PRACTICAL APPLICATION OF MODULAR OFF-SITE BUILD: A COMMISSIONING PERSPECTIVE

Baird, A. Technical Director, WPL

Abstract

A range of biological wastewater treatment technologies is available from manufacturers in the UK including variations on the submerged aerated filter (SAF). One of those companies is WPL which has supported postgraduate university research at Cranfield University on the internal hydrodynamics of reverse cyclic SAF reactors. The research was applied in a pilot engineering design project investigating how the rate of removal of organic contaminants can be improved by reducing the ratio of media to wastewater inside the tank. The focus of the research and development work has been to develop a WPL Hybrid-SAF™, which incorporates offsite build and modularisation to aid the efficiency of installation and commissioning as well as enhanced process and energy efficiency. The hybrid model, which has a patent pending, has been applied in nearly 10 UK water utility and large commercial projects for carbonaceous and tertiary nitrification. Substantial efficiency gains have been achieved in terms of process and energy consumption as well as installation. In one application a 2,000 population equivalent (PE) plant was installed in a single morning, with commissioning commencing immediately. Furthermore, 3D computational fluid design (CFD) modelling of the treatment process for an individual site makes it possible to offer an accurate estimation of project resource requirements, including process requirement, workforce skills, costings, construction and commissioning.

Keywords

Chemical parameters

BOD_5	Biochemical oxygen demand (5-day test)
COD	Chemical oxygen demand
DO	Dissolved oxygen
MLSS	Mixed liquor suspended solids
MLVSS	Mixed liquor volatile suspended solids
NH_4^+	Ammonium ion
NO_3^-	Nitrate nitrogen
NTU	Nephelometric turbidity units
O_2	Oxygen
TSS	Total suspended solids
VSS	Volatile suspended solids

Reactor acronyms

BAF	Biologically aerated filter
CSTR	Continuously stirred tank reactor
IFAS	Integrated fixed film activated sludge
PFR	Plug flow reactor
SAF	Submerged aerated filter
WPL SmartCell™	WPL's patent pending design

Introduction

Water scarcity and need to reuse water are increasing the demand for packaged wastewater treatment plants globally. In addition, regulation is tightening as governments face growing environmental concerns about wastewater disposal. Market analyst Technavio has projected growth in the global packaged wastewater treatment market at a compound annual rate of about 9% from 2015-19.

The legacy of the higher operational cost of packaged treatment plants over traditional activated sludge and trickling filter plants has historically posed a challenge to the growth of the market, but new technological approaches have made significant efficiency gains in recent years. When whole life equipment costs are considered, there are multiple areas in the delivery of these systems that can be honed. Firstly, they require electricity - for air blowers, water pumps and drives - so improved efficiency throughout the process train can reduce energy footprint and cost. The configuration of the treatment process and hydraulics, including the media, have historically been underexplored and are ripe for optmisation. Finally, the industry is learning quickly that offsite construction, faster installation and easier maintenance also provide significant scope for enhanced competitiveness.

The two main segments in the packaged wastewater treatment market are municipal and industrial. Technavio's analysis shows the global municipal segment is expected to grow steadily from 2015-19, reaching a revenue of around US$13 billion by the end of 2019. Uptake of packaged treatment plants by UK utilities is increasing as they seek to meet tightening Environmental discharge consents on constrained sites.

Available technologies

UK packaged treatment plant manufacturers offer a complete range of biological treatment technologies including rotating biological contactors (RBCs), sequential batch reactors (SBRs) membrane bioreactors (MBRs) and variations of submerged aerated filter (SAF) technology. These larger above ground packages are generally designed around one section of the treatment process and cover inlet screens, grit removal, primary settlement, sludge storage, biological treatment, final settlement and clarification.

