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EFFECT OF OPERATING CONDITIONS IN MEMBRANE MODULE PERFORMANCE

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Abstract

The performance of a membrane module depends not only on the membrane properties but also on the operating conditions. Current efforts usually focus on the enhancement of membrane characterization, less attention has been paid to the process parameters in which the membrane itself should be operated. The decision on operating conditions is generally based on experience, looking on handbook or suggestion of membrane manufacturers. However, the transport equation governing the performance of the membrane system varies in particular application and situation. Therefore, a general procedure for the design and operation strategy should be introduced for any given application. In our previous study, a simple combined model was developed to predict the permeation in cross-flow ultrafiltration of protein solution. Then, the - steady state permeate flux was estimated from the model and the correlation to operating condition is established. From the governing equation, it should be possible to study the effect of operating condition on the cost for any given application. In this study, the configuration is assumed as feed and bleed operating mode and a model which incorporates the friction loss is introduced. Then, it is applied to investigate the effect of operating parameters such as the pressure and the recirculation flow rate to the average cost per unit volume permeate. The average cost is the cost per unit volume permeate of an existing module. The total cost includes a fixed component relating to the size of the existing module and the operating component associated with the energy usage. The simple optimization routine (cyclic coordinate method) is also used to determine the most cost effective module operation.

Keywords: Combined Model, Cross-flow, Energy Cost, Simulation, Ultrafiltration

Introduction

The operation of cross-flow ultrafiltration is strongly affected by the flux behavior. The declination of permeate flux depends not only on the membrane properties but also the operating conditions. Current researches and development efforts are directed primarily to improve membrane performance, both in terms of rejection and flux. Less attention has, however, been paid to the process parameters in which the membrane itself should be operated.

In operation, the decision on operating conditions is usually based on experience, looking on handbook or suggestion by membrane manufacturers. However, the transport equation governing the performance of the membrane system varies in particular application and situation. Therefore, a general procedure for the design and operation strategy should be introduced for any given application.

In our previous study [1], a simple combined model was developed and showed the applicability in the prediction of flux behavior in cross-flow ultrafiltration of protein solution.

In [2], steady state permeate flux is estimated from the model and the correlation of the operating condition is established. The estimation by mean of the model can be widely applied for any practical process to determine the transport equations governing the physical performance of the membrane for protein separation. From the governing equation, it should be possible to study the effect of operating condition on the cost for any given application. This operating condition will depend on factors such as the feed flow rate, fixed cost and the cost of energy at the site in question.

In this study, the configuration is assumed as feed and bleed operating mode and a model which incorporates the friction loss is introduced. Then, it is applied to investigate the effect of operating parameters, the pressure and the recirculation flow rate to the average cost per unit volume permeate. The average cost is the cost per unit permeate volume of an existing module. The total cost includes a fixed component relating to the size of the existing module and an operating component associated with energy usage. The simple optimization routine (cyclic coordinate method) is also used to determine the most cost effective module operation.

System Configuration and Simulation

System Configuration

The operational configuration assumed in formulating the optimization problems investigated in this work is described as follows. The operational configuration is assumed to be continuous feed and bleed mode. This mode of operation, shown schematically in Figure 1, is the most common method used for continuous full-scale operation [3,4]. Two pumps may be required: the feed pump provides the trans-membrane or system pressure, while the recirculation pump maintains the desired cross-flow rate through the modules. A portion of the loop is continuously bleed off as retentate at a flow rate (R).

