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RECOVERY OF PROTEIN FROM MUNG BEAN STARCH PROCESSING WASTEWATER BY ROTATING ULTRAFILTRATION

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Abstract

Mung bean wastewater containing valuable protein is very potential to be recovered for reuse. In this study, rotary disk ultrafiltration was employed to recover this protein. The effects of transmembrane pressure (TMP) and membrane rotational speeds on process efficiency were studied and the optimum condition was chosen based on membrane permeate flux and protein retention. The results suggested that the use of TMP of 1.2 bar and rotating speed of 1,683 rpm under total recycle mode tended to achieve highest permeate flux (43 L/m^{3}h) compared to those using lower TMP and rotating speeds. The permeate fluxes under total recycle mode and batch concentration mode tended to increase with processing time, indicating the effectiveness of rotating shear force. In addition, the effect of stabilization technique on process performance under batch concentration mode was also studied. However, the variable did not show positive impacts on permeate flux and protein retention improvement. The optimum condition to achieve volume concentration factor (VCF) of 5 was TMP of 1.2 bar and rotating speed of 1,403 rpm without stabilization. Under this condition, the average flux, protein retention and energy consumption were 42 L/m^{2}h, 96% and 81 kWh/m^3, respectively.

Keywords: Mung bean, Rotating membrane disk, Ultrafiltration, Wastewater.

Nomenclatures

C_b	Solute concentration in the feed, mg/L
C_p	Solute concentration in the permeate, mg/L
I	Radius gyration, m
J	Permeate flux, m/s
k	Velocity factor
P_b	Permeate back pressure, kPa
P_i	Applied pressure, kPa
P_t	Power of rotating disk motor, kW
Q_f	Permeate flow rate, m^3/h
R_j	Solute retention, %
R_m	Membrane resistance, m^{-1}
r_i	Inner membrane radius, m
r_o	Outer membrane radius, m
R_{if}	Irreversible resistance, m^{-1}
R_t	Total resistance, m^{-1}
R_{rf}	Reversible resistance, m^{-1}

Greek Symbols

$\gamma_m \omega$	Mean membrane shear rate, 1/s
μ	Viscosity, Pa.s
ρ	Density, kg/m^3
ω	Angular velocity, rad/s

Abbreviations

TMP	Transmembrane Membrane Pressure
UF	Ultrafiltration
VCF	Volume Concentration Factor

1. Introduction

Mung bean is a legume that contains high amount of proteins (~27%) [1]. However, in production of mung bean starch and vermicelli, proteins have to be removed to obtain high quality products. As a result, the wastewater discharged contains significant amount of proteins and starch and is potential to cause environmental impact. The chemical oxygen demand (COD) of this liquid waste is in the range of 9,300-16,316 mg/L [2]. Since the restriction of environmental regulation and increasing of wastewater treatment cost are concerned, higher yield and value product are demanded [3]. In addition, recovery of proteins from the wastewater stream is also crucial needed since it is not only reduced load of wastewater treatment system but also to fully utilize the recovered components.

There are several methods have been used to recover proteins from wastewater of mung bean starch processing such as isoelectric precipitation, centrifugation followed by freeze or spray drying [1] and membrane filtration [4]. Ko et al. [4] employed a cross flow ultrafiltration (UF) with membrane molecular weight cut off (MWCO) 3 kDa to recover proteins from mung bean processing wastewater. Although about 90% protein was recovered, the permeate flux was very low (4.3 L/m^{2}h). It is worthy to note that very limited study has been reported on recovery of protein from mung bean processing wastewater using membrane technology in the literature and industrial practice. The main reason is probably due to low permeate flux.

Many researchers used cross flow UF system to recover protein from various wastewater stream because of its advantages e.g. higher quality and selectivity over traditional methods (e.g. alkaline extraction followed by acid precipitation) [5-10]. However, cross flow UF system also has limitation of permeate flux due to concentration polarization and fouling. For conventional cross flow filtration, high feed velocity is usually required to decrease the deposition and accumulation of solute and particle on membrane surface. However, high pressure drop and transmembrane pressure (TMP) at high feed velocity are also produced. At high TMP, the compact gel or cake layer is often developed, causing to increase fouling resistance and probably change membrane selectivity [11, 12].

