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# Removal of phenol from wastewater using spiral-wound reverse osmosis process: Model development based on experiment and simulation

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ABSTRACT

The removal of the ubiquitous phenol and phenolic compounds in industrial wastes is a critical environmental issue due to their harmful threats to wildlife and potential adverse human health effects. The removal of such compounds is therefore of significant importance in water treatment and reuse. In recent years, reverse osmosis (RO) has been successfully utilised in several industrial processes and wastewater treatment including phenol removal. In this paper, a new model based on a spiral-wound RO process is developed for the removal of phenol from wastewater. A simplified mathematical algorithm using an irreversible thermodynamic approach is developed. This results in a set of non-linear Differential and Algebraic Equations (DAEs), which are solved based on a number of optimised model parameters using a combined methodology of parameter estimation and experimental phenol-water data derived from the literature. The effects of several operational parameters on the performance (in terms of removal of phenol) of the process are explored using the model.

## 1. Introduction

The heavily industrial world we live in today continues to generate large volumes of wastewater containing industrial effluents, sewage and other harmful by-products, which are disposed into rivers and oceans. At the same time, the need for clean potable water continues to increase at a worrying rate due to increase in population and associated demand. The urgent need to treat and reuse water has never been greater in the modern world.

This paper focuses on developing efficient methods for treating wastewater by improving the reliability and efficiency of the underlying separation and filtration processes. The net result of this work is the significant reduction of the probability of accidental release of these harmful compounds into the recycled water by implementing different water treatment approaches in many indirect potable water reuse schemes [1].

Phenol and phenol compounds (aromatic compounds) represent a significant group of pollutants present in wastewater resulting from the manufacture of pesticides, herbicides, disinfectants, pharmaceuticals and dyes [2]. Also, the presence of trace amounts of these compounds has restricted the reuse of water in different industrial applications [3]. The successful treatment processes of phenol compounds removal from wastewater include catalytic wet air oxidation (CWAO), UV/$H_2O_2$ and RO. CWAO used trickle bed reactor using CUO, Zn, CO oxides as a heterogeneous catalyst and pure oxygen as oxidant of phenol [4]. However, the UV/$H_2O_2$ process requires a lot of energy but with a risk of increasing the carbon concentration of the reused water [5]. Among these technologies, RO is very promising, because of its ability to remove water/wastewater constituents such as phenol compounds [6–8]. Additionally, the rapid growth of RO as a commercially attractive separation process in seawater desalination has paved the way for industrial effluents treatment as a promising technology for water recycling and reuse [9,10]. Thus, seawater desalination and wastewater treatment are the core technologies for producing clean water [11] and provided valuable opportunity to avoid the complete diminution of fresh water resources [12]. Specifically, the use of RO as a key treatment process in water reclamation applications has been confirmed to offer several advantages including; minimum thermal damage, high packing density as well as lower energy consumption [13].

Several RO theoretical transport models have been explored by various researchers to predict solute and solvent fluxes resulting in three types of models; the pore model (diffusion and convection-based), the nonporous model (diffusion–based) and the phenomenological model based on thermodynamic [14]. The solution-diffusion and the irreversible thermodynamic models are the most widely used to describe the performance of membrane separation systems. The validity of these models has been tested by Murthy and Gupta [15] who

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**Nomenclature**

| | |
|---|---|
| b | Feed channel friction parameter (atm s/m$^4$) |
| $B_s$ | Solute transport coefficient considering the Solution-diffusion model (Eq. (4)) (m/s) |
| $C_{p(av)}$ | Average permeate solute concentration in the permeate channel (kmol/m$^3$) |
| $C_{s(x)}$ | Brine solute concentration in each point along the x-axis (kmol/m$^3$) |
| $C^{\sim}_{s(x)}$ | The mean solute concentration in each point along the x-axis (kmol/m$^3$) |
| $C_{w(x)}$ | Solute concentration at the membrane wall in each point along the x-axis (kmol/m$^3$) |
| $D_{b(x)}$ | Diffusivity of feed in each point along the x-axis (m$^2$/s) |
| $F_{b(x)}$ | Feed flow rate in each point along the x-axis (m$^3$/s) |
| $F_{p(x)}$ | Permeate flow rate in each point along the x-axis (m$^3$/s) |
| $F_{p(Total)}$ | Total permeated flow rate for the whole unit (m$^3$/s) |
| $J_{s(x)}$ | Solute molar flux through the membrane in each point along the x-axis (kmol/m$^2$ s) |
| $J_{w(x)}$ | Water flux in each point along the x-axis (m/s) |
| $k_{(x)}$ | Mass transfer coefficient in each point along the x-axis (m/s) |
| L | Length of the membrane (m) |
| $L_p$ | Solvent transport coefficient (m/atm s) |
| $P_{b(x)}$ | Feed pressure in each point along the x-axis (atm) |
| $P_p$ | Permeate pressure (atm) |
| R | Gas low constant $\left(R=0.082\frac{\text{atm m}^3}{\text{K kmol}}\right)$ |
| $Rec_{(Total)}$ | Total water recovery for the whole unit (dimensionless) |
| $_{Rej}$ | The rejection coefficient of the membrane (dimensionless) |
| $T_b$ | Feed temperature (°C) |
| $t_f$ | Feed spacer thickness (m) |
| W | Width of the membrane (m) |
| x | The dimension along the x-axis (m) |
| $\Delta x$ | Length of sub-section (m) |
| $\Delta P_{b(x)}$ | Trans-membrane pressure in each point along the x-axis (atm) |
| $\Delta\pi_{s(x)}$ | The osmotic pressure difference in each point along the x-axis (atm) |
| $\sigma$ | Reflection coefficient (dimensionless) |
| $\omega$ | The solute permeability constant of the membrane (Spiegler-Kedem model) (kmol/m$^2$ s atm) |
| $\phi_{(x)}$ | Parameter defined in Eq. (17) |