The package can be supplied as a full turnkey manufactured product and delivered as a single unit for smaller population numbers or as multiple units connected in series making up a complete treatment works. Packaged treatment plants are built offsite and delivered on the day they are required. In terms of efficiency, the smaller the footprint the lower the cost of installation, both in terms of backfill materials (generally concrete) and transportation. Offsite build offers the manufacturer a number of benefits:

- Quality of manufacture in a controlled environment
- Consistency in quality
- The ability to test the integrity of products produced
- Just-in-time manufacture
- More complex design, allowing improved hydrodynamics
- Reduced health and safety risk when compared to onsite construction
- Higher tolerance build minimises footprint without compromising process

SAF technology

WPL operates globally and has been manufacturing packaged treatment plants for over 25 years at its facility in the UK town of Waterlooville, Hampshire. The packages have been based on submerged air filtration (SAF) technology and incorporate primary settlement, biological treatment - in the propriety SAF - and final clarification. SAFs are well established in the treatment of municipal and industrial wastewaters and are often used as an alternative to conventional biologically aerated filters (BAFs) (Pedersen et al., 2015, Priya and Ligy 2015, Moore et al., 2001; Moore et al., 1999). SAF reactors are widely used for secondary and tertiary treatment applications with configurations including upflow, downflow or a combination of the two when internal recirculation is used (Khoshfetrat et al., 2011; Gálvez et al., 2003).

SAF reactors are typically arranged in a series of cells, with internal dividing baffles to increase treatment efficiency and encourage segregation of heterotrophic and nitrifying processes (Hu et al., 2011). Biofilms are grown on a plastic support media, which is submerged in wastewater and can be either, structured or random packed. Media specific surface areas range from 150 to 1,200 m^2/m^{-3} with SAFs most commonly using 150 to 600 m^2/m^{-3} (Khoshfetrat et al., 2011; Hu et al., 2011). Aeration of submerged media is provided by coarse or fine bubble diffusers. Coarse bubble diffusers are often selected over fine due to the shearing of air bubbles when in contact with the media, which generates a larger mass transfer surface area, similar to that of fine bubbles (Rusten, 1984; Hodkinson et al., 1998). In SAFs with static media, contaminant diffusion into the biofilm occurs from a combination of forward fluid velocities and circulatory mechanisms influenced by aeration.

Wang et al. (2005) investigated the influence of support media fill ratio in suspended carrier biofilm reactors. A media fill ratio of 50% was found to be optimal for the removal of chemical oxygen demand (COD) with efficiencies of 73%, whilst a >70% media fill ratio was crucial to achieve 52% ammonium (NH_4^+) removal. Rusten et al. (2006) investigated the effect of media fill ratio on treatment efficiency in moving bed biological reactors (MBBRs), concluding that <70% was the optimum media fill ratio for NH_4^+ removal. Similarly Pedersen et al. (2015), compared the removal of NH_4^+ in fixed and moving media bed reactors, concluding that static media beds offered significant advantage over moving beds, providing protection of the nitrifying bacteria in the biofilm. The WPL bioreactor moves very slowly in comparison to MBBR technologies and, due in part to its shape, offers protection to the nitrifying bacteria, whilst giving the benefits of a moving bed.

Internal fluid velocities within SAF reactors have a direct influence over process performance, with high velocities increasing biofilm detachment and washout potential (Burrows et al., 1999). In contrast, low velocities increase solids retention, causing media blinding and reduction in mass transfer efficiency (Priya and Ligy, 2015).

Airlift reactors use aeration and a fraction of flow is constantly recirculated to maintain a stable biofilm thickness. Airlift reactors have two zones, an inner aeration column and an outer draft space. The inner aeration column is raised a nominal distance from the bottom of the reactor. When aerated, a density difference occurs between inner aeration column and draft space, causing fluid movement through the draft space and into the aeration column (Kilonzo et al., 2006). Therefore changes in draft space baffle position can be used to control the recirculation flow rate (Benthum et al., 2000). In fixed-film bioreactor engineering, directional fluid movement is typically achieved through strategic aeration as described by Rusten et al., (2006).

