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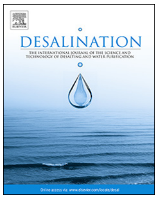

Performance analysis of a medium-sized industrial reverse osmosis brackish water desalination plant

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ABSTRACT

The implementation of Reverse Osmosis (RO) technology is noticeably increased to produce freshwater from brackish and seawater resources. In this work, performance analysis of a multistage multi pass medium-sized spiral wound brackish water RO (BWRO) desalination plant (1200 m^3/day) of Arab Potash Company (APC) located in Jordan is evaluated using modelling and simulation. For this purpose, a mathematical model for the spiral wound RO process based on the principles of solution diffusion model is developed. The model is then used to simulate the operating conditions of low-salinity brackish water RO (BWRO) desalination plant. The results obtained are then compared against the real industrial data of BWRO desalination plant of APC which shows a high-level of consistency. Finally, the model is used to analyse the impact of the operating parameters such as salinity, pressure, temperature, and flow rate on the plant performance. The sensitivity analysis confirms that both feed flow rate and operating pressure as the critical parameters that positively affect the product salinity.

1. Introduction

The Red Sea and groundwater are considered as the most important available resources of water in Jordan which spread over 80% of the country in different quantity and quality [1]. Desalination of seawater and brackish water is an important choice to provide potable, agricultural and reuse water especially in the regions suffering from water scarcity [2–4]. Interestingly, brackish water desalination plants are considerably used in Jordan as a potential source of freshwater specially to cope water scarcity and to rectify the shortage of a good quality water in Jordan [5].

The Reverse Osmosis (RO) technology has been increasingly considered as one of the cheapest and promising methods for salinity reduction [6–9]. Having said this, the RO technology is a successful process to remove almost all constitutes of dissolved solids in sea and brackish water. The membrane modules are provided in several types including hollow fiber, plate and frame, tubular and spiral wound. However, spiral wound module is the most popular among RO membrane modules [10]. The RO and especially spiral wound module is mainly designed with several stages and orders to consider the quality of the produced water and economics. Interestingly, this technology has witnessed a rigorous development especially in improving both the water quality and recovery. This has happened due to the development of a new generation of RO membranes that commensurate with high-level of salt rejection and water permeation at a realistic energy consumption. Moreover, this technology is more flexible to be scaled up (ranging from small-sized to large-sized) and requires lower operating cost and energy consumption compared to thermal processes like multistage flash distillation (MSF) [8, 11, 12]. Therefore, there are much interest to model and optimize the RO process to satisfy specific requirements of water.

A thorough review of the open literature confirms several attempts of spiral wound RO modelling based on the principles of solution diffusion model and irreversible thermodynamic model [13–17]. The models developed are used to quantify the transport phenomenon of water and solute through the membrane.

In this respect, the area of seawater and brackish water RO desalination plant modelling of different sizes with various limitations and assumptions has been carried out by several studies based on spiral wound module. This in turn provides several faces of semi-empirical models that predict the plant performance with the aid of experimental data. Several examples of the models developed for this purpose and based on solution diffusion model are illustrated in the next.

Abbas and Al-Bastaki [11] and Abbas [14] presented a semi-

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Nomenclature

A_m	Effective area of the membrane (m^2)
$A_{w(T)}$	Water transport coefficient at operating temperature (m/atm s)
A^*	The spacer characteristics (dimensionless)
$B_{s(T)}$	Solute transport coefficient at operating temperature (m/s)
C_b	The bulk solute concentrations at the feed channel (kg/m^3)
C_f	The operating feed solute concentrations at the feed channel (kg/m^3)
$C_{f(RW)}$	The feed water feed concentration (kg/m^3)
C_w	The solute concentration on the membrane surface at the feed channel (kg/m^3)
C_p	The permeate solute concentration at the permeate channel (kg/m^3)
C_r	The retentate solute concentration of a membrane module (kg/m^3)
C_{td}	The total drag coefficient (dimensionless)
D_b	The solute diffusion coefficient of feed at the feed channel (m^2/s)
d_h	The hydraulic diameter (m)
Q_s	The solute flux through the membrane (kg/m^2 s)
J_w	The water flux through the membrane (m/s)
k	The mass transfer coefficient at the feed channel (m/s)
k_{dc}	Constant in Eq. (19) (dimensionless)
L	The membrane length (m)
m_f	Parameter in Eq. (22)
n	The spacer characteristics (dimensionless)
P_f	The operating feed pressure of a membrane module (atm)
P_r	The retentate pressure of a membrane module (atm)
P_p	The permeate channel pressure of a membrane module (atm)
Q_b	The bulk feed flow rate at the feed channel of a membrane module (m^3/s)
Q_f	The operating feed flow rate at the feed channel of a membrane module (m^3/s)
$Q_{f(RW)}$	The feed water feed flow rate (m^3/s)
Q_p	The permeate flow rate at the permeate channel of a membrane module (m^3/s)
Q_r	The retentate flow rate at the feed channel of a membrane module (m^3/s)
Re_b	The Reynolds number of the bulk at the feed channel (dimensionless)
Rec	Total permeate recovery of a membrane module (dimensionless)
Rej	The observed solute rejection of a membrane module (dimensionless)
Rel_{ac}	The accurate solute rejection of a membrane module (dimensionless)
T	The operating feed temperature of a membrane module (°C)
t_f	Height of feed channel (m)
U_b	The bulk feed velocity at the feed channel of a membrane module (m/s)
W	The membrane width (m)

