ACHIEVABLE EFFLUENT QUALITY FROM BIOLOGICAL NUTRIENT REDUCTION SYSTEMS UNDER AUSTRALIAN CONDITIONS - MODELLING AND FULL SCALE OPERATING EXPERIENCE

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Abstract

The imposition of very stringent effluent quality requirements within Australia has resulted in the adoption of biological nutrient removal processes for many larger sewage treatment plants. Effluent limits of 5mg/L total nitrogen and 1mg/L total phosphorus have been imposed. In order to achieve these effluent quality criteria in a cost effective manner, it has proven necessary to further refine the fundamental design procedures as presented by the University of Cape Town (WRC, 1984) and generally as adopted for IAWPRC Activated Sludge Model No. 1 (Henze et al, 1987) and as expanded for biological phosphorus removal (Wentzel et al, 1990) in the IAWQ Activated Sludge Model No. 2 (Gujer et al, 1995). Of particular concern under Australian domestic sewage conditions were sludge production and achievable effluent nutrient concentrations. Investigations were undertaken into the basis of the models and subsequent research and refinement to the models developed. The findings were implemented for the design of full-scale plants. Actual operating results have demonstrated very low effluent nutrient concentrations of less than 4mg/L total nitrogen and less than 0.3 mg/L total phosphorus.

INTRODUCTION

The biological phosphorus removal process was discovered more or less by accident, as have most biological wastewater treatment processes. The earliest plants deliberately developed or modified to achieve biological phosphorus removal relied heavily on empirical data and experience at other plants. Little was understood about the science, microbiology or process kinetics of the reactions occurring. In true engineering fashion, the need to get on with providing facilities left little time or money for research and development work.

Initially seen as a method of achieving a degree of phosphorus removal whilst reducing chemical consumption, the desirability of the process became apparent where downstream reuse of the product water was common. The elimination of additional salt contribution by eliminating or minimising chemical dosing was an obvious benefit in addition to the reductions achievable in operating costs. Drier countries such as South Africa and Australia found the process particularly appealing.

The variable levels of performance or lack of performance achieved at the early plants demonstrated the need for additional research into the process. The Marais group at the University of Cape Town in South Africa carried out much of the initial research into the biological phosphorus removal process and subsequent modelling. These models serve as the basis of many of the commercially available computer simulation packages available today.

2.0 DEVELOPMENT OF INITIAL MODELS IN SOUTH AFRICA

In order to develop a true fundamental model of the activated sludge process, the Marais group sought a method of characterising all inputs and outputs for the process that would obey the laws of conservation of energy and mass. The conventional measure of BOD_5 was abandoned as many highly different substrates can exert the same biochemical oxygen demand over the five-day period of the test. Longer periods for the BOD test were rejected as being to cumbersome and ignoring the presence of non-biodegradable organic material that will contribute to sludge production.

The Marais group ultimately determined that the Chemical Oxygen Demand (COD) test was the most appropriate basis for modelling. The adoption of the COD as the basis permitted an oxygen balance to be carried out over the activated sludge process. Furthermore, as measurement of the utilisation of oxygen in a biological system is a measure of the electron transfer occurring within the microorganisms and therefore ultimately a measure of energy, the COD test satisfied the requirement where a measure of both energy and mass conservation could be carried out.

The raw sewage entering the treatment plant was characterised by four components;

- Non-biodegradable soluble COD that passes through the treatment system unaltered and emerges in the final effluent.
- Non-biodegradable particulate COD that accumulates as part of the mixed liquor suspended solids and ultimately emerges in the waste activated sludge stream.
- Readily Biodegradable COD that is rapidly metabolised by the microorganisms (not to be confused with dissolved biodegradable COD all of which is not readily assimilated).
- Slowly Biodegradable COD that is slowly metabolised by the microorganisms and includes all particulate, some colloidal and some soluble biodegradable COD.

Following characterisation of the influent, modelling of simple carbonaceous removal systems was carried out. The key factors in these first steps of fundamental modelling were to determine the yield applicable for the consumption of substrate and the modelling of the so-called endogenous respiration rate. To permit this modelling, it was assumed that the active biomass could be treated as a uniform heterogenous heterotrophic biomass. This simplification was critical to the early model development however it was acknowledged that the biomass comprised both complex bacterial and protozoan populations.