At high volumetric loadings, SAFs suffer from flow shortcutting, therefore it is important to study the hydrodynamic properties of the reactors in order to optimise flow regimes. Biofilm diffusion and dispersion characteristics are influenced by SAF hydrodynamics, which is defined by three parameters:

- Mass transport efficiency (dispersion/advection)
- Mass transfer efficiency (aeration)
- Diffusive mass transfer (bulk flow to biofilm)

Many studies have been performed using estimations of *Peclet* number (*Pe*), axial dispersion coefficients (*D*), dispersion number (*d*) and Reynolds number (*Re*) to describe mass transport and transfer dynamics in biofilm reactors (Stevens et al., 1986; Romero et al., 2011; Lamia et al., 2012). Application of these methods would offer insight into how fluid moves and mass transport dynamics of SAF reactors (Rexwinkel et al., 1997).

In many applications, upflow and airlift SAF reactors are preferred due to improved fluid circulation, however the hydrodynamics are not yet fully understood (Pedersen et al., 2015). Most research on SAFs focuses on process efficiency and particularly variations in the influent wastewater volumetric and aeration loadings, without considering the internal hydrodynamics (Gálvez et al., 2003; Albuquerque et al., 2012; Bibo et al., 2011). The impact of media fill ratio, internal recirculation, internal baffles, aeration rates and biofilm growth on the media is often excluded from SAF design practices.

The importance of hydrodynamic conditions in SAF reactors is investigated in a limited number of studies to date. Fluid dynamics and efficiencies impact significantly on design and ultimately site and carbon footprint. Refining the hydrodynamics can deliver multiple knock-on benefits to a utility or industrial user as the plant size required to service a given population is smaller and requires less space on site. Reducing site footprint also has a direct impact on the ability to produce compact SAF units offsite - it makes them easier to transport, install and commission. This is especially important where access for large vehicles is restricted. A reduction in the operating power required reduces carbon footprint and energy costs. It also speeds up commissioning.

Main content

WPL SAF treatment plants, sold under the WPL HiPAF® brand, provide easily-installed below-ground tanks. They are well established for use in both small commercial and water utility applications across the UK. During 2011, demand for above-ground SAF technology in easily transportable units increased. This was driven by the requirement for hire equipment and led WPL to develop modular above-ground equipment that was easier and significantly lower cost to install than traditional in-ground civil construction. This led WPL to develop hire equipment supplied in modules treating up to approximately 1,000 PE. These modules can be used in various applications including treatment provision during temporary shut-down for maintenance or to ensure a site meets its discharge consent where it is at risk of a breach. The WPL SAF is manufactured in steel tanks for ease of transportation, offloading and set-up. This was an easy step for WPL as it required upscaling of the biological zone to treat larger population loadings. The result was a WPL SAF installed in a steel above-ground box using the existing HiPAF® design.

Figure 1: Example of a below ground WPL HiPAF® packaged multi-unit wastewater treatment plant.

Figure 2: A 10,000 PE steel WPL SAF modular tertiary wastewater treatment plant.

More recently, in a drive to reduce power consumption, installation costs and footprint, WPL has been improving SAF efficiency by refining the design of the process hydraulics. One aspect of this work has involved reviewing the size and parameters of the plastic media used and investigating its density and efficiency at different fill rates. During 2015-16 a substantial amount of work was done to calculate the efficiency of the SAF bioreactor design used by WPL. It was found that the flow characteristics did not follow the expected plug flow design. Instead, the reverse was seen, with the baffle walls not just allowing removal of diffuser legs, but playing an intrinsic part in the reactor cell hydraulics. This understanding led to a comprehensive review of the components used in WPL SAF technology. The first element under review was the media used within the biozone and the investigation included its surface area, construction material and density.

Initial lab tests revealed that the existing product had a high specific gravity, leading to it sinking to the bottom of the tank. Its tubular shape meant the media soon filled with biomass and sludge, increasing its weight to the point that a significant amount of air was required to move and therefore scour sludge and dead biomass. The shape of the product did not lend itself to even flow distribution and dead spots were seen in the tank, potentially leading to septicity. The surface area of $150m^2/m^3$ was at its most effective when exposed to high loading rates, however the inherent drawback was the limited potential surface area available for treatment.

