Journal of Membrane Science 546 (2018) 215–224

Contents lists available at ScienceDirect

Journal of Membrane Science

journal homepage: www.elsevier.com/locate/memsci

Uncertainty propagation in a model of dead-end bacterial microfiltration using fuzzy interval analysis

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ARTICLE INFO

Keywords:
Fuzzy interval analysis
Uncertainty
Wastewater reclamation
Bacterial fouling
Water purification

ABSTRACT

Uncertainty is inherent in experimentation, modeling, and analysis. Variations and errors in parameter estimates or physical processes are unavoidable and can affect the reliability of model predictions. Therefore understanding the role of uncertainty is embedded in the process of modeling and approximating the real world. In this manuscript we consider uncertainty propagation in a theoretical model of water/wastewater treatment. In dead-end microfiltration contaminated water is fed through a membrane that filters out colloids, bacteria, and protozoa. However, these particles foul the membrane reducing the filter productivity, which is alleviated by periodically reversing the flow, i.e. backwashing. We investigate how uncertainty in sensitive parameter estimates propagates to the estimates of the optimal amount of volume of water that is filtered in a fixed time period and the associated backwashing timing and duration. We find that the model provides conservative estimates for the total volume since the uncertainty is not propagated symmetrically with respect to over and underestimating specific measurable quantities. The uncertainty in the timing is more symmetric implying that there is essentially an equal amount of uncertainty for increasing or decreasing the frequency and duration of backwashing. We identified biofilm production as propagating the most uncertainty in the volume estimate. The fouling rate has the most effect on the timing estimates. Additionally we explored the affect of asymmetric parameter distributions and find that, for most parameters, asymmetry does not lead to increased asymmetry in predicted optimal regimes, implying that uncertainty in the skewness is likely not an issue.

1. Introduction

Uncertainty is inherent in any scientific investigation. There are several ways to categorize uncertainty but one of the most useful is to distinguish between epistemic and aleatory uncertainty. The former refers to uncertainty due to limited knowledge and can often be reduced by obtaining more data or deeper understanding of the process. For example, errors in estimating parameter values can be reduced by refining experiments and models. The latter refers to uncertainty that cannot be reduced but is embedded in the process. This is often what is meant by 'random' when there is a stochastic process that governs the physical environment. Examples in the context of water treatment include stochastic distribution of pores in membranes, fluctuations in influent water quality, and variations in fluid mechanics. Fig. 1 demonstrates inherent aleatory uncertainty in membrane pore sizes and distributions. In addition to variable pore size, the distribution of bacterial deposition contributes to irreducible uncertainty (See Fig. 2). In the context of mathematical modeling a similar distinction is made between 'model uncertainty' and 'parametric uncertainty' [1–3]. In this manuscript we focus on the latter and how this uncertainty in parameter estimates propagates through the model.

Understanding the impact of uncertainty is vital for interpreting and implementing both quantitative and qualitative predictions that depend on modeling. The role of uncertainty has matured dramatically since the introduction of the concept in the late 1960's and '70s [7]. One of the main emphasis was on calculating extremes to estimate bounds on operational failure or extreme events [8,9]. For example, in [10], the authors describe mathematical methods to bound uncertainties in flood discharge, primarily to guide insurance decisions. As uncertainty quantification became more refined, more interest was shown in determining where input uncertainty might transport throughout the process of data collection, model formulation, model analysis, and model prediction [11,12].

It is now relatively accepted that uncertainty analysis refers to a broad group of methods designed to estimate, bound, and track uncertainty that is introduced in a mathematical modeling framework [3,13,14]. In the following sections we describe a method for bounding the propagation of uncertainty using interval analysis. Interval analysis

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http://dx.doi.org/10.1016/j.memsci.2017.10.029
Received 16 July 2017; Received in revised form 9 October 2017; Accepted 11 October 2017
Available online 13 October 2017
0376-7388/

