**Problem 2:**

For single-stage seawater RO, ignoring the effect of pressure drop and concentration polarization,

1. Investigate the effect of membrane investment on SEC for the following three cases
   * 1. No ERD, no minimum recovery requirement
     2. ERD efficiency = 96%, no minimum recovery requirement
     3. ERD efficiency = 96%, minimum recovery = 30%
2. Comment on the effect of membrane properties (i.e., permeability, area) and ERD on energy consumption

**Solution:**

(a)

|  |
| --- |
| function SWRO\_OPT()  %% optimization code for seawater reverse osmosis ignoring concentration polarization and retentate pressure drop  %% written by Mingheng Li, California State Polytechnic University, Pomona    %% case1: No ERD, no minimum recovery requirement  eta = 0; %% no ERD  ymin = 0;  gamma\_vec = 0.1:0.1:2;  for i = 1: length(gamma\_vec);  [NSEC\_vec(i) alpha\_vec(i) y\_vec(i) z\_(i)] = RO1OPT(gamma\_vec(i),eta,ymin);  end  figure(1);  set(gca,'FontSize',16);  plot(gamma\_vec, alpha\_vec,'o-');  hold on;  plot(gamma\_vec, y\_vec,'rs-');  legend('\alpha\_{opt}','y\_{opt}');  xlabel('\gamma');  ylabel('optimal pressure and recovery');    figure(2)  set(gca,'FontSize',16);  plot(gamma\_vec, NSEC\_vec,'o-');  xlabel('\gamma');  ylabel('optimal normalized SEC');    %% case2: ERD, no minimum recovery requirement  eta = 0.96; %% ERD efficiency  ymin = 0;  gamma\_vec = 0.1:0.1:2;  for i = 1: length(gamma\_vec);  [NSEC\_vec(i) alpha\_vec(i) y\_vec(i) z\_(i)] = RO1OPT(gamma\_vec(i),eta,ymin);  end  figure(3);  set(gca,'FontSize',16);  plot(gamma\_vec, alpha\_vec,'o-');  hold on;  plot(gamma\_vec, y\_vec,'rs-');  legend('\alpha\_{opt}','y\_{opt}');  xlabel('\gamma');  ylabel('optimal pressure and recovery');    figure(4)  set(gca,'FontSize',16);  plot(gamma\_vec, NSEC\_vec,'o-');  xlabel('\gamma');  ylabel('optimal normalized SEC');    %% case3: ERD, minimum recovery requirement  eta = 0.96; %% ERD efficiency  ymin = 0.3;  gamma\_vec = 0.1:0.1:2;  for i = 1: length(gamma\_vec);  [NSEC\_vec(i) alpha\_vec(i) y\_vec(i) z\_(i)] = RO1OPT(gamma\_vec(i),eta,ymin);  end  figure(5);  set(gca,'FontSize',16);  plot(gamma\_vec, alpha\_vec,'o-');  hold on;  plot(gamma\_vec, y\_vec,'rs-');  legend('\alpha\_{opt}','y\_{opt}');  xlabel('\gamma');  ylabel('optimal pressure and recovery');    figure(6)  set(gca,'FontSize',16);  plot(gamma\_vec, NSEC\_vec,'o-');  xlabel('\gamma');  ylabel('optimal normalized SEC');    figure(7)  set(gca,'FontSize',16);  plot(gamma\_vec, NSEC\_vec+0.1\*gamma\_vec./y\_vec,'bo-');  hold on;  plot(gamma\_vec, NSEC\_vec+0.3\*gamma\_vec./y\_vec,'rs-');  plot(gamma\_vec, NSEC\_vec+0.5\*gamma\_vec./y\_vec,'gd-');  plot(gamma\_vec, NSEC\_vec+0.7\*gamma\_vec./y\_vec,'m>-');  xlabel('\gamma');  ylabel('NSEC+w\beta');  legend('w=0.1','w=0.3','w=0.5','w=0.7','Location','NorthWest');          function [NSEC alpha y z] = RO1OPT(gamma,eta,ymin)  %% Matlab code to minimize specific energy consumption in one-stage SWRO.  x0=[gamma\*0.6, 0.5, 2];  options = optimset('Display','off','Algorithm','active-set','TolCon',1e-10,'MaxIter',1e5,'MaxFunEvals',1e5);  exitflag = -10;  x=x0;  while exitflag~=1;  [x, fval,exitflag] = fmincon(@(x)ro1\_objfun(x,gamma,eta,ymin),x,[],[],[],[],[],[],@(x)ro1\_confun(x,gamma,eta,ymin),options);  end  alpha = x(1);  y = x(2);  z = x(3);  y=(1-alpha)\*(1-exp(-z));  NSEC = (1+y\*eta-eta)/alpha/y;    function f = ro1\_objfun(x,gamma,eta,ymin)  %% objective function  alpha = x(1);  y = x(2);  z = x(3);  f = (1+y\*eta-eta)/alpha/y;    function [c, ceq] = ro1\_confun(x,gamma,eta,ymin)  %% constraints  alpha = x(1);  y = x(2);  z = x(3);  err = 1e-9;  c = [...  alpha-1+err;  err-alpha;  err-z;  ymin+err-y;  ];    ceq = [...  y-(1-alpha)\*(1-exp(-z));  gamma-alpha\*(y+alpha\*z);  ];    function f = ro1\_objfun(x,gamma,eta,ymin)  %% objective function  alpha = x(1);  y = x(2);  z = x(3);  f = (1+y\*eta-eta)/alpha/y;    function [c, ceq] = ro1\_confun(x,gamma,eta,ymin)  %% constraints  alpha = x(1);  y = x(2);  z = x(3);  err = 1e-9;  c = [...  alpha-1+err;  err-alpha;  err-z;  ymin+err-y;  ];    ceq = [...  y-(1-alpha)\*(1-exp(-z));  gamma-alpha\*(y+alpha\*z);  ]; |

|  |  |
| --- | --- |
|  |  |
|  |  |
|  |  |
| Figure: Top: ηERD = 0, Ymin = 0; Middle: ηERD = 96%, Ymin = 0; Top: ηERD = 96%, Ymin = 30%; | |

(b) From the above figures, it is observed that improving membrane permeability or increasing membrane area would reduce specific energy consumption, however, it becomes flat as γ becomes sufficiently large. ERD significantly reduces energy consumption while the optimal recovery is much lower than the case without ERD. With the constraint of a minimum recovery, the optimal SEC may be higher.

Below is a figure shows the total cost of energy consumption (represented by NSEC) and membrane cost (represented by β) for case (iii) studied above. Several different weights on membrane cost are considered. It is consistent with industrial design that ϒ is between 0.5-1 for sustainable SWRO process.

|  |
| --- |
|  |
| Figure: Optimal ϒ to minimize the total of energy and membrane cost in SWRO. |