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An experimental study on the impact of bioflocculation on activated sludge separation techniques

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ABSTRACT

Membrane bioreactors have become a well-established alternative for conventional activated sludge systems with a filtration instead of a sedimentation step to separate the sludge from the purified water. Both separation processes, however, depend on good bioflocculation for their performance. Small activated sludge constituents are known to be detrimental in activated sludge filtration, while poor settling can often be attributed to improper floc formation. Therefore, the aim of this paper is to further unravel the relationship between bioflocculation and activated sludge separation processes. To this end, synthetic influents with different mono-over-polyvalent (M/P) cationic compositions are used to create activated sludges with different morphologies and bioflocculation states during a 178 days experiment. The activated sludges were characterized by microscopic image analysis, relative hydrophobicity, extracellular polymeric substances, and were subjected to sedimentation, dead-end and submerged crossflow filtration tests. The deflocculating effect of a high M/P ratio is affirmed, inducing the release of colloidal material that caused severe fouling. Sludge flocs became empty and did not settle well. In the low M/P reactor, overall a better separation performance was observed but a non-expected filamentous bulking episode caused bad settleability and bad crossflow filterability, while dead-end filterability was good since a porous, well structured fouling layer was formed. Hence, it is concluded that dead-end filtration tests cannot asses sludge filterability in MBRs and that big activated flocs cannot contribute to the cake layer and cannot ensure its porosity in this way. Hydrophobicity was generally higher in the low M/P reactor but this might be attributed to an abundance of filaments during part of the testing period. No conclusive information could be extracted regarding the role of EPS, thus the use of EPS as a fouling or bioflocculation indicator is (again) questioned.

1. Introduction

Membrane bioreactors (MBRs) are becoming state of the art technology for communal and industrial waste water treatment, providing many advantages over conventional activated sludge systems, like a reduced footprint and effluent of consistently high quality, enabling direct potential reuse [25].

However, the main drawback of MBR technology remains the fouling, which is defined as the accumulation of rejected constituents in the retentate at the membrane surface. Fouling leads to higher operational costs through necessary control mechanisms, cleaning operations and membrane replacement. Preventing fouling can, therefore, strongly improve MBR water production efficiency [11].

Activated sludge filtration can be performed in two modi operandi. In dead-end filtration, the feed and permeate flow are in the same direction and all the feed's constituents are deposited on the membrane surface, creating an in depth filtration cake layer. Dead-end filtration can be used as a measure for mechanical activated sludge dewaterability and it is known from filtration theory and the Carman Kozeny equation that small and irregular grain sizes lead to a lower cake porosity and a higher cake resistance [7,20,41].

Crossflow filtration, although requiring energy for recirculation, is more suitable for MBR processes. In crossflow filtration, feed and permeate flows are perpendicular to each other. The mixing provides the necessary back transport to prevent most of the activated sludge from depositing on the membrane. In practice, semi-crossflow filtration is achieved in immersed MBR configurations where air scouring provides back transport to the fouling components at

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the submerged membrane. Side-stream configurations are operated in full-crossflow conditions but are generally less preferred than immersed configurations due to higher energy demands [25].

Membrane fouling can be attributed to three governing factors: membrane and module characteristics, operation conditions and feed and biomass properties, the latter being this work's focus [26].

Activated sludge bioflocculation, which specifies the process governing the equilibrium between floc growth/attachment and floc decay/detachment, is greatly affected by the influent's composition and feeding regime. E.g., intermittently feeding, leading to feast and famine cycles, has shown to produce sludge with a well balanced population of filamentous and floc-forming bacteria and good settling properties [9].

A group of feed components that exerts influence on bioflocculation, are monovalent and polyvalent cations. These cations and their relative abundance interact with the negatively charged functional groups present in the activated sludge and extracellular polymeric substances (EPS) [48].

Sobeck and Higgins [40] examined three theories for cation-induced bioflocculation, namely the alginate theory, the Dejarguin, Landau, Verwey, and Overbeek (DLVO) theory and the divalent cation briding (DCB) theory. Thus far, no study has proven the relevance of the DLVO-theory in MBR filtration, and while some studies have indicated the significance of the alginate theory, the majority of research affirms the potential of the divalent cation bridging theory, which states that polyvalent cations are able to form cationic bridges between negatively charged EPS constituents in activated sludge flocs, hence promoting bioflocculation. As monovalent cations would compete for these binding sites, and since they are not charged highly enough to form cationic bridges, a high amount of monovalent cations is deemed undesirable for bioflocculation [2,3,43,45,51].

