E-WAter
Official Publication of the European Water Association (EWA)

R.M.Alkhaddar[1] and D.A.Phipps[2] C.Cheng[3]

Today and Tomorrow!
Research Prospects for Aerobic Biological Liquid Waste Treatment for Reduction of Carbon Load.

ABSTRACT

The development of aerobic biological wastewater treatment has reached a critical state. The increased severity of legislative pressure means that performance of waste treatment plants must become ever more efficient if discharge consents are to be met. Treatment plants are now hard pressed to meet the new regime. Over the last thirty years there have been some significant advances leading to substantial improvements in performance. The introduction of different modes of contacting gave a boost to treatment efficiency, as did more sophisticated analysis of both biological and engineering aspects of plant design and operation. However, more recently, the rate of improvement has diminished and today the performance of modern plant is increasing only gradually. Designers and operators are working ever harder to gain even small improvements. As the complexity of biological treatment plants becomes more apparent, the sophistication of the methods needed to analyse and control it increases. In addition, there is a growing demand for process intensification whereby the same throughput can be obtained in smaller plant with associated savings in both capital and recurrent costs.

1. INTRODUCTION

The last thirty years has seen a steady increase in the pressure on waste disposal methods with ever tighter limits on discharges of liquid wastes. As various schemes for water quality improvement have produced substantial results, this pressure has increased. Many river estuaries receiving water from industrialised areas (e.g. The Mersey Basin, Tees Estuary etc.) are now at their cleanest for over 150 years(1) and it is inconceivable that any form of damaging discharge could be allowed. Indeed, the problem is now more one of accidental spills rather than illegal discharges, though sadly the latter are still not unknown! Penalties are slowly becoming sufficient to act as a significant deterrent, though of course many "accidental" and not a few deliberate pollution incidents do still occur. However, industry will have to do more. During 2000 the Environment Agency prosecuted 694 businesses and individuals, compared to 566 prosecutions

---

[1] Reader in Water Engineering, Liverpool John Mores University, Clarence Street, Liverpool L3 5UG, UK, Tel: +44-151-231 3627, Fax: +44-151-709 4957, Email: r.m.alkhaddar@livjm.ac.uk
[2] Deputy Director, School of Biomolecular Sciences, Liverpool John Moores University, Byrom St.
[3] Postgraduate Student, School of Biomolecular Sciences, LJMU

in 1999. In the northwest region of England, the EA prosecuted 66 businesses in the period of April-June 2003 with total fines of £ 372,545(2)(3).

However, whilst the environmental gains are undoubtedly welcome, the problem of industrial liquid waste disposal continues to grow. With the implementation of the Landfill Regulations in July 2002(4) yet another route for "easy" disposal of liquid waste is being closed off. But recent estimates suggest that in the Northwest about 450,000 tonnes of liquid special waste require disposal annually(5). Costs are beginning to rise; low grade, non-hazardous waste now costs £20-30 per tonne at the factory gate for removal (+ transport). Special wastes which can no longer go to landfill may cost £60-100 per tonne if they can be dealt with by simple chemical and/or biological means, whilst incineration is typically over £600 per tonne, even if capacity is available(6).

If recent suggestions are true and the landfill tax is to be increased further(7) then costs will rise and the pressure to find alternative, more economical means of treatment and disposal will continue to spiral upwards. In this scenario simple physical or chemical treatment becomes less favourable as it leaves a residue, which still requires disposal. Biological treatment is not without difficulty, but a properly designed and operated bio-treatment plant offers a number of advantages when dealing with carbonaceous waste. Not least is that the absolute mass of material can be substantially reduced. At the same time toxic pollutants can be substantially transformed into less damaging materials. Of course this process is not perfect and as analytical methods improve there is an increasing awareness of the impact of ultra-trace components such as the hormone mimics.

Biological treatment methods have been used on a wide scale for over 100 years(8). Initially limited to treatment of domestic sewage, bio-treatments are now available for all but the most recalcitrant waste. Aerobic treatment of liquid waste is a key part of the treatment. Indeed, it is often the only feasible and practicable route for the degradation of dilute organic pollutants in aqueous waste. (Anaerobic digestion is more suited to dealing with high COD, low toxicity wastes such as farm slurry or sewage sludge.)

