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Design of Reverse Osmosis Process for the Purification of River Water in the Southern Belt of Bangladesh

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The salinity of on-site river water of the industry is high as 13,000 ppm due to intrusion of salt from the sea in the southern belt of Bangladesh. This leads to increasing level of corrosion of equipment and a number of industries are facing increasing production cost because of that. On the other hand, Department of Environment (DOE) of Bangladesh are reducing/stopping the use of underground water and pursuing major municipalities and industrial units to increase the use of surface water such as river water. Bringing water from an up-stream point of the river by constructing a pipeline is not an economically viable option. The technical water such as demineralised water can be supplied to process and power industries for general cooling and boiling equipment by treating the river water using the Reverse Osmosis (RO) process. For this purpose, in this work, design of RO process for the purification of highly saline river water of the southern belt of Bangladesh is considered using model based techniques. RO process model is developed within ASPEN custom modeller. Water specific data are taken from Rupsha river and Karnafuli river. The simulation results of the model are compared with those of available in the literature. Finally, a systematic approach of model based demineralisation RO process development is presented.

1. Introduction

Abundance and quality water supply is essential for all living species. Sustainable agriculture and industrial production need steady supply of freshwater. In many parts of the today's world, desalination plays a vital role for sustaining human habitation besides the existing conventional water treatment technologies. Membrane based RO process has become a popular method to supply the fresh water from seawater and brackish water in different regions. RO (Figure 1) is a pressure driven process which under pressure reverses the flow direction of the solvent (in the opposite direction of osmosis process). Substantial efforts have been made by researchers on freshwater production (Sassi, 2012) and wastewater treatment (Stoller et al., 2016) using the RO. Rapid growth of membrane desalination processes enhanced the removal of ionic contaminants (Sassi and Mujtaba, 2013), pharmaceutical active compounds (Gur-Reznik et al., 2011) and other types of effluents from chemical, petrochemical, electrochemical, food, paper and tanning industries.

Demineralised water can be supplied to several industries by treating the saline water using the RO process. However, there are limited studies on the production of demineralised water. Demineralised water is completely free (or almost) of dissolved minerals (Kremser et al. 2006) which has total dissolved solids (TDS) as low as 1 mg/l. Kremser et al. (2006) described operating experience on demineralized water plant.

In this work, RO based desalination process is considered using three stages described by (Sassi, 2012) as shown in Figure 1. The plant nominal operating and design parameters (of commercial Film Tec spiral wound RO membrane elements) are taken from Abbas (2005). Firstly, the model prediction is validated against those reported by Sassi and Mujtaba (2010). Secondly, an optimization problem incorporating a process model is formulated to optimize the design and operating parameters in order to minimize specific energy consumption and the results are compared with Sassi (2012). Since those models (Sassi, 2012) are validated for freshwater production, the model parameters such as (water and salt permeability coefficients) needs to be updated for demineralised water. A structure of the RO network is developed based on RO network (two-stage seawater pass and two-stage brackish water pass). Different parameters are updated for the model from the literature.

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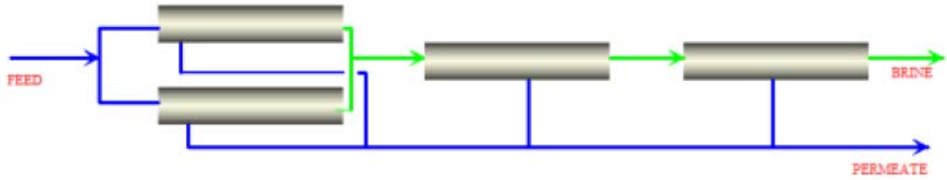

Figure 1: Schematic diagram of three tapered stages RO process.

2. Current status of RO in Bangladesh

During the design and construction phase of several industries, underground water was abundant in the surrounding areas and dependency on the underground water was not a problem for these industries. The salinity of on-site river water of the industry is high due to intrusion of salts from the sea into the rivers in the southern belt of Bangladesh (The World Bank, 2015) and also Baten et al. (2015). During the dry season when river water flow is sluggish, freshwater problem is acute in this region. Current river water salinity is as high as 13,000 ppm in the southern belt of Bangladesh (Rahman et al. 2014). Besides, salt intrusion has degraded the soil and water quality in the last thirty years due to the diversion of water from the upstream rivers (Rahman, 2011).