The yield factor was determined from published microbiological chemostat studies utilising single bacteria cultures. Based on these a yield factor of 0.666 was adopted. This adoption of this factor dictates that for mg of biodegradable substrate consumed by the biomass, 0.666mg is converted to cell matter and 0.333mg is converted to carbon dioxide and water. By definition, 0.333mg of oxygen must be consumed in the process. The adoption of this yield factor is the very basis of all fundamental models derived from the South African work.

The modelling of the endogenous respiration was far more complex. Many practitioners at the time adhered to the “maintenance” energy concept of the active biomass however application of this concept did not adhere to experimental results generated. Marais and his co-workers ultimately determined that the death predation concept most accurately reflected observed behaviour. The adoption of this concept is not surprising as it was known at the time that the protozoa within the biomass preyed on the bacteria and that the bacteria metabolised substrate from the influent sewage and that released from death of the protozoan population. In the absence of protozoa, the activated sludge heterotrophic bacteria undergo a very low rate of natural death as cited by Marais. Whilst acknowledging the role of the protozoan population within the biomass and the different substrates utilised, the models continued to treat the heterotrophic biomass as heterogenous.

With the adoption of the yield factor and the death predation concept, the actual death predation was measured for a wide range of aerobic pilot plants operating at differing temperatures and sludge ages. The measured rate was found to be near constant for any given temperature. The derived value of 0.24/d nett death predation rate at 20^0C was subsequently adopted for all future modelling.

For the models to prove truly useful it was essential to be able to predict the solids production within the system and the resultant operating Mixed Liquor Suspended Solids (MLSS) concentration and waste activated sludge production. The various components of the biomass including the endogenous residue from the death predation process could be determined on a COD basis however this need to be related back to volatile suspended solids (VSS). Measurements on MLSS samples from a broad range of pilot plants demonstrated a COD to VSS ratio of typically 1.48mgCOD/mgVSS. As this is also the COD to VSS ratio calculated from the simplified chemical structure of a bacteria ($C_5H_7O_2N$) it appeared reasonable to adopt this value as a constant.

The simple aerated activated sludge process could now be reasonably accurately modelled and the oxygen balance carried out to support the model basis. Extension of the model to incorporate nitrogen removal was then undertaken. It was well known that the process of nitrification was carried out biologically by select nitrifying bacteria. The nitrification process was modelled at a completely separate microbiological population with separate yield factors based on ammonia nitrogen as the substrate and separate death-predation rates with the nitrifying bacteria experiencing very little predation within the activated sludge process. Oxygen consumption was modelled based on the stoichiometry of the overall nitrification process.

The denitrification process is carried out by heterotrophic bacteria. A range of pilot plant studies by Marais and his co-workers demonstrated that the rate of denitrification was substrate dependent (readily biodegradable COD or slowly Biodegradable COD) with a third rate experienced attributed to nitrate respiration through the death-predation process. The equivalent oxygen respiration rate for denitrification with RBCOD as a substrate was so nearly identical to that experienced under aerobic conditions that it was assumed that all bacteria could utilise either dissolved oxygen or nitrate as an oxygen source when metabolising RBCOD. The equivalent oxygen consumption rate measured when utilising SBCOD as a substrate was considerably less than that for aerobic conditions. Results from a number of pilot plant studies suggested an equivalent oxygen consumption rate 38% of that experienced under aerobic conditions. It was postulated that only a proportion of the heterotrophic biomass could hydrolyse and metabolise SBCOD during denitrification. No basis however could be given for the empirically derived fraction of 0.38.

A major limitation of the pilot plant studies used to determine the SBCOD denitrification rate was that all of the experiments utilised very similar influents and that the internal recirculation rate range used was restricted to a very narrow range of typically 2 to 4 times the inflow rate. This resulted in a similar proportion of nitrate always being recirculated to the anoxic zone and thus not surprisingly giving consistent results. This restriction would subsequently a major short fall in the modelling of denitrification.

The biological phosphorus removal process was modelled as a separate bacterial population in much the same manner as the nitrifying organisms. Enhanced culture pilot plant studies were carried out utilising acetate supplemented feed. Yields and death predation rates were determined from these studies and incorporated into the models. Much debate still exists within the research community as to the specific bacteria undertaking the biological phosphorus removal and their role in denitrification. Further debate will occur until a consistent model is resolved.