Wastewater treatment technology has gone through a vast amount of development in the past century. A number of well established technologies are now available for wastewater treatment. These range from the reliable Trickling Bed Filters (TBF), Airlift Reactor and the related Biological Aerated Filter (BAF) to the Activated Sludge Process (ASP), through the Rotating Biological Contactors (RBC) to Sequencing Batch Reactors (SBR), and to the relatively newer technologies of Biological Fluidised Bed Reactors (BFBR) and Membrane Bioreactors (MBR). In addition, there are the engineered versions of natural eco-systems such as reed beds. There is an enormous output of research material dealing with different aspects of each technology, so much so that it is difficult to discern where progress is being made. Much of the work is done at laboratory or pilot scale and there is rather less information about trials at full-scale. What is needed is a synthesis of the body of existing data to direct new research efforts.

Although the different technologies appear quite diverse there are some important underlying principles. For any aerobic bioprocess consideration needs to be given to the nature of the organisms involved, treating them as an eco-system rather than as single species. This means looking at factors affecting growth and succession as well as the effect of shorter variations in parameters such as pH and dissolved oxygen. At the heart of the system is oxygen transfer and there is a wide range of systems each with its own claim to efficiency. The third aspect of any system is an understanding of the hydraulics. Not only is there a need for a design with low energy consumption but also for one, which optimises contact between phases. The fourth aspect that needs to be considered is modelling and control. As knowledge of the characteristics of the system becomes ever more detailed so the models describing wastewater treatment plants become more detailed and with them control strategies and their implementation are becoming ever more sophisticated. Bearing this in mind it is first appropriate to consider what alternatives are currently available for aerobic biological treatment for carbon removal and then to explore where such systems may develop in the future.

2. AVAILABLE TECHNOLOGY FOR AEROBIC BIO-TREATMENT

Trickling bed filters (TBF):

Trickling filters, one of the oldest bio-treatment systems, consist of a bed of inert coarse media over which the wastewater is distributed. The most widely used design of filters is a bed of stones 1-3m deep. Wastewater is applied over the surface of the filter by a horizontal rotating arm. As the wastewater trickles through the filter bed, a microbial growth establishes itself on the surface of the bed media in a fixed film. The wastewater passes over the stationary microbial population, providing contact between the microorganisms and the organics. It is simple to construct and to operate. Though more advanced versions with back-wash are more complex. The ecology of this system has been extensively studied and its limitations are well known but there is little that can be done to improve its efficiency. It is particularly susceptible to shock-loads or trace pollutants, which damage the micro-flora.

Biological aerated filters (BAF)

The BAF can be seen as a development of the tricking bed filter. It can operate in a range of modes (upflow, downflow with and without external aeration etc) and is generally more efficient than the TBF. However the BAF has been criticised, as there is need for careful operation with back-wash a possibility.

Sequencing Batch Reactors (SBR):

A Sequencing Batch Reactor is a complete-mix activated sludge system without a secondary clarifier. Within the aeration basin, a number of different sequences are completed. Aeration and clarification are accomplished in one tank.

Main advantages of SBR,

- Simple construction
- Plant can fit into almost any shape
- Flow through plants require regular shaped sites
- Fewer channels and pipe work
- Easily scaleable
- Can be adapted to both nitrification and denitrification.

However there are disadvantages. Because of the sequential “draw and fill” mode of operation care needs to be taken that there is sufficient storage capacity to hold influent prior to processing(9).

Rotating Biological Contactors (RBC):

Rotating Biological Contactors consist of thin discs, set vertically and rotating about their horizontal axes so that the disc surface alternately dips into and out of the wastewater in the holding tank. The disc carries a surface a film of biomass which comes into regular contact with both the wastewater and the air. The microorganisms in the biomass remove organic matter from the wastewater. The principle is simple but in practice the operation is more complex. This treatment is prone to excessive build up of biomass on the contactor, which requires regular maintenance. Biofilm sloughing off the discs leaves with the effluent and must be separated downstream if high efficiency removal is required. Nevertheless, many systems are in operation but they are also recognised as being fragile and subject to severe problems with shock-loading or unexpected inputs.

Advantages of RBCs,

- Short contact periods due to the large active surface.
- Capable of handling a wide range of flows.
- Good settling characteristics of Biomass /can easily be separated.
- Operating costs are low
- Short retention time.
- Low power requirements.
- Low sludge production and excellent process control.