In order to improve the performances, many hydrodynamic techniques such as a gas-liquid two-phase flow, back-flush or back-shock process have been used in cross flow membrane system [13]. Alternatively, rotary ultrafiltration system is also one of dynamic shear-enhanced membrane system. It produces hydraulic turbulence to rub membrane surface and consumes less energy for the pump to produce the required TMP and recirculation flow [12]. In rotary UF system, the feed flow rate can be low since the high shear rate is built from the moving membrane disk [11]. Although dynamic shear-enhanced filtration generates high shear rate but fouling especially at very high TMP still occurs. Therefore, the optimum condition is necessary even in dynamic shear-enhanced filtration to optimize permeate quality, process efficiency and energy consumption [13].

The aim of this study was to recover protein from mung bean starch processing wastewater and to evaluate the performance of rotary ultrafiltration. The study focused on the effects of TMP and membrane rotational speed on the process efficiency. The optimum condition was chosen based on permeate flux and protein retention.

2. Materials and Methods

The following sub-sections will describe wastewater sample characterization and chemicals used to conduct filtration experiments. Membrane performance evaluation under different conditions will also be provided followed by the procedure employed to analyse fouling mechanism.

2.1. Chemicals and wastewater sample

Chemical for analysis and membrane cleaning used in this study were bovine serum albumin (BSA) (Sigma Chemical Co.), Coomassie Brilliant Blue G-25 (BIO-RAD Laboratories Inc), H_2PO_4, HCl and NaOH (RCI-Labscan Limited). Mung bean processing wastewater was collected from mung bean starch processing factory, Patumpthanee, Thailand and kept at -20°C before use. The characteristics of wastewater were determined and the results are shown in Table 1.

Table 1. Characteristics of mung bean processing wastewater.

Characteristics	Value
Turbidity (NTU)	591
SS (mg/L)	10981.8
TS (mg/L)	58282.9
COD (mg/L)	42971.2
Protein (%w/w)	2.0
pH	4.8-5.8

2.2. Rotary ultrafiltration system

Single shaft module (CRD-01-152SS, Novoflow GmbH, Germany) consisting of ceramic membrane disks ($MgAl_2O_4$) with a mean pore size of 7 nm (~15kDa) and an effective membrane area of 360 cm^2 was used in this study. The inner and outer dimensions of membrane were 25.5 and 152 mm, respectively. The thickness of membrane disk was 4.5 mm Single membrane disk and two membrane disks were used for total recycle mode and batch concentration mode. Membrane disks were mounted with one rotating shaft. The permeate was collected from flat hollow channel as shown in Fig. 1. The permeate weight was recorded every 1 min using electronic balance connected to a computer. The system can be automatically back-flushed [14].

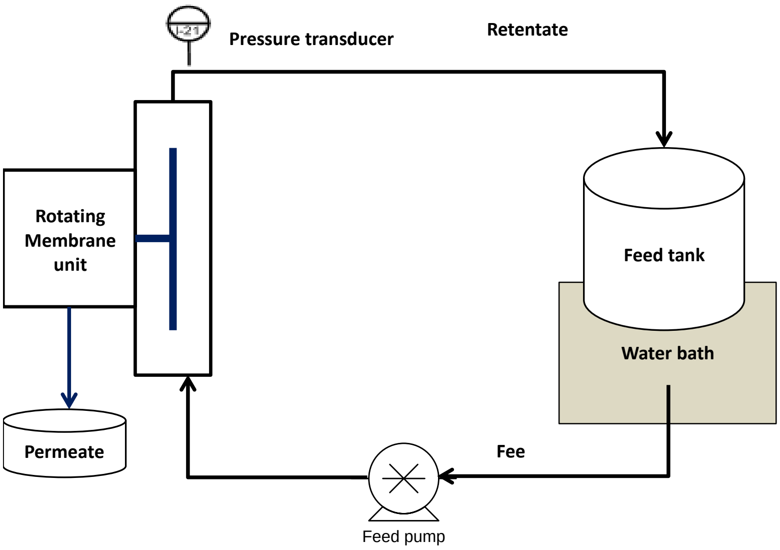

Fig.1. Diagram of rotary ultrafiltration system.

