MEMBRANE CLEANING USING ELECTRIC PULSE IN DEAD END ULTRAFILTRATION OF PROTEINACEOUS SOLUTION

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ABSTRACT

Dead end ultrafiltration of Bovine Serum Albumine (BSA) using a polymeric membrane has been studied. Membrane fouling for such fine biological product due to the formation of filter cake and adsorption of the proteinaceous solution is the major bottleneck for such separation process. The application of electric pulses has shown an effective means in cleaning the membrane and reducing the fouling rate for dead-end ultrafiltration of BSA. The flux is significantly increased by both electrophoretic motion of solutes away from the membrane surface and electro-osmosis occurring in the filter cake. An automated experimental rig equipped with data acquisition system has been developed to test the effectiveness and performance of such membrane cleaning. The improvement of flux becomes more pronounced with increasing electric field strength. The effects of other processing variables such as pulse interval, pulse duration, ionic strength of the electrolyte, pH of the solution and solution concentration were studied on this membrane cleaning technique. Data are analysed for its average flux, average cake concentration, average percentage of cake and water recovery for every cleaning condition. It is found out that the chemical and physical properties of the solution (pH and ionic strength of the electrolyte) have a great effect on this membrane cleaning method. Protein solution at pH 8 and 0.01M ionic strength of the electrolyte gave the best membrane cleaning performance. Shorter pulse interval and with relatively 10 seconds pulse duration are the optimum conditions on application of pulse to remove the filter cake from the membrane.

1. INTRODUCTION

Ultrafiltration of colloidal and proteinaceous solutions has become increasingly important in recent years in widely diversified fields such as biotechnology, electronics, biomedicines, food and beverage processing and wastewater treatment. One of the major bottlenecks in the application of the ultrafiltration process is the flux decline with time due to membrane fouling. Such flux decline is mainly attributable to the formation of highly filter cake caused by accumulation of the protein solutes on the membrane surface¹. To maintain a high flux for extended periods of time, therefore, it is necessary to prevent a continuous buildup of proteinaceous solutes on the membrane surface.

The application of continuous electric field such as in conventional electrofiltration has known to be effective in reducing the rate of membrane fouling. The potential use of electric fields to control membrane fouling and filter cake formation has been studied^{2,3,4,5,6,7,8,9}. This approach utilises the inherent surface charge of dispersed materials when brought into contact with a polar (e.g. aqueous) solvent such as water. This may arise from a combination of various mechanisms, including ion association, ion absorption or ion dissolution¹⁰. The electrochemical properties of the membrane surface and the dispersed materials or solutes can have significant influence on the nature and magnitude of the interactions between the membrane and the substances being processed and the separation characteristics. The utilisation of such properties by the application of external electric fields can potentially give substantial improvement to the performance of membrane separation. In particular, such processes make use of two electrokinetic phenomena. The first one is electrophoretic, the transport of charged surface relative to a stationary liquid by an electric field, for example the movement of ion or particles between electrodes which occurs when an electric field is imposed on a dispersed system (ion or particle). The second one is electro-osmosis, the transport of liquid relative to an immobile charged surface by an electric field, for example the movement of an electrolytes solution relative to a membrane pore or filtercake under the influence of potential gradient⁴. Both of the electrokinetics phenomena are similar, the distinction being whether the frame of reference is a solid or a liquid. The magnitudes of both phenomena depend on the applied electric field gradient and Zeta potential (electric potential at the particles' shear between the mobile and immobile parts of the double layer)¹¹.

The conventional electrofiltration can be an effective means of reducing both the concentration polarisation and membrane deposition but it has some drawbacks with respect to economics and ease of operation. The disadvantages of this process are listed as follows:

- (i) The limitation of the process stream or relatively low conductivity.
- (ii) A high-energy requirement.
- (iii) Substantial heat production.
- (iv) Changes in the process feed due to reaction at the electrode.

For this reason, attention has been directed to the use of pulsed electric fields^{10,12,13,14,15}. This process has the same mechanism at work in preventing fouling as conventional electrofiltration. The distinction is that the electric field is applied at certain intervals, which can be adjusted to the process needed. In some cases, the process can be enhanced further to produce flux that is higher than that obtained from the conventional electrofiltration⁹. By applying the electric pulse on dead-end filtration, it has been reported that the rate of fouling was reduced^{8,14,16,17}. The advantages of the dead-end filtration process over the cross-flow filtration are higher average percentage of water recovery and filter cake concentration while giving a more acceptable range of permeation rate.

