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1. THE HISTORY OF THE ACTIVATED SLUDGE PROCESS

In the first half of the nineteenth century the use of sewage systems emerged as a mechanism for the removal of sewage in cities. This replaced older processes which at one extreme simply involved the emptying of chamber pots into the street. However, sewage systems do not treat wastewater; they merely move the waste from one location to another. The need to actively clean wastewater, due to the role played by untreated water in spreading waterborne diseases, became clear by the mid 1880s. The need to produce a clean, healthy, water supply was exacerbated by both the large scale production of wastewaters and increasing population densities, both by-products of the burgeoning industrial world. These problems were particularly acute in England, leading to a Royal Commission on River Pollution being established in 1865 and re-established in 1874. The latter led to the Rivers Pollution Prevention Act (1876).

Some progress treating wastewaters containing pollutants in the form of waste organic matter was made in the second half of the 19th century using physico-chemical processes and anaerobic methods. Starting in the 1880s attempts were made at treatments based upon the biological oxidation of the pollutants. This involves bringing together a wastewater containing pollutants with aerobic microorganisms and oxygen. Biological oxidation has the potential to reduce the organic pollutants to a mixture of carbon dioxide, nitrogen, water and other compounds. These methods had little success because biological oxidation turned out to be a very slow process.

In the period 1913–1914 Edward Arden and William T. Lockett, working at the Davyhulme wastewater treatment plant (Manchester, UK), carried out a series of lab-scale experiments. During this they discovered the key step to making aerobic oxidation work. It was already known that aerobic oxidation produced a suspension, or ‘sludge’. In earlier work the resulting sediment had been removed from the reactor vessel. Arden and Lockett discovered that if the sediment was retained then the process became significantly more efficient. By retaining the sediment over a series of experiments they were able to reduce the time for “full oxidation” of sewage from weeks to less than twenty-four hours. Arden and Lockett named the sediment ‘activated sludge’, as it evidently contained an active agent that improved the process, and coined the phrase the ‘activated sludge process’.

At its heart the activated sludge process essentially entails the use of two units: an aerated biological reactor and a settling unit (or clarifier). In the former the pollutants are degraded by microorganisms (the active agent that puts the ‘activated’ into ‘activated sludge’). However, the key to the success of the activated sludge process is the use of a settling unit.

Although not directly realised at the time, aerobic microorganisms flocculate to form settleable solids. These solids are removed from the effluent stream by sedimentation and then returned to the aeration process in a more concentrated culture. It is this recycling of a concentrated activated sludge from the bottom of the clarifier to the biological reactor that drives down the time for “full oxidation” of the wastewater.

On April 3, 1914, at a meeting of the Society of Chemical Industry at the Grand Hotel in Manchester, England, Arden and Lockett presented their results in a now classic paper, “Experiments on the Oxidation of Sewage Without the Aid of Filters”, which was later published in the Journal of the Society of Chemical Industry. Following dissemination of their new method the activated sludge process was rapidly adopted by the waste-water treatment industry. By 1916 the first full-scale continuous-flow activated sludge process plant was being in use to treat wastewater at Worcester. One hundred years after this landmark event, the activated sludge process has become the most commonly used aerobic process for the biological treatment of both domestic and industrial wastewaters [19]. (Australia’s first activated sludge plant, the Glenelg Wastewater Treatment Plant, was fully operational by December 1932 [9]).

2. TOO MUCH OF ANYTHING IS BAD

Central to the success of the activated sludge process is the ‘activated sludge’. However, a significant drawback of the activated sludge process is the production of excess ‘sludge’. The expense for treating this can account for 50–60% of the total operating costs in a wastewater treatment plant [1, 4, 14]. Traditional methods for disposing of excess sludge, such as incineration, the use of landfill sites, and dumping at sea, are becoming increasingly regulated in many countries due to environmental concerns about the presence of potentially toxic elements. Furthermore, a combination of the limited amount of land available for landfill, particularly in urban areas, with increasingly stringent legislation has resulted in the economic costs of using landfill sites raising sharply. Thus there is a pressing need, and growing interest, in methods that reduce the volume and mass of excess sludge produced as part of biological wastewater treatment processes.

Excess sludge production can be reduced by increasing sludge biodegradability by disintegrating it within the reactor. This approach works primarily by disintegrating bacterial cell walls.

Although many different techniques to decrease sludge production have been investigated, the most widely adopted techniques in commercial activated sludge plants are chemical treatments and ozone treatments [15]. In these methods a part of the sludge is removed from the reactor and treated with ozone in a sludge disintegrator. This ozonation stage converts the live sludge into a mixture of soluble substrate and particulates. The liquidized sludge is then returned to the bioreactor as a feed solution where the soluble substrate is biodegraded by live sludge. This technique has been shown to lead to much lower levels of mixed liquor suspended solids (MLSS).

In practice a target value for the MLSS is specified. If the steady-state MLSS value is below (above) the target value then the plant is said to be operating in a state of negative (positive) excess sludge production. The transitional case when the

steady-state MLSS value is equal to the target value corresponds to zero excess sludge production.

The first mathematical model that was used to investigate how the process variables associated with a sludge disintegration unit (SDU) effect the steady-state MLSS value was developed and analysed by Yoon [20]. In Yoon's model the sludge disintegration unit is not modelled per se. Instead sludge disintegration terms are added to a conventional activated sludge model. These terms assume that the disintegrator unit destroys the biochemical activity of the sludge, converting a fraction, α , directly into usable substrate and the remainder, $(1 - \alpha)$, into organic particulates. This model forms the basis of all subsequent work in the area.

