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Multi- Stage Reverse Osmosis Seawater Desalination System Using Cellulose-Acetate hollow-Fiber Membrane

[1]Ehab Salah Ali, [2]Mohamed Refaat Diab, [3]Mohamed S. Abd Alhadi
[1]Mech. Engineer in Holding Water Co.
[2,3]Prof. Faculty of Engineering, Minia University

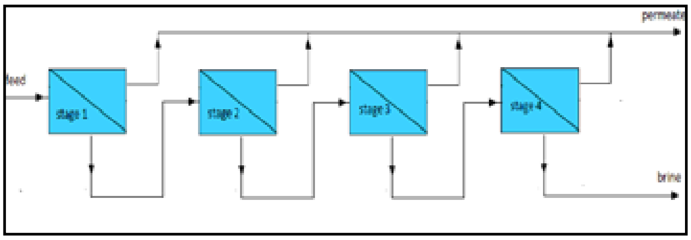
Abstract
Intake, pretreatment, post-treatment and disposal cost of reverse osmosis, RO, seawater desalination plant represent about 25% of total cost per cubic meter of permeate product. The present study investigates the effect of proposed arrangements of RO modules of desalination system upon the required feed sea water flow for the same purified water production. A mathematical simulation model of proposed modules arrangements has been developed. The derived governing equations were simultaneously solved using Engineering Equation Solver. The effects of different operating conditions on the ratio of purified water production to feed seawater rates are investigated.

Keywords
Seawater Desalination- Reverse Osmosis-Hollow Fine Module

I. Introduction
The rapid growth of RO process is because it is able to produce fresh water with lower cost [1]. Reverse osmosis desalination plant consists of four main parts intake and pretreatment, high pressure pumps, RO membrane and post treatment (disposal and permeate treatment) [2]. Intake, pretreatment and disposal cost of RO desalination plant represent about 25% of total cost per cubic meter of permeate product [3]. The present study investigates the effect of proposed arrangements of RO modules of desalination system upon the required feed sea water flow for the same permeate product and consequently upon the cost of cubic meter of permeate per day. If the flow rate of sea water is reduced for a proposed modules arrangement, the cost of the intake, pretreatment and dosing installation (including construction, filters, piping, feed pumps and dosing units) will be consequently reduced and hence, the total cost of the permeate will be reduced. In case of an old plant, charging the brine to new stage is economically feasible when there is a need to increase the capacity of the plant without changing the intake and the pretreatment units.
The RO plant is divided into stages. Each stage consists of number of modules. The exit brine from a stage is fed to the next stage. Figure 1 shows the proposed arrangements under investigation in this study. In RO desalination system which uses cellulose triacetate membrane, the only available construction is the hollow fine module in the markets [4].

A. Physical Model
In practice, RO plant consists of a number of modules connected in parallel. This number is determined by dividing the required purified water flow rate by the permeate flow rate produced from a module.
In the present study, the total number of modules is divided into stages. For simplicity, the number of modules in the first stage is considered 100 modules. The number of modules in a following stage is determined by dividing the total brine flow rate exit from the preceding stage by the specified feed water flow rate.
The feed water flow rate for a RO module for a specific membrane type is taken in the present study equal to the specified vales in manufacturer catalogues [5]. The pressure drop due to flowing through a module is assumed constant and equals to 100kPa [6]. Booster pumps may be used to regain this pressure drop.

III. Mathematical Model
The objective of the computations was to predict performance of proposed reverse osmosis modules arrangements subject to the following constraints: The final product concentration should be less than 500 ppm[7], feed flow rate is constant, four stages is taken as the limit in this study and the calculations are based on seawater temperature of 25°C. Fig. 2 shows one module of proposed reverse osmosis modules arrangements.



