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Optimal backwashing in dead-end bacterial microfiltration with irreversible attachment mediated by extracellular polymeric substances production

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ABSTRACT

Microfiltration and ultrafiltration are methods of removing colloidal impurities from water and wastewater. One of the major issues when dealing with the practical implementation of membranes is the reduction of water productivity as the foulants accumulate on the membrane surface or within the pores. Membrane regeneration by periodic backwashing is an effective method of reducing fouling; however, to date the timing and duration of the backwashing for effective fouling control is largely only empirically determined.

In this manuscript, we present an optimal control formulation to determine the timing and duration for membrane regeneration by backwashing. In this formulation, we use the direction of the flow as the control variable and make predictions regarding the optimal protocol. We explicitly include irreversible attachment due to bacterial deposition and biofilm formation on the membrane and demonstrate that irreversible attachment of bacteria has important ramifications for the effective timing of hydraulic backwashes as well as the efficiency in producing clean water. In particular, we find that irreversible attachment and additional fouling due to exo-polymeric substance (EPS) production and biofilm formation decreases the maximum filtration volume. Additionally, as the effectiveness of membrane regeneration declines, the timing of the cycling is also altered. In general, including the role of EPS in biofouling substantially changes predictions of backwashing timing and implies important considerations for practical predictions.

1. Introduction

Dead-end microfiltration (MF) and ultrafiltration (UF) are used in a variety of industrial and municipal settings as efficient and practical methods for removing turbidity, microorganisms, and other colloidal pollutants [1–3]. During bacterial filtration, accumulation of microorganisms on the MF/UF membrane surface or within its porous matrix causes fouling [4,5]. In most environmental applications, the flow is periodically reversed, in the time frame of tens of minutes, to control what is operationally termed "reversible fouling" [6,7]. This procedure, variably referred to as backwashing, backflushing, or backpulsing removes a fraction of the accumulated foulant thereby partially regenerating the filter in the short-term [8–12]. The complementary portion of foulants that is not removed by backwashing contributes to irreversible fouling in the long-term [13–15]. Such foulants are removed by chemical cleaning when productivity drops below a predetermined acceptable level, which is performed typically over a time frame of weeks or months. In practice, the timing and duration of the backwashing cycles is determined empirically – often using proprietary scheduling algorithms developed by the manufacturer. Input is also provided by consulting engineers when on-site pilot-scale testing is performed in support of plant design or to comply with regulations [1].

Since the permeate water is used to flush the filter, frequent backwashing will decrease the net yield of filtered water. Therefore, one aim is to backwash as little as possible. However, when microfiltering bacteria, there is an additional difficulty if the backwashing cycles are too far apart, namely, the formation of a thick cake of irreversibly attached microorganisms on the filter in the form of a biofilm [16,17]. Although earlier work has

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demonstrated the effectiveness of backwashing to control fouling during filtration of colloids, bacteria, and natural water e.g. [6,7,12,15], in general, there is a lesser degree of understanding regarding the development, prevention, and optimal removal of biofilms formed on MF/UF membranes [18]. The aim of this manuscript is to extend our previous results to rigorously include the effects of biofilm formation on modeling the dynamics and optimal control of the filtration/regeneration process from a more basic standpoint.

Extracellular polymeric substances (EPS) fouling of membranes is a substantially complex phenomenon since flux decline is dependent on (i) the total concentration, conformation, and composition of each of its individual components including polysaccharides, proteins, lipids as well as nucleic, humic, and uronic acids, (ii) its spatial distribution within a multi-species biofilm, (iii) its interactions with other foulants present in the feed water, including microorganisms, and (iv) its propensity and ability to allow bacterial colonization of membrane surfaces [5,16,18,19]. EPS fouling mechanisms elucidated using simplistic model solutions [20,21] may not apply to fouling in the simultaneous presence of other non-EPS foulants and in a complex EPS mixture due to differences in the cake layer morphology/permeability caused by variations in foulant transport and interactions with membrane surfaces [22]. Similarly, insights gained from biofouling experiments with single bacterial species [16,23] also cannot be easily extrapolated to a more realistic scenario of fouling caused by multiple bacterial species due to differences in the rate of EPS secretion, the composition of EPS, and consequently its specific interactions with the membrane surface.

