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Investigation of the filtration characteristics of pilot-scale hollow fiber submerged MF system using cake formation model and artificial neural networks model

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ABSTRACT

The submerged hollow fiber MF membrane offers a cost-effective means of removing particles and pathogens from water for drinking water production. Fouling, however, has been regarded as a major obstacle to the economical operation of membrane systems. This study focused on the investigation of the filtration characteristics of pilot-scale submerged hollow fiber membrane system using the cake formation model, based on the critical flux concept, and on the prediction of the performance of membrane filtration using artificial neural networks model (ANNs) from a long-term pilot-scale operation data.

A cake formation model was applied to analyze the axial flux variations, the specific cake resistance, and the critical flux in hollow fiber membrane. The artificial neural network was applied to the simultaneous simulation of transmembrane pressure (TMP) variations in a pilot-scale membrane system.

The experimental results indicated that the seasonal variations in raw water quality parameters significantly affected `the membrane permeability. The temperature of the feed water ranged from 2.1 to 26.4 °C, and the turbidity ranged from 1.0 to 500 NTU, which led to completely different conditions in summer and winter. The algae concentration ranged from 0 to 47 mg/m^3, as did the chlorophyll-a concentration, which also led to completely different conditions in spring. A stepwise increase in the imposed flux showed that the apparent critical flux was about 60 L/m^{2}h in summer and winter. Moreover, the apparent critical flux was about 40 L/m^{2}h in spring. The cake formation model calculation was also compared with the experimental data to better understand the fouling in the hollow fiber membrane modules, and ANNs was applied to simultaneously predict the long-term membrane performance.

1. Introduction

Membrane filtration with microfiltration (MF) and ultrafiltration (UF) membrane has become a common technology for drinking water treatment. MF and UF is viable for particle and large molecular organics removal in treatment plants of all sizes that treat a wide range of raw water types [1]. The MF membranes in the hollow fiber configuration are widely used due to their high membrane-surface-area-to-footprint ratio, high mechanical strength and backwashing capability at low module and energy cost compared to alternatives such as plate-and-frame, spiral-wound or tubular membranes [2–4]. Nevertheless, fouling has been identified as a significant issue in hollow fiber membrane filtration for drinking water production [5]. Depending on the quality of the raw water, membrane filtration requires several pretreatment processes, which can include coagulation, flocculation, sedimentation, softening, oxidation, adsorption, and/or granular filtration [6,7]. Since the hydrodynamic conditions in hollow fiber membranes are much more complex than those in other types of membranes, understanding the filtration behavior of hollow fibers is essential to improving the operation and design of the hollow fiber system [8–12]. Although bench-scale research has provided some understanding of fouling [9–13] relatively a small number of studies have been done on a pilot scale.

This study focused on the investigation of the filtration characteristics of pilot-scale submerged hollow fiber MF membrane system using the cake formation model based on the critical flux concept, and on the prediction of the performance of membrane filtration using the artificial neural networks model from long-term pilot-scale operations data. The effects of temperature, turbidity, algae, and other water quality parameters on membrane permeability were considered under various feed water conditions. Experiments were performed to correlate the raw water quality and the critical flux in pilot-scale tests.

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2. Theory

2.1. Cake formation model

The Hagen-Poiseuille equation and the cake formation model that was modified with the critical flux concept were used to predict the performance of hollow fiber membranes under constant flux. The cake formation model describes the permeate flux decline due to the formation of a particle cake layer on the membrane surface. The reason for this application, we supposed that the size of particle in the feed water can be bigger than membrane pore size due to coagulation pre-treatment process.

The raw water collected from Han-river was used as the feed water and have undergone the process of coagulation pre-treatment using poly aluminium chloride. The reason for applying "cake model" was to suppose the size of particles in the feed water to be bigger than MF pore size, 0.1 um.

Only a broad outline of the model is given here, since details are provided separately [14,15]. Fig. 1 illustrates the flow and geometry of a single fiber in a hollow fiber membrane module.

The model can be applied in two ways. The model can be used to find the system parameters, including α_c and J_c, by fitting the model with the experimental data. Once these parameters are known, the model equations can be used to simulate the TMP profiles under various operating conditions (Table 1).

Table 1
Summary of model equations for the hollow fiber membrane system.

