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Optimization of operating conditions in ultrafiltration process for produced water treatment via the full factorial design methodology

Seyed Mahdi Seyed Shahabadi *, Amin Reyhani *

Young Researchers and Elites Club, North Tehran Branch, Islamic Azad University, P.O. Box 11365-11155, Tehran, Iran

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ABSTRACT

In order to optimize the ultrafiltration process for produced water treatment the main and interaction effects of three operating parameters like temperature, transmembrane pressure (TMP), and cross flow velocity (CFV) on permeate flux, fouling resistance, and total organic carbons (TOC) rejection using PAN350 membrane was investigated by applying a two-level full factorial design (FFD) analysis. For permeate flux and fouling resistance, TMP was the most significant factor followed by the temperature and CFV in terms of importance, respectively. However, in case of TOC rejection, CFV was the most significant factor and the importance of the main effect of CFV was followed by the temperature and TMP, respectively. The analysis revealed that *T*–TMP, *T*–CFV, and TMP–CFV interactions have significant effects on permeate flux, fouling resistance, and TOC rejection, respectively. Model adequacy checking indicates appropriateness of fit of the models. Optimum temperature, TMP, and CFV were found to be 50 °C, 3.9 bar, and 1.75 m/s, respectively. Also, regarding removal efficiency of PAN350 membrane under optimum operating conditions, it was demonstrable that it would be a potential choice for industrial applications.

1. Introduction

Produced water (PW) is one of the major pollutants of the aquatic environment, which is generated daily by a variety of industrial sources, especially by oil refining processes [1]. Due to their toxic nature and effects on the environment, the proper management of PW is becoming a major issue for the public and regulators due to the high volumes generated and the disposal practices of many gas and oil companies. Conventional wastewater treatment technologies such as coagulation, flocculation, air flotation, and gravity separation normally cannot meet the high purity requirements for discharge of PW [2]. Membrane filtration is one of the treatment techniques used for oily wastewater treatment, which started since 1973. A number of researchers reported the effectiveness of ultrafiltration (UF) processes for the treatment of oil-in-water emulsions [3,4]. Distinct advantages of membrane technology for treatment of PW include reduced sludge, high quality permeate, absence of chemical addition, and the possibility of total recycle water systems [5]. These advantages, when considered along with the small space requirements, moderate capital costs, and ease of operation make membrane technology an economically competitive alternative or addition to traditional wastewater treatment technologies [6–8]. However, Membrane processes inherently suffer with the basic limitation of flux decline with time due to concentration polarization of solute at the membrane surface, which can be controlled by adjusting the operating conditions like temperature, transmembrane pressure (TMP), pH, and cross-flow velocity (CFV) [9]. Research shows that there is still an enormous interest in this field. Interesting studies are available, although they are limited in terms of factors variability. Membrane filtration is a complex process, and disregarding the interaction of factors may result in erroneous conclusions. A reliable solution to this problem would be to consider all interaction effects as well as main effects. For this reason, a design of experiments method, called full factorial design (FFD) could be helpful to optimize the UF process.

FFD is a multi-factor cross-group design. It not only can test the differences between various levels of each factor, but also can test the interaction between the factors [10]. This method requires greater number of experiments compared with fractional design or Taguchi method and provides very accurate results on the interaction between any two factors. Yi et al. [10] used FFD to study the flux decline of anionic polyacrylamide removal from water by modified polyvinylidene fluoride UF membranes. Factors investigated were pH of the solution (3–10), total dissolved solids (TDS)

* Tel.: +98 (938)1404081 (S.M. Seyed Shahabadi). Tel.: +98 (912)2435963 (A. Reyhani).

E-mail addresses: mehdi.shahabadi7@gmail.com (S.M. Seyed Shahabadi), aminreyhani@gmail.com (A. Reyhani).

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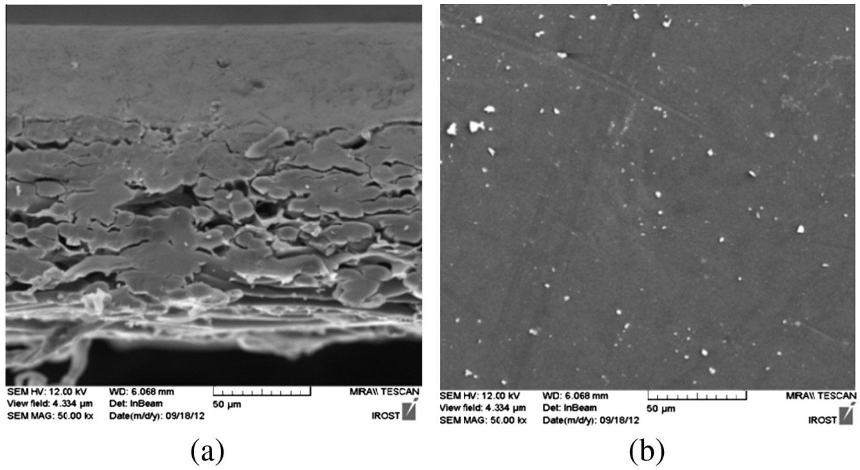

Fig. 1. SEM image of PAN350 as a fresh polymeric membrane: (a) Cross section, and (b) Surface.

