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Gravity-driven membrane system for secondary wastewater effluent treatment: Filtration performance and fouling characterization

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ABSTRACT

Gravity-driven membrane (GDM) filtration is one of the promising membrane bioreactor (MBR) configurations. It operates at an ultra-low pressure by gravity, requiring a minimal energy. The objective of this study was to understand the performance of GDM filtration system and characterize the biofouling formation on a flat sheet membrane. This submerged GDM reactor was operated at constant gravitational pressure in treating of two different concentrations of secondary wastewater effluent. Morphology of biofilm layer was acquired by an *in-situ* and on-line optical coherence tomography (OCT) scanning in a fixed position at regular intervals. The thickness and roughness calculated from OCT images were related to the variation of flux, fouling resistance and permeate quality. At the end of experiment, fouling was quantified by total organic carbon (TOC) and adenosine tri-phosphate (ATP) method. Confocal laser scanning microscopy (CLSM) was also applied for biofouling morphology observation. The biofouling formed on membrane surface was mostly removed by physical cleaning confirmed by contact angle measurement before and after cleaning. This demonstrated that fouling on the membrane under ultra-low pressure operation was highly reversible. The superiority and sustainability of GDM in both flux maintaining and long-term operation with production of high quality effluent was demonstrated.

1. Introduction

Membrane bioreactor (MBR) technology, a combination of biological treatment with membrane filtration, has got an enhanced application in wastewater treatment and reclamation over the past two decades [1]. With several advantages such as higher quality of effluent and lower footprint, the global market of MBR was expanded with a compound annual growth rate (CAGR) of 11.2% through 2005–2015, and further it is expected to be $777.7 million by 2019 [2,3]. Among different process configurations, the submerged (or immersed) MBR is the mostly used one, which allows less energy consumption and more compact installation, and thus has possessed 98% of global MBR market [3].

Nevertheless, compared to biological treatment processes, the conventional MBR is to some extent constrained in higher capital equipment and operating costs such as cleaning and fouling control. Thus, researches on novel MBR configuration and reactor designs have been conducted to promote MBR technology into more feasible and practical implementation [4].

Gravity-driven membrane (GDM) filtration system is one of the beneficial submerged MBR developed configurations. It has a wide spectrum for water treatment, including diluted wastewater and surface water with variable contaminant levels and mainly shows attractive potential in water reuse or seawater pre-treatment [5]. The GDM filtration was firstly tested by the Swiss Federal Institute of Aquatic Science and Technology (Eawag) [5–7]. The system is operated under ultra-low pressure (40–60 mbar) with less maintenance compared to traditional membrane filtration systems such as ultrafiltration (UF) [8,9]. In a lab-scale test, the flux stabilization in the range of 2–20 L/m^2 h was reached without the need of backwashing [10,11]. The viability of GDM filtration has been proved considering the scarcity of energy and stricter regulations in wastewater treatment. The increasing capacity and broaden application of MBR also calls for centralized robust systems and facilities, which are often insufficient in developing and transition countries, causing lack of adequate and microbiologically safe drinking water in these areas. Solutions to safe water supply in these regions have been proposed in decentralized forms such as

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ground water wells and point-of use (POU) systems [9]. Feasibility of these solutions has been verified in a slice of specific areas, but still failed in worldwide application in terms of either heavier burden on construction or unreliability of water quantity and quality. Thus GDM, as an energy-saving approach, can play an important part in both advanced wastewater and household tap water treatment.

The inevitable membrane fouling is a typical problem in all membrane filtration applications. Membrane fouling is mainly resulted from both pore blocking and cake layer formation, especially in UF and microfiltration (MF) systems, where the pore blocking is caused by colloids and soluble organics such as extracellular polymeric substances (EPS), and cake layer is caused by large particles like sludge flocs [12].

The membrane fouling is of great interest in GDM research. A previous study assumed that at early stage, the pore blocking dominates the flux drop, while then the stable flux in GDM filtration was attributed by the cake layer formation on the membrane surface in expanded operation time [13]. Besides, while operated under dead-end mode with quite low TMP, the mechanism of membrane fouling in GDM can be different from that in normal MBR, which is usually equipped with pumps for extra pressure [10,11]. Moreover, studies about fouling mechanism in GDM will provide the fundamental information for optimizing the GDM system and achieving its practical application.

The effluent (or permeate) quality is also used for evaluation of filtration systems. The composition of effluent shows indirectly the retained substances by the filtration process by comparing with influent and reflects the filtration performance. In this regard, liquid chromatography-organic carbon detection (LC-OCD) has been used as an effective tool to analyze colloidal and soluble organics in solutions [14,15]. Furthermore, biofouling characterization can be carried out by quantification of attached biomass in terms of adenosine triphosphate (ATP) and organic foulants in terms of total organic carbon (TOC) [16–18]. Fouling can be evaluated by measuring membrane surface properties such as hydrophobicity and hydrophilicity, which can be determined by contact angle. The contact angle measurement can also assess the fouling reversibility before and after cleaning [19].