2.3. Performance evaluation of membranes

Effect of TMP and rotational speed

3 L of mung bean starch wastewater was adjusted to pH of 5.4 with either 5N HCl or 1N NaOH. The effects of membrane rotational speeds (842-1683 rpm) and TMP

(0.1-1.2 bar) on permeate flux and protein retention were performed. The corresponding mean shear rate (γ_m) at various rotating speeds calculated using Eq. (1) is shown in Table 2. At each rotating speed, TMP was stepwise increased with interval of 0.1 bar. The positive net TMP were calculated using Eq. (2) with the applied pressure (P_i) ranges shown in Table 2. Each experiment was operated under total recycle mode (return permeate and retentate to feed tank) at temperature of 50±1ºC. The permeate flux was recorded every 1 min. The permeate and retentate samples were taken every 10 min for protein content analysis.

Table 2. Experimental conditions.

Membrane rotational speed (rpm)	Mean shear rate (10^5 1/s)	Applied pressure (bar)
842	0.48	0.43-1.33
1122	0.81	0.52-1.42
1403	1.20	0.65-1.55
1683	1.70	0.80-1.70

Comparison of long-term flux behaviour under total recycle mode

3 L of mung bean starch processing wastewater was adjusted to pH of 5.4 with 5N HCl and 1N NaOH before feeding into the system. The system was operated for 4 h with membrane rotational speed of 1683 rpm under total recycle mode. Three different levels of TMPs (above threshold flux, threshold flux and below threshold flux) were tested. The threshold flux was determined by linear regression [15]. Each experiment was operated at temperature of 50±1 ºC. The permeate and retentate samples were taken every 30 min for protein content analysis.

Batch concentration mode

The experiments were also carried under batch concentration mode. The influences of operating technique, stabilization and without stabilization on permeate flux, fouling and protein retention was studied. In stabilization experiment, the permeate was recycle back to the feed tank while the TMP was stepwise increased (0.4, 0.6, 0.8 and1.0). After that the operation was performed under batch concentration mode at TMP of 1.2 bar, temperature of 50°C, rotating speed of 1403 rpm.

The experiment was carried out until the volume concentration factor which the ratio of the initial feed volume to the retentate volume (VCF) of 5.4 was achieved. In without stabilization experiment, the operation was carried out under batch mode at TMP of 1.2 bar, temperature of 50°C, rotating speed of 1403 rpm. The samples of permeate and retentate were taken every 30 min for protein analysis.

2.4. Calculated parameters

The mean membrane shear rate (γ_m) for this rotating disk module system can be calculated by the following equations [16];

$$\gamma_m = 0.057(\kappa\omega)^{1.8} r^{1.6} \nu^{-0.8} \quad (1)$$

where k is the velocity factor (0.42 for this system [16, 17]), ω (rad/s) is the disk angular velocity, r (m) is the outer membrane radius and v (m^2/s) is the fluid kinematic viscosity.

TMP (kPa) is the different pressure between applied pressure (P_i, kPa) and average permeate back pressure (P_b, kPa) [12]. Thus TMP can be calculated from Eq. (2);

$$\text{TMP} = P_i - P_b \tag{2}$$

where P_b is the result from the centrifugal force that bring permeates to the edge of membrane. However, permeates can be forced to the hollow center permeate collection tube by transmembrane pressure force [12]. P_b can be calculated using the following equation;

$$P_b = \frac{\rho(\omega I)^2}{2} \tag{3}$$

where ρ (kg/m^3) is the permeate density and ω (rad/s) is the membrane rotational speed, I is the radius of gyration for a flat rotating ring and can be calculated using the following equation;

$$I = \sqrt{\frac{r_i^2 + r_o^2}{2}} \tag{4}$$

where r_i and r_o (m) are the inner and outer membrane radius, respectively. The observed solute retention (R_j) is calculated by the equation as follows;

$$R_j = 1 - \frac{C_p}{C_b} \tag{5}$$

where C_p and C_b are the solute concentration in the permeate and in the feed, respectively. In addition, energy consumption per m^3 of permeate (specific energy, E_c) can be calculated by the following equation [13];

$$E_c = \frac{P_t}{Q_f} \tag{6}$$

where P_t is the sum of power of rotating disk motor (kW) and Q_f is the permeate flow rate (m^3/h).

2.5. Analysis of membrane fouling resistance

Based on Darcy's law, the resistances of permeate flow during ultrafiltration are given by

$$R_t = \frac{TMP}{\mu J} \tag{7}$$

$$R_t = R_m + R_{rf} + R_{if} \tag{8}$$

where μ is the solvent viscosity (Pa.s) and J is the volumetric flow rate of permeate per unit area of membrane (m/s), R_t is the sum of R_m (membrane resistance), R_{rf} (the resistance caused by reversible fouling) and R_{if} (the resistance caused by irreversible fouling). The R_t was calculated using the permeate flux and condition at the end of each run using Eq. (7). It is worthy to note that Eq. (7) can be also applied when some resistances are removed. After filtration of starch processing wastewater, the water was used to flush the membrane surface to remove R_{rf}. Water flushing was operated using clean water at rotating speed of 842 rpm and TMP of 0.1 bar for 15 min. After water flushing, the water flux was measured at TMP 1.2 bar and rotating speed 842 rpm to obtain the sum of irreversible fouling resistance (R_{if}) and membrane resistance (R_m) using Eq (7) with some modification. Then a chemical cleaning was applied by circulating 1.5% NaOH solution at 50°C, TMP 0.1 bar and rotating speed of 842 rpm for 30 min to remove irreversible fouling. The chemical cleaning solution was removed by water flushing until the pH was returned to 7. Then the water flux measured at TMP 1.2 bar and rotating speed 842 rpm to determine R_m using Eq. (7) with some modification. The R_{rf} was calculated using based on the results obtained (R_t, R_m+R_{if} and R_m).

2.6. Analytical methods

The protein content was analyzed using Bradford method. pH was measured with pH meter(S20 SevenEasy, Mettler Toledo, USA). The turbidity of raw material was measured by Turbi Check (Lovibond, Germany). The viscosity of raw material was measured with capillary viscometer.

2.7. Statistical plan

Completely randomized design was used throughout this study. Fouling resistance data were subjected to analysis of variance (ANOVA) and mean comparison was carried out using Duncan's Multiple Range Test (DMRT).

3. Results and Discussion

3.1. Effect of TMP and rotational speed

The membrane process performance indicators including permeate flux, retention and energy consumption is generally dependent on TMP and cross flow velocity or rotating speed in this study. Figure 2 shows the effect of rotating speed and TMP on average permeate flux**.** At higher rotating speed, the greater permeate flux was obtained. Since higher shearing force on membrane surface was generated at higher rotating speed. Therefore, the membrane surface fouling could be reduced leading to increase in permeate flux. In addition, permeate flux increased markedly with TMP at (high) rotating speed of 1403 and 1683 rpm. Generally, driving force increase with TMP leading to increase in permeate flux. At the same time, fouling layer would be formed. This study observed that the impact of TMP on permeate flux was more remarkable when high rotating speed was applied compared with those at lower rotating speed. This result indicated that fouling layer was removed due to shear force on the membrane surface.

Figure 3 shows that at each stepwise increasing of TMP, flux behaviours were varied with TMP and rotating speed. At the lowest rotating speed (842 rpm), the permeate flux obviously decreased with time. This might be the result of rapid formation of membrane fouling due to low shear force on the membrane surface. At the highest rotating speed (1683 rpm), the permeate flux at low TMP was almost stable but remarkably decreased with at high TMP level. This could be explained by the balance between fouling removal rate (induced by shear force) and fouling formation rate (induced by convective flow). The impact of rotating speed and TMP on flux improvement and energy consumption are considered for the optimum condition determination.

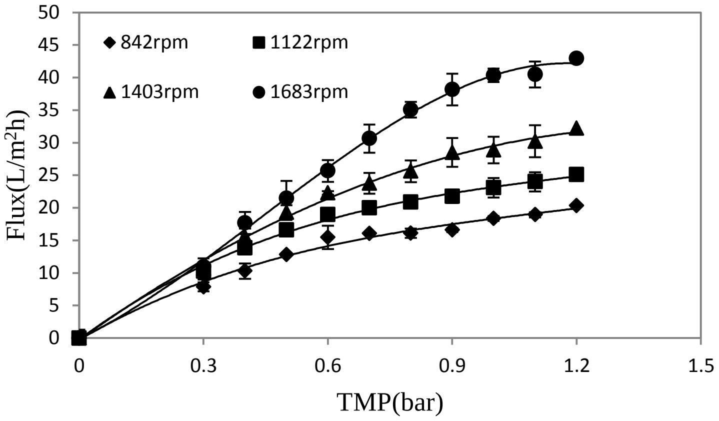

Fig. 2. Permeate flux with TMP at different rotating speed.

