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Modeling of concentration polarization and permeate flux variation in a roto-dynamic reverse osmosis filtration system

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HIGHLIGHTS

- CFD model to predict concentration polarization (CP) on membrane interface
- Roto-dynamic filtration system used for reverse osmosis in laminar regime of operation
- Shear rate created by rotor, helps to reduce CP layer and enhance the permeate flux.
- Permeate flux does not change much with aspect ratio but increases with feed pressure.
- Feed flow rate increase shear rate but not effective to increase permeate flux.

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ABSTRACT

Concentration polarization (CP) is a critical issue during desalination by cross-flow reverse osmosis (CFRO) filtration system and it is known that shear rate on the membrane surface can help its mitigation. Roto-dynamic filtration systems provide an easy way to generate high shear rate on membrane surface, and hence reducing CP. However the studies related to the growth of CP layer in roto-dynamic CFRO filtration is very limited. In this paper we developed a computational frame-work where flow and solute transport were simulated using ANSYS-Fluent V14.5 but physics of reverse osmosis through the membrane were implemented using “user defined functions” (UDFs). The development of the CP layer in a roto-dynamic CFRO filtration system has been discussed for different operating conditions such as inlet location, rotation speed, gap between the disk and the membrane and feed pressure. The effects of these parameters on permeate flux are also discussed. It is noted that angular speed of rotor and feed pressure are very effective parameters than others to enhance the permeate discharge. The understanding about the CP layer growth and its influence on permeate flux from the present study will help in better and efficient design of roto-dynamic CFRO filtration systems.

1. Introduction

Researches in desalination and wastewater recycling are presently directed towards enhancing the filtration efficiency and reducing the cost and environmental footprint of these processes [1]. Spiral wound membrane is an important component of cross flow reverse osmosis (CFRO) systems as employed during desalination and wastewater recycling. These membranes face major operational issues such as scaling and fouling, which further lead to uneven flow distribution and increase in friction. Accumulation of salt on the membrane surface or concentration polarization (CP) is identified as the main cause, which further reduces the permeate flux due to osmotic pressure build-up across the membrane. CP in spiral wound systems has been extensively studied numerically and experimentally [2–13]. One of the widely used mitigation measure includes the use of spacers, facilitating the flow on the retentate side to increase of the shear rate on the membrane surface. The effect of shear rate cannot be totally harnessed in spiral wound cross low filtration systems as there is a trade-off between the reduction of CP layer and the increase in pressure drop [1]. Jaffrin [14,15] discussed the role of roto-dynamic filtration systems, which involve a rotating discover a membrane, or a rotating membrane in an enclosed chamber. This rotary action imparts motion to the feed flow and generates high shear rate on the membrane surface. Thus roto-dynamic filtration systems are promising as they inherently decouple the pressure drop and shear rate on the membrane surface. The benefits of dynamic filtration are two folds [16]. Firstly these ensure lesser accumulation of solute on the membrane surface and hence decrease the solute/salt transmission to the permeate side. Secondly, the rotating disk systems within a certain range of angular velocity produce different flow

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structures with co-existence of circular and spiral waveforms. These waveforms, which are formed on both rotating and stationary walls [24] assist further reduction of CP layer on the stationary membrane.

The CP layer formation, its growth and its behavior with varying flow characteristics has been extensively studied for CFRO systems. The growth of the CP layer along the flow has been observed experimentally and successfully replicated numerically with the help of CFD calculations. The two way coupling between the permeate flux which builds the CP layer and the CP layer in-turn reducing the flow to the membrane through resistance is established and can be simulated. It is also known that the effect of increase in shear rate on the membrane surface reduces solute concentration polarization and hence the osmotic pressure [36,37]. This in turn increases the trans-membrane driving pressure and hence the permeate flux rate. Also it is known that the CP layer keeps on growing along the length of the channel [35–37].

Unfortunately in the literature, there is a dearth of studies which try to build a similar understanding for CP in roto-dynamic systems. This essentially forms a motivating factor for the authors to work towards fundamental understanding of the concentration polarization in dynamic filtration systems. To the best of authors' knowledge, the past attempts and studies [28–30,38] related to dynamic filtration mainly focused on experimental studies of ultra and nano-filtration processes. Some of those also performed computational simulations to compare the integral permeate flux with the experimental results. It was apparent from those studies that operating parameters such as angular speed of the rotating plate (Ω), gap between the plate and membrane (h) and magnitude of the feed flow (Q) affect permeate flux. However there are no discussions available in literature about the effect of above-mentioned parameters on the development of the CP-layer, in time and space inside a dynamic filtration system. It is important to quantify the effect of these parameters on the shear rate, CP layer thickness and permeate flux. So this gap in literature defines a goal of this study. It will help to develop an understanding and hence the suitable range of these parameters to build efficient and economic roto-dynamic filtration systems. However there are certain issues such as the requirement of huge surface areas and operational cost for large-scale RO or NF plant, may be of concern for its suitability in commercial desalination plant. So further researches may be needed to design suitable roto-dynamic RO filtration systems, which can overcome the above-mentioned limitations.

