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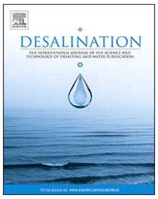

Theoretical performance prediction of a reverse osmosis desalination membrane element under variable operating conditions

Evangelos Dimitriou[a,*], Panagiotis Boutikos[b], Essam Sh. Mohamed[a], Slawomir Koziel[c], George Papadakis[a]

[a] Agricultural University of Athens, Department of Natural Resources and Agricultural Engineering, 75 Iera Odos Street, Athens 11855, Greece
[b] Laboratory of Solar and Other Energy Systems, National Center for Scientific Research "Demokritos", 153-10 Aghia Paraskevi Attikis, Greece
[c] Reykjavik University, Engineering Optimization & Modeling Center, School of Science and Engineering, Menntavegur 1, 101 Reykjavik, Iceland

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ABSTRACT

Sea Water Reverse Osmosis (SWRO) desalination systems powered by Renewable Energy (RE) can reduce drastically costs, specific energy consumption and CO_2 emissions. A direct connection of a SWRO desalination system with RE technologies such as photovoltaics, can result in lowering the specific energy consumption due to the part-load operation of the desalination unit. However, due to the variable nature of solar energy, the membranes could operate outside of their nominal operating ranges. Therefore, research is needed to investigate the effect of the variable operation (non-stable pressure and flow rate) on the membranes. This paper presents the development of a dynamic mathematical model of a spiral wound reverse osmosis membrane module aiming to investigate the mass transfer in the membrane under non-constant operating conditions. The main pursue of the model is to investigate the physical compaction, as well as the raise of the concentration polarization in order to predict the performance of the membrane under variable operating conditions. The results show a water flux drop of 0.2×10^{-3} kg/m^2·s due to the sudden increase in the applied pressure, when the impact of physical membrane compaction was taken into consideration under non-constant operating conditions.

1. Introduction

Sea water desalination belongs at the forefront of today's global water, energy, and climate challenges [1]. Producing fresh water via water desalination is essential for arid, water-scarce regions, but it is expensive and energy-intensive. Renewable energy (RE), technologies such as photovoltaics and wind turbines, create an opportunity for developing low-cost and low-emission desalination units. A direct (battery-less) connection of a photovoltaic system with a SWRO desalination unit has been investigated in 2008 [2]. A few years later, the SWRO unit was incorporated into a polygenaration microgrid topology in order to study its operation under variable operating conditions. Experimental studies showed that a direct connection of a SWRO unit with RE technologies could result in lowering the specific energy consumption due to the part-load operation of the desalination unit [3–5].

Nevertheless, the variable operating conditions of the desalination unit (non-constant pressure and flow rate) is expected to decrease the life time of the RO membranes, mainly due to the increase of the concentration polarization which affects the membrane performance. The theoretical work on membranes started very early, studying the mass transfer as well as the pressure drop in order to evaluate the membrane performance [6]. A few years later, theoretical models were developed based on Kimura – Sourirajan analysis for the performance prediction of a spiral wound membrane element under isothermal conditions [7,8]. Afterwards, extensive theoretical investigation has taken place concerning concentration polarization which is the main reason of the membrane's scaling [9]. Several theoretical and experimental studies were conducted concerning the concentration polarization in commercial spiral wound membranes in order to predict the long-term permeate flow loss from membrane fouling [10,11]. In recent years, special attention was given to the impact of physical membrane compaction on reverse osmosis membrane performance [12,13].

This study constitutes a new approach in the model simulation, developing a theoretical model of a membrane element of a SWRO desalination unit under variable operating conditions. More specifically, a dynamic mathematical model of a spiral wound reverse osmosis membrane module is developed in order to investigate the mass transfer in the membrane element (the solvent and the solute flux, the concentration at the permeate and retentate side) under variable pressure and flow rate operation of a SWRO desalination unit depending on the

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* Corresponding author.
E-mail address: vdimt@aua.gr (E. Dimitriou).

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available power of the RE technologies. MATLAB has been utilized as a programming environment for the development and implementation of the mathematical model. This theoretical work results in the prediction of the performance i.e. the permeate flow and quality of a membrane element in non-constant operating conditions (pressure and flow rate). The study of the performance parameters, such as the solvent and the solute flux as well as the concentration at the permeate and retentate side, gives directions for the optimization of the membrane element (design parameters and membrane properties) of the unit in order to reinforce the membrane structure under non-stable operating conditions, investigating the physical compaction as well as the fluctuation in the concentration polarization coefficient. The theoretical results were validated with experimental data of a spiral wound membrane element (Filmtec, SW30-4040) of a small scale SWRO desalination unit which is installed at the Agricultural University of Athens, as well as, with results provided by industrial software form related the specific membrane element. In addition, this work could lead to a further theoretical and experimental investigation of the membranes (membrane structure and chemical degradation) in order to evaluate the membrane lifetime at variable operation. Furthermore, this research will provide new knowledge on membrane characteristics such as lower response to hydraulic resistance and durable surface texture that should be modified for the development of RO membranes capable of working under non constant conditions with minimal physical compaction.

