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Comparison of a deterministic and a data driven model to describe MBR fouling

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HIGHLIGHTS

- A long term (462 days) modelling study was carried out in a UCT-MBR plant.
- A more reliable TMP description can be achieved by using a deterministic and a data driven model.
- Specific conditions were identified under which each of the models perform better.
- The most relevant operating conditions affecting the TMP were identified.
- Deeper insights into MBR fouling operating under different conditions were revealed.

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ABSTRACT

Membrane bioreactors (MBRs) are a combination of activated sludge bioreactors and membrane filtration, enabling high quality effluent with a small footprint. However, they can be beset by fouling, which causes an increase in transmembrane pressure (TMP). Modelling and simulation of changes in TMP could be useful to describe fouling through the identification of the most relevant operating conditions. Using experimental data from a MBR pilot plant operated for 462 days, two different models were developed: a deterministic model using activated sludge model n°2d (ASM2d) for the biological component and a resistance in-series model for the filtration component as well as a data-driven model based on multivariable regressions. Once validated, these models were used to describe membrane fouling (as changes in TMP over time) under different operating conditions. The deterministic model performed better at higher temperatures (>20 °C), constant operating conditions (DO set-point, membrane air-flow, pH and ORP), and high mixed liquor suspended solids (>6.9 g L^{-1}) and flux changes. At low pH (<7) or periods with higher pH changes, the data-driven model was more accurate. Changes in the DO set-point of the aerobic reactor that affected the TMP were also better described by the data-driven model. By combining the use of both models, a better description of fouling can be achieved under different operating conditions.

1. Introduction

Membrane bioreactors (MBRs), a combination of activated sludge bioreactors and membrane filtration units for biomass retention, have increased in popularity as a wastewater treatment technology over the last decade due to their unique advantages, such as their high effluent quality and small footprint [1]. These characteristics have made them especially appropriate for upgrading wastewater treatment plants where water reuse is required and/or available space is limited. However, MBRs may have high operating energy requirements [2], specifically to prevent fouling. In that sense, the increase of transmembrane pressure (TMP) is a clear indicator of the fouling phenomena. As reported by Judd and Judd [1], the rejected constituents in the retentate tend to accumulate at the membrane surface, leading to an increase in the TMP for a given flux, which is collectively referred to as fouling. The main MBR foulants are colloidal, dissolved and particulate substances excreted by microorganisms present in the biomass, including bound extracellular polymeric substances (EPS) and soluble microbial products (SMP) [3]. Due to the complexity of the biological processes and membrane filtration phenomena taking place in MBRs, it is difficult to determine the optimal way to operate a MBR. For this reason, full scale MBRs are commonly

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Abbreviations

ASM	activated sludge model
ASM2d	activated sludge model n°2d
COD	chemical oxygen demand (mg L^{-1})
DO	dissolved oxygen (mg L^{-1})
EPS	exopolymeric substances (mg L^{-1})
LM	linear model
MBR	membrane bioreactor
MLSS	mixed liquor suspended solids (g L^{-1})
MLSSana	mixed liquor suspended solids from the anaerobic compartment (g L^{-1})
MLSSm	mixed liquor suspended solids from the membrane compartment (g L^{-1})
ORP	oxidation reduction potential (mV)
RMSE	root mean square error
SMP	soluble microbial products (mg L^{-1})
TKN	total Kjeldahl nitrogen (mg N L^{-1})
TMP	transmembrane pressure (mbar)
UCT	University of Cape Town

List of symbols

$\propto$	specific cake resistance according to cake thickness (m g^{-1})
$A(t)$	irreversible blocked membrane surface (m^2)
A_0	membrane surface (m^2)
$J(t)$	permeate flux (L m^{-2} h^{-1}, LMH)
K_{NH_4}	half saturation coefficient for autotrophic organisms (m g^{-1})
$R_c(t)$	cake resistance by accumulation of solids (m^{-1})
$R_{irr}(t)$	irreversible accumulation of solids (m^{-1})
R_m	intrinsic membrane resistance (m^{-1})
$R_{tot}(t)$	total membrane resistance (m^{-1})
$w(t)$	cake mass related to the sludge solids concentration (g)
$\eta(T,t)$	sludge viscosity (g m^{-1} h^{-1})
η_{NO_3}—H	anoxic reduction factor for growth of heterotrophic organisms