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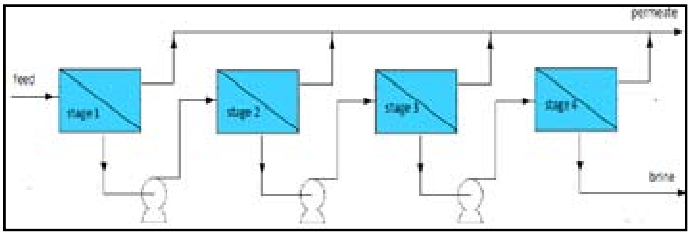


(b)

Fig. 1: Four Stages Reverse Osmosis Arrangements. (a) Without Booster Pumps. (b) With Booster Pumps

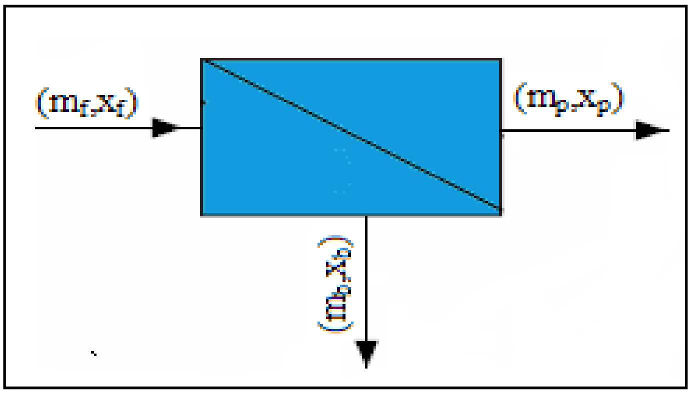


Fig. 2: One Module of Proposed Reverse Osmosis Modules Arrangements

Osmotic pressure can be calculated by the following equation [8].

$$\pi = 0.07584 X_{fi} \quad (1)$$

The water recovery and salts rejection are two parameters used to evaluate reverse osmosis performance and are defined as [9]

$R = (m_p/m_f) \times 100$ (2)

$SR = (1 - (X_p/X_f)) \times 100$ (3)

Mass and salt balances:

$$m_{fi} = m_{pi} + m_{bi} \quad (4)$$

$$m_{fi} x_{fi} = m_{pi} x_{pi} + m_{bi} x_{bi} \quad (5)$$

The following relation defines the rate of water passage through a semi-permeable membrane [10].

$$m_{pi} = (\Delta p_i - \Delta \pi_i) k_w A \quad (6)$$

$$\Delta p_i = p_{average} - p_{pi} \quad (7)$$

$$\Delta \pi_i = \pi_{average} - \pi_{pi} \quad (8)$$

$P_{average}$ and $\pi_{average}$ are the average hydraulic and osmotic pressures on the feed side and are given by

$$p_{average} = 0.5(p_{fi} + p_{bi}) \quad (9)$$

$$\pi_{average} = 0.5(\pi_{fi} + \pi_{bi}) \quad (10)$$

The following relation defines the salt through the membrane [10].

$$m_{si} = (x_{average} - x_{pi}) k_s A \quad (11)$$

$$x_{average} = \frac{x_{fi} m_{fi} + x_{bi} m_{bi}}{m_{fi} + m_{bi}} \quad (12)$$

Values of K_w and K_s are taken from manufacturer manuals [5]. The salinity of permeate is calculated by the following equation.

$$x_{pi} = \frac{m_{si}}{m_{pi}} \quad (13)$$

Substituting Equation (6) and Equation (11) into Equation (2-13)

$$x_{pi} = \frac{k_s (x_{average} - x_{pi})}{k_w (\Delta p_i - \Delta \pi_i)} \quad (14)$$

Permeate concentration average after n stages is calculated by the following equation.

$$x_{permeate} = \frac{\sum_1^n m_{pi} x_{pi}}{\sum_1^n m_{pi}} \quad (15)$$

Total permeate flow rate after n stages is calculated by the following equation.

$$M_{permeate} = \sum_1^n m_{pi} \quad (16)$$

Permeate recovery for proposed reverse osmosis modules arrangements after n stages is calculated from the following equation.

