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ENHANCED BIOLOGICAL PHOSPHORUS REMOVAL: MODELLING AND EXPERIMENTAL DESIGN

GESTIMULEERDE BIOLOGISCHE FOSFAATVERWIJDERING: MODELBOUW EN EXPERIMENTEEL ONTWERP

door

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Summary

Enforcement of more stringent legislation to protect our environment stimulates the interest to remove phosphorus from wastewater by means of a biological process rather than a chemical precipitation. The investment costs of chemical treatment plants are lower than for biological treatment plants, but the annual operating costs are significantly higher. Moreover, the Enhanced Biological Phosphorus Removal (EBPR) plant produces a qualitatively rich sludge, effectively improving the sustainability of the biological treatment process. Additionally, only minor process modifications, i.e. adding an anaerobic phase ahead of the aerobic phase, are necessary to upgrade existing treatment plants to achieve EBPR.

The EBPR process can be described as a twofold process

(a) In an anaerobic phase cell internal polyphosphate chains are hydrolysed to orthophosphates, a process which delivers the necessary energy for the PolyPhosphate Accumulating Organisms (PAOs) to store internal storage polymers as poly-β-hydroxybutyrate (PHB)

(b) In the following anoxic or aerobic phase the internal carbon polymers are utilised creating energy for growth and excess phosphate uptake from the wastewater.

Since the discovery of the EBPR process (first indications in 1959 with a real breakthrough in 1976) an important number of articles has been published by researchers with different fields of expertise. These studies comprise the underlying biochemical mechanisms, the micro-organisms involved in the process, the external factors focussed on the process, the engineering aspects of EBPR, simulation of the process as well as experiences with full scale applications.

The often conflicting literature data were evaluated critically with special interest for the complementarity of the results emerging from the different disciplines. Despite the development of a standard Activated Sludge Model (ASM1 in 1987 with new releases in the 1990's) no real consensus was reached for modelling the EBPR process. The kinetic and stoichiometric parameters are discussed and even for the nomenclature no global approach could be reached. Moreover, too many parameters have been determined rather on a mathematical basis than a biochemical one.

This Ph.D. study contributes to the modelling of the overall process of biological phosphorus removal on a well founded scientific basis, such that on a short term real scale applications can be managed properly by the industrial operator using a limited number of proven parameters.

A summary of the different aspects dealt with in this study are formulated as:

(a) The study encompasses an exhaustive overview of the different results published in literature, from the impact of possible nitrate introduction in the anaerobic phase to experiences with full scale applications

(b) The study evaluates the early EBPR studies with the current state-of–the–art.

(c) The studies identify the bottlenecks for biochemical mechanisms and process configurations, practically evaluates them and makes suggestions for best practices.

(d) The study identifies the causes for failed EBPR activity.

For parts (a) and (b) the reader is referred to paragraphs 2 and 3 in chapter 1, the literature review. In the following sections the results from published articles dealing with parts (c) and (d) are elaborated on. Paragraph 4 from chapter 1 also deals with these aspects.

In the early stage of this research an analysis procedure for the determination of PHAs (the most important carbon storage polymer in PAOs) in activated sludge samples was tested and validated by means of a Round Robin test. Aiming at an overall approach, the biomass were sampled from different

EBPR treatment units. The results from this research are presented in Chapter 2. Each lab used slightly modified methods. It was observed that the use of an internal standard improved the reproducibility of the method, that using dichloro(m)ethane as solvent instead of chloroform improves the GC analysis and that shaking the reaction tubes during heating improves the esterification reaction. It was shown that the standard deviation of measurements in each lab and the reproducibility between the labs was very good. Experimental results obtained by different laboratories using this analysis method can be compared. The gas chromatographic method allows for PHV, PH2MB and PH2MV analysis as well. With the publication of the Activated Sludge Model No3 and the general acceptance that storage polymers are of prime importance for non-PAOs, analysis of internal storage components becomes a prerequisite for modelling the activated sludge processes.

In Chapter 3 three of the most cited EBPR configurations were compared with the aim to obtain information on the best process configuration. It was shown that the SBR configuration was the better configuration for modelling the EBPR process. Among the continuous processes the UCT process will be better for these wastewaters containing high ammonia concentrations. In practice the increased number of recycles causes increased pumping costs and thus increased operating cost of the process. The microbial diversity developed in the continuous installations fed with a complex substrate as meat extract did not allow for stable process operation. Complete phosphorus removal could not be achieved. Using acetate as sole carbon sources, caused production of extracellular polymers with subsequent blockage of tubes. The more recycles are involved the higher the chance for possible blockage, a phenomenon often observed in lab-scale installations. During stable operating conditions and using acetate as sole carbon source revealed complete phosphorus removal. From the experimental evidence gained on the SBR installation it was observed that using acetic acid instead of sodium acetate did not result in any phosphorus removal profile. It was observed that special care is necessary when performing experiments to avoid even extremely low amounts of oxygen entering the reactor during anaerobic conditions. During a short period deterioration of the EBPR activity was observed. No conclusive evidence was gained to explain this phenomenon. It was observed that during that period very high internal PHB concentrations were observed. Overall, It was proven that the SBR configuration was extremely robust and fast recovery was always observed.

Modelling the anaerobic and aerobic processes in Chapter 4 it was observed that, the experimentally observed profiles could perfectly be simulated using simple models. The results were validated using experimental data collected in batch experiments with sludge from the continuous installations. Identification of the microbial community present in the SBR system revealed that four different groups of organisms were present, each representing about 10% of the total bacterial population. Two groups could not be identified, one group belonged to the genus *Pseudomonas* and the fourth group contained representatives of the lactic acid bacteria. It was clearly observed that the dominant microbial population did not belong to the genus *Acinetobacter*.

Recent research indicates that sulphates, after reduction to sulphide, can negatively influence the process. The possibility for the phenomena to occur in full scale plants is realistic. In Chapter 5 experimental evidence is gathered that a mixture of acetic acid and lactic acid as carbon sources allows for simultaneous removal of phosphorus and sulphate. Sulphate reduction induces growth of filamentous bacteria (*Beggiatoa*) that oxidise the produced sulphide. After several operating cycles the filamentous population became dominant and phosphorus removal did not occur anymore. Optimising the process, i.e. by taking care that the active biomass is retained in the reactor, these results provide a solid basis for concurrent phosphorus and sulphate removal.

In Chapter 6 attention is focussed on the effects of temperature on the EBPR performance. It was observed no consensus existed at all regarding the influence of temperature on the EBPR process. It was shown that the stoichiometry of the anaerobic processes was insensitive to long-term temperature changes, whereas the kinetics of the aerobic and anaerobic processes where clearly affected. The aerobic phosphorus uptake rate showed a maximum in the interval between 15 and 20°C. All other anaerobic and aerobic conversion rates increased with increasing temperature. A simplified Arrhenius equation was used to describe the effect of temperature on the reaction rates. It was shown that a prediction of the temperature effect on a full scale biological nutrient removal plant is not straightforward because of the different influence of temperature on the sub-processes. All these influences should be accounted for.

The best practices presented in *Chapter 7* focuses on optimal experimental design of experiments (OED), i.e. procedures to design a limited number of experiments giving rise to a maximal information content. The experimenter will select the experimental region and perform one experiment. From then onwards following experimental conditions will be chosen from the experimental region solely based on their predicted information content. The method is applied to calibrate models of phosphorus removing activated sludge systems. The structural and practical identifiability of the parameters are addressed. The D-criterion was found to give the best performance for the selection of the experimental conditions. The selection of a limited number of experiments reduces the intrinsic difficulties the identification of these models is in general faced with, i.e. the model complexity and the lack of reliable measurements.

In *Chapter 8* emphasis was put on the practical aspects of efficiently calibrating ASM2d. The calibration procedure was based on an 'expert approach' rather than on a system engineering approach. With only changing a limited number of parameters the model proved well capable of describing the performance of the pilot plant. New findings are that oxygen entering the treatment plant via the influent has an important influence on the simulated phosphate effluent concentrations. Further, reactions occurring in the final clarifier affect the effluent concentrations and should be accounted for when simulating the overall process by introducing for instance, a virtual anoxic reactor in the sludge return line.