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Evaluation of ultrafiltration process fouling using a novel transmembrane pressure (TMP) balance approach

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ABSTRACT

The successful operation of ultrafiltration (UF) membrane processes is dependent on the ability to assess and manage membrane fouling, because membrane fouling reduces process efficiency and results in increased operation and maintenance costs. An evaluation of current fouling characterization methods identified limitations with the use of specific flux and transmembrane pressure (TMP) for interpreting fouling trends. This paper proposes that fouling characterization may be improved by distinguishing between the membrane and associated foulants. A new TMP balance approach has thus been developed that quantifies the pressure loss associated with foulants as well as membrane deterioration and facilitates the direct comparison of membrane fouling at different flux values. A method for presenting TMP balance data relative to filtration, backwash, CEB, and CIP events is also discussed that enables the TMP balance to differentiate between physically and chemically unresolved membrane fouling. The TMP balance approach is demonstrated using over 7000 h of runtime data from an UF pilot filtering conventionally pretreated surface water.

1. Introduction

Membrane fouling is a major operating challenge for ultrafiltration (UF) membrane processes [1–4] in drinking water treatment, and successful operation is dependent on the ability to manage fouling through the incorporation of pretreatment [5,6], the selection of operating parameters [7–10], and the implementation of chemical cleaning regimes [11–16]. To effectively implement fouling management strategies, it is necessary to monitor membrane fouling through the interpretation of process data. Standard practice for constant flux membrane processes currently expresses fouling in terms of pressure via transmembrane pressure (TMP) or specific flux calculations.

TMP is a function of the pressure drop across the membrane barrier and is commonly used to assess membrane fouling in laboratory scale experiments [17,18], pilot investigations [19–21], and full-scale applications [22]. In UF processes, the TMP is calculated using Eq. (1) for direct filtration operation, and the feed pressure (P_{feed}) is influenced by the membrane material, fouling development, water flux, and water temperature. A generic temperature correction factor (TCF) may be applied to calculate the temperature corrected TMP (TCTMP) (Eq. (2)) that accounts for the effects of water viscosity by normalizing to a standard temperature of 20 °C [23,24], and manufacturers often develop membrane specific TCFs that also account for the influence of water temperature on the membrane material [25]. A variety of operating decisions may be based on TMP including the selection of backwash and cleaning intervals for fouling management [26,27].

$$\mathrm{TMP} = P_{feed} - P_{filtrate} \tag{1}$$

$$\mathrm{TCTMP}_{20\,^\circ\mathrm{C}} = \mathrm{TMP}_t(\mathrm{TCF}) = \mathrm{TMP}_t\left(\frac{\mu_{20\,^\circ\mathrm{C}}}{\mu_t}\right) \tag{2}$$

where $\mathrm{TCTMP}_{20\,^\circ\mathrm{C}}$ is the TMP temperature corrected to 20 °C, bar, TMP_t is the TMP at temperature t, bar, $\mu_{20\,^\circ\mathrm{C}}$ is the absolute viscosity at 20 °C, cP, μ_t is the absolute viscosity at temperature t, cP.

The specific flux is calculated by normalizing the flux (Eq. (3)) for temperature and pressure, as shown in Eq. (4). The resultant calculation reports the volume of water filtered per unit of surface area and pressure drop. When membrane fouling occurs, the specific flux decreases as a result of a corresponding TMP increase. In drinking water membrane applications, specific flux calculations are frequently used to monitor membrane fouling during both pilot-scale evaluations [28–30] and full-scale water treatment [31,22].

$$J_t = \frac{Q}{A} \tag{3}$$

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$$J_{SP} = \frac{(J_t)(\mathrm{TCF})}{\mathrm{TMP}_t} \tag{4}$$

where J_t is the flux at temperature t, L/m^2-h, Q is the volumetric flow rate, L/h, A is the membrane surface area, m^2, J_{SP} is the specific flux, L/m^2-h-bar

There is a limitation with the use of specific flux for characterizing the performance of low pressure UF processes. Fig. 1 presents the relationship between specific flux and TMP assuming a constant flux and membrane surface area. The figure demonstrates that the specific flux calculation, which is a function of TMP, is mathematically non-linear over the typical TMP range for drinking water UF processes. As TMP values are input into the specific flux equation (Eq. (4)), the specific flux decrease exponentially, and this non-linearity means that small changes in TMP result in disproportionate changes to the specific flux. Using Fig. 1 as an example, an increase in the TMP from 0.138 bar to 0.207 bar represents a 0.069 bar change in TMP and a 153 L/m^2-h-bar change in specific flux; whereas, an increase in TMP from 0.345 bar to 0.414 bar again represents a 0.069 bar change in TMP but yields a specific flux change of 30.5 L/m^2-h-bar. The significance of specific flux non-linearity at low TMP values is that it complicates the interpretation of specific flux data for assessing membrane fouling. In other words, specific flux trends may give a false impression of fouling severity, because a 10 L/m^2-h-bar change at 0.138 bar does not have the same meaning as a 10 L/m^2-h-bar change at 1.03 bar. Data analyses using ratios such as J_{SP}/J_{SP0} or TMP/TMP$_0$, where J_{SP0} and TMP$_0$ are reference values, also suffer from the non-linearity limitation.