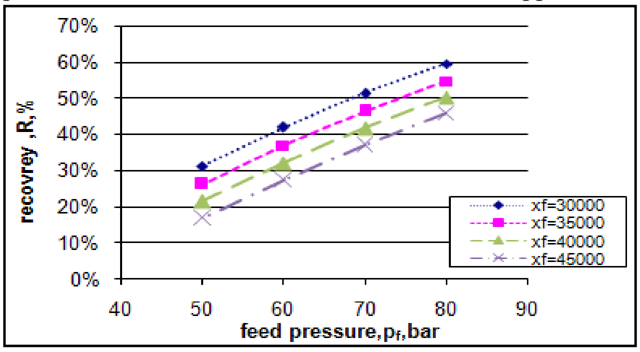
$$R_{system} = \frac{\sum_1^n m_{pi}}{m_f} \quad (17)$$

IV. Results and Discussion

Seawater salinity is taken 30000 ppm, 35000 ppm, 40000 ppm, and 45000 ppm. The operating parameters considered are the feed pressure and the feed water concentration with and without booster pumps for hollow fine module design.

The results present the effect of changing feed pressure ranging from 50 to 80 bar on permeate salinity and recovery with different feed water salinity. The recovery of RO system is a function of permeate flow rate as indicated in Equation (2). Permeate flow rate is a function of feed pressure as indicated in Equation (6). The recovery increases with increasing feed pressure. Permeate salinity is a function of feed pressure as indicated in Equation (14). Permeate salinity decreases with increasing feed pressure. Fig. 3 shows the effect of changing feed pressure on one stage RO system. If feed pressure increases from 50 bar to 80 bar, recovery increases by about 120%. The Permeate salinity decreases with increasing feed pressure.

Fig. 4 shows the effect of changing feed pressure on two stages RO system. Figure 4 (a) illustrates that permeate salinity decreases by about 37% with increasing feed pressure from 50 bar to 80 bar. Figure 4 (b) indicates that recovery increases by about 85% with increasing feed pressure from 50 bar to 80 bar. The difference between permeate salinity with and without booster pumps doesn't exceed 3%. The difference between recovery with and without booster pumps is about 2%. Figure 5 illustrates the effect of changing feed pressure on three stages RO system. Figure 5 (a) indicates that permeate salinity decreases by about 35% with increasing feed pressure from 50bar to 80 bar. Figure 5 (b) shows that recovery increases by about 70% with increasing feed pressure from 50 bar to 80 bar. The difference between permeate salinity with and without booster pumps doesn't exceed 5%. The difference between recovery with and without booster pumps is about 2%. There is no operate point for three stages without booster pumps for the case of 50 bar feed pressure (xf=45000 ppm) because permeate concentration exceeds the limit of 500 ppm.



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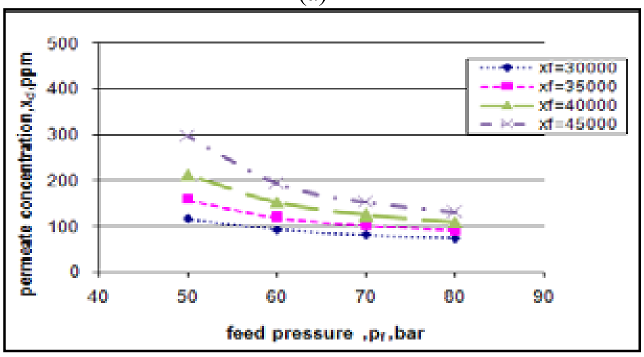

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Fig. 3: Effect of Changing Feed Pressure on One Stage Reverse Osmosis Sea Water Desalination Parameters. (a) Permeate Concentration. (b) Recovery

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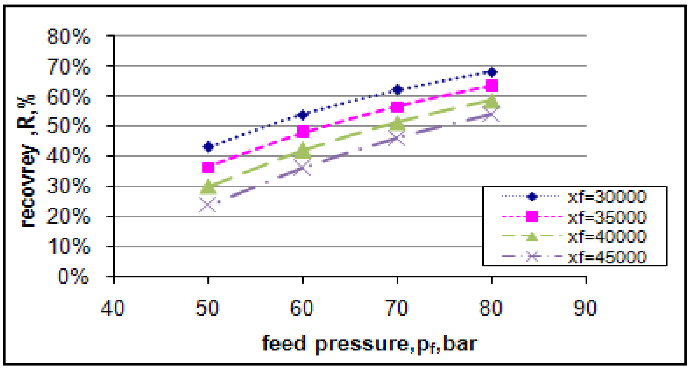

