Transport Phenomena Analysis for Evaluating the Optimum Operating Conditions of Reverse Osmosis Processes

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Available online at: www.isca.in
(Received 25th April 2011, revised 3rd May 2011, accepted 31st May 2011)

Abstract

In this work, a mathematical model for predicting the performance of reverse osmosis (RO) desalination plants was developed. The proposed model is based on basic transport equations of salt and water across the membrane. The influence of operating variables on the separation efficiency of RO processes can be evaluated by depending on the equations of transport phenomena. The theoretical predication produced by the developed model was compared with the normalized data obtained by Saehan company software CSM2000-program. The comparison indicated that agreement of theoretical values relative to normalized values is about 85%. For specifying the optimum operating conditions, the optimization analysis was carried out by depending on the Modifi cation Hook and Jeeves method. The proposed analysis applied a nonlinear objective function representing the concentration of product water as a function of operating conditions (feed water concentration, operating pressure, and percent recovery).

The optimum concentration of permeate water is governed relative to percent recovery with range about (10-46.67%), the test is repeated for different values of feed water concentration (1000, 3000, and 10000 ppm). The results have shown that, the average of improvement in the optimum values of permeate concentration is about 67%. Also, the optimum concentration of permeate water is inspected for feed water concentration with range (500-10000 ppm), the range of increasing in the optimum permeate concentration is 55.8%. Furthermore, the optimum concentration of permeate water is computed for range of applied pressures in arrange (6.5-25 bar). The results indicated that, when the average operating pressures was increased by 12.7%, the quality of permeate water was improved by 18.8%.

Key words: Desalination, efficiency, optimization, operation conditions.

Introduction

The increasingly broad range of requirements of purified water due to the development of all aspects in our lives has been motivated the water treatment industry to refine existing techniques, combine methods and explore new water purification technologies.

A number of technologies have been developed, However, reverse osmosis and multi stage flash evaporation are considered to be the main methods, which are applied in large-scale plants of the more than 7500 water desalination plants in operating worldwide, 60% are located in the Middle East.
Membrane based separation processes have become the important unite operations for concentration and purification of solutions. These processes offer many advantages over conventional separation processes such as low operating cost (less energy intensive), case of operation under ambient temperature, where no phase change is involved[1].

Transport of solvent or solutes through membranes can occur by different mechanisms, depending on the structure and nature of the membrane[2].

Many types of membrane filtration are basically identical in process and differ only in the size of the particles to be separated and the nature of membrane used. All these processes use the applied pressure with semi-permeable membranes to separate feed water stream into permeate and concentrated or brine streams.

Process optimization is one of the main areas in chemical process design and analysis. The major feature of the area is that it provides a systematic frame work for improving the design and operation of chemical processes.

Nevertheless, from a practical point of view, the main objective for water desalination plants relative to industrial fields is the capability of using the water production for industrial fields such as, cooling towers, heating systems and other purposes. These systems are essential to improve the quality of water with a high degree of purification. Consequently, the two stages of RO principles have been applied to increase the quality of desalinated water.

As mentioned above, the quality of permeate is considered the main characteristic that must be under control and monitoring. There are various manners that can be used to improve the quality of desalinated water, as follows:
The ability of using the brackish water with low salinity as raw water to RO plants after pretreatment.
Operating the RO plants under high recovery percent or high applied pressure.
Selecting professional types of membranes with high salt passage and percent recovery.
Increasing the efficiency of pretreatment systems for reducing the influence of fouling then, saving the membranes for operation under high efficiency. The ability of using the developed pretreatment technology, such as Nano-filtration systems is considered one of the professional methods for solving the fouling problems.
The capability of applying the two stages of RO principle.

In the present work, the optimization concept will focus on the first and second reasons and tested the influence of raw water quality, percent recovery and pressure on the quality of water production to obtain a better understanding of the characteristics and behavior of selected membrane module, and how external factors such as feed properties and utility affect on the optimal operation of RO system.