In order for the cleaning of membrane by electric pulse to be an effective method in reducing membrane fouling, the applied voltage must be higher than the critical voltage required to push particles or molecules away from the membrane surface^{18,19}. Chemical and physical properties of the solute such as the ionic strength of the electrolyte, solute concentration and the pH of the solution^{1,19} and the properties of each electric pulse such

as the pulse interval and pulse duration^{12,14,16,17} can also affect the performance of this membrane cleaning method. A force balance model has been developed for both cross flow filtration¹⁰ and for the case of dead-end filtration¹⁸. Both models show a liner relationship between magnitude of applied voltage and electrophoretic mobility of solutes or particles with the electrophoretic force; the backward force to push away solutes or particles away from the membrane surface under the influence of electric fields.

In the present work, dead-end ultrafiltration using Bovine Serum Albumine (BSA) as the test system is used to investigate the effectiveness of cleaning the membrane using electric pulse. In order to give a more efficient and accurate representation of experimental results, an automated test rig equipped with data acquisition system has been designed, developed and constructed to enable direct collection of reliable and reproducible data over a wide range of conditions. Effects of the following processing variables are presented on the membrane cleaning method for dead-end ultrafiltration of proteinaceous solution. The selected processing variables are as follows:

- (i) Variation of the application of the pulse interval.
- (ii) Variation of the pulse duration.
- (iii) Variation of the pH of the feed.
- (iv) Variation of ionic strength of the electrolyte.
- (v) Variation of the feed concentration.
- (vi) Variation of the electric field strength (voltage).

2. ANALYSIS AND CALCULATION OF DATA

In analysing the data, 4 parameters of results are considered as follows:

- (i) Average filtration rate.
- (ii) Average percentage cake recovery.
- (iii) Average percentage water recovery.
- (iv) Average cake concentration.

Average filtration rate is calculated as follows:

$$\frac{\text{Total permeate volume collected (L)}}{[\text{Active membrane area (m}^2\text{)}] [\text{Total time taken (h)}]} \quad (1)$$

Average percentage cake recovery is calculated as follows:

$$\frac{(\text{Weight of particle collected})}{c_f V_f + c_r V_c} \times 100 \quad (2)$$

Where;

c_f is the feed concentration (g/L)

V_f is the filtrate volume (L)

V_c is the volume of liquid collected with the cake (L)

In calculating average percentage cake recovery, it was assumed that the volume of particles in the cake was very small compared to the total volume of the slurry collected on discharge of the cake.

Average percentage water recovery is calculated as follows:

$$\frac{\text{Volume of filtrate}}{\text{Volume of filtrate} + \text{Volume of retentate (discharge with cake)}} \times 100 \quad (3)$$

Average cake concentration is the average cake concentration in the cake collected after every application of the electric pulses and is determined using a spectrophotometer.

3. MATERIALS AND METHODS

In this work, the filtration rate, the pressure, the temperature and the pH were monitored and recorded online. The electric pulse was applied at certain intervals and duration. The filter cake was released immediately upon completion of pulse application by opening the valve at the bottom of the filtration module.

A PC was connected to the system to collect data, control and adjust operational parameters using software called “GW-Basic computer programme”. The PC was connected to devices such as temperature probe, pressure transducer probe, level sensors and solenoid valves via the General Purpose Interface Bus (GPIB). The other main components are an A/D converter (to convert analog signals into digital signals readable to PC), signal conditioner, membrane module, feed reservoirs, pressurised gas (nitrogen free oxygen), pH meter, pressure transducer, temperature probe, balance, and nylon tubes (to complete the flow of feed to membrane module via the ‘serkit’ reinforced Nylon 66 tube fitting). Figure 1 shows the schematic diagram of the experimental set-up.

Figure 1: Schematic diagram of the experimental rig for ultrafiltration of BSA.

The filtration module was divided into two sections called the feed chamber and the permeate chamber, respectively. Both sections were fastened together using bolts and silicon rubber gasket. The overall dimensions of the process feed chamber were 11.2 cm x 3.4 cm x 0.2 cm with an effective working area of membrane equals 23 cm². The membrane was held on a stainless steel support and mesh. Both support and mesh form the cathode. Electrical contact was provided to the electrode through a stainless steel rod inserted through the wall of the permeate chamber and connected to the negative pole of the power source. In the feed chamber, a flat sheet (platinised titanium) was used to serve as an anode.