Different industries are facing increasing production cost due to salinity of water as it corrodes equipment. For industrial purpose, these salts need to be removed to avoid reduction in plant efficiency. Bringing water from an up-stream point of the river by constructing a pipeline is not an economic and viable option. The excessive use of underground water depleted water table of freshwater and as result, salt water enters into the freshwater aquifers. Elevated blood pressure and cardiovascular and related chronic diseases among young have been reported. DOE are very concerned about this and pursuing major municipalities and industrial units to increase the use of surface water such as river water and reduce/stop the use of underground water (DOE, 2016). The rising demand of drinking water justifies the increasing attention in the onsite demineralization plant where river water is to be processed for industrial purpose using RO process by national and multinational companies such as KAFCO etc. Industrial project planning and design depends on whether the product and process is sustainable. Sustainable supply of fresh water supplies to a region leads to quality of life. The technical water such as demineralised water can be supplied to process and power industries for general cooling and boiling equipment using the RO process (Li, 2012). Bangladesh government is getting more and more concerned to conserve underground water to be used mainly for drinking water. To comply with government and DOE directives and also for long term sustainability, the different industries in Bangladesh are implementing RO unit onsite to supply demineralized and potable water from surface water instead of underground water.

3. Modelling of RO process

Due to availability of computational tools such as Aspen plus, Aspen Custom modeller, gRPROMS, Matlab, there has been growing implementation of model based activities in process design and operations over the past decades. Mujtaba et al. (2017) recently presented model based techniques in desalination process. Simulation and optimisation are used as cost-effective tools for different engineering system. In this work, RO based desalination process model will be developed within Aspen Custom modeller for design and optimisation study.

The permeation through membranes was modelled using several approaches include the solution-diffusion model, pore models and irreversible thermodynamic model; all these models are special cases of the statistical-mechanical model (Sassi, 2012). RO process model based on solution-diffusion model and thin film theory have been developed to investigate the effect of different operating and design parameters on the performance of the system. RO systems arranged in three tapered stages for brackish water was studied by Sassi and Mujtaba (2010). Each element is modeled by a set of nonlinear algebraic equations which is described in Table 1.

4. Model validation

Membrane parameters and spacer characteristics and feed operating conditions of the model reported by Sassi and Mujtaba (2010) is shown in Table 2. The model is verified against those reported by Sassi (2010) and previously by Abbas, (2005). Comparison of the water recovery and salt rejection with those predicted by Sassi and Mujtaba (2010) data and this work is shown in Table 3. A good agreement was found.

Table 1: Model equations

Overall balance	$Q_f = Q_p + Q_r$	(1)	Salt balance	$Q_f C_f = Q_p C_p + Q_r C_r$	(2)
Water flux	$Jw = B_w(\Delta p - \Delta\pi)$	(3)	Salt flux	$Js = B_s(C_m - C_p)$	(4)
Water flow via membrane	$Q_p = J_W A$	(5)	Material balance around membrane	$C_p = J_s / J_v$	(6)
Concentration polarization	$\phi = \frac{C_m - C_p}{C_b - C_p} = \exp(J_w / k)$	(7)	Reynolds no, *Re*	$= \frac{\rho d_h u}{\mu}$	(8)
Mass transfer coefficient Sherwood No	$Sh = \frac{kd_h}{D}$	(9)		$Sh = 0.0664 K_{dc} \mathrm{Re}^{0.75} Sc^{0.33} \left(\frac{2d_h}{L_f}\right)^{0.5}$	(10)
Average bulk flow	$Q_B = \frac{Q_f + Q_r}{2}$	(11)	Average velocity in feed side, *U*	$= \frac{Q_B}{W h_{sp} \varepsilon}$	(12)
Water Recovery; *WR*%	$= (Q_P / Q_f) \times 100$	(13)	Salt rejection; *SR* %	$= (1 - \frac{C_p}{C_f}) \times 100$	(14)
Pressure drop	$\Delta P_f = \frac{\rho u^2 L C_{td}}{2 d_h}$	(15)	Specific energy	$E = \frac{\Delta P_f Q_f}{\eta Q_p}$	(16)

Table 2: Membrane parameters and spacer characteristics and feed operating conditions

Membrane parameters and spacer characteristics				
Parameter	Water permeability B_w (m/bar s)	Area, A (m^2)	membrane length L (m)	membrane width w (m)
Value	0.000000939	37.2	1.0	37.2
Parameter	Salt Permeability B_s (m/ s)	Spacer height, h_{sp}(m)	Spacer hydraulic diameter, d_h(m)	Element length L_f (m)
Value	0.0000000565	0.000593000	0.0008126	0.00277
Feed operating conditions				
Parameter	Flow, Q_f (m^3/h)	Concentration, C_f (ppm)	Pressure, P_f (bar)	Temperature, T_f(°C)
Value	20.4	2,540	12.2	28.8

Table 3: Comparison operational data with Abbas and Sassi data and this work results

Parameter	Plant Data	Abbas (2005)	% Dev.	Sassi (2010)	% Dev.	This work	% Dev.
Water recovery %	58.82	58.6	0.37	58.0	1.39	58.05	1.31
Salt rejection %	97.6	98.9	1.33	98.6	1.02	98.66	1.09

5. Optimization of operating and module design parameters

An optimization problem incorporating a process model is formulated to optimize the design and operating parameters in order to minimize specific energy consumption constrained with fixed product demand and quality.