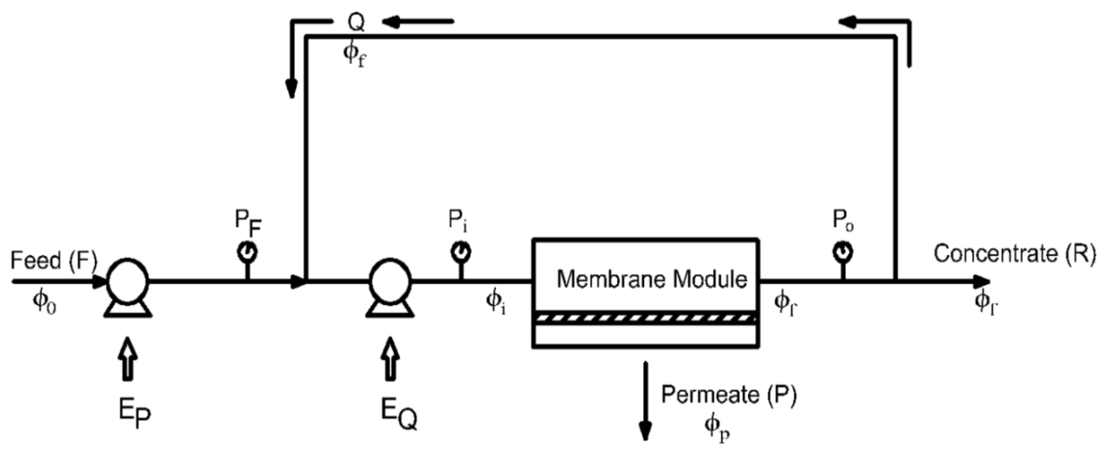

Figure 1. Schematic of membrane system operational configuration

Modeling of Module Performance

The model for simulation of the membrane plant is discussed. The simulation is necessary for the calculation of energy usage, which is an important factor in determination of the total cost of the plant.

Due to the shear stress exerted by the tangential feed flow, the accumulation of the retained species in the membrane is reduced, and the nearly steady state operation can be attained. The determination of steady state permeate flux is significant in the design and optimization problem. In our previous study [1], a simple combined model was developed and showed the applicability in the prediction of flux behavior in cross-flow ultrafiltration of protein solution. In [2], it is considered to apply the model proposed in [1] to predict the steady state permeate flux from the experimental data. After that, a new method using dimensional analysis is also developed to predict the steady state permeate flux from the operating conditions such as the trans-membrane pressure, the feed flow rate and the feed volume fraction in various range. The correlated equation provides a good estimation of experimental results.

In ultrafiltration, the pressure also affects the permeate flux, thus, the frictional pressure loss should be taken into account. In this module model, the flow channel is divided imaginarily into a number of segments in which the average values of transport properties are assumed to apply. The membrane channel is equally divided by length. For each increment, the permeate flux equation is applied to calculate the flux. The pressure drop for the increment is also incorporated. By carrying out mass balance the concentration of the next increment is estimated. The pressure drop will determine the operating pressure of the next increment. The detail of the mathematical form is discussed as follows.

Material and component balance for entire module

$$F = R + P \tag{1}$$

$$F\phi_0 = R\phi_{\mathrm{f}} + P\phi_{\mathrm{p}} \tag{2}$$

In this study, it is assumed that the protein is fully rejected by the membrane, and thus, $\phi_p = 0$.

At the mixing point of the feed stream and recirculate stream:

$$F\phi_0 + Q\phi_{\mathrm{f}} = \left(F + Q\right)\phi_{\mathrm{i}} \tag{3}$$

Dividing the membrane module from ϕ_i to ϕ_f to n intervals, each has the length

$$l = \frac{L}{n} \tag{4}$$

The flow rate and cross-flow velocity of the first segment

$$Flow_1 = F + Q \tag{5}$$

$$\phi_1 = \phi_{\mathrm{i}} = \frac{F\phi_0 + Q\phi_{\mathrm{f}}}{F + Q} \tag{6}$$

$$u_1 = \frac{F + Q}{A_{\mathrm{cross}}} = \frac{F + Q}{h \times w} \tag{7}$$

Where wxh is the cross-sectional area of the membrane, w is the width and h is the height of the membrane module.

