone and the remainder is divided into three aerated zones, each with separate DO control. Internal recycle pumps (72 MLD max. per lane) were installed in the final aerated zone to return mixed liquor to the anoxic zone for nitrogen removal.

An average MLSS concentration of 3,600 mg/l was selected, giving a design solids loading on the clarifiers of 8.1 $kg/m^2.h$ at the peak flow of 150 MLD (equivalent to a clarifier upflow velocity of 1.38 m/h). These are very aggressive clarifier loading rates in comparison to conventional activated sludge, but HYBACS sludge has excellent settlement characteristics.

The original surface aerators (10 x 80kW rated power) were replaced by a fine bubble diffused aeration system and three turbo blowers operating as duty/ assist/ standby (500 kW rated power each).

Effluent Quality from the HYBACS Upgrade

The performance of the HYBACS Upgrade is summarised in Table 3.

Table 3: Summary of Effluent Quality during Performance Test

Parameter	Guaranteed value	Average during Performance Test
Average flow (MLD)	100	101
COD (mg/l)	-	27
BOD (mg/l)	15	9.7
SS (mg/l)	20	9.2
NH_3-N (mg/l)	3 *	0.58
Total nitrogen (mg/l)	-	9.0
Total phosphorus (mg/l)	3	1.1

Note: * The effluent ammonia concentration of 3 mg/l was an informal target, not a guaranteed value.

Nitrification was established within just 5 days of commissioning the SMART units and the mean effluent ammonia concentration from then until 31/01/14 has been 0.60 mg/l.

The average aerobic F:M ratio (based on the aerated biomass in the aeration tanks) during the performance test was 0.44 kg BOD/kg MLSS.d.

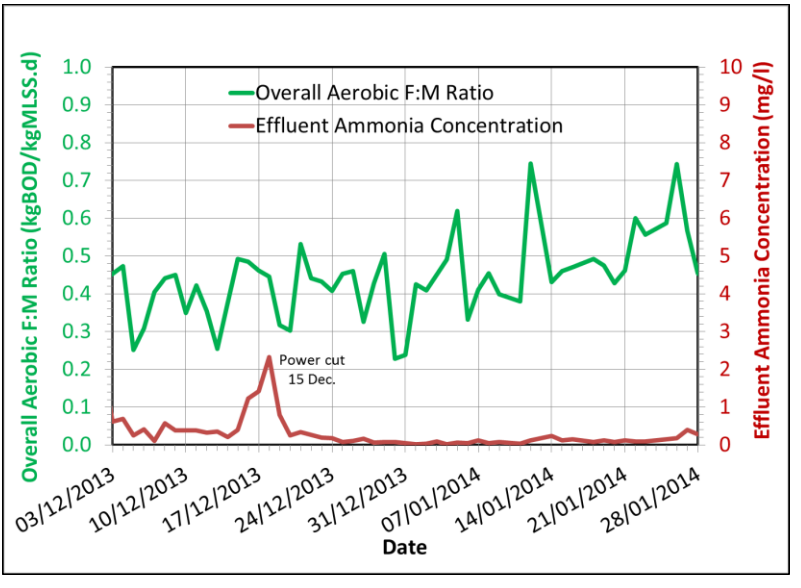


Figure 8: Loading Rate and Effluent Ammonia Concentration

Wastewater temperatures in Bahrain vary between 23°C and 36°C. During the performance test the average was 29°C, which will accelerate biological activity in accordance with the Arrhenius equation. Reported kinetic coefficients for the growth of autotrophic bacteria vary but the 'typical value' of θ suggested by Metcalf & Eddy (2004) is 1.053 (unitless). Thus the F:M of 0.44 kg/kg.d at 29°C can be corrected to a temperature of 10°C, giving:

$$k_{10} = \frac{k_{29}\theta^{(10-20)}}{\theta^{(29-20)}} = 0.17\,\text{kg/kg.d}$$

This is substantially higher than typical design F:M ratios of around 0.075 kg/kg.d needed for high degrees of nitrification and nitrogen removal for UK conditions. The difference may be attributed to the hydrolytic action of the SMART units to accelerate the biochemical reactions within the aeration lanes.

Other installations in the UK, New Jersey (USA) and South Korea have demonstrated the cold-weather performance of HYBACS.

