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Models for optimisation and control of aerobic membrane bioreactors

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Summary

The increasing demand by citizens and environmental organizations for cleaner waters led governments worldwide to convert water protection into one of their priorities. Key stakeholders in charge of operating wastewater treatment facilities are therefore in need of adequate, cost-effective technologies to meet the requirements of this and future generations. The membrane bioreactor (MBR) technology, combining biological treatment with membrane filtration, is currently receiving keen interest herein, providing water of excellent quality fit for reuse. Its commercial growth has been significant in the last decade, but till present day the technology is still perceived as a high-cost option, impeding definitive market breakthrough. The problem lies in the fouling of the membranes which causes their permeability to decline and requires suppression measures like backwashing, membrane aeration and chemical cleanings to sustain operation. Despite many studies, the fouling process is still poorly understood and described, resulting in installations that are designed and operated conservatively and therefore cost-ineffectively, leaving room for optimisation.

In this PhD thesis, a pure modelling approach was adopted in pursuit of more cost-efficient MBR plants. It entailed the investigation of main design and operational related parameters in a virtual model-based setting as well as the application of models to real data. The subject of process control for biology and filtration was addressed too. Activated sludge models (ASM), benchmark simulation models (BSM) and principal component analysis (PCA) were used in particular to achieve the specific goals that were set out.

The applicability of ASM models to MBRs for optimising energy consumption was assessed on a community-scale MBR treating high strength domestic wastewater for recycling purposes. ASM2d was chosen as biological process model to account for the presence of phosphate accumulating organisms. A tracer test was carried out to determine the hydraulic behaviour of the plant. To realistically simulate the aeration demand, a dedicated aeration model was developed incorporating the dependency of the oxygen transfer on the mixed liquor suspended solids (*MLSS*)

concentration and allowing differentiation between coarse and fine bubble aeration, both typically present in MBRs. A steady-state and dynamic calibration was performed, and the calibrated model was able to predict effluent nutrient concentrations and sludge concentrations accurately. Linking the model output with empirically derived correlations for energy consumption also allowed an accurate prediction of the energy consumption. A validation of the model was performed by effectively applying better operational parameters, identified through a model-based scenario analysis, to the plant. This resulted in a reduction in energy consumption by 23% without compromising effluent quality, as was accurately predicted by the model.

Model-based life-cycle cost assessment was used to quantify the effect of design choices and operational parameters on full-scale hollow fibre membrane bioreactor costs. Different options were subjected to a long-term dynamic influent profile and evaluated using ASM1 for effluent quality, aeration requirements and sludge production. The simulation results served as input for specific cost models for capital (*capex*) and operational expenditure (*opex*) generated using representative heuristic and empirical available cost data, to calculate the net present value (*NPV*) on a 30-year basis. Results revealed that the amount of contingency built in to cope with changes in feed water flow has a large impact on *NPV*. A buffer tank to reduce influent dynamics is an economically viable option. Membrane cost and lifetime is decisive in determining *NPV*. Operation at higher sludge retention time (*SRT*) increases the *NPV* due to higher aeration costs at higher *MLSS* levels, though the analysis is very sensitive to sludge treatment costs. A higher sustainable flux demands greater membrane aeration, but the increase in *opex* is offset by lower *capex* as the required membrane area is reduced.

A benchmark simulation model (BSM-MBR) was developed to allow fair comparison of operational and control strategies for MBRs in terms of effluent quality and operational costs. The configuration of the existing BSM1 for conventional activated sludge (CAS) plants was adapted using reactor volumes, pumped sludge flows and membrane filtration for the water-sludge separation. The BSM1 performance criteria were extended for an MBR taking into account additional pumping requirements for permeate production and aeration requirements for membrane fouling prevention. Aeration costs and efficiency were described with aforementioned dedicated model. A comparison with three large-scale MBRs showed BSM-MBR energy costs to be realistic. A proof of concept demonstrated the usefulness of BSM-MBR for identifying control strategies to lower operational costs without compromising effluent quality.

Recognizing the economical potential of operating MBRs in a hybrid configuration, i.e. the combination of MBR and CAS, the benchmark simulation concept was used to investigate their dynamic behaviour and the effect of different levels of CAS and MBR integration on effluent quality and operational cost. BSM1 was chosen to represent the conventional and BSM-MBR the MBR part of the hybrid plant. The BSM-MBR aeration model was adapted slightly and used throughout, i.e. also in BSM1. A parallel, in series and integrated plant layout were defined as well as certain rules, procedures and controllers with regard to influent partitioning, sludge distribution, settler operation and aeration. Both the choice of layout and the influent partitioning ratio between the conventional and MBR lane had a significant influence on effluent quality but not so much on total operational costs. The optimal results that were achieved for each layout were however similar and found to be prevailing at high influent rates towards the MBR lane.

Finally, a data-driven modelling approach was investigated for membrane fouling control, using principal component analysis (PCA) and fuzzy clustering (FC) to extract the necessary monitoring information out of online measured transmembrane pressure data (*TMP*) from a lab-scale MBR. Of the three tested PCA techniques the two functional methods proved useful to cope with noise and outliers as opposed to the common standard PCA, while all of them presented similar capabilities for revealing data trends and patterns. The expert functional PCA approach enabled the distinction of reversible and irreversible fouling. The b-splines approach provided a more objective way of functionalising the data set, though at increased complexity. The FC algorithm, applied after PCA, was suited for data analysis, but did not allow a correct classification of all data. Factor analysis was used instead to completely split the different fouling effects and classify the data in a more pragmatic approach. Overall, the tested techniques appeared useful and can serve as the basis for automatic membrane fouling monitoring and control.

Besides the main outcomes of the work, i.e. knowledge buildup and a set of powerful model-based tools to achieve improved cost-effective MBR design and operation, various research needs and promising future paths were identified throughout the thesis and listed. Amongst them the development of a sound sludge rheology model as it impacts mixing, pumping, filtration, aeration as well as biokinetics and a risk index model that expresses the link between MBR operation and membrane fouling in terms of a risk index, which can be used while consensus-based explicit mechanistic models of membrane fouling are under development.