confirmed that the Spiegler and Kedem model is more accurate for estimating the membrane performance. Having said this, Mujtaba [16] showed that the solution-diffusion model is the simplest model and one that is widely used for describing the mechanism of transport in RO systems. Geraldes et al. [17] have developed a one-dimensional model for spiral-wound RO membranes based on the solution-diffusion model but neglected the diffusion flow in the feed side. Sagne et al. [18] have considered an unsteady state one-dimensional model based on the solution-diffusion model for the rejection of dilute aqueous solution of five volatile organic compounds from brackish water. However, the model neglected the concentration polarisation impact. Oh et al. [19] developed a one-dimensional model based on the solution-diffusion model to analyse the performance of a spiral-wound RO process. This assumes a constant mass transfer coefficient and a constant water flux. Kaghazchi et al. [20] proposed a one-dimensional model based on the solution-diffusion model and the bulk flow rate is calculated as an average value of inlet and outlet feed flow rates.

In summary, sea and brackish water desalination have been extensively modelled as one-dimensional models with several assumptions [21]. However, a limited number of published models describing spiral-wound RO process especially for wastewater treatment is available in the literature [22].

For example, Ahmad et al. [23] developed a lumped model for unsteady state simulation based on the extended Spiegler and Kedem model. They then validated it with experimental data of pre-treated palm oil mill effluent as a feed using a pilot plant scale RO system. Verliefde et al. [24] proposed a transport model based on the Spiegler and Kedem model for the rejection of organic solutes for nano-filtration membranes. While, Sundaramoorthy et al. [25] developed a one-dimensional model by assuming the validity of the solution-diffusion model and validated it against the experimental data of chlorophenol Later, Fujioka et al. [26] have developed a one-dimensional model based on the irreversible thermodynamic model and used an iteration method to obtain the friction parameter.

To the best of author's knowledge, only Fujioka et al. [26] developed a distributed model for a spiral-wound RO process for wastewater treatment relying on the Spiegler and Kedem model. The model assumed zero pressure at the permeate side and was validated with experimental data of N-nitrosamine rejection.

Although there are number of methods applied for the removal of phenol from wastewater, spiral-wound RO process is selected in this research to investigate in detail the effectiveness of this process. Although experimental investigation would be desirable, it has been decided to resort to a model-based investigation methodology accepting the fact that a reliable model must be used for this purpose. Firstly, a detailed one-dimensional process model is developed relaxing the assumption made by Fujioka et al. [26]. Secondly, several model parameters have been estimated using a parameter estimation technique [27] combined with experimental data of Srinivasan et al. [28]. Finally, the validated model is used in simulation mode to assess in detail the effect of various design and operating parameters on the performance of the RO process in terms of removal of phenol from wastewater.

## 2. Model development

### 2.1. The assumptions

The following assumptions are considered to develop the new model:

a) A flat membrane sheet with negligible channel curvature.

b) Validity of the Spiegler-Kedem model for the transport of water and solute through the membrane.

c) Validity of the Darcy's law where a constant friction parameter is assumed to characterise the pressure drop.

d) Constant pressure of 1 atm on the permeate side.

e) Constant solute concentration in the permeated channel and the average value is calculated from the inlet and outlet calculated concentrations.

f) Complete mixing in the y-axis of the feed channel due to the existence of a network of spacers.

g) Isothermal process.

### 2.2. Governing equations

The working equations of the non-linear solvent and molar solute fluxes are [29]:

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

$$J_{s(x)} = J_{w(x)}(1-\sigma)C^{\sim}_{s(x)} + \omega\Delta\pi_{s(x)} \quad (2)$$

Where $\sigma$ is the reflection coefficient and equals zero for complete coupling between the solvent and solute fluxes within the membrane