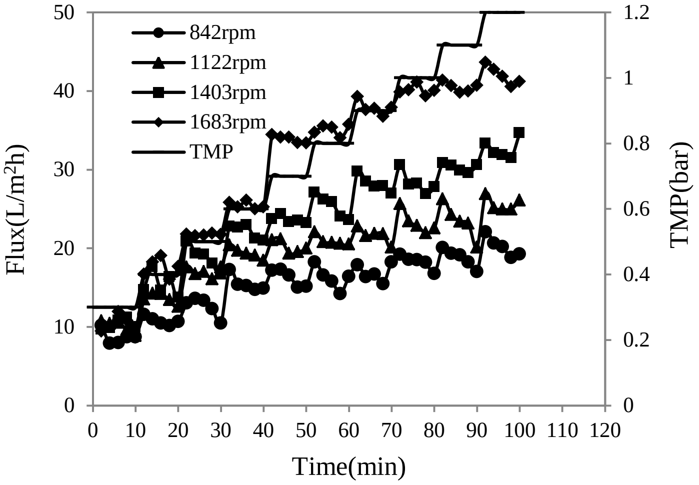

Fig. 3. Flux profiles in TMP stepping experiments at different rotating speed.

As shown in Fig. 4, the specific energy consumption varied as varying rotating shear rates and TMPs. At TMP of 0.3 bar, the specific energy consumption increased with rotating speed. At low TMP, the permeate flux was probably controlled by driving force (TMP) rather than back transportation of mass moving away from the membrane surface induced by shear force (see in Fig. 2). It is worthy to note that the power of rotating disk motor relates to rotating speed and the power consumption increase with rotating speed. When TMP increased, the specific energy consumption decreased noticeably, especially at rotating speed of 1683 rpm and then slightly decreased afterward. At TMP higher than 0.7 bar, the permeate flux increased insignificantly. As a result, the specific energy consumption was almost constant with TMP. Considering permeate flux and specific energy consumption from these results, rotating speed of 1683 rpm and TMP of 1.2 bar was possibly considered as the optimum condition for protein recovery from mung bean starch processing wastewater. In addition, the specific energy consumption was also analyzed based on the average flux taken from 15 min of operation, practically, the permeate flux obtained from longer operation time data is required. However, this result is suitable for preliminary guidance.

There are some flux concepts known as important technique for choosing the optimum condition in membrane filtration, such as limiting, critical and threshold fluxes [13, 15]. These concepts can be used to control fouling in cross flow filtration. Although dynamic shear-enhanced filtration modules are capable regarding the accumulation of particle on the membrane, the high permeate flux obtained at high shear rate also cause severe cake layer by convective transport of particles through the membrane surface [15].Therefore, in this present work, the permeate fluxes below threshold, at threshold and above threshold fluxes (at rotating speed of 1683 rpm) were also studied and compared under long-term operation under total recycle mode. The threshold flux is defined as a flux at, or below which, fouling formation is minimum and almost constant. However, the method for determination of threshold flux may vary. In this study, the threshold flux was determined from Fig. 2 using linear best fitting curve with the regression coefficient (R^2) higher than 0.99 [18]. In this study, the threshold flux was obtained at TMP of 0.8 bar and the flux obtained at TMP of 0.4 bar was chosen as below threshold flux.

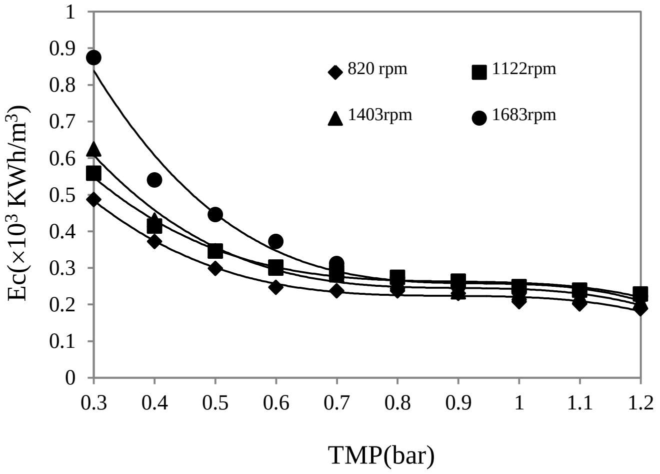

Fig. 4. Effect of rotating speed and TMP on specific energy consumption.