The main determining factor for the development of irreversibly attached bacteria is the formation of a biofilm. Biofilms consists of microorganisms enmeshed in EPS along with other particulate matter within the bulk water [24,25]. EPS facilitates cohesion and adhesion, hydration, and protection of the embedded microbes from predators. Biofilm dynamics have been widely studied because of their impact in disease transmission, corrosive properties, and most importantly their tolerance to disinfection [26]. These investigations have shown that it is very difficult to remove an established biofilm using physical or chemical means. Typically, the biofilm typically grows back in a short time once the challenge to the bacteria (antibiotics, biocides, or mechanical scraping) is stopped. Therefore it is vital to prevent the biofilm formation rather than try and treat the established biofilm [18]. Consequently, we have proposed to time backwashes before 'significant amounts' of EPS are secreted and bacteria are irreversibly attached to membrane surfaces [16,17,27,28]. More importantly, we show here that the timing can be estimated using an optimal control formulation.

We note that mathematical treatment of membrane fouling has a relatively long history [29]. One frequent approach consists of empirically driven, blocking-laws that describes the dynamics of the volume of filtered water as the flux or pressure changes [30,31]. The goals of these models are to estimate the power law relationship based on experimental observations and thus to diagnose the fouling regime. This is useful in industrial and municipal settings by troubleshooting fouling and helping point to intuitive changes in the filtration regime. However, these models cannot typically be used to predict the fouling behavior for a wider range of settings and are not simple to use for mathematical optimization. Recently, we introduced a more rigorous model that describes the change in flux with respect to time, accounting for the reduced flux due to foulant accumulation during constant pressure filtration [32]. This model can also be adjusted to describe the change in the pressure during constant flux operation [27]. The former is more often used in laboratory/bench models while the latter is more often used in practical applications. Using optimal control theory, we were able to propose the backwashing protocol that optimizes the total volume of clean water which is the main control target used in industry [28]. This model captures the experimental data quite well; however, we neglected irreversible attachment, assuming that backwashing was able to remove all of the accumulated foulant, regardless of its residence time on the membrane. In the present study, we demonstrate the effect of irreversible attachment on the optimal control analysis of our model.

Previously, we described the fouling and regeneration process as a two- step process, controlled by a control variable u which denotes the direction of the flow. The flow changes direction during backpulsing so $u = u(t)$ is an explicit function of time [28]. Forward filtration is represented by $u=1$, while flow reversal was described by $u = -1$. In constant pressure operation, accumulation occurs during forward filtration at a rate proportional to the flux, which is proportional to the transmembrane pressure drop. The proportionality parameter is the inverse of resistances (resistance in series model) which is related to the foulant on the filter. In regeneration, we assumed that foulant was removed from the filter at a rate proportional to the flux, and that this proportionality was constant. Constant flux operation is represented similarly, with the pressure related to the flux by inverting the resistance in series relation. Here extend our analysis to include irreversible attachment of bacteria by way of EPS formation. EPS affects the system in two primary ways. First, accumulation of EPS on the membrane filter reduces the flux of fluid through the filter by increasing the total resistance to water transport. Second, EPS immobilizes the bacteria and other foulants onto the filter, hindering detachment during flow reversal. Therefore, we also need a description of EPS production. In the next section, we describe the experimental protocol that we use to determine the EPS dynamics that are additional in this study. We then introduce our mathematical model and the framework of optimal control. Following that we describe the implications of EPS formation. We compare our optimal control trajectories with those where regeneration is independent of EPS. When the EPS affects the flux (which it almost surely does) the optimal solution is similarly distinct. Finally, we close the manuscript with some remarks regarding directions that remain to be explored.

2. Mathematical model

Based on our previous study [28] the filtration and regeneration processes are initially described separately. During the forward filtration process, the accumulation of bacteria, B is proportional to the raw water flux through the membrane, J:

$$\frac{dB}{dt} = KJ. \tag{1}$$

where K is a constant that describes the water quality. Very high K indicates rapid fouling, e.g. induced by poor water quality.

If we assume the filter is initially clear of bacterial foulants, we have an initial condition:

$$B(0) = 0, \tag{2}$$

The flux, J, is assumed to be proportional to the pressure differential, ΔP, and inversely proportional to the resistance on the membrane. This is similar to the empirical descriptions developed by others [33]. Here, three kinds of resistance are considered: R_m, the resistance generated by clean membrane; R_b, the resistance generated by bacteria; and R_e resistance from EPS (denoted E). The flux is: