Rinsing Condition Optimization of the Membrane Fouled by Yeast Suspension

Yangyang Guo¹,², Zhaoyu Qiao¹,ᵇ, Zhan Wang¹,ᶜ*, Huijia Luo¹,²,ᵈ and Xi Wang³,ᵉ*

¹Beijing Key Laboratory for Green Catalysis and Separation, Department of Chemistry and Chemical Engineering, Beijing University of Technology, Beijing, 100124, P.R. China
²Beijing Boda Water Co., Ltd, Beijing 100176, P.R. China
³Centre of Sino-Western Cultural Studies, School of Humanities and Social Sciences, Macao Polytechnic Institute, Macao, 999078, P.R. China
ᵃemail: y18831333348@163.com,ᵇemail: 943195362@qq.com,
ᶜ*Corresponding author’s e-mail: ᵇemail: wangzh@bjut.edu.cn
ᵈemail: luohuijia@bdawater.com
ᵉemail: dwhx4077@163.com

Abstract. In order to sufficiently study the effects of stirring speed and temperature on the membrane flux, the flux recovery rate (FRR) and model parameters (k₁, k₂, k₃, and Rᵢ) of the PAN membrane (200kDa) fouled by yeast suspension, a series of rinsing experiments were carried out. Meanwhile, the instantaneous membrane flux was predicted by the rinsing model and corresponding regression equation of model parameters was obtained. The result indicated that the model shows a good agreement (R²>0.9700) and the temperature has a more significant effect on FRR and model parameters (k₁, k₂, k₃, and Rᵢ). FRR increased from 58.40% to 99.41% when the temperature increase from 25°C to 55°C (the rate constant of dissolution increased from 0.00371 m⁻¹ to 0.00531 m⁻¹) while it only increased from 55.67% to 67.50% when the stirring speed increases from 200 rpm to 800 rpm (the rate constant of dissolution increased from 0.00366 m⁻¹ to 0.00456 m⁻¹). In addition, the rinsing condition can be optimized by the combination of the prediction model of flux (equation (1)) and the regression equation (equation (2)) to obtain the optimal cleaning condition.

1. Introduction

The application of the membrane bioreactor (MBR) in some kinds of sewage treatment (municipal, domestic and industrial wastewater) has been gained the rapidly increasing [1-4], especially in the places where water is scarce [5, 6]. Meanwhile, rinsing (by using the synergy of shear force and temperature) as one of the most commonly used cleaning methods has been widely used in MBR, and it can be used to alleviate the membrane fouling and improve the membrane filtration efficiency [7-9]. Rinsing can remove foulants from the membrane surface and it widely suitable for the ultrafiltration (UF) membrane due to the most foulants were deposited on the membrane surface [10-12]. For example, Zhang et al. [10] found that the UF membranes fouled by dairy wastewater at a higher shear stress (>16Pa) can assist membrane cleaning to obtain a higher membrane performance recovery (>80%). Guo et al. [13] found that the flux recovery rate can reach 90% at a temperature of 25°C and
stirring speed of 200 rpm for the PAN membrane (200kDa) fouled with sodium alginate (SA) solution. However, it is difficult to find a suitable rinsing condition to the membrane cleaning due to fact that the instantaneous membrane flux is difficult to prediction. Although the higher FRR can be obtained at a higher temperature or a higher shear stress, the energy expenditure is also very high [10]. Therefore, it is very important to find the optimal membrane rinsing condition by the prediction model of the membrane flux.

In this study, the yeast suspension as feed to foul the PAN membrane (200kDa), then a series cleaning experiments were carried out at a fixed cleaning condition (shear stress, temperature and rinsing time). The effects of shear stress, temperature and rinsing time on the membrane flux were carefully discussed. In addition, the instantaneous flux was predicted by the membrane rinsing model and it can be used to optimal the cleaning condition of the PAN membrane (200kDa) fouled with yeast suspension.

2. Materials and Methods

2.1. Materials
The yeast was provided by the Beijing Chemical Engineering Factory. The polyacrylonitrile (PAN) ultrafiltration membrane (200kDa) were purchased from ANDE Membrane Separation Technology Engineering Company, Beijing Co., Ltd.

2.2. Feed suspension
The concentration of feed suspension: yeast suspension (2.0g/L).

2.3. Experimental equipment and operating conditions
The experiment step: the virgin membrane with the effective filtration area of 37.39 cm² was immersed in the DI-water for 12 hours at a temperature of 4 °C to remove the glycerin before the experiment. Then the PAN (200 kDa) UF membrane was compact at 0.2 MPa for 10 min and measure the pure water flux at 0.1 MPa for 10 min. The yeast suspension was used to fouling the membrane at 0.1 MPa for 60 min. Finally, the fouling membrane were rinsing at different stirring speeds (200, 400, 600 and 800 rpm), temperature (25, 35, 45 and 55 °C) and rinsing time (2, 5, 10, 20, 30 and 40 min).