Biological Fluidised Bed Reactor (BFBR):

Development of fixed-film bioreactors has popularised the use of fluidised beds in biochemical engineering. Applications include, BOD removal, nitrification, and denitrification. The ultimate goal is the development of high-rate biological reactions and consequential reduced reactor volumes and land requirement. The potential advantages of BFBRs as an alternative to conventional treatment processes have been widely accepted in small systems, but less so in large ones. The hydrodynamics of the system have been extensively studied(10), but there is still a scarcity of knowledge regarding practical handling of the technology. The performance of the reactor is strongly dependent upon the features of the biomass developed and the ability of the carrier to retain high concentrations of micro-organisms within the reactor(11).

In aerobic wastewater treatment, the bio-film tends to be more cohesive, and develops at a faster rate than in anoxic and anaerobic modes of operation. Examination of the bio-film development has revealed a definite optimum film thickness beyond which further growth is counterproductive, due to mass transfer limitations. Excessive growth can cause clogging or particle elutriation, necessitating intermittent removal of overgrown bio-particles to control expanded bed height, the clean particles subsequently being replaced into the reactor. This involves the possible use of back flushing, vibratory screening apparatus, or external cleaning devices, and increased system complexity arising from the incorporation of such units into reactor design.

Advantages of Immobilised film Bioreactors:

- High biomass concentration which can be achieved
- Unlike activated sludge plants the need for recycle flows to
- maintain biomass within the treatment process is reduced
- Process intensification
- Simplicity of design and operation
- Biologically robust
- Easily scaleable

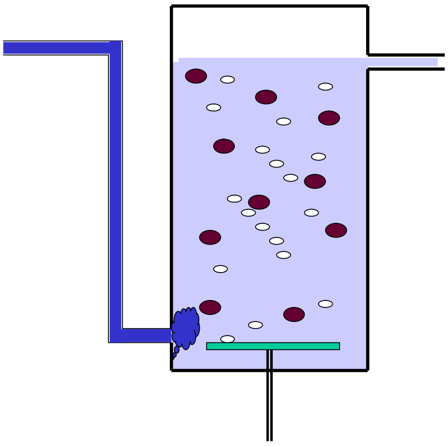

Figure (1) Single pass air fluidised 3-phase bio-reactor

Membrane Bioreactors (MBR):

Membrane processes have been used for water and tertiary treatment and polishing for a number of years. The more widely used membranes are those that rely on an imposed pressure gradient to force water through the membrane, while retaining particulates and, in some cases, solutes.

Table 1: Classification of pressure-driven membrane separation processes

Membrane process	Size cut-off range (µm)	Examples of materials separated
Microfiltration (MF)	0.05-1.5	microbial cells, large colloids, small particles
Ultrafiltration (UF)	0.002-0.05	macromolecules, viruses, colloids
Nanofiltration (NF)	0.0005-0.007	viruses, humic acids, organic molecules, Ca^{2+}, Mg^{2+}
Reverse osmosis (RO)	0.0001-0.003	aqueous salts, metal ions

Pressure-driven membrane processes can be categorised by the molecular weight or particle size cut-off of the membrane, as summarized in Table 1. MF and UF membranes are considered to effect species separation by a sieving mechanism and hence they remove particles larger than their size-cut-off limits, where as both NF and RO membranes are considered to include both sieving and diffusion-controlled transport. NF and RO membranes are operated at high differential pressure (up to 100 bars). UF membranes are operated at differential pressures in the range 1-10 bar. MF membranes are operated at differential pressures $\geq$ 5 bar.

High capital and operational costs as well as inadequate knowledge on membrane application in wastewater treatment were predominant factors in limiting the domain of this technology(12). The development of less expensive and more effective membrane modules regained interest. Membrane modules have evolved form being utilised for water and tertiary treatment to being integrated into secondary wastewater treatment. These systems are now most commonly referred to as membrane bioreactors (MBRs).

The advantages associated with the MBR can be summarised as follows:

1. The retention of all suspended matter and most soluble compounds within the bioreactor leads to excellent effluent quality.
2. Capable of meeting stringent discharge requirements and opening the door to direct water reuse.
3. The possibility of retaining all bacteria and viruses results in a sterile effluent, eliminating extensive disinfection and the corresponding hazards related to disinfection by-products(12).

