Separation and Purification Technology 141 (2015) 160–169

Contents lists available at ScienceDirect

Separation and Purification Technology

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

Investigation of membrane fouling mechanisms using blocking models in the case of shear-enhanced ultrafiltration

Wenxiang Zhang [*], Luhui Ding [*]

EA 4297 TIMR, University of Technology of Compiegne, 60205 Compiegne Cedex, France

ARTICLE INFO

Article history:
Received 29 July 2014
Received in revised form 5 November 2014
Accepted 14 November 2014
Available online 9 December 2014

Keywords:
Ultrafiltration
Blocking model
Shear rate
Membrane fouling
Membrane cleaning

ABSTRACT

Shear-enhanced ultrafiltration is considered as an important membrane technology that can contribute to pre-treat dairy wastewater and recycle valuable components such as milk proteins. However, to be efficient, it necessitates the establishment of proper methods for the assessment of membrane fouling. Four membrane blocking models proposed by Hermia were used to quantify and assess the membrane fouling of shear-enhanced filtration observed in dairy wastewater treatment. The experiments were performed with various shear rates, mean transmembrane pressure (TMP), temperature and membrane types. Good agreement between complete pore blocking model and experimental data was found, confirming the validity of the Hermia models for assessing the membrane fouling of shear-enhanced filtration system and that only some "sealing" of membrane pores occurs which is due to the high speed shearing effect. Furthermore, the increments of shear rate, TMP, and temperature can decrease the degree of "sealing" of membrane pores and improve filtration performance. In addition, a three-step membrane cleaning mode has achieved very satisfying results in subsequent membrane cleaning. This work confirms that, unlike traditional filtration mode (dead-end and cross flow filtration), high shear dynamic filtration possesses a low degree of membrane fouling and a higher membrane permeability recovery after cleaning.

1. Introduction

Shear-enhanced membrane filtration, which outweighs the traditional cross flow membrane filtration process in stable permeate flux, excellent rejection and low concentration polarization [1], has been widely applied in wastewater treatment [2], chemical engineering [3], medical engineering [4] and food engineering [5] as well as biotechnological separations [6]. Shear-enhanced membrane filtration currently suffers from high energy consumption, membrane fouling and high equipment cost, etc. Especially, membrane blocking, cake formation or concentration polarization remain huge problems that hinders large-scale industrial applications owing to shortened membrane life and increment of operational cost [7]. In order to overcome these drawbacks, numerous strategies have been introduced to eliminate membrane fouling, including membrane washing before cake fouling formation [8], appropriate hydraulic conditions [9], the utilization of chemical cleaning process [10] and operation with threshold flux instead of limiting flux [11]. However, fouling mechanisms of shear-enhanced filtration systems, which are highly important for choosing the most effective procedure for membrane restoration and operation for reducing membrane fouling, are still unclear and need further research.

Ultrafiltration as a promising technology has been applied to pre-treat dairy wastewater and recycles valuable component-protein [2]. In this filtration process, fouling is typically caused by milk proteins, lactose and mineral salts present in water that adhere to the surface and pores of the membrane. De Kruif et al. [12] found that casein micelles and whey proteins were the main foulants during UF dairy wastewater and form cake layer on membrane surface. Rabiller-Baudry et al. [13] treated skim milk by UF membrane and concluded that inorganic fouling was negligible with the neutral to alkaline pH. After cleaning the fouled membrane which was used to regenerate of dairy wastewater, larger than 5 µm organic–inorganic precipitate was found by Scanning Electron Microscopy–Energy Dispersive Spectroscopy (SEM–EDS). This layer is mainly composed of proteins, silica and calcium carbonate and existed in cake layer or pore blocking [13]. Thus, organic cake fouling mainly including casein micelles and whey proteins is the dominant resistance for UF of dairy wastewater. But these studies were all performed using cross flow modules and the shear rate of membrane surface was moderate. When shear-enhanced filtration systems were used, concentration polarization and cake layer

---

[*] Tel.: +33 3 4423 4634; fax: +33 3 4423 7942.
E-mail address: Luhui.ding@utc.fr (L. Ding).

http://dx.doi.org/10.1016/j.seppur.2014.11.041
1383-5866/© 2014 Elsevier B.V. All rights reserved.