Apart from *absorbing* or attaching fine material to the floc, preventing this material from floating around and foul the membrane, the interaction between floc size and fouling propensity can also be derived from a balance of forces. According to the crossflow filtration model of Broeckmann et al. [8], a particle near the membrane surface is subjected to two opposing forces: the permeation force, exerting suction towards the membrane and the aeration-induced drag force, providing back transport. As the influence of the latter increases with particle size, a maximum *cut-off* diameter can be calculated from the balance of forces. Only the particles that are smaller than this diameter are able to actively contribute to the fouling layer, while for larger particles, the effects of the drag force are high enough, such that they cannot stay on the membrane surface.

The extent of membrane fouling in MBRs can be assessed using an experimental flux-stepping method, where either the flux or the transmembrane pressure (TMP) is step-wisely increased and the resulting TMP or flux is measured [27].

The critical flux, another concept, was introduced by Field et al. [17] and was originally defined as the flux, below which no fouling occurs and above which fouling becomes significant. Two definitions were introduced based on the steady state flux-TMP profile, defining the critical flux as the flux for which this profile deviates from linearity. In the *strong form* definition, the slope for subcritical conditions was deemed equal to the slope found in the clean water profile, whereas in the *weak form*, a higher resistance was allowed due to initial resistance increase caused by adsorption and concentration polarization, which even takes place at very low fluxes [16].

However, as illustrated by Bouhabila et al. [5], measuring the critical flux in accordance with [17], is time consuming as for each flux, a steady state TMP has to be reached. Moreover, there is no guarantee this steady state TMP even exists or that it is stable in the long run.

In practice, there exists a maximum fouling rate for which the filtration is deemed economically feasible, and above which operational costs outweigh benefits. In this context, the sustainable flux has been introduced. For this flux, the TMP increases at gradual, acceptable rate, limiting the need for chemical treatment [4].

Two practical methods have been used, based on concepts introduced by Le-Clech et al. [28]. Both methods define a flux, which is often denoted as *critical*, but due to reasons described above, the term *sustainable* is more appropriate.

The first method defines a sustainable flux based on the maximum fouling rate, which can be defined as an increase in TMP or filtration resistance (R) during each flux value in the flux-step profile. Using an arbitrary TMP-increase of 10 Pa/min, this concept was demonstrated by van der Marel et al. [46].

The second method, as illustrated by Guglielmi et al. [19], defines the transition to unsustainability on the flux that leads to a permeability loss of more than 90%, using the average pressure obtained during the filtration step.

The aim of this research is to investigate the influence of bio(de)flocculation on activated sludge separation processes. Different M/P ratios are imposed to achieve different bioflocculation states. The resulting sludges are tested for settleability, dead-end and crossflow filterability to assess process performance for, respectively, classical sedimentation, dead-end dewatering and membrane bioreactor systems. Different assessment tools are exploited.

It has, however, to be stressed, that it is not the intention of this paper to explain why which bioflocculation state is induced; we merely want to establish significantly different bioflocculation states.

2. Materials and methods

2.1. Lab-scale activated sludge systems

2.1.1. Reactor set-up

Two 20 L lab-scale activated sludge systems, each connected to a 5 L conical settling tank, were seeded with activated sludge from a full-scale municipal waste water treatment plant. The reactors were continuously stirred and aerated, resulting in an average dissolved oxygen concentration of over 4 mg/L. On average, 1 L, thus 1/25th of the total reactor volume, was wasted on a daily basis, resulting in an SRT of 25 days. The pH was monitored on a daily basis and adjusted using 2 M NaOH or HCl when it deviated from 6 to 8.

2.1.2. Influent

Two synthetic waste water feeds were designed, based on the work of Van de Broeck et al. [43]. Table 1 depicts the feed

Table 1
Synthetic waste water feeds.

Feed 1 low M/P		Feed 2 high M/P	
Component	mg/L	Component	mg/L
$C_6H_{12}O_6$	4080	$C_6H_{12}O_6$	4080
Yeast extract	240	Yeast extract	240
$(NH_4)_2HPO_4$	347	$(NH_4)_2HPO_4$	901
$FeCl_3$	139	$FeCl_3$	14
$CaCl_2$	132	$CaCl_2$	91
NH_4NO_3	955	K_2HPO_4	3000
KCl	138	NaCl	120
Na_2SO_4	212	$MgSO_4{\cdot}7H_2O$	120
$MgCl_2.6H_2O$	602		
M/P	2.02	M/P	17.4
Ionic strength	23 mM	Ionic strength	28 mM