On the other hand there are some disadvantages associated with MBR technology:

1. High capital costs due to expensive membrane units and high-energy costs due to the need for a pressure gradient have characterised the system.
2. Concentration polarization and other membrane fouling problems can lead to frequent cleaning of the membranes, which stop operation and require clean water and chemicals.
3. Another drawback can be problematic waste activated sludge disposal. Since the MBR retains all suspended solids and most soluble organic matter, waste activated sludge may exhibit poor filterability and settlement ability properties(12).

Activated Sludge Process (ASP):

The activated sludge process is one of the oldest biological wastewater treatment techniques. A mixture of wastewater and a complex eco-system of free-living, but aggregated, micro-organisms generally known as biological sludge is agitated and aerated. The bacteria break down organic material using part of it for energy and liberating carbon dioxide and part for growth and reproduction. "Biological solids" are subsequently separated from the treated wastewater in a separate clarifier and returned to the aeration process as needed. The ASP is controlled by such factors as pH, the level of oxygenation, the flow rate of the feed and by recycling a proportion of the microorganisms carried out of the system in the treated effluent in order to maintain the proper concentration and activity of the bacteria required for efficient operation. A balance is then achieved between the growth of new organisms and their removal by wasting.

Not surprisingly, given its importance in the treatment of domestic sewage and mixed waste, the ASP has been extensively studied but although it has been known for almost 100 years it is only relatively recently that it has been at all well understood and even now much still remains to be done to improve performance(13)(14). Sludge bulking is a common problem, often brought about by a change in temperature. Bulking and poor settlement ability, which in turn leads to problems in the quality of the effluent, is often caused by the growth of filamentous organisms.

The ASP has also been investigated by modelling. The complexity of the system makes predictive modelling difficult but there are a number of well-known descriptions of the system that can be used both predictively and for control. Indeed, commercial software, e.g. GPS-X, is now readily available which can be used to design the ASP and to build predictive models so as to design control systems. Nevertheless many systems are operated sub-optimally and they are also recognised as being fragile and subject to severe problems with shock-loading or unexpected inputs.

Engineered natural processes e.g. reed beds:

When the use of RBTS is mentioned with reference to wastewater treatment, it is understood to mean an area of constructed wetland planted with some form of higher reeds (usually Phragmites Australis) for the treatment of domestic wastewater and stormwater. RBTS operate as constructed wetlands with subsurface flow and are thus described as *vegetated submerged beds* (VSB). That is to say that flow and subsequently purification of waste material occurs beneath the bed surface, as opposed to above the surface in the case of *over-land flow* systems. Beds are constructed with impervious liners to segregate the bed media and processes from the surrounding subsoil, which makes them self-contained systems.

Beds are filled with a porous media (most commonly sand and/or gravel and soil) and sloped in order to sustain a flow through the bed. Reeds are either pre-grown and planted as mature plants or planted as seedlings. The beds are saturated to maintain the growth of vegetation.

Wastewater is pre-treated and in some cases pre-screened and pre-settled before application to the bed through a means of variable inlet regulator. Influent then passes through the inlet/distribution zone where aeration occurs, from which it flows through the vegetated area of the bed. Upon contact with the vegetated area of the bed the influent is acted upon by a combination of *physical, chemical* and *biological* processes which reduce the levels of toxicity. The wastewater remains in the bed for a period of generally 5/6 days after which it flows out of the bed through the outlet zone and is discharged gradually into the surrounding soil media. In some cases, treated waste (effluent) is returned to another reed bed and the process repeated (Hybrid Systems). Subsurface flow through the bed is characterised into two main areas of interest, *horizontal* and *vertical* flow systems. The processes by which purification occurs are essentially the same in each case, however the performance and characteristic behaviour is different for each.

3. PROCESS INTENSIFICATION

Process Intensification, (PI) is a concept originally defined for the chemical process industry. In essence, PI is the improvement of the process to obtain the same or preferably better yields in more physically compact and energy efficient plant. In the chemical process industries, PI has largely focused on heat-exchange and reactor efficiency, but its principles are much more broadly applicable.

