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Deposition of extracellular polymeric substances (EPS) and microtopographical changes on membrane surfaces during intermittent filtration conditions

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Abstract

Extracellular polymeric substances (EPS) play a significant role in modifying surface characteristics, eventually creating conditions suitable for bacterial attachment. The purpose of this study was to investigate the fouling potential of the EPS present in the effluent of an aerobic membrane bioreactor during intermittent filtration conditions. The aerobic rotational membrane system (ARMS) is a novel compact reactor which is designed to convert ammonia nitrogen in concentrated wastewater to nitrates with high conversion rates. The effluent from the reactor contains significant amounts of dissolved substrates which include EPS produced by the biofilm and salts. A series of cross-flow filtration tests were conducted with intermittent once a day short filtration periods using SEPA CFII membrane test cell and an RO membrane. The intermittent tests runs were conducted for overall filter use times of 1, 2, 4, and 6 days. Progression of the microtopographical changes, amount of EPS accumulation, and flux characteristics were evaluated. The images taken by atomic force microscopy (AFM) showed a layer of soft deposits forming over a strong sublayer firmly covering the membrane surface within a short time. The sublayer consisted of distinct modular units which were firmly attached to each other and to the membrane surface. The amount of EPS deposited on the membranes increased with use time and the membranes became significantly hydrophilic. The membrane flux declined gradually after each daily intermission until the 5th ± 1 day, then a small increase in flux was observed. The flux increase may be due to dislodging of some of the deposited material from the membrane surface due to shearing during cross-flow filtration conditions.

Keywords: Extracellular polymeric substances (EPS); Soluble microbial products (SMP); Biofouling; Membrane morphology; Reverse osmosis; Intermittent filtration; Atomic force microscopy (AFM)

1. Introduction

Membrane fouling is one of the key limitations of thin-film membrane processes for long-term use. The fouling process gradually reduces the membrane flux, eventually leading to bacterial attachment, and structural failure of the membrane. In aqueous systems, fouling is caused by sorption and trapping of the substrates on the membrane surface and within the membrane matrix. During reverse osmosis, the filtration takes place by transport of water molecules through the molecular matrix of the membrane. The extent of membrane fouling is often quantified by loss of flux below a "critical flux" value. However, the flux decline is detected at the advanced stages of fouling after the membrane morphology is significantly altered and a significant fraction of the channels within the lattice structure of the membrane loose their ability to transport water molecules.

The nanoporous morphology of membranes provide suitable characteristics for molecular deposition which eventually leads to bacterial attachment [1]. The biofouling process initially starts with the deposition of substrates such as extracellular polymeric

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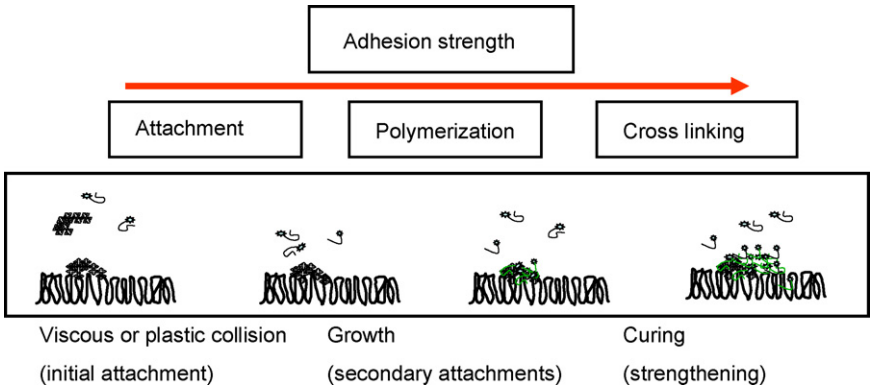

Fig. 1. Progression of EPS deposition on membrane surface.