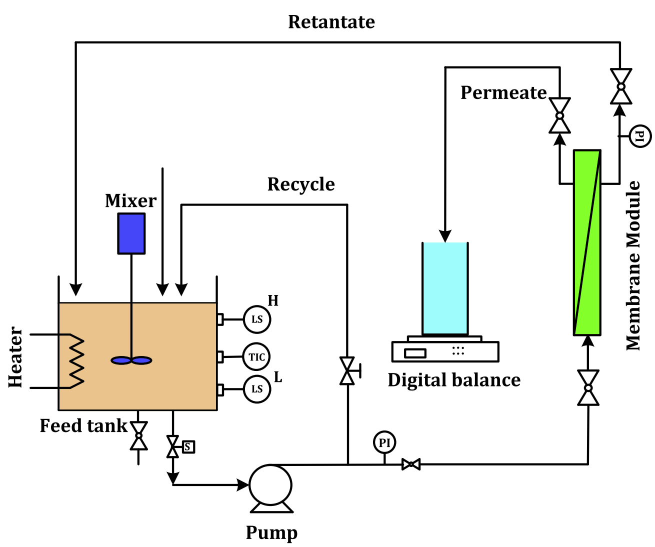

Fig. 2. Schematic diagram of the UF experimental setup.

(0–3.5 g/L), concentrations of anionic polyacrylamide (C) (10–100 mg/L), and TMP (0.07–0.2 MPa). TMP was found to be the most influential parameter for flux decline. Also, they found that C, pH, and C–pH interaction are significant in the flux decline regression model. Zularisam et al. [11] applied FFD in coagulation–ultrafiltration hybrid process for natural organic matter removal from drinking water. The factors considered were specific UV_{254nm} absorbance (SUVA), flocculation retention time (FRT), alum dosage, and pH. Statistical analysis of result has shown the main effect of alum, pH, SUVA and the two level interactions of alum and FRT, alum and SUVA, alum and pH, FRT and SUVA, and SUVA and pH were the significant model terms.

In current study, in order to optimize the UF process the effect of operating parameters (factors) was investigated via the FFD of experiments. The important operating conditions such as temperature (30–50 °C), TMP (2–5 bar), and CFV (0.75–1.75 m/s) were chosen so as to study their main and interaction effects on the responses: permeate flux, fouling resistance, and total organic carbons (TOC) removal. The effects of these factors are not predetermined and previous reports in the literature represent their different influence on the mentioned responses [12–15]. Also, the ranges of the factors were selected based on the capability of the experimental setup, economic considerations, and membrane operating limits. A regression model was presented for each response and optimization of the process was carried out to maximize permeate flux and TOC rejection and minimize fouling resistance. Finally, the performance of UF process under optimum conditions was investigated for using in industrial applications.

2. Materials and methods

2.1. Membrane

In this study, a rectangular flat-sheet polymeric membrane (PAN350) was used in the UF system that was purchased from Sepro Company (America). This membrane has a high hydrophilic feature with contact angle = 44° and is formed from polyacrylonitrile. Its molecular weight cut-off is 20 kDa. Recommended operating limits by company for PAN350 are as follows: pH range (3–10), pH range for chemical cleaning (3–10), temperature range (0–100 °C), pressure range (1–10 bar), and pure water flux (1000 L/m^2 h bar). The effective surface area of PAN350 during experiments was 66 cm^2. PAN350 is formed from two layers called top layer with 1 µm thickness, and sub layer as support. These layers can be seen in Fig. 1a. Surface of membrane before ultrafiltration is shown in Fig. 1b.

2.2. Process feed

The real PW used in the experiments consisted of oil and grease (816 mg/L), TSS (96 mg/L), TOC (278 mg/L), COD (560 mg/L as O_2),

Table 1
Experimental ranges and levels of the factors used in the factorial design.

Variable	Coded symbol	Values of coded levels		
		−1	0	+1
Temperature, *T* (°C)	X_1	30	40	50
Trans-membrane pressure, TMP (bar)	X_2	2	3.5	5
Cross-flow velocity, CFV (m/s)	X_3	0.75	1.25	1.75