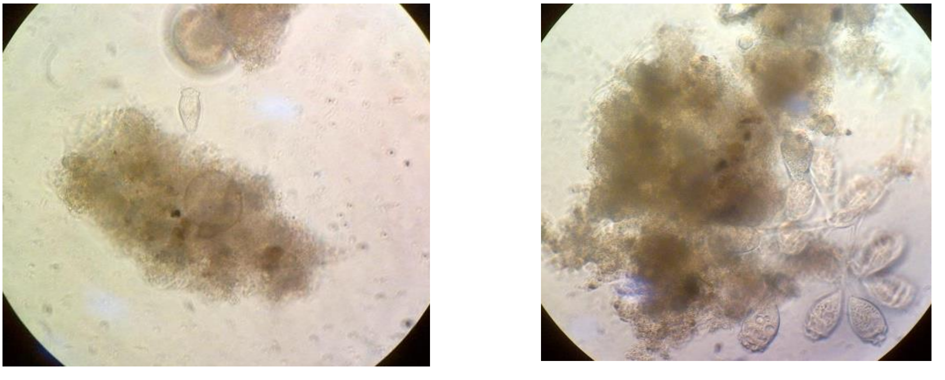
The solids retention time, based upon the volume of the aerated zones of the activated sludge stage, was 2.1 days on average during the performance test.

The remaining eight aeration lanes at Tubli WPCC continue to operate as a conventional activated sludge process, treating the same wastewater as the HYBACS process. These lanes operate at a F:M ratio of approximately 0.2 kg/kg.d and do not nitrify during the coldest months and only partially during the warmest.

Sludge Settlement and Floc Characteristics

Good sludge settleability and an absence of foaming have been observed in all HYBACS installations, treating a variety of municipal and industrial wastewaters.

Microscopic examination reveals a Filament Index of 0 or 1, indicating that the majority of flocs contain one or no filaments (Jenkins *et al* 1986). The flocs are relatively large and dense, though not granular, with a healthy balance of ciliates and protozoa.



(Magnification x 200, phase contrast, unstained)

Figures 9 & 10: Examples of Activated Sludge Flocs from HYBACS

The sludge volume index (SVI) of the HYBACS sludge at Tubli WPCC since commissioning has varied between 21 and 58 ml/g, with a mean of 42 ml/g. In comparison, the SVI of the conventional activated sludge in the unconverted aeration lanes is typically 80-120 ml/g.

The hindered settling velocity of HYBACS sludge at Tubli WPCC is typically 6-8 m/h, hence clarifiers can operate at significantly higher loading rates. The HYBACS clarifiers at Tubli WPCC typically operate at a solids loading rate of 6 kg/m^2.hr, but have achieved over 14 kg/m^2.hr whilst maintaining discharge standards.

Figure 11: Demonstration of HYBACS sludge settlement at Tubli WPCC

(HYBACS sludge in foreground, conventional activated sludge on the right, after 200 seconds of settlement)

The large, dense floc structure also provides good thickening and dewatering characteristics of the surplus sludge.

Power Consumption

SMART units have an inherently efficient oxygen transfer, owing to the low-speed rotation of biomass between the air and water phases. Most of the oxidation occurs in the aeration lane where an efficient fine bubble aeration system was installed as part of the project. The average total power consumption of the HYBACS plant during the performance test period was 0.23 kWh/m^3 treated, or 0.42 kWh/kgCOD removed. These figures include all power consumed by influent and RAS pumping as well as the SMART units and aeration system.

Conclusions

Hybrid activated sludge (HYBACS) is a remarkably simple and effective method of increasing the treatment capacities of existing activated sludge plants.

The first stage, comprising attached growth reactors called SMART units, is unique in its design and function. It facilitates the rapid enzymatic hydrolysis of particulate and macromolecular COD into fragments which can be assimilated by the biomass in the RAS, which is recycled through the SMART unit.

The second stage of HYBACS is a conventional activated sludge process, comprising aeration tanks, anoxic zones and clarifiers in whatever configuration is required to achieve the required discharge quality. The pre-hydrolysis of the wastewater in the SMART unit enables the aeration tanks to operate at substantially higher loading rates than conventional activated sludge systems. Thus an existing activated sludge plant may be upgraded for increased capacity, enhanced discharge quality, or both, without a substantial increase in plant footprint. The upgrade may be achieved rapidly, without the need to take existing aeration lanes out of service.

The consistent good settleability of the HYBACS sludge allows an increased loading rate to be applied to clarifiers and provides good quality final effluent.

The retention of existing assets within a HYBACS upgrade often represents a significant cost advantage relative to a new-build solution. In the case of Tubli WPCC, the upgrade cost was £14m for 60 MLD of additional capacity and a considerable improvement in effluent quality.

HYBACS is a simple process to operate and maintain, since the SMART units are fully automated. The regular operational tasks are the same as a conventional activated sludge process and so minimal additional training is required.

Acknowledgements

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