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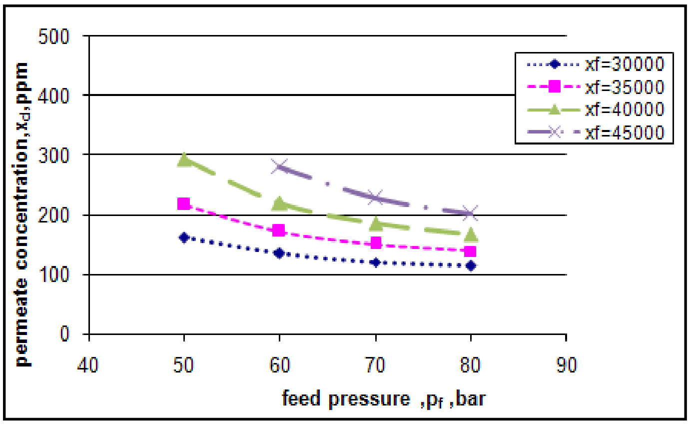

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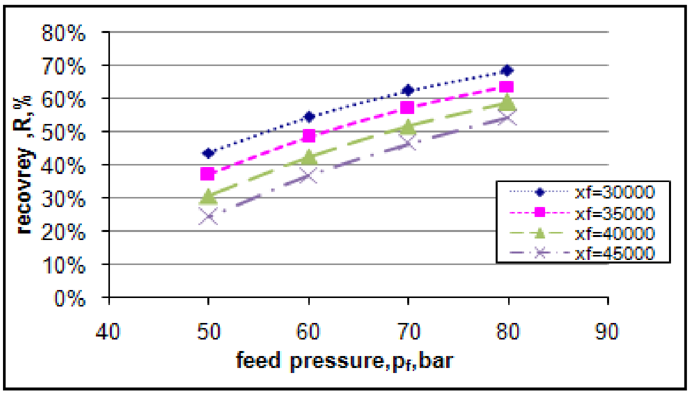

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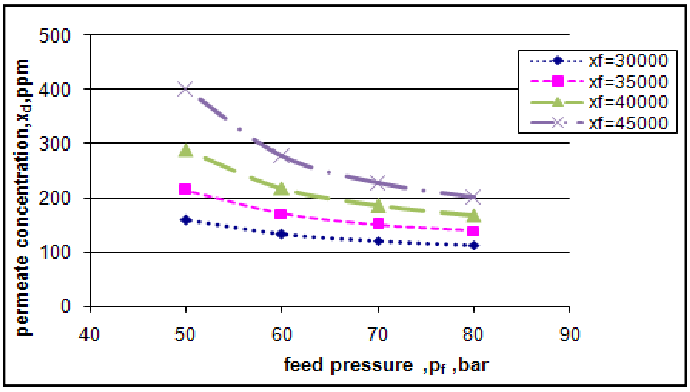

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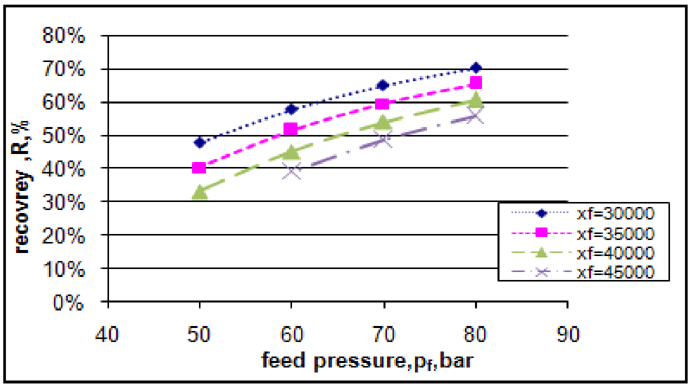
Fig. 4: Effect of Changing Feed Pressure on Two Stages Reverse Osmosis Sea Water Desalination Parameters. (a) Permeate Concentration Without Booster Pumps. (b) Recovery Without Booster Pump. (c) Permeate Concentration With Booster Pumps. (d) Recovery With Booster Pumps