The disadvantage of considering PI for a large bio-plant is partly one of scale and partly one of complexity. Very few chemical processes outside petroleum refining deal with such large volumes and flow rates as are found in a large ASP. Large fermentors, which might be taken to be the analogue of the ASP, are much more closely defined than an ASP. Fermentors have both feeds and operating conditions tightly specified and they normally use only a single micro-organism regardless of whether they are operated for bio-mass production or secondary metabolite formation.

4. EXAMPLE - IMPROVING THE ASP

A number of steps can be taken to improve the ASP. Many of these are also applicable to other systems as well.

Controlling the Nature of biomass:

The ASP contains a complex community of micro-organisms. It has become apparent that the operational efficiency of such plants depends intimately on the condition of this eco-system. Well known problems such as sludge bulking are directly attributable to a change in the dominant species (in this case to the appearance of filamentous organism). The sequencing batch reactor (SBR) is one means of reducing or controlling this problem, but it would be convenient if the tendency to sludge bulking could be detected at an early stage, preferably well before the change in sludge character became visible. Community analysis using conventional microbiological techniques to identify and enumerate individual species of micro-organism is both too complex and too time consuming. Direct microscopic identification of major species is possible(12) but requires both training and considerable experience to be effective. The potential of molecular biology in this area is just becoming apparent. Fluorescence In-Situ Hybridisation (FISH) is an invaluable tool in molecular ecology. Individual bacteria of targeted species are detected microscopically, located and quantified in the background of a complex population. The technique is rapid. Samples are hybridised with oligonucleotide probes labelled with fluorophores. FISH is very specific and gives unambiguous results if suitable controls are used. Typical of the results which can be obtained is the identification of the predominant species in P-removing bio-sludge(15).

Other techniques such as Polymerase Chain Reaction- Denaturing Gradient Gel Electrophoresis (PCR-DGGE) can be used to measure the biodiversity of the total bacteria population in a sample, giving a unique population fingerprint. This technique allows population shifts to be mapped out and offers considerable promise, as does the use of computer interpreted image analysis to measure filamentous growth(16).

Altering the amount of biomass:

Most ASPs are operated with reasonably constant biomass concentration and age. To achieve this sludge re-cycling and wasting are carefully balanced. The mixed liquor suspended solids (MLSS) is the usual measure of sludge concentration. In principle better removal of COD might be obtained by using high MLSS, but problems are often encountered with foaming and aeration. In one series of experiments MLSS of over 50,000g.m^{-3} were maintained using a novel co-current self-aspirating down-flow aeration system(17). Such systems have not been exploited commercially but point the way to possible developments.

An alternative to using free-living micro-organisms would be to turn to some type of suspended culture. There are many accounts of immobilised cell reactors, where a single species of organism is used for a specific purpose(18) but biofilm reactors with a mixed community of micro-organisms have more potential for general treatment. Given that the volumes to be treated are large and the wastewater is likely to contain both high COD and particulates, a fixed bed system e.g. BAF or similar would be unlikely to provide the solution. Similarly, rotating disc or other similar fixed film contactors are unlikely to be built to the required scale. However, expanded bed or fluidised-bed systems could be employed. In principle the capital cost of providing a large volume of a suitable support could look unattractive. However, cost is not the only criterion. Large scale fluidised-bed plants have not received general acceptance, although smaller scale plants dealing with domestic wastewater are becoming quite common, particularly in areas where connection to a main treatment systems is not possible. In these cases compact 3-phase fluidised-bed systems offer a competitive alternative. Of course, the technology is still not well developed, but far from being a disadvantage this can be seen as an opportunity since there is considerable potential for improvement of performance i.e. PI.

The nature of the support is key here and a wide range of materials has been tested. A recent study considered some of the more important factors and examined a range of materials(19). Particular attention was paid to particle density and a three phase air-fluidised system was tested, which although it gave COD removals not significantly better than an ASP offered the possibility of simpler operation with no sludge re-cycle and much lower sludge wasting.

In addition further work needs doing on the interaction of solid phase content with other factors such as aeration efficiency. In experiments using a neutrally buoyant solid phase consisting of polypropylene beads 5mm diameter it was shown that mass transfer efficiency as measured by K_{la} depended on the solids content with a maximum at about 40% solids(20).