Mathematical analysis

The Kimura-Sourirajan analysis[3] describes the mathematical equations for the solvent and solute transport through the membrane by depending on mass transfer phenomena. The transport of solvent is proportional to the effective pressure where the proportional constant is called pure water permeability:

$$N_B = A * \Delta P \quad \ldots\ldots \ (1)$$

The effective pressure can be defined as the difference between the feed pressure and osmotic pressure across the membrane as follows:

$$\Delta P = P - \Delta\pi \quad \ldots\ldots.. \ (2)$$

So,

$$\Delta P = P - [\pi(X_{A3}) - \pi(X_{A2})] \ldots\ldots. \ (3)$$

Then, the pure water flux can be written as follows:

$$N_B = A * [P - \pi(X_{A2}) + \pi(X_{A3})] \ldots\ldots \ (4)$$

While the transport of solute is proportional with the concentration difference cross the membrane; so,

$$N_A = \frac{D_{AM}}{\delta} (C_{M2} X_{AM2} - C_{M3} X_{AM3}) \quad \ldots\ldots \ (5)$$

The above equations can be transformed by assuming a simple linear relationship between the concentration of solute in the solution phase and membrane phase[4]. Thus the following definition can be predicted:-

$$C_2 X_{A2} = K C_{M2} X_{AM2} \ldots\ldots \ (6)$$

$$C_3 X_{A3} = K C_{M3} X_{AM3} \ldots\ldots \ (7)$$

Now, equation (5) can be written as:

$$N_A = \frac{D_{AM}}{K\delta} (C_2 X_{A2} - C_3 X_{A3}) \ldots\ldots. \ (8)$$

By depending on the principle of material balances, the total flux can be written as follows:-.

$$N_A = N_A * X_{A3} + N_B * X_{A3} \ldots\ldots.. \ (9)$$

Substituting the last equation in equation (6) results:

$$N_B = (\frac{D_{AM}}{K\delta})(\frac{1-X_{A3}}{X_{A3}})(C_2 X_{A2} - C_3 X_{A3}) \ldots\ldots (12)$$

The solute transfer from the concentrated boundary solution is represented by the following relation[5]:-

$$N_A = X_A(N_A + N_B) - D_{AB}C_1 \frac{dX_A}{dZ} \ldots\ldots. (13)$$

Whereas the flux of the solute in the region (0<z< δ) may be written as the sum of the convection and diffusive fluxes.

By using equation (7) the last equation can be written as follows:

$$\frac{dX_A}{dZ} = \frac{N_A + N_B}{D_{AB}C_1}(X_A - X_{A3}) \ldots\ldots (16)$$

The integration of this equation gives;

$$\ln(X_A - X_{A3}) = \frac{N_A + N_B}{D_{AB}C_1} Z \quad \ldots\ldots (17)$$

The boundary conditions for this equation are:

$Z = 0.0$ when $X_A = X_{A1}$

$Z = \delta$ when $X_A = X_{A2}$

After applying the boundary conditions, equation (17) can be rewritten as follows:-

$$\ln(\frac{X_{A2} - X_{A3}}{X_{A1} - X_{A3}}) = (\frac{N_A + N_B}{D_{AB}C_1})\delta \ldots\ldots.. (18)$$

Defining the mass transfer coefficient on the high pressure side of the membrane (k)[6].

$$k = \frac{D_{AB}}{\delta} \ldots\ldots.. (19)$$

Mathematical Assumptions

For the present analysis, the fowling simplifying assumptions are made relative to Kimura-Sourirajan analysis:

The molar density of is constant, i.e.

$$C_1 = C_2 = C_3 = C$$

The osmotic pressure of solution is proportional to the mole fraction of the solute, i.e.

$$\Pi(X_A) = BX_A$$

The transport of solute across the membrane is small comparing to the transport of solvent, i.e.