The analysis of roto-dynamic filtration systems will have two major aspects, one being the hydrodynamics of such systems and second being the solute transport modeling for the RO process. The permeate flow rates through the membrane in such filtration systems are usually very small as compared to the feed flow rates. Hence it can be assumed that the effect of permeate flow rate on the flow pattern within the rotary reverse osmosis system is negligible and flow can be analyzed based on the extensive studies of closed stator–rotor cavity systems in fluid mechanics literatures. For the stator–rotor cavity system, the disk rotation leads to an axisymmetric flow pattern with two distinct boundary layers formed near the stator and the rotor [17]. In addition to the swirl velocity, the flow within the boundary layers near rotor and stator is radially outward and inward respectively [18]. Thus a flow field resembling the cross flow filtration over the membrane is developed. These boundary layers may be merged or disjoint. In the case of a disjoint boundary layer a centrally rotating or non-rotating fluid core exists [17,19]. The nature of flow field inside a roto-dynamic system is governed by the angular speed of the rotor and the gap between stator and rotor [20–24]. The dimensionless parameters, which can be used to characterize various base flow patterns in a stator–rotor cavity, are Reynolds number (Re) and aspect ratio (G) [25]. In terms of the velocity scale (ΩR) and length scales (R, h) these parameters are defined as follows,

$$\mathrm{Re} = \frac{\Omega R^2}{\nu} \quad \text{and} \quad G = \frac{h}{R}, \tag{1}$$

where Ω, R, h and ν are respectively angular speed of the rotor, radius of the rotary system, gap between rotor and stator, and kinematic viscosity of fluid. Daily et al. [25] presented a figure indicating different flow regimes in the (Re, G) parameter space. This figure serves as the essential reference map distinguishing various flow regimes such as laminar, turbulent, joint or disjoint boundary layers etc. For continuous operation of cross-flow filtration, a feed flow (Q) is maintained by including inlet and outlet to the rotor cavity system. Poncet et al. [26,27] demonstrated that the magnitude of the feed flow affects the nature of the base flow created due to rotation of the rotor. They proposed the following dimensionless variable to quantify the effect of feed flow rate on the velocity field.

$$Q^* = \frac{Q}{\nu R} \tag{2}$$

They found experimentally that weak through-flow preserves the base flow inherent to a stator–rotor cavity system, but as the feed flow becomes strong it dominates the flow field characteristics and the flow pattern can significantly change. Bouzerar et al. [28] studied dynamic-ultra and nano filtration systems. They compared the vibratory separation systems with the rotary systems. They found that the rotary systems were superior in performance. Torras et al. [29,30] performed experimental study on ultra and nano-filtration rotary disk device. They observed the increase in the trans-membrane pressure due to the decrease in osmotic pressure, which was an outcome of a reduced CP layer. Thus their experimental investigation confirmed the influence of shear rate on permeate flux. Later Ling et al. [31] performed numerical studies considering the permeate flux along with fluid flow, but neglecting the species transport. They discussed the radial variation of permeate flux, trans-membrane pressures and effect of spacers.

Accurate prediction of concentration polarization during cross-flow filtration in a rotary system requires a suitable model for physics of reverse osmosis. Wijmans et al. [32] provided the basic review on the pore flow model and the solution–diffusion RO model. They derived the required phenomenological equations based on the solution–diffusion model and validity of the model was demonstrated. Sabalani et al. [33] critically reviewed the published studies on CP in ultrafiltration and reverse osmosis processes and suggested quantification techniques with a review of experiments performed to visualize and quantify concentration polarization. Paul [34] presented the reformulation of the solution diffusion theory so as to bring the non-linear flux behavior in to picture which becomes significant with increased feed flow concentrations. The solution diffusion model seems to be the widely accepted one and many researchers used this approach to simulate the fully coupled fluid flow, species transport and reverse osmosis. Ahmad et al. [35] simulated CP layer development in channel along the direction of flow. They used ANSYS-Fluent V6.0 to model flow and transport but assumed the membrane to be impermeable wall while simulating the fluid flow inside the channel. Wardeh et al. [36] simulated flow and transport in a channel that was filled with spacer using CFX for reverse electrodialysis applications. For incorporating the RO physics, both of these numerical studies developed user defined functions, which were linked to the solver. Recently Diaz et al. [37] performed an experimental study and simulated using COMSOL for modeling RO in a slit type channel. The effect of cross flow and shear rate on the concentration polarization was studied at different Reynolds numbers in the laminar regime. These researches helped understand the growth of the CP layer in the cross flow reverse osmosis process.

In the present work we have simulated RO filtration in a roto-dynamic system using ANSYS-Fluent V14.5. We have noted that in most of the reported work in the literature [28–30], the values of Q^* were quite high (approximately between 230 and 691), and the effect of disk rotation was superseded by the feed flow rate to a large extent. In those previous studies the shear rate on the membrane surface was mainly generated due to the feed flow rate and the disk rotation seemed to be redundant. This important aspect was considered in this paper