2.4. Methods
The flux recovery rate (FRR) can be obtained by following equation:

$$FRR = \frac{J_t}{J_0} \times 100\%$$

(1)

The following equation can be used to predict the instantaneous membrane flux:

$$J(t) = \mu \left( R_\alpha + R \left( e^{\alpha t} + \frac{k_1}{\alpha + k_4 + k_2} + \frac{k_3}{\alpha + k_4 + k_5} \right) + \left( R_f(0) - R_i \right) \left( e^{\beta t} + \frac{k_1}{\beta + k_4 + k_2} + \frac{k_3}{\beta + k_4 + k_5} \right) \right)$$

$$\Delta p = -k_1 (t_2 + k_3) - \frac{(k_1 + k_2 + k_3)^2 - 4k_1k_2}{2} - \frac{(k_1 + k_2 + k_3)^2 - 4k_1k_2}{2}$$

(2)

where $\Delta p$ is the transmembrane pressure (Pa), $\mu$ is the viscosity (Pa·s) $R_f(0)$ is the initial fouling resistance at the rinsing time of 0 (m⁻¹), $R_i$ is the constant (m⁻¹), $k_1$ is rate constant of swelling (s⁻¹), $k_2$ is rate constant of dissolution (s⁻¹) and $k_3$ is rate constant of deposition (s⁻¹).

3. Results & Discussion
In order to sufficiently study the effects of stirring speeds and temperatures on the membrane flux in the rinsing process. A series of experiments were carried out in different rinsing conditions (figure 1). The PAN membrane (200 kDa) fouled by yeast suspension was rinsing at the stirring speed of 200, 400, 600 and 800 rpm (at 25 °C) (figure 1(a)). The membrane flux increased with the increasing of
stirring speed at the fixed rinsing time. For example, the membrane flux increases from $2.22 \times 10^{-5} \text{ m/s}$ (200 rpm) to $2.70 \times 10^{-5} \text{ m/s}$ (800 rpm) after 40 min due to the increase of Reynolds number [13]. The corresponding $FRR$ increased from 55.67% to 67.50% (figure 2(a)). Meanwhile, the membrane flux increases with the extension of the rinsing time at fixed stirring speed. The membrane flux quickly increased at the initial few minutes (10 min) then this trend increased slowly. This is because that the loose foulants were removed quickly while the compact foulants were removed slowly [10]. The membrane flux increases from $1.26 \times 10^{-5} \text{ m/s}$ to $2.07 \times 10^{-5} \text{ m/s}$ after the cleaning time of 10 min while the after 30min only increase from $2.07 \times 10^{-5} \text{ m/s}$ to $2.33 \times 10^{-5} \text{ m/s}$ (400 rpm).

Figure 1. The effect of stirring speeds (a) and temperatures (b) on the membrane flux, and the model prediction of instantaneous flux.

It can be seen from figure 1(b), the PAN membrane (200 kDa) fouled by yeast suspension was rinsing at the temperature of 25, 35, 45 and 55 °C (at 400 rpm). The membrane flux also increased with the increase of temperature at the fixed rinsing time and the membrane flux also increased with the extension of the rinsing time at fixed temperature. However, the temperature had a more significant effect on the membrane flux than stirring speed. The membrane flux increased by 70.26% (from $2.22 \times 10^{-5} \text{ m/s}$ to $2.70 \times 10^{-5} \text{ m/s}$) when the temperature increased by 30 °C while the flux increased by only 21.62% (from $2.33 \times 10^{-5} \text{ m/s}$ to $3.97 \times 10^{-5} \text{ m/s}$) when the stirring speed increased by 600 rpm. This is because the high temperature can weaken the compact foulants [11]. $FRR$ increased from 58.40% to 99.41% (figure 2(b)). In addition, the membrane flux has a quickly increasing trend (from $1.26 \times 10^{-5} \text{ m/s}$ to $2.07 \times 10^{-5} \text{ m/s}$) in the first 20 min and this trend became slowly after 20 min (only increase from $2.07 \times 10^{-5} \text{ m/s}$ to $2.33 \times 10^{-5} \text{ m/s}$) (at 400 rpm). Therefore, compared with stirring speed, higher rinsing temperature is more favorable for rinsing to obtain a higher $FRR$.