3.2. Comparison of long-term flux behavior

This section was designed to compare the impact of TMP on flux behaviour and fouling resistances and the results are shown in Fig. 5. As can be seen, three operating conditions (different TMPs) gave different permeate flux behaviours. It is important to note that the permeate flux during the first 2 min of operation was not observed. Above threshold flux (TMP of 1.2 bar), the permeate flux did not stable during 2-18 min of operation. It increased sharply in during 18-40 min and then increased gradually afterward. At threshold flux (TMP of 0.8 bar), permeate flux did not stable during 2-6 min of operation. It gradually increased in the first 8-30 min and increased slightly afterward. Below threshold flux (TMP of 0.4 bar), the permeate flux was almost stable throughout the operation. These were probably due to the different characteristics of fouling layer developed under different flux levels [18]. It might be explained by the conceptual particle deposition model with shear-induced transportation [18].

Since the average size of particle in mung bean wastewater was 33.3 µm, three main forces were possibly involved including hydrodynamic drag of filtration (particle moving from bulk flow to membrane surface by permeate convective force), shear-induced transport (particle moving away from membrane surface to bulk flow) and foulant-membrane/foulant interaction (particle accumulate on the membrane surface and inside the membrane pore). At high TMP (1.2 and 0.8 bar), it was possible that the initial flux (in the first few seconds) was very high. As a result, the fouling layer (reversible and irreversible fouling) was rapidly formed on the membrane surface. The interaction among particle-particle as well as particle-membrane probably determined fouling reversibility. At high shear force (rotating speed 1683 rpm), fouling layer rapidly formed on the membrane surface in the first few seconds was removed away from the membrane surface to bulk flow leading to remarkably increase in permeate flux. However, an increase in permeate flux operated at TMP of 0.8 bar was less compared with that at TMP of 1.2 bar suggesting that fouling layer form at the first few second at lower TMP (corresponding to lower initial flux or lower convective drag force) was less severe. Below threshold flux (TMP of 0.4 bar), the permeate flux remained almost constant. Under this condition, shear force, hydrodynamic drag force and foulant-membrane interaction forces were balance resulting in a stable permeate flux [18].

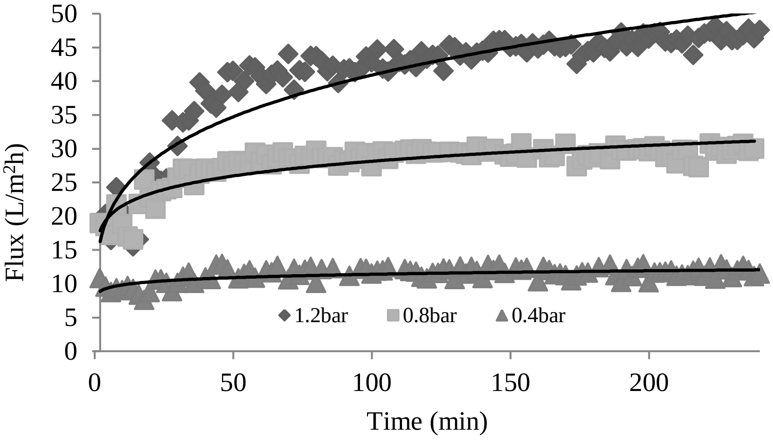

Fig. 5. Permeate flux as a function of time under total recycle mode at rotating speed of 1,683 rpm.

In addition, the irreversible fouling of all operated TMPs were not significant difference ($P>0.05$) as shown in Table 3. However, the reversible fouling resistance at TMP of 0.4 bar was significantly higher than those at TMP 1.2 and 0.8 bar suggesting that back transportation of particles moving away from membrane surface to bulk solution at TMP of 0.4 bar was less than those of the other. Protein retentions at all TMP were higher than 99% since the pore size membrane was much smaller than the size of most particles (3-190 µm). As mentioned above, dynamic filtration system with rotating membrane disk generates high shear rate ($>10^5$1/s) which is very effective in fouling reduction. For this study, the results showed that operating at rotating speed of 1683 rpm and TMP of 1.2 bar could give the most efficiency with specific energy consumption of 0.256 kWh/m^3.