A new design was sought to replace this product and a buoyant open-structured media identified, with a larger surface area, not exceeding $310m^2/m^3$. In laboratory trials this media was found to be very buoyant and again required significant aeration to get movement of media and subsequent scouring. Due to the buoyant nature of the media, when used in full-scale installations, care had to be taken to ensure the media was retained in the tank. Having used this media for a number of years in both full-scale and hire equipment, further works were undertaken to look at efficiency of treatment, air requirements and optimisation. After preliminary laboratory trials working on varying densities of media, an optimum specific gravity was selected. This proved to have all the benefits WPL were looking for to complement the unique hydraulic design of the HiPAF®.

Having been the focus of many years of research, mainly on the internal flows across the media, media fill rates and energy requirements, the WPL SAF is now close to its final iteration. Branded as the WPL SmartCell™, it is now ready for commercialisation, with the caveat that research and development will continue over the next three years.

The SmartCell™ retains additional traditional primary settlement and final clarification either as an integral tank or as individual treatment cells, with an enhanced biozone. It is this element that is critical to the treatment process. It can be used in new build, retrofit and refurbishment applications. The modular design optimises installation and reduces health and safety risk and maintenance requirements.

A number of sites have now been designed to incorporate downflow pipes rather than the traditional baffle walls. This offers a number of benefits, but primarily allows flexibility in how flows are dispersed over the media, optimising treatment and further reducing the size of the required biozone by up to 20%. The downpipes can also be strategically placed to ensure the tank has no dead spots and, rather than using scour air to prevent the accumulation of dead biomass, the process air undertakes this task. Whilst during the day-to-day running of the plant, scour is only used intermittently, it does mean that a smaller plant using one blower can be sized for process only rather than scour reducing the air requirements.

Case study 1: Hydraulic reconfiguration deployed at two sites

WPL has installed enhanced models of its WPL Hybrid-SAF™ wastewater treatment plants at two utility sites – Site 1 in Cheshire and Site 2 in Staffordshire. Some 12 Hybrid-SAF™ modules were installed in four treatment streams at Site 1 wastewater treatment works (WwTW) and six modules are now providing two additional treatment streams at Site 2 WwTW.

Each of the two site installations was delivered and offloaded over two days and was set up and commissioned within five days – Site 2 in October and Site 1 in early November 2015 and the plants are likely to be needed at these sites for approximately five years. However, they can be transported from site-to-site as required in the future. The utility was very clear about the number of streams required and the need for the SAF units to be transportable. The utility did not want to be left with stranded assets if the requirements of the site changed after five years and saw the flexibility of the Hybrid-SAF™ as a key advantage.

WPL was asked to develop the transportable systems as the existing single-stage rock tricking filter plants were experiencing ammonia compliance incidents during low flow and colder conditions. The new plants are required to achieve an effluent quality of 4mg/l ammonia and can be switched off when warmer weather returns – saving energy.

Figure 3: Packaged treatment plants can be easily lifted onsite.

In dry weather and colder weather the levels of ammonia in untreated effluent can rise considerably. The previous winter the utility had had to hire additional packaged plants from WPL at short notice when the plant at Site 2 struggled to cope with the higher levels of ammonia. Rather than having to hire equipment it was decided to upgrade Site 1 and Site 2 by adding SAF units. The SAF systems have been individually sized to treat the dry weather flow (DWF) for each site: 2,050m^3/d for Site 2 and 4,000 m^3/d for Site 1. Each stream treats a nominal 1,000m^3 wastewater and the additional treatment is expected to be required for three-to-five months a year.

Site 1 and Site 2 installations were both designed to optimise flow dispersal in the biozone by incorporating downflow pipes rather than traditional baffle walls. The pipes were carefully located to ensure the tank has no dead spots which meant that the size of the biozone in each unit was reduced by up to 20%.

The client specified variable speed drives (VSDs) on the blowers to optimise energy efficiency. The use of VSDs can achieve an energy saving of up to 30% over standard drives. Design developments focusing on health and safety issues have removed the requirements for high-level access for routine maintenance. Ground-level sensors and fixed diffusers Hybrid-SAF™ units at Site 1 and Site 2 have removed the need for high-level inspection.

Figure 4: A 5,000 PE WPL Hybrid-SAFTM modular wastewater treatment plant installed at Site 1 in 2017.

Case study 2: Media replacement halves air requirement

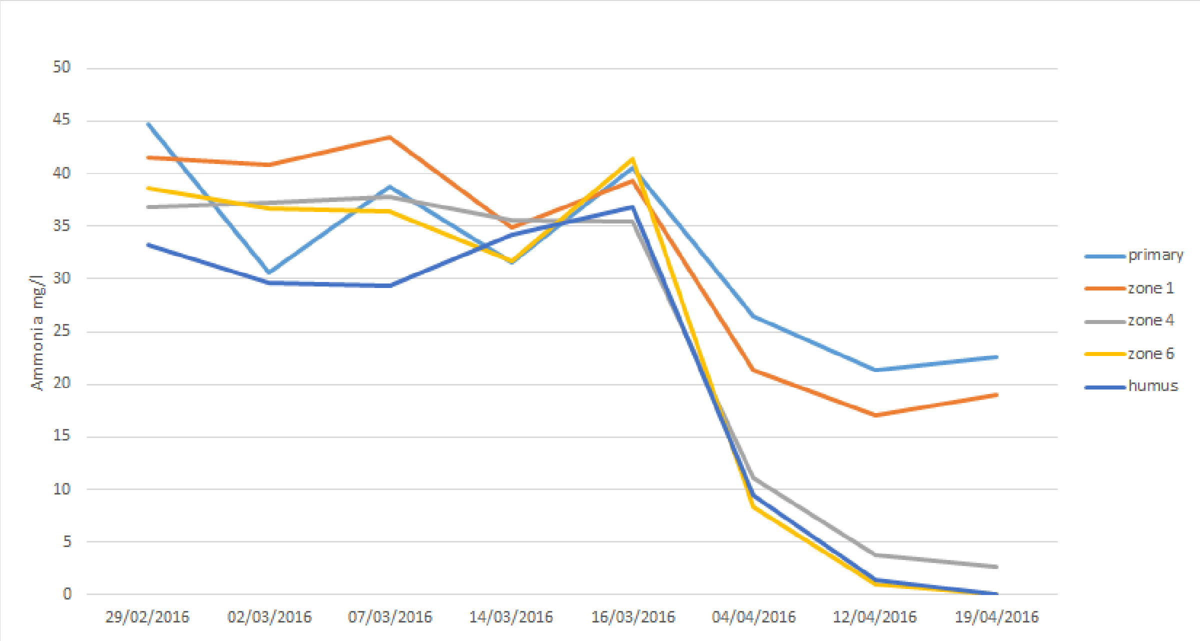
WPL has undertaken a number of small refurbishments on plants that were struggling to maintain performance within the required Environment Agency discharge consent. One of these sites was a utility 100 PE plant consistently close to the consent requirements.

The plant was regularly impacted by storm water ingress and recovery was slow. This was due in part to peak-loading occurring in the mornings as high flow levels arrived from a school. The challenge was to upgrade the plant within the confines of the existing site and regulate effluent quality with sufficient margin to keep within consents during periods of slow recovery.

As the SAF had a predetermined volume to house the media, a higher surface area product of $310m^2/m^3$ was used throughout the unit, replacing the existing $220m^2/m^3$ media. However a freeboard of 10% was provided in the biozone to enable the slow but free movement of the media. The existing aeration had been installed some 15 years previously and used coarse bubble diffusers. The decision was taken to retain it, which allowed a straightforward replacement of the media in this instance without upgrading the baffle configuration. The media replacement meant that air requirement to achieve the same PE was halved, meaning that the plant could now process 189 PE – nearly double the flow and load.