Aeration efficiency:

There is a huge literature and a bewildering variety of schemes for aeration. However, new variants are always being proposed, as for example described above. What is far less commonly considered is the thorough examination and analysis of the plant to determine whether aeration efficiency is maintained throughout the system. In one example a large ASP was subject to a thorough survey(21). The plant consists of 3 storage basins, linked to a aeration basin with the overflow fed to a clarifier and discharge from there to a receiving water course. The aeration basin was approximately 5m deep with a square cross-section of about $100m^2$. A preliminary examination of operating practice for the aeration basis revealed that it was unlikely to be operating effectively. Design consideration showed that the existing surface aerator would be incapable of providing effective mixing in an un-baffled tank with the dimensions given. A survey of the DO content of the basin showed poor mixing with the bottom third of the basin being essentially anoxic. In effect if the system could be modified to give better mixing and aeration, a gain of effective capacity of almost one third could be achieved!

Physical plant design (flow hydraulics):

The plant described above was analysed to examine the residence time distribution in the main aeration basin using tracer technique to obtain the data. Figure 2 shows this in outline. It was possible to model this situation using a modified version of the Tanks in Series model which is well understood in the chemical process industries. This version of the model consists of three tanks in series, coupled with a further tank representing the anoxic zone and a by-pass. This model has been used elsewhere to describe behaviour in other unrelated plant and so is considered to have good general applicability(22)(23).

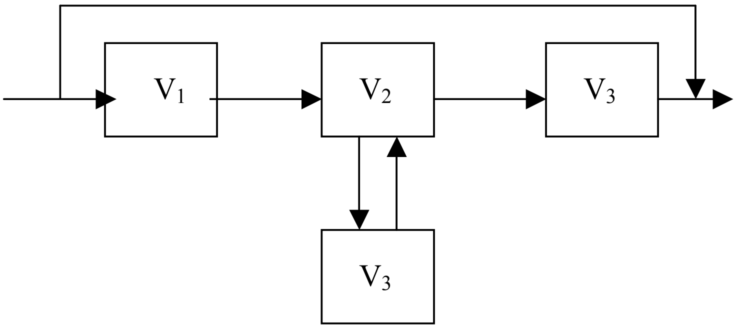

Figure 2: Analysis of flow in an aeration basin via the modified tanks-in-series model

The design of this plant and many similar conventional ASPs with a single contactor/aerator basin is inherently inefficient. Treating the basin as a single perfectly mixed tank shows that that a change to a series of tanks emulating plug-flow could lead to an increase in efficiency of up to 25%. In addition, the separate basins could be optimised to different conditions with further efficiency gain. Of course, this efficiency gain is offset by an increase in complexity of design and operation. Moreover, it is most unlikely that it could be retrofitted in an existing plant. However, it is worthwhile bearing in mind for future design.

Temperature:

A large conventional ASP is only very poorly temperature controlled and normally operates with a mesophilic regime. However, facultative thermophilic bacteria can be isolated from mesophilic wastewater treatment facilities and it follows that the plant operating temperature might be increased without loss of all viable organisms. As might be expected, microbial community analysis by PCR-DGGE demonstrates that thermophilic aerobic biological treatment reactors support completely different cultures than similar mesophilic.

In one example a laboratory scale thermophilic aerobic wastewater treatment reactor using peptone and starch as primary carbon sources has been described(24). The microbial community was studied by combination of culture-independent methods. The temperature in the reactor varied almost periodically between 30-65°C within an operational batch. Denaturing gradient gel electrophoresis (DGGE) of PCR-amplified 16S rDNA partial sequences (PCR-DGGE) revealed the changes in the community, and it became stable when the performance of the reactor became stable. Rapid modern analytical methods may enable profiling of the different organisms and allow its changes to be followed precisely enough to comprehend the process performance based on community structure.

Aerobic thermophilic treatment has been applied mostly to low-temperature, high-organic-strength wastewater, e.g. pulp and paper waste, slaughter house waste etc(24)(25). If the organic strength of the wastewater is high enough, autothermal, or self-heating, thermophilic treatment can be achieved, as occurs with ATAD sludge treatment A substantial heat of reaction is released by the biological oxidation of the organic material - approximately 15 kJ/kg COD reduction. However, many opportunities exist for thermophilic wastewater treatment of high-temperature medium or low-strength wastewaters using a properly engineered system. It is possible to speculate that thermophilic processes could be economic where low grade waste heat was available e.g. at power stations. A research project at Liverpool John Moores University is looking at thermophilic aerobic treatment for waste metalworking fluids[26,27,28]. The use of a Thermophilic Aerobic Technology (TAT) system has shown potential to enhance overall performance. Its performance at higher temperatures and under more stable conditions is also being investigated.