3. MICRO-POLLUTANTS

Wastewaters originating from the municipal sector contain an array of xenobiotic micropollutants. Common micropollutants include hormones, metals, pesticides, pharmaceutical compounds, polycyclic aromatic hydrocarbons (PAH), surfactants, and volatile organic compounds. Many of these products are characterised as pharmaceutical and personal care products (PPCPs).

Micropollutants leaving in the effluent stream of a wastewater treatment plant (WWTP), or entrapped in sludge that is removed from the WWTP, may have an adverse ecotoxic impact on the environment, particularly on aquatic ecosystems. Organic micropollutants (OMPs) have been detected downstream of WWTPs at concentrations in the range of ng/L to $\mu\text{g/L}$. OMPs have been detected in groundwaters, lakes, rivers and sediments. It is unsurprising then that they are detected in drinking waters. This has lead to legislation in Europe mandating that industry and states reduce their release.

Municipal WWTPs have been designed to remove biodegradable organic carbon residues. They have not been specifically designed for removing micropollutants. Consequently most of these compounds are only partially removed. However, WWTPs are the first line of defense (perhaps the only non-legislative line of defense?) against the environmental risk posed by micropollutants. There is therefore a growing scientific interest in investigating how effective WWTPs are in removing micropollutants and whether it is possible to optimise their removal without adversely effecting the effectiveness of WWTPs in removing macro-pollutants.

In WWTPs the main mechanisms by which micropollutants are removed include: biodegradation, cometabolism (the ability of microorganisms to degrade non-growth substrates in the presence of growth substrates [3]), sorption to sludge and volatilisation. These four mechanisms do not necessarily apply to all contaminants. For example, heavy metals are only removed by sorption and only volatile organic compounds are removed by mass transfer into the gas-phase. Additional mechanisms may apply to some contaminants. For example, heavy metals can be removed by precipitation.

Identifying the relative importance of these mechanisms for emerging new micropollutants is a major challenge and provide a major application of mathematical models. For example, understanding the relative importance of the main removal mechanisms

can lead to improved depletion of micropollutants in conventional WWTPs, reducing their environmental impact. Thus accurate and well developed mathematical models can help to optimise the removal of micropollutants from WWTPs without the need for significant plant upgrades. However, there is currently little agreement in the modelling literature as to how these processes should be modelled [18].

4. MATHEMATICAL MODELS

Although the activated sludge process was brought to the attention of engineers and scientists in 1914 (to be exact, on the 3rd April 1914) the first mathematical models for the process were not developed until almost 55 years latter, in the late 1960s and early 1970s [10, 11, 17].

These early models built upon a pioneering study in the field of microbiology [8]. In microbiology it is straightforward to design an experiment in which one micro-organisms grows through the consumption of one limiting substrate, all other substrates required for growth being in excess. Similarly the early models for the activated sludge process assumed that there is one limiting substrate, one limiting microorganism and one rate-limiting biochemical reaction. Although these are all valid assumptions in the microbiology context, there is no reason to believe that they are true for the activated sludge process: a typical wastewater contains many types of substrates and a typical aerated reactor contains many types of micro-organisms. However, the unreasonable effectiveness of mathematics in the natural sciences once again rears its head!

More detailed models have subsequently been devised. At one end this involves extensions of the basic model that remain analytically tractable. An important extension in this direction is due to Chung and Neethling [2] who enlarged the microbiology of the basic model in two ways. Firstly, they introduced a slowly biodegradable substrate component which is hydrolysed to produce small soluble organic materials. (These are the limiting substrate of the basic model). Secondly, they allowed a fraction of the dead biomass to be recycled back into the soluble substrate pool.

At the other end models have been developed which include sufficiently detailed microbiology that they are no longer amenable to analysis, an example of such models is the activated sludge models developed by the IWA [7, 12, 16]. Of these the activated sludge model number 1 (ASM1) [6] is the most well known. This has become an internationally accepted standard for activated sludge modeling, particularly of WWTPs.

The ASM1 model includes eight processes that are fundamental to the activated sludge process. These are: aerobic and anoxic growth of heterotrophic biomass, death of heterotrophic biomass, aerobic growth of autotrophic biomass, decay of autotrophic biomass, ammonification of soluble organic nitrogen and hydrolysis of both entrapped particulate organic matter and entrapped organic nitrogen. Together these processes describe nitrogen and chemical oxygen demand within suspended-growth treatment processes, including mechanisms for nitrification and denitrification.

Through its inclusion of the eight fundamental processes the model has been found to give a good description what happening in the activated sludge process *provided* that

the wastewater has been characterised and the model calibrated. Wastewater characterisation requires the determination of 12 parameters. Model calibration involves determining two physical parameters (associated with oxygen) and 19 parameters associated with microbial processes. Although some of the microbial parameters may be assumed to be relatively constant between different WWTPs, characterisation and calibration remain a non-trivial process. Finally, the wastewater must be of domestic or municipal, but not industrial, in origin.

Recent developments in the mathematical modeling of the activated sludge process are reviewed in [5, 13]. However, the ‘basic model’ and its extensions remains an attractive modelling approach for many exploratory investigations because such models are easy to calibrate.

5. SCOPE OF PRESENTATION

This presentation illustrates the use of the basic model and the two-step model, due to Chung and Neethling [2], to model: the activated sludge process, the problem of having too much sludge and the removal of micropollutants. An introduction will be provided to the ASM-1 model.

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