Direct observation of biofouling structure on membranes is straightforward. In this way, various observation techniques have been widely reported. Confocal laser scanning microscopy (CLSM) yields images to display the morphology and composition of biofouling, showing different constituents such as proteins and polysaccharides by fluorescent staining [20]. However, sample preparation such as drying and staining also mechanically changes the morphology and components distribution of fouling layer [21,22]. For this reason, some on-line imaging techniques have also been proposed. Among them, optical coherence tomography (OCT) has been used in biofilm monitoring in many studies, which surpasses others as an on-line, *in-situ* and non-destructive observation technique by maintaining the original appearance of object [23–24]. OCT was used to assess the impact of the biomass deposition on the flux decrease at early stage [25]. In spacer filled channel the image analysis of OCT scans enabled the spatial distribution of the biomass [26–27]. The innovation facilities the acquirement of authentic information of biofilm for quantitative analysis in the thickness, roughness and porosity of fouling layers [10]. The *in-situ* observation also allows repeated and continuous investigation, providing the dynamic development of biofouling for further studies of fouling mechanisms [23,25–28].

Recent researches on GDM system are mostly limited to applied aspects of different processes such as seawater pretreatment and surface water treatment. For example, Peter-Varbanets et al. studied the flux stabilization in a side-stream GDM system. They found that the stable flux was attributed to the deposition and formation of non-dissolved material and irremovable fouling, as well as the structure changes of fouling caused by biological activities [5,6]. They also tested the intermittent operation in treating river water by ultra-low pressure ultrafiltration, and confirmed its role in leading to higher fluxes [7]. Akhondi et al. explored the influence of different temperature and hydrostatic pressure on flux variation and fouling structure in a side-stream GDM ultrafiltration system for seawater pretreatment. The results showed the improved temperature and gravity pressure both contributed to higher flux in an extended operating time, where cake layer has predominated fouling on membranes. Besides, the general structural change of fouling had also been described and was suggested to be an explanation of permeate flux [13]. Wu et al. also studied the seawater pretreatment by GDM but in a submerged system. In this research, the stable flux was related to different system configurations, membrane types and prefiltration, likewise the fouling mechanisms. These studies provide information about the flux and fouling performance from different aspects, but only a few mentioned about wastewater treatment. Hence, more detailed and on-line information are required for better understanding of filtration and fouling mechanisms in GDM system.

The objective of this study was, therefore, to evaluate the filtration performance and fouling aspects in a submerged GDM system using UF membrane under ultra-low pressure. The flux variation and permeate quality was measured at regular intervals to assess the filtration performance. By using OCT, the on-line fouling development was monitored and related with the performance, as well as the formation rate, in terms of thickness and cake layer resistance, could be obtained. The fouling characterization was also carried out at the end of operation.

2. Materials and methods

2.1. Set-up and operation of submerged GDM system

A customized ultra-low pressure GDM system was used in this study with two following experiments (Fig. 1). A flat sheet, polysulfone (PS) UF membrane with 20 kDa molecular weight cut-off (MWCO, PHILOS, Republic of Korea) was immersed upright in a polymethyl methacrylate (PMMA) filtration tank of 70 cm height. Effective membrane area was 0.0045 m^2 (0.09 m $\times$ 0.05 m). The OCT probe was mounted on a motorized frame (Welmex) to monitor the membrane and biofouling formation, allowing the movement in x, y and z directions as accurate steps in micrometer scale.

During the experiment, the system was operated under dead-end mode at constant temperature (20 ± 1 °C). A synthetic secondary wastewater effluent was used as feed solution to grow the biofilm on the membrane according to Nopens et al. [29]. A 0.5 mL activated sludge collected from a lab aerobic activated sludge system was added into the tank at the beginning to enhance the formation of biofilm. Based on different dilution ratio, the chemical oxygen demand (COD) of feed solutions used in two experiments were 15 mg/L (E1) and 7.5 mg/L (E2), respectively. Total organic carbon (TOC) concentration of two feed waters were 4.9 ± 0.2 mg/L (E1) and 2.6 ± 0.1 mg/L (E2). The feed water was pumped into a level regulator to keep a constant level of water head in the tank, which is 45 cm above the membrane. Thus the gravity pressure was constant at 45 mbar. The permeation water was collected from the bottom of the tank. The whole system was covered with aluminium foil to avoid the growth of algae. GDM operation was continued for 6 weeks and 7 weeks, respectively in E1 and E2. The feed solution was refreshed every week.