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Optimisation of reverse osmosis based wastewater treatment system for the removal of chlorophenol using genetic algorithms

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HIGHLIGHTS

- A one-dimensional model is developed for the wastewater treatment RO process.
- The optimisation problem is solved by augmenting the model with a GA platform.
- The weight factors of genetic algorithm have a large impact on optimal solutions.
- The rejection is optimized by considering the economic aspects of energy savings.

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ABSTRACT

Reverse osmosis (RO) has found extensive applications in industry as an efficient separation process in comparison with thermal process. In this study, a one-dimensional distributed model based on a wastewater treatment spiral-wound RO system is developed to simulate the transport phenomena of solute and water through the membrane and describe the variation of operating parameters along the x-axis of membrane. The distributed model is tested against experimental data available in the literature derived from a chlorophenol rejection system implemented on a pilot-scale cross-flow RO filtration system with an individual spiral-wound membrane at different operating conditions. The proposed model is then used to carry out an optimisation study using a genetic algorithm (GA). The GA is developed to solve a formulated optimisation problem involving two objective functions of RO wastewater system performance. The model code is written in MATLAB, and the optimisation problem is solved using an optimisation platform written in C++. The objective function is to maximize the solute rejection at different cases of feed concentration and minimize the operating pressure to improve economic aspects. The operating feed flow rate, pressure and temperature are considered as decision variables. The optimisation problem is subjected to a number of upper and lower limits of decision variables, as recommended by the module's manufacturer, and the constraint of the pressure loss along the membrane length to be within the allowable value. The algorithm developed has yielded a low optimisation execution time and resulted in improved unit performance based on a set of optimal operating conditions.

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1. Introduction

The use of reverse osmosis (RO) is becoming more and more popular in seawater and wastewater treatment because of the low cost of water production and solute rejection compared to other thermal processes [1]. A number of studies have been conducted to maximize the performance of the system. Such studies have investigated the transport phenomena of water and solute through the membrane by improving current mathematical models and identifying the optimum set of operating variables. The optimisation of seawater RO desalination system has been carried out using different methods including, global optimisation algorithm [1], Sequential Quadratic Programming (SQP) [2], Mixed-Integer Non-Linear Programming (MINLP) [3], Genetic Algorithm (GA) [4] and multi-objective optimisation and genetic algorithm (MOO + GA) [5]. In many applications, the use of GA has yielded better results in optimisation in comparison to other conventional methods [6]. For instance, GAs have been used extensively in different areas of chemical engineering process design and operation, such as, distillation system [7], semi-batch reactor [8], multi-phase catalytic reactor (hydrogenation reaction system)

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[9], microchannel reactor (emerged as a novel technology for the synthesis of liquid hydrocarbons applications) [10] and steam reforming of hydrocarbons for the generation of hydrogen and synthesis gas [11]. Also, Fang et al. [12] have combined an integrated Neural Network (NN) dynamic model and GA approach to optimise the performance of a full-scale municipal wastewater treatment plant with substantial influent fluctuations.

The use of GA to optimise the seawater RO desalination processes has already been implemented in a number of studies. Guria et al. [5] used the multi-objective optimisation and Non-dominated Sorting Genetic Algorithm (NSGA) technique for desalination of seawater using a spiral-wound and tubular RO modules. The optimisation problem consisted two or three objective functions of maximizing the water flux in addition to minimizing the permeate concentration and cost of filtration of a real existing plant. Murthy and Vengal [4] used a single objective genetic algorithm technique (SGA) to optimize the rejection of NaCl in a laboratory scale RO desalination system of a disc-shaped flat cellulose acetate membrane. The experiments were carried out by varying the inlet feed flow rate and the overall water flux at constant feed concentration. In this study, the mechanism of water and solute transport are measured using the Spiegler and Kedem model. Djebedjian et al. [13] implemented GA with a solution-diffusion model to optimize the performance of a real RO desalination plant predicted the best operating pressure difference across the membrane, which enhances the water flux with low permeate concentration. Moreover, the modelling and prediction of the membrane fouling rate in a micro-filtration (MF) pilot-scale drinking water production system was achieved using the genetic programming by Lee et al. [14]. Park et al. [15] used GA for analysing the performance of pilot-scale RO system. Bourouni et al. [16] used GA to optimise the optimal configuration of a hybrid system of a small RO unit coupled with renewable energy source (photovoltaic and wind). Finally, Yuen et al. [17] used the non-dominated sorting genetic algorithm (NSGA) to maximize the removal of ethanol from the beer and minimize the removal of the extract (taste chemicals) for hollow fibre lab-scale beer dialysis module.

In contrast, to the best of our knowledge, the optimisation of RO based wastewater treatment using GA has been rarely used to find the optimal values of operation that can be achieved within the manufacturer specification. Okhovat and Mousavi [18] used GA to model the rejection of arsenic, chromium and cadmium ions as a function of transmembrane pressure and initial concentration of pollutants in a nanofiltration (NF) pilot-scale system. Soleimani et al. [19] investigated the treatment of oily wastewaters with commercially polyacrylonitrile (PAN) ultra-filtration (UF) membranes by using artificial neural networks (ANNs) to predict the permeation flux and fouling resistance. GA was then used to optimize the operating conditions of trans-membrane pressure, cross-flow velocity, feed temperature and pH. The objective was to maximize the permeation flux while minimizing the fouling behaviour.

To the best of author's knowledge, there has not been any study that uses GA optimisation technique for distributed model for optimising the removal of organic compound such as chlorophenol using a spiral-wound RO process. Therefore, this paper aims to present a one-dimensional model for the rejection of chlorophenol from aqueous solution of different concentrations using a pilot-scale of an individual TFC Polyamide spiral-wound RO filtration system. The distributed model is able to give an accurate picture of the transport across the membrane. An optimisation study of chlorophenol rejection is subsequently implemented using GA. The optimisation process is carried out by manipulating the inlet decision variables of the feed pressure, flowrate and temperature for five different feed concentrations of chlorophenol. The optimized rejections with a constraint of low pressure loss were investigated to provide further evidence of the results.

2. Modelling and simulation of spiral-wound RO

The main objective of this section is to develop a one-dimensional distributed model that can be used to predict accurately the variation of operating parameters along the x-axis of membrane. It is important to understand the interaction between the transport theories through the membrane in order to develop a numerical model that incorporates the spatial variation in fluid properties.

2.1. Assumptions

The following assumptions are made to develop the proposed process model:

1. The solution-diffusion model is used for mass transport through the module.
2. The membrane characteristics and the channel geometries are assumed constant.
3. Validity of Darcy's law where the friction parameter is used to characterize the pressure drop in the feed channel.
4. Constant atmospheric pressure at the permeate channel.
5. A constant solute concentration is assumed in the permeate channel and the average value will be calculated from the inlet and outlet permeate solute concentrations.
6. The underlying process is assumed to be isothermal.

3.2. Governing equations

The water $J_{w(x)}$ and solute $J_{s(x)}$ fluxes (m/s, kmol/m^2 s) can be calculated using the solution-diffusion model of Lonsdale et al. [20] (Assumption 1):

$$J_{w(x)} = A_w(\Delta P_{b(x)} - \Delta\pi_{s(x)}) \quad (1)$$

$$J_{s(x)} = B_s(C_{w(x)} - C_{p(av)}) \quad (2)$$

where A_w, B_s, $\Delta P_{b(x)}$ and $\Delta\pi_{s(x)}$ are solvent transport coefficient (m/atm s), solute permeability coefficients of the membrane (m/s), pressure difference and osmotic pressure difference at any point along the x-axis (atm) respectively. Also, $C_{w(x)}$ and $C_{p(av)}$ (kmol/m^3) are the molar solute concentration on the membrane surface and the average permeate concentration respectively.

The pressure difference between the feed and permeate channels at any point, $\Delta P_{b(x)}$ (atm), is related to the pressure in both the feed and permeate channels.

$$\Delta P_{b(x)} = P_{b(x)} - P_p \quad (3)$$

where $P_{b(x)}$ and P_p (atm) are the feed at any point along the feed channel and constant permeate pressure (Assumption 4) respectively.

The following two equations work well for solute flux and the difference of osmotic pressure:

$$J_{s(x)} = J_{w(x)} C_{p(av)} \quad (4)$$

$$\Delta\pi_{s(x)} = RT_b(C_{w(x)} - C_{p(av)}) \quad (5)$$

$$\Delta\pi_{s(x)} = RT_b\left(\frac{J_{s(x)}}{B_s}\right) \quad (6)$$

where R and T_b $\left(\frac{\text{atm m}^3}{\text{K kmol}} \text{ and K}\right)$ are the gas constant and constant brine temperature (Assumption 6) respectively. The combination of Eqs. (4), (6) and (1) gives.

$$J_{w(x)} = A_w\left(\Delta P_{b(x)} - RT_b\frac{J_{w(x)}C_{p(av)}}{B_s}\right) \quad (7)$$

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