$N_A << N_B$ or $X_{A3} << 1$

By using the above assumption, the water and salt flux can be written as follows:

$$N_A = X_{A3} * N_B \ldots\ldots. (20)$$

$$N_B = \frac{N_A}{X_{A3}} = \frac{D_{AM}}{K\delta}(\frac{C_{A2} - C_{A3}}{C_{A3}}) \ldots\ldots (21)$$

To facilitate the solution of design equations, the dimensionless parameters will be applied as follows:-

$$\gamma = \frac{B}{C * P} \ldots. (22)$$

$$\phi = \frac{(D_{AM} / K\delta)}{(A * P / C)} \ldots\ldots. (23)$$

$$\lambda = \frac{k}{(D_{AM} / K\delta)} \ldots\ldots (24)$$

Now, equation (17) becomes:

$$N_B = A * P[1 - \gamma(C_{A2} - C_{A3})] \ldots\ldots. (25)$$

So,

$$C_{A2} = C_{A3}(1 + \frac{1}{\gamma * C_{A3} + \phi}) \ldots\ldots (26)$$

And,

$$C_{A3} = \frac{C_{A2} - C_{A3}}{\lambda * \ln(\frac{C_{A2} - C_{A3}}{C_{A1} - C_{A3}})} \ldots\ldots (27)$$

Also,

$$C_{A1} = C_{A3}[1 + \frac{1}{\gamma * C_{A3} + \phi} * \exp(-\frac{1}{\lambda * (\gamma * C_{A3} + \phi)})] \ (28)$$

The last equation is an important formula; it directly expresses the relationship between the product stream concentration and the reject stream concentration as functions of dimensionless arameters without involving the term boundary concentrated concentration.

Optimization Analysis: The performance of an RO system is usually connected directly to feed pressure, permeate flow and salt rejection. For efficient evaluation of RO system, it is necessary to compare between these two variables at the same conditions.

During the operation stages, system conditions such as operating pressure, feed temperature, percent recovery and feed concentration can vary considerably. Two simple equations show the relationship among the operation parameters. The first equation express the effects of operation variables on permeate water flow rate as follows:-

$$Q_p = A(\pi) * S * TCF * FF * (P_f - \Delta\pi - \frac{\Delta P_{fc}}{2} - P_P) \quad (29)$$

The difference of osmotic pressure cross the membranes and its value can be obtained as follows:-

$$\Delta\pi = \pi - \pi_P \; ..... \; (30)$$

The value of osmotic pressure of the water on the high pressure side of the membrane can be expressed as follows[7]:-

$$\pi = \pi_f * \frac{C_{fc}}{C_f} * PF \; ...... \; (31)$$

Where:-

$$C_{fc} = C_f * \frac{\ln[1/(1-R)]}{R} \; ...... \; (32)$$

The pure water permeability coefficient varies depending on the average osmotic pressure and specific to the element itself.

The salt concentration in permeate water is affected by several variables as shown in the following equation[8]:-

$$C_P = \frac{D_{AM}}{k\delta} * C_{fc} * PF * TCF * \frac{S}{Q} \; ...... \; (33)$$

The objective function relies on a large number of quantities that are separated into variables, with respect to which the function is minimized, and the parameters which are regarded as constants during the optimization calculation.

Finally, the objective function is optimized by using the modified Hook and Jeeves optimization method.

Results and Discussion

Effect of Percent Recovery on Quality of Permeate Water: The design of recovery rate of new commercial RO systems has been increased subsequently to the availability of membrane elements with increasingly higher salt rejection.

Figures (1), (2), and (3) show the change in optimum product water salinity as a function of percent recovery and permeate flow rate at different feed water flow rates. The calculation have repeated for various range of feed concentration, (1000, 3000, and 10000 ppm) respectively, and it’s shown that the permeate concentration was increased with increasing of feed concentration. All the figures show that when the percent recoveries of water increases, the optimum permeate water concentration will also increase. However, the higher recovery and higher permeate flux require higher feed pressure. The increase in feed pressure with recovery rate at a given permeate flux is due to increasing the average feed salinity and osmotic pressure. The results shown that, the average of improvement in the optimum values of permeate concentration is about 67%

Effect of Feed Water Salinity on the Quality of Permeate: The purpose of optimization section is to achieve the optimum product characteristics by the operation of RO systems at the optimum operation conditions.

The water concentration is considered as one of the significant parameters that affect the quality of permeated water. Generally, as the feed water concentration increases, the values of total dissolved solids or conductivities of permeated water will be increased. Consequently, the operation requirements will be more difficult and the membrane life time will be reduced due to the chemical cleaning repetition for removing the inorganic salt precipitation on the membrane surfaces.