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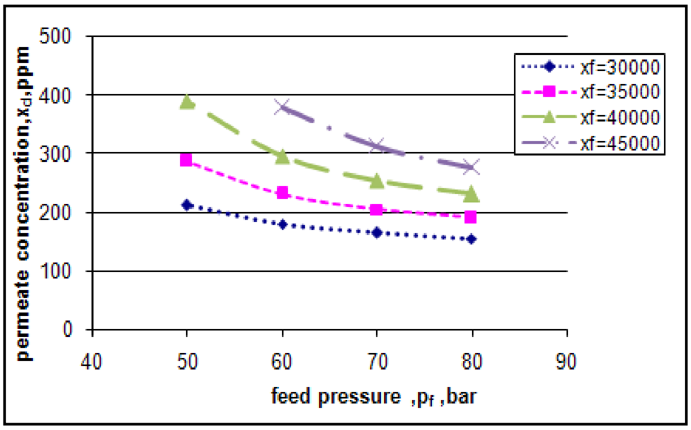

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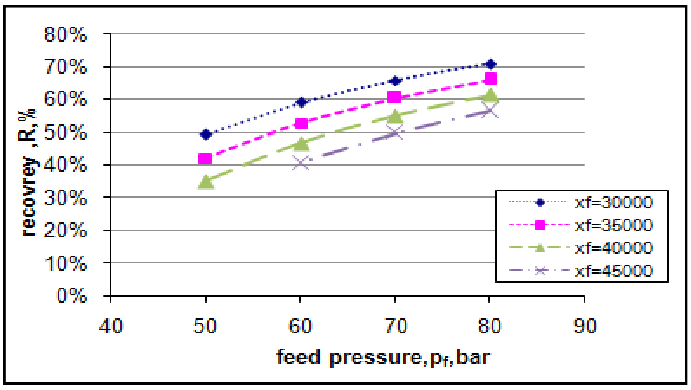

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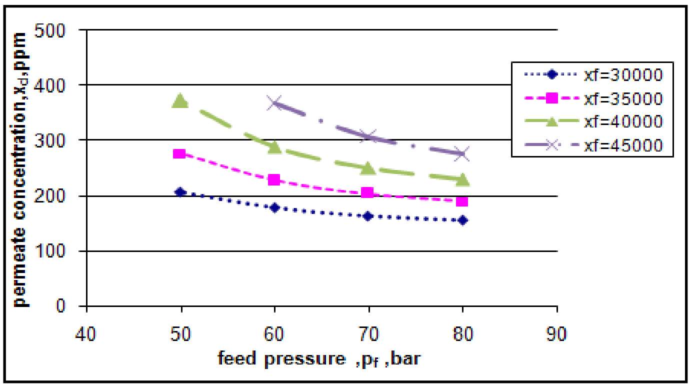

Fig. 5: Effect of Changing Feed Pressure on Three Stages Reverse Osmosis Sea Water Desalination Parameters. (a) Permeate Concentration Without Booster Pumps. (b) Recovery Without Booster Pumps. (c) Permeate Concentration With Booster Pumps. (d) Recovery With Booster Pumps.