substances (EPS) which form a highly hydrated nanogel layer on the membrane surface. EPS, also referred as soluble microbial products (SMP) in the literature, are large molecular weight compounds that are excreted by bacteria [2–5] and play a significant role in bacterial adhesion onto solid surfaces by altering the physicochemical characteristics such as charge, hydrophobicity, and the polymeric properties [6–10]. Experimental studies with bacterial cultures show that when the EPS concentration is low, cell adhesion onto solid surfaces is inhibited by electrostatic interactions. However, when the EPS concentration is increased, cell adhesion is enhanced by polymeric interactions [11]. EPS also create scaffolds with suitable physical characteristics and interconnected pore structures that promote cell attachment, proliferation, and differentiation [2,12–14]. The forces of interaction between the membrane surface and EPS may be physical (adsorption), chemical (covalent bonding), or electrostatic (van der Waals forces). The roughness characteristics of the membrane surface can change the surface forces by orders of magnitude. The compatibility of the molecular dimensions of EPS and the membrane roughness define the distribution of asperities at points of contact and the adhesion strength. Recent studies show that there exists an optimal shape of the contact surface and an object which result into optimal adhesion to a substrate via molecular interaction [15]. However, the contact angle limitation can be overcome by size reduction and as the size becomes smaller the shape becomes less important for attachment [16].

The presence of active groups within the membrane matrix determines the ability of the membrane material to form bonds with water and other substrates. The greater the tendency for a material to associate with water (i.e., through hydrogen bonding) the more hydrophilic the membrane becomes. Hydrophilic membranes have higher water fluxes than hydrophobic membranes and generally preferred for water treatment applications. Hydrophilicity influences the wettability and adhesion characteristics of substrates to the membrane material [17,18]. Hydrophobic substrates tend to form clustered groups to lower the interfacial free energy and also show higher tendency to deposit on surfaces. Due to their bioadhesive characteristics and flexible molecular structures, EPS exhibit both wetting and cross-linking functions. The interactions between water, EPS, and membrane result into anchoring of the EPS to the membrane surface. As the EPS accumulation increases on the membrane, the deposited substrates form a stronger matrix by cross-linking to form a gel layer on the membrane surface as shown in Fig. 1. The gel layer offers an environment that is rich in nutrients with active groups which make it possible for bacterial attachment. EPS may contain both hydrophilic and hydrophobic sites on its chemical structure and enable the polymer to deposit on both hydrophilic and hydrophobic surfaces as shown in Fig. 2. Although the initial adhesion mechanisms of the polymer may be different; the bonding strength increases over time due to flexibility and cross-linking of EPS on the membrane surface. The ability of EPS to effectively stick to wet surfaces indicates that some of the water molecules within the EPS matrix can easily be replaced with the water molecules on the membrane surface.

The operational parameters such as quality of feed stream, temperature, pH, filtration cycle time, and cross-flow velocity may affect the rate of membrane fouling. Because EPS play a significant role on modifying surface characteristics which eventually lead to bacterial attachment, it is important to understand the morphological changes caused by EPS accumulation during the initial stages of fouling. Understanding of the adhesion mechanisms of EPS on membrane surfaces will allow development of technologies to reduce biofouling rates of membranes. Atomic force microscopy (AFM) has been used for determination of surface roughness of flat sheet membranes [17,19]. The purpose of this study was to investigate the fouling potential of the EPS present in an aerobic bioreactor effluent, and evaluate the morphological changes on the membrane surface during intermittent filtration conditions. A series of cross-flow filtration tests were conducted as intermittent once a day short filtration runs

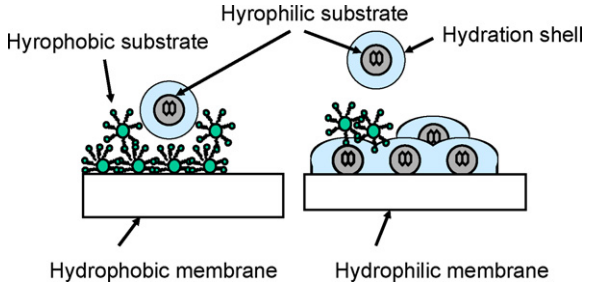

Fig. 2. Adhesion mechanisms of hydrophilic and hydrophobic substrates on membrane surfaces.