Table 3. Fouling resistance and protein retention under total recycle mode at rotating speed of 1,683 rpm.

TMP	**R_t (x10^{12}) (1/m)**	**R_{if} (x10^{12}) (1/m)**	**R_{rf} (x10^{12}) (1/m)**	**Average protein retention (%)**
1.2	13±0.65^b	9.4±0.67^{ns}	1.5±0.06^b	99.4±0.00
0.8	13±1.68^b	10.2±1.93^{ns}	0.5±0.30^b	99.3±0.00
0.4	16±0.75^a	10.3±0.43^{ns}	3.4±0.92^a	99.3±0.00

Note: Each value is mean of triplicate ± SD. Different letters in the same column indicate the significant difference ($p<0.05$) , ns = non significant difference

3.3. Permeate flux and protein retention and fouling during batch concentration mode

It has been reported that the permeate flux started with batch concentration mode was lower than that of operation started with total recycling mode [19]. Therefore, the experiments were also carried out under batch concentration mode to investigate the effectiveness of using stabilization and without stabilization. The results are shown in Fig. 6. Both permeate fluxes decreased slightly during 15-125 min due to concentration polarization and fouling and gradually increased with time afterward. These results were slightly difference in pattern to those found in total recycle mode.

As mentioned in the previous section, these could be explained by the conceptual of particle deposition, accumulation and removal. The sheared force generated by rotating disk could effectively enhance back transportation from membrane surface, resulting in reduction of accumulation of particles and fouling on the membrane surface [19]. However, their effectiveness was less compared with those observed in total recycle mode. These might be due to the impact of viscous concentration polarization and severe membrane fouling during batch concentration mode. However, the permeate flux behaviour obtained under total recycle mode and concentration mode of this study was different from those found during microfiltration of baker yeast using rotating disk membrane [20]. The permeate flux of baker yeast remarkably decreased with operation time and concentration. Since baker yeast and microfiltration membrane with 0.2 µm pore size were used, fouling mechanism and characteristics were probably different from those found in this study. In addition, the shear rate used was also different levels leading to different ability in fouling removal. These results suggest that process variable parameters including feed properties, membrane pore size and level of shearing rate probably play important role in flux behaviour and fouling characteristic affecting the effectiveness of sheared enhance membrane system.

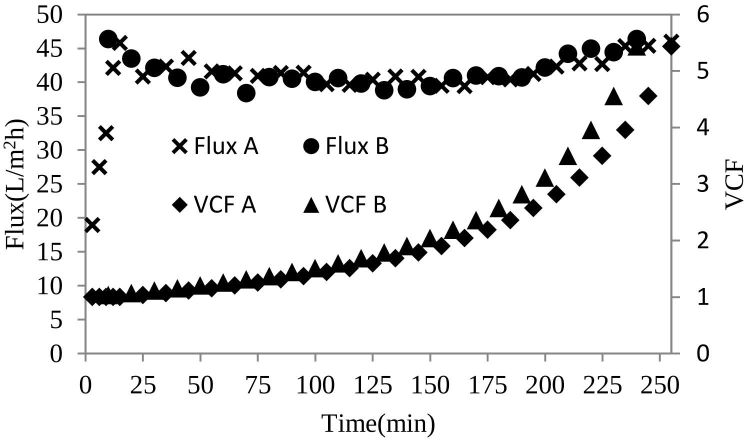

Fig. 6. Comparison of permeate flux and VCF under batch mode between operating Mode A (Stabilization for 15 min) and B (Without Stabilization) at rotating speed of 1403 rpm.