A Nadir (Hoechst, AG) flat sheet membrane with a 30,000 MWCO was selected for the experiment. A $\frac{3}{4}$ inch, 3.0L pressurised vessel made from reinforced polypropylene which can withstand pressure up to 833 kNm⁻² and temperature of 52°C was used as the feed tank. The concentration of BSA was selected to be 1 g/L and pH maintained at 8 for most experiments except for the variation of feed pH and feed concentration. Phosphate buffer is used as the electrolyte where BSA is dispersed in 0.01M phosphate buffer except for the variation of ionic strength of the electrolyte. The phosphate buffer is prepared by mixing same ionic strength of di-Sodium Hydrogen Orthophosphate (Na₂HPO₄) and Sodium Dihydrogen Orthophosphate (NaH₂PO₄·2H₂O) to give a specific pH of solution required.

4. RESULTS AND DISCUSSIONS

The average flux for normal filtration (without any membrane cleaning) for 1 g/L BSA dispersed in 0.01M phosphate buffer at pH 8 was found to be 16.25 L/m²h. Figure 2 (graph a) shows how the average flux dropped continuously with time as the BSA molecules form a filter cake continuously on the membrane surface throughout the filtration process. Figure 2 (graph b) shows how the average flux varies with time for 1 g/L BSA at pH 8

Figure 2: Flux vs. time for ultra filtration process for 1 g/L BSA dispersed in 0.01M phosphate buffer at pH 8, (a) normal filtration; (b) application of pulse at 90 minutes interval.

dispersed in 0.01M phosphate buffer with membrane cleaning using electric pulse. For that particular graph, 100 V electric strength (applied voltage) with 10 seconds pulse duration was applied for every 90 minutes pulse interval. It is clearly shown that the flux increased immediately after every 90 minutes interval of application of the pulses. This shows that the electric pulse is an effective means to remove the filter cake and prevent the membrane fouling. For other pulse durations and pulse intervals, it also shows the same trend. The following discussion will study the effect of processing variables on the effectiveness of this membrane cleaning method.

4.1 Effect of pulse interval

Figure 3 and Figure 4 show the effect of pulse interval on average flux, average cake concentrations, average percentage water recovery and average percentage cake recovery. Pulse interval of 10, 20, 40, 60 and 90 minutes are chosen with 10-second pulse interval for 1 g/L BSA dispersed in 0.01 phosphate buffer at pH 8.

Figure 3: Effect of pulse interval on average flux and average cake concentration with 10s duration, 1 g/L BSA, 0.01M ionic strength, pH 8 and 100V electric strength.

Figure 4: Effect of pulse interval on average percentage cake and water recovery with 10s duration, 1 g/L BSA, 0.01M ionic strength, pH 8 and 100V electric strength.

As the pulse interval increases from 10 minutes to 90 minutes, the average flux decreases from 39.2 L/m²h to 20.1 L/m²h. For the average percentage cake recovery, its value decrease from 93.7% to 60.3% as the pulse interval increases from 10 to 90 minutes. As the filtration process proceeds, the filtration rate will drop continuously throughout the experiment because the BSA molecules keep forming the filter cake on the membrane surface. Once the electric pulses are applied, the BSA molecules are removed from the membrane surface under the effect of electrophoretic force which is applied more often at the shorter pulse interval. Hence, the average flux and the average percentage recovery of cake are higher at shorter pulse interval compare to the longer pulse interval as clearly shown in Figure 3 and Figure 4.

Effect of pulse interval on average cake concentration and average percentage water recovery show a similar trend. Both of them increased as the pulse interval was increased. The average cake concentration increased from 2.08 g/L to 3.38 g/L when the pulse interval was increased from 10 to 90 minutes whereas the average percentage water recovery increases from 54.9% to 81.9% as the pulse interval was increased from 10 to 90 minutes. Relatively, with longer pulse interval, more amount of BSA molecules deposited on the membrane surface as the filtration process continued before any membrane cleaning takes place. For every discharge of filter cake, the retentate volume discharged after every pulse interval with the cake essentially remains constant since the withdrawal of the filter cake is controlled automatically at the same period of withdrawal and under the effect of the same running pressure. Hence, its volume collected should be almost the same for every withdrawal. As shown clearly in equation (2) and equation (3), the average water recovery and average cake concentration are greatly dependent on the volume of the retentate. At longer pulse interval, less total volume of retentate was collected. As a result, the average cake concentration and the average percentage water recovery are higher at longer pulse interval.