In addition to the mathematical limitation of specific flux, both specific flux and TMP share a common limitation as fouling assessment tools in that neither metric distinguishes between the physical membrane and the foulant layer. This paper suggests that improvements in membrane process operation may be achieved by modifying the manner in which UF process data is compiled, analyzed, and reported. Accordingly, a new method termed the TMP balance is presented that quantifies the pressure contribution of foulant material at the membrane surface [32]. The TMP balance provides a new tool to improve the interpretation of pressure data for the identification and management of membrane fouling. Operating data from a constant flux, direct filtration drinking water UF pilot test is used to demonstrate the usefulness of this new method.

2. Materials and methods

2.1. Development of the TMP balance equation

TMP is dynamic during the operation of membrane processes as foulants accumulate and separate from the membrane surface and pore structure. Once normalized for temperature, TCTMP values are affected by foulant deposition and removal during filtration, backwash, CEB, and CIP process events. The TMP balance approach chronologically organizes TCTMP data in terms of these process events by classifying TCTMP data according to number (i), sequence (J), cycle (K), period (L), and flux case (M). As graphically illustrated in Fig. 2, an operating sequence consists of consecutive filtration and backwash events; whereas, an operating cycle is comprised of a series of sequences culminating in a chemically enhanced backwash (CEB). Operating periods contain multiple cycles before culminating in a chemical clean-in-place (CIP) event, and further classification of TCTMP data may be made according to the flux case if the flux set-point is changed during the operation of a constant flux processes. Thus, given the standard nomenclature TCTMP$_{ijklm}$, the second recorded TCTMP value in the first sequence, cycle, period and flux case of a data set would be written as TCTMP$_{21111}$.

TMP balance values identify the pressure loss associated with membrane fouling and structural deterioration by subtracting the intrinsic membrane pressure loss from the total TMP (TMP$_T$). The basis for the TMP balance approach is a new pressure-in-series concept derived from the resistance-in-series model. In the literature, resistance-in-series is commonly used to describe membrane fouling [14,33,34] by defining the total flow resistance as the summation of individual resistance factors. This paper describes total flow resistance by incorporating a standard intrinsic membrane resistance factor (R_M), a new delta intrinsic membrane resistance factor (ΔR_M), and a generic fouling factor (R_F) into the modified Darcy's law equation (Eq. (5)). The ΔR_M term recognizes that physically and chemically [35,36] induced membrane structural changes occur over time that modify flow resistance. These structural changes are therefore a relevant factor affecting the TMP$_T$ during operation.

$$J_t = \frac{Q}{A} = \frac{\mathrm{TMP}_t}{\mu_t(R_M + \Delta R_M + R_F)} \tag{5}$$

where R_M is the intrinsic membrane resistance factor, bar-h-m^2/L-cP, R_F is the generic fouling factor, bar-h-m^2/L-cP, ΔR_M is the delta intrinsic membrane resistance factor, bar-h-m^2/L-cP.

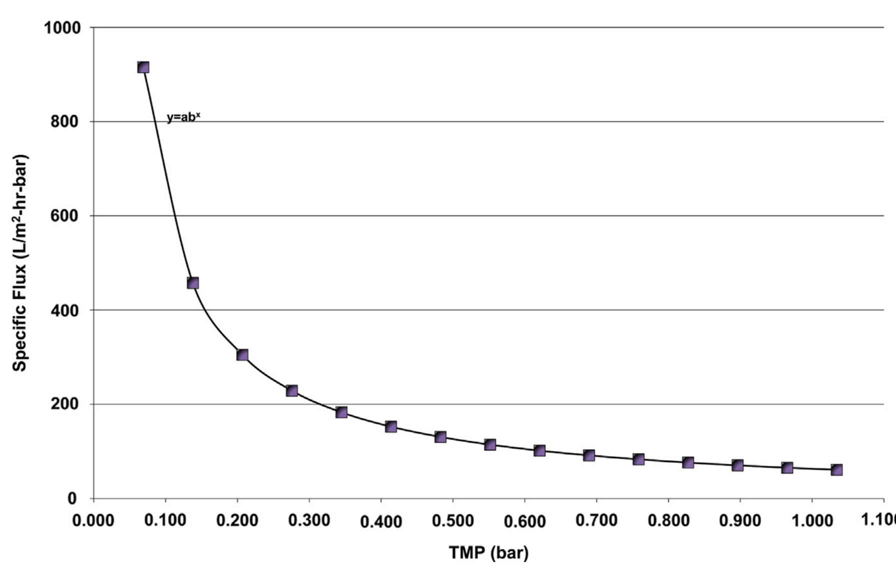

Fig. 1. Relationship between specific flux and TMP (Flux: 63.0 L/m^2-h, Surface area: 40 m^2).