As mentioned in the previous section, these could be explained by the conceptual of particle deposition, accumulation and removal. The sheared force generated by rotating disk could effectively enhance back transportation from membrane surface, resulting in reduction of accumulation of particles and fouling on the membrane surface [19]. However, their effectiveness was less compared with those observed in total recycle mode. These might be due to the impact of viscous concentration polarization and severe membrane fouling during batch concentration mode. However, the permeate flux behaviour obtained under total recycle mode and concentration mode of this study was different from those found during microfiltration of baker yeast using rotating disk membrane [20]. The permeate flux of baker yeast remarkably decreased with operation time and concentration. Since baker yeast and microfiltration membrane with 0.2 µm pore size were used, fouling mechanism and characteristics were probably different from those found in this study. In addition, the shear rate used was also different levels leading to different ability in fouling removal. These results suggest that process variable parameters including feed properties, membrane pore size and level of shearing rate probably play important role in flux behaviour and fouling characteristic affecting the effectiveness of sheared enhance membrane system.

The permeate flux using stabilization (Mode B) increased with stepwise increasing of TMP during the first 15 min of operation. The highest flux at 15 min (TMP 1.2 bar) was 45.7 L/m^{2}h. This value was relatively close to that of without stabilization (mode A). In addition, fouling resistances, protein retentions were not significant difference ($P>0.05$) (see Table 4). This result suggested that using stabilization was not beneficial in fouling reduction, protein retention. In contrast, the use of stabilization led to increase total processing time. In this case, total processing times to achieve VCF of 5.4 using stabilization and without stabilization were 255 and 240 min, respectively.

Although the irreversible fouling resistances operating with and without stabilization were not different, the result of protein retention suggested that loose fouling layer was possibly formed when stabilization technique was employed. The effect of stabilization technique was difference from those found during microfiltration of chicory juice [19]. It was possibly due to the difference in feed characteristics, membrane pore size and rotating speed. These differences probably lead to difference in fouling characteristics influencing the effectiveness of stabilization with stepwise increasing of TMP method. In this study, membrane pore size (7 nm) was smaller than those of particles and soluble molecules, thus external fouling (reversible and irreversible fouling) would dominate. This external fouling was probably sensitive to applied shear force.

Since stepwise increasing of TMP is effective when internal fouling (almost irreversible) mechanism dominate, usually found in microfiltration of mixture molecules [21], stabilization of the system during ultrafiltration of mung bean processing wastewater did not helpful in fouling reduction. Generally, energy consumption is remarkably reduced by increasing number of rotating membrane disk mounted with the system. For batch concentration mode, two membrane disks were mounted. This led to increase in membrane area, giving the energy consumption of 81 kWh/m^3.

Table 4. Effect of stabilization technique on fouling resistance and protein retention.

Mode	R_m (10^{12}) (1/m)	R_t (10^{12}) (1/m)	R_{if} (10^{12}) (1/m)	R_{rf} (10^{12}) (1/m)	Protein rej. (%)
Mode A	1.6 ± 0.00^{ns}	13.1 ± 1.79^{ns}	11.3 ± 1.68^{ns}	0.1 ± 0.11^{ns}	93.9
Mode B	1.6 ± 0.00^{ns}	13.0 ± 0.67^{ns}	10.8 ± 1.20^{ns}	0.6 ± 0.54^{ns}	96.2

Note : Mode A (stabilization for 15 min) and ode B (without stabilization), each value is mean of triplicate ± SD, ns= non significant difference ($p>0.05$)

4. Conclusions

The rotary disk membrane system was successfully employed to recovery protein from mung bean starch processing wastewater. The permeate flux remarkably increased with rotating speed of membrane disk or TMP. The energy consumption was dependent on permeate flux achieved. The minimum energy consumption was 222.5 kWh/m^3 when the system was operated under total recycle mode at TMP of 1.2 bar and rotating speed of 1683 rpm. The shear-force generated by rotating disk could effectively remove fouling from the membrane surface and enhance mass transfer in the concentration polarization layer as indicated using an increase in the permeate fluxes operated under total recycle mode (total operation time 200 min) and batch concentration mode (total operation time 240-255 min). The permeate flux operated TMP 1.2 bar and rotating speed of 1403 rpm under batch concentration mode (VCF=5) was approximately 42 L/m^{2}h which is about 10 times higher than that reported in the literature using conventional cross flow system. The stabilization technique had no benefit for permeate flux improvement, fouling and protein retention. In contrast, the permeate flux and protein retention were higher than that of stabilization. The operation times to achieve VCF of 5.4 with stabilization was longer (255 min) compared to that without stabilization (240 min). The energy consumption during batch concentration mode was 81 kWh/m^3.

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