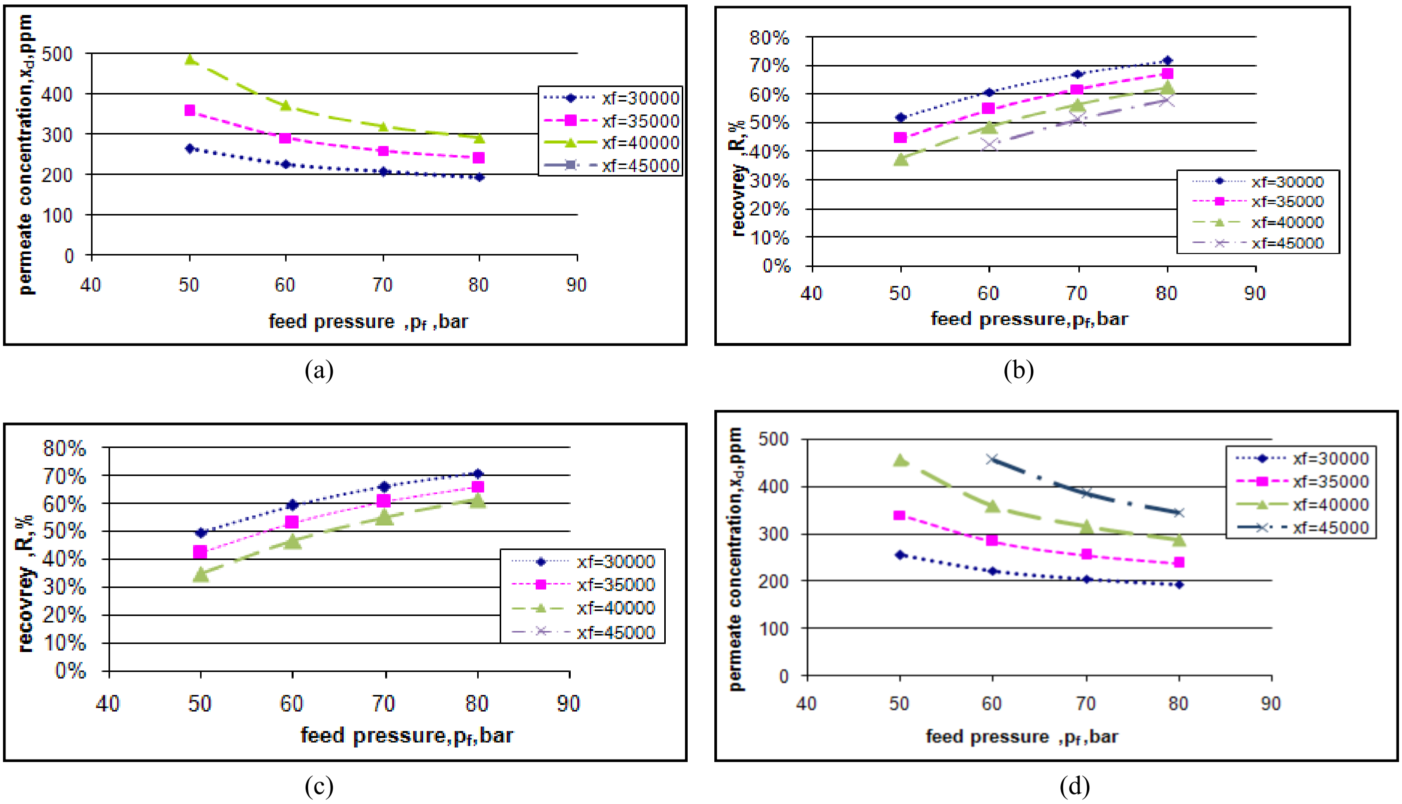

Fig. 6: Effect of Changing Feed Pressure on Four Stages Reverse Osmosis Sea Water Desalination Parameters. (a) Permeate Concentration Without Poster Pumps. (b) Recovery Without Poster Pumps. (c) Permeate Concentration With Poster Pumps. (d) Recovery With Poster Pumps

Fig. 6 shows the effect of changing feed pressure on four stages RO system. Fig. 6(a) indicates that there are no operate points for four stages without booster pumps at 45000 ppm feed salinity because the permeate concentration exceeds the limit of 500 ppm and the osmotic pressure is higher than feed pressure, therefore, there is no flow of permeate. Fig. 6 (b) shows that recovery increases about 65% with increasing feed pressure from 50 bar to 80 bar. Figure 6 (c) shows permeate salinity (with booster pumps) decreases by about 32% with increasing feed pressure from 50 bar to 80 bar. The difference between permeate salinity with and without booster pumps doesn't exceed 6%. The difference between recovery with and without booster pumps is about 2%.

