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Activated sludge characteristics affecting sludge filterability in municipal and industrial MBRs: Unraveling correlations using multi-component regression analysis

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ABSTRACT

In the field of membrane bioreactors (MBRs) many membrane fouling related questions still remain unanswered. The goal of this research is to unveil some of the black-box features of activated sludge filterability by correlating the results from activated sludge filterability measurements following the Delft Filtration Characterization method (DFCm) with a large set of activated sludge characteristics. Ten different MBRs in Belgium and the Netherlands were sampled in both winter and summer. All samples were subjected to the DFCm, automated image analysis and an extensive set of standardized measurements. No clear correlation could be found between a single sludge parameter and activated sludge filterability. However, a combination of sludge morphology and relative hydrophobicity (RH) allows for a clear classification of activated sludge into two classes, i.e., *bad* and *poor to good*, implying that deflocculation and a low RH have a negative impact on activated sludge filterability. Furthermore, for sludge samples having *poor to good* filterability, accurate estimations of sludge filterability can be made when including more parameters. The main conclusion is that filterability can be predicted by analyzing the *bioflocculation state* of the activated sludge.

1. Introduction

The market share of membrane bioreactors (MBRs) in the field of biological wastewater treatment has increased significantly in the last decade [1,2]. The combination of an activated sludge process with a membrane filtration step for biomass separation offers a number of advantages among which an excellent effluent quality, a small footprint and a complete decoupling of the hydraulic and sludge retention time (HRT and SRT, respectively) [3]. However, despite extensive research efforts membrane fouling in MBRs is still far from being fully understood [4] mainly due to the inherent interactions among the activated sludge, the influent and applied process conditions. Activated sludge filtration in an MBR is indeed a physical process of which the efficiency is dictated by activated sludge filterability, which, on its turn, is dictated by the interactions between the biomass, the wastewater and the operational conditions. These interdependencies add complexity to the problem of fouling and often lead to conflicting conclusions in literature. As a result, controversial results are commonly encountered, e.g., for the influence of biomass concentration, relative hydrophobicity and EPS on membrane fouling.

1.1. Biomass concentration or mixed liquor suspended solids (MLSS)

The impact of biomass concentration on membrane fouling has been examined extensively and in the early days of MBRs it was often considered as one of the main foulant parameters. However, with an increasing number of publications contradictory results are being presented. In the review paper of Le-Clech et al. [5], it is noticed that some authors report an increasing biomass concentration as a positive impact on membrane fouling, whereas others report a negative correlation whilst yet another group finds the influence of MLSS insignificant. More recently, also the existence of an optimal MLSS concentration range is suggested [6]. The lack of a clear correlation between MLSS concentration, which is basically the simplest parameter to measure, and any other foulant

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characteristics indicates that the MLSS concentration (alone) is a poor indicator for biomass fouling propensity [5].

1.2. Relative hydrophobicity (RH)

Membranes used in MBRs are typically made hydrophilic to improve their water permeability. Low hydrophobicity of sludge flocs is thus expected to cause high fouling due to stronger interactions with the membrane surface. Moreover, a decreasing activated sludge hydrophobicity results in floc deterioration [7] which on its turn again leads to severe membrane fouling [8]. In contrast, Meng et al. [9] found that the RH of activated sludge is positively correlated with membrane fouling.

1.3. Extracellular polymeric substances (EPS)

EPS have recurrently been labeled as the main cause for membrane fouling in membrane bioreactors. EPS are, by definition, of microbial origin and can be divided into two subclasses, i.e., extractable EPS (eEPS) and soluble microbial products (SMP) which are bound to the sludge flocs or free in the bulk solution, respectively. The composition and the amount of EPS, and thus their fouling propensity, are highly dependent on the condition of the activated sludge microbiology. An activated sludge under stress is known to produce more and/or other EPS [10]. Nonetheless, EPS is generally measured as such and no distinction is made between different fractions or compositions of EPS, e.g., sugars are usually measured as an equivalent of D-glucose according to the method of Dubois et al. [11]. Although some sugars cause more membrane fouling than others [12,13], most often no further classification is made between different types of polysaccharides. Since the actual fouling relevant fraction of EPS is still unknown, a standard method to measure this fraction does not yet exist [4] which leads to conflicting results for the reported impact of EPS on membrane fouling by different authors.