Figure (4) illustrates the proportional relation between raw water concentration and optimum permeates concentration. As the raw water concentration increases, the diffusion of salts from the high concentrate side will be increased. Consequently, the concentration of permeate will also increase. During the continuous operation, the negative affects of salt concentration on the membrane efficiency will appear due to the inorganic salt precipitation. Moreover, the influences of concentration polarization phenomena will contribute to reduce the quality of permeate due to the increase in the feed water concentration.

The proposed Figure shows the optimum value of permeate concentration for range of water concentration between (500-3000) ppm. The permeate concentration computed as a function of feed water quantity and permeate recovery.

Effect of Applied Pressure on the Quality of Permeate Water: Reverse osmosis systems equipped with spiral wound membrane elements are designed to operate at constant flux rate (i.e., to produce a constant permeate flow). Over operation time, the feed pressure is adjusted to compensate the influence of feed water temperature, salinity and permeate flux decline due to fouling or compaction of the RO membrane.

The applied pressure represents another operating variable that influence the efficiency of RO plants. Any variation in its values will effect on the properties of permeate stream. The form of objective function that describes the concentration of permeate water is a function of various parameters, and the pressure has a large affect on the quality of water production. Figures (5) and (6) present the effect of applied pressure on the salinity of optimum permeate water for various values of feed water rates and raw water concentration. The figures indicate the inversely relation between them. As the applied pressure increases, the optimum quantity of permeate water will also improve due to the dilution effects.). The results indicated that, when the average operating pressures increased by 12.7%, the quality of permeate water is improvement by 18.8%.

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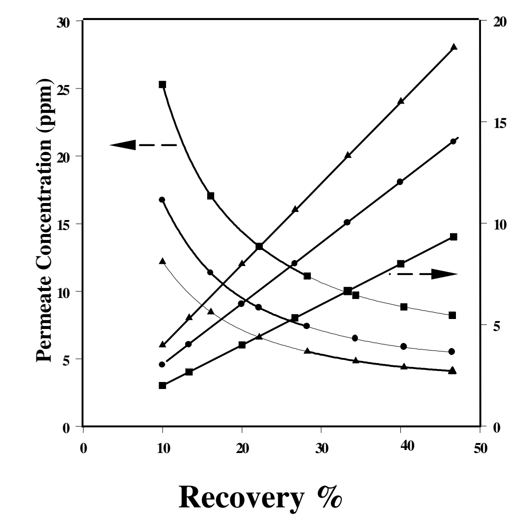
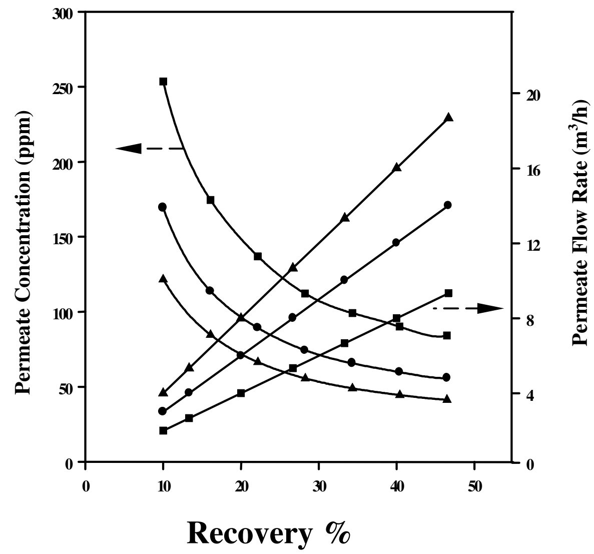
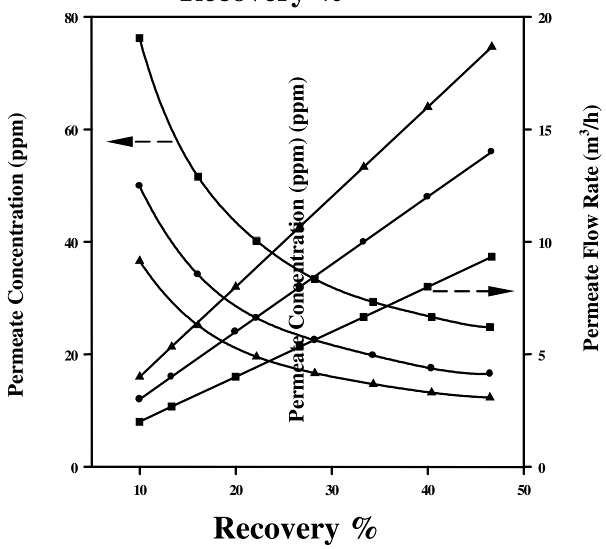
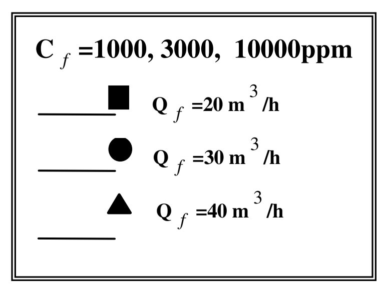
Nomenclatures