4.2 Effect of pulse duration

Pulse duration is another parameter which can affect the effectiveness of this membrane cleaning method. Pulse durations of 3, 5, 7.5, 10, 15, 20 and 40 seconds with 20 minutes pulse interval of 100 V voltage strength for 1 g/L BSA dispersed in 0.01 phosphate buffer at pH 8 were chosen. Figure 5 shows the effect of pulse duration on the average flux and the average cake concentration. It shows clearly that as the pulse duration was increased from 3 to 10 seconds, the average flux increased from 22.5 L/m²h to 28.4 L/m²h. When the

Figure 5: Effect of pulse duration on average flux and average cake concentration with 20 minutes interval, 1 g/L BSA, 0.01M ionic strength, pH 8 and 100V electric strength.

Figure 6: Effect of pulse duration on average percentage cake and water recovery with 20 minutes interval, 1 g/L BSA, 0.01M ionic strength, pH 8 and 100V electric strength.

pulse duration was further increased longer to 15, 20 and 40 seconds, the average flux started decreasing to 26.1, 25.7 and 22.5 L/m²h respectively. The highest average flux was found at 10-second pulse duration. The average cake concentration shows a similar trend as the average flux where the maximum average cake concentration was found at 10 seconds pulse duration.

Figure 6 shows the effect of pulse duration on the average percentage cake recovery and the average percentage water recovery. Both values increased as the pulse duration was increased from 3 to 10 seconds but then they started decreasing as a long pulse duration was applied, from 10 to 40 seconds. The average percentage cake recovery was 91.8% at 3 seconds pulse duration and then increased to 93.8% at pulse duration of 10 seconds and decreased to only 67.7% as the longer pulse duration of 40 seconds. The average percentage water recovery increased from 57.2% at 3 seconds to 64.2% at 10 seconds and then decreased to 58.4% as a longer pulse duration of 40 seconds was applied.

From the force balance model¹⁸, the molecules need to be removed at a certain distance away from the membrane surface in order to be swept out from the membrane module at every application of pulse. At a shorter pulse duration, the time allowed is not long enough to remove the BSA molecules to the minimum distance away from the membrane to facilitate sweeping them out, since at the same time, they are also experiencing forward force by viscous drag due to the pressure driven flow, the forces arising from electro-osmosis in the cake and in the membrane. On the other hand, the properties of the filter cake might have changed on application of a longer pulse duration (15, 20 and 40 seconds) in such away as to produce an increase in resistance of fluid to flow. This may be due to the change in the morphology of firmly adhering layers produced by the action of electric pulse¹⁰. Local changes in conductivity, pH and temperature on application of the electric field might change the structure of the BSA molecules¹³. This might lead to such an effect. Changes in pH will change the electrophoresis mobility of BSA molecules as shown in Table 1, which will be discussed in detail in Section 4.3 on the effect of pH solution. It has been found that protein BSA is a biological material which is very sensitive toward temperature and pH. Furthermore, if the applied longer electric pulse reconstructed BSA molecules around the membrane pores so as to increase the effective surface of BSA, the observed effect might be expected.

Table 1: Effect of pH on electrophoretic mobility of BSA molecules in 0.01M phosphate buffer.

pH of Solution	Electrophoretic Mobility 10 ⁻⁸ m ² /sV
5	-0.70
6	-1.11
7	-1.83
8	-1.95

4.3 Effect of pH solution

The effect of pH was also studied where 4 sets of pH solutions at pH 5, pH 6, pH 7 and pH 8 were chosen. Figure 7 shows the trend of the results on the average flux and the average cake concentration. As the pH of the solution was increased from 5 to 8, both average flux and average cake concentration increased from 18.6 to 28.3 L/m²h and from 2.05 to 2.61 g/L respectively. Figures 8 shows the effect of pH on the average percentage recovery of cake and average percentage recovery of water. The trend is quite similar to the average flux and average cake concentration. As pH was increased from 5 to 8, the average percentage recovery of cake increases from 86% to 96%, whereas for average percentage recovery of water, it increased from 51% to 60.3 % as the pH was increased from pH 5 to pH 8. The effect of pH gives a very systematic and same trend of results as the pH of the solution increases from pH 5 to pH 8. All the results increased as the pH was increased. This sort of pattern is expected since higher pH will result in higher zeta potential¹¹.

Figure 7: Effect of pH on average flux and average cake concentration with 20 minutes interval, 10s duration, 1 g/L BSA, 0.01M ionic strength and 100V electric strength.