Rheological properties such as the viscosity and density at each segment are correlated by the following equations [5]:

$$\mu_{\mathrm{j}} = 8.94\times10^{-4}\exp\left(13.5482\phi_{\mathrm{j}}\right) \tag{8}$$

$$\rho_{\mathrm{j}} = 1000\left(1-\phi_{\mathrm{j}}\right)+1360\phi_{\mathrm{j}} \tag{9}$$

In Eq. (9), 1000 and 1360 are densities of water and protein, respectively.

The permeate flux is then estimated [6]:

$$\mathrm{St_m} = \frac{J_{\mathrm{ss}}}{u} = 3.66\times10^{-7}\left(\frac{P}{\rho u^2}\right)^{0.27}\left(\frac{\rho u d_{\mathrm{h}}}{\mu}\right)^{0.52} \tag{10}$$

$$J_{\mathrm{j}} = 3.66\times10^{-7}\left(\frac{P_{\mathrm{j}}}{\rho_{\mathrm{j}} u_{\mathrm{j}}^2}\right)^{0.27}\left(\frac{\rho_{\mathrm{j}} u_{\mathrm{j}} d_{\mathrm{h}}}{\mu_{\mathrm{j}}}\right)^{0.52} u_{\mathrm{j}} \tag{11}$$

The pressure loss at each segment is calculated as follows:

$$\Delta P_{\mathrm{j}} = 4 f \rho_{\mathrm{j}} \frac{l}{d_h}\frac{u_{\mathrm{j}}^2}{2} \tag{12}$$

Where f is the Fanning friction factor [7, 8]:

$f = \frac{24}{\mathrm{Re_j}}$ for laminar flow in rectangular channel (Re<2000)

$f = \frac{0.079}{\mathrm{Re_j^{0.25}}}$ for turbulent flow (smooth pipes, Blasius correlation) (Re>2000)

The characteristic length for calculating the Reynolds number and the pressure loss is the hydraulic diameter, which is twice the distance between the plates $2w$. The concentration, flow rate and velocity of the next section are determined from the previous one by the mass balance shown as follows:

$$Flow_{\mathrm{j+1}} = Flow_{\mathrm{j}} - w\times l\times J_{\mathrm{j}} \tag{13}$$

$$\phi_{\mathrm{j+1}} = Flow_{\mathrm{j}}\times\phi_{\mathrm{j}} / Flow_{\mathrm{j+1}} \tag{14}$$

$$u_{\mathrm{j}} = \frac{Flow_{\mathrm{j}}}{h\times w} \tag{15}$$

The inlet pressure at each segment is calculated from the previous segment and the pressure loss is given as:

$$P_{\mathrm{j+1}} = P_{\mathrm{j}} - \Delta P_{\mathrm{j}} \tag{16}$$

The characteristics of the segment such as rheology properties, permeate flux, pressure loss are then estimated by the equations (8), (9), (11), (12). By mass balance and pressure loss, the retentate concentration leaving the increment and the inlet pressure for the next increment is calculated. The procedure is repeated until the last segment.

The total energy generated by the pumps [3, 7]:

$$\begin{aligned} E_{\mathrm{pumps}} &= E_{\mathrm{P}} + E_{\mathrm{Q}} \\ &= F \times P_{\mathrm{F}} + \left\{ F \times \left(P_{\mathrm{i}} - P_{\mathrm{F}} \right) + Q \times \left(P_{\mathrm{i}} - P_{\mathrm{o}} \right) \right\} \\ &= F \times P_{\mathrm{i}} + Q \times \Delta P_{\mathrm{loss}} \end{aligned} \tag{17}$$

Where,

E_P, E_Q is the energy generated by the feed pump and recirculation pump

P_F, P_i, P_o is the pressure outlet of the feed pump, inlet and outlet pressure of the module

ΔP_{loss} is the total pressure loss over the module and pipes

For the simplification, the total pressure loss is calculated as:

$$\Delta P_{\mathrm{loss}} = \sum_{\mathrm{j}} \Delta P_{\mathrm{j}} \tag{18}$$

Economics Consideration

Energy Cost

The energy cost per year by the pumps is expressed as

$$C_{\mathrm{pumps}} = \frac{E_{\mathrm{pumps}}}{\eta} \times \frac{3600}{1000} \times 8000 \times \text{energy cost} \tag{19}$$

