Chemical Engineering Journal 276 (2015) 331–339

Contents lists available at ScienceDirect

Chemical Engineering Journal

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

Filtration of natural organic matter using ultrafiltration membranes for drinking water purposes: Circular cross-flow compared with stirred dead end flow

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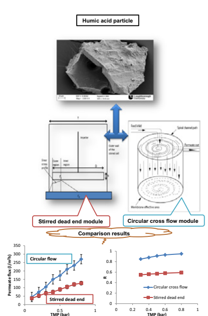
HIGHLIGHTS

- Ultrafiltration of natural organic matter is studied.
- Circular flow and stirred dead end modules are compared.
- Mass transfer coefficient improved significantly compared to classical modules.
- Dean vortices in thin circular flow aids permeation flux.
- Better rejections compared with stirred dead end.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 21 January 2015
Received in revised form 12 April 2015
Accepted 14 April 2015
Available online 25 April 2015

Keywords:
Membrane filtration
Ultrafiltration
Circular cross flow
Stirred dead end flow
Mass transfer coefficient
Humic acid

ABSTRACT

Application of ultrafiltration membranes for removal of humic acids is investigated below. Membrane filtration processes were compared using two different set-ups: circular flow and stirred dead end flow. The transmembrane pressure, temperature, feed concentration, pH, ionic strength and shear stresses applied on the membrane surfaces were kept constant whilst the permeate flux and solute rejection were measured during the experiments with both set-ups. It was shown that the rejection (both the observed and the true rejection) in the case of circular flow was higher than in the case of dead end flow. The mass transfer coefficients were determined for both set-ups. In the case of stirred dead end, it ranged in from 2.14 to 4.72×10^{-6} m/s; however, for circular cross flow system, the mass transfer coefficients were found in the range 2.24–3.22×10^{-5} m/s. Comparison of the mass transfer coefficients obtained for both systems showed that it was significantly higher for circular flow systems as compared with stirred dead end system at similar operating conditions. Energy consumed per volume of purified water by circular flow system (0.345 kW) was found to be much lower when by stirred dead end system (0.955 kW). This proved that the performance of circular flow system was more efficient in terms of rejection, mass transfer coefficient and energy consumption.

1. Introduction

Clean and safe drinking water is one of the basic needs for the survival of human beings especially under extreme conditions. Regular sources of drinking water in the events of natural disasters are often polluted by harmful/hazardous components which can cause considerable losses of life. Urgent purification of polluted water under such extraordinary conditions for immediate consumption is a major priority [7]. Membrane processes such as microfiltration (MF) and ultrafiltration (UF) have been widely used for water treatment in recent years [25,34]. They have been used as

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http://dx.doi.org/10.1016/j.cej.2015.04.075
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Nomenclature

C_F	humic acid concentration in the feed (kg m^3)
C_M	humic acid concentration at the membrane surface (kg m^3)
C_P	humic acid concentration in the permeate (kg m^3)
D	diffusion coefficient (m^2/s)
D_t	stirred dead end cell diameter (m)
De	Dean number (–)
d_i	hydraulic diameter (m)
d_c	equivalent centreline diameter of curved channel (m)
h	height of the impeller blade (m)
J_V	volumetric flux (m/s)
k	mass transfer coefficient (m/s)
L	membrane channel length (μm)
Re	Reynolds number (–)
T	operating temperature (K)
u	cross flow velocity (m/s)
Greek letters	
δ	momentum boundary layer (–)
τ	shear stress (*Pa*)
μ	dynamic viscosity (*Pa s*)
ρ	fluid density (kg/m^3)
ω	angular velocity (rad/s)

alternative technologies to conventional methods such as coagulation, sedimentation, ozonation, granular activated carbon [14], flocculation/chlorination [4] and slow sand filtration [18] etc. The reason is that membrane processes are not only cost effective but also offer simple operation conditions, high output production with lower energy consumption and chemicals. However, one of the critical issues of membrane technology in water treatment is membrane fouling. Fouling results a considerable decline in productivity over time and is caused by specific interactions between the membrane and the components in feed water [35,39]. Fouling results in an accumulation of colloidal matter, organic and inorganic compounds, microorganisms on membrane surfaces and within membrane pores [21,38]. This is often referred to as irreversible loss of permeate flux through the membrane [26,40].