The optimization result (Shown in Table 4) is verified against those reported by Sassi and Mujtaba (2010) and a good agreement was found.

$$\underset{P_f;\, Q_f;\, L_f;\, H_{sp}}{Max} \quad E \tag{17}$$

Subject to

Equality Constraints *Process model*; (18)

fixed product demand (19)

and product quality (salt concentration less than 100 ppm) (20)

Inequality Constraints $P_f^l \le P_f \le P_f^u$; (21)

Inequality Constraints $Q_f^l \le Q_f \le Q_f^u$; (22)

Inequality Constraints $L_f^l \le L_f \le L_f^u$; (23)

Inequality Constraints $d_f^l \le d_f \le d_f^u$ (24)

Table 4: Optimization Results of Problem comparison

Parameter	Base case Abbas (2005)	Optimized conditions Sassi (2005)	Optimized conditions This work
Feed pressure (bar)	12.2	13.6	13.5
Feed flow (m^3/h)	20.4	14.6	14.7
Specific energy consumption (kWh/m^3)	0.7304(Calculated)	0.5865	0.5823

6. Case Study for demineralized water

Raw river water parameters are shown in Table 5. Symbols in Table 5 their usual meaning.

Table 5: Raw Water Specification Rupsha River and Dolphin Jetty KARNAPHULI High Tide and Low Tide

pH	Conductivity (mS)	Turbidity (NTU)	TDS (ppm)	Total Hardness (ppm)	TSS (ppm)	Silica (ppm)	COD (ppm)	DO (ppm)
7.19 - 7.59	5 -36,000	14.2 26.2	-400 26,000	- 30 - 4,000	30 - 300	1.5 - 6	10 - 35	5.09 - 6.71
8.0	33,600	190.3	27,500	4,070	294.5	3.0	61.2	
7.8	24,100	88.8	21,355	2,830	138.5	5.7	26.2	

Different design patterns have been developed to reduce the TDS in RO permeate. Finally, two stage seawater modules and two stage brackish water module are used to develop for the demineralized water treatment from above salinity of the water. Brackish water unit enhances the quality of the demineralized water.

Both structures are same as shown in Figure 2 and the characteristic parameters of the seawater module (SW30XLE-400) and brackish water module (BW30-400) are presented in Table 6. For this work, the membrane parameters and spacer characteristics and feed and other operating conditions are same those shown in Table 2. Both modules have two pressure vessels arranged in series stages and 2 element in series. Same RO model is used here. Considering the river high salinity (27500 ppm), the simulation module is carried out for this work composed of seawater pass RO system and Brackish water pass RO system connected in a series. Table 7 shows the input parameters of the proposed RO network. The yielded % water recovery (WR) and % salt rejection (SR) is presented in Table 8.

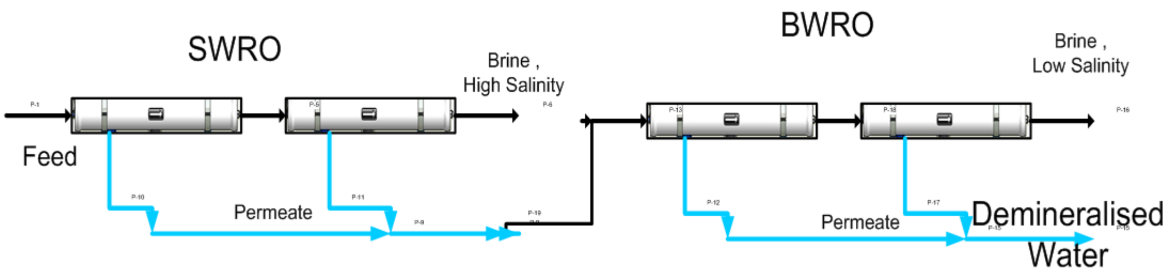

Figure 2: Schematic diagram of structure of series RO process.