The E_{pumps} is the energy required of the two pumps (feed pump and recirculation pump) and will be determined by Eq. (17). The calculation of annual energy cost is based on 8000 h/year operation (24 h/day and 333 days/year operation). η is the pump efficiency factor and is assumed to be 0.7. Energy cost is the cost as $/kWh, and is assumed to be 0.08$/kWh in this study. The assumed value is based on the electricity price for industrial sector in USA [9].

Fixed Cost

In an existing membrane module, the fixed cost C_0 includes the membrane replacement and cleaning, labor cost, capital cost, administrative cost. This cost does not depend on the permeate volume. For the calculation purpose, the fixed cost is converted to the energy equivalence based on the Eq. (19);

$$E_{\mathrm{equi.}} = C_0 \frac{\eta}{\text{energy cost}} \times \frac{1000}{3600} \times \frac{1}{8000} \tag{20}$$

Average Cost per Unit Volume Permeate

The average cost per unit volume is calculated as the required energy per unit volume permeate. The required energy includes the energy for the pumps and the equivalent energy of the fixed cost.

$$E_{\text{required}} = \frac{E_{\text{fixed cost}} + E_{\text{pumps}}}{\text{volume permeate}} \tag{21}$$

The volume permeate is the summation of permeate at each increment or simply by the total mass balance

$$\text{volume permeate} = F - R = F\left(1 - \frac{\phi_0}{\phi_{\text{f}}}\right) \tag{22}$$

Formulation of the Problem

In this study, it is considered that the membrane module is plate-and-frame and exists. Therefore the membrane module dimensions, feed flow rate and the fixed cost are already determined. The effect of operating parameters, inlet pressure and recirculation flow rate is investigated. The baseline configuration is assumed in Table 1.

Table 1. Baseline Configuration

Parameters	Value
Feed flow rate (m^3/h)	0.2
Inlet pressure (kPa)	500
Recirculation flow rate (m^3/h)	15
Initial protein fraction (m^3/m^3)	0.1
Fixed cost in equivalent energy (J/s)	600000
Energy cost ($/kWh)	0.08
Efficiency of pumps (%)	70
Temperature (^{o}C)	25
Module length (m)	15
Module height (mm)	7
Module width (m)	20

In the simulation of the problem, in order to determine the inlet concentration ϕ_i, the final retentate concentration ϕ_f is required. Therefore, first the outlet concentration is assumed to be the inlet concentration and the calculation is performed until the last increment. Then, the new outlet concentration is estimated and compare to the current value. The iteration is conducted until the difference between the new and old value of ϕ_i is smaller than 0.01. The algorithm proposed is shown in Figure 2

