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# Fouling indices for low pressure hollow fiber membrane performance assessment

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ABSTRACT

This study evaluated the use of fouling indices to describe low pressure membrane fouling. One critical aspect of this study was the use of a bench-scale hollow fiber membrane system that imitated full-scale operation (constant flux with automatic hydraulic backwash and chemical cleaning). Fouling indices were based on a resistance-in-series model. Two different hollow fiber membrane types (membrane A and B) were tested with water from two water utilities (A and B) and three other natural sources (oligotrophic, algal bloom impacted, and wastewater impaired). The bench-scale testing included use of the same membrane as utilized at Utility B. Most fouling was reversible by hydraulic backwash and chemical cleaning. Specific flux and fouling indices for the bench-scale system were higher than those determined from full-scale data but fouling index ratios were comparable, suggesting a similar fouling nature. At similar organic loading, fouling was specific to water source and membrane type, i.e., no generalization on the impact of water source was possible. Full-scale data were compared with bench-scale data to validate the use of fouling indices. Fouling indices based on a resistance-in-series are useful tools to describe membrane performance data for both raw and pretreated water, for different water sources, and different membrane types.

## 1. Introduction

A significant technical challenge for membrane processes is membrane fouling, manifested at full-scale by the increase in required operating pressure to maintain a targeted water production rate. Fouling includes the short term and reversible increase in transmembrane pressure (TMP) due to the accumulation of rejected materials that cannot be avoided in the dead-end mode operation of low pressure (LP) membranes. Irreversible fouling, hydraulic and chemical, is the longer-term loss of permeability not recoverable after hydraulic backwash (BW) or chemical cleaning (CC).

Although different fouling types (reversible versus irreversible, hydraulic versus chemical) are well defined in the literature, results reported from bench-scale fouling studies conducted in laboratories have generally not reported different fouling types. These studies were often conducted at conditions not typical of full-scale practice (not including hydraulic BW and/or CC), use of flat-sheet membranes at constant pressure operating mode instead of using hollow fibers (HF) at constant flux operating mode, or use of a crossflow system instead of dead-end as used at full-scale (Crozes et al. (1997), Tarabara et al. (2002), and Howe et al. (2007)). Due to the complex nature of membrane fouling, changing

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one component of a membrane system can drastically change membrane performance and make the bench-scale data far from applicable to realistic practice. It is therefore critical to conduct studies at controlled conditions, as well as simulating those at full-scale.

Most membrane fouling by natural water sources involves natural organic matter (NOM). Inconsistent results have been reported in the literature regarding membrane fouling by NOM, possibly due to different testing conditions, with many deviations from full-scale practice. Different measures of NOM, including total organic carbon (TOC), total nitrogen (TN), dissolved organic nitrogen (DON), ultraviolet (UV) absorbance, NOM molecular weight distribution, and NOM source have been found to have certain impacts on membrane fouling but no single characteristic has been demonstrated to control fouling (e.g., Lee et al. (2004, 2006), Lozier et al. (2008)). More likely, complex interactions between characteristics of the water, membrane material, and system configuration that vary from site to site are responsible for fouling. For instance, Huang et al. (2008b) found that both particle size and stability were important in fouling. Higher TOC and DON levels have also been reported to cause more severe fouling of low-pressure membranes (Lozier et al. (2008)).

Fouling indices have been developed by means of simple, short, empirical filtration tests to quantify the level or degree of membrane fouling. The silt density index (SDI) is a widely used fouling index for reverse osmosis (RO) membranes. The modified fouling index (MFI) (also used for RO membranes) has been reported to be insensitive to the presence of smaller particles and an unsatisfactory correlation with colloidal fouling has been observed for full-scale membrane installations (Boerlage et al., 1998, 2003). The MFI-UF (tested with a polyacrylonitrile 13 kDa UF membrane) was developed to account for the presence of smaller particles but at constant pressure (Boerlage et al., 1998, 2003). Many researchers have attempted to attribute membrane fouling to one of several mechanisms, including blockage of membrane pores at the membrane surface, development of a cake layer at the membrane surface, and adsorption of matter within the membrane pores, using equations summarized by Hermia (1982) and extended by numerous other researchers. This approach to fouling, known as the blocking laws, has several limitations, including that the original model was derived for constant pressure, declining flux operation, and that the model assumes that only one of these mechanisms is active at any given time in the operation cycle, whereas in full-scale operation it is likely that several fouling mechanisms might occur simultaneously. Thus, the blocking laws have not had predictive value for relating bench-scale results to full-scale operation.

Recently, a group of researchers (Jacangelo et al. (2006); Lozier et al. (2008); Huang et al. (2008a,b, 2009)) proposed a unified modified fouling index for low pressure membrane performance assessment at constant flux. The original model was based on cake layer formation to determine a reversible fouling index and on intermediate pore blockage to determine an irreversible fouling index. The newer version presented in Lozier et al. (2008) and Huang et al. (2009) assumed fouling is solely caused by the formation of a cake layer. Different types of fouling indices could be calculated using different data, with or without hydraulic backwash or chemical cleaning. A question remaining is whether bench-scale and full-scale data are comparable.

This paper focuses on further development and validation of fouling indices to assess membrane performance. Fouling studies were conduced at bench-scale while simulating full-scale conditions. The fouling indices were based on a resistance-in-series model. A key feature of this development is that fouling is not attributed to a specific mechanism so the model can be valid regardless of whether cake filtration, pore constriction, or some combination of fouling mechanisms is occurring. Different types of fouling were clearly defined and described. The validated fouling indices were then used to describe membrane fouling and compare performance of two different membrane types tested with three different characteristic waters normalized to similar organic loading (TOC and DON/DOC). The work is part of a recent larger study of low pressure membrane fouling (Nguyen (2010); Tobiason and Nguyen (2011)).

## 2. Materials and methods

### 2.1. *Water sources and membrane properties*

Waters from two water utilities (plant A and B) and three other natural surface water sources were used. Both raw and coagulated waters from water treatment plant A were tested. This water was colored (30–40 color units, CU) with moderate TOC (3.5 mg/L). Utility B used the same membrane (membrane A) as the one used for some of the bench-scale tests. The membrane feed water was coagulated with alum and mixed with backwash water (90%–10%, respectively). This water had moderate TOC levels (3.8 mg/L and 4.9 mg/L for the raw and membrane feed water respectively; full-scale recycle may have caused higher TOC in the membrane feed water). Three natural water sources with different NOM origins (oligotrophic, algal impacted, and wastewater impaired) but with similar NOM concentrations achieved by dilution with DI water (2 mg C/L and 1/17 DON/DOC ratio) were tested. Table 1 summarizes the quality of all water sources utilized in this study.

Two commercial membranes, named membrane A and B, were utilized for the research project. While membrane A was utilized throughout this study, membrane B was used only for the experiments with 3 natural water sources. Both membranes are hollow fiber, outside-in type, and have PVdF base material. The membrane characteristics are shown in Table 2.

### 2.2. *Membrane module and system*

Mini membrane modules were fabricated in the laboratory using the two types of hollow fiber membranes. A semi-rigid clear plastic tube 25.4 cm long and 1.3 cm diameter was used as the membrane housing. On one end of the tube the gap between the membrane fibers and the membrane housing was sealed by epoxy; this end served as the permeate collection and backwash feed side. At the other end, the fibers were potted/sealed by either injecting epoxy inside the lumen of each fiber or deadended together. This allowed one end of the membrane module to be open for better removal of solids during backwashing. This potting technique also made it