2. Model development

2.1. Overview

For the optimal design of an RO unit coupled with renewable energy devices, a one dimensional (1-D) mathematical model was developed for a spiral wound membrane module. The model is based on mass and momentum balances for the fluid flow in the feed and permeate channel and on membrane mass transfer relationships for the flux of the solute and solvent through the membrane.

An illustration of the unwounded spiral wound membrane element is presented in Fig. 1, whereas, Fig. 2 illustrates the flow direction inside the membrane element in the x-direction. The spiral wound module of length 'L' and width 'W' consists of a certain number of flat sheet membranes wrapped around a central tube. Each membrane separates the membrane element into two channels: the feed spacer channel with thickness h_f and the permeate spacer channel with thickness h_p. The feed solution flows axially through the feed channel and results as a brine at the exit of the feed channel. The water and salt species that permeate thought the membrane they flow perpendicular to the permeate channel. The permeate channel is closed from its one end, while the other is connected with the central tube from which the fresh water is coming out.

In order to simplify the mathematical description, the following assumptions have been made:

i) The feed and permeate channel at the spiral wound membrane module are considered to be flat (negligible curvature), since the thickness of the channels is much lower than the radius of the module.
ii) At the feed (or brine) and permeate channel, the solute concentration, the fluid velocity and pressure vary only in the *x*-direction (1-D model).
iii) Plug flow in both channels.
iv) Negligible axial diffusive mass transport in both channels.
v) Negligible components of brine and permeate flow velocities along the *x*-direction.
vi) The solution – diffusion model is valid for the transport of solvent and solute through the membrane.
vii) The concentration polarization is quantified by the film theory.
viii) The physicochemical properties (viscosity, density, etc.) of the fluid in each stream are depended on the temperature and the salinity [14].

The total mass balance and the solute mass balance at any point along the feed (or brine) channel are given by:

$$\frac{du_b(x)}{dx} = -\frac{V_w(x)}{h_b} \tag{1}$$

$$\frac{dC_b(x)}{dx} = -\frac{V_w(x)}{u_b(x)h_b}(C_b(x) - C_{f,m}(x)) \tag{2}$$

where u_b (m/s) is the fluid velocity at the brine channel, V_w (m/s) is the volume flux or the permeate velocity [$V_w = Jt_{ot}/\rho_p$], J_{tot} (kg/m^2·s) is the total permeate flux through the membrane, ρ_p (kg/m^3) is the density of the permeate, h_b (m) is the brine channel thickness, C_b, $C_{f,m}$ (kg/m^3) is the solute concentration at the brine channel and at the feed – membrane interface respectively.

The pressure drop at each point along the feed (or brine) channel is written as:

$$\frac{dP_b(x)}{dx} = -\lambda\frac{\rho u_b^2(x)}{2d_{h,b}} \tag{3}$$

where P_b (Pa) is the pressure at the brine channel, λ is the friction factor, ρ (kg/m^3) is the fluid density and $d_{h,b}$ (m) is the hydraulic diameter at the brine channel.

The friction factor can be estimated by the following expression [15]:

$$\lambda = 6.23K_\lambda \,\mathrm{Re}^{-0.3} \tag{4}$$

where *Re* is the Reynolds number and the factor K_λ is a constant related

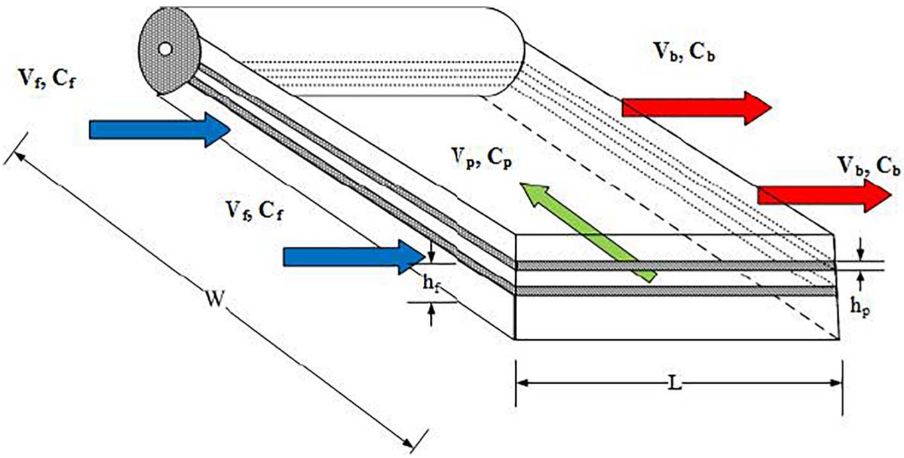

Fig. 1. An unwounded spiral wound membrane element.