Various approaches for minimising membrane fouling and concentration polarization had been proposed. These include chemical methods such as modification of membrane surface to minimise interactions between the membrane and the deposits [20], physical method such as mechanical scouring [41], and hydrodynamic methods such as improved module design and fluid flow arrangements in order to reduce solute deposition on the membrane [33]. A useful method in overcoming concentration polarization is a creation of flow instabilities [19]. The use of eddies, Taylor vortices during pulsation rotating membrane filter [8] and secondary flow (Dean vortex flow) [16] are among these options. However, the drawback of such rotating module systems is that more energy is required for scaling up and, thus they have limited large-scale development for commercial purposes. Chung et al. [9] and Chung et al. [10] studied an alternative method to create centrifugal vortices which result from the onset of unstable flow in spiral wound membrane ducts. At sufficiently low flow rates (that is at Reynolds numbers below some critical value) the velocity in the curved channel flow is approximately stream wise parabolic. However, at higher Reynolds number (or Dean number) above a critical value, centrifugal instabilities cause secondary flow containing stream wise oriented Dean vortices similar to Taylor vortices. The presence of these vortices enhance back migration through convective flow away from the membrane surface, depolarising the solute build up near the membrane surface, thus resulting in an increase of membrane permeation rate [11,27,29]. Al-Bastaki and Abbas [2] reviewed methods of improving membrane performances and reducing fouling by the presence of fluid instabilities. These techniques had proven to be successful in other applications such as gas–liquid contactors for blood oxygenation [36]. The presence of vortices results in an improved oxygen transfer by a factor from 2 to 4 [28]. Ghogomu et al. [15] studied the performance of several curved membrane channels designs and found that the mass transfer was improved compared to classical models. At the same time the curved channels were showed to be more energy efficient. This was caused by the formation of Dean vortices, which proved to be effective in reducing both the concentration polarization and fouling.

It is well known that membrane module configurations can have a noticeable impact on filtration processes [31]. However, the extent to which one system performs better/worse under similar conditions cannot be easily quantified. Therefore, it is essential to develop conditions for comparison of the performance of different membrane systems with respect to hydrodynamics (Reynolds number, membrane surface shear, etc.) and operating conditions such as feed concentration, pH, transmembrane pressure (TMP) etc, whilst comparison of these different membrane systems is still possible. In order to compare two different membrane systems informative comparison has to be made with adequate experimental details provided, which were missing in some of the earlier papers, e.g., see discussions by Becht et al. [3].

Below ultrafiltration of humic acid was studied using a stirred dead end cell (model XFUF07601; Merck Millipore, Darmstadt, Germany) and a circular flow device (Amicon, Massachusetts, USA). The transmembrane pressure, temperature, feed concentration, pH, ionic strength and shear stresses on membrane surfaces were kept constant whilst the permeate flux and percentages of solute rejection were measured during the experiments with both systems. Humic acid concentration was fixed at 30 mg/l at pH between 7 and 8 and salt concentration at 0.01 M NaCl. The ultrafiltration data are compared in terms of permeate fluxes and solution rejections as well as the effects of convective mass transfer in the stirred dead end and circular flow devices. The obtained results showed noticeable differences under controlled experimental conditions. The objective is to demonstrate a significant improvement in the mass transfer coefficient and energy consumption in the case of circular flow as a result of the presence of secondary flows (Dean vortices). The TMP was kept reasonably small (less than 2 bar) in our experiments to imitate emergency situations (e.g., natural disasters) when the high pressure filtration equipment is not available and portable water filtration kits are used for drinking water purposes [34].

2. Experimental

2.1. Materials

Experiments were performed with Microdyn-Nadir (Wiesbaden, Germany) regenerated cellulose membrane (UC100: RC100) with molecular cut off (MWCO) of 100 kDa and porosity of 54%. The porosity was determined using pycnometric method [32]. The membrane samples were first soaked with deionized water for 1 h, water was changed every 20 min interval to remove