A serious problem with moving towards a thermophilic regime is that oxygen solubility decreases markedly with temperature. One way so far largely unexploited of dealing with this would be to use a pressurised system. Many microbial processes operate at elevated pressure either by default, as in tower fermenters where the pressure at the bottom may be ~3 times atmospheric or by design ~10 times atmospheric as in the Deep-Shaft process. There seems to be ample scope for exploiting the pressure driven increase in oxygen solubility, though the increase in solubility of other gases, notably carbon dioxide may create some problems. One solution to this problem is the use of pure oxygen instead of air. To make this process more efficient a gas re-cycle system may be used.

Physical properties of the biofilm:

The level of sophistication with which this problem is being addressed was illustrated by An interdisciplinary study where an attempt was made to simulate fluid flow in defined pure-culture biofilms at the level of continuum mechanics. The work linked image acquisition and semi-automated image analysis within extended 3D-regions of biofilm structures, using state-of-the-art confocal laser scanning microscopy, and which allowed both the generation of real-life starting geometries for simulation purposes and the direct comparison of computed and experimental data(29).

5. WHAT MIGHT AN INTENSIFIED AEROBIC BIO-TREATMENT PLANT BE LIKE?

It is interesting to speculate on the design, construction and operation of an intensified aerobic bio-digester. On the one hand there are some unifying principles as outlined above which need to be considered on the other hand technologies such as membrane bio-reactors and the Deep-Shaft process show how far apart systems can become. Of course this also leads to the conclusion that there is no unique solution and that in every case the plant chosen will have to respond to local needs. What is certain is that the knowledge base will continue to increase and the operation of any bio-reactor will become more sophisticated. The impact of molecular biology has not yet really been felt but the “Lab-On-a-Chip” may become an integral part of the bio-reactor instrumentation! In addition numerous other adjuncts to bio-treatment will find a place in the repertoire, various pre- and post treatment options will be added to the main system to make it more effective and responsive.

What may be seen can be listed below:

- Physical design would be multi-tank perhaps based on the SBR
- Hydraulically well analysed and modelled
- Well instrumented and controlled, including rapid methods for community analysis (FISH, DGGE etc) with algorithms for predicting significant changes in population diversity leading to feed-forward control perhaps based on a genetic algorithm or fuzzy logic.
- May operate with fixed film: (three-phase fluidised bed reactors offer considerable possibilities).
- May operate at high bio-mass concentration.
- Thermophilic organisms could be used.
- Hyperbaric aeration could counteract low oxygen solubility and high demand.
- Oxygen could be used partly or wholly in place of air.
- Pre and post treatment strategies would be optimised.

REFERENCES:

(1) Anon, (2001) Salmon leaps in the Mersey 10 years early, Liverpool Daily Post 8th November 2001.

(2) Environment Agency (2001) "Spotlight on business environmental performance Report 2000", an Environment Agency Publication.

(3) Environment Agency (2003) "Spotlight on business environmental performance Report 2002", an Environment Agency Publication.

(4) HMSO, The Landfill (England and Wales) Regulations 2002, ISBN 0 11 039590 5.

(5) Biffa, 2001. http://www.biffa.co.uk/pdfs/sc8.pdf.

(6) Parr-May, J , (2003), "Delivering Sustainable Development", Presentation to CIWEM Northwest and North Wales Branch One Day Conference The Implementation of the EC Landfill Directive/How do we do it? 13th June 2003, Peter Jost Centre, John Moores University, Liverpool.

(7) Anon, (2001a) http://www.accountancyage.com/News/1129878.

(8) Ardern, E., (1917)," A Resume of the Present Position of the Activated Sludge Process of Sewage Purification.", J. Soc. Chem. Ind., 36,. 822 .

(9) Wilderer, P.A., Irvine, R.L. and Goronszy, M.C. (2001) "Sequencing Batch Reactor Technology" IWA Publishing, London.

(10) Muroyama, K. and Fan, L.S. (1985). "Fundamentals of gas-liquid-solid fluidisation" AIChE Journal,31, 1-34.