run conservatively to avoid operational problems. Mathematical models can help to identify the best operating strategies through model-based optimisation [4]. However, a widely accepted general mathematical model able to cover all system variables does not yet exist [5]. Although the biological processes have been described, fouling development within the filtration component is still under discussion. There are some successful efforts to model the biological processes occurring in MBRs that rely on activated sludge models (ASM) [6]. In some cases, ASM-like models have been extended to include additional state variables to incorporate fouling descriptors (e.g., SMP), with limited success [7]. Other models have focused more on the understanding of the physical processes to properly describe membrane aeration [6] and to determine operating costs for ideal membranes [4] or optimal energy-saving strategies regarding fouling [8]. However, the complexity of fouling, which is influenced by several factors and the lack of consensus on a specific fouling indicator [9] increase the difficulty of modelling the filtration process. Overall, none of the deterministic approaches for modelling fouling have led to a widely accepted general model that has been validated at different scales and under operating conditions. Rather, deterministic models are only applicable in very specific cases. Empirical data and expert knowledge have also been applied to control fouling strategies [10], but the complexity of the process makes those systems vulnerable.

When there is a lack of fundamental knowledge about a specific process (e.g., fouling development) but a significant amount of experimental and historical data is present, data-driven models can be a good option. Currently, successful data-driven MBR models include chemometric approaches that have been used to predict transmembrane pressure (TMP) [11] and chemical cleaning intervals [12] as linear regressions. TMP has also been used to describe fouling behaviour by means of principal component analysis and fuzzy clustering [13]. Furthermore, artificial neural networks have been adopted to predict TMP in ultrafiltration membranes for water treatment [14] or to predict the fouling behaviour of microfiltration membranes under constant flux conditions [15]. A statistical approach linking long-term and short-term permeability evolution with operating variables in full-scale MBRs, with flux as the main factor affecting long-term fouling followed by temperature, food to microorganisms and sludge retention time, was also studied [16]. Other recent studies used 2-D fluorescence monitoring data to describe TMP, the effluent quality descriptors and biomass concentrations [17,18]. However, the comparison of a deterministic model and a data-driven model to describe filtration can help to overcome the limitations of using a single model. Such a study would determine which approach better describes filtration processes and in which operating conditions.

The objective of this work is to illustrate the comparison of deterministic and data-driven models for the TMP description in MBRs and the utility of both approaches for a more reliable description of fouling. To that aim, two different models were developed and evaluated. Although there are a lot of interactions affecting fouling (e.g., operating parameters, biological characteristics of the sludge, influent characteristics), TMP is a clear indicator of the fouling phenomena, being used as dependent variable in our models. The accuracy of both models was assessed and compared using experimental data from an industrial scale MBR pilot plant over 1.5 years of operation under different conditions.

2. Materials and methods

2.1. Experimental system

The experimental pilot plant was a MBR with a University of Cape Town (UCT) configuration able to biologically remove organic matter, nitrogen and phosphorous. The influent wastewater (4.25 m^3 td^{-1}) was obtained directly from the full-scale wastewater treatment plant sewer at Castell d'Aro (Catalonia, Spain), where the MBR pilot plant is located. Specifically, the UCT-MBR pilot plant was equipped with a primary settler and a screening system to prevent the entrance of large particles. The bioreactor had a total volume of 2.26 m^3 divided into anaerobic (14% of the total volume), anoxic (14%) and aerobic (23%) compartments and a compartment with submerged microfiltration flat sheet membranes (49%). The membranes had a total membrane area of 8 m^2 (LF, Kubota, Japan), with a nominal pore size of 0.4 μm, working at 9 min of filtration and 1 min of relaxation. The permeate production for the whole period ranged from 120 L h^{-1} to 200 L h^{-1} (15–25 L m^{-2} h^{-1}, LMH), and membrane aeration for the whole period fluctuated between 6 and 12 m^3 h^{-1}. The UCT configuration pilot plant was operated at an average sludge retention time of 25 ± 6 d and a hydraulic retention time of 0.50 ± 0.05 d. The