Table 6: The characteristics of spiral wound membranes (Sassi, 2012)

Parameter	Element type	
	BW30-400	SW30XLE-400
Diameter of the element (m)	0.201	0.201
Membrane module area (m^2)	37	37.2
Module Feed flow range (m^3/h)	0.8–19	0.8–16
Maximum operating pressure (bar)	41	83
Water permeability (m bar s)	0.000000939	0.000000350
Salt permeability (m/s)	0.0000000565	0.000000032

A demineralization plant is to be set up at the bank of Karnaphuli, for KAFCO. KAFCO needs 5.5x10^6 m$^{3/}$y or 628 m^3/h demineralised water for its production processes and civic uses and the total water demand is met by using underground water at present. In order to reduce the usage of underground water, KAFCO is planning to use the Karnaphuli river water as a source of raw feed water. The power plants at Rupsha needs 628 m^3/hr demineralised water. Possible way may be feed raw water may be distributed into *N* number of feed into the similar *N* number of unit shown in Figure 3. *N* is required amount of demineralised water by specific industry divided by 6.17 m^3/h (6.17 m^3/h is demineralised water produced from 20.4 m^3/h pre-treated water for the models in Table 8).

Table 7: Input parameters of the membranes

		Module length, L	Module width, W	SPACER MESH LENGTH, Lf	SPACER WIDITH, HSP	SPACER DIAMETER, DF	Salt Permeability, Bs	Water Permeability, Bw
SW30XLE-400	2x2	1	37.2	0.00277	0.000893	0.000285	0.0000000319	0.0000003497
BW30-400	2x2	1	37.2	0.00277	0.000593	0.000285	0.0000000565	0.000000939

Table 8: Simulation Results

Cases	Pressure (bar)	C_f (ppm)	Specific energy (kWh/m^3)	WR %	SR %	TCP (ppm)	TFLOW (m^3/hr)
SW30XLE-400	83	27,500	6.06	47.53	99.70	81.80	9.70
BW30-400	12.2	81.80	0.588	63.64	98.99	0.82	6.17

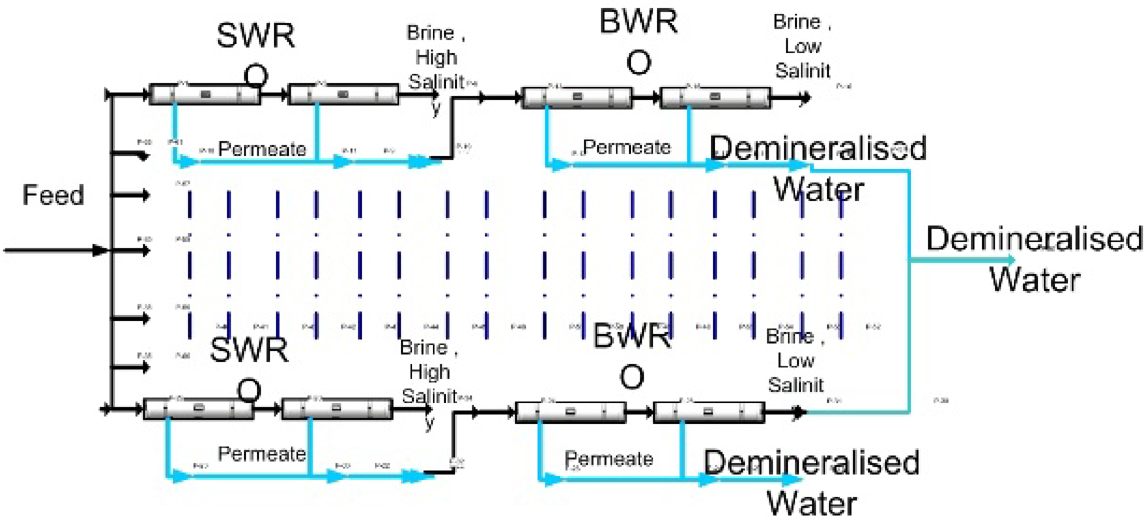

Figure 3: Schematic diagram RO process.

7. Conclusions

Climate change and other factors increase the water salinity of the river water in Bangladesh. Shortages of potable water, catastrophic effect of aquatic eco-system and soil fertility leads to prevent underground water to be used by industries. The setup of RO plant for industrial water such as demineralised water saves substantial amount of ground water resources. In this work, a systematic methodology considering TDS limit in the final permeate of RO based demineralised process is designed to meet the local needs. The aspen custom model is verified against the operational data of Abbas (2005) and optimisation result by Sassi and Mujtaba (2010). Model prediction has good agreement. In future optimisation study can be carried out by varying the different geometric parameter

Nomenclature

A	Membrane surface area (m^2)	Δp	transmembrane pressure difference(bar)
B	permeability (m/ bar.s)	ΔP_f	Pressure across the membrane(bar)
C	salt concentration (kg/m^3)	Q	Volumetric flowrate (m^3/s)
J	flux (m/s or kg salt/(m^2/s))	Sh	Sherwood number
k	mass transfer coefficient (m/s)	Sc	Schmidt number
ϕ	Concentration polarization factor	$\Delta\pi$	osmotic pressure difference (bar)

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