(11) Harris, C. (2000). "Three Phase Fluidised Bed Reactor For Biological Wastewater Treatment" PhD thesis, School of Built Environment, Liverpool John Moores University, UK.

(12) Cicek, N (2002) "membrane Bioreactors in the Treatment of wastewater Generated form Agricultural Industries and Activities" Paper presented at the AIC 2002 meeting, CSAE/SCGR program, Saskatoon, Saskatchewan July 14-17.Weblink: http://www.engr.usask.ca/societies/csae/PapersAIC2002/CSAE02-404.pdf.

(13) Henze, M., Gujer,W., Mino, T. and van Loosdrecht, M. (1998), "Activated sludge models,ASM1,ASM2,ASM2d and ASM3", IWA, London.

(14) Eiklelboom, D.H. (2000) Process Control of Activated Sludge Plants by Microscopic Investigation, IWA Publishing, London.

(15) Bond, P.L., Keller,J. and Blackall,L.L (1999),"Bio-P and non-bio-P bacteria identification by a novel microbial approach" Water Science and Technology, 39 (6), 13–20.

(16) Jenne, R., Banadda, E.N., Philips, N and Van Impe, J.F. (2002)," Image analysis as a monitoring tool for Activated Sludge Properties in lab scale installations" Proceedings of the 5th Specialised Conference on Small Water and Wastewater Treatment Systems, Istanbul , vol 2, p.1117-1122,

(17) Guest, A., Dyson, C. and Phipps, D.A. (2003), Liverpool John Moores University, UK, Unpublished results.

(18) Wright, P.C. and Raper ,J.A. (1996) "A Review of Some Parameters Involved in Fluidized Bed Bioreactors", Chem. Eng. Technol. 19(1), , pp 50-64.

(19) Harris,C. Alkhaddar,R. and Phipps,D. (2002) "An Experimental Study of Soluble COD Removal In A Three Phase Aerobic Biological Fluidised Bed Reactor (BFBR)", Proceedings of the 5th Specialised Conference on Small Water and Wastewater Treatment Systems, Istanbul, , pp.879-889, ISBN 975-561-225-4.

(20) Phipps, D.A., Alkhaddar, R. and Khan, G. 2003, Liverpool John Moores University, UK, Unpublished results.

(21) Phipps, D.A. and Alkhaddar, R. (2003), Liverpool John Moores University, UK, Unpublished results.

(22) Alkhaddar,R. Higgins,P; Phipps,D and Andoh,R (1999), "Investigation Into the Retention-Time Distribution of a Hydrodynamic Vortex Separator" The Journal of the Chartered Institution of Water and Environmental Management. Vol.13, No.4, pp.255-261. ISBN 0951 7359.

(23) Alkhaddar. Cheong,C H. Phipps,D. Andoh,R and James, A.J., (2001), "The Development of a Mathematical for the Prediction of the RTD of a Vortex Hydrodynamic Separator". Innovative Technologies in Urban Drainage, Proceedings of NOVOTECH 2001, Lyon, France, 25-27 June, ISBN 2-9509337-3-4, pp835-842.

(24) Stover, E., Thomas, M. and Puvay, M. (2002)."Thermophilic treatment proves an excellent pretreatment option for high-temperature, high-organic-strength wastewater" Industrial Wastewater 1, (2) 2002

(25) LaPara, T.M. and Alleman, J.E., (1999)"Thermophilic Aerobic Biological Wastewater Treatment," Water Research, 33, 895-908.

(26) Cheng, C., Phipps D.A., Alkhaddar, R.M. (2004), Thermophilic Aerobic Wastewater Treatment of Waste Metalworking Fluids. Paper in preparation for submission.

(27) Cheng, C., Phipps D.A., Alkhaddar, R.M. (2004), "Treatment of spent metalworking fluids", A paper submitted to Water Research Journal.

(28) Cheng, C., Phipps D.A., Alkhaddar, R.M. (2004), "Treatment of waste metalworking fluids" Proceedings of the 5th IWA UK Young Researchers Conference, 19-20 May, Southampton, UK.

(29) Bungartz,H-J., Kuehn, M., Mehl, M., Hausner M. and S. WuertzWater (2000), "Fluid flow and transport in defined biofilms: experiments and numerical simulations on a microscale" Water Science and Technology Vol 41 No 4-5 pp 331–338 © IWA Publishing.