In order to optimize the membrane rinsing condition, the model (equation (2)) was used to fit the experiment data and the corresponding model prediction of the instantaneous membrane flux were shown in figure 1. The model predictions and the experiment data show a good agreement ($R^2 > 0.9700$) and the corresponding model parameters ($k_1, k_2, k_3$ and $R_i$) were shown in Table 1. The values of $k_1, k_2, k_3$ and $R_i$ were all increased with the increasing of stirring speed or temperature. Meanwhile, the temperature also shows more significant effect on the model parameters than stirring speed. For example, the $k_2$ (rate constant of dissolution) increased from 0.00366 s$^{-1}$ (25 °C) to 0.00456 s$^{-1}$ (55 °C) while it only increased from 0.00371 s$^{-1}$ (200 rpm) to 0.00531 s$^{-1}$ (800 rpm). Therefore, the temperature has the more significant effect on the model parameters. In addition, the model parameters were used for the regression of the rinsing condition (stirring speed and temperature) [14] and the corresponding regression equation (equation (3)) were show in Table 1. The rinsing condition can be optimized by the combine of equation (2) and equation (3).
Figure 2. The effect of stirring speeds ((a)) and temperatures ((b)) on the membrane flux recovery rate.

Table 1. The model parameters under different cleaning conditions and the corresponding regression equation.

| $T$ (°C) | $n$ (rpm) | $k_1$ ($s^{-1}$) | $k_2$ ($s^{-1}$) | $k_3$ ($s^{-1}$) | $R_i$ (m$^{-1}$) | Regression equation |
|----------|-----------|------------------|------------------|------------------|-----------------|---------------------|
| 25       | 200       | 0.00             | 0.00             | 0.00             | 6.3382          | $k_1 = 2.8449 \times 10^{-5} T + 9.4525 \times 10^{-7} n + 5.8669 \times 10^{-3}$ |
|          |           | 674              | 366              | 182              | $8 \times 10^{12}$ | $k_2 = 4.6196 \times 10^{-5} T + 1.6965 \times 10^{-8} n + 5.6054 \times 10^{12}$ |
| 25       | 400       | 0.00             | 0.00             | 0.00             | 6.3946          | $k_3 = 8.5392 \times 10^{-5} T + 2.5930 \times 10^{-7} n - 1.0878 \times 10^{-3}$ |
|          |           | 693              | 371              | 187              | $9 \times 10^{12}$ | $R_i = 2.4863 \times 10^{10} T + 5.0478 \times 10^{6} n + 5.8669 \times 10^{-3}$ |
| 25       | 600       | 0.00             | 0.00             | 0.00             | 6.5049          | $717$              | $8 \times 10^{12}$ |
|          |           | 427              | 236              | $5 \times 10^{12}$ | $k_1 = 2.8449 \times 10^{-5} T + 9.4525 \times 10^{-7} n + 5.8669 \times 10^{-3}$ |
| 25       | 800       | 0.00             | 0.00             | 0.00             | 6.6483          | $731$              | $8 \times 10^{12}$ |
|          |           | 456              | 337              | $8 \times 10^{12}$ | $k_2 = 4.6196 \times 10^{-5} T + 1.6965 \times 10^{-8} n + 5.6054 \times 10^{12}$ |
| 35       | 400       | 0.00             | 0.00             | 0.00             | 6.7293          | $731$              | $8 \times 10^{12}$ |
|          |           | 412              | 291              | $6 \times 10^{12}$ | $R_i = 2.4863 \times 10^{10} T + 5.0478 \times 10^{6} n + 5.8669 \times 10^{-3}$ |
| 45       | 400       | 0.00             | 0.00             | 0.00             | 6.9153          | $757$              | $1 \times 10^{12}$ |
| 55       | 400       | 0.00             | 0.00             | 0.00             | 7.1646          | $776$              | $2 \times 10^{12}$ |

4. Conclusions
In this study, the effect of stirring speeds and temperature on the membrane flux, the flux recovery rate ($FRR$) and model parameters ($k_1$, $k_2$, $k_3$ and $R_i$) was systematically studied. The result show that the temperature shows more significant effect on the membrane flux, $FRR$ and model parameters than stirring speed. $FRR$ can reach 99.41% at a stirring speed of 400rpm and a temperature of 55°C. In addition, the model predictions and experiment data also show a good agreement ($R^2 > 0.9700$). The rinsing condition can be optimized by the combine of equation. (1) and equation. (2).

Acknowledgements
This paper is one of the phased achievements for the research of evolution regularity of effective area of membrane pore in MBR for actual membrane process (pollution + cleaning) and model establishment (No. 22078003), a general project of the National Social Science Fund.

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