A	Pure water permeability constant.	mol/m ^{2} .s.bar
C	Molar concentration of the solution.	mol/m ^{3}
C_1, C_2, C_3	Molar concentration in the solution phase 1, phase 2 and phase 3 respectively.	mol/m ^{3}
C_{M2}, C_{M3}	Molar concentrations in the membrane phase in equilibrium with X_{A2}, X_{A3} respectively.	mol/m ^{3}
C_{fc}	Average feed-concentrate concentration.	mol/m ^{3}
D_{AB}	Diffusivity of solute in the feed solution.	m ^{2} /s
$D_{AM} / K\delta$	Solute transport parameter.	m/s
FF	Fouling factor.	
k	Mass transfer coefficient on the high pressure side of the membrane.	m/s
K	Interfacial equilibrium constant for solute.	
L	Length of the membrane element.	m
N_A	Solute flux through the membrane.	mol/m ^{2} .s
N_B	Solvent flux through the membrane.	mol/m ^{2} .s
P	Operating pressure.	bar
P_P	Permeate pressure.	bar
P_F	Feed pressure.	bar
$P.W.P$	Pure water rate.	kg/h
Q_F, Q_p, Q_R	Flow rate in feed, permeate and brine respectively.	m ^{3}/hr
PF	Concentration polarization.	
S	Effective area of the membrane.	m ^{2}
T	Temperature	^{o}K
TCF	Temperature factor constant.	
X_{A2}, X_{A3}	Molar fraction of solute in solution 2 and 3 respectively.	
X_{AM2}, X_{AM3}	Molar fractions of solute in membrane phase in equilibrium with X_{A2}, X_{A3} respectively.	
TDS	Total dissolved Salt	mg/l
z	Thickness of the concentrated boundary layer.	m
dp	Pressure drop cross the membranes.	bar

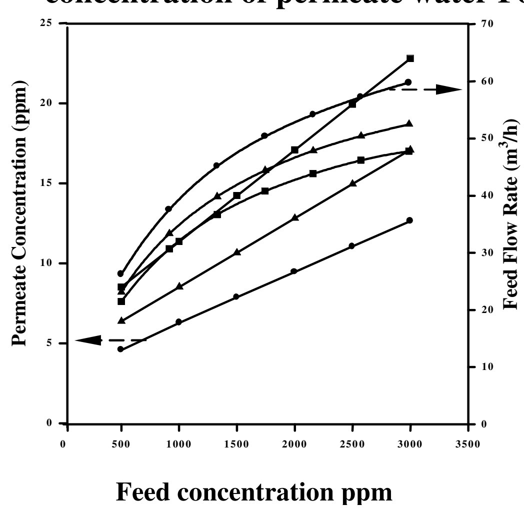








Figures-1,2 and 3: show the Influence of percent recovery and permeate flow rate on the optimum concentration of permeate water For different feed water concentration