In our opinion, there are two main reasons why results in MBR research are often contradictory, i.e., (*i*) there is a lack of standardized methods for crucial analyses, like EPS and all its sub-fractions and (*ii*) most of the studied sludge characteristics are interconnected in one way or another to other sludge characteristics. For example, bound EPS serve as a matrix for microbial aggregates and are as such linked with bioflocculation, and thus with sludge morphology. Apart from that, some components present in the eEPS (e.g., proteins) strongly contribute to sludge floc hydrophobicity. On top of that according to Drews [4], depending on the applied method, the group of eEPS overlaps with other polymer fractions. This further stresses the need for (*i*) standard methods to be used for all MBR-related research and (*ii*) a broader approach for MBR-data interpretation trying to unravel some of the interdependencies of sludge characteristics in relation with membrane fouling. With this paper, we want to focus on the latter aspect.

The goal of this research is to unveil some of the black box features of activated sludge filterability. Ten different MBRs in Belgium and the Netherlands, treating both municipal (4) and industrial (6) wastewaters, were sampled in both winter and summer. The Delft Filtration Characterization method (DFCm) was chosen to determine activated sludge filterability [14], instead of calculating sludge properties from process permeability, i.e., flux and TMP, in each installation. The process permeability itself is a weak indicator for sludge filterability since it cannot be completely decoupled from, e.g., the operational history of the membrane. The DFCm on the other hand, is an off-line method in which the filtration behavior can be related exclusively to the fouling propensity of the activated sludge. Each sample was subjected to a set of activated sludge analyses, such as relative hydrophobicity, image analysis and EPS. The selection of parameters was based on state-of-the-art literature on membrane fouling in MBR.

The obtained relationships can help in pinpointing the main causes of fouling and can assist in implementing the correct remedial actions to improve process efficiency.

2. Methods and materials

2.1. Delft Filtration Characterization method (DFCm)

Delft University of Technology has developed a small-scale filtration characterization installation combined with a measuring protocol to investigate the activated sludge filterability [14]. The DFCm comprises several steps, from the determination of membrane resistance to the membrane cleaning. The main step of the DFCm is the activated sludge filtration step, a short-term experiment, performed in an installation (Fig. 1a) with the following characteristics. A single sidestream tubular ultrafiltration membrane tube (Norit X-flow, diameter = 8 mm, length = 1 m, membrane area = 0.025 m^2 and nominal pore size = 0.03 μm) forms the basic filtration system of the unit. A peristaltic pump is used for the activated sludge recirculation with a cross-flow velocity (CFV) of 1 m/s (single-phase flow). The permeate is extracted at a constant flux of 80 L/m^2 h. Activated sludge samples collected from different MBRs are filtered under identical operational circumstances. In this way, differences in filterability can be related, exclusively, to the properties of the MBR activated sludge sample.

During the filtration step, several parameters, such as, transmembrane pressure, flux, temperature and pH are monitored and stored in a computer data file using the software application Testpoint (National Instruments). The main output of an experiment is the evolution of the resistance during filtration. This resistance is calculated using Darcy's law. The filtration resistance is plotted as a function of the permeate production per unit of membrane surface. As a result of the fouling of the membrane during filtration, filtration resistance will increase. The slope of the curve gives an indication of the activated sludge filterability, e.g., a steep curve corresponds to poor filterability. For easy comparison between different tests, the value ΔR_{20} is used. This value is defined as the increase in resistance after a specific permeate production of 20 L/m^2 (Fig. 1b). Using MBR sludge with bad filterability, i.e., > 3.0, too high cake resistance resulted in permeate production less than 20 L/m^2. In those cases ΔR_{20} values were computed by mathematically extrapolating resistance build-up until a predicted total volume of 20 L/m^2 permeate was reached. For the interpretation of ΔR_{20} values, an adaptation of the classification proposed by Geilvoet [15] is used in this paper. The original classification comprised only 3 classes and was only based on experiments with municipal activated sludge samples, which usually have better filterability compared to industrial activated sludge samples. In this paper, both municipal and industrial samples were analyzed. Hence, the scale was extended with an additional low class with 3.0 as cut-off level.

Bad: $\Delta R_{20} > 3.0$
Poor: $1 < \Delta R_{20} < 3.0$
Moderate: $0.1 < \Delta R_{20} < 1$
Good: $\Delta R_{20} < 0.1$

2.2. Image analysis

A fully automated image analysis procedure, ACTIAS (ACTivated sludge Image Analysis System), is used for the characterization of the activated sludge composition [16].

All sludge samples are diluted to 1.0 gMLSS/L prior to microscopic analysis. The dilution is made with permeate to maintain the