3.0 INITIAL BNR EXPERIENCE IN AUSTRALIA

The South African models were first used in Australia in the early 1980's with a number of plants constructed based on the model outputs. These early experiences demonstrated that the model outputs did not accurately reflect all aspects of full-scale plant behaviour. Of particular concern was the high sludge production experienced in full-scale plants when compared to the models. Solids production was often underestimated by as much as 35% resulting in bioreactors, return activated sludge pumping systems, sludge digestion and solids dewatering facilities falling well short of their design capacities. The impact on projected operating costs was significant due to dramatically increased sludge disposal costs.

Further research in South Africa also cast doubts on the validity of some of the established process kinetics such as denitrification rates. This was of particular concern within Australia where influent total nitrogen loads are probably the highest experienced world wide due to the high consumption of fresh meat preserved with nitrates.

The identified limitations of the fundamental models and the need to achieve very high effluent standards prompted further development work by Australian practitioners.

4.0 MODEL DEVELOPMENT IN AUSTRALIA

4.1 Sludge Production

The higher than anticipated sludge production experienced in Australia was of considerable concern and was the first indication that refinement of the published models was warranted. Unlike the South African studies, the measured COD:VSS ratio for the biosolids was found to be considerably lower than the adopted 1.48. Values as low as 1.33 were measured in both pilot plants and full-scale plants. A review of more recently published data demonstrated that values up to 1.6 had been experienced in pilot plants utilising settled sewage.

More detailed chemical structures for the components of the biomass (bacteria, protozoa, endogenous residue and non-biodegradable particulate COD) were sought and identified. This exercise not only improved the predicability of the COD:VSS ratio, it also improved the prediction of the normal metabolic nutrient uptake into the biomass by identifying the nitrogen and phosphorus content of the individual biomass components.

A second factor impacting on sludge production was the death predation rate. Tests at BNR plants and intermittent activated sludge plants demonstrated that the death predation rate experienced was considerably reduced with increasing length of exposure to unaerated conditions. This aspect was successfully modelled by identifying the protozoan population as a separate component of the biomass and evaluating the selection pressures exerted during unaerated periods. It has been known for over 30 years that the protozoa found in activated sludge plants are obligate aerobes and that unaerated periods can damage the population. The modelling of these selection pressures has been confirmed in measurement of process kinetics in full-scale plants and through microbiological examination of the biomass. It is surprising that recent a number of European studies attempting to correlate the protozoan population to plant influent and operating characteristics have neglected to assess the fundamental consideration of exposure to non-aerated conditions.

The third factor influencing sludge production was the very basic consideration of influent characterisation. The COD:BOD ratio for typical Australian domestic sewage is of the order of 2.3:1 as against the South African value of 2.1:1. Many Australian designers did not question this difference and proceeded to adopt the default fractions for the various COD components. Investigations carried out by our group demonstrated that the increased COD load was entirely due to an increase in the non-biodegradable particulate COD load. This had the impact of significantly increasing sludge production.

4.2 Denitrification

The inadequacies of the original denitrification models proved particularly vexing as the prevention of nitrate leakage to the anaerobic zone of a BNR plant is critical to optimum performance of these systems. After much evaluation of the available data in the literature, revised modelling procedures were developed to accurately predict not only the rate of denitrification that could be achieved but also the extent of denitrification that could be achieved.

The basis of the model modifications was to divide the biomass into its components based on the substrate utilised and the oxygen source utilised. The components identified and modelled were;

- Bacteria RBCOD utilising Denitrifying
- Bacteria SBCOD utilising Denitrifying
- Bacteria RBCOD utilising Aerobic

- Bacteria SBCOD utilising Aerobic
- Protozoa Bacteria consuming Aerobic

It was assumed that the lysis products from the death of the protozoa would comprise both RBCOD and SBCOD components and would be consumed by the appropriate bacterial groups with the oxygen source available at the time.

The determination of the minimum mass fractions required for each process as a function of sludge age is carried out in a similar manner to that for the autotrophic bacteria carrying out the nitrification process. For the denitrification processes, the anoxic mass fraction is substituted for the aerobic mass fraction with the utilisation of both RBCOD and SBCOD being carried out in parallel. This greatly simplifies the determination of the minimum sludge age required for any given operating temperature range.