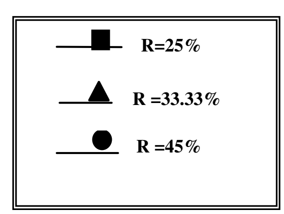
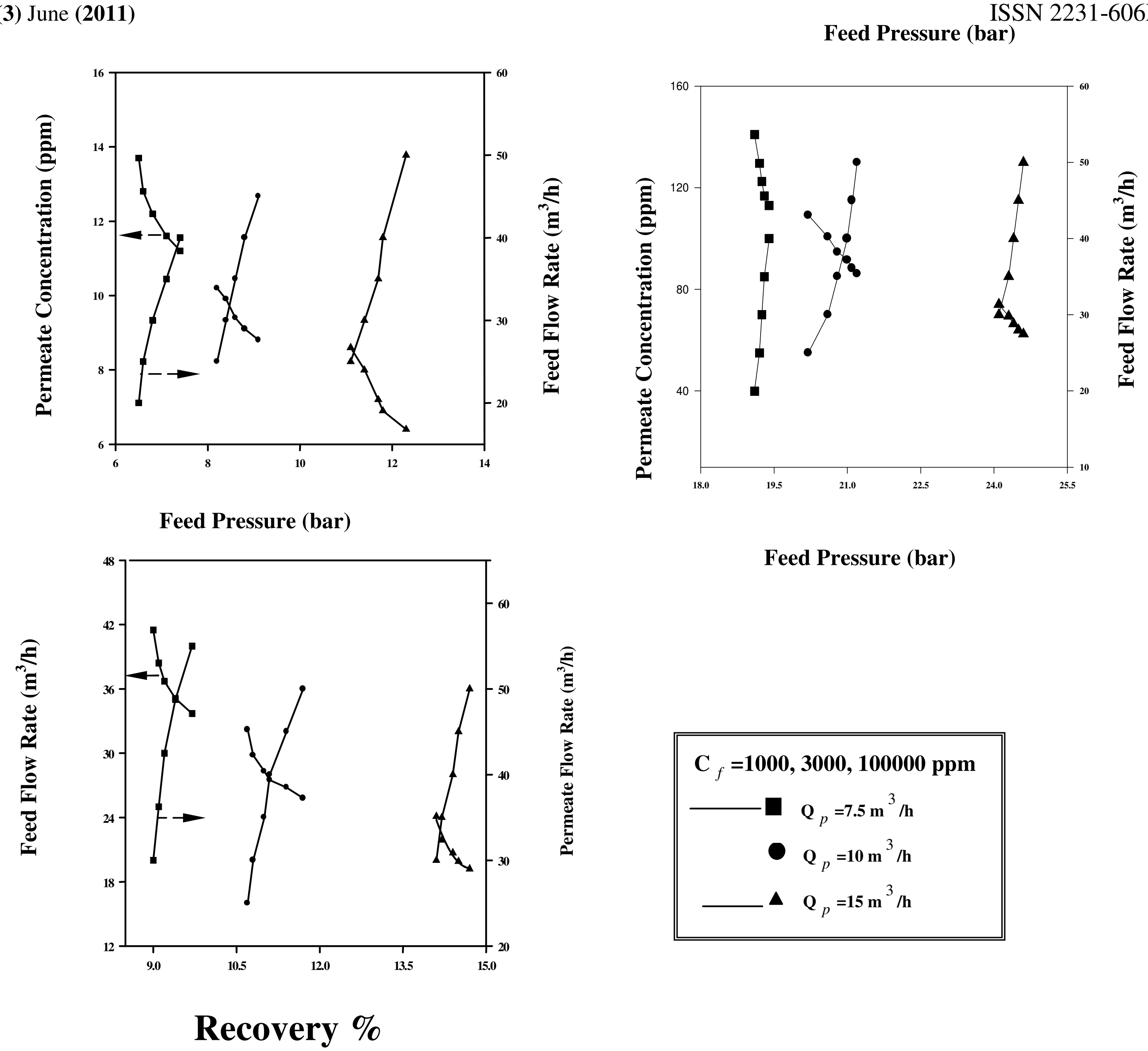


Figure-4: Influence of feed concentration and feed flow rate on the optimum concentration of permeate water



Figures-5, 6 and 7: show the Influence of feed pressure and feed flow rate on the optimum concentration of permeate water with various feed water concentration.