Figure 8: Effect of pH on average percentage cake and water recovery with 20 minutes interval, 10s duration, 1 g/L BSA, 0.01M ionic strength and 100V electric strength.

Table 1 shows the analysis of BSA molecules on its electrophoretic mobility. It clearly shows that as the pH was increased from pH 5 to pH 8, the magnitude of electrophoretic mobility increased from $-0.70 \times 10^{-8} \text{ m}^2/\text{sV}$ to $-1.95 \times 10^{-8} \text{ m}^2/\text{sV}$. Cleaning the membrane using electric field (such as electric pulse) makes use of BSA surface charge, resulting in the movement of BSA molecules away from the membrane surface at the rate that depends on their electrophoretic mobility. The force balance model for dead end filtration¹⁸ shows a linear relationship between electrophoretic mobility and the electrophoretic force, the backward force responsible to remove the BSA molecules away from the membrane surface under the influence of electric field. Hence, the electrophoretic force is expected to be higher at higher electrophoretic mobility of BSA molecules, and from the current study, it is shown to be more effective at pH 8 as indicated in Table 1. As shown in Figures 7 and 8, the optimum pH is 8.

4.4 Effect of ionic strength of electrolyte

Electrolyte ionic strength of 0.1M, 0.01M, 0.001M and 0.0001M were used to investigate its effect on the result for 1 g/L BSA dispersed in phosphate buffer at pH 8 and with application of 100V and 10 seconds pulses at 20 minutes pulse interval.

Figure 9 shows the effect of electrolyte ionic strength as the average flux and the average cake concentration. When the electrolyte strength was reduced from 0.1M to 0.01M, the average flux increased from 14.7 L/m²h to 28.3 L/m²h. As the electrolyte strength was further reduced to 0.001M and 0.0001M, the average flux reduced to 27.0 L/m²h and 22.2 L/m²h respectively. The same trend was observed for the average cake concentration when the electrolyte strength was reduced from 0.1M to 0.01M, 0.001M and 0.0001M, the average cake concentrations were 1.69 g/L, 2.61 g/L, 2.60 g/L and 2.30 g/L respectively.

Figure 9: Effect of ionic strength of electrolyte on average flux and average cake concentration with 20 minutes interval, 10s duration, 1 g/L BSA, pH 8 and 100V electric strength.

Figure 10: Effect of ionic strength of electrolyte on average percentage cake and water recovery with 20 minutes interval, 10s duration, 1 g/L BSA, pH 8 and 100V electric strength.

Figure 10 shows the effect of ionic strength of electrolyte on the average percentage recovery of water and percentage recovery of cake. As the electrolyte strength was reduced from 0.1M to 0.01M, 0.001M and 0.0001M, the average percentage recovery of cake were 75.6 %, 96.0%, 94.3% and 89.3% respectively, whereas the average percentage water recovery were 44.7%, 60.3%, 60% and 56.5% respectively. From all of these results, it can be concluded that the optimum condition is at 0.01M electrolyte strength. This phenomenon can easily be explained by analysing the property of BSA molecules dispersed in those 4 different ionic strengths of electrolytes at pH 8. Table 2 shows the magnitude of its respective electrophoretic mobility of pH 8 with ionic strength of 0.1M, 0.01M, 0.001M and 0.0001M. Even though there is no clear relationship between ionic strength and electrophoretic mobility, the graph clearly shows that the magnitude of electrophoretic mobility was found to be the highest at 0.01M. The value of electrophoretic mobility of BSA at this electrolyte strength (0.01M) is $-1.95 \times 10^{-8} \text{ m}^2/\text{sV}$. Hence, the observed results are expected as explained in Section 4.3 and the optimum ionic strength for the current membrane cleaning is at 0.01M.

Table 2: Effect of ionic strength of electrolyte on electrophoretic mobility in phosphate buffer at pH 8.

Ionic Strength of Electrolyte	Electrophoretic Mobility 10 ⁻⁸ m ² /sV
0.1M	-0.01
0.01M	-1.95
0.001M	-1.89
0.0001M	-1.07

4.5 Effect of feed concentration

The effect of feed concentration is tested with concentration of 0.1, 0.5, 1.0, 2.5, 5.0 and 10 g/L. Figure 11 shows this effect on the average flux and the average cake concentration. It clearly shows that as the feed concentration increases from 0.1 to 10 g/L, the average flux decreases from 65.1 to 12.5 L/m²h. This phenomena is expected that relatively BSA molecules deposited on the membrane surface is more and faster at higher feed concentration which results lower average flux. An opposite pattern is observed for the average cake concentration where its value increases from 0.47 to 11.95 g/L as the feed concentration increases from 0.1 to 10 g/L. The higher the feed concentration, relatively more BSA molecules present at the feed solution were swept out after every withdrawal of filter cake at 20 minutes interval, giving higher average cake concentration. Figure 12 shows its effect on the average percentage recovery of water and cake.