Tables 1 to 4 summarize the results of the study for seawater desalination using cellulose triacetate membrane (hollow fine module design) under different feed pressure and different feed salinity. The tables indicate that recovery increases to about 150 % with increasing feed pressure from 50 bar to 80 bar as indicated in Equation (2) and Equation (6). It is clear from Table (4) that there aren't operating points as the permeate salinity exceeds 500 ppm or the osmotic pressure was higher than feed pressure. The difference between recovery with and without poster pumps is about 1%. Recovery reaches about 60 after two stages for case of 80 bar feed pressure.

V. Conclusion

The results show that the permeate flow rate for all sea water concentrations increases with increasing feed water pressure. When operating the system at high water feed pressure- for all the considered concentrations- two stages arrangement is adequate, while at low pressures, three and four stages produce higher permeate flow rates. In case of seawater concentration of 45000 ppm booster pumps between stages are require in order to avoid permeate concentration over 500 ppm.

Table 1: Results Summary for 30000 ppm Feed Seawater Salinity

Feed sea water salinity = 30000 ppm					
P_f (bar)	Booster pumps (without/ with)	Recovery, %			
		One stage	two stage	three stage	four stage
80	Without	59.4	68.1	70.1	70.9
	With	--	68.5	70.8	71.7
70	Without	51.3	62.0	65.0	66.0
	With	---	62.5	65.8	67.2
60	Without	41.9	53.8	57.8	59.3
	With		54.4	58.9	60.9
50	Without	31.3	43.0	47.7	49.7
	With		43.8	49.2	51.9

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Table 2: Results Summary for 35000 ppm Feed Seawater Salinity

Feed sea water salinity = 35000 ppm					
P_f (bar)	Booster pumps Without/ with)	Recovery, %			
		One stage	Two stages	Three stages	Four stages
80	Without	55	63.3	65.3	66.1
	With	--	64	66	67
70	Without	46	57	59	61
	With	---	57	60	62
60	Without	37	48	51	53
	With		48	53	55
50	Without	26	36	40	42
	With		37	42	45

Table 3: Results Summary for 40000 ppm Feed Seawater Salinity

Feed sea water salinity = 40000 ppm					
P_f (bar)	Booster pumps	Recovery, %			
		One stage	Two stages	Three stages	Four stages
80	Without	50	58	60.5	61.4
	With	--	59	61	62
70	Without	42	51	54	55
	With	---	52	55	57
60	Without	32	42	45	47
	With		43	47	49
50	Without	22	30	33	35
	With		31	35	37

Table 4: Results Summary for 45000 ppm Feed Seawater Salinity

Feed sea water salinity = 45000 ppm					
P_f (bar)	Booster pumps	Recovery, %			
		One stage	Two stages	Three stages	Four stages
80	Without	46	54	56	—
	With	--	54	57	58
70	Without	37	46	49	—
	With	---	47	50	51
60	Without	27	36	39	—
	With		37	41	42
50	Without	17	24	—	—
	With		24	—	—

Nomenclature

A membrane area, m^2

k_w water permeability, kg/(m^2 s kPa)

k_s salt permeability, kg/(m^2 s ppm)

$M_{permeate}$ Total permeate flow rate for proposed arrangement, kg/s

m flow rate, kg/s

p pressure, kPa

Δp pressure drop across the membrane, kPa

Δπ osmotic pressure drop across the membrane, kPa

R permeate recovery, dimensionless

R_{system} system permeate recovery, dimensionless

SR salt rejection, dimensionless

X salinity, ppm

$X_{average}$ average salinity in the feed compartment, ppm

π Osmotic pressure, kPa

Subscripts

b Brine

f Feed

p Permeate

i Module No. i

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Ehab Salah Ali received his B.S. degree in mechanical engineering from faculty of engineering, Assiut University, Egypt, in 2009. He was a mechanical engineer in research department in Holding Water Company in Sohag from 2010 until now. His research interests include brackish water and sea water desalination using reverse osmosis system.