Subscript

μ_b	The bulk viscosity at the feed channel of a membrane module (kg/m s)
ρ_b	The bulk density at the feed channel of a membrane module (kg/m^3)
$\Delta P_{drop,\ E}$	The pressure drop of the spiral wound element (atm)
π_b	The bulk osmotic pressure at the feed channel (atm)
π_p	The osmotic pressure at the permeate channel (atm)
ϵ	The void fraction of the spacer (dimensionless)

rigorous model to investigate the performance of a small-sized BWRO desalination plant of four pressure vessels arranged in three tapered stages. Each pressure vessel holds three spiral wound membranes of Dow/FilmTec BW30-400 membranes in series. Geraldes et al. [18] developed a numerical model for spiral wound two stage seawater RO desalination plant (1000 m^3/day) and used for simulation and optimisation. Majali et al. [19] analysed the performance of the Sharjah BW small-sized RO plant (production capacity of 237.5 m^3/day) using a rather simple model. The plant contains two stages of 30 and 12 pressure vessels, respectively, each pressure vessel holding six membranes connected in series. Lee et al. [10] studied the dynamic characteristics and process operation of the Jeddah large-sized RO desalination plant operated in the Kingdom of Saudi Arabia (production capacity of 56,800 m^3/day). For this purpose, a dynamic model is developed based on the work of Oh et al. [15], Marriott and Sørensen [20], Lee and Lueptow [21]. Kaghazchi et al. [16] developed a steady state model to analyse the performance of two industrial seawater RO plants (capacity of 3456 m^3/day and 52 m^3/day respectively) based on FilmTec SW30HR-380 spiral wound membrane modules. The first seawater RO plant contains 294 parallel pressure vessels while the second RO plant contains 32 pressure vessels connected in series. Each pressure vessels holds 7 membranes in series. Ruiz-Saavedra et al. [22] presented a simple design method that comprises a sophisticated modelling and originally conceived for the application to subterranean BWRO desalination plants in the Canary Islands, Spain. The input data of chemical composition, pH, SDI, temperature, plant production and membrane manufacturer design guideline are required to design the RO system and operating pressure that ensures the product quality.

However, most studies are carried out for small-sized plants and few studies have been conducted for medium and large-sized BWRO desalination plants. Also, the impact of operating temperature on transport parameters has not been considered. Also, the majority of these models are developed under the assumptions of constant physical properties and mass transfer coefficient.

This research is mainly related to the BWRO desalination plant of APC producing low-salinity water. To the best of the authors' knowledge, there has not yet been any study to model the medium-sized BWRO plant and to analyse the plant performance under various operational parameters. Therefore, the primary aim of this study is to develop a steady state numerical model of algebraic and non-linear equations for spiral wound RO process based on the principles of solution diffusion model. Then, a full model of multi-stage multi-pass BWRO of APC is developed to simulate the actual plant. The characteristics of the model developed in this paper are as follows:

- the variation of model transport parameters is considered against the variation of feed temperature and fouling factor;
- the osmotic pressure in both feed and permeate channels is investigated using the empirical correlation of Toray membrane USA Inc. (membrane manufacturer);
- new solute rejection and recovery rate correlations are derived from the material balance equations.

Due to the existence of real data gathered from the plant operator, the model developed will be examined and validated against reliable experimental data. Then, the plant performance will be explored against the operating conditions via a sensitivity analysis study.

Note that the model developed has the capacity to select the number