As the feed concentration increases, both average percentage recovery of water and cake increased. At lower feed concentrations (0.1 and 0.5 g/L), all BSA molecules are recovered from the membrane surface during withdrawal of filter cake at interval of 20 minutes, since the average percentage recovery of cake is above 100% for both of them. The value is slightly over 100% due to error arising in the accuracy of the equipment used in carrying out those measurements. Increasing the feed concentration from 1 g/L to 5 g/L, would still give high recovery of cake which is more than 90%. Increasing the feed concentration up to 10 g/L, would reduce the average percentage recovery of cake to only 73.1% due to the higher absorption and interaction between BSA molecules and the membrane surface when increasing the bulk concentration^{1,20}.

Figure 12 also shows how the average percentage water recovery varies with feed concentration. Its value reduced from 77.8 % to 38.8 % as the feed concentration was increased from 0.1 g/L to 10.0 g/L. It is obvious that at higher feed concentrations, more BSA molecules are deposited on the membrane surface, hence giving lower flux as shown in Figure 11 and consequently, giving lower average percentage water recovery as clearly stated in equation (3). This is because the volume of retentate for every withdrawal of filtercake is almost constant as discussed in Section 4.1.

Figure 11: Effect of feed concentration on average flux and average cake concentration with 20 minutes interval, 10s duration, 0.01M ionic strength, pH 8 and 100V electric strength.

Figure 12: Effect of feed concentration on average percentage cake and water recovery with 20 minutes interval, 10s duration, 0.01M ionic strength, pH 8 and 100V electric strength.

Figure 13: Effect of applied voltage on average flux and average cake concentration with 20 minutes interval, 10s duration, 1 g/L BSA, 0.01M ionic strength and pH 8.

Figure 14: Effect of applied voltage on average percentage cake and water recovery with 20 minutes interval, 10s duration, 1 g/L BSA, 0.01M ionic strength and pH 8.

4.6 Effect of applied voltage

The effect of varying the strength of applied voltage from 12.5 V to 100 V of 10 seconds duration at 20 minutes are chosen for 1 g/L BSA dispersed in 0.01M phosphate buffer at pH 8. Figure 13 and Figure 14 summarised the results. Generally for all cases, the average flux, average cake concentration, average percentage cake recovery and average percentage water recovery increased as the applied voltage was increased from 12.5 V to 100 V. Figure 13 shows that the average flux increased from 19.2 L/m²h to 28.3 L/m²h whereas the average cake concentration increased from 1.94 g/L to 2.61 g/L. Figure 14 shows that

the average percentage cake recovery increased from 91.7 % to 96 % whereas the average percentage water recovery increased from 52.6 % to 60.3 %. All results show a very systematic effect of applied voltage.

From the analysis of Force Balance Model developed for similar work by Ahmad *et al.*¹⁸, it is shown that the magnitude of electrophoretic force which is the main driving force to push away BSA molecules from the membrane surface under influence of an electric field (such as pulse) has a linear relationship with the applied voltage. In other words, its magnitude increases as the applied voltage increases from 12.5 V to 100 V as discussed in Sections 4.3 and 4.4, and the results show that membrane cleaning by electric pulses becomes more effective as shown in Figures 13 and 14.

5. CONCLUSION

Membrane cleaning using electric pulses for dead-end ultrafiltration of protein solution is an effective method in preventing membrane fouling. Electric pulses enable removal of more than 90% BSA molecules deposited on membrane surface and the average flux returned to its original value immediately after every application of electric pulses. The automated experimental rig enables direct collection and reproducibility of a wide range of data in order to provide more efficient and accurate representation of experimental results. The effects of processing variables such as pulse interval, pulse duration, pH, electrolyte strength, feed concentration and applied voltage on average flux, average cake concentration, average percentage cake and water recovery are presented. Analysis from all the results show that the performance of membrane cleaning using electric pulse for protein solution is optimal at a shorter pulse interval (10 minutes), with a pulse duration of 10 seconds, at an electrolyte strength of 0.01M and pH 8, at low feed concentration and with highest magnitude of applied voltage (100V).

6. REFERENCES

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