**Problem 3:**

An industrial 2-stage brackish water reverse osmosis (BWR) without inter-stage pump has the following parameters:

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| Parameter | Value |
| Number of pressure vessels per train | 42 |
| Number of 1st stage pressure vessels | 28 |
| Number of 2nd stage pressure vessels | 14 |
| Number of membrane elements per vessel | 7 |
| Area per element, ft2 | 400 |
| Feed pressure, , psi | 40.6 |
| Feed osmotic pressure, , psi | 9 |
| Feed flow, , gpm | 1,525 |
| Permeate pressure, , psi | 16.4 |
| Permeate flow, , gpm | 1,234 |
| Retentate pressure drop in 1st stage, , psi | 24.9 |
| Retentate pressure drop in 2nd stage, , psi | 18.2 |
| Pump head, , ft | 360 |

1. Show that k = 2.12×10-5 psi/gpm2 (in the first stage) and Lp = 0.11 gfd/psi.
2. Using process parameters provided in part (a), find the relationship between pump energy consumption and recovery.
3. Comment on the effect of recovery on energy consumption, waste disposal and capital cost.

**Solution to Problem 3:**

Solution to part (a) and (b) can be find below:

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| function BWROCaseStudy()  %% code written by Mingheng Li, Cal Poly Pomona  H = 360; %% pump head  P0 = 40.6; %% feed pressure before pump  Pf = 16.4; %% permeate pressure  dP0 = P0 + 0.4327\*H-Pf;    %dP0 = 180.1; %% transmembrane hydraulic pressure at inlet, psi  Qf = 1525; %% feed rate, gpm  k = 2.12e-5; %% pressure drop parameter,  A = 400\*28\*7; %% membrane area, ft2  Lp = 0.110/24/60; %% hydraulic permeability, 0.11gfd/psi  dpi0 = 9; %% transmembrane osmotic pressure at inlet, psi    deltap1 = 24.9; %% pressure differential in the first stage  deltap2 = 18.2; %% pressure differential in the second stage  Qp = 1234; %% permeate rate    gamma = A\*Lp\*dpi0/Qf;  alpha = dpi0/dP0;  kappa = k\*Qf^2/dpi0;  omega = kappa/alpha;  [tt,ppqq,p1,q1,p2,q2] = RO\_2STAGES(gamma,kappa,alpha);      figure(1);  set(gca,'FontSize',16);  plot(tt,ppqq(:,1)\*dP0,'b-');  hold on;  plot(tt,dpi0./ppqq(:,2),'r--');  plot([0 1 2],dP0-[0,deltap1,deltap1+deltap2],'bo');  plot([0],dpi0,'ro');  legend('\DeltaP', '\Delta\pi')  xlabel('Stage number');  ylabel('Transmembrane pressures (psi)');    figure(2)  set(gca,'FontSize',16);  plot(tt,ppqq(:,2)\*Qf,'b-');  hold on;  plot(tt,Qf-ppqq(:,2)\*Qf,'r--');  plot([0 2],Qf-[0,Qp],'bo');  plot([2],Qp,'ro');  xlabel('Stage number');  legend('Q\_r', 'Q\_p')  ylabel('Flows (gpm)');        ysp\_vec = [0.78:0.02:0.9,0.91:0.01:0.96];  for i=1:length(ysp\_vec);  Qf\_vec(i) = Qp/ysp\_vec(i);  gamma\_vec(i) = A\*Lp\*dpi0/Qf\_vec(i);  kappa\_vec(i) = k\*Qf\_vec(i)^2/dpi0;  alpha\_vec(i) = fsolve(@(alpha)RO\_y(gamma\_vec(i),kappa\_vec(i),alpha,ysp\_vec(i)),0.02);  end    dP0\_vec = dpi0./alpha\_vec;  dP\_pump\_vec = dP0\_vec-P0+Pf;  NSECth = dP\_pump\_vec./ysp\_vec/dpi0;    figure(3)  set(gca,'FontSize',16);  plot(ysp\_vec,NSECth,'o-');  xlabel('Recovery');  ylabel('NSEC neglecting pump efficiency');          function f = RO\_y(gamma,kappa,alpha,ysp)  %%ysp is the target recovery;  [tt,ppqq,p1,q1,p2,q2] = RO\_2STAGES(gamma,kappa,alpha);  y = 1- ppqq(end,2);  f = y-ysp;    function [tt,ppqq,p1,q1,p2,q2] = RO\_2STAGES(gamma,kappa,alpha)  %% model to solve profiles of p and q in a two-stage RO  [t,pq] = ode45(@(t,pq) RO\_DIMENSIONLESS(t,pq,gamma,kappa,alpha),[0:0.05:1],[1 1]);  p1= pq(end,1);  q1=pq(end,2);  gamma2 = gamma/2/q1^2; %% membrane area is a half than before  alpha2 = alpha/q1/p1;  kappa2 = kappa\*4\*q1^3; %% flow area is a half than before  [t\_2,pq\_2] = ode45(@(t,pq) RO\_DIMENSIONLESS(t,pq,gamma2,kappa2,alpha2),[1:0.05:2],[1 1]);  tt=[t;t\_2];  ppqq = [pq; ones(21,1)\*[p1 q1].\*pq\_2];  p2 = pq\_2(end,1);  q2 = pq\_2(end,2);    function dx = RO\_DIMENSIONLESS(t,x,gamma,kappa,a)  %% dimensionless model of RO  dx = zeros(2,1);  dx(1) = -kappa\*a\*x(2)^2;  dx(2) = -gamma/a\*x(1)+gamma/x(2); |



b) Relationship between recovery and pump energy consumption:



Note that the optimal recovery in this BWRO process corresponding to the lowest energy consumption is higher than 90%. This is very different from SWRO process.

(c) In industrial BWRO, the brine disposal charge is about $900 per mega gallon. In a 7MGD RO plant, if the recovery increases from 80% to 90%, the brine volume would reduce about 1 mega gallon per day (or roughly a saving of $320,000/year). The pump energy consumption will reduce by approximately 10%, or $35,000/year. However, there is a risk that membrane might prematurely foul at very high recoveries which should be quantified by experiments.