Other efficiencies were leveraged in terms of project delivery. Removal of the legacy media was undertaken with a vacuum tanker rather than manually, reducing time on site and the risk associated with entering a confined space. As the SAF tank was over 15 years old, minor alterations and improvements were undertaken. All aeration pipes were inspected and those showing signs of wear were removed and replaced. These works accounted for only a further day onsite.

Media was delivered to site in 2m³ bags that could be moved and positioned next to the tank using a vehicle with a small hydraulic crane attached. It was then manually loaded into the SAF tank, retaining grid replaced and flow introduced.



Case study: Graph showing ammonia reduction from sampling positions in five different zones within the SAF tank, from commissioning of the 189 PE plant. The samples were taken over six weeks and full nitrification was achieved relatively quickly.

Whilst the project was a straightforward switch in media, different techniques in media removal, site organisation and project management enabled a significant reduction in time on site. As a consequence, significant cost savings were made. The alternative to this enhancement of the process would have been a much bigger capital project, involving an extension or replacement. Refurbishment of the existing infrastructure reduced capital cost, health and safety issues of major construction works, and has reduced tanker movements reducing the environmental impact.

Figure 5: A 15 year old WPL HiPAF® wastewater treatment plant – the refurbishment nearly doubled the flow and load from 100 to 189 PE.

Conclusion

This paper deals primarily with the biological phase of treatment, offering small footprint, high-efficiency above-ground Hybrid-SAF™ modules that can be installed as temporary works or as permanent installations. The advantages are significant when comparing with traditional onsite build. The package is a fully pre-assembled unit ready to be placed directly onto a concrete base.

Figure 6: The flexible packaged WPL Hybrid-SAF™ units can be installed in series to form a multi-unit wastewater treatment plant.

Integral packaged treatment plants manufactured off-site offer easy-to-install units with a reduced site footprint. These systems are mainly viable when using high-rate filters and where the population equivalent measure does not exceed 1,000. The advantages are significant when compared with the traditional onsite-build of trickling filters or concrete tanks used as activated sludge plants.

Constructing a works based on packaged treatment plant reduces onsite installation time and mitigates issues with prolonged confined entry, reducing health and safety risk. The primary drawback with packaged plant is the size of tanks that can be produced and shipped to site, limiting the population equivalent that can be served.

A small number of UK manufacturers offer modular off-site manufactured tanks. The units can be used temporarily to allow remedial works to be undertaken on existing assets or permanently installed. Due to the modular nature of the SAF units, they can be expanded or reduced to meet fluctuations in demand. Modular tanks can handle higher population equivalents than single packaged plants and can offer economical secondary treatment for up to 5,000 PE and economical tertiary treatment for up to 10,000 PE.

A number of sites in the UK have been retrofitted with improved media or media has been added to activated sludge tanks to provide a fixed-film process. These have had varying levels of success and have generally used media with a significantly higher surface area than 310m^2/m^3, with some manufacturers claiming >1,000m^2/m^3. Generally speaking they have been converted or adapted to work as an MBBR. However MBBR technology relies on a lower fill rate, around 50%, and has significantly higher turbulence than the WPL SAF, causing biomass to be mechanically scoured as the media collides, thus theoretically negating the outside surfaces of potential for fixed-film growth.

WPL is one of the first companies to closely examine the internal hydrodynamics of SAFs and the research has proven that the removal of organic contaminants can be improved by reducing the ratio of media to wastewater inside the tank, eliminating dead zones, reducing the need for scouring and cutting energy use.

By reconfiguring the baffles to fully-segment the biozone, the risk of process shortcuts and dead zones has been eliminated. Each biozone segment, where both carbonaceous and nitrifying processes take place, is filled with high-voidage plastic filter media. Air to oxygenate the influent and scour excess biomass from the media is introduced continuously below each chamber by a series of diffusers. Optimisation of the specific gravity of the media ensures it now circulates as efficiently as possible. Refining multiple aspects of the process has succeeded in delivering a variety of benefits and mitigating process risks associated with variable loads.