Nomenclature

A_m	membrane surface (m^2)	k_c	pore blocking constant at $n = 0$ (s/m^6)
TMP	transmembrane pressure (bar)	PL	permeability loss index
γ_m	mean membrane shear rate (s^{-1})	$R2$	coefficient of multiple determination
J	permeate flux of solution ($L\,m^{-2}\,h^{-1}$)	n	parameter of pore blocking model (dimensionless)
t	time (min)	ω	angular velocity of rotating disk (rad)
V	permeate volume (mL)	v	the fluid kinematic viscosity (m^2/s)
k_b	pore blocking constant at $n = 2$ (s/m^2)	r	the disk radius (m)
k_s	pore blocking constant at $n = 1.5$ ($s^{0.5}/m^{1.5}$)	k	the velocity factor
k_i	pore blocking constant at $n = 1$ ($1/m^3$)		

formation could be delayed by stronger shear-induced diffusion [14].

In previous investigations, many mathematical models were proposed for explaining the membrane fouling mechanism, including blocking models [15], concentration polarization models [16] and cake filtration models [17]. For these mathematical models, the choice of membrane depends on the particle size of the feed solution. As for concentration polarization models, they are used if the particle diffusion effect is dominant, while cake filtration models can be applied to describe particles accumulation on the membrane surface. The membrane blocking model is appropriate to analysis membrane fouling, when the size of membrane pores is larger than particle size, solutes may penetrate and block the membrane pores and a cake layer form on membrane surface. Four different kinds of blocking models (complete blocking, intermediate blocking, standard blocking, and cake filtration) based on pore-blocking laws were put forward to explain the dead-end filtration by Hermia and Bredee [18]. The four blocking models are presented in Table 1. These models based on Darcy law were developed specifically for the dead-end filtration. Hwang and Lin [19] found various membrane presented different blocking types, e.g., standard blocking exists in a MF-Millipore membrane, a Durapore membrane has an intermediate blocking, and a complete blocking occurs in an Isopore membrane. In addition, the blocking models could change from a complete blocking to cake model during filtration. A new mathematical model was proposed to describe the thickness of cake formed on the membrane surface during protein filtration [20]. Another smooth transition model, which considers the change from pore blocking fouling to cake filtration resistance with time, was introduced to simplify the cumbersome process that use different models to explain the entire filtration process [21]. Recently, some studies [5,22] devoted to cross-flow filtration and could help to explain the fouling mechanism of cross-flow filtration. Because the amount of solutes contained in the convective flow along membrane surface is larger than that removed by cross flow action, this is similar to dead-end filtration. Moreover, to our knowledge, there is no description available of the membrane fouling mechanisms of shear-enhanced filtration system by pore blocking models.

This investigation applied blocking model to analyze fouling mechanism in shear-enhanced ultrafiltration for dairy wastewater pre-treatment. The effect of shear rate, membrane type, TMP and temperature on the fouling mechanism and blocking index were studied. The identification of the membrane fouling mechanisms resulting from batch experiments is expected to contribute to their potential application to continuous filtration tests in the future.

2. Theory

Based on the pore blocking mechanism, the permeate flow decline can be explained by

$$\frac{d^2t}{dV^2} = k\left(\frac{dt}{dV}\right)^n \tag{1}$$

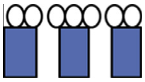
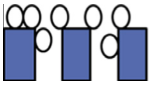
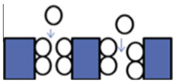
where V and t are the permeate volume and filtration time, and k and n are the resistance coefficient and blocking index where n is a dimensionless number of the fouling mechanism [16,17,23]. Normally, four pore blocking fouling mechanisms (listed in Table 1) are considered.

In complete pore blocking, all particles depositing on membrane surface only involve in “sealing” of membrane pores. It is an idealized condition assumes that no particles situated on top of other particles or on membrane surface. Complete pore blocking ($n = 2$):

$$J_{n=2} = \frac{J_0(k_bA_m)}{t} \tag{2}$$

where k_b is a complete pore blocking coefficient, A_m is the membrane area, J_0 is the initial flux and $J_{n=2}$ is the flux.

Table 1
Four models of membrane fouling proposed by Hermia.

Pore blocking models	n	Linear equation	a	b	Physical concept	Schematic diagram
Complete pore blocking (model 1)	2	$\ln(J) = \ln(a/t)+\ln(b)$	1	$J_0k_bA_m$	Formation of a surface deposit	
Internal pore blocking (model 2)	1.5	$J^{-1/2} = at + b$	$(2-n)k_s\sqrt{A_m}$	$J_0^{-1/2}$	Pore blocking + surface deposit	
Intermediate pore blocking (model 3)	1	$J^{-1} = at + b$	$(2-n)k_iJ_0$	J_0^{-1}	Pore constriction	
Cake formation (model 4)	0	$J^{-2} = at + b$	$(2-n)k_cJ_0^2$	J_0^{-2}	Pore blocking