Meaning	Model equations
Local velocity of the liquid inside a fiber	$\frac{dv(x,t)}{dx} = \frac{4D_oJ(x,t)}{D_i^2}$
Local pressure inside a fiber	$\frac{dp(x,t)}{dx} = -\frac{32\eta v(x,t)}{D_i^2}$
Local flux	$J(x,t) = \frac{\Delta p(x,t)}{\eta R_t(x,t)} = \frac{(p_o - p(x,t))}{\eta(R_m + R_c(x,t))}$
Local hydraulic resistance of the cake formed on the membrane surface	$R_c(x,t) = \frac{\alpha_c \rho_p \phi_c D_o}{2} 1\mathrm{n}\left(\frac{D_o + 2\delta_c(x,t)}{D_o}\right)$
Local thickness of the cake layer	$\frac{d\delta_c(x,t)}{dt} = \frac{\phi_b}{\phi_c - \phi_b} \frac{D_o}{D_o + 2\delta_c(x,t)} (J(x,t) - J_c)$

Symbols

$v(x,t)$	local velocity
x	longitude coordinate from the dead-end
D_i	inner diameter of the fiber
$p(x,t)$	local TMP
p_o	atmospheric pressure
R_m	membrane resistance
α_c	specific cake resistance
ϕ_b	volume fraction of particles in bulk solution
ϕ_c	volume fraction of deposits in bulk solution
$J(x,t)$	local flux
t	time for filtration
D_o	outer diameter of the fiber
η	liquid viscosity
R_t	total filtration resistance
R_c	cake resistance
ρ_p	particle density
δ_c	thickness of the cake layer
J_c	critical flux

2.2. Artificial neural networks model (ANNs)

The cake formation model was used to analyze the axial flux variations, the specific cake resistance, and the critical flux in hollow fiber membranes. The application of the cake formation model was possible, however, only in each case. This model is also mathematically complex and ideally requires very detailed knowledge of the filtration process as well as characterization of the membranes [16]. Therefore, the use of the cake formation model was very limited. It was thus necessary to use the ANNs to predict the membrane performance from the long-term pilot-scale operations data.

ANNs is an information processing system that roughly replicates the behavior of the human brain by emulating the operations and connectivity of biological neurons [17]. It consists of an interconnected group of artificial neurons and processes information using a connectionist approach to computation. In most cases, an ANNs is an adaptive system that changes its structure based on the external or internal information that flows through the network during the learning phase. In more practical terms, neural networks are non-linear statistical data modeling tools. They can be used to model complex relationships between inputs and outputs or to find patterns in data. From the middle of 1990s, ANNs have been successfully applied to different types of the membranes; microfiltration [18,19], ultrafiltration [20], nanofiltration [21]. ANNs was used in this study to predict the membrane filtration performance with a perceptron network (MLP) that had a back-propagation training algorithm. Fig. 2 illustrates a fully connected multi-layer perceptron. The MLP consists of three or more layers of nodes: one input layer, one output layer, and one or more hidden layers. The input vector x passed to the network is directly passed to the node activation output of the input layer without any computation. One or more hidden layers of nodes between the input and output layers provide additional computations. Then the output layer generates the mapping output vector z. Each of the hidden and output layers has a set of connections, with a corresponding strength-weight, between itself and each node of the preceding layer. MLPs have been adapted for the simulation of TMP variations in a pilot-scale membrane system.

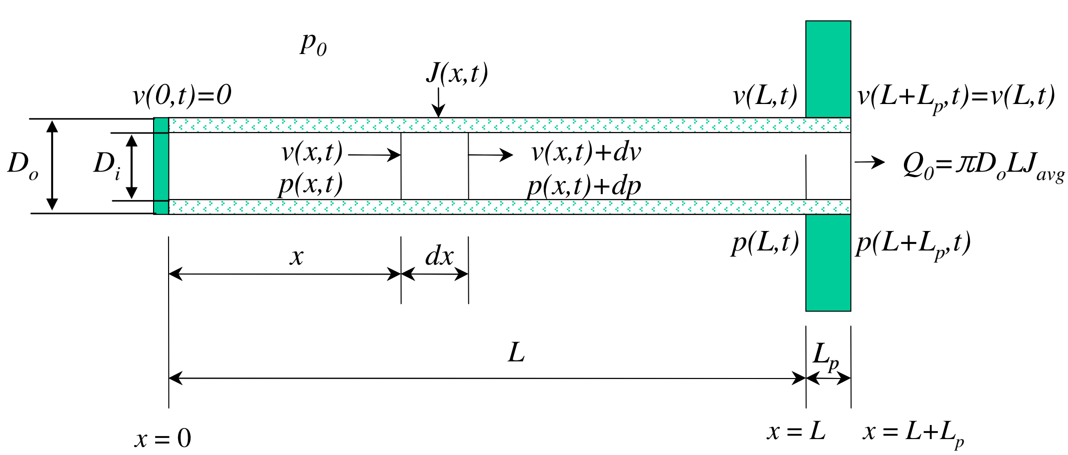

Fig. 1. Permeation flow through the hollow fiber membrane.