The inclusion of the protozoan population permits the oxygen demand exerted in the aerobic zone only by this group to be calculated. The true oxygen demand that can be exerted anoxically can then also be accurately calculated thus eliminating the over estimation of this value inherent in the original models.

Improvements in the design of the denitrification process have permitted the development of plants achieving very high levels of nitrogen removal. This has eliminated the need for highly flexible systems thus reducing costs.

A further benefit of the improved extent of denitrification achievable is that the amount of nitrate returned in the return activated sludge is reduced. This reduces the size of the primary anoxic zone required for denitrification of this stream and therefore also reduces the minimum sludge age required. Further capital cost savings can therefore be made

5.0 SUMMARY

Very few BNR plants currently operating within Australia consistently comply with the statutory effluent quality limits. Of the 28 operational BNR plants, only a few are providing satisfactory performance. Actual performance requirements vary due to differing regulatory requirements in the various states. The most stringent requirements apply in Queensland where typical effluent quality requirements are 5 mg/L total nitrogen and 1 mg/L total phosphorus. Many plants designed utilising the commercial simulation packages without appropriate compensation of the default input variables fail to meet their performance requirements. In other states, a large number of plants designed on the same basis under more lenient effluent quality standards struggle to comply with limits of 10 mg/L total nitrogen in conjunction with a high degree of biological phosphorus removal.

It is not simply plants designed utilising default values in computer simulations that have failed to meet their performance requirements. Designs imported directly from overseas have also failed due to the higher nutrient loads experienced in Australia. It is clear that the days of the text book solution to waste water treatment able to be implemented by any reasonably experienced engineer are gone. The development of simple, reliable and easily operated advanced biological waste water treatment systems requires the design engineer to have a thorough understanding of the micro-biology, biochemistry and process kinetics in addition to the mandatory civil, mechanical, electrical and control requirements.

Application of the modifications to the design models presented here has permitted development of a plant which continuously (100%) achieves less than 5 mg/L total nitrogen. This same system has achieved less than 0.1 mg/L ortho-phosphate and less than 0.3 mg/L total phosphorus for periods of several months without any chemical dosing provided on-site and without effluent filtration. Another plant recently commissioned is demonstrating similar excellent performance with improved reliability of the phosphorus removal process through improved reliability of the aeration system.

The modifications developed for the design models based on fundamental microbiological considerations has permitted not only this improved performance and reliability of the BNR plants, but also provided simplified operation and reduced capital and operating costs; the ultimate aim of any technology development.

6.0 ACKNOWLEDGEMENTS

Hindsight is a wonderful thing. With more data and full-scale experience the South African researchers may well have adopted a similar modelling approach as outlined here. The work carried out by Professor Marais and continued by Professor Ekama has permitted the development of full-scale high performance plants. This review presented should not be taken as criticism of their work but as acclamation of the thoroughness in the research and the ongoing quest to further improve the understanding of the processes involved. The publishing of so much data and the assistance provided to the author by Professor Ekama in particular demonstrates the commitment and willingness to benefit all. Without this group we would still literally be pouring chemicals down the drain.

DISCUSSION

Question David Searby Wessex Water

What about performance under storm conditions , does this cause you problems ?

Answer

Experience with sustained 5 DWF is possibly our worst case. The dilute effluent slows everything down. 95% compliance is tricky 80% is no problem, i.e. it rains 15% of the time. At 5DWF the performance deteriorated from 0.3 mg/l total phosphorus to 1 mg/l total phosphorus. It therefore depends on what the limits are . Recovery was very rapid once the rain stopped.

Question Richard Kellagher HR Wallingford

What about temperature effects it tends to be much colder in the UK ?

Answer

Typical of works tested at 18 to 26OC . In the temp range 14 to 24OC is not unusual in the regions . It does get cold in the winter in Australia.

Question Martin Osborne Reid Crowther

Are 90%ile standards set for N and P ? In the UK we use annual average for standards

Answer

The standards vary from state to state, Queensland is 85%, Victoria is 90% and NSW is 90%. The rules keep changing s it is a tough game to play.