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Simulation and analysis of an industrial water desalination plant

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Abstract

In this paper, an industrial medium-scale brackish water reverse osmosis plant based on Dow/FilmTec BW30-400 spiral-wound membrane modules was simulated and its performance investigated. Actual operating data is used to validate the computer package. The semi-rigorous model was found to represent the plant with good accuracy; the relative errors in the overall water recovery and salt rejection were 0.37 and 1.33%, respectively. The effects of the arrangement of membrane modules, the operating pressure and the feed flow rate on the performance of the plant were investigated. The single-stage configuration in which all pressure vessels are arranged in parallel was found to yield the best results in terms of the production rate, product quality and overall pressure drop across the feed channel. At low to moderate operating pressures and feed rates, increasing both operating variables will result in higher water production rates and salt rejection. However, high operating pressures lead to a deterioration of the quality of the product whereas high flow feed rates, contrary to one's expectation, result in a reduction in the production rate.

Keywords: Water desalination; Reverse osmosis; RO simulation; RO performance; Spiral-wound membranes

1. Introduction

Desalination of both sea and ground waters has been utilized for water supply throughout the world for over 40 years. At the end of the year 2001, there was a global installed desalination capacity of about 8.7 billion gallons per day [1]. The Gulf region is the most active in this regard as it suffers from severe shortages of fresh water.

The two most widely used desalination techniques are reverse osmosis (RO) and multi-stage flash (MSF) distillation with market shares of about 42.5 and 39.1%, respectively, of worldwide installed capacity. For brackish waters RO is, by far, the most widely employed process whereas for seawaters MSF remains the most popular technique [1]. However, in recent years, RO has significantly increased its market share for seawater desalination because of the significant progress in membrane technology and the advantages this technology offers compared to the thermal desalination techniques, MSF and multi-effect evaporation (MED). The advantages of RO include low energy requirement, low temperature of operation and low water production costs. In a study conducted in 2001, Wade [2] has shown the water production costs for an RO process with an energy recovery system to be much lower than those corresponding to MSF and MED. Using plants with a capacity of 31,822 m^3/d and a fuel cost of US$1.5/GJ as a basis of comparison, Wade estimated the water production costs for MSF, MED and RO with brine booster to be (in US$/$m^3$) 1.04, 0.95 and 0.75, respectively.

Recently, new high flux and lower salt passage membranes have been introduced together with improved efficiency pumping equipment. Also, the pre-treatment processes have witnessed significant improvements in their effectiveness. These achievements have lead to large reductions in the water production costs [3,4]. Today, seawater RO plants are being built to produce water at a forecast cost of about $0.5/$m^3$ [5,6]. Further cost reductions can be achieved through process optimization.

The performance of RO desalination processes is affected by many factors, which include:

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- The condition of the raw water and the effectiveness of the pre-treatment procedures.
- Membrane: type, size and the number of modules used and their arrangement.
- The rate and degree of fouling and cleaning ability.
- Operating conditions, such as feed pressure, temperature and permeate recovery.
- The efficiency of pumps (high pressure and booster pumps) and energy recovery systems.

In this work, a semi-rigorous model is presented and coded in Matlab for the simulation of reverse osmosis water desalination plants. The computer program is validated using actual operational data and results obtained from the Dow/FilmTec ROSA software package. It is then used to investigate the performance of an industrial medium-scale brackish water RO plant in terms of membrane module configurations and two key operating parameters, namely the operating pressure and feed flow rate.

2. Plant description

The considered industrial plant is an RO process used to desalinate brackish water drawn from a 74 m deep well. It started operation 9 years ago (October 1995) and continues to operate smoothly. It treats about 20.4 m^3/h of raw water having total dissolved solids (TDS) of about 2540 ppm. The water conversion is maintained close to 59% by adjusting the feed pressure. The nominal plant operating conditions are given in Table 1.

The plant consists of three steps, namely the pre-treatment section to control fouling and scaling of the membranes, the main processing unit to produce a permeate with the desired salinity and the post-treatment section to control the quality of the product potable water. The pre-treatment section consists of chemical and physical operations, which include chlorination with calcium hypochlorite, sand filtration, dechlorination using sodium meta-sulfite, activated carbon filtering and ultra-violet treatment. Membrane scaling is controlled by the addition of an antiscalant and sulfuric acid dosing. This stringent pre-treatment scheme helps extend the time during which the membranes remain in operation. The average membrane lifetime since start-up is well over 5 years.

The pre-treated water is delivered to the main processing facility by a high-pressure pump. This unit is composed of four pressure vessels arranged in three tapered stages, Fig. 1A. Each vessel contains three Dow/FilmTec BW30-400 membranes in-series [7]. The feed water flows from one stage to the next before leaving the plant as brine with an average concentration of about 6080 ppm. The collected permeates from all stages are blended and passed through a post-treatment phase to control the quality of the product water. The post-treatment phase includes the addition of caustic soda, ozonation, activated carbon filtering and finally dosing with fluoride.

Table 1
Process parameters and operating conditions

Parameter	Value
Feed conditions	
Q_f (m^3/h)	20.4
c_f (kg/m^3)	2.54 (2540 ppm)
P_f (Pa)	1.22×10^6
T_f (°C)	28.8
Feed pH	6.5–6.9
Fluid properties	
ρ (kg/m^3)	1000
ν (m^2/s)	1.02×10^{-6}
D (m^2/s)	1.2×10^{-9}
α (Pa/kg m^{-3})	7.79×10^4
Membrane and spacer characteristics	
Membrane type	Dow/FilmTec BW30-400 (spiral wound)
Maximum feed flow (m^3/h)	19.31
Minimum feed flow (m^3/h)	3.63
Maximum operating pressure	4.1×10^6
Maximum operating temperature (°C)	45
pH range, continuous operation	2–11
R_m (Pa s/m)	1.0655×10^{11}
R_s (s/m)	1.7712×10^7
l (m)	2.77×10^{-3}
L (m)	1
w (m)	37.2
A (m^2)	37.2
h_{sp} (m)	5.93×10^{-4}
d_h (m)	8.126×10^{-4}
k_{dc} (dimensionless)	1.501
A' (dimensionless)	7.38
n (dimensionless)	0.34

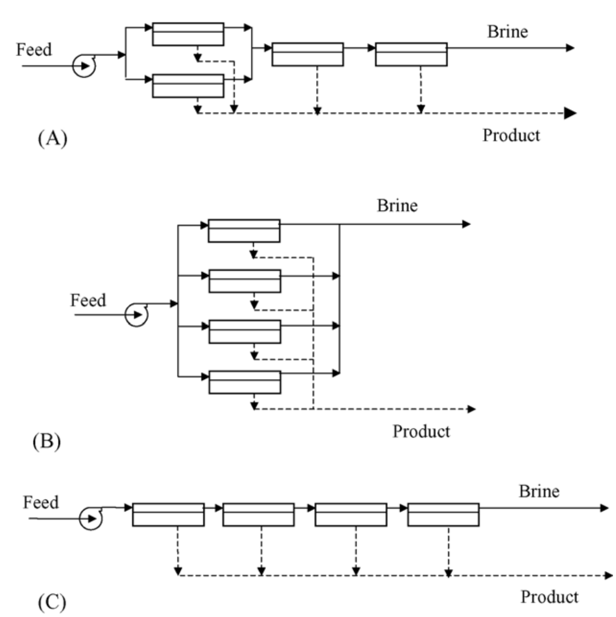

Fig. 1. Three possible configurations of the pressure vessels. (A) Three tapered stages, (B) single-stage straight-through and (C) four straight-through stages.