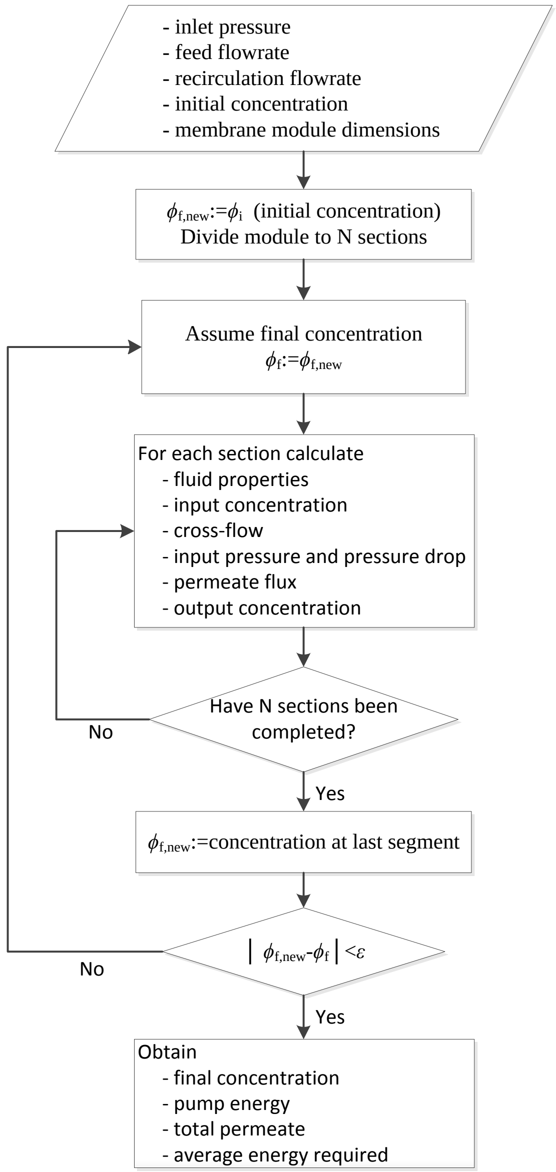

Figure 2. Algorithm for the simulation of the problem

After the simulation step, the values of total permeate and pump energy are obtained and the energy required can be estimated by Eq. (21). The aim is to minimize the energy requirement. The simple optimization routine, cyclic coordinate method [10], is used to determine the most cost effective module operation. Often in the solution of multivariable optimization problems it is desired to be done with a gradient-free algorithm. This may be the case when gradient evaluations are difficult, or in fact gradients of the underlying optimization method do not exist. Such a method that offers this feature is the method of the cyclic coordinate search, the simplest method for nonlinear optimization. The idea of this method is to find the optimum in one coordinate while the others are kept constant. The position at which the optimum is achieved is used as the basic for the search in the next coordinate one iteration is completed if all the coordinates is involved. The procedure is repeated and will stop when no further improvement of the objective function.

Results and Discussion

Effect of Inlet Pressure Operation

Figure 3 shows the effect of the operating pressure on the average cost. Other parameters are kept constant, recirculation flow rate is $Q = 15m^3/h$ - and membrane module geometry is 20×15×0.007 m^3.

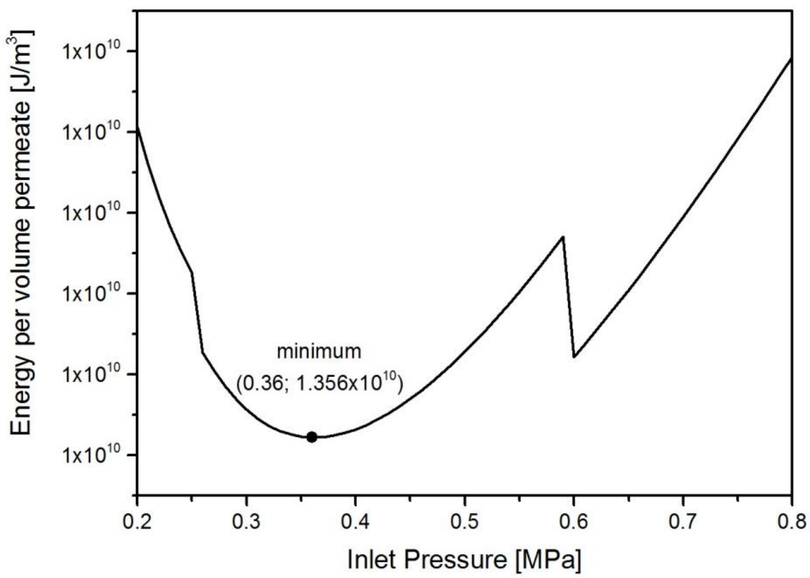

Figure 3. Effect of inlet pressure on the energy per unit permeate

From the figure, it is shown that the increase of the inlet pressure first decreases the average energy cost of the membrane plant. However, further increase of pressure makes the average energy cost also increases. It can be explained as follows. The increase in pressure operation is more beneficial for the permeate flux with the order of 0.27 as shown in equation (10). Therefore, the volume permeate increases which leads to the decrease of average energy cost. However, equation (17) shows that the power consumption for the pump rise much faster than the increase of permeate flux (the order is 1). Therefore, after decrease and reach a critical value, the average energy cost will increase with the increase of operating pressure.