Research and development into SAF technology undertaken by WPL has culminated in the WPL SmartCell™, which is a compact module with counter-current hydraulics to ensure constant flow over optimised media, avoiding the requirement for reduced media fill rates. With a 90% fill rate, the SmartCelll™ has sufficient open-voidage to avoid fouling or becoming sludge-bound when applied in secondary treatment. The design also takes into account the impact of physical colliding or scouring of the media, and protects the growth of the biomass due to its unique shape and speed of movement. With the slow movement of the media, any build-up of sludge is carried to the surface where it washes out with other solids to be captured in final settlement.

Research into SAF efficiency is on-going and WPL is supporting a PhD at Portsmouth University over the next three years (2017-2020) to review the efficiencies achieved in more detail and to optimise energy use. The study will examine the data and technical information already generated and hone it into a design protocol for all WPL SAF systems. Consideration is given to the following elements, in relation to the design for the SmartCelll™.

1. **Module size**

The size of the modules should give optimum performance, balanced by the need to transport, manufacture and handle them safely. Size of the individual modules is therefore governed by the following constraints:

- Maximum permissible width without it being classed as an abnormal load notifiable to the highways authorities. This aspect of sizing is critical as access at most rural wastewater treatment sites is designed to the maximum width, which is required for desludging tankers.
- Cube-shaped modules were deemed the most efficient for maximising transportable tank volume, even though some oxygen transfer efficiency can be gained using taller tanks. Height can limit road transportation options, so using taller tanks delivered to site horizontally was dismissed in the standard module design, but can be considered for a design-and-build project. The external tank envelope was sized to maximise media capacity but minimise transport risk.

2. **Inlet and outlet pipework**

In instances where a pumped flow is to be used, investigation into incoming flow velocities will be carried out and the system and optimised. The same goes for the exact entry points of flow within the bed – at present some short circuiting on the first cell occurs. Gravity-fed systems suffer less from the first cell being hydraulically bypassed, but the study will optimise inflows. The outlet pipework appears to offer no process benefits, but this will be investigated using CFD modelling in a PhD research study.

3. **Gridding**

Both top and bottom gridding is used to encapsulate the media and prevent it from discharging into the environment. This product is expensive and its loss reduces the operational volume available. Due to its structure, the media also creates back-pressure within the reactor. The nature of this back-pressure is largely understood, but an investigation is required to fully evaluate the process benefits or drawbacks of using this type of encapsulation.

4. **Downpipes**

Currently the downpipes are spaced evenly throughout the tank on the assumption that lateral flows will be even and so will mixing. No consideration has been fully given to the effect of backflow during low diurnal peaks or forward flow during peak flow. This element will be critical to product development as it will allow WPL to optimise the cells for enhanced secondary treatment, BOD removal and to predict where within the process nitrification will stabilise. Due to the significant variances in flow seen in packaged treatment plants this is seen as an area that may be difficult to design.

5. **Diffusers**

WPL currently uses coarse bubble diffusers as these were the subject of a significant investigation into oxygen transfer rates using fine, medium and coarse bubble diffusers. The study formed part of a previous PhD, *An Evaluation Of The Robust Aerobic Digestion System* by Nick Sherlock (2009). This study looked into oxygen transfer rates using fine, medium and coarse bubble diffusers, which found coarse bubble diffusers gave the best performance with the added benefit of reduced fouling and maintenance. The ongoing work will look at maintenance and long-term installation when using a fixed diffuser leg versus a removable one.

6. **Media**

As previously described, the neutrally buoyant media has been optimised for buoyancy, biomass thickness and type but has not been fully investigated. Its performance in an anoxic environment will also be reviewed and considered.

It is hoped that data gathered from the PhD research will enable full optimisation of the existing plant, allowing greater treatment efficiencies per cubic meter of media and enhanced oxygen transfer through positioning of the downpipes. It is also hoped that clearly identified and stabilised zones will be created allowing both nitrification and denitrification to occur in the same SmartCelllTM. If bio-stabilisation can be achieved, a review of phosphorus (P) removal will be undertaken, subject to time constraints. The SAF process has come a long way, but there is still further to go in terms of process efficiency and power consumption.

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