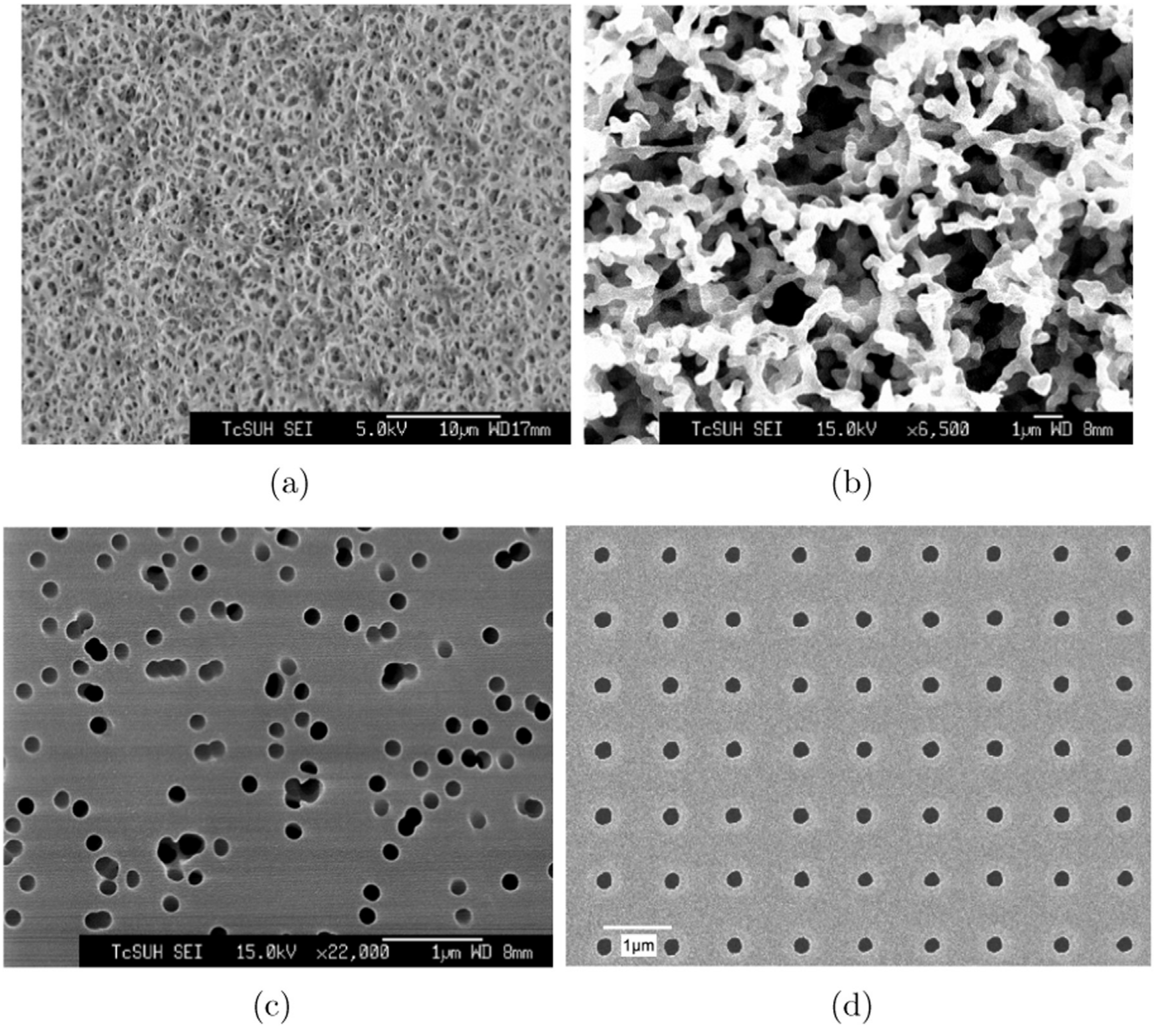

Fig. 1. Micrographs of different types of microfiltration membranes visually demonstrating that the distribution of pores is subject to uncertainty. Materials and formation include PVDF phase-inversion (a), cellulose casting (b), track-etched polycarbonate (c), and lithographically-defined polyimide (d) [4].

has been extensively used since it was introduced in the 1960's and can be used to estimate upper and lower bounds for uncertainty [15]. By extending this methodology by allowing for 'fuzziness' in the parameters, the concept of fuzzy interval analysis ([16–18]) can extend our understanding in two important ways. First, the concept of fuzziness when considering parametric uncertainty allows us to explore parameter variations that are non-probabilistic [18]. That is we can consider possible values of parameters when the actual statistics of the distributed parameter statistics are either not available, or not well understood. This avoids the confusion that arises in probabilistic treatment where the distribution statistics of the parameter must be specified in order to proceed with any calculations [19]. Secondly, we can explore where uncertainty aggregates by following the uncertainty in membership functions that define fuzzy sets. As far as we are aware, this is one the first applications of quantitatively incorporating aleatory uncertainty in MF fouling modeling. The goals of this manuscript are two-fold: first we aim to understand how uncertainty propagates through our model [20,21]; secondly, since there are so many methods for uncertainty propagation, we will attempt to explain clearly the benefits of our methodology – the main one being able to classify predictions as conservative or aggressive with respect to the uncertainty.

The manuscript is organized as follows. We first specify the uncertainty analysis we use here, including interval analysis and fuzzy sets. We then describe the engineering application and model that we have in mind. Because these have been described previously in some detail ([20–23]), we attempt to keep this discussion brief. Finally, we describe the results of the fuzzy interval analysis and what conclusions we can make from our analysis.

1.1. Microfiltration

Obtaining clean water from impaired sources is important in a variety of settings including industrial, chemical, and environmental applications. In fact, this is one of the United Nations' Millennium Development Goals to provide safe drinking water and sanitation to the growing population. Microfilters are used to separate particulate contaminants such as colloids (contributing to turbidity) and microorganisms; however this leads to a decline in the productivity of the filter as foulants accumulate on the filter surface. A variety of methods have been introduced to increase the longevity of the filters and increase the productivity by manipulating the filter geometry, water flow, and chemical additives. Typical methods include dead-end filtration using flat sheets or hollow fibers [24–27].

In this manuscript we focus on the simplest geometry described by a flat sheet membrane that is placed perpendicular to the flow. This has the advantage of guaranteeing the outflow water that is collected is purified up to the level specified by the membrane filter. One drawback is that dead-end filters foul relatively quickly, which can be combated by periodic backwashing to regenerate the membrane in an attempt to