Effect of Recirculation Flow Rate on the Average Energy Cost

Figure 4 shows the effect of the recirculation flow rate on the total cost. Other parameters are kept at constant, inlet pressure TMP = 500 kPa and membrane module geometry is 20×15×0.007 m^3.

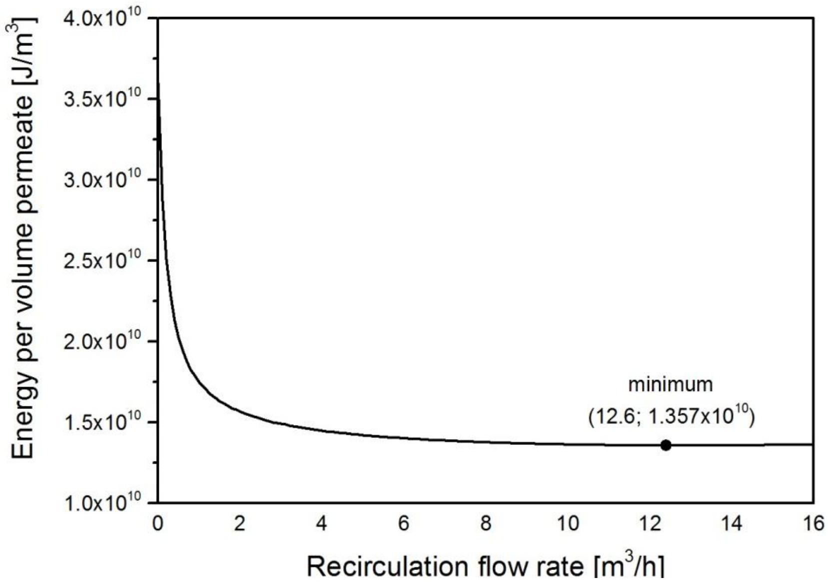

Figure 4. Effect of recirculation flow rate on the average energy cost

From the figure, it is shown that the increase of the recirculation flow rate first decreases the average energy cost of the membrane plant. However, further increase of recirculation flow rate makes the average energy cost also increases. It can be explained as follows. The increase in flow rate would be more beneficial for high shear rate and the permeate flux as shown in equation (10). Therefore, the permeate volume increases which leads to the decrease of average energy cost. However, equations (17) and (12) show that the power consumption rises much faster in high flow rate conditions and also faster than the increase of permeate flux (the order of dependency is 1.75). Therefore, after decrease and reach a critical value, the average energy cost will increase with the increase of flow rate.

Optimum Operating Parameters

The case study is an existing membrane module which has the feed flow rate, membrane module dimensions, and fixed cost in equivalent energy as shown in Table 1. The boundary for the inlet pressure is from 100kPa to 800kPaand the recirculation flow rate is from 0 to 25 m^3/hr. The cyclic coordinate search along two directions, inlet pressure and recirculation flow rate, is applied to find the minimum energy requirement. The results show that the membrane plant should operate at inlet pressure of 800kPa, and the recirculation flow rate of 10.4 m^3/hr. The correspondence energy per unit volume permeate is $1.3354x10^{10}$.

Conclusions

In this paper, a simulation of a membrane plant was discussed. The flow channel is divided into a number of segments base on the module length, in which the variation of properties and the pressure loss is considered. The effect of operating parameters such as recirculation flow rate, inlet pressure on the economic view point of membrane operation is investigated. All the parameters have the critical point which minimizes the average energy cost of the membrane plant while other parameters are kept constant. The cyclic coordinate search method was employed for finding the optimum operation conditions of the membrane plant. The procedure presented is